Thermochemical conditions for the formation of Archean lode gold mineralization at Atlantic City-South Pass, Wyoming

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Thermochemical conditions for the formation of Archean lode gold mineralization at Atlantic City-South Pass, Wyoming

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Iowa State University, 1990
Thermochemical conditions for the formation of Archean lode gold mineralization at Atlantic City-South Pass, Wyoming

by

Krista I. McGowan

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### TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENERAL INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>SECTION I. RARE EARTH ELEMENT STUDIES OF THE ARCHEAN \</td>
<td>4</td>
</tr>
<tr>
<td>SOUTH PASS SUPRACRUSTAL BELT: IMPLICATIONS FOR THE CRUSTAL EVOLUTION OF</td>
<td></td>
</tr>
<tr>
<td>THE WYOMING PROVINCE</td>
<td></td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>5</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>6</td>
</tr>
<tr>
<td>REGIONAL GEOLOGY</td>
<td>10</td>
</tr>
<tr>
<td>Wyoming Archean Province</td>
<td>10</td>
</tr>
<tr>
<td>South Pass Supracrustal Belt</td>
<td>12</td>
</tr>
<tr>
<td>TRACE ELEMENT GEOCHEMISTRY</td>
<td>19</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>42</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>50</td>
</tr>
<tr>
<td>SECTION II. ORIGIN OF ARCHEAN LODE GOLD MINERALIZATION AT ATLANTIC</td>
<td>51</td>
</tr>
<tr>
<td>CITY-SOUTH PASS: FLUID INCLUSION, STABLE ISOTOPE, AND TRACE ELEMENT</td>
<td></td>
</tr>
<tr>
<td>STUDIES</td>
<td></td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>52</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>54</td>
</tr>
<tr>
<td>GEOLOGICAL SETTING</td>
<td>58</td>
</tr>
<tr>
<td>MINERALIZATION IN THE ATLANTIC CITY-SOUTH PASS DISTRICT</td>
<td>67</td>
</tr>
<tr>
<td>Mining History</td>
<td>67</td>
</tr>
<tr>
<td>Lode Gold Deposits</td>
<td>68</td>
</tr>
<tr>
<td>GEOCHEMISTRY</td>
<td>71</td>
</tr>
<tr>
<td>Trace Element Geochemistry</td>
<td>71</td>
</tr>
<tr>
<td>Stable Isotope Ratio Analysis</td>
<td>73</td>
</tr>
<tr>
<td>Fluid Inclusion Analysis</td>
<td>86</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

SECTION I.

Figure 1. Regional geologic setting of the South Pass Supracrustal Belt (modified from Bayley, 1968) 7

Figure 2. General geology of the South Pass Supracrustal Belt (modified from Hausel, 1987) 13

Figure 3. General geology of the Atlantic City-South Pass district (modified from Bayley, 1968) 16

Figure 4. Chondrite-normalized REE plot for tholeiitic Miners Delight Amphibolite Belt (MDAB) samples 24

Figure 5. Chondrite-normalized REE plot for Archean TH1 and TH2 tholeiites (Condie, 1981), average Roundtop Mountain Greenstone Fm. tholeiite (Condie and Baragar, 1974), and MDAB sample DIP4-1 25

Figure 6. Chondrite-normalized REE plot for range and average MDAB 2 amphibolites, and average modern calcalkaline and continental rift tholeiites (Condie, 1981) 27

Figure 7. Chondrite-normalized REE plot for MDAB andesites 28

Figure 8. Chondrite-normalized REE plot for range and average MDAB andesite, and average Archean andesite type 2 and modern high-K calcalkaline andesite (Condie, 1981) 29

Figure 9. Chondrite-normalized REE plot for greywackes from the Atlantic City-South Pass district. 30

Figure 10. Chondrite-normalized REE plot for range and average Atlantic City-South Pass greywacke, average Archean shale (McLennan and Taylor, 1984), and post-Archean North American Shale Composite (NASC, Taylor and McLennan, 1985) 31

Figure 11. Chondrite-normalized REE plot for graphitic schists from the Atlantic City-South Pass district 32

Figure 12. Chondrite-normalized REE plot for type 1 Atlantic City-South Pass graphitic schists and the Soudan 33
slate (Wildeman and Haskin, 1973)

Figure 13. Chondrite-normalized REE plot for type 2 Atlantic City-South Pass graphitic schists, AAS (McLennan and Taylor, 1984), and NASG (Taylor and McLennan, 1985)

Figure 14. Chondrite-normalized REE plot for type 2 Atlantic City-South Pass graphitic schists, and Onwantin and Ventersdorp graphitic schists (Wildeman and Haskin, 1973)

Figure 15. La-Th-Sc ternary plot for Atlantic City-South Pass metasediments

Figure 16. Hf-Th-Co ternary plot for Atlantic City-South Pass metasediments

Figure 17. Chondrite-normalized REE plot for cherts from the Atlantic City-South Pass district.

Figure 18. Chondrite-normalized REE plot for iron formation of the Goldman Meadows Fm.

SECTION II.

Figure 1. Regional geologic setting of the South Pass Supracrustal Belt (modified from Bayley, 1968)

Figure 2. General geology of the South Pass Supracrustal Belt (modified from Hausel, 1987)

Figure 3. General geology of the Atlantic City-South Pass district (modified from Bayley, 1968)

Figure 4. Chondrite-normalized REE plot for samples from the Gold Dollar mine

Figure 5. Histogram of S isotope values


Figure 7. Carbon isotope data for the Atlantic City-South Pass district and for worldwide Archean gold deposits. Worldwide and reservoir data from Colvine
et al. (1988, 1984)

Figure 8. Plot of $\delta^{13}C$ vs. $\delta^{18}O$ for early and late calcite and Tornado carbonate from the Atlantic City-South Pass district and worldwide Archean gold-related carbonate. Worldwide data from Colvine et al. (1984) and Golding et al. (1987)

Figure 9. Plot of $\delta^{18}O$ vs. $dD$ for the Atlantic City-South Pass district and various reference fluids. Data sources: Archean lode gold, Colvine et al. (1984); Mother Lode, Bohlke and Kistler (1986), Weir and Kerrick (1987); Canadian Cordillera, Nesbitt and Muehlenbachs (1989). Curves for equilibration of various water/rock ratios with igneous and sedimentary rocks from the equations of Field and Fifarek (1985)

Figure 10. Compositional variability of fluid inclusion types from the Atlantic City-South Pass district

Figure 11. Histograms of freezing data, Types 1 and 2 inclusions

Figure 12. Histogram of homogenization data, Types 2 and 3 inclusions

Figure 13. Histogram of freezing data, Type 3 inclusions

Figure 14. P-T conditions for formation of Atlantic City-South Pass lode gold deposits. Solvus for $XCO_2=0.16$ and $XNaCl=0.35$ estimated from the data of Bowers and Helgeson (1983). Isochore for bulk fluid calculated using FLINCOR (Brown, 1989) and the equation of Brown and Lamb (1989)

Figure 15. $fO_2$-$pH$ diagram for 350°C, 3.75 kb. Thermo-dynamic data from Barton (1969), Helgeson (1969), Murray and Cubicotti (1983), Ohmoto (1972), and Shenberger and Barnes (1989)
LIST OF TABLES

SECTION I.
Table 1. REE data. Values in ppm except as noted 20
Table 2. REE data for comparison samples. Values in ppm except as noted 22

SECTION II.
Table 1. REE data for the Gold Dollar mine 72
Table 2. Stable isotope data for the Atlantic City-South Pass district 75
GENERAL INTRODUCTION

This dissertation is divided into two sections. The first section deals with rare earth and trace element studies of Archean metasedimentary and metavolcanic rocks of the South Pass Supracrustal Belt, part of the larger Wyoming Province. The South Pass terrane is host to the largest gold mining district in Wyoming, the Sweetwater district, which is one of the few known, mineable Archean lode gold deposits in the United States. In view of the controversy surrounding the origin of Archean lode gold mineralization, better geochemical and tectonic constraints on the setting of mineralization are important to any genetic model. Rare earth element patterns for greywackes, graphitic schists, and cherts all show Eu depletions similar to post-Archean sediments, indicating a provenance which included Eu-depleted rocks. Similar results have been obtained by other workers for metasediments elsewhere in the Wyoming Province. Calcalkaline amphibolites have patterns similar to Andean-type orogenic andesites, and tholeiitic amphibolites show LREE enrichments. Rare earth element geochemistry of both types of metaigneous rocks suggest the involvement of thick continental crust during magmagenesis. Results for both metaigneous and metasedimentary rocks indicate that the Wyoming Province preserves a different tectonic environment than that of most Archean cratons, perhaps an active continental margin.

The second section discusses fluid inclusion, stable isotope, and trace element analyses of rocks from the Atlantic City-South Pass gold district. Sulfur isotope analyses of sulfides (-1.0 to 3.6 o/oo) are
consistent with data for most other Archean lode gold mineralization. Carbon isotope ratios on carbonates (d^{13}C = -1.5 to -11.0 o/oo) are among the lightest yet recorded for an Archean gold deposit. Carbon from graphitic schists associated with gold-quartz veins gives values of -19.1 to -28.5 o/oo. Oxygen isotope values calculated from vein quartz (d^{18}O = 7.36 to 10.38 o/oo) and hydrogen values (dD = -125 to -55) obtained from fluid inclusions define a field which partly overlaps the metamorphic/magmatic fluid fields.

Primary and/or pseudosecondary fluid inclusions include: 1) one- and two-phase gaseous CO_2-CH_4 inclusions; and 2) two- three- and four-phase CO_2-CH_4-H_2O-NaCl-CaCl_2 inclusions with variable gas-water ratios. Compositionally similar fluid inclusions were found in quartz from the gold district and from the US Steel iron mine, with the exception that no CH_4-bearing inclusions were found in samples from the iron mine. Average bulk fluid composition is: XH_2O=0.8039, XCO_2=0.1615, XNaCl=0.0346. Average salinity is 12.24 NaCl equiv. wt. %. Secondary aqueous inclusions have salinities of 12 to 30 NaCl equiv. wt. %, with 13 to 29 wt. % CaCl_2. Phase separation is indicated by variable gas/water ratios, similar gas densities in both Types 1 and 2 inclusions, and by homogenization to both vapor and to liquid in Type 2 inclusions. Multiple generations of carbonic fluids are indicated by endmember CH_4- or CO_2-rich compositions. Estimated trapping conditions for the average bulk fluid composition with T_{HOT}=275°C are 3.75 kb, 350°C.

Megascopic wallrock alteration is slight, and rare earth element
studies on marginal wallrocks of the Gold Dollar vein did not indicate any geochemically recognizable alteration signature. Locally elevated gold contents of graphitic schists and iron formation suggests that these rocks may simply have been chemically more favorable sites for gold deposition.

