1990

Gold mineralization at the American Girl B-zone mine Cargo Muchacho Mountains southeasternmost California

Raul H. Borrastero
The University of Montana

Let us know how access to this document benefits you.
Follow this and additional works at: https://scholarworks.umt.edu/etd

Recommended Citation
Borrastero, Raul H., "Gold mineralization at the American Girl B-zone mine Cargo Muchacho Mountains southeasternmost California" (1990). Graduate Student Theses, Dissertations, & Professional Papers. 7578.
https://scholarworks.umt.edu/etd/7578

This Thesis is brought to you for free and open access by the Graduate School at ScholarWorks at University of Montana. It has been accepted for inclusion in Graduate Student Theses, Dissertations, & Professional Papers by an authorized administrator of ScholarWorks at University of Montana. For more information, please contact scholarworks@mso.umt.edu.
GOLD MINERALIZATION AT THE AMERICAN GIRL B-ZONE MINE,
CARGO MUCHACHO MOUNTAINS, SOUTHEASTERNMOST CALIFORNIA.

By

Raúl H. Borra.stero

B. S., Universidad Nacional de Córdoba, Argentina, 1981

Presented in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

University of Montana

1990

Approved by

[Signatures]

Chairman, Board of Examiners

Dean, Graduate School

Date

April 27, 1990
UMI Number: EP38379

All rights reserved

INFORMATION TO ALL USERS
The quality of this reproduction is dependent upon the quality of the copy submitted.

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

UMI
Dissertation Publishing

UMI EP38379
Published by ProQuest LLC (2013). Copyright in the Dissertation held by the Author.
Microform Edition © ProQuest LLC.
All rights reserved. This work is protected against unauthorized copying under Title 17, United States Code
Gold Mineralization at the American Girl B-Zone Mine, Cargo Muchacho Mountains, Southeasternmost California, (112 pp.)

Director: Ian M. Lange

The American Girl B-zone mine is located in the Cargo Muchacho Mt (CMM), Imperial Co., CA, 20 km NW of Yuma, AZ. The CMM are in the upper plate of the SW-dipping Laramide age Chocolate Mt Thrust. Other regional structural events include mid-Tertiary detachment and the late Tertiary San Andreas Transform Fault.

The CMM consist of mid-Jurassic quartzo-feldspathic gneisses with minor schists, and a co-magmatic suite of granitic rocks (diorite to leucogranite). Gold deposits are spatially associated with and controlled by low angle (15-40°) faults. High angle normal faults crosscut the low angle structures and ore zones.

The B-zone forms part of a group of structurally stacked Au-mineralized low angle shear zones. It is located below the Am. Girl-Main and above the C-zone. The B-orebody lies within a low angle fault zone between gneissic granites (footwall) and quartzo-feldspathic gneisses (hanging wall). It strikes N 70° W and dips 17-30° SW crosscutting the foliation and general structure of the wall rocks. It is 350m long, 150m wide and 1.5-8.4m thick. The base of the ore is marked by a thin, continuous clay-gouge (base-structure) and a 0.1-1.5m wide chlorite breccia zone.

The B-orebody is characterized by folded areas of massive Au-bearing quartz veins, gneiss and schist, that were subsequently fractured, brecciated and mineralized. Minerals include native Au, pyrite, chalcopyrite, galena, magnetite, scheelite, quartz, calcite and fluorite. Types of disseminated Au-bearing mineralization include: (1) massive quartz veins, (2) banded quartz vein-pyritic schist, and (3) gneiss and schist. Wall rock alteration consists of widespread propylitization (chl-ep-cc), and a phyllitic assemblage (ser-qz) restricted to the ore zone. The Ag/Au ratios are low (0.9). Fluid inclusions from Au-bearing quartz gave Th of 272-300°C, and low salinities (1-9% NaCl eq).

Structural and textural evidence suggest formation of the B-orebody by a combination of two hydrothermal events that probably resulted from the overprinting of mid-Tertiary detachment on Laramide thrusting. Important similarities between the B-zone and nearby gold deposits (e.g. Picacho, Mesquite, Riverside) indicate that the B-orebody may have been partially formed by similar processes (detachment fault-related) but at deeper crustal levels (lower plate setting) than the other deposits.
ACKNOWLEDGEMENTS

I would like to thank the American Girl Mining Company for providing the opportunity to work during the summer of 1988, information regarding the deposit, and logistic support throughout this study. The exchange of ideas with Richard Thompson (formerly with American Girl Co.), Dennis Laybourn and Judy Moore was most valuable. Also, the staff and personnel of the company in general were always ready to help.

I am especially indebted to Dr. Ian Lange, Chairman of the Thesis Committee, for his continuous and always important help and advice both personal and academic throughout my stay at the University of Montana. Dr. James Sears and Dr. Keith Osterheld gracefully agreed to be members of the Thesis Committee. Dr. Roy Krouse from the University of Calgary, provided sulfur isotope determinations. John Cuplin and Scott Helm helped in taking the slides for thesis presentation. Finally, my especial thanks to all the Faculty, Staff and fellow students at the Geology department, who make the Graduate Program most enriching and enjoyable.
## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Location</td>
<td>1</td>
</tr>
<tr>
<td>Brief Mining History of the Cargo Muchacho</td>
<td>1</td>
</tr>
<tr>
<td>District</td>
<td>1</td>
</tr>
<tr>
<td>Previous Work</td>
<td>3</td>
</tr>
<tr>
<td>Purpose and Scope</td>
<td>6</td>
</tr>
<tr>
<td>Methodology</td>
<td>6</td>
</tr>
<tr>
<td>II. GEOLOGY OF THE CARGO MUCHACHO MOUNTAINS</td>
<td>7</td>
</tr>
<tr>
<td>Regional Setting</td>
<td>7</td>
</tr>
<tr>
<td>Rock Units</td>
<td>9</td>
</tr>
<tr>
<td>Tumco Formation</td>
<td>9</td>
</tr>
<tr>
<td>Quartz Diorite</td>
<td>11</td>
</tr>
<tr>
<td>Quartz Monzonite</td>
<td>11</td>
</tr>
<tr>
<td>Granite</td>
<td>13</td>
</tr>
<tr>
<td>Leucogranite</td>
<td>13</td>
</tr>
<tr>
<td>Pegmatites</td>
<td>14</td>
</tr>
<tr>
<td>Rhyodacite Porphyry</td>
<td>14</td>
</tr>
<tr>
<td>Metamorphism and Tectonics</td>
<td>14</td>
</tr>
<tr>
<td>Mineralization and Alteration</td>
<td>15</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (continued)

Summary Characteristics of some Gold Deposits 17

Tumco Camp 17

Padre-Madre 17

Cargo Muchacho 18

III. GEOLOGY OF THE AMERICAN GIRL VALLEY 19

Introduction 19

Structure 19

Mineralization and Alteration 22

Alteration Related to Regional Metamorphism? 22

Alteration Related to Gold Mineralization 25

Fluid Inclusions 27

Stable Isotopes 28

Summary Charact. of the Old Amer. Girl Mine 28

IV. GEOLOGY OF THE AMERICAN GIRL "B" ZONE 31

Introduction 31

General Characteristics 31

Structure and Geometry 39

Lower Plate 39

Upper Plate 42

Discussion 45

Lithologies 47

Footwall 48

Ore Zone: Types of Gold Mineralization 49

I. Massive Quartz Veins 49
### TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>II. Banded Quartz Veins-Pyritic Schist</td>
<td>51</td>
</tr>
<tr>
<td>III. Pyritic Tumco Rocks</td>
<td>51</td>
</tr>
<tr>
<td>Hanging Wall</td>
<td>52</td>
</tr>
<tr>
<td>Mineral Textures and Paragenesis</td>
<td>52</td>
</tr>
<tr>
<td>Massive Gold-bearing Quartz Veins</td>
<td>55</td>
</tr>
<tr>
<td>Pyrite-Magnetite-Chalcopyrite-Galena (Gold?)</td>
<td>56</td>
</tr>
<tr>
<td>Scheelite</td>
<td>56</td>
</tr>
<tr>
<td>Carbonates (Fluorite)</td>
<td>57</td>
</tr>
<tr>
<td>Wall Rock Alteration</td>
<td>57</td>
</tr>
<tr>
<td>General Distribution</td>
<td>57</td>
</tr>
<tr>
<td>Alteration Mineral Assemblages</td>
<td>59</td>
</tr>
<tr>
<td>Chlorite-Epidote-Calcite (Propylitic Alt.)</td>
<td>59</td>
</tr>
<tr>
<td>Sericite-Quartz (Phyllitic Alteration)</td>
<td>61</td>
</tr>
<tr>
<td>Metal Zoning</td>
<td>63</td>
</tr>
<tr>
<td>Distribution of Gold</td>
<td>63</td>
</tr>
<tr>
<td>Metal Ratios</td>
<td>65</td>
</tr>
<tr>
<td>Fluid Inclusions</td>
<td>66</td>
</tr>
<tr>
<td>Sulfur Isotopes</td>
<td>68</td>
</tr>
<tr>
<td>V. DISCUSSION AND INTERPRETATIONS</td>
<td>73</td>
</tr>
<tr>
<td>Controls of Alteration-Mineralization</td>
<td>73</td>
</tr>
<tr>
<td>Paragenetic Sequence of the B-orebody</td>
<td>75</td>
</tr>
<tr>
<td>Genetic Models</td>
<td>81</td>
</tr>
<tr>
<td>Comparison of the B-orebody with Nearby Gold Deposits</td>
<td>87</td>
</tr>
<tr>
<td>Deposits within the American Girl Valley</td>
<td>87</td>
</tr>
<tr>
<td>TABLE OF CONTENTS (Continued)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposits within the Cargo Muchacho Mountains</td>
<td>88</td>
</tr>
<tr>
<td>Deposits within Southeasternmost California</td>
<td>90</td>
</tr>
<tr>
<td>VI. CONCLUSIONS AND RECOMMENDATIONS</td>
<td>94</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>98</td>
</tr>
<tr>
<td>APPENDIX I. STATISTICAL ANALYSIS OF METAL GRADES</td>
<td>104</td>
</tr>
<tr>
<td>Summary Statistics</td>
<td>104</td>
</tr>
<tr>
<td>Correlation Coefficient</td>
<td>108</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Location of the American Girl Mine</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Location of Mines and Prospects, Cargo Muchacho Mountains</td>
<td>4</td>
</tr>
<tr>
<td>3.</td>
<td>Generalized Regional Geologic Map of Southeasternmost California</td>
<td>8</td>
</tr>
<tr>
<td>4.</td>
<td>Generalized Geology of the Cargo Muchacho Mountains</td>
<td>10</td>
</tr>
<tr>
<td>5.</td>
<td>Geologic Map of the American Girl Valley, Cargo Muchacho Mountains</td>
<td>20</td>
</tr>
<tr>
<td>6.</td>
<td>Geologic Longitudinal Section of the American Girl Valley</td>
<td>23</td>
</tr>
<tr>
<td>7.</td>
<td>Geologic Cross Section of the American Girl Valley</td>
<td>24</td>
</tr>
<tr>
<td>8.</td>
<td>Map of Alteration Zones and Gold Reserves in the American Girl Valley</td>
<td>26</td>
</tr>
<tr>
<td>9.</td>
<td>$\delta^{18}O$ and $\delta D$ Data from the American Girl and Padre-Madre deposits</td>
<td>29</td>
</tr>
<tr>
<td>10.</td>
<td>Generalized Geologic Cross Section of the B-Shear Zone and B-Orebody</td>
<td>32</td>
</tr>
<tr>
<td>11.</td>
<td>Schematic Geologic Longitudinal Section of the B-Ore Zone</td>
<td>34</td>
</tr>
<tr>
<td>12.</td>
<td>Structural Contour, Top of &quot;B&quot; Fault Zone</td>
<td>35</td>
</tr>
<tr>
<td>13.</td>
<td>Structural Contour, Top of B-Orebody</td>
<td>36</td>
</tr>
<tr>
<td>14.</td>
<td>Structural Contour, Base of B-Orebody</td>
<td>37</td>
</tr>
<tr>
<td>15.</td>
<td>Structural Contour, Base of B-Fault Zone</td>
<td>38</td>
</tr>
<tr>
<td>16.</td>
<td>Photograph, Feeder vein</td>
<td>40</td>
</tr>
<tr>
<td>17.</td>
<td>Photograph, Chlorite Breccia</td>
<td>40</td>
</tr>
<tr>
<td>18.</td>
<td>Photomicrograph, Chlorite Breccia</td>
<td>41</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>19.</td>
<td>Photograph, Anastomosing Fault Pattern</td>
<td>41</td>
</tr>
<tr>
<td>20.</td>
<td>Photograph, Ductile Deformation</td>
<td>43</td>
</tr>
<tr>
<td>21.</td>
<td>Photograph, Ductile Deformation</td>
<td>43</td>
</tr>
<tr>
<td>22.</td>
<td>Photograph, Curviplanar Normal Fault</td>
<td>44</td>
</tr>
<tr>
<td>23.</td>
<td>Photomicrograph, Post-mineralization Breccia</td>
<td>44</td>
</tr>
<tr>
<td>24.</td>
<td>Isopach Contour of the B-Orebody</td>
<td>46</td>
</tr>
<tr>
<td>25.</td>
<td>Photograph, Ore Types I and II</td>
<td>50</td>
</tr>
<tr>
<td>26.</td>
<td>Photomicrograph, Chlorite stockwork</td>
<td>50</td>
</tr>
<tr>
<td>27.</td>
<td>Photomicrograph, Pyrite-Magnetite-Chalcopyrite</td>
<td>53</td>
</tr>
<tr>
<td>28.</td>
<td>Photomicrograph, Compositional Layering</td>
<td>53</td>
</tr>
<tr>
<td>29.</td>
<td>Paragenesis of Alteration and Ore Minerals</td>
<td>54</td>
</tr>
<tr>
<td>30.</td>
<td>Photomicrograph, Calcite Stockwork</td>
<td>58</td>
</tr>
<tr>
<td>31.</td>
<td>Photomicrograph, Late stage Calcite Veining</td>
<td>58</td>
</tr>
<tr>
<td>32.</td>
<td>Photomicrograph, Fine Grain Quartz veinlets</td>
<td>62</td>
</tr>
<tr>
<td>33.</td>
<td>Photomicrograph, Sericite (± quartz) vein</td>
<td>62</td>
</tr>
<tr>
<td>34.</td>
<td>Gold Grade Distribution, B-Orebody</td>
<td>64</td>
</tr>
<tr>
<td>35.</td>
<td>Fluid Inclusion Data from Gold-Bearing Quartz Veins, B-Orebody</td>
<td>67</td>
</tr>
<tr>
<td>36.</td>
<td>Distribution of δ²⁹S in Epithermal Deposits</td>
<td>72</td>
</tr>
<tr>
<td>37.</td>
<td>FO₂-pH Diagram Showing Mineral Stabilities</td>
<td>74</td>
</tr>
<tr>
<td>38.</td>
<td>Schematic Genetic Model for the American Girl B-zone</td>
<td>85</td>
</tr>
<tr>
<td>39.</td>
<td>Distribution of Gold Grades, B-orebody</td>
<td>105</td>
</tr>
<tr>
<td>40.</td>
<td>Distribution of Silver Grades, B-orebody</td>
<td>106</td>
</tr>
<tr>
<td>41.</td>
<td>Distribution of Copper Grades, B-orebody</td>
<td>107</td>
</tr>
</tbody>
</table>
LIST OF FIGURES (continued)

42. Scatter Plot of Gold and Silver Grades 110
43. Scatter Plot of Copper and Gold Grades 111
44. Scatter Plot of Copper and Silver Grades 112


<table>
<thead>
<tr>
<th>TABLE</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Chronologic Summary of Geologic Events in the Cargo Muchacho Mountains</td>
<td>12</td>
</tr>
<tr>
<td>2.</td>
<td>Approximate Average Abundance of Alteration Minerals in the American Girl B-Zone</td>
<td>60</td>
</tr>
<tr>
<td>3.</td>
<td>Sulfur Isotopes Data, B-Orebody</td>
<td>70</td>
</tr>
<tr>
<td>4.</td>
<td>Tentative Paragenetic Sequence of the B-orebody Mineralization</td>
<td>76</td>
</tr>
<tr>
<td>5.</td>
<td>Comparison of the American Girl B-zone Deposit with other Gold Deposits in Southeasternmost California</td>
<td>91</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

Location

The American Girl mine is at the center of the Cargo Muchacho mountains, Imperial County, southeasternmost California, approximately 20 km northwest of Yuma, Arizona (Fig. 1 and 3). The area is part of the Mohave Desert physiographic province with elevations ranging from 200 to 800 meters above sea level. Rocks are generally well exposed except where covered by gravel along valley bottoms and talus along slopes.

This report is divided into two parts. Chapter I through III present background information. Chapters IV through VI present data derived from this study on the American Girl B-zone deposit and environs.

Brief Mining History of the Cargo Muchacho District

Mining activity in the district began as early as the end of the 1700’s as a small placer operation (Henshaw, 1942). However, production was not recorded until 1879, and through 1950 an estimated 215,000 ounces of gold were produced from mines located in the Tumco, American Girl, Padre-Madre and Cargo Muchacho valleys (Morton, 1977) (Fig. 2).

Mining at the old American Girl mine began in 1892 and continued on a small scale until 1916. It was reopened in 1936 and produced gold until 1939 (Morton, 1977). In 1977, Newmont Exploration Limited
FIGURE 1: Location of the American Girl Mine (adapted from Morton, 1977).
initiated an exploration program that resulted in the delineation of nine economic gold-bearing zones, with an open pit mineable reserve of 6.4 million short tons that grade 0.051 oz Au/ton (1.75 ppm), located in the Padre-Madre and American Girl canyon areas, and an underground reserve of 1.2 million short tons that grade 0.232 oz Au/ton (7.95 ppm), in the American Girl canyon area (current American Girl B-zone mine) (Guthrie, et al, 1987).

In 1986, Eastmaque Gold Mines Limited purchased the Cargo Muchacho property, and formed its subsidiary American Girl Mining Corporation to exploit the deposits. Since January 1989, American Girl Mining Joint Venture, a joint venture between Eastmaque and Morrison-Knudsen, has been operating the deposits. The underground mine development and mill construction for the American Girl "B" zone orebody is presently underway. Also, 4,000 tons/day of ore are produced from two open pit operations at the Padre-Madre area. The crushed ore is placed on heaps and leached by a weak sodium cyanide solution. Gold is extracted by a three stage carbon stripping system (Eastmaque Limited Annual Report, 1987).

Previous Work

The first real account of the geology and mineralization of the Cargo Muchacho mountains was carried out by Henshaw (1942). This author stated that all previous geological work in the area consisted in a few brief geological descriptions found in Blake (1853), Draper (1911), and Brown (1918). Henshaw pointed out the mesothermal nature and structural control of ore deposits.
American Girl Valley study area is 33 x 33 km, "J ~ \V', 77, a Padre-Madre Valley.

Hydrothermal systems: Leucogranite, Biotite Granite, Quartz monzonite, Quartz diorite.

Metamorphic and metasomatic rocks:
- Vitrified "formation"
- Tumco Formation

FIGURE 2: Location of Mines and Prospects, Cargo Muchacho Mountains (after Branham, 1988).
Dillon (1976), described in detail the regional geology of southeasternmost California, primarily emphasizing the lithologic and tectonic evolution of the Cargo Muchacho and Chocolate mountains. In their study of the Picacho mine, Drobeck and others (1986), interpreted the Padre-Madre mine as a detachment fault-related deposit, formed at lower structural levels than Picacho.

The idea of multiple events mineralization for the Mohave desert region has been suggested recently by several authors. Gold probably was initially syngenetic according to Chevillon and Norris (1986), or introduced and concentrated during plutonism and/or regional metamorphism (Tosdal and Haxel, 1985). Subsequent events could have remobilized and further concentrated the gold. Tosdal and Smith (1987), described the style of gold mineralization at the American Girl, Padre-Madre and Mesquite mines, considering it distinct from epithermal detachment fault-related such as at the Picacho mine.

Guthrie and others (1987), performed some fluid inclusion and stable isotope work in the area, concluding that the American Girl and Padre-Madre deposits were formed by an amagmatic mesothermal system developed during the waning stages of metamorphism, which they linked to the late Cretaceous-early Tertiary thrusting. Finally, Branham (1988) described the gold deposits in the American Girl valley area, defining two types of gold occurrences: (1) gold-bearing quartz veinlet stockworks that form low grade disseminated zones; and (2) high grade banded quartz-gold veins.
Purpose and Scope

The principal objectives of this investigation were to interpret the relationship of gold occurrences to the wall rocks, mineralogy, and wall rock alteration suite of the low angle, southwest dipping American Girl "B" zone. The study focused on the structural and lithological controls, mineral paragenesis and textures, and metal distribution of the gold-sulfide mineralization. Finally, a genetic model for the formation of the American Girl "B" zone was formulated, which may be applicable to other low-angle fault-related deposits in the region.

Methodology

Detailed geologic mapping at scale 1" = 20' (approximately 1:250) and systematic sampling were conducted in the American Girl B-zone underground mine during July-September 1988. Laboratory work followed consisting of petrographic studies and the examination and testing of fluid-filled inclusions in quartz. Three sulfur isotope analyses of pyrite were also obtained. Structural contour and isopach maps were constructed, and statistical analysis and metal ratios were calculated, in order to better understand the geometry and metal distribution within the deposit.
CHAPTER II

GEOLOGY OF THE CARGO MUCHACHO MOUNTAINS

Regional Setting

The Cargo Muchacho is an isolated mountain range (Fig. 1) that lies within a discontinuous belt of Mesozoic metamorphic core complexes that extend from Sonora, Mexico north through the Cordillera into southwestern Canada (Coney, 1980; De Ridder and Johnson, 1987).

The Cargo Muchacho mountains are in the upper plate of the Chocolate mountains thrust, which presumably underlies the range at an unknown depth (Dillon, 1976; De Ridder and Johnson, 1987). This thrust and an 18 km wide plain of alluvial gravels separate the range from the Chocolate mountains to the north (Fig. 3). The Chocolate mountains thrust (late Cretaceous-early Paleocene) is a major northwest-striking structural feature of southeastern California that separates two distinct geologic terranes (Haxel and Dillon, 1978). Upper plate rocks are continental basement terrains, composed of Proterozoic (?) and Mesozoic gneisses, and granitic rocks metamorphosed to amphibolite facies; lower plate rocks are the Mesozoic Orocopia Schist which exhibits oceanic affinities and probably accumulated outboard of a continental margin (Dillon, 1976; Haxel and Dillon, 1978).

Other major structural events affecting the region include low angle, normal ("detachment") faults of mid-Tertiary age which reflect extensional movement in a southwest-northeast direction (Guthrie, et al, 1987). Finally, the youngest major structure is the easternmost splay of
the late Tertiary San Andreas fault system (Fig. 3).

**Rock Units**

The Cargo Muchacho Mountains consist mainly of middle Jurassic (De Ridder and Johnson, 1987) quartzo-feldspathic gneisses (Tumco Formation) with minor schists (Vitrifax "Formation"), intruded by a Jurassic (Tosdal, et al, 1984), co-magmatic suite of granitic rocks ranging in composition from diorite to leucogranite (Guthrie, et al, 1987; Branham, 1988). Tertiary rocks are limited to rhyodacite dikes that intrude the west flank of the range (Fig. 4), and small remnants of basalt flows, west of the American Girl canyon (Dillon, 1976) (Table 1).

**Tumco Formation**

This formation crops out along the mountain flanks and as septums between granitic rocks (Fig. 4). It consists mainly of fine to medium grained, foliated, biotite quartzo-feldspathic gneiss with interlayered biotite, sericite and hornblende schists and amphibolites (Guthrie, et al, 1987; Dillon, 1976). Henshaw (1942), considered this formation as a metasedimentary sequence. However, the protolith is interpreted by others (e.g. De Ridder and Johnson, 1987; Branham, 1988), as silicic volcanic and volcanioclastic rocks with locally interbedded mafic volcanic units.

A sample taken from the Tumco valley is a dark-green, fine grain, weakly foliated rock, composed of 65% quartz, 25% biotite, 5% K-feldspar, 1% plagioclase, 1% muscovite, 2% magnetite, and minor epidote and sericite; biotite is clearly lineated and polygonal.
FIGURE 4: Generalized Geology of the Cargo Muchacho Mountains (after Branham, 1989).
(recrystallization) textures in quartz are common. Locally, disseminated pyrite up to 2% is also present (Branham, 1988; Ahlrichs, 1978; Diamond Drill Data).

Also included within the Tumco Formation are units and lenses of quartz-kyanite and sericite-biotite schist, informally referred to as the Vitrifax "Formation" (Henshaw, 1942; Dillon, 1976). Campbell and Wright (1950) considered the Vitrifax "Formation" as a regionally metamorphosed series of predominantly pelitic sediments. Dillon (1976) however, suggested that the rocks are a product of hydrogen metasomatism of the Tumco Formation. Presently, its origin is unknown.

Quartz Diorite

This rock is dark gray, medium to coarse grained, composed of 15-20% quartz, 5-10% orthoclase, 40-45% plagioclase, 10-20% biotite, 15-20% hornblende, and 2-5% epidote (Branham, 1988). The biotite-hornblende quartz diorite is strongly foliated and gneissic, grades into granodiorite and intrudes the Tumco Formation (Platt, 1982). The strong foliation and deformation of this unit suggests it is one of the oldest intrusions in the mountain range (Platt, 1982; De Ridder and Johnson, 1987; Branham, 1988) (Table 1).

Quartz Monzonite

Quartz monzonite crops out in the southeastern part of the range (Fig. 4). It is a weakly foliated rock composed by 24-28% quartz, 29-35% k-feldspars, 25-28% plagioclase and lesser amounts of biotite, hornblende and epidote (Ahlrichs, 1978). It varies locally from a well
<table>
<thead>
<tr>
<th>Period</th>
<th>Age (MA)</th>
<th>Name</th>
<th>Rock or Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td></td>
<td>Gravel</td>
<td>Alluvial and talus deposits</td>
</tr>
<tr>
<td>Late Miocene</td>
<td>13-10</td>
<td>Basalt</td>
<td>Olivine basalt flows</td>
</tr>
<tr>
<td>Neogene</td>
<td>?</td>
<td>San Andreas</td>
<td>Rotation and tilting caused by normal and strike-slip faulting (NW-SE)</td>
</tr>
<tr>
<td>Oligocene-Miocene</td>
<td>?</td>
<td>Rhyodacite</td>
<td>Porphyritic sills and dikes</td>
</tr>
<tr>
<td>Eocene-Oligocene</td>
<td>~50</td>
<td></td>
<td>Relaxation and extensional tectonics. Detachment faulting (NE-SW dir.); brittle deform.</td>
</tr>
<tr>
<td>Early Tertiary</td>
<td>70-50</td>
<td></td>
<td>Reg. uplift and cooling, crustal thickening</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>87-70</td>
<td></td>
<td>Major thrusting (Choc. Mt thrust; NE-SW dir.); ductile deformation</td>
</tr>
<tr>
<td>Late Jurassic</td>
<td>?</td>
<td></td>
<td>Regional metamorphism</td>
</tr>
<tr>
<td>Middle Jurassic</td>
<td>165</td>
<td>Granite</td>
<td>Moderately foliated; incl. bi and hb-bi granites leucogranite, pg and apl.</td>
</tr>
<tr>
<td></td>
<td>173</td>
<td>Quartz Monzonite</td>
<td>Weakly foliated; includes a hb-rich variety.</td>
</tr>
<tr>
<td></td>
<td>?</td>
<td>Quartz Diorite</td>
<td>Well foliated; intrudes the Tumco formation</td>
</tr>
<tr>
<td></td>
<td>161</td>
<td>Tumco Formation</td>
<td>Bi-qz-feld gneiss. Includes sericite schist, quartzite and qz-ky (Vitrifax &quot;Fm.&quot;)</td>
</tr>
<tr>
<td>Late Paleozoic</td>
<td>?</td>
<td>?</td>
<td>Highly deformed quartzite and marble; SE of range.</td>
</tr>
</tbody>
</table>

Compiled from Dillon (1976); Platt (1982); De Ridder and Johnson (1987).
foliated, biotite-hornblende bearing porphyry to a massive, medium-grained hypidiomorphic rock (Guthrie, et al, 1987). Contacts between quartz monzonite and the other three principal rock types are relatively abrupt (Platt, 1982).

**Granite**

Granite outcrops in the central portion of the range (Fig. 4), is medium-grained, well to weakly foliated and composed by 10-20% mafics (biotite and hornblende), 25-30% quartz, 25-30% k-feldspar, 30-35% plagioclase, and minor sphene, magnetite, epidote and zircon. Two types of granite are defined depending upon the presence of hornblende: biotite granite (bgr), and hornblende-biotite granite (hbgr). Contacts with the Tumco Formation and other intrusives are generally gradational (Branham, 1988; Guthrie, et al, 1987; Dillon, 1976).