Data for the Atlantic City-South Pass district are similar to those of younger mesothermal gold deposits such as those of Alaska and the Canadian Cordillera, suggesting that the Archean deposits were also formed in a continental margin subduction-related tectonic environment. In contrast, the greenstone-hosted type of deposit was formed in a tectonic environment lacking the presence of evolved continental crust.
SECTION I.

RARE EARTH ELEMENT STUDIES OF THE ARCHEAN SOUTH PASS SUPRACRUSTAL BELT:

IMPLICATIONS FOR THE CRUSTAL EVOLUTION OF THE WYOMING PROVINCE
ABSTRACT

Archean supracrustal rocks of the South Pass Supracrustal Belt (SPSB) preserve evidence of at least four metamorphic/deformational episodes. Tholeiites show two different rare earth element (REE) patterns, one similar to Archean TH2 tholeiites or modern calcalkaline tholeiites, the other with pronounced LREE enrichment and slight HREE depletion. These LREE-enriched tholeiites have no Archean analogs, and no exact modern counterparts, but show some similarities to highly LREE-fractionated modern continental rift tholeiites. Andesites are virtually identical to Archean andesite type AA2 and to modern high-K calcalkaline andesites. Metasediments are enriched in LREE, have a small negative Eu anomaly, and their patterns resemble post-Archean sediments more closely than the average Archean shale (AAS). La-Th-Sc and Hf-Th-Co ternary plots reveal a linear trend for the metasediments, indicating a mixed mafic volcanic and recycled sedimentary provenance. REE date for igneous and sedimentary rocks of the SPSB is consistent with that reported from other parts of the Wyoming Province, and indicates the presence of thick lithosphere early in its geologic history. However, in contrast to the northwestern Wyoming Province of Montana, the tectonic environment appears to be an active continental margin, rather than a rift-bounded ensialic basin (Mogk and Henry, 1988).
INTRODUCTION

The South Pass terrane (Fig. 1) is host to the largest gold mining district in Wyoming, the Sweetwater district (Fig. 2), which is one of four known, mineable Archean lode gold deposits in the United States. In view of the controversy surrounding the origin of Archean lode gold mineralization, better geochemical and tectonic constraints on the setting of mineralization are important to any genetic model.

Archean greenstone-hosted lode gold deposits are second only to early Proterozoic paleoplacers for total cumulative world gold production. While greenstone-hosted gold deposits occur only in rocks of Archean age, turbidite-hosted gold deposits occur throughout geologic time. These deposits occur in thick successions of deep marine turbiditic greywacke, black shale, and argillite, and often contain minor quantities of intercalated volcanic rocks (Woodall, 1976). 'Mesothermal' gold deposits such as those of the Canadian Cordillera, Alaska, and California are usually considered to be of the turbidite-hosted type (Hutchinson, 1987). Other than the difference in host rock lithology, turbidite-hosted gold deposits share many geological and geochemical characteristics with the greenstone-hosted type. Hutchinson (1987) classified both as 'eugeosynclinal', and concluded that the turbidite-hosted type is simply a younger evolutionary variant of the greenstone-hosted type, and attributed the lithologic differences to the effects of plate tectonic evolution on the composition of late Proterozoic and early Paleozoic deep marine eugeosynclinal successions.

Recent studies (e.g., Card et al., 1989) indicate that the Superior
Figure 1. Regional geologic setting of the South Pass Supracrustal Belt (modified from Bayley, 1968)
Province of Canada, the world's most prolific area of greenstone-hosted lode gold deposits, is composed of a series of accreted oceanic terranes. Rocks of the northern Wyoming Province in southwestern Montana exhibit a variety of metamorphic and structural styles that developed over the first billion years of continental growth in North America, but are dominated by continental margin type tectonic settings (Mogk and Henry, 1988). Continental crust has been documented in the northern Wyoming Province at 3.6 Ga (Wooden et al., 1988; Mogk and Henry, 1988). The North Snowy Block mobile belt in the western Beartooth Mountains, separating an eastern terrane composed mainly of late Archean plutons and older supracrustal remnants from a western terrane dominated by high-grade platform-type metasedimentary sequences and lacking large volumes of mafic rocks or eugeosynclinal sediments, has been interpreted as a Cordilleran-type continental margin (Mogk and Henry, 1988). The western terrane includes most of the rocks of the Gallatin, Madison, Tobacco Root, Ruby, and Blacktail Ranges, and has been interpreted as a rift-bounded ensialic or Tethyan-type basin in which only a small amount of oceanic crust was produced (Mogk and Henry, 1988). Closure of the basin occurred during continental collision at 2.70 to 2.75 Ga (Mogk and Henry, 1988; Wooden et al., 1988).

Recent geochrononologic investigations indicate that the Wind River Range is at least as old, but its tectonic setting is somewhat less well-established. Koesterer et al. (1987) documented the existence of continental crust as old as 3.4 Ga in the west-central Wind River Range. Hulsebosch and Frost (1989) obtained dates of 3.8 Ga on basement
gneisses and metasediments. Koesterer et al. (1987) and Hulsebosch and Frost (1989) obtained rare earth element patterns on metasediments of the Medina Mountain area which are similar in shape and REE abundance to modern clastic sediments, indicating a provenance which included evolved continental crust. Previous REE studies of Archean rocks, especially sediments, have made the mistake of generalizing data obtained from rocks of oceanic affinity to cover the entire Archean, regardless of tectonic setting (e.g., Taylor and McLennan, 1985).

The objectives of this section are to: 1) describe the geological setting of Archean metasedimentary and metavolcanic rocks of the South Pass Supracrustal Belt; 2) Utilize REE and other trace element data in petrogenetic modelling of the rocks; 3) compare the trace element characteristics of South Pass Supracrustal Belt rocks to those of other Archean rocks of the Wyoming Province; and 4) describe implications of trace element data for crustal evolution and metallogenesis of turbidite-hosted gold deposits in the Wyoming Province.
REGIONAL GEOLOGY

Wyoming Archean Province

The Wyoming Archean cratonic province includes a major portion of Wyoming and parts of western South Dakota, southern Montana, eastern Idaho, and northern Utah. Of the three known minable Archean gold deposits in the United States, all but the Ropes (Michigan) mine are located within the Wyoming Province.

Precambrian rocks of the Wyoming Province are divided into three types: early quartzofeldspathic gneisses, metamorphosed supracrustal sequences, and late Archean granites (Hausel, 1985). The potassium-poor early quartzofeldspathic gneisses have been dated at 2.8 to 3.0 Ga and may represent protocontinental masses upon which supracrustal sequences such as the South Pass terrane were deposited (Stuckless et al., 1985).

Condie (1981) defined three types of metamorphosed supracrustal sequences found in Archean crustal provinces: stable shelf, high-grade, and greenstone belt. All three types were reported by Hausel (1985) to be present in the Wyoming Province. The stable shelf sequences are late Archean to early Proterozoic in age and consist of quartzites, marbles, and metapelites interpreted as epicontinental successions deposited along the margins of the Archean craton (Hausel, 1985). High-grade terrains, such as Copper Mountain in the Owl Creek Mountains and Granite Mountain in central Wyoming, are characterized by layered gneiss, amphibolite, and mica schist sequences containing orthoquartzite and iron formation.

The greenstone belts are synformal basins containing layered
sequences of metavolcanic and metasedimentary rocks. Although the South Pass terrane has been called a greenstone belt (Hausel, 1987, 1985), there is some doubt as to the validity of this classification. The generalized stratigraphic succession in a greenstone belt as described by Condie (1981) consists of a basal ultramafic to tholeiitic volcanic suite, overlain by calcalkaline and/or felsic volcanics, and finally by a fining-upward sedimentary sequence. The sedimentary section is dominated by metagreywacke, but may also contain metapelite, metaconglomerate, metaquartzite, metachert, and iron formation (Condie, 1981). Koesterer et al. (1987) argue that while the fragmentary supracrustal sequences of the Wind River Range do not show close similarity to classic greenstone belts, they do resemble sediment-dominated fragments of supracrustal rocks in high-grade terranes such as Upernavik, Labrador (Bridgwater et al., 1975), where there is good field and isotopic evidence for the presence of preexisting continental crust. Although the South Pass terrane possesses some features of a classic greenstone belt, the characteristic basal ultramafic to mafic volcanic sequence is fragmentary and the sequence is dominated by metasedimentary rocks of the Miners Delight Formation. 'South Pass Supracrustal Belt' is probably a better description of these rocks.

Many of the metamorphosed supracrustal sequences of the Wyoming Province are interpreted to have been deposited on basement complexes of early quartzofeldspathic gneiss, although in most regions the nature of the basement has been obscured by emplacement of late Archean (2.5 to 2.7 Ga) orogenic granites (Stuckless et al., 1985). These potassium-
rich granites intruded the older gneisses and domed, folded, and/or intruded the supracrustal rocks (Hausel, 1985).

**South Pass Supracrustal Belt**

Archean rocks of the Wind River Range include high grade gneisses, the South Pass Supracrustal Belt (SPSB, Fig. 1), and younger intrusive granitoids. About 80% of the range consists of late Archean syn-to post-tectonic sialic plutons varying from deformed granodiorite to undeformed K-rich granite. These granitoids are locally orthopyroxene-bearing in the west, but mainly biotite-bearing in the east (Hulsebosch et al., 1985). The remainder of the range consists of older supracrustal sequences and gneisses of supracrustal derivation. This Archean crustal block was thrust westward over Paleozoic and Mesozoic sedimentary rocks during the Laramide orogeny. Tilting during thrusting resulted in a general increase in depth of exposure from east to west across the range (Mitra and Frost, 1981; Koesterer et al., 1987).

The four main stratigraphic units of the SPSB and a gneiss complex are shown in Figure 2. Hausel (1990) defined the Diamond Springs Formation and mapped the gneiss complex, whereas the Goldman Meadows, Roundtop Mountain Greenstone, and Miners Delight Formations were named by Bayley (1965a-d). Although supracrustal rocks of the SPSB were assumed to have been deposited on a gneissic basement similar to the older orthogneisses found elsewhere in the Wind River Range (Hausel, 1987), the presence of older basement rocks in the SPSB has only been recognized recently. Quartzofeldspathic and augen gneisses of the gneiss complex along the northwestern edge of the supracrustal belt
Figure 2. General geology of the South Pass Supracrustal Belt (modified from Hausel, 1987).
Granodiorite and granite
Orthoamphibolite
Miners Delight Fm.

Roundtop Mountain Greenstone Fm.
Goldman Meadows Fm.
Diamond Springs Fm.
Gneiss

Springs placers on Buttes

Belt (modified from Hausel, 1987)
(Fig. 2) contain thin lenses of metapelite, quartzite, amphibolite, and rare ultramafic schists and serpentinite (Hausel, 1990). Hulsebosch (Univ. of Hawaii, 1989, pers. comm.) indicated that the South Pass gneisses are migmatites similar to migmatitic gneisses of the Medina Mountain area in the west-central part of the Wind River Range.