**Leucogranite**

This rock is exposed in the northern portion of the range (Fig. 4). It is a slightly foliated to massive, medium- to coarse-grained, pale pink rock, composed of 40% quartz, 40% k-feldspar (mostly microcline), 5% plagioclase, 10% biotite, magnetite, apatite and zircon (Henshaw, 1942, and this study). Dillon (1976) considered this unit to be part of the biotite granite suite. However, the overall massive nature of the leucogranite and the presence of leucogranite pegmatites crosscutting the foliated granite (Branham, 1988), suggests a probable younger age.
Pegmatites

Pegmatites are abundant north of the American Girl valley. They vary in grain size from medium-grained aplitic veinlets to coarse-grained muscovite-k-feldspar-quartz pegmatite dikes; some pegmatites change along strike into quartz veins (Branham, 1988). Northward from the north wall of the American Girl canyon, the pegmatites become increasingly numerous toward the leucogranite from which, according to Henshaw (1942), they appear to be emanating.

Rhyodacite Porphyry

This unit, equivalent to the andesite unit of Henshaw (1942), is exposed at the west end of the American Girl valley (Fig. 4). It is pale greenish-gray and porphyritic, with 1-5% hornblende phenocrysts in a greenish groundmass of biotite, k-feldspar and plagioclase (Branham, 1988). It intrudes older metamorphic rocks both along foliation as a sill and across foliation as a dike.

Metamorphism and tectonics

The Cargo Muchacho mountains are characterized by south dipping (15° to 40°), low angle faults that cut the weakly to moderately foliated metasedimentary-intrusive complex. These low angle shears developed over a long time span as a result of complex crustal movements.

Some authors believe that the low angle faulting in the American Girl and Padre-Madre areas may have initially occurred during regional metamorphism because of the parallelism of shear zones and rock
foliation (De Ridder and Johnson, 1987; Guthrie, et al, 1987); regional metamorphism probably occurred during the Late Jurassic (Table 1).

The low angle faults were presumably reactivated during the Chocolate mountains thrusting event, which moved the Cargo Muchacho mountains upper plate northeastward. This late Cretaceous thrusting was followed by regional uplift, cooling and finally by large scale mid-Tertiary detachment faulting, which resulted in brittle deformation along low angle faults, including older structures that had previously experienced thrust movement (Frost and Martin, 1983; De Ridder and Johnson, 1987) (Table 1). Later, high angle normal faults like for example the Araz fault (Fig. 4), presumably related to the San Andreas Fault system, cut and offset some of the low angle structures (Platt, 1982; Guthrie, et al, 1987).

Significantly, the low angle faults that host the mineralization at least in the American Girl "B" zone, appear to crosscut the foliation of the rocks, suggesting a post-metamorphism initial movement (probably during thrusting), overprinted by detachment faulting which is the dominant structural style observable in the underground mine.

Mineralization and Alteration

Most of the gold mineralization and alteration is confined to the west and west-central part of the range (Fig. 2). Gold deposits are mainly associated with and controlled by low angle faults although steeply dipping fissure veins (e.g. Cargo Muchacho mine) and placer accumulations (e.g. Jackson gulch; Padre-Madre valley) are also present.
All gold deposits have certain characteristics in common, but the style of gold deposition varies from place to place depending upon local geologic conditions. Characteristics in common include their spatial association with low angle structures, their generally tabular, elongated shape, and simple mineralogy (sulfides-oxides).

The general trend of the deposits is east-west, parallel to the major low angle faults in the area; their dips are moderate, ranging in most cases from 15° to 40° to the south.

The most important deposits in the range are associated with the Tumco Formation, either entirely hosted by this Formation (Tumco camp), or as their hanging wall (American Girl B-zone; Padre-Madre) or as their footwall (American Girl-Main); quartz diorite is the host rock in the Cargo Muchacho deposit. Apparently, there is a close relationship between fracturing and rock type. The Tumco Formation and the quartz diorite seem to shatter more extensively, creating better channelways than the other rocks in the range (Henshaw, 1942). Indeed, the quartzo-feldspathic Tumco seems to be the most receptive to mineralization as a result of permeability related to foliation and fracturing (Morton, 1977; Platt, 1982).

Gold is fine-grained (1-20 microns), and closely associated with pyrite or Fe oxide pseudomorphs after pyrite. Gold also occurs with chalcopyrite and as fillings in vein quartz (Henshaw, 1942; Hausen, 1978; Guthrie, et al, 1987). The auriferous pyrite occurs in quartz veins and veinlets, in fractures lacking quartz and as disseminations (Platt, 1982; Guthrie, et al, 1987).

Alteration minerals associated with gold-mineralized areas consist
mainly of chlorite, sericite, and quartz. Chlorite is the most abundant
both above and below the gold mineralized zones, and where rocks are
crushed, it is commonly widespread. Sericite and/or quartz are more
restricted to the gold-bearing areas, generally located within a halo of

In addition to gold, deposits of copper, kyanite, sericite, mica,
and wollastonite occur in the district. However, only the kyanite and
sericite deposits (located in the Vitrifax "Formation") have yielded any
significant commercial production (Morton, 1977).

Summary Characteristics of Some Gold Deposits

Tumco Camp

This area is located in the Tumco valley and includes the Golden
Cross, Golden Crown and Golden Queen occurrences (Fig. 2). About 50% of
the old gold production of the district came from this area (Morton,
1977). The mineralized zones are lenticular to tabular bodies in Tumco
gneiss, with an average thickness of 1.5-4.5 meters (5'-15') (Morton,
1977). The ore bodies lie parallel to foliation striking N 40°-80° E and
dipping 25°-50° SE. The mineralized zones are not well defined and they
"look much like the rest of the formation" (Morton, 1977). Gold is very
fine grained and free; sulfide minerals are uncommon but pyrite and
chalcopyrite are present.

Padre-Madre

Morton (1977), reports the presence of two subparallel veins
(Padre y Madre), that are about 90 m to 150 m (300'-500') apart. The veins are in quartz diorite (?), and in some exposures appear to be parallel to foliation. They generally strike N 10°-30° W, but range from N 50° W to N 50° E, dipping 20°-60° S.

Currently, American Girl Mining Joint Venture is operating two open pits in the area. The mineralization is in a broad zone of subparallel low angle faults within the Tumco gneiss, that dips 15° to the south; the footwall is quartz monzonite. Most of the mineralization occurs in the western part (west pit), and it is restricted to the lowermost structure (De Ridder and Johnson, 1987). The thickness of mineralized zones is variable but can be as much as 20 m (70').

Cargo Muchacho

This mine consists of a quartz vein in a shear zone in quartz diorite (Morton, 1977). The vein is 1.2-2.4 m (4'-8') wide, strikes approximately NS and dips about 55° E. Chloritic alteration occurs mainly in the hanging wall. In addition to gold, pyrite and tabular zones of scheelite are present (Morton, 1977).

Apparently, the N end of the vein is truncated by an E-trending normal fault (Henshaw, 1942). However, Branham (1988), reports that the vein is still present at the N end of the workings and instead, it is cut off at depth by a south dipping low angle fault (detachment fault?).
CHAPTER III

GEOLOGY OF THE AMERICAN GIRL VALLEY

Introduction

The American Girl valley is at the central part of the Cargo Muchacho mountains, bisecting the range in a west to east direction (Fig. 4). The area is composed of quartzo-feldspathic gneisses (Tumco Formation), including quartz-kyanite and sericite schists (Vitrifax "Formation"), and a co-magmatic suite of granitic intrusive rocks (Fig. 4 and 5). The structure, topography, mineralization, and alteration in the American Girl valley is intimately controlled by low angle faults (Fig. 4 through 8).

Structure

The structure of the American Girl valley is dominated by the south to southeast dipping, low angle American Girl and C-zone faults (Fig. 5). The B-zone fault, which contains the gold-rich B-orebody, lies between them (Fig. 5, 6, and 7). These structures strike generally EW and dip 20°-35° to the south. From the American Girl Decline area to the east, these faults are a single structure, but spread apart to the west (Fig. 5, 6, and 7).

According to Branham (1988), the low angle faults are characterized by 1.5-30 m (5'-100') wide zones of gneissic, mylonitic, and schistose rocks with intensely crushed central portions that contain abundant clay gouge and chlorite alteration (Fig. 8). Gentle undulations
Rock units:

- Qal - Quaternary alluvium and talus.
- Td - Tertiary(?) rhyodacite porphyry sill and dike.
- V - Vitrifax formation undifferentiated metasomatic altered rocks.
- Vm - Vitrifax formation, muscovite schist unit.
- Vk - Vitrifax formation, Kyanite-quartz granofels.
- mbgr - Muscovite-biotite garnet granite, weakly foliated
- Bgr - Biotite granite
- Bgr2 - Biotite Granite (Secondary intrusion)
- Hbg - Hornblende-biotite granite
- Mz - Mix zone of migmatitic granite and Tumco Formation
- Qd - Quartz diorite
- d - Diorite
- pT - Middle Jurassic Tumco Formation: Gneiss, schists and arkosites.

Symbols:

- Contact between units
- Foliation - strike and dip.
- Schistose - Shear zone
- Low angle fault
- Fault
- Quartz veins
- Pegmatites
- Edge of study area
- Prospect pit
- Survey marker
- Mining shaft
- Adit

FIGURE 5: Geologic Map of the American Girl Valley, Cargo Muchacho Mountains (Adapted from Branham, 1988).
or "warps" with amplitudes of as much as 60 m (200'), are present along the fault planes. This wave-like geometry may have influenced the localization of mineral deposits. For example, the American Girl and American Boy mines are at the apex of antiformal warps in the faults (Fig. 6), whereas the C-zone and B-zone are within broad synformal troughs (Branham, 1988; Guthrie, et al, 1987).

High angle faults that trend generally N to NW also occur in the American Girl valley. These structures form "tear faults" between low angle shears and may not cut off either the overlying or underlying low angle structure (Guthrie, et al, 1987; Branham, 1988).

Mineralization and Alteration

Alteration Related to Regional Metamorphism(?)

The Vitrifax rocks (quartz-kyanite and mica-Al-silicate schists), are considered by some authors (Dillon, 1976; Branham, 1988), to be the product of an early (synmetamorphic) alteration-metasomatic event. The rocks are exposed along the west and south edge of the American Girl valley (fig. 4 and 5). In particular, Dillon (1976) believed the Vitrifax rocks to be the product of an unusual process of leaching of the Tumco Formation by hydrogen metasomatism. Alkali (Na, K, etc.) and alkaline-earth (Ca, Mg, etc.) metals were leached by highly acidic solutions, leaving behind and thus concentrating aluminum and silica. This author also considered that rock type variation (e.g. quartz-kyanite; staurolite schist; sericite schist) is due to different levels of leaching during regional metamorphism.
FIGURE 6: Geologic Longitudinal Section of the American Girl Valley, Cargo, Muchacho Mountains (Adapted from Branham, 1988).
FIGURE 7: Geologic Cross Sections of the American Girl Valley, Cargo Muchacho Mountains (Adapted from Branham, 1988).
However, as stated by other authors (e.g. Henshaw, 1942; Campbell and Wright, 1950; this study), the Vitrifax rocks may well be the product of regional metamorphism affecting rocks of different composition throughout the Tumco rocks sequence. The Vitrifax rocks could have been derived from compositionally favorable, aluminum-rich layers and/or lenses (e.g. pelitic units, laterite soils) within the overall silicic Tumco Formation. Interlayering of Vitrifax schist and quartzo-feldspatic Tumco occurs in several localities (e.g. Tybo Decline area) (Fig. 5).

**Alteration Related to Gold Mineralization**

Branham (1988), studied the seven newly discovered gold mineralized zones located in the east and central portions of the American Girl valley (Fig. 8). He defined two main types of gold deposits: (I) disseminated, low grade gold occurrences in the Tumco Formation; and (II) high grade, massive, sheared, ribbon quartz-gold-bearing veins in granite. The American Girl-Main, Tybo, and Quartzite Block are type I mineralization. The B-zone, C-zone, American Girl Extension, and the American Boy are type II gold deposits (Fig. 8).

The disseminated gold deposits (type I), occur within low angle shears that cut the Tumco rocks and Mesozoic intrusions. The mineralized zones form tabular bodies that can be more than 30 m (100') thick. Chlorite alteration is generally intense, both within and around gold zones. Sulfides, mainly pyrite and minor chalcopyrite are abundant (3-5%). Quartz-pyrite veinlets and granular, fine-grained quartz-replacement zones (e.g. "Quartzite Block"), are the most common forms
FIGURE 8: Map of Alteration Zones and Gold Reserves in the American Girl Valley, Cargo Muchacho Mountains (Adapted from Branham, 1988).

ALTERATION MINERALOGY ZONES:

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi</td>
<td>Chlorite zone with minor amounts of quartz, epidote, calcite, siderite, pyrite and minor hematite, magnetite, rutile, sphene. May overprint earlier assemblages.</td>
</tr>
<tr>
<td>Qtz-py</td>
<td>Quartz-pyrite alteration - granular &quot;quartzitic&quot; silification.</td>
</tr>
<tr>
<td>Biot</td>
<td>Biotite-quartz zone often includes pyrite, chalcopyrite, epidote, tourmaline. May be overprinted by Chlorite zone in part.</td>
</tr>
<tr>
<td>Epi</td>
<td>Epidote rich zone. May contain quartz, Kfeldspar, minor garnet, magnetite or amphibole.</td>
</tr>
<tr>
<td>Tourmaline veining and pods</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>Magnetite veinlets</td>
</tr>
<tr>
<td>Act</td>
<td>Actinolite alteration with minor pyrite, garnet, epidote and calcite.</td>
</tr>
<tr>
<td>Ser-py</td>
<td>Sericite-pyrite alteration (barren and mineralized)</td>
</tr>
<tr>
<td>Vitrifax metasomatized zones (Refer to text for zone definition)</td>
<td></td>
</tr>
<tr>
<td>Vp</td>
<td>Vitrifax pyrophyllite alteration (Zone II)</td>
</tr>
<tr>
<td>Vk</td>
<td>Vitrifax kyanite (Zone I)</td>
</tr>
<tr>
<td>Vm</td>
<td>Vitrifax muscovite (mainly Zone II, may include Zone III and Zone IV)</td>
</tr>
</tbody>
</table>

Gold Reserves (gravels hypothetically removed)

At surface
Below surface

NOTE: Alteration projected as if younger gravels are removed.
of silicification localized along gold mineralized zones (Branham, 1988).