Neodymium crustal residence ages from the Medina Mountain supracrustals indicate that continental crust existed in the area at or before 3.4 Ga (Koesterer et al., 1987). Paleosomes in the Medina Mountain migmatites may be examples of these oldest supracrustal rocks.

Ultramafic rocks of the Diamond Springs Formation are the oldest stratigraphic unit of the South Pass terrane. Outcrops are fragmented and poorly exposed, and consist of serpentinite, talc-actinolite schist, and amphibolite. Geochemical analyses by Hausel (1987) indicate that the serpentinites and talc-actinolite schists are of basaltic to ultramafic komatiitic chemical affinity, while the amphibolites are of tholeiitic to basaltic komatiitic affinity. Relict cumulus textures are preserved in some serpentinites.

The Diamond Springs Formation is unconformably overlain by metasedimentary rocks of the Goldman Meadows Formation. This unit consists of metapelite, quartzite, fuchsite quartzite, amphibolite, and iron formation. Stratigraphic succession within the Goldman Meadows Formation is described in detail by Bayley et al. (1973). The iron formation consists of alternating bands of magnetite and metachert with varying amounts of hornblende and grunerite and averages about 30% Fe (Bayley, 1963). Well-foliated lenses and selvedges of quartz-chlorite
schist, chlorite-garnet schist, and chlorite-amphibole-garnet-magnetite schist occur with the iron formation (Bayley et al., 1973). Both iron formation and schists locally contain 1-5% sulfide minerals (Hausel, 1987). Euhedral to anhedral pyrite occurs in layers or lenses parallel to foliation, while secondary pyrite and chalcopyrite occurs in crosscutting veinlets. The iron formation was minable because the section was structurally thickened (Bayley, 1963). Iron formation outside of the structure at Iron Mountain (site of the US Steel mine, no. 30, Fig. 3) is about 50 m thick, but attains widths of up to 400 m within the structure (Bayley, 1963).

The contact between the Goldman Meadows Formation and the overlying Roundtop Mountain Greenstone Formation is gradational to disconformable (Bayley et al., 1973). This unit is composed of amphibolite, pillowed metabasalt, chlorite schist, and metatuff. Chemical compositions of these rocks are mainly in the range of high-magnesia basalt to tholeiitic andesite, although rare basaltic komatiite has also been reported (Hausel, 1987).

The youngest of the Archean supracrustal units, the Miners Delight Formation, comprises about 85 to 90% of the South Pass Supracrustal Belt and is in fault contact with the underlying Roundtop Mountain Greenstone Formation on both flanks (Bayley et al., 1973). The Miners Delight Formation has been downdropped relative to the older formations. Although metagreywacke is the most abundant rock type, the Miners Delight Formation also contains greywacke schist, metaconglomerate, pelitic schist, graphitic schist, metavolcanic rocks, and metachert.
MINE LOCATIONS

1. Willow Creek
2. Franklin
3. Alpine
4. Carissa
5. Monarch
6. Carrie Shields
7. B & H
8. Doc Barr
9. Duncan
10. Mary Ellen
11. Tabor Grand
12. St. Louis
13. Old Hermit
14. Outpost
15. Ground Hog
16. Big Chief
17. Soules & Perkins
18. Garfield
19. Dexter
20. Rose
21. Diana
22. Midas
23. Caribou
24. Snowbird
25. Smith Gulch
26. Gold Dollar
27. Miners Delight
28. Monte Carlo
29. Tornado
30. US Steel
Figure 3. General geology of the Atlantic City-South Pass district (modified from Bayley, 1968)
The metagreywackes are poorly sorted, graded turbidites (Bayley et al., 1973).

Garnet-biotite, and andalusite schists occur along the western margin of the district in the vicinity of the Franklin mine. Here, thermal effects of intrusion of the Louis Lake batholith caused contact metamorphism to upper amphibolite facies. Granulite-facies contact metamorphism has been reported around the margins of the Louis Lake Batholith in the west-central Wind River Range (Koesterer et al., 1987).

Metaigneous rocks of komatiitic, tholeiitic, and calcalkaline chemical groups, and intercalated graphitic schist, metachert, metagreywacke, and metaconglomerate together form a northeast-trending belt in the Atlantic City-South Pass district (Fig. 3) collectively called the Miners Delight Amphibolite Belt (Bow, 1986). Narrow outcrops of graphitic schist occur near the north and south margins of the orthoamphibolites shown in Figure 3. Metachert outcrops primarily in the vicinity of the Gold Dollar and Miners Delight mines (nos. 26 and 27, Fig. 3). Earlier workers considered most metaigneous rocks of the district to be intrusive, but flows, pyroclastic and volcaniclastic rocks, and dikes or sills are all present. Although coarse holocrystalline textures and cross-cutting relations indicate some amphibolites to be intrusive, abundant relict volcanic textures suggest that most metaigneous rocks of the amphibolite belt are probably extrusive (Bow, 1986). Tholeiitic amphibolites (orthoamphibolites) are most abundant in the central and southwestern part of the belt. Thin, green tremolite-actinolite schist units of komatiitic chemical affinity
(Bow, 1986; Hausel, 1987) occur enclosed within orthoamphibolite or at the contacts between orthoamphibolite and metagreywacke and are interpreted as having been erupted during the initial phase of a volcanic event (Bow, 1986). Calcalkaline amphibolites occur in the central part of the belt and become more abundant toward the northeast. Meta-andesite flows and associated metatuffs exposed on Peabody Ridge near the Gold Dollar and Miners Delight mines (Fig. 3) are calcalkaline (Bow, 1986; Hausel, 1987).

Rocks of the SPSB form a tightly folded, northeast-trending synform and have been metamorphosed to upper greenschist-lower amphibolite facies. Two separate mining districts, the Atlantic City-South Pass district and the Lewiston district, are located on opposite limbs of the synform. Bayley (1968), Bayley et al. (1973), and Hodge and Worl (1965) described three distinct metamorphic/deformational episodes in the SPSB. Recognition of older basement rocks, in the form of a gneiss complex, indicates there were at least four such episodes in the SPSB, though the earliest of these is as yet unstudied. Koesterer et al. (1987) document four corresponding metamorphic/deformational events in the Medina Mountain area of the Wind River Range.
TRACE ELEMENT GEOCHEMISTRY

Thirty-four samples of greywacke, graphitic schist, chert, metaandesite, and orthoamphibolite from the Miners Delight Formation, and iron formation from the Goldman Meadows Formation were analyzed for REE and other trace elements by instrumental neutron activation analysis (INAA). Samples were broken to chips using a Chipmunk crusher, then sorted by hand under a binocular microscope to remove those with weathered surfaces or staining. The chips were then ground to -200 mesh powder using a Spex shatterbox with a mullite chamber and puck. Analyses were done by X-ray Assays Laboratory in Toronto. Rare earth element data for Atlantic City-South Pass samples are listed in Table 1, REE data for comparison samples in Table 2, and other trace element values in Appendix B. Chondrite values used in normalization were taken from the data of Boynton (1984).

Major element analysis by Hausel (1987) indicate that amphibolites of the Miners Delight Amphibolite Belt (MDAB) are of tholeiitic, calcalkaline, or komatiitic chemical affinity. Rare earth element data for tholeiitic MDAB amphibolites (orthoamphibolites) are shown in Figure 4. The samples fall into two patterns. Figure 5 compares REE plots for average Archean TH1 (depleted) and TH2 (enriched) tholeiites (Condie, 1981), average Roundtop Mountain Greenstone Formation (RMG) tholeiite (Condie and Baragar, 1974), and MDAB sample DIP4-1 (MDAB type 1). The TH1 and TH2 plots are the two major REE pattern types reported for Archean tholeiites in other parts of the world. The average RMG tholeiite and DIP4-1 have curve shapes and REE abundances similar to
Table 1. REE data. Values in ppm except as noted

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^Data from Condie (1981).
^bData from Condie and Baragar (1974).
^cData from McLennan and Taylor (1984).
^dData from Taylor and McLennan (1985).
^eData from Wildeman and Haskin (1973).
^fNormalized.
Table 2. (continued)

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Figure 4. Chondrite-normalized REE plot for tholeiitic Miners Delight Amphibolite Belt (MDAB) samples
Figure 5. Chondrite-normalized REE plot for Archean TH1 and TH2 tholeiites (Condie, 1981), average Roundtop Mountain Greenstone Fm. tholeiite (Condie and Baragar, 1974), and MDAB sample DIP4-1
average Archean tholeiite TH2 and to modern calcalkaline tholeiites. However, REE patterns for the majority of MDAB orthoamphibolite samples do not resemble either TH1 or TH2. The MDAB 2 tholeiites have La/Sm of 3.43 to 4.94 and La/Yb of 10.26 to 16.13, indicating pronounced LREE enrichment and a slight HREE depletion. Figure 6 compares the MDAB 2 tholeiites to patterns for modern calcalkaline and continental rift tholeiites. Light REE enrichment lies between these values.

Rare earth element plots for andesites from the calcalkaline metaigneous units (Fig. 3), calcalkaline amphibolites of the MDAB, and from andesitic flows intercalated with metasediments of the Miners Delight Formation are shown in Figure 7. The range and average REE values for Atlantic City-South Pass andesites are very similar to the average Archean andesite AA2 and average modern high-K calcalkaline andesite (Condie, 1981) in Figure 8.

Rare earth element plots for greywackes are shown in Figures 9 and 10. The range and average values for Atlantic City-South Pass greywackes are compared to the average Archean shale (AAS; McLennan and Taylor, 1984) and to the post-Archean North American Shale Composite (NASC; Taylor and McLennan, 1985) in Figure 10. The NASC curve is very similar in shape and REE abundances to other post-Archean sediment composites from other parts of the world. Curves for Atlantic City-South Pass greywackes show enriched LREE and a small negative Eu anomaly, and slightly depleted HREE. The LREE portion of the curves more closely resembles NASC than AAS.

Plots for graphitic schists are shown in Figures 11 to 14. Unlike
Figure 6. Chondrite-normalized REE plot for range and average MDAB 2 amphibolites, and average modern calcalkaline and continental rift tholeiites (Condie, 1981)
Figure 7. Chondrite-normalized REE plot for MDAB andesites
Figure 8. Chondrite-normalized REE plot for range and average MDAB andesite, and average Archean andesite type 2 and modern high-K calcalkaline andesite (Condie, 1981)
Figure 9. Chondrite-normalized REE plot for greywackes from the Atlantic City-South Pass district.
Figure 10. Chondrite-normalized REE plot for range and average Atlantic City-South Pass greywacke, average Archean shale (McLennan and Taylor, 1984), and post-Archean North American Shale Composite (NASC, Taylor and McLennan, 1985)
Figure 11. Chondrite-normalized REE plot for graphitic schists from the Atlantic City-South Pass district.
Figure 12. Chondrite-normalized REE plot for type 1 Atlantic City-South Pass graphitic schists and the Soudan slate (Wildeman and Haskin, 1973)
Figure 13. Chondrite-normalized REE plot for type 2 Atlantic City-South Pass graphitic schists, AAS (McLennan and Taylor, 1984), and NASC (Taylor and McLennan, 1985)
Figure 14. Chondrite-normalized REE plot for type 2 Atlantic City-South Pass graphitic schists, and Onwantin and Venterdorp graphitic schists (Wildeman and Haskin, 1973)
the greywackes, the graphitic schists show two different REE patterns. Two samples with the overall lowest total REE content also have positive Eu anomalies. These samples are compared with AAS and the Soudan slate (Wildeman and Haskin, 1973) in Figure 12. The Soudan slate, a carbonaceous slate from the Soudan iron formation, Minnesota, also has a strong positive Eu anomaly, but contains higher total REE than the Atlantic City-South Pass samples.

The second type of graphitic schist pattern has a small negative Eu anomaly. These schists are shown compared to AAS and NASC in Figure 13 and to the Onwantin slate from Sudbury, Ontario, and the Ventersdorp shale from South Africa in Figure 14.

Ternary La-Th-Sc and Hf-Th-Co plots for Atlantic City-South Pass greywackes and graphitic schists are shown in Figures 15 and 16. The sediments display linear trends between the Archean average mafic volcanic rock (AMV, Taylor and McLennan, 1985) and the average tonalite-trondhjemite (TT) in both plots.

Rare earth element plots for cherts are shown in Figure 17. The cherts outcrop in belts parallel to the MDAB (Fig. 3) with the most extensive outcrops in the vicinity of the Gold Dollar and Miners Delight mines. Elsewhere in the MDAB, thin chert units may be found intercalated with graphitic schists or with coarser clastic sediments. The cherts are very dark grey to black. All have unusually high total REE, and all but one sample have negative Eu anomalies.

Rare earth element plots for iron formation from the Goldman Meadows Formation are shown in Figure 18. The iron formations contain
Figure 15. La-Th-Sc ternary plot for Atlantic City-South Pass metasediments
AC/SP Sediments

Figure 16. Hf-Th-Co ternary plot for Atlantic City-South Pass metasediments.

- △ greywackes
- ○ graphitic sch.
- ★ AMV
- □ TT
Figure 17. Chondrite-normalized REE plot for cherts from the Atlantic City-South Pass district.
Figure 18. Chondrite-normalized REE plot for iron formation of the Goldman Meadows Fm.
varying amounts of silicates, carbonates, and sulfides in addition to iron oxides and quartz. The sample with highest total REE was also the most silicate-rich. Carbonate-bearing iron formation has higher total REE than sulfide-bearing iron formation, and higher HREE than all samples except one silicate-bearing iron formation. All samples show positive Eu anomalies. The sulfide-bearing iron formation samples have an enhanced positive Eu anomaly and show depleted La values.
DISCUSSION

The Archean Wyoming Province shares many geological, geochemical, and mineralization characteristics with Proterozoic and younger orogenic belts, but differs significantly from most other Archean terranes, the major exception being the Canadian Slave Province. Characteristics of both provinces include the areal dominance of turbiditic sedimentary rocks over volcanic rocks, lesser abundance of plutonic granitoids compared to other Archean provinces, and the presence of turbidite-hosted gold deposits, which, although common in Phanerozoic sediments, are uncommon in other Archean terranes.

Two types of volcanic belts are recognized in the Slave Province, the Yellowknife type, dominated by a thick, lower basaltic unit, and the Hackett River type, dominated by intermediate to felsic volcanics with only minor amounts of basalt. Hackett River type volcanics can occur anywhere in the stratigraphic section, but are most common near the top (Padgham, 1985). Ultramafic rocks are unknown in either type (Padgham, 1986, 1985).

Although the thick metabasalt sequence of the Roundtop Mountain Greenstone Formation invites comparison with the Yellowknife type volcanic belt, with one exception, these rocks are chemically different from metaigneous rocks of the Miners Delight Amphibolite Belt. An important difference between volcanic sequences in the Slave and Wyoming Provinces is the presence of ultramafic rocks in the latter.

Sialic basement rocks are abundant in the Slave Province, and have also been recognized in the Australian Yilgarn and Pilbara blocks (Gee
et al., 1981) and the Rhodesian craton (Nisbet et al., 1981). Extension of the Slave basement produced a blockfaulted terrane prior to deposition of the supracrustal rocks (Padgham, 1985). During the 2.7 to 2.55 Ga thermal event, the presence of thick sialic crust in the proto-Slave craton allowed for extensive felsic volcanism, producing pyroclastic debris that was reworked into the abundant turbiditic sediments (Padgham, 1985).

The existence of evolved continental crust throughout a large part of the Wyoming Province has been documented by U-Pb zircon dates as old as 3.8 Ga and early Archean Lu-Hf and Nd model ages on both basement gneisses and metasediments (Hulsebosch and Frost, 1989). Neodymium crustal residence ages of 3.4 Ga have been obtained on metasediments of the Medina Mountain area of the Wind River Range (Koesterer et al., 1987), and field and geochemical data for rocks of the SFSB support the existence of older continental crust in the area. The gneiss complex (Fig. 2) appears to be a remnant of this older crust. Although the fragmentary nature of outcrops and extensive metamorphic recrystallization of the Diamond Springs Formation makes interpretation difficult, relict cumulus textures in some serpentinites suggest the possibility of oceanic crust produced after rifting or sagging within the early craton. The Diamond Springs Formation may be analogous to platform-phase greenstones of the Yilgarn Block, Western Australia (Groves and Batt, 1984). Chemical and pelitic sediments of the Goldman Meadows Formation record deposition in a shallow, tectonically stable platform-type environment. Submarine basaltic volcanism of the
Roundtop Mountain Greenstone Formation and eugeosynclinal sediments of the Miners Delight Formation mark a change to deeper marine conditions of deposition.

Metabasalts of the Roundtop Mountain Greenstone Formation and orthoamphibolites of the MDAB were defined as tholeiitic on the basis of major element chemistry (Hausel, 1987; Bow, 1986). Rare earth element analysis shows that only the composite Roundtop Mountain Greenstone Formation sample of Condie and Baragar (1974) and one MDAB sample (DI-P4-1) have REE abundances similar to those reported for Archean tholeiites elsewhere (TH2, Condie, 1981). All other MDAB amphibolites show significant LREE enrichments which are greater than any previously reported for Archean tholeiites. The strongly fractionated LREE suggest an evolved magma source.

Rare earth element patterns for calcalkaline metaigneous rocks of the Atlantic City-South Pass district are more definitive than the tholeiites. These curves (Fig. 8) closely resemble those of the average Archean andesite type 2 (AA2) and modern high-K calcalkaline andesite (HKA). Similar REE patterns are reported for Hackett River andesites of the Slave Province (Ewing, 1979). Compositionally, the Hackett River andesites more closely resemble continental calcalkaline volcanics than those of the modern arc environment. High-K calcalkaline andesites occur in some continental margin arc systems such as the Andes, which are underlain by thick lithosphere (Condie, 1981). Rare earth element data for both tholeiitic and calcalkaline metaigneous rocks of the Miners Delight Formation thus suggests the presence of
thick lithosphere during magmagenesis.

Trace element analysis of Miners Delight metasediments provides further evidence for the contribution of older continental crust to SPSS rocks. Rare earth element compositions of terrigenous clastic sediments are believed to reflect the REE composition of the upper crustal rocks exposed to erosion (Taylor et al., 1986). The REE patterns of Archean sediments show greater diversity than those of post-Archean sediments. Most examples reported to date lack any significant Eu anomaly and have been modeled by an approximate 1:1 mix of extreme mafic and felsic patterns consistent with derivation from an Archean upper crust dominated by a bimodal basalt/tonalite-trondhjemite-granodiorite igneous suite (McLennan and Taylor, 1984; Taylor et al., 1986). Archean crustal differentiation is believed to have occurred largely at mantle depths, while post-Archean differentiation occurred through intracrustal processes (Taylor and McLennan, 1985). Although all major post-Archean sediment types show Eu depletions, Taylor et al. (1986) consider Eu-depleted Archean sediments to be anomalies related to local source areas of K-rich, Eu-depleted felsic igneous rocks produced by intracrustal melting within the plagioclase stability field.

In contrast to the average Archean shale of McLennan and Taylor (1984), Archean sediments of the Miners Delight Formation have Eu anomalies. This characteristic is shared by Archean metasediments of the west-central Wind River Range (Hulsebosch and Frost, 1989), and the Madison and Beartooth Mountains (Vargo et al., 1989). Middle Archean Sm-Nd ages from the Madison and Beartooth Mountain metasediments
indicate derivation from an older continental terrane, probably located to the east (Vargo et al., 1989). Demonstrably Archean metasediments with post-Archean REE patterns thus appear to be a widespread, integral component of the Wyoming Province. Taylor et al. (1986) observed Eu-depleted REE patterns in high-grade metasediments of the Limpopo belt and the Western Gneiss terrane, and concluded that only high-grade terranes preserved geochemical evidence for the existence of local enclaves of evolved continental crust, and that these terranes represented a different tectonic setting from greenstone belts. The Wyoming Province, however, preserves such rocks on a large scale, indicating that continental source areas must have been fairly widespread. This implies that the transition from an upper crust dominated by mantle-derived igneous rocks to one dominated by rocks produced by intracrustal melting was not as sharp as claimed by McLennan and Taylor (1984), and did not necessarily occur at the Archean/Proterozoic boundary.

Since metaigneous rocks of the MDAB show strongly fractionated REE patterns similar to modern examples where interaction with continental crust is indicated, another implication is for the existence of a modern, continental margin type subduction-related environment during the Archean in the western Wyoming Province. This contrasts with other Archean terranes such as the Superior Province, which is thought to consist of a series of accreted island arc terranes (Card et al. 1989).