The quartz-gold vein deposits (type II), occur along south dipping low angle faults in granitic rocks. Gold is hosted by massive, ribbon, white quartz veins, and quartz-stockwork veinlets, containing pyrite, sericite and chlorite. Chloritic alteration is widespread generally forming a conformable halo about mineralized areas, that commonly includes lesser sericitic and silicic alteration. Quartz-magnetite veinlets and schorlite also occur. Post gold carbonate veinlets and rare fluorite crosscut the quartz veins (Branham, 1988). Gold mineralized zones are generally not very thick, but can reach 9 m (27') (Guthrie, et al, 1987).

Fluid Inclusions

Branham (1988) studied fluid inclusions in barren quartz veins, gold-quartz veins, kyanite and pegmatites from different locations in the American Girl valley. He stated that:

"gold-quartz vein samples preserve three generations of fluid inclusions with temperatures of homogenization modes at 160°C, 210°C, and 305°C. Temperatures of melting range from -1.3°C to -7.6°C, with inferred salinities of 2.23 to 11.23 weight percent NaCl equivalent. Carbon dioxide had been found only in one poorly mineralized gold vein. No daughter products have been observed in these inclusions".

Also, Guthrie and others (1987), cited two groups of homogenization temperatures in quartz veins: (1) 200°C-250°C for CO₂ inclusions; and (2) 150°C-170°C for non-CO₂ inclusions that represent a later crushing event.
Stable Isotopes

Oxygen ($\delta^{18}O$) and hydrogen ($\deltaD$) stable isotope data presented by Guthrie and others (1987) indicate two distinct fluid sources for the quartz veins: (1) magmatic-meteoric fluids that mixed, and (2) metamorphic fluids (Fig. 9). They stated that gold is more common with veins exhibiting a metamorphic signature. However, Branham (1988), favors a magmatic fluid source for the gold-bearing veins.

Sulfur isotope data ($\delta^{34}S$) from two types of pyrite (in gold mineralized zone, and in non-mineralized Tumco), show very similar signatures ranging from -1.0% to -5.4%, compatible with an igneous source (Guthrie, et al., 1987; Branham, 1988).

Summary Characteristics of the Old American Girl Mine

The old American Girl mine (American Girl shaft, Fig. 5) was described by Henshaw (1942), and Morton (1977). It is composed of three essentially parallel veins in Tumco Formation "arkosite", that strike nearly EW and dip 25°-70° S. The veins are from N to S the Blue, White, and Brown veins. The Brown is the principal one; it dips 25°-35° S, ranges up to 12 m (40') in thickness and is parallel to the "relict bedding" (foliation?) in arkosite. The Blue and the White veins dip much more steeply (70° S).

The mineralogy (Morton, 1977) includes gold, silver, chalcopyrite, covellite, chalcocite, bornite, galena, and sphalerite; secondary minerals are azurite, malachite, cuprite, copper, and chrysocolla. Gangue minerals include quartz, pyrite, calcite, sericite, chlorite, biotite, fluorite, magnetite and hematite.
FIGURE 9: $\delta^{18}O$ and $\delta D$ Data from the American Girl and Padre-Madre Deposits (After Guthrie, Cockle and Branham, 1987).
Gold is fine-grained (−325 mesh) and occurs free or enclosed in grains of pyrite and chalcopyrite. Wall rocks have undergone intense sericitization, chloritization and feldspathization (Morton, 1977).

Recently, Newmont Exploration Ltd. identified three mineralized zones east of the old American Girl shaft (Platt, 1982; Guthrie, et al, 1987; De Ridder and Johnson, 1987). They are composed of structurally stacked shear zones (Fig. 5, 6, and 7): (1) American Girl-Main, close to the surface; (2) "C" zone, deep in the system; and (3) "B" zone, between them, which constitutes the main focus of this investigation and will be discussed more extensively in chapter 4. The American Girl-Main zone is the eastern extension of the Brown-White-Blue veins group.
CHAPTER IV

GEOLOGY OF THE AMERICAN GIRL "B" ZONE

Introduction

The American Girl "B" zone is one of the recently discovered gold mineralized areas in the American Girl valley. It is mined by underground methods and access is by a decline from the valley’s south slope (Fig. 5). During the summer of 1988, detailed geologic-geotechnical mapping at scale 1"= 20’ (~ 1 : 250) was conducted in the mine. Samples were collected from the mine, diamond drill cores and a few from outside the deposit area, in order to compare lithologic units, structural styles, mineralogy and alteration among other mineralized areas and country rocks within the mountain range.

A total of 75 thin and polished-thin sections and 22 double-polished fluid inclusion sections were prepared and studied at the University of Montana, Missoula. Also, three samples of pyrite were sent to the University of Calgary, Alberta, for sulfur isotope determinations. The results of this investigation are described, discussed and summarized in the following sections.

General Characteristics

The American Girl "B" zone forms part of a group of stacked low angle shear zones in the American Girl valley (Fig. 5, 6 and 7). It is
FIGURE 10: Generalized Geologic Cross Section (DD') of the B-shear zone and the B-orebody (Adapted from American Girl Mining Files); see Fig. 8 for section location.
located below the American Girl-Main zone and above the "C" zone (Fig. 10).

The B-orebody is located within and along a low angle, highly fractured zone (B-fault zone), that defines a wide synform or synclinal warp containing the orebody at its top (Fig. 10-15). It is mainly hosted by gneisses and schists of the Tumco Formation (hanging wall) approximately along its contact with foliated granitic intrusive rocks (footwall). The ore zone strikes N 70° W and dips 17° to 30° southwest, crosscutting the foliation and general structure of the wall rocks.

The ore zone is approximately 350 m (1100') long by 150 m (500') wide, ranging in thickness from 1.5 m (5') to 8.4 m (27.5'). Lateral limits of the ore are defined on a gold grade-thickness basis, although the structure may continue. The lower limit is generally marked by a continuous 5 cm to 15 cm (2 to 6 inches) thick, wavy clay-gouge zone (base-structure) (Fig. 11). The upper limit of the ore is generally defined by the relatively unfractured and unaltered Tumco gneiss of the hanging wall.

Gold is very fine grained (1-20 microns; Hausen, 1978) and disseminated irregularly throughout the orebody. Based on lithologic affinities, three types of gold mineralization are defined: (I) Massive quartz veins; (II) Banded, massive quartz veins and sheared pyritic Tumco schist; and (III) Sheared, pyritic Tumco schist and gneiss. Commonly, more than one ore type may be present at a given area.
FIGURE 11: Schematic Geologic Longitudinal Section of the B-zone (EE'); see Fig. 8 and 12-15 for section location.
AMERICAN GIRL MINING CORP.  
Structural Contour (Top of 3-fault zone)  
Contour Interval 18'3""  
@ Drill Hole 9763  

FIGURE 12: Structural Contour.  
Top of "B" Fault Zone (see Fig. B for map location).
FIGURE 13: Structural Contour, Top of B-orebody (see Fig. B for map location).
FIGURE 14: Structural Contour, Base of B-orebody (see Fig. B for map location).
FIGURE 15: Structural Contour, Base of "B" Fault Zone (see Fig. 8 for map location).
Structure and Geometry

The B-zone is a low-angle structure located at the top-center of a synformal, highly fractured zone that ranges from 12 m to 30 m (40'-100') in thickness (Fig. 10-15).

The top of the ore and the fault zone are parallel and very close to each other. However, the base of the fault zone, although also essentially parallel, is 3 m to 6 m (10' to 20') below the base of the ore (Fig. 10-15).

The clay-gouge structure (base-structure) at the base of the orebody (Fig. 11), divides the B-fault zone into two plates with distinct structural styles: (1) Lower plate (footwall); and (2) Upper plate (ore zone and hanging wall) (Fig. 11).

Lower Plate

The footwall rocks are rather intensely foliated and fractured. Foliation is of variable strike but generally steeply dipping, changing to gently dipping and locally ptygmatically folded approaching the ore zone. The main fracture systems affecting the footwall are: (1) NW-SE-, and (2) NS (NNW to NNE)-striking, both steeply dipping (40º - 90º SW and NE). System one is generally filled with calcite, minor chlorite and hematite; system two is filled with hematitic clay gouge and some calcite. Both systems are composed of thin fractures (2 cm-1 m wide; 1"-3"), and tend to merge upward with the base-structure (Fig 11 and 16). They may have acted as "feeder veins" during the mineralization of the B-orebody.
FIGURE 16: High angle footwall fracture (feeder?), merging upward with the base-structure (598 stope).

FIGURE 17: Chlorite breccia within the footwall, immediately below the base structure (537W stope, looking W).
FIGURE 18: Chlorite breccia. Quartz fragments in chlorite-rich matrix (// nicols).

FIGURE 19: Splitting of the base-structure into the footwall, subparallel to the ore zone (537 stope, looking E).
The footwall gneissic-mylonitic fabric, grades upward into a 2 cm to 1.5 m (0.5"-5'") wide chlorite breccia zone at the base of the base-structure (Fig. 11 and 17). This chlorite breccia consists of very fine-grained, chlorite-rich matrix and matrix-supported angular to subangular quartz (+ feldspar and epidote) fragments (Fig. 17 and 18). These breccia fragments are of both, broken massive vein quartz and wall rocks. Areas of chlorite breccia also contain gold although grades are frequently subeconmic.

The base-structure is a 5-15 cm (2"-6") thick, dense, comminuted clay-gouge microbreccia (Fig. 11 and 16). It is generally a smooth, undulating, wave-like surface composed of numerous antiforms and synforms. It sometimes splits in more than one branch into the lower plate, forming semi-anastomosing fault patterns subparallel to the ore zone (Fig. 11 and 19).

**Upper Plate**

The upper plate contains both the orebody and the hanging wall (Fig. 11). The orebody is characterized by finely folded areas of massive quartz, schist and gneiss (Fig. 20 and 21) that are in turn intensely fractured, brecciated, and commonly offset by an intricate system of high angle normal faults. These steeply dipping (40° - 90°) curviplanar and listric normal faults, crosscut and offset the hanging wall rocks above, but flatten at depth and sharply curve, merging with the gently dipping base-structure (Fig. 11). The two main systems of these high angle normal faults within the orebody strike NNW-SSE, and NNE-SSW. The offset along individual structures in generally small (0.1
FIGURES 20 AND 21: Ductile deformation of banded massive quartz veins—Tumco rocks (377 stope).
FIGURE 22: Curviplanar normal normal fault displacing massive quartz veins in the ore zone. This structure merges downward with the base-structure (dark left corner) (598S stope).

FIGURE 23: Breccia with calcite veinlets within fragments only suggesting post-mineralization brecciation (X nicols).
Breccias up to one meter (3 ft) thick are fairly common, both approximately parallel (breccia "sill") or perpendicular (breccia "dike") to the base-structure. The clasts of massive quartz vein, various rock types, pyrite and breccia fragments are matrix-supported. The breccia fragments indicate multiple brecciation; pyrite, calcite and quartz veinlets within clasts only, suggest that both pre- and post-mineralization brecciation events occurred (Fig. 23).

Faults that cut and displace both the orebody and the base-structure are rare in the underground mine. Where found, they are steeply dipping normal faults with little offset (1-2 m; 3-5 ft), striking approximately east-west.

Isopach contours of the ore zone show a very variable thickness of the B-orebody (Fig. 24), ranging from 1.5 to 8.4 meters (5'-27.5'). However, there are two main areas with fairly constant average thickness, (1) north and west, with an average thickness of 2.3 m (7.5'), and (2) south and southeast, with an average thickness of approximately 4.6 m (15') (Fig. 24). The "highs" and "lows" within the thicker area (2) are probably related to high angle structures within the ore zone.

**Discussion**

The structure and geometry of the B-zone suggest two principal structural events follow by an episode of post-mineralization fracturing. The first event (compressional) ductilely deformed and finely folded massive Au-bearing quartz veins and Tumco rocks. These
FIGURE 24: Isopach Contour of the B-orebody (see Fig. 8 for map location).
veins were probably formed by an amagmatic hydrothermal system that developed during Laramide thrusting (see chap. 5 for further discussion). The second event (extensional) strongly fractured and brecciated (curviplanar normal faults, chlorite breccias) the ore zone. Hydrothermal convection originated during this second structural event (detachment faulting), caused widespread wall-rock alteration, sulfide-oxide deposition and probably remobilization and/or additional introduction of gold (see following sections and chap. 5 for further discussion). Finally, a later extensional event offset and further brecciated the B-orebody. This sequence of events is consistent with the regional tectonics in which late Cretaceous-early Tertiary thrusting (compressional) was followed by mid-Tertiary detachment faulting (extensional) and finally by the San Andreas system extensional event.

The structural style of the B-zone appears primarily dominated by the detachment fault-related features described above, like stacked shear zones (American Girl-Main, B- and C-zones), anastomosing fault patterns, chlorite breccias and curviplanar normal faults that merge with but do not offset the base-structure. All these structural features are characteristic of a lower plate setting in detachment systems (Adams, et al, 1983; Mathis, 1982).

**Lithologies**

The B-orebody's base-structure is approximately along the contact between lower plate foliated granitic rocks (mainly biotite granite or bgr) and upper plate silicic Tumco schist and gneiss (Fig. 10 and 11).
Within and along the ore zone, massive Au-bearing quartz veins have largely replaced the country rocks (Fig. 20-22). The host rocks themselves are highly fractured and altered as a result of subsequent deformation and mineralization making the identification of protoliths rather difficult.

**Footwall**

The lithology of the footwall essentially consists of gneissic "bgr" with minor quartz diorite, Tumco gneiss(?) xenoliths and pegmatites. The biotite granite is medium grained, foliated, sheared and highly fractured and altered. The bgr is also locally porphyritic especially close to the ore zone, with k-feldspar phenocrysts up to 1 cm in length. Evidence of strain are common with strong undulose extinction in quartz, bending and offset twinning in feldspars, highly brecciated areas, etc. Some evidence of recrystallization is also present with abundant "suture" textures and incipient polygonal textures in quartz. All of the original biotite and amphibole (hornblende?), and most of the plagioclase have been altered to a propylitic assemblage of chlorite-epidote-calcite-sphene and lesser amounts of sericite.

Other rock types include some small exposures of quartz diorite found in the underground mine. This rock is dark green, coarse-grained, slightly foliated with approximately 25% hornblende, 10% quartz, 10% plagioclase (~An45), 3% biotite and secondary minerals including sericite, chlorite, epidote and sphene.

Irregular-shaped bodies of foliated (steeply dipping foliation), fine grain, dark green xenoliths are included within the footwall bgr.
They are mainly composed of quartz, k-feldspar, plagioclase, and predominantly tabular, pseudomorphic chlorite-epidote-actinolite (after amphiboles?). The source of the xenoliths is unknown but they may correspond to the amphibolite layers interpreted by Dillon (1976) as metamorphosed mafic dikes and sills contained in the Tumco Formation.