Although the possible contribution of continental sources to the provenance of Miners Delight metasediments was recognized fairly early
(Condie, 1967), the importance of a volcanic component has been ignored. On the basis of modal compositions recalculated from Condie's (1967) data, McLennan and Taylor (1984) argued that Miners Delight greywackes were derived totally from granitic and/or recycled sedimentary source rocks. Of eight other localities examined, only the North Spirit Lake greywackes (Donaldson and Jackson, 1965) were assigned to the same category. Major and trace element chemical data do not support this conclusion. Ojakangas (1985) compared major element chemistry of twelve North American Archean greywackes from the Superior, Slave, and Wyoming Provinces, and found that all analyses, except those of North Spirit Lake greywackes, clustered in a field on a $K_2O/Na_2O$ diagram which also includes average dacites, tonalites, diorites, andesites, and rhyodacites. In most of these sediments, a mafic volcanic input has been documented (McLennan and Taylor, 1984). The relatively high modal quartz and prevalence of sedimentary over volcanic rock fragments in Miners Delight greywackes is misleading. Sand-sized detrital quartz is traditionally interpreted as evidence for a plutonic or cratonic source, but quartz-rich sand can also be derived by reworking of felsic pyroclastic sources (Ojakangas, 1985), and mafic components, which have a greater susceptibility to chemical weathering, may not survive transport as large fragments. Although relict sedimentary structures such as graded bedding are preserved in many beds, matrix constituents are fine grained, and have been recrystallized during the metamorphic/deformational episodes affecting the SPSS. After diagenesis and metamorphism, the mafic component would only show up chemically.
La-Th-Sc and Hf-Th-Co ternary diagrams (Figs. 15 and 16) for SPSB greywackes and graphitic schists both show linear trends between AMV (average mafic volcanic) and TT (tonalite-trondhjemite) for the metasediments, indicating that mixing of sources was important. The compatible element data indicates that one of these was a mafic volcanic component.

The MDAB cherts have an unusually high REE content. Patterns overlap those of other sediment types but have a more pronounced negative Eu anomaly. The cherts are all dark colored, glassy, and in outcrop may frequently be observed to interfinger with graphitic schists and/or greywackes. Cherty, silicified volcanic ash has been described in the Pilbara Block and in South Africa (Lowe, 1982), the Slave Province (Boyle, 1961), and interbedded with iron formation in Minnesota (Lavery, 1972). The MDAB cherts lack relict textures suggestive of such an origin, but could have been contaminated by a fine-grained component such as airfall tuff, which would lead to an elevated REE content. The REE patterns are consistent with a felsic volcanic component.

Rare earth element patterns for iron formation are similar to those reported for Archean iron formation from Finland (Laajoki and Lavikainen, 1977), Canada (Fryer, 1977a,b), and Greenland (McGregor and Mason, 1977). Absolute REE contents of Archean iron formation are usually lower than normal crustal abundances, and positive Eu anomalies are characteristic (Fryer, 1983). The sulfide-bearing samples (Fig. 14) show the largest Eu enrichments and depletions of La relative to Ce. Barrett et al. (1988) report that La enrichment and enhancement of the
Eu anomaly are indications of a direct hydrothermal contribution into seawater, but that preservation of a hydrothermal signature is most likely in a basin where circulation was restricted and bottom waters strongly reduced. The characteristic sedimentary package of such a basin includes carbonaceous slates and unworked distal turbidites, sediments typical of the Miners Delight Amphibolite Belt rather than the Goldman Meadows Formation. The positive Eu anomalies of two graphitic schist samples may also be an indication of hydrothermal activity.
CONCLUSIONS

1. The dominant REE pattern for tholeiitic Miners Delight amphibolites indicates an evolved magma source.
2. Calcalkaline amphibolites have similar REE patterns to modern Andean-type orogenic andesites.
3. Sediments from the western part of the Wyoming Province all show REE patterns more closely resembling post-Archean sediment composites than AAS.
4. Ternary plots indicate a mafic volcanic component to the sediments.
5. Both metasedimentary and metavolcanic rocks provide geochemical evidence for the presence of thick lithosphere early in the geologic history of the western Wyoming Province, corroborating similar evidence for the northern Wyoming Province in Montana. On a wide scale, the Wyoming Province preserves evidence for the existence of evolved continental crust in the Archean.
6. In contrast to the varied tectonic settings of the northern Wyoming Province, rocks of the SPSB appear to preserve an active continental margin type environment. Gold mineralization in the SPSB can therefore be expected to be similar to that found in other continental margin subduction-related environments, regardless of age.
SECTION II.

ORIGIN OF ARCHEAN LODE GOLD MINERALIZATION AT ATLANTIC CITY-SOUTH PASS:
FLUID INCLUSION, STABLE ISOTOPE, AND TRACE ELEMENT STUDIES
ABSTRACT

The Atlantic City-South Pass gold district is hosted by dominantly metasedimentary Archean supracrustal rocks (approx, 2.8 Ga) of the South Pass Supracrustal Belt at the southern end of the Wind River Mountains, Wyoming. Although Archean in age, the district shares geological and geochemical features with Proterozoic turbidite-hosted type gold deposits. Approximately 335,000 oz of gold have been produced from quartz veins in shear zones localized along the contacts of metaigneous rocks of the Miners Delight Amphibolite Belt with the surrounding metagreywackes.

Sulfur isotope analyses of sulfides (-1.0 to 3.6 o/oo) are consistent with data for most other Archean lode gold mineralization, and do not indicate an equivocal source of sulfur. Sulfur may have been leached from the older Goldman Meadows Formation. Carbon isotope ratios on carbonates ($d^{13}C = -1.5$ to $-11.0$ o/oo) are among the lightest yet recorded for an Archean gold deposit. Carbon from graphitic schists associated with gold-quartz veins gives values of $-19.1$ to $-28.5$ o/oo. The carbon isotope data indicate an organic carbon component, probably derived from graphitic sediments of the district. Although oxygen isotope values calculated from vein quartz ($d^{18}O = 7.36$ to $10.38$ o/oo) and hydrogen values ($dD = -125$ to $-55$) obtained from fluid inclusions define a field which partly overlaps the metamorphic/magmatic fluid fields, the ore fluids were probably evolved formation waters.

Primary and/or pseudosecondary fluid inclusions include: 1) one- and two-phase gaseous CO$_2$-CH$_4$ inclusions; and 2) two- three- and four-
phase \( \text{CO}_2-\text{CH}_4-\text{H}_2\text{O}-\text{NaCl}-\text{CaCl}_2 \) inclusions with variable gas-water ratios. Compositionally similar fluid inclusions were found in quartz from the gold district and from the nearby US Steel iron mine, with the exception that no \( \text{CH}_4 \)-bearing inclusions were found in samples from the iron mine. Average bulk fluid composition is: \( X_{\text{H}_2\text{O}}=0.8039, X_{\text{CO}_2}=0.1615, X_{\text{NaCl}}=0.0346 \). Average salinity is 12.24 NaCl equiv. wt. %. Secondary aqueous inclusions have salinities of 12 to 30 NaCl equiv. wt. %, with 13 to 29 wt. % \( \text{CaCl}_2 \). Phase separation is indicated by variable gas/water ratios, similar gas densities in both Types 1 and 2 inclusions, and by homogenization to both vapor and to liquid in Type 2 inclusions. Multiple generations of carbonic fluids are indicated by endmember \( \text{CH}_4^- \) or \( \text{CO}_2^- \)-rich compositions. Estimated trapping conditions for the average bulk fluid composition with \( T_{\text{H2OT}}=275^\circ \text{C} \) are 3.75 kb, 350°C.

The most likely source of gold was leaching of the sedimentary pile. The deposits were formed in a subduction-related tectonic environment similar to that responsible for younger turbidite-hosted gold deposits such as those of southern Alaska, and in contrast to the volcanic-dominated environment of greenstone-hosted deposits where thick, evolved continental crust was lacking.
INTRODUCTION

Despite the worldwide similarity of geochemical, light stable isotope, and fluid inclusion characteristics of Archean greenstone-hosted lode gold deposits, considerable controversy exists in the literature concerning the source of hydrothermal fluids and ore components involved in the formation of these deposits.

While greenstone-hosted gold deposits occur only in rocks of Archean age, turbidite-hosted gold deposits occur throughout geologic time. These deposits occur in thick successions of deep marine turbiditic greywacke, black shale, and argillite. Minor quantities of volcanic rocks are commonly intercalated with the greywackes (Woodall, 1976). 'Mesothermal' gold deposits such as those of the Canadian Cordillera, Alaska, California, and other areas are usually considered to be of the turbidite-hosted type (Hutchinson, 1987). Other than the difference in host rock lithology, turbidite-hosted gold deposits share many geological and geochemical characteristics with the greenstone-hosted type. Hutchinson (1987) classified both as 'eugeosynclinal', and concluded that the turbidite-hosted type is simply a younger evolutionary variant of the greenstone-hosted type, and attributed the lithologic differences to the effects of plate tectonic evolution on the composition of late Proterozoic and early Paleozoic deep marine eugeosynclinal successions.

Fluid sources proposed for turbidite-hosted gold deposits include: 1) metamorphic (Bohlke and Kistler, 1986; Goldfarb et al., 1988; Leach et al., 1987); 2) meteoric (Nesbitt et al., 1986); 3) mixed metamorphic
and meteoric (Kerrich, 1987); and 4) metamorphic with a possible magmatic component (Kontak et al., 1990). Possible fluid sources for the greenstone-hosted type of deposit are: 1) metamorphic (Kerrich and Fryer, 1979; Groves and Phillips, 1987); 2) magmatic (Burrows et al., 1986; Cameron and Hattori, 1987; Burrows and Spooner, 1986); 3) mantle degassing/granulitization (Colvine et al., 1988; Cameron, 1988); 4) meteoric (Nesbitt et al., 1986); and 5) evolved marine (Hutchinson and Burlington, 1984).

The few known examples of mineable Archean lode gold mineralization found in the United States include the Atlantic City-South Pass (Wyoming) district, the Jardine (Montana) mine, and the Ropes (Michigan) mine. The age of the largest producing gold mine in North America, the Homestake (South Dakota) mine, has been estimated at late Archean to lower Proterozoic (Hutchinson, 1987), although a recent study favors an early Proterozoic age (Caddey et al., 1990).

Most greenstone-hosted gold deposits are spatially related to major shear zones (Colvine et al., 1988), and many mesothermal gold deposits are also believed to be spatially and genetically related to major structures such as strike-slip faults (Bohke and Kistler, 1986; Nesbitt and Muehlenbachs, 1988; Schroeder et al., 1988). However, gold mineralization of the Atlantic City-South Pass district shows no obvious spatial relation to major structures. The district is located hundreds of kilometers north of the Wyoming lineament (Condie, 1982), the closest large-scale structural feature.

Recent literature suggests that most Archean gold deposits are
epigenetic (e.g., Colvine et al., 1984). However, some deposits are
intimately associated with iron formation, chert, and carbonaceous
sediments, which resemble the exhalites spatially related to volcanogenic
massive sulfide deposits (Hutchinson and Burlington, 1984). All three
rock types are found at the Atlantic City-South Pass (Bayley, 1968),
Contwyoto Lake (Kerswill, 1986), Agnico-Eagle (Wyman et al., 1986), and
Kolar (Hamilton and Hodgson, 1986; Siddaiah and Rajamani, 1986)
deposits. Iron formation has been proposed as a source from which gold
was mobilized and concentrated as a result of regional metamorphism
(e.g., Rye and Rye, 1974; Fripp, 1976; Ladeira, 1980). Brookins and
Brown (1966) and Rye and Rye (1974) suggested that the source of sulfur
for mineralization in the Jardine and Homestake deposits respectively,
was the sulfides indigenous to the iron formation.

Sediments, especially carbonaceous sediments, have been proposed as
a source of gold, especially in the turbidite-hosted type of deposit
(Boyle, 1986). Keays (1984) proposed that organic- and sulfide-rich
interflow sediments may be an important source of gold for all Archean
gold deposits, since these sediments would trap gold released from
favorable source rocks (e.g., komatiites) during the seafloor alteration
stage and keep it in the system until it could be concentrated by
subsequent metamorphic processes. According to Hutchinson et al. (1980)
and Hutchinson and Burlington (1984), the carbonaceous strata may be
products of hydrothermal discharges rich in methane and ethane generated
by inorganic water-rock reactions during sub-sea floor convective
hydrothermal circulation. These units may have provided carbonyl,
cyanide, and thiocyanide ions which subsequently complexed with Au and transported Au in solution. Recent fluid inclusion studies suggest that CO2-bearing fluids are the dominant transporting media for Au (e.g., Smith et al., 1984). The contribution of C from graphitic schists in some deposits is supported by carbon isotope data (Colvine et al., 1984).

Chert horizons are associated with many Archean lode gold deposits and are interbanded with ankeritic and pyritic strata at Agnico-Eagle (Barnett et al., 1982), with iron formation at Contwyoto Lake (Kerswill, 1986) and Kolar (Hamilton and Hodgson, 1986); and with graphitic schists at Atlantic City-South Pass.

The present study of the Atlantic City-South Pass district incorporates fluid inclusion, stable isotope (S, C, O, H), trace and rare earth element analyses. Specific questions to be addressed include: 1) the source of the ore-forming solutions, gold, and associated metals; 2) the genetic relationship between gold mineralization and spatially related iron formation, graphitic schist, and chert; and 3) the relationship among deposits of the Atlantic City-South Pass district, typical turbidite-hosted gold deposits, and Archean greenstone-hosted lode gold deposits.
GEOLOGICAL SETTING

The South Pass Supracrustal Belt (SPSB, Fig. 1), located at the southern end of the Wind River Range, is the largest of the fragmentary Archean supracrustal terranes in the Wyoming Archean cratonic province. Of the three known minable Archean gold deposits in the United States, all but the Ropes (Michigan) mine are located within the Wyoming Province. About 80% of the Wind River Range consists of late Archean syn- to post-tectonic sialic plutons varying from deformed granodiorite to undeformed K-rich granite. These granitoids are locally orthopyroxene-bearing in the west, but mainly biotite-bearing in the east (Hulsebosch et al., 1985). The remainder of the range consists of older supracrustal sequences and gneisses of supracrustal derivation. This Archean crustal block was thrust westward over Paleozoic and Mesozoic sedimentary rocks during the Laramide orogeny. Tilting during thrusting resulted in a general increase in depth of exposure from east to west across the range (Mitra and Frost, 1981; Koesterer et al., 1987).

The four main stratigraphic units of the SPSB and a gneiss complex are shown in Figure 2, and are described more fully in Section I. Hausel (1990) defined the Diamond Springs Formation and mapped the gneiss complex, whereas the Goldman Meadows, Roundtop Mountain Greenstone, and Miners Delight Formations were named by Bayley (1965a-d). Although supracrustal rocks of the SPSB were assumed to have been deposited on a gneissic basement similar to the older orthogneisses found elsewhere in the Wind River Range (Hausel, 1987), the presence of
Figure 1. Regional geologic setting of the South Pass Supracrustal Belt (modified from Bayley, 1968)
Figure 2. General geology of the South Pass Supracrustal Belt (modified from Hausel, 1987)
Granodiorite and granite
Orthoamphibolite
Miners Delight Fm.

Roundtop Mountain Greenstone Fm.
Goldman Meadows Fm.
Diamond Springs Fm.
Gneiss

Dickie Springs paleoplacers
Oregon Buttes

upracrustal Belt (modified from Hausel, 1987)
older basement rocks in the SPSB has only been recognized recently. Quartzofeldspathic and augen gneisses of the gneiss complex along the northwestern edge of the supracrustal belt (Fig. 2) contain thin lenses of metapelite, quartzite, amphibolite, and rare ultramafic schists and serpentinite (Hausel, 1990). Hulsebosch (Univ. of Hawaii, 1989, pers. comm.) indicated that the South Pass gneisses are migmatites similar to migmatitic gneisses of the Medina Mountain area in the west-central part of the Wind River Range. Neodymium crustal residence ages from the Medina Mountain supracrustals indicate that continental crust existed in the Wind River Range at or before 3.4 Ga (Koesterer et al., 1987). Paleosomes in the Medina Mountain migmatites may be examples of these oldest supracrustal rocks.

Ultramafic rocks of the Diamond Springs Formation are the oldest stratigraphic unit of the South Pass terrane, and are unconformably overlain by iron formation and metapelites of the Goldman Meadows Formation. Both iron formation and pelitic schists locally contain 1-5% sulfide minerals (Hausel, 1987). Euhedral to anhedral pyrite occurs in layers or lenses parallel to foliation, while secondary pyrite and chalcopyrite occurs in crosscutting veinlets. The iron formation was minable because the section was structurally thickened (Bayley, 1963). Iron formation outside of the structure at Iron Mountain (site of the US Steel mine, no. 30, Fig. 3) is about 50 m thick, but attains widths of up to 400 m within the structure (Bayley, 1963).

The Goldman Meadows Formation is overlain by 1500 m of pillowed metabasalt of the Roundtop Mountain Greenstone Formation. The youngest
MINE LOCATIONS

1. Willow Creek 18. Garfield
2. Franklin 19. Dexter
3. Alpine 20. Rose
5. Monarch 22. Midas
6. Carrie Shields 23. Caribou
10. Mary Ellen 27. Miners Delight
12. St. Louis 29. Tornado
13. Old Hermit 30. US Steel
14. Outpost
15. Ground Hog
16. Big Chief
17. Soules & Perkins

PRECAMBRIAN

Granodiorite and granite (Louis Lake Batholith)

Leucodacite and tonalite
Figure 3. General geology of the Atlantic City-South Pass district (modified from Bayley, 1968)
of the Archean supracrustal units, the Miners Delight Formation, comprises about 85 to 90% of the South Pass Supracrustal Belt and is in fault contact with the underlying Roundtop Mountain Greenstone Formation on both flanks (Bayley et al., 1973). The Miners Delight Formation has been downdropped relative to the older formations. Although metagreywacke is the most abundant rock type, the Miners Delight Formation also contains greywacke schist, metaconglomerate, pelitic schist, graphitic schist, metavolcanic rocks, and metachert. The metagreywackes are poorly sorted, graded turbidites (Bayley et al., 1973).

Garnet-biotite, and andalusite schists occur along the western margin of the district in the vicinity of the Franklin mine. Here, thermal effects of intrusion of the Louis Lake batholith caused contact metamorphism to upper amphibolite grade. Granulite-grade contact metamorphism has been reported around the margins of the Louis Lake Batholith in the west-central Wind River Range (Koesterer et al., 1987). Metaigneous rocks of komatiitic, tholeiitic, and calcalkaline chemical groups, and intercalated graphitic schist, metachert, metagreywacke, and metaconglomerate together form a northeast-trending belt in the Atlantic City-South Pass district (Fig. 3) collectively called the Miners Delight Amphibolite Belt (Bow, 1986). Narrow outcrops of graphitic schist occur near the north and south margins of the orthoamphibolites shown in Figure 3. Metachert outcrops primarily in the vicinity of the Gold Dollar and Miners Delight mines (nos. 26 and 27, Fig. 3). Earlier workers considered most metaigneous rocks of the
district to be intrusive, but flows, pyroclastic and volcaniclastic rocks, and dikes or sills are all present. Although coarse holocrystalline textures and cross-cutting relations indicate some amphibolites to be intrusive, abundant relict volcanic textures suggest that most metaigneous rocks of the amphibolite belt are probably extrusive (Bow, 1986). Tholeiitic amphibolites (orthoamphibolites) are most abundant in the central and southwestern part of the belt. Thin, green tremolite-actinolite schist units of komatiitic chemical affinity (Bow, 1986; Hausel, 1987) occur enclosed within orthoamphibolite or at the contacts between orthoamphibolite and metagreywacke and are interpreted as having been erupted during the initial phase of a volcanic event (Bow, 1986). Calcalkaline amphibolites occur in the central part of the belt and become more abundant toward the northeast. Meta-andesite flows and associated metatuffs exposed on Peabody Ridge near the Gold Dollar and Miners Delight mines (Fig. 3) are calcalkaline (Bow, 1986; Hausel, 1987).

Rocks of the SPSB form a tightly folded, northeast-trending synform and have been metamorphosed to upper greenschist-lower amphibolite facies. Two separate mining districts, the Atlantic City-South Pass district and the Lewiston district, are located on opposite limbs of the synform, and together comprise the largest gold district in Wyoming, the Sweetwater mining district (Fig. 2). Bayley (1968), Bayley et al. (1973), and Hodge and Worl (1965) described three distinct metamorphic/deformational episodes in the SPSB. Recognition of older basement rocks, in the form of a gneiss complex, indicates there were at
least four such episodes in the SPSB, though the earliest of these is as yet unstudied. Koesterer et al. (1987) document four corresponding metamorphic/deformational events in the Medina Mountain area of the Wind River Range. The following geochronology for the SPSB and associated gold mineralization further interprets and augments sequences of events described by Bayley et al. (1973) and Bow (1986).