Quartz and quartz-feldspars pegmatites up to 3 m (10') thick, occur as discontinuous bodies both along and cutting across foliation. Concordant pegmatitic segregations are also common within Tumco xenoliths.

Ore Zone: Types of Gold Mineralization

According to lithologic affinities, three types of gold mineralization (ore types) are found. They include massive quartz veins, banded quartz vein-pyritic schist and pyritic Tumco rocks.

I. Massive quartz veins

The veins are composed of massive, white, sheared quartz with minor inclusions of pyritic Tumco schist (Fig. 25). The veins were ductilely deformed and well folded, and later strongly shattered forming stockwork-like structures (Fig. 26). These structures were filled with chlorite-sulfides, quartz-sericite (sulfides), quartz, hematite and minor calcite veins and veinlets. Zones containing massive quartz veins are generally high grade, with gold-grade averages ranging from 0.20 to 0.35 oz Au/ton (6-11 ppm).
FIGURE 25: Types of gold mineralization within the B-orebody: lower massive quartz veins (type I); upper banded quartz veins-pyritic schist (377W stope looking S). Both ore types are Au-bearing (see text).

FIGURE 26: Chlorite veinlets stockwork across massive, shattered Au-bearing quartz (// nicols).
II. Banded Quartz Vein-Pyritic Schist

Banded quartz vein-pyritic schist is characterized by the interlayering of massive, white quartz veins with dark-green, pyrite-rich Tumco schist (Fig. 25). This ore type was ductily deformed into open folds and fine ptygmatically folded areas (Fig. 20 and 21), and subsequently crosscut (and often offset) by high angle fractures (Fig. 22). The schist bands show compositional layering, with quartz (feldspar) rich and chlorite-sericite-muscovite rich layers. These bands are cut by fine-grain chlorite and quartz-pyrite veins and veinlets.

Two types of pyrite are found: (1) euhedral, disseminated crystals predominantly restricted to the schist bands; and (2) anhedral, fine grains, in fine-grained chlorite and quartz veinlets that crosscut both massive quartz and schist bands. Both types of pyrite may occur together and range up to 7% by volume. Type II, the most abundant ore type in the B-orebody, also is high in gold [average values range from 0.20 to 0.35 oz Au/ton (6-11 ppm)].

III. Pyritic Tumco Rocks

Pyritic Tumco schist and/or gneiss ("arkosite") with minor massive quartz veins are predominantly low grade zones. Areas of silicic, Au-bearing schist show compositional layering of quartz-feldspars and biotite-chlorite-muscovite-sericite. Also, polygonal quartz textures are common.

The Tumco gneiss, composed primarily of quartz, k-feldspar and plagioclase is slightly foliated to massive. Sutured and incipient polygonal textures in quartz indicate some degree of recrystallization
of the rock. Pyrite in this ore-type is both disseminated and contained in quartz veins and veinlets. It often occurs in mutual contact with magnetite and chalcopyrite with no apparent evidence of replacement probably indicating a co-genetic relationship (Fig. 27). However, this evidence is not totally conclusive because this texture may also be formed in other ways (Guilbert and Park, 1986), for example by total replacement of one mineral by another. Average gold grades are for the most part low, ranging from 0.05 oz Au/ton (1.5 ppm) to 0.20 oz Au/ton (6 ppm).

Hanging Wall

The hanging wall is composed of foliated, commonly porphyroblastic, medium-grained quartzo-feldspathic Tumco gneiss. It is weakly fractured and propylitically altered, weakly to moderately magnetic and locally contains disseminations of very fine grain pyrite.

Polygonal textures in quartz are common reflecting recrystallization of the rock. Also, distinct compositional layering between quartz-feldspar and biotite-muscovite bands (Fig. 20) may be original bedding, probably representing a quartz-feldspathic siltite interstratified with clay-rich layers (now mica-rich bands).

Mineral Textures and Paragenesis

The ore stage mineralogy of the B-orebody is simple and was determined by means of detailed geologic mapping, petrography and ore microscopy (Fig. 29). It consists of native Au (and/or electrum?),
FIGURE 27: Co-existent (and co-genetic?) pyrite (py), chalcopyrite (cp) and magnetite (mg) within the B-orebody (reflected light).

FIGURE 28: Compositional layering between quartz-feldspar-rich bands (light) and micas-rich bands (dark). Tumco gneiss of the B-orebody's hanging wall (// nicols).
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Metamorphism</th>
<th>Thrusting</th>
<th>Detachment</th>
<th>Post-detachment (weathering)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorite (#ox)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz veins (+)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and veinlets (#)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epidote (o)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcite (o#)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sericite (##)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrite (###x)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetite (###x)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sphene (x)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clays (&amp;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite (&amp;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limonite (&amp;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcopyrite (#)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scheelite (##)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galena (#)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zeolite (&amp;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorite (#)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold (*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*) disseminated in ore zone  (+) veins in ore zone
(#) veinlets in ore zone      (x) disseminated in wall rocks
(o) veinlets in wall rocks    (&) secondary mineral

FIGURE 29: Paragenesis of Ore Minerals and Alteration of the B-orebody
together with pyrite, chalcopyrite, galena, magnetite, scheelite, quartz, calcite and fluorite. Mineral paragenesis is not always discernible because of the lack of contact between some of the prevalent mineral assemblages. However, textural and structural relationships suggest two principal mineralization events that are characterized by: (1) massive Au-bearing quartz veins; and (2) sulfides-magnetite (± gold?) and carbonates. The latter is subdivided into two stages of mineralization without an obvious time break: (A) pyrite-magnetite-chalcopyrite-galena (± gold?); and (B) calcite (± scheelite and fluorite). Event (1) is characterized by massive replacement, whereas open space filling is the prevalent depositional style of the second event of mineralization.

**Massive Gold-bearing Quartz Veins**

Structural preparation for subsequent mineralization resulted from movement in the upper plate of the Chocolate mountains thrust during the late Cretaceous-early Tertiary. This probably initially formed the low angle shear zones in the American Girl valley (see discussion chapter 5). Thus, mineralization in the American Girl B-orebody appears to have begun with major quartz precipitation, that largely replaced rocks of the Tumco Formation within and along a low angle shear zone. Quartz is white, massive and medium-grained. Fine grain, randomly oriented quartz veinlets (<1mm thick) are common (Fig. 32) and constitute up to 15% of the massive quartz vein areas.

Because gold is very fine-grained (1-20 microns, Hausen, 1978) and very rarely visible, its paragenesis is mainly based on assay data
combined with detailed geologic mapping. In general, gold grades are highest (average values of 0.20-0.35 oz Au/ton) in areas having massive quartz veins (Ore Types I and II), and lower grades (average values of 0.05-0.20 oz Au/ton) are found in those lacking them (Ore Type III), thus suggesting a close association of massive quartz veins and gold.

**Pyrite-Magnetite-Chalcopyrite-Galena (Gold?)**

Pyrite is the most abundant sulfide mineral. It occurs as disseminations of cubic crystals (type 1) with an average diameter of about 2 mm or as anhedral masses in small veinlets (type 2) together with chlorite, sericite (Fig. 33) and/or quartz. It locally composes up to 6-8% of the orebody.

Magnetite occurs within both the ore zone and the hanging wall in two forms: (1) euhedral, coarse grains up to 2-3 mm in diameter; and (2) anhedral, fine grains, usually associated with chloritized biotite areas. The amounts of magnetite are locally up to 5% by volume, and type (1) magnetite is commonly in contact with pyrite and chalcopyrite suggesting a co-genetic relationship (Fig. 27).

Chalcopyrite can range up to 1% locally. It occurs as interstitial, anhedral, fine-grained masses in small quartz and quartz-sericite veinlets, or as tiny inclusions in pyrite crystals. Trace amounts of galena are spatially associated with chalcopyrite and thus appear to represent the same stage of deposition as this mineral.

**Scheelite**

This mineral is sparsely distributed in the orebody, generally
within highly brecciated areas where it occurs filling cavities and "coating" quartz fragments or as short, discontinuous veinlets. Microscopically, scheelite is a high relief, anhedral and low interference color mineral. Under reflected light, it has a pale-gray color, is anisotropic and has a low reflectivity, although higher than quartz.

Grades range up to 1% WO₃ (Dennis Laybourn, 1989, personal communication).

Carbonates (Fluorite)

Calcite is by far the most abundant carbonate, and is clearly a late stage mineral (Fig. 30 and 31) found mainly in veins [up to 0.15m (0.5)’ thick] and veinlets, but also locally as replacements of chlorite, epidote and plagioclase. The footwall contains the greatest amount of calcite (up to 15%); amounts decrease upward into the ore zone and hanging wall (<3% in average) (Table 2). Also, within the calcite-rich footwall, the upper levels of the mine generally tend to contain more calcite than the lower, downdip levels.

Purple fluorite is rare as small veinlets within the ore zone in the lower levels of the mine.

Wall Rock Alteration

General Distribution

The hydrothermal alteration suite (and/or retrograde greenschist
FIGURE 30: Calcite veinlets crosscutting shattered quartz veins, B-orebody (X nicols).

FIGURE 31: Calcite (cc) veinlet across chlorite (dark)-epidote(ep) (X nicols).
facies metamorphism) is predominantly propylitic. It is dominated by a chlorite envelope with lesser amounts of epidote and calcite, asymmetrically distributed about the gold mineralized zone (Fig. 11). A phyllitic assemblage consisting of sericite-quartz veinlets is also present, and essentially restricted to the ore zone (Fig. 11).

The observed alteration mineral assemblages could be the result of either low grade metamorphism (retrograde metamorphism, Branham, 1988), or hydrothermal alteration. In the B-orebody area, the strong localized control and zonation of alteration and mineralization by faults and fractures supports a hydrothermal origin for at least part of the propylitic and phyllitic alteration suites (Fig. 29).

**Alteration Mineral Assemblages**

A summary of the alteration assemblages in the American Girl B-zone is shown in Table 2. Propylitic alteration (chlorite-epidote-calcite) is the most widespread alteration assemblage and affects the footwall, ore zone, and hanging wall rocks. Phyllitic alteration (sericite-quartz) primarily affects the ore zone and sparsely affects the footwall as well.

**Chlorite-Epidote-Calcite (Propylitic Alteration)**

Chlorite is the most abundant mineral in this assemblage. It occurs both as replacement of biotite, and minor hornblende and plagioclase, and as veinlets. Epidote occurs mainly replacing plagioclase whereas calcite forms numerous late stage veins and veinlets with minor replacement. Calcite and epidote tend to decrease in amount
TABLE 2, Approximate Average Abundance of Alteration Minerals in the American Girl B-zone.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Footwall</th>
<th>Ore Zone</th>
<th>Hanging Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Propylitic</td>
<td>Prop.</td>
<td>Phyll.</td>
</tr>
<tr>
<td>Dominant alt. assem.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative intensity</td>
<td>Weak</td>
<td>Moderate</td>
<td>Strong</td>
</tr>
<tr>
<td>Host rock</td>
<td>biotite granite</td>
<td>biotite granite</td>
<td>chlorite breccia</td>
</tr>
<tr>
<td>Approx. width</td>
<td>+25m (+80')</td>
<td>0.6-2.5m (2-8')</td>
<td>0.3-1.5m (1-5')</td>
</tr>
<tr>
<td>Minerals (% volume)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorite</td>
<td>10-20</td>
<td>20-30</td>
<td>30-50</td>
</tr>
<tr>
<td>Sericite</td>
<td>4-6</td>
<td>4-6</td>
<td>4-6</td>
</tr>
<tr>
<td>Calcite</td>
<td>6-10</td>
<td>4-6</td>
<td>2-4</td>
</tr>
<tr>
<td>Epidote</td>
<td>4-6</td>
<td>4-6</td>
<td>2-3</td>
</tr>
<tr>
<td>Pyrite</td>
<td>-</td>
<td>(1)</td>
<td>1-2</td>
</tr>
<tr>
<td>Chalcopy.</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Galena</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scheelite</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Biotite (unaltered)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
with increasing chlorite toward the ore zone (Table 2).

The footwall is more widely altered, with alteration extending up to more than 30 m (100’) from the base-structure (Fig. 11). Three subzones of propylitic alteration within the footwall were delineated (Table 2): (1) weak, approximately 25 m (80’) wide, characterized by altered biotite granite with abundant calcite and minor chlorite veinlets; (2) moderate, up to 2.5 m (8’) wide and imposed on the biotite granite. In places, most of the original minerals except K-feldspar and quartz, have been almost totally replaced by a chlorite-rich propylitic assemblage, thus, giving the granite a "pseudoporphyritic" appearance. The third subzone (3) is strongly altered, up to 1.5 m (5’) wide, usually attached to the ore zone and base-structure, and characterized by a fine grain, matrix-supported chlorite breccia composed by quartz fragments in a chlorite-rich matrix (Fig. 11 and 18; Table 2).

The hanging wall is less altered than the footwall, probably as a reflection of its lesser degree of fracturing. The alteration diminishes gradually and extends approximately 6 m (20’) outward from the ore zone. Unlike the footwall, the hanging wall still preserves partially altered to unaltered biotite crystals.

Sericite-Quartz (Phyllitic Alteration)

This alteration assemblage is almost exclusively restricted to the ore zone (Fig. 11). It is composed of fine-grained sericite-quartz (± pyrite) veinlets (Fig. 33) that crosscut massive quartz and Tumco rocks with no apparent wall rock replacement. They are visible under the microscope but very difficult to distinguish megascopically. Wherever
FIGURE 32: Fine grain quartz (± sericite) veinlets crosscutting coarse grain massive quartz (X nicols).

FIGURE 33: Sericite (± quartz)-sulfides veinlet across massive quartz; black cubes are of pyrite (X nicols).
their relationship is apparent, sericite appears to be younger than chlorite, replacing and/or crosscutting it.

Sericite replacement of feldspars is also present throughout the wall rocks (Table 2), but probably is mostly a product of retrograde metamorphism, and/or minor weathering at the near-surface upper levels of the mine (598 stope).

Samples of sericite from gold-bearing quartz veins from the Padre-Madre area have been dated by K/Ar methods at about 48 MA, indicating a mid-Eocene age of deposition (Platts, 1982; Guthrie, et al, 1987).

**Metal Zoning**

**Distribution of Gold**

Gold grades are maximum (and generally above cut off) within and along the ore zone, but they sharply diminish outward into both the footwall and the hanging wall.

The distribution of gold is shown in Figure 34, a map of the B-orebody showing the intercepts of at least 1.5 m (5') thickness in Reverse Circulation Holes. Gold-grade contours are at 0.05, 0.10, 0.25 and 0.50 oz Au/ton. Generally, two distinct zones of gold grades can be identified: (1) N-NE and W, with grades of <0.25 oz Au/ton (<7.5 ppm); and (2) S-SE, with gold grades of >0.25 oz/ton (>7.5 ppm). These zones are also coincident with the thin and thick ore zones, respectively (see Figure 24 and page 45).
ZONE 1

ZONE 2

FIGURE 34: Gold Grade Distribution (in ounces per ton); B-orebody (see figure 8 for map location).
Metal Ratios

A good positive correlation between Ag and Au values exists [correlation coefficient (Rp) is 0.77 (see Appendix I for details)]. The Ag/Au ratio in the B-orebody is low relative to crustal abundance, with an average value of 0.9. This ratio varies from approximately 0.7 at the near-surface upper levels of the mine, to 1.1 at the lower levels. This apparently reflects a vertical zonation of the Ag/Au ratios, in which the oxidized upper levels of the orebody are enriched in gold relative to silver that has been leached. Low Ag/Au ratios are also found in many other deposits in the region (e.g. Padre-Madre, Picacho, Mesquite, Riverside, Sheep Tanks, Oatman, etc).

The Cu/Au and Cu/Ag ratios were also calculated but show generally low correlation coefficients (see Appendix I), and no apparent distribution pattern or zonation. However, more data is needed to estimate their possible validity as geologic indicators of "source" direction.

Titley (1987), on the basis of ratios of produced grades of Ag and Au, divided Arizona ores of all epochs into two domains, the Naco (SE Arizona) and the Western Deserts (central and SW Arizona) domains. The latter is characterized by a Proterozoic gneiss-greenstone-granite basement and scattered Mesozoic-Cenozoic cover. Most deposits of the Western Deserts domain show Au enrichment relative to the ratio of the Ag/Au crustal abundance (clarke ratio; 17.5:1), whereas most districts of the Naco domain are enriched in Ag with respect to the ratio. He stated that
"the time-enduring character of precious-metal metallogenesis present in Arizona domains appears to be a manifestation of properties of specific kinds of crust and defines, in a fundamental way, the nature of metallogenic provinces".

The low Ag/Au ratios found in the American Girl B-orebody (much lower than the clarke ratio), and other deposits of southeasternmost California (Padre-Madre, Mesquite, Picacho, Riverside; see table 5), may also represent inheritance from specific kinds of crust. Their proximity and geologic similarities with the Western Deserts domain indicate that they probably are located within a western extension of this "Au-enriched, Ag-depleted" metallogenic province.

Fluid Inclusions

A total of 22 double-polished fluid inclusion sections from gold-bearing quartz veins, calcite veins, scheelite-bearing zones and pegmatites were studied. Unfortunately, only inclusions from quartz veins were suitable in size and quantity for analysis. A U.S.G.S heating/freezing stage was used for observation and testing. Primary inclusions were used; criteria for primary origin were based on isolated occurrence, irregular shape, and somewhat larger size than associated secondary inclusions (Roedder, 1984). Fluid inclusions in quartz from the B-orebody are generally small (5-25 microns), liquid-rich with a low vapor/liquid ratio, and a bubble that occupies 3-6% of the volume (10-15% in area). No daughter minerals were observed.

Temperatures of homogenization (Th) range from 213°C to 342°C with
FIGURE 35: Fluid Inclusion Data from Gold-bearing Quartz veins, B-orebody.
a mean temperature of 286.3°C. No pressure corrections were applied to these temperatures so the actual trapping temperatures are higher. The data are shown in Figure 35; other statistics include:

Sample size, n = 37

Median = 290°C

Mode = 305°C

Range = 129°C

St. Dv., s = 31.3°C

St. Error (Mean) = s/\sqrt{n} = 5.15°C

99% confidence interval of the mean:

\[ 286.3 \pm 2.75 \times 5.15 = 286.3 \pm 14.2 \]

\( (272°C, 300.59°C) \)

The freezing data are scattered and probably insufficient to be statistically significant. Temperatures of melting (Tm) range from -1°C to -6°C, which correspond to salinities of approximately 1.7% to 9.2% NaCl equivalent.

In summary, temperatures of homogenization of fluid inclusions from gold-bearing quartz veins in the B-orebody are in the interval of 272°C to 300.5°C (without pressure corrections) with a 99% confidence.

**Sulfur Isotopes**

Three samples of pyrite from the B-orebody, analyzed in the laboratory of Dr. H. Roy Krouse, University of Calgary, give very
similar values of $\delta^{34}S$, with an average of -7%. (Table 3). Two of the samples (AG-B, AG-C) were of disseminated, euhedral pyrite, and the other (AG-A) of anhedral pyrite from veinlets (Table 3). The very close $\delta^{34}S$ values for both types of pyrite suggests a similar source of sulfur.

When $\delta^{34}S$ values are within a narrow range, centered about 0% (of the Canyon Diablo meteorite and presumed mantle value), it is commonly believed that sulfur was derived from well homogenized, primary igneous sources (Field and Fifarek, 1985; Faure, 1986). Compositions of magmatic sulfur range from -3% to 3% $\delta^{34}S$ (Field and Fifarek, 1985). However, those of the component oxidized and $^{34}S$-enriched sulfate (up to +10%) and reduced and $^{34}S$-depleted sulfide (up to -10%) forms are more variable because of redox reactions (Field and Fifarek, 1985).

Sedimentary sulfides of diagenetic-syngenetic or later epigenetic origin can have extraordinarily large ranges of $\delta^{34}S$ values (-50% to 50%) (Field and Fifarek, 1985). Furthermore, sulfides variably depleted in $^{34}S$ are considered typical of those formed by biogenic processes (Field and Fifarek, 1985).

The $\delta^{34}S$ values of -6.8, -6.9, and -7.2% in pyrite from the B-orebody are consistent with the $\delta^{34}S$ values obtained by Branham (1988) for the American Girl valley deposits in general (see chapter 3). Judging from the general data of sulfur isotope geology briefly summarized above, the $\delta^{34}S$ values for the B-orebody are not clearly indicative of any specific source of sulfur and indeed, sulfur may have been derived from many possible sources ranging from magmatic to sedimentary or biogenic, and/or magmatic with country rock
TABLE 3: Sulfur Isotopes Data (*), B-orebody

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>$\delta^{34}$ S</th>
<th>Stope Loc.</th>
<th>Ore Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG-A</td>
<td>Anhedral veinlet Py.</td>
<td>-7.2</td>
<td>437-S</td>
<td>I</td>
</tr>
<tr>
<td>AG-B</td>
<td>Euhedral diss. py from Au-rich area.</td>
<td>-6.8</td>
<td>437-S</td>
<td>I</td>
</tr>
<tr>
<td>AG-C</td>
<td>Euhedral diss. py from Au-poor area.</td>
<td>-6.9</td>
<td>537-W</td>
<td>III</td>
</tr>
</tbody>
</table>

(*) ± 0.2 per mil
contamination.

In figure 36, the B-orebody is placed within the "Zoned Polymetallic Veins" deposits because of similarities with this group, and lack of general isotopic data from detachment fault-related deposits. In most of the deposits of that group (e.g. Rico, Ouray, Western Cascades, etc), a magmatic source of sulfur is advocated. Field and Fifarek (1985, p. 114) define the zoned polymetallic vein deposits by saying:

"These deposits may exhibit characteristics suggestive of a deeper (than volcanic-hosted and sediment-hosted epithermal deposits) level of hydrothermal mineralization, such as fluid inclusions having higher salinities and homogenization temperatures; a not uncommon magmatic component to the hydrothermal fluids as deduced from hydrogen- and oxygen-isotope data; host rocks that include plutonic and sedimentary lithologies; alteration that lacks widespread and pervasive zones of advanced argillic and alunitic assemblages; and ores that contain relatively abundant sulfides and sulfosalts of the base metals."

In conclusion, very close $\delta^{34}S$ values suggest a similar source of sulfur for the two types of pyrite (euhedral disseminated and anhedral from veinlets) from the B-orebody studied. The actual source of sulfur is unknown but the $\delta^{34}S$ values obtained (~ -7%) indicate a wide variety of possible sources.
FIGURE 36: Distribution of $\delta^{34}S$ in Epithermal Deposits (Adapted from Field and Fifarek, 1985).
CHAPTER V

DISCUSSION AND INTERPRETATIONS

Controls of Alteration-Mineralization

The mineralization-alteration which produced the American Girl B-
orebody is primarily structurally controlled. Low angle shear zones,
faults, fractures, and breccia zones within both upper and lower plates
provided ideal structural pathways for the circulation of mineralizing
solutions into the B-zone. Detachment fault-related features appear to
be the dominant structures that controlled the mineralization of the B-
orebody. Fluids moved primarily laterally along the low angle shear
zones (e.g. B-zone; C-zone; etc). Vertical migration through connecting
steeply-dipping fractures (feeders) in the upper plate (i.e. curviplanar
and listric structures, chapter IV), allowed fluid interaction between
successively stacked low angle shear zones.

Fluid-filled inclusions in vein quartz indicate that ore fluids of
the first mineralization event (massive Au-bearing quartz veins, see
Fig. 26) were hot (272°-300°C, without correction for pressure), low to
moderate salinities (1.7-11.2% NaCl equivalent) waters (this study and
Branham, 1988). The second mineralization event (detachment fault-
related) had co-genetic(?) pyrite (± chalcopyrite) and magnetite (Fig.
27), accompanied by chlorite- and sericite-dominated alteration
assemblages and late stage calcite veining (fig. 31). Thus, the general
sequence of hypogene mineralization for this event is:
FIGURE 37: Log fO₂-pH diagram showing mineral stabilities for the system Au-Fe-CaO-H₂O-A_hO₄⁻-SiO₂-NaCl-C-S-H₂O at 250°C and CO₂ partial pressure of 1 atm. Dashed lines represent Au solubilities (after Romberger, 1988). Neutral pH at 250°C is approximately 5.5. Parameter values for the B-zone system are unknown but the values used for the diagram seem reasonable for this system.
py ----> py + mg + chl ----> ser (± Au) ----> calcite

This mineral sequence is the product of a changing mineralizing fluid through time. It may be explained by changes in oxygen fugacity (and pH) as can be seen in the fO₂-pH diagram showing mineral stabilities (see Fig. 37). The arrow illustrates that in the B-zone, near-neutral (neutral pH at 250°C is approx. 5.5) mineralizing solutions may have evolved from reducing to more oxidizing conditions. The presence of sericite (Phyllic alteration) corroborates this interpretation because this mineral forms in neutral to slightly alkaline solutions (Romberger, 1988). Gold was probably transported as a bisulfide complex and precipitated as a result of the decrease in solubility caused by more oxidizing conditions (Fig. 37).

Paragenetic Sequence of the B-orebody

The paragenetic sequence of the B-orebody was difficult to determine because of the lack of crosscutting relationships and other data about timing among some of the prevalent mineral assemblages (Fig. 29). However, a tentative generalized sequence (Table 4), based upon regional tectonics, structural features found in the B-zone mine, mineral paragenesis and alteration of the B-orebody and assay data, is discussed below.

1- Early pyrite generation.

Pyrite (up to 2%) has been found in non-mineralized areas of the Tumco
TABLE 4: Tentative Paragenetic Sequence of the B-orebody Mineralization (see text for discussion).

1- Early pyrite generation.

2- Thrust faulting. Massive gold-bearing quartz veins (± sulfide deposition?). Ductile deformation.

3- Detachment faulting; brittle deformation and brecciation accompanied by:
   a) Propylitic alteration and sulfide mineralization (pyrite ± magnetite ± chalcopyrite ± galena).
   b) Remobilization and perhaps additional introduction of gold; phyllitic alteration.
   c) Post-ore carbonate veinlets ± scheelite ± fluorite.

4- Post-mineralization fracturing and brecciation (no mineralization).

5- Supergene redistribution of gold.
Formation (Ahlrichs, 1978; Branham, 1988; Drilling Data). Two samples of pyrite from those areas gave -1% and -3.1% \(\delta^{34}S\) values (Branham, 1988), indicating a different sulfur isotope signature from pyrite from the B-orebody (~7%, \(\delta^{34}S\), this study). This suggests either that (1) the pyrite differences are a function of different laboratories and really not much different or (2) the differences are real. Explanation two is most probably correct and the pyrite from Au-bearing areas is probably genetically different from the non Au-mineralized Tumco pyrite. Therefore, pyrite may have formed in the Tumco rocks by pre-mineralization processes, including (1) sedimentation of the Tumco Formation protolith, and/or (2) middle Jurassic magmatism or regional metamorphism. At present, the answer is not known.

2- Thrust faulting; ductile deformation accompanied by massive gold-bearing quartz veins (± sulfide deposition?)

The B-orebody shows delicately folded areas of massive Au-bearing quartz, banded massive quartz-Tumco rocks and Tumco rocks (Fig. 20, 21 and 25), suggesting that ductile deformation probably due to compressional tectonics operated. Because the B-zone crosscuts the foliation of the country rocks, this deformational style cannot be explained by regional metamorphism. Thus, ductile deformation is probably the result of compressional movement in the upper plate of the Chocolate mountain thrust (late Mesozoic-early Tertiary), that initially formed the B-shear zone. A hydrothermal system deposited the massive Au-bearing quartz veins which were subsequently ductilely deformed. The American Girl-main and C-shear zones may have also formed at this time
too. Furthermore, Henshaw (1942) and Dillon (1976), believed that the low angle faults in the American Girl valley were thrust faults because of foliation plots showing tops to the north (Dillon, 1976), and the presence of drag folds indicating thrust movement in the American Girl old mine (Henshaw, 1942). Because the assay data indicates a close association between massive quartz veins and higher gold grades, gold is inferred to have been deposited in greater amounts during this first hydrothermal event. Fluid inclusions in quartz for this event of mineralization show temperatures of homogenization ranging from 272°C to 300°C.

3- Detachment faulting; brittle deformation and brecciation. The ductilely deformed areas of massive Au-bearing quartz veins and associated rocks within the B-orebody, appear to have been subjected to a later episode of extension. Steeply dipping normal faults crosscut and offset previously folded areas (Fig. 22); brecciation and shattering of massive quartz veins are common, with chlorite breccias along the footwall (Fig. 11, 17 and 18), and abundant stockwork structures, veins and veinlets within the ore zone (Fig. 26 and 33). The style of extensional deformation resembles that of a detachment fault (low angle normal) system. Structural features typical of those systems like the base-structure microbreccia (Fig. 11, 17 and 21), "curviplanar" normal faults that merge but do not offset the base-structure (Fig. 11 and 22), chlorite breccias along the footwall (Fig. 11, 17 and 21), anastomosing fault patterns (Fig. 10, 11 and 19), and stacked shear zones as represented by the American Girl-main, "B" and "C" zones (Fig 10), are
all present in the B-ore zone and its environs.