1. Deposition of oldest supracrustal rocks, possibly accompanied by ultramafic to mafic igneous activity. These rocks are preserved in the gneiss complex;

2. Deformation, metamorphism, and migmatization of the gneiss complex;

3. Deposition of ultramafic to mafic igneous rocks of the Diamond Springs Formation, possibly related to rifting or sagging within the early craton. This may be analogous to the platform-phase greenstones of the Yilgarn block, Western Australia (Groves and Batt, 1984);

4. Deposition of quartzite, iron formation, and pelitic sediments of the Goldman Meadows Formation in a tectonically stable, continental margin or platform type environment;

5. Deposition of submarine basaltic volcanic rocks of the Roundtop Mountain Greenstone Formation;

6. Deposition of a thick turbidite sequence derived from both cratonic and volcanic sources, accompanied by relatively minor, late volcanic activity of komatiitic to calcalkaline character;

7. Intrusion of tonalite dikes and stocks;

8. Compression, initial folding, and regional metamorphism to
amphibolite facies at ~2.8 Ga (Stuckless et al., 1985). Development of axial plane cleavage faults in the Goldman Meadows and Roundtop Mountain Greenstone Formations, which are intruded by diabase. Intrusive amphibolites of the Miners Delight Amphibolite Belt may also have been emplaced at this time. Emplacement of barren quartz Big Atlantic and Mammoth leads in shear zones north and south of the amphibolite belt;

9. Major, NE-trending faulting. Renewed foliation-parallel and oblique shearing concentrated at points of competency contrast within and adjacent to metaigneous rocks of the amphibolite belt. Emplacement of all major gold-quartz veining at ~2.75 Ga (Cannon et al., 1965). This is a Pb date on galena from the Snowbird mine, and is the only date on the mineralization itself;

10. Intrusion of the Louis Lake Batholith and satellite plutons at ~2.6 Ga (Stuckless et al., 1985), local refolding of the supracrustal pile near South Pass City, contact metamorphism to upper amphibolite grade;

11. Emplacement of postdeformational pegmatites;

12. Emplacement of Proterozoic diabase dikes at 2010 to 1270 Ma (Condie et al., 1969);

13. Late, major ENE-WSW and NW-SE faulting. Retrograde greenschist grade metamorphism at ~1.4 Ga (Bayley et al., 1973). Some of the late faults contain minor Cu-rich quartz-calcite veins with trace amounts of gold.
MINERALIZATION IN THE ATLANTIC CITY-SOUTH PASS DISTRICT

Mining History

Gold has been produced from both lode and placer mining operations in the South Pass Supracrustal Belt. Placer gold was first discovered in the Sweetwater mining district in 1842 (Trumbull, 1914; Spencer, 1916). Discovery of the Carissa lode in 1867 resulted in a gold rush (Trumbull, 1914). By 1871, the principal veins of the district had been discovered, but the boom was short-lived and the district was essentially abandoned by 1875 (Spencer, 1916).

The 1879 discovery of the Burr lode on Strawberry Gulch, approximately twelve miles east of Atlantic City, led to establishment of the Lewiston district. Although the Burr ore was reported to be very rich (Bartlett and Runner, 1926), no production records are available for mines of the Lewiston district. Its history paralleled the boom-bust cycle of the Atlantic City-South Pass district.

Only limited amounts of gold have been produced from the Sweetwater district from 1879 to the present. Past gold production was estimated by Hausel (1987) to be 334,520 oz for the Atlantic City-South Pass district and 21,391 oz for the Lewiston district. A recent, unsuccessful attempt was made in 1987 by the Carissa Gold Co. to reopen the Carissa mine.

Spencer (1916) was the first to record location and extent of iron deposits of the Atlantic City-South Pass district. Exploration and development were begun in 1954 by US Steel Co. More than 90 million tons of taconite were produced from the open pit mine in iron formation

Lode Gold Deposits

There is a close spatial association between the historic gold mines of the Atlantic City-South Pass district and the northeast-trending Miners Delight Amphibolite Belt (MDAB, Fig. 3). Both barren and productive quartz lodes are associated with the belt. Quartz veins are most commonly hosted by shear zones in amphibolite or at the metaigneous-metasediment interface. Veins and shears are present but less common in metagreywacke, graphitic schist, tonalite, metabasalt, and iron formation (Hausel, 1985).

The shears of the Atlantic City-South Pass district are narrow, steeply dipping (60°-90°), and parallel foliation on a regional scale. Locally, they cut the regional schistosity. Macroskopically, the shears are permeable cataclastic zones containing quartz lenses, veins, and/or stringer zones that are often sheared themselves. Most shears pinch and swell along strike and can be traced for distances of 1 to 2 km or more, but continuous veins are rare. Most gold has been produced from lodes composed of numerous, sheared quartz veins 0.5 to 2.5 m thick. The ore typically consists of rich lenses or shoots separated by lower-grade material.

Although strike veins are the most abundant type, the trends of veins containing workable ore do not necessarily parallel the northeast-trending regional foliation. The chronologically early Big Atlantic and Mammoth leads, located north and south of the MDAB along the section
from the Garfield mine to east of the Snowbird mine (Fig. 3), are conformable, wide (up to 20 m) bands of what appears to be vein quartz and can be traced for kilometers across the district (Bayley et al., 1973). Both have been intensively prospected but neither has shown shoots of pay ore, although Knight (1901) reported subeconomical gold in the Mammoth lead. The Miners Delight and Diana veins change from strike veins to cross veins along their length (Hausel, 1989; Trumbull, 1914). The Alpine, Gold Dollar, Monte Carlo, Old Hermit, Outpost, Tabor Grand, and Tornado mines were all developed along cross veins (Bartlett and Runner, 1926; Hausel, 1986, 1989; Trumbull, 1914). The B and H, Duncan, and Mary Ellen mines are developed on conjugate vein sets which include cross and strike veins (Hausel, 1986, 1989).

Gold in the shears occurs in sulfides (arsenopyrite, pyrite, and pyrrhotite) and as fracture fillings in quartz. Spencer (1916) reported that gold also occurred in sheared metagreywacke schist. Pyrrhotite, pyrite, calcite, siderite, chalcopyrite, and minor amounts of scheelite, tourmaline, and galena are also found in the veins. Gold values in the shear zones appear to be spotty, but are enriched at ore shoots. Most of the ore shoots are short and lens shaped, although some are more than 30 m long. Armstrong (1948) reported that ore shoots were localized at the intersections of veins or shears, in zones of repeated fracturing, and at points of sudden change in vein attitude.

Electron probe microanalysis of arsenopyrite from coexisting arsenopyrite-pyrite pairs gave arsenopyrite compositions of 34.71 to 36.72 atom % As. These compositions are too arsenic-rich to have
equilibrated with pyrite (Sharp et al., 1985), but fall within a range that could have equilibrated with pyrrhotite. Other sulfide samples were found to contain pyrite replacing pyrrhotite, suggesting that the pyrite in the arsenopyrite-pyrite pairs may be secondary.

Megascopic wallrock alteration is slight. Most gold-quartz veins are surrounded by a narrow (2 to 30 cm) alteration halo composed dominantly of sericite, chlorite, and K-feldspar. Bayley et al. (1973) reports that plagioclase in vein wallrocks is replaced by microcline to distances of up to 2 m from a vein. Arsenopyrite haloes around the Carissa lode persist intermittently for 2 to 3.5 m from the vein in places, but most veins do not show extensive sulfidation of the wallrocks.

No attempt has been made to explore the deeper ores of the district, although the value of the ore has proven continuous to the greatest depths yet mined and considerable vertical extent seems likely for the major veins (Bayley, 1968; Hausel, 1987). The bottom level of the deepest mine in the district, the Carissa mine, is only 120 m below the surface. At that depth, the workings are still in ore.
GEOCHEMISTRY

Trace Element Geochemistry

Thirty-four samples of greywacke, graphitic schist, chert, meta-andesite, and orthoamphibolite from the Miners Delight Formation, and iron formation from the Goldman Meadows Formation were analyzed for REE, gold, and associated trace metals by lead fire assay and instrumental neutron activation analysis (INAA) at X-ray Assays Laboratory in Toronto. Eleven additional samples from the Gold Dollar mine were analyzed for REE by INAA at Chemex Labs in Nevada. Samples were first broken to chips using a Chipmunk crusher, then sorted by hand under a binocular microscope to remove those with weathered surfaces or staining. The chips were ground to -200 mesh powder using a Spex shatterbox with a mullite chamber and puck. Rare earth element data for the Gold Dollar mine are listed in Table 1, gold and other trace element values are listed in Appendix B. Chondrite values used in normalization were taken from the data of Boynton (1984).

Veins of the Atlantic City-South Pass district show little development of visible wallrock alteration, a characteristic considered by Boyle (1986) to be typical of the turbidite-hosted type of gold deposit. Rare earth element analysis was undertaken on thirteen samples from the Gold Dollar mine to determine whether ore zones might have a characteristic geochemical signature, regardless of visible alteration. The Gold Dollar mine is the only mine of the Miners Delight group to still have accessible underground workings. The vein at the adit level is entirely hosted in orthoamphibolite and consists of several splays of
Table 1. REE data from the Gold Dollar mine

<table>
<thead>
<tr>
<th>Sample</th>
<th>La</th>
<th>Ce</th>
<th>Sm</th>
<th>Eu</th>
<th>Gd&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Yb</th>
<th>Lu</th>
<th>La/Sm&lt;sup&gt;b&lt;/sup&gt;</th>
<th>La/Yb&lt;sup&gt;b&lt;/sup&gt;</th>
<th>La/Lu&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Gd/Yb&lt;sup&gt;b&lt;/sup&gt;</th>
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<td>45.00</td>
<td>4.70</td>
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<td>17.40</td>
<td>1.60</td>
<td>0.50</td>
<td>3.21</td>
<td>10.11</td>
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<td>20.10</td>
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<td>25.10</td>
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<td>11.14</td>
<td>9.87</td>
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</table>

<sup>a</sup>Values calculated graphically.
<sup>b</sup>Normalized.
quartz separated by wallrock slivers. The sample traverse contained footwall, intercalated wallrock, and hanging wall rocks.

Chondrite-normalized plots for all samples are shown in Figure 4. Two unaltered orthoamphibolite samples are included for comparison. The curves are clustered fairly closely, and all show LREE enrichment and Eu depletion. No change in REE abundance was found with increasing proximity to the vein, and both footwall and hangingwall samples plot in the same field.

Stable Isotope Ratio Analysis

Stable isotope (S, C, O, H) ratios were determined on sixty-one samples of sulfide minerals, carbonate minerals, graphite, vein quartz, and fluids from fluid inclusions in vein quartz from various mines of the Atlantic City-South Pass district. Values of $d^{13}C$, $d^{18}O$, and $dD$ were obtained using a Finnegan Delta-E mass spectrometer with a 9 cm deflection radius. Values of $d^{34}S$ were measured on a 6° 60° sector nuclide stable isotope ratio mass spectrometer. Analytical precision is generally better than ± 0.05 o/oo for values of $d^{13}C$ and $d^{18}O$, ± 0.05 to 0.10 o/oo for $d^{34}S$, and ± 1 o/oo for $dD$. Sample preparation and analytical methods are described in Appendix A. Results are listed in Table 2.