This extensional, detachment fault style of deformation, therefore, was superimposed on earlier thrust faults, reactivating some pre-existent low angle shear zones (e.g. B-zone) and/or creating new ones. The ground was thus prepared for additional mineralization and/or remobilization. Significantly, overprinting of extensional deformation (mid-Tertiary detachment faulting) on compressional deformation (Laramide thrust faulting), has been widely documented in the southwestern U.S. (e.g. Frost and Martin, 1983; Coney and Harms, 1984; Frost, et al, 1984; Haxel and Grubensky, 1984).

The detachment fault structural event was accompanied by:

3a- Sulfide mineralization (pyrite ± magnetite ± chalcopyrite ± galena), followed by (3b) Remobilization and perhaps further introduction of gold.

Structural preparation during detachment faulting resulted in a second mineralization event characterized by sulfides ± magnetite (± gold?). Because gold adheres to or occupies fractures in pyrite and chalcopyrite, but is rarely enclosed in sulfides (Henshaw, 1942; Hausen, 1978; Guthrie, et al, 1987), gold deposition may be later than sulfide formation. Thus, gold could have been remobilized and/or added to the rocks. Furthermore, assay data show that areas of Tumco rocks within the B-orebody (ore type III, see chapter 4) that contain only minor massive Au-bearing quartz veins have low but still economic gold grades (0.05-0.20 oz Au/ton). Finally, the spatial correspondance between detachment
fault structural features (e.g. base structure, curviplanar normal faults, chlorite breccia), and the gold-mineralized zone, is additional permissive evidence of gold remobilization and/or introduction during the detachment faulting hydrothermal event.

3c- Post-ore carbonate veinlets ± scheelite ± fluorite.
Calcite veins and veinlets are clearly late because they crosscut all other mineral assemblages (Fig. 30 and 31). Scheelite also appears to be late because it is present in breccia zones as small veinlets or coating breccia fragments.

4- Post-mineralization fracturing and brecciation.
Breccias containing calcite or pyrite solely within fragments (Fig. 23), indicate post-mineralization brecciation. Other evidence includes the offset of the ore zone (and the base-structure) by high angle normal faults, which is also apparent in a mountain-range scale (e.g. Araz fault, fig. 4).

5- Supergene redistribution of gold.
Supergene redistribution of gold is indicated by the association of free gold with goethite and pseudomorph hematite after pyrite (Hausen, 1978). Also, Ag/Au ratios that are approximately one in hypogene ores, are less than 1 (see chap. 4) in the oxidized, near-surface areas of the orebody (e.g. 598 stope). This is also indicative of the action of descending meteoric waters.
Genetic Models

Any genetic model proposed to explain the formation of the American Girl B-orebody should be compatible with the following:

(1) The low angle shear zone that contains the B-orebody is one of a group of stacked mineralized shear zones in the American Girl valley.

(2) The B-shear zone crosscuts the general structure and fabric of the metamorphic and metaplutonic wall rocks.

(3) All rocks within the orebody and especially the banded quartz veins-Tumco schist areas are delicately folded and ductilely deformed.

(4) Folds are in turn crosscut and often offset by an intricate system of curviplanar and listric normal faults that form part of an overall detachment fault structural style that characterized the B-zone.

(5) Textural and structural relationships suggest two principal mineralization events characterized by: (1) massive Au-bearing quartz veins, and (2) sulfides-magnetite (± gold?) and carbonates.

(6) High gold grades are generally associated with massive quartz vein-bearing areas, but extensive areas of ore lacking massive quartz veins also contain lower but economic grades.

(7) Wall rock alteration is characterized by widespread propylitization within and around the orebody, and a phyllitic assemblage restricted to the ore zone only.
The presence of faults that offset the orebody, and evidence of multiple episodes of brecciation.

Fluid inclusions from gold-bearing quartz veins show temperatures of homogenization ranging from 270°C to 300°C (uncorrected for pressure).

The ores have low base metal contents and very low silver/gold ratios.

In addition, the genetic model should be consistent with the general aspects of the regional tectonic evolution.

Several genetic models for the formation of the Cargo Muchacho mountains gold deposits have been proposed. They are briefly discussed below.

**Model 1:** Guthrie and others (1987), proposed that a mesothermal hydrothermal system developed during the waning stages of metamorphism, which they linked to the Laramide thrusting event. They based that interpretation upon the parallelism between the low angle shears that contain the mineralization and the rock foliation.

At the American Girl B-zone, however, the orebody appears to crosscut the foliation of the country rocks, thus suggesting a post-metamorphic origin for the mineralization. Also, more recent data (De Ridder and Johnson, 1987) assigned a late Jurassic age (pre-thrusting) to the regional metamorphism in the Cargo Muchacho mountains (see Table 1).
Model 2: Branham (1988), interpreted the quartz-gold veins in the American Girl valley as a product of magmatic fluids from cooling (Jurassic) granites along Jurassic extensional faults. He stated that low angle (Au-mineralized?) shear zones are cut by Jurassic pegmatites, thus giving a time constraint for the mineralization. He also suggested that later Laramide thrusting and/or mid-Tertiary detachment reactivated the faults, only crushing the quartz veins without any additional mineralization.

At the B-zone orebody, however, there is no evidence of pegmatites cutting the ore zone. Furthermore, the B-orebody is unmetamorphosed and crosscuts wall-rock foliation. These data are therefore inconsistent with the pre- (or syn-?) metamorphic (see Table 1), magmatic origin proposed by Branham (1988).

Model 3: Drobeck and others (1986), proposed a mid-Tertiary detachment fault-related model for the Picacho gold deposit, which was also applied to the Mesquite and Padre-Madre deposits (see Fig. 2 and 3 for location). They believed the latter deposit was formed in a lower plate detachment fault setting, at deeper crustal levels than at Picacho.

The fact that detachment fault-related structures strongly control the location and geometry of the B-orebody favors a similar (to Picacho and Padre-Madre) model for the formation of the B-zone. Nevertheless, some of the other evidence listed above (e.g. the ductile deformation of massive Au-bearing quartz veins) do not appear to fit well with a single extensional detachment model.
Because of the complexity of the mineralization in the B-zone, and the abundance of apparently contradictory data seen in genetic models previously proposed in other studies, a single mineralizing event seems unlikely. The preferred genetic model proposed in this study is presented below.

**Model 4:** Structural features, textural relationships, and alteration mineralogy suggest the American Girl B-orebody formed as a result of two hydrothermal events. The first developed during the compressional late Mesozoic-early Tertiary thrusting event. The second, which overprinted the first, developed during the extensional mid-Tertiary detachment faulting event which terminated the systems.

The sequence of events (Fig. 38) probably began with movement along shears in the upper plate of the Chocolate mountains thrust that brought up deep, hot rocks to high crustal levels, possibly generating an amagmatic(?) hydrothermal system (Henley, 1985). Hot (greater than 272-300°C), low to moderate salinity hydrothermal fluids circulated through and deposited gold-bearing massive quartz veins along low angle shear zones, that were subsequently deformed and ductilely folded. Regional uplift and crustal overthickening, resulting from thrusting, was followed by a period of compressional relaxation and extensional tectonics resulting in the major mid-Tertiary detachment faulting (Coney and Harms, 1984; Frost and Martin, 1983; De Ridder and Johnson, 1987). The detachment event reactivated earlier, low angle shears in the lower plate of the detachment fault, fracturing and brecciating the massive Au-bearing quartz veins and associated rocks, and creating new
Middle Jurassic meta-sedimentary and meta-volcanic rocks (igneisses and schists of the Tuaco Fault) middle Jurassic granitoids.

Late Cretaceous-early Tertiary thrusting bringing up deep, hot rocks to upper crustal levels generating an anagaatic (?) hydrothermal system; deposition of massive Au-bearing quartz veins.

Continued thrusting and ductile deformation delicately folds the massive Au-bearing quartz veins and associated rocks (schist and gneiss).

Regional uplift and crustal thickening occurs.

Compressional relaxation is followed by extensional aid-Tertiary detachment faulting partially reactivating low angle shears. Fracturing and brecciation of massive quartz veins and associated rocks. Volcanism and sedimentation in fault-controlled basins (found at the Picacho-Mesquite area).

Continued extension and crustal thinning: development of interboudin faults and normal faults in the lower plate. Crustal thinning causes heat flow originating hydrothermal convection.

Sulfides and magnetite precipitate in favorable sites; gold is remobilized and/or additional gold is introduced into the system.

Later movement offsets and further brecciates the ore zones.

FIGURE 38: Schematic Genetic Model for the American Girl B-zone deposit (adapted in part from Drobeck et al, 1986).
channelways for additional mineralization. Renewed hydrothermal activity was possibly the result of elevated geothermal gradients due to rapid uplift of lower plate rocks during extension (Spencer and Welty, 1986; Doblas, et al, 1988; Tempelman-Kluit, 1984; etc). Propylitic and phyllitic alteration mineral assemblages formed within and about low angle shears; gold was remobilized and perhaps additional gold was introduced into the system at this time. Later, post-detachment movement, probably associated with the San Andreas Fault system, caused post-mineral fracturing, rebrecciations and minor displacement of the orebody. Finally, weathering may have been responsible for some remobilization of metals and the changing of original Ag/Au ratios.

Coeval igneous intrusions that may have been sources of heat and/or fluids or metals, do not outcrop within the mountain range. The Jurassic granitic suite is pre-mineralization, and the small, shallow, undeformed and unaltered body of rhyodacite porphyry (see Fig. 4) is apparently post-mineralization (Branham, 1988). However, the possibility exists of a hidden mineralizing intrusion (De Ridder and Johnson, 1987; Branham, 1988).

The source of gold for the Cargo Muchacho mountains deposits is unknown but remobilized, originally syngenetic Au in metamorphic rocks (Chevillon and Norris, 1986), and Jurassic igneous rocks (Tosdal and Haxel, 1985), has been proposed. Recently, however, lead isotope data (Frost, 1989, 1990), from the Mesquite deposit (see Figure 3 for location), shows that none of the units within the vicinity of that deposit (including Mesozoic intrusions, pegmatites, leucogranites, and host gneisses) are genetically linked to the gold. Rather, Frost (1989,
1990) determined the gold was derived from 1.3 to 1.4 Ga basement and redepotted via a Tertiary felsic intrusion at Mesquite. The nearby location and many similarities of the B-orebody with the Mesquite deposit (see following section), are compatible with a similar argument regarding the source of Au for the American Girl B-zone. However, Tertiary felsic intrusions have not been located within the Cargo Muchacho mountain range.

**Comparison of the B-orebody with nearby Au Deposits**

The B-orebody is similar in many respects to Au mineralized areas within the American Girl valley, the Cargo Muchacho mountain range and other deposits within the region. In order to gain an insight into possible genetic relationships with the mineralization of the B-orebody, characteristics of these Au deposits are compared and discussed below.

**Deposits within the American Girl Valley**

In the American Girl valley, the American Girl-Main and C-zones are spatially associated with the B-zone, forming a group of stacked, low angle shear zones (Fig. 10). These zones, together with the American Boy at the east end of the valley (see Fig 5), are all part of the same structural setting of low angle shears that form interconnected, anastomosing fault patterns and host tabular gold mineralized zones. Also, the steeply dipping curviplanar normal faults (Fig. 11) within the B-orebody may be feeder veins of the American Girl-Main (A.G.-Main) zone located above. Likewise, the steeply dipping fractures of the B-ore zone
footwall (feeders?; Fig. 11 and 16), may be curviplanar normal faults of the C-zone located below. Because of the lack of mine development, little is presently known about those zones. However, information from drill holes and old workings (Henshaw, 1942; Platt, 1982; Branham, 1988) show that they share many similarities with the B-zone including presence of massive Au-bearing quartz veins, Au-bearing Tumco rocks (A.G.-Main), widespread propylitic and minor phyllic alteration, and their mineralogy and structure. Differences include wall rocks (the American Boy and C-zones are within granites), geometry (the A.G.-Main ranges up to 30m (100’) thick), size and gold grades.

The spatial association and overall identical nature of the B-orebody and the other Au-mineralized areas in the American Girl valley, strongly suggest a similar mode of formation.

**Deposits Within the Cargo Muchacho Mountains**

In the Cargo Muchacho mountains, the Padre-Madre Au deposit south of the American Girl valley, is also similar in most respects to the B-zone. It is located along a south dipping low angle shear zone, is hosted by the Tumco Formation, has Ag/Au ratios of approximately one, and the footwall is a quartz monzonite. Furthermore, gold mineralization appears to be controlled, in addition to the low angle shear zone, by steeply dipping fractures (curviplanar normal faults?) (R. Thompson and J. Moore, 1988, personal communication). On the other hand, the Padre-Madre deposit lacks significant massive quartz veining, is slightly higher in Cu than the B-zone, lower in gold (0.051 oz/ton), ranges up to 20m (70’) in thickness and appears to be parallel to the foliation of
the country rocks.

The Padre-Madre ore may be equivalent to the low-gold, pyritic Tumco rocks (ore type III) defined for the B-orebody (see chapter 4). The lack of massive Au-bearing quartz veins (ore type I in the B-orebody) and banded massive quartz-pyritic schist (ore type II) in the Padre-Madre deposit, suggest the possible absence of the first hydrothermal event (related with thrust faulting). However, the second event (related with detachment faulting), seems a plausible formation mechanism. This interpretation is consistent with the detachment fault model proposed by Drobeck and others (1986) for the Picacho, Mesquite and Padre-Madre deposits.

The Tumco camp area, north of the American Girl valley (Fig. 2), appears to have characteristics distinct from the deposits located south of the valley. The mineralized zones lie parallel (at low angles) to bedding planes in the Tumco Formation, are lenticular to tabular but neither the footwall nor the hanging wall are well defined (Morton, 1977). The ore zones are composed "simply of the country rock", i.e. essentially unaltered and unbrecciated, and sulfide minerals are uncommon (Morton, 1977). Branham (1988) and De Ridder and Johnson (1987) state that gold in the Tumco valley is associated with quartz-magnetite zones which are cut by leucogranite pegmatites.

Except for the low angle character of the mineralization in the Tumco valley, none of the other characteristics correspond well with the geology of the American Girl B-zone in particular, or the deposits south of the American Girl valley in general. This evidence suggest that
different genetic history for the deposits north of the American Girl valley (i.e. Tumco valley) may be applicable. Gold mineralization related to the Jurassic period of granitic intrusion and metamorphism (see Table 1) seems a likely scenario.

**Deposits Within Southeasternmost California**

The B-zone deposit is similar in many respects with nearby Au deposits including Picacho, Mesquite and Riverside (see Fig. 3 for location). They all form tabular, shallowly dipping orebodies that are spatially associated and controlled by low angle detachment structures (Picacho, B-zone, Riverside), or high angle normal faults (Mesquite). They are, like the B-zone, mainly hosted by highly brecciated Mesozoic (or Precambrian?) quartzo-feldspathic gneisses and schists, have low Ag/Au ratios, low base metal contents, similar mineralogy and fluid inclusions with low to moderate salinities (Table 5). The sequence of mineral deposition generally consists of early sulfides, follow by disseminated, very fine-grained gold and later carbonates. They all show a similar regional tectonic history; the Picacho, Mesquite and B-zone deposits are found in a similar structural setting within the upper plate of the Chocolate mountains thrust (Fig. 3). Finally, most of these deposits do not show an obvious link between Au mineralization and intrusions.

However, significant differences between the Mesquite, Picacho, Riverside (MPR) and the B-zone deposits are also apparent. For example, the B-zone shows evidence of two hydrothermal events, the second of which (detachment fault) may be equivalent to the ore-forming event at
TABLE 5, Comparison of the American Girl B-zone deposit with other gold deposits in southeasternmost California.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Picacho 1</th>
<th>Mesquite 2</th>
<th>Riverside 3</th>
<th>Am.Girl B-zone 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant</td>
<td>low angle</td>
<td>high angle</td>
<td>low angle</td>
<td>low angle</td>
</tr>
<tr>
<td>structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brecciation</td>
<td>intense</td>
<td>moderate</td>
<td>intense</td>
<td>moderate</td>
</tr>
<tr>
<td>Alteration</td>
<td>silicif.-sericite</td>
<td>weak silic.</td>
<td>silicif.-sericite</td>
<td>propylitic-phyllic</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Au-py-hm-cc</td>
<td>Au-py-hm-cp-cc</td>
<td>Au-py-hm-cp?-cc</td>
<td>Au-py-cp-gn-mg-sch-cc</td>
</tr>
<tr>
<td>Ag/Au</td>
<td>low (0.2)</td>
<td>low</td>
<td>low (0.8)</td>
<td>low (0.9)</td>
</tr>
<tr>
<td>Base metals</td>
<td>none(?)</td>
<td>low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>T° of Homog.</td>
<td>201-226°C</td>
<td>220-225°C</td>
<td>165-225°C</td>
<td>272-300°C</td>
</tr>
<tr>
<td>Salinity</td>
<td>&lt;1%</td>
<td>~1%</td>
<td>0-13%</td>
<td>1-9% NaCl eq.</td>
</tr>
<tr>
<td>Hydrotherm.</td>
<td>meteoric</td>
<td>meteoric</td>
<td>meteoric?</td>
<td>magnat-meteor or metam (?)</td>
</tr>
<tr>
<td>fluids</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tonnage(Mt)</td>
<td>9.7</td>
<td>41.5</td>
<td>(?)</td>
<td>1.2</td>
</tr>
<tr>
<td>Au (oz/t)</td>
<td>0.038</td>
<td>0.056</td>
<td>(?)</td>
<td>0.232</td>
</tr>
</tbody>
</table>

1.- Drobeck and others, 1986.
4.- This study.

Mineralogy
(py)pyrite; (hm)hematite; (cc)calcite; (cp)chalcopyrite; (gn)galena (mg)magnetite; (sch)scheelite
the MPR deposits. Several features, probably related to the first mineralization event (thrust faulting) are therefore unique of the B-zone, and include the presence of massive Au-bearing quartz veins, intense folding and ductile deformation within the ore zone, higher temperatures of homogenization of fluid inclusions (Table 5), overall dominant mesothermal textures, etc. Other differences including the presence of widespread chloritic alteration, lesser degree of oxidation (than MPR deposits), stacked mineralized shears, chlorite breccias, anastomosing fault patterns and the lack of associated Tertiary sedimentary and volcanic rocks in the B-zone, suggest relatively deeper levels of formation for this deposit than for the MPR deposits, which are generally shallow and of epithermal character (Manske, et al, 1988; Drobeck, et al, 1986; Wilkinson, et al, 1988).

The idea of relatively deep crustal levels for the Cargo Muchacho mountains gold deposits was first proposed by Drobeck and others (1986) in their genetic model of the Picacho deposit. They considered the Padre-Madre deposit (south of the B-zone) as localized along a lower plate detachment interboudin setting. The structural and geologic evidence presented in this study and briefly listed above, appears to confirm that interpretation, suggesting a similar structural setting of a lower plate detachment fault for the second stage of the formation of the B-zone and associated deposits in the American Girl valley.

It is important to point out that recent lead isotopic data for the Mesquite deposit (Frost, 1990), indicated a genetic link between gold mineralization and Tertiary felsic intrusions. Hopefully, with the
eventual availability of similar lead isotopic data for other Au deposits (e.g. B-zone), this important finding may lead to new interpretations and a better understanding of the genesis of Au deposits in the southeasternmost California region.
Conclusions and Recommendations

Conclusions

1. The B-zone orebody is hosted by a low angle fault zone situated between gneissic granites (footwall) and quartzo-feldspathic gneisses of the Tumco Formation (hanging wall). It is part of a group of structurally stacked low angle shear zones in the American Girl valley.

2. Three lithologic types of disseminated gold mineralization within the B-orebody are defined: (I) high Au-grade, massive quartz veins; (II) high Au-grade, banded quartz vein-pyritic schist; and (III) low Au-grade gneiss and schist.

3. The B-zone orebody shows the following mineral paragenesis: (1) massive Au-bearing quartz; and (2) sulfides-magnetite (± gold) and carbonates. The latter stage is subdivided into: (A) pyrite-magnetite-chalcopyrite-galena (± gold?); and (B) calcite (± scheelite and fluorite).

4. Wall rock alteration is characterized by a widespread propylitization (chlorite-epidote-calcite). A phyllitic alteration (sericite-quartz veinlets) is restricted to the ore zone only.

5. The Ag/Au ratios are low relative to the clarke ratio (17.5:1), and average 0.9, probably the result of inheritance from specific (Au-enriched, Ag-depleted) kinds of crust. Within the orebody, the Ag/Au ratios show a vertical zonation probably due to Ag
remobilization during weathering. The ratios change from 0.7 at the upper levels to 1.1 at the lower levels of the mine.

6. Temperatures of homogenization of fluid inclusions from gold-bearing quartz veins range from 272°C to 300.5°C (uncorrected for pressure). A few salinity determinations gave 1.7% to 9.2% NaCl equivalent.

7. Sulfur isotope determinations from two types of pyrite (euhedral disseminated, and anhedral in veinlets) show very similar $\delta^{34}$S values suggesting a similar source of sulfur. An average of -7%. $\delta^{34}$S are compatible with a wide variety of sulfur sources.

8. The alteration-mineralization of the B-orebody is controlled by an intricate fracture system that essentially shows a detachment fault-related geometry and structural style typical of a lower plate detachment setting (lower plate interboudin).

9. Structural features, textural relationships, and alteration mineralogy of the B-orebody suggest formation by a combination of two hydrothermal events. This is probably the result of the overprinting of two regional tectonic events, the late Cretaceous-early Tertiary thrusting, and the mid-Tertiary detachment.

10. The genetic model for the B-orebody may be applicable to other deposits within the range especially for deposits south of the American Girl valley. Some deposits, however, may not show both mineralizing events (Padre-Madre?). The particular case of the Tumco camp, north of the American Girl valley, deserves especial consideration because its distinct characteristics may represent a somehow different (older?) genetic history.
Nearby Au deposits within southeasternmost California (Picacho, Mesquite, Riverside) show important similarities with the B-zone deposit. Evidence indicate that the B-orebody may have formed by similar processes (detachment fault-related) but at deeper crustal levels than the other deposits.

**Recommendations**

The recognition of detachment fault-style structural features in the B-orebody should be considered there and elsewhere for exploration and mining purposes. The interpretation of structural problems from a detachment fault perspective may lead to a better understanding of the geometry and ore continuity. In the case of exploration within the mountain range, structural reinterpretations may help to defining target areas. For example, the "steeply dipping" vein system at the Cargo Muchacho mine (see chapter II) could be part of an upper plate setting grading downward into a low angle detachment surface(?); likewise, the Brown-Blue-White veins at the American Girl old shaft (see chapter II) seem to be part of an integrated high angle (the Blue and White)-low angle (the Brown) fault system.

In addition, as mining of the B-orebody proceeds, it would be important to perform systematic sampling of a selected suite of trace elements (e.g. Pb-W-Hg-Sb-As-Te), that may lead to a better understanding of metals zonation patterns, possible extensions of the gold mineralization and fluid flow directions. Furthermore, recent data (Frost, 1990) indicated that lead isotopic analyses on gold, associated
sulfides and country rocks is a very promising method to "fingerprint" the Au source(s) in highly extended terranes and, thus should be considered as a potential exploration tool in the Cargo Muchacho area.
REFERENCES


Elevatorski, E. A., 1987, Gold-silver bulk-tonnage deposits, Minobras Mining Services, 131 pp..


--- 1981, Mineralogic examination of core specimens from select DDH holes at the Cargo Muchacho gold deposit, Imperial County, California: Newmont Exploration Limited Internal Report.


Morton, P. K., 1977, Geology and mineral resources of Imperial County, California: County Report 7, California Division of Mines and Geology, p. 47-61.


Roedder, E., 1984, Fluid Inclusions, Reviews in Mineralogy, v. 12, Mineralogical Society of America, 644 pp..


Jurassic intra-arc basin, Geological Society of America Abstracts with Programs, v. 16, n. 5, p. 338.


APPENDIX I

STATISTICAL ANALYSIS OF METAL GRADES

Using the assay data for Au, Ag and Cu from the underground B-
orebody, an average grade for each metal was calculated for every 6 m
(20)' interval. These 73 "equal width" intervals represent the sample
size (n) considered in this analysis.

The data were introduced to a mainframe computer using the
statistical package "S".

Summary statistics

A general summary statistics follows *:

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>Var</th>
<th>StDv(s)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>0.235</td>
<td>0.17</td>
<td>0.046</td>
<td>0.215</td>
<td>1.042</td>
</tr>
<tr>
<td>Ag</td>
<td>0.199</td>
<td>0.127</td>
<td>0.033</td>
<td>0.182</td>
<td>0.808</td>
</tr>
<tr>
<td>Cu</td>
<td>2.66</td>
<td>2.16</td>
<td>3.22</td>
<td>1.79</td>
<td>8.33</td>
</tr>
<tr>
<td>Au/Ag</td>
<td>1.39</td>
<td>1.27</td>
<td>0.61</td>
<td>0.78</td>
<td>3.6</td>
</tr>
<tr>
<td>Cu/Ag</td>
<td>20.8</td>
<td>18.0</td>
<td>196</td>
<td>14</td>
<td>75</td>
</tr>
<tr>
<td>Cu/Au</td>
<td>19.5</td>
<td>13.2</td>
<td>525</td>
<td>23</td>
<td>176</td>
</tr>
</tbody>
</table>

* grades in oz/t

The 95% confidence interval for the Au-Mean is (0.185, 0.285), with an
standard error of 0.02521.

The data have been plotted in histograms for each metal (see
FIGURE 39: Distribution of Gold Grades (in ounces per ton) in the B-orebody.
\[ n = 73 \]
\[ \bar{x} = 0.199 \]
\[ \text{median} = 0.127 \]
\[ s = 0.182 \]

**FIGURE 40:** Distribution of Silver Grades (in ounces per ton) in the B-orebody.
\[ n = 73 \]
\[ \bar{x} = 2.66 \]
\[ \text{median} = 2.16 \]
\[ s = 1.79 \]

FIGURE 41: Distribution of Copper Grades (in ounces per ton) in the B-orebody.
enclosed graphics); very extreme values were eliminated from the graphics (not from summary statistics) for simplicity. Both Au and Ag show a unimodal distribution skewed to the right (high values), whereas Cu shows a bimodal distribution also skewed to the right. The skewness of the distribution curves is also reflected by the mean being larger than the median in all cases.

**Correlation coefficient**

Pearson's correlation coefficients (Rp) have been calculated for the paired data Au-Ag, Cu-Au and Cu-Ag, giving the following values:

\[
\begin{align*}
\text{Rp}(\text{Au, Ag}) &= 0.77 \\
\text{Rp}(\text{Cu, Au}) &= 0.50 \\
\text{Rp}(\text{Cu, Ag}) &= 0.56
\end{align*}
\]

In addition, "robust" correlation coefficients (Rg) were calculated with the following results:

\[
\begin{align*}
\text{Rg}(\text{Au, Ag}) &= 0.61 \\
\text{Rg}(\text{Cu, Au}) &= 0.25 \\
\text{Rg}(\text{Cu, Ag}) &= 0.44
\end{align*}
\]

"Robust" statistics gives parameters that are not affected by very extreme values (either too high or too low); for example the median is a "robust" measure of location, whereas the mean is not. In the case of Rg, the data are correlated according to the ranks of the values rather
than the values themselves (as in Rp) hence, avoiding the influence of extreme values.

These data show high positive correlation between Au and Ag, medium positive correlation between Cu and Ag, and fairly low positive correlation between Cu and Au.

The Rp's by mine zones are:

598
Rp(Au, Ag) = 0.57; Rp(Cu, Au) = 0.53; Rp(Cu, Ag) = 0.78

537
Rp(Au, Ag) = 0.91; Rp(Cu, Au) = 0.76; Rp(Cu, Ag) = 0.72

437
Rp(Au, Ag) = 0.62; Rp(Cu, Au) = 0.23; Rp(Cu, Ag) = 0.05

377
Rp(Au, Ag) = 0.83; Rp(Cu, Au) = 0.38; Rp(Cu, Ag) = 0.43

The enclosed graphics are scatter plots of bivariate data (Au-Ag, Cu-Au, and Cu-Ag) with the computed fitted line for each case. Extreme values are not included in the graphics for simplicity; nevertheless, the equations include all the data.

The equations of the fitted linear regressions are:

\[ \text{Ag} = 0.045 + 0.656 \text{Au} \]
\[ \text{Au} = 0.075 + 0.060 \text{Cu} \]
\[ \text{Ag} = 0.048 + 0.057 \text{Cu} \]
\[ \text{Au} = 0.0537 + 0.911 \text{Ag} \] (not shown in graphic)
FIGURE 42: Scatter Plot of Gold and Silver Grades (in ounces per ton).
FIGURE 43: Scatter Plot of Copper and Gold Grades (in ounces per ton).

\[ y = 0.25 + 0.06x \]

- \( n = 73 \)
- \( R_p = 0.50 \)
- \( R_g = 0.25 \)
FIGURE 44: Scatter Plot of Copper and Silver Grades (in ounces per ton).