Sulfur

Sulfur isotope ratios were measured on nine arsenopyrite and seven pyrite samples, and one pyrrhotite sample. Arsenopyrite and pyrite samples were collected from veins and wallrocks from gold mines. Pyrite and pyrrhotite samples were collected from sulfidic iron formation of
Figure 4. Chondrite-normalized REE plot for samples from the Gold Dollar mine.
Table 2. Stable isotope data for the Atlantic City-South Pass district

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<tr>
<th>Sample</th>
<th>$^{34}$S$^a$</th>
<th>$^{18}$O$^b$</th>
<th>$^{13}$C$^c$</th>
<th>DB$^b$</th>
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$^a$Per mil (o/oo) relative to Canyon Diablo Troilite (CDT).
$^b$Per mil relative to Standard Mean Ocean Water (SMOW).
$^c$Per mil relative to Pee Dee Belemnite (PDB).
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**fluid inclusions**

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the Goldman Meadows Formation and from sulfide-bearing metamorphic quartz segregations in the iron formation. Values of $d^{34}S$ range from -1.0 to 3.6 o/oo (Fig. 5) and are similar to data reported for most other Archean lode gold deposits (Colvine et al., 1988; Lambert et al., 1984). Arsenopyrite values (2.6-3.6 o/oo) are heavier than those for pyrite (-1.0 to 1.7 o/oo). One sample of pyrrhotite from the US Steel iron mine (1.2 o/oo) falls in the range of the pyrites. These values and the sulfur isotopic range of worldwide Archean lode gold deposits are shown in Figure 6.

**Carbon and Oxygen**

Carbon and oxygen ratios were measured on fifteen carbonate mineral samples of calcite or siderite. The samples include vein material from gold mines and carbonate vein and segregation material from iron formation and mafic metaigneous rocks. Carbon isotopic values of -1.5 to -10.9 o/oo and $d^{18}O$ values of 5.5 to 23.6 o/oo were obtained. Calcite vein and segregation material from the gold and iron mines had $d^{13}C$ values of -6.4 to -10.9 o/oo and $d^{18}O$ values of 5.5 to 23.6 o/oo. Vein siderite from the Tornado Cu mine had $d^{13}C$ values of -3.2 to -4.1 o/oo and $d^{18}O$ values of 18.3 to 19.9 o/oo. The $d^{13}C$ and $d^{18}O$ values of carbonate from mafic metaigneous rocks (regional alteration) range from -1.5 to -8.3 o/oo and 7.3 to 12.2 o/oo, respectively. The $d^{13}C$ values for vein calcite are among the lightest yet reported for an Archean lode gold deposit. Three of the heaviest $d^{13}C$ values are from vein siderite and regional calcite from the Roundtop Mountain Greenstone Formation. Carbon isotope values are compared with those of other Archean lode gold
Figure 5. Histogram of S isotope values
deposits in Figure 7. A plot of $d^{13}\text{C}$ vs. $d^{18}\text{O}$ shows three groups of carbonate from the Atlantic City-South Pass district (Fig. 8). Most samples fit into the range of values reported for Australian and Canadian gold-related carbonate of Archean age. These include vein and segregation carbonate in the gold and iron mines and carbonate related to regional alteration of mafic igneous rocks. Calcite and siderite from the Tornado mine has similar $d^{13}\text{C}$ but heavier $d^{18}\text{O}$ values. All calcite from the Snowbird mine and one sample from the iron mine have light carbon and heavy oxygen isotopic values. Late calcite samples are from the Snowbird and US Steel mines.

Carbon ratios were measured on graphite in five graphitic schists, intimately associated with gold deposits of the Atlantic City-South Pass district. Strongly negative values of -19.1 to -28.5 o/oo were obtained.

Oxygen and Hydrogen

Oxygen isotope data for most Archean gold deposits have been obtained by measuring $d^{18}\text{O}$ on vein quartz and then calculating the $d^{18}\text{O}$ of the fluid in equilibrium with the quartz. Values of $d^{18}\text{O}$ for vein quartz have been found to be largely independent of host rock lithology, and $d^{18}\text{O}$ of quartz in wallrocks immediately adjacent to the veins has been found to match that of the vein quartz (Colvine et al., 1984). Most hydrogen isotope data have come from analyses of hydroxysilicates such as chlorite and sericite in the vein margins. Relatively few data are available for fluids extracted from fluid inclusions. In the present study, oxygen isotope data have been collected directly from
Figure 7. Carbon isotope data for the Atlantic City-South Pass district and for worldwide Archean gold deposits. Worldwide and reservoir data from Colvine et al. (1988, 1984)
Figure 8. Plot of d$^{13}$C vs. d$^{18}$O for early and late calcite and Tornado carbonate from the Atlantic City-South Pass district and worldwide Archean gold-related carbonate. Worldwide data from Colvine et al. (1984) and Golding et al. (1987)
fluids extracted from fluid inclusions as well as by measuring d$^{18}$O on vein quartz and calculating d$^{18}$O of the fluid in equilibrium with the quartz. Equilibrium temperatures have been derived from fluid inclusion measurements.

Oxygen and hydrogen ratios measured on fluids from fluid inclusions in twenty samples of vein quartz from various mines ranged from -10.7 to 3.5 o/oo and -125 to -55 o/oo, respectively (Table 2). Oxygen isotopic values were also measured on ten samples of vein quartz and range from 10.06 to 14.19 o/oo. Fluid isotopic compositions in equilibrium with quartz at 350°C were calculated using the equation of Clayton et al. (1972) and range from 7.36 to 10.38 o/oo. The calculated fluid values are heavier than those of the corresponding fluid inclusions and are preferred. The range defined extends to lighter hydrogen values than have been reported for Archean gold deposits, but overlaps that of mesothermal gold of the Canadian Cordillera (Fig. 9). According to the equations of Field and Fifarek (1985), the field for Atlantic City-South Pass ore fluids also indicates equilibration with sedimentary rocks at temperatures between 300°C to 400°C (Fig. 9).

Isotopic analysis of fluids from fluid inclusions has also been used by Goldfarb et al. (1986) and Murowchick et al. (1987), but has a number of potential difficulties. Taylor (1987) reports that direct measurement of d$^{18}$O on fluid inclusions should only be made on inclusions in a non-oxygen bearing host mineral. Contamination by fluids from secondary inclusions may be difficult to avoid. Murowchick
Figure 9. Plot of $d^{18}$O vs. $d$D for the Atlantic City-South Pass district and various reference fluids. Data sources: Archean lode gold, Colvine et al. (1984); Mother Lode, Bohlke and Kistler (1986), Weir and Kerrick (1987); Canadian Cordillera, Nesbitt and Muehlenbachs (1989). Curves for equilibration of various water/rock ratios with igneous and sedimentary rocks from the equations of Field and Fifarek (1985)
et al. (1987) argue that thermal decrepitation preferentially releases CO₂-rich fluids from primary inclusions with higher internal pressures than those of the aqueous secondary inclusions. However, if the secondary inclusions contain dense fluids which homogenize at low temperatures (100°-200°C), they will decrepitate before the gas-rich primary inclusions once internal pressures of ~800 to 1000 bars are reached (Goldfarb et al., 1988). If mechanical crushing is used, Goldfarb et al. (1986) recommend long crushing times during fluid extraction, since initial crushing preferentially releases fluids from secondary inclusions. Secondary inclusions were rare in most Atlantic City-South Pass samples (<10%, and often <5%), and, owing to the small quantities of fluid present, long crushing times were used (E. Ripley, Indiana Univ., 1988, pers. comm.). Another source of analytical error is related to fluid composition. In a mixed H₂O-CO₂ system, oxygen isotope fractionation between the two species during analysis must also be considered. In the procedure described in Appendix A, oxygen isotope fractionation could occur during steps 3-6. If the possibility of contamination from secondary inclusions is minimized by choice of sample and long crushing, hydrogen isotope fractionation is unlikely.

Fluid Inclusion Analysis

Fluid inclusions were examined in 60 sections of vein quartz from 18 mines of the Atlantic City-South Pass district. Workable inclusions were found in only twelve mines, the Alpine, Carissa, Franklin, Gold Dollar, Mars, Mary Ellen, Miners Delight, Mormon Crevise, Rose, Smith Gulch, Tornado, and US Steel Fe mines. The Alpine, Carissa, Gold Dollar,
Mary Ellen, Smith Gulch, and Tornado mines had accessible underground workings. Samples from other mines were collected from mine dumps. Microthermometric measurements were made on a Fluid Inc. adapted US Geological Survey gas flow heating/freezing stage calibrated with synthetic fluid inclusions.

Based on phase observations at room temperature, three types of fluid inclusions were identified in vein quartz. All three types are found in vein quartz of the gold district and in metamorphic quartz segregations from the US Steel Fe mine. These are: 1) gaseous, 2) gas plus water (± daughter crystals), and 3) aqueous (± daughter crystals) inclusions. The gaseous inclusions range from 2 to 15 μ and commonly have negative crystal shapes, although they may also occur in irregular or rounded shapes. The Type 2 inclusions are 2 to 30 μ and generally rounded to irregular in shape. Type 3 aqueous inclusions are frequently large (6 to 65 μ), ragged, and faceted, or rounded and irregular shapes.

Types 1 and 2 inclusions from some mines (e.g., Mormon, Miners Delight, Monte Carlo) are frequently elongated and spindle-shaped, suggesting trapping during deformation. Most vein quartz has been partly or completely recrystallized. Inclusions considered to be of primary origin occur in unrecrystallized areas of quartz. These areas may be identified by the large number of inclusions which they contain.

Most inclusions, however, occur either in healed fractures which terminate at grain boundaries, in healed fractures which crosscut grain boundaries, or along grain boundaries. Gaseous and gas-water
Inclusions often occur together in the same plane. All observed planes of gas-water inclusions have variable gas ratios. Some deposits (e.g., Rose mine) have quartz with a very high percentage of gas inclusions, and comparatively few gas-water or aqueous inclusions.

Compositional variability within the three types is described below and summarized in Figure 10. Raw fluid inclusion data are presented in Appendix C. The carbonic phase in Types 1 and 2 inclusions ranges from pure CO$_2$ to nearly pure CH$_4$, with only a scattering of values in between (Appendix C). No methane inclusions were observed in samples from the US Steel Fe mine. Data points for the US Steel Fe mine are shaded in the histograms. The following types and compositions of fluid inclusions were observed:

1) One- and two-phase gaseous inclusions. These primary or pseudosecondary inclusions are either methane- or carbon dioxide-rich. Freezing data for these inclusions are given in Figure 11. Methane gaseous inclusions were not observed in the US Steel Fe mine. Methane gaseous inclusions from the gold mines homogenize at temperatures in the range $-83.3^\circ$ to $-90.7^\circ$C, corresponding to CH$_4$ densities of 0.21 to 0.25 g/cm$^3$ (Angus et al., 1978). Gaseous carbon dioxide inclusions were found in quartz samples from all mines, melt from $-58.1^\circ$ to $-56.6^\circ$C, and homogenize to liquid from $-10.9^\circ$ to $24.9^\circ$C, corresponding to CO$_2$ densities of 0.99 to 0.71 g/cm$^3$ (Angus et al., 1976). Type 1 inclusions usually occur in pseudosecondary planes along with Type 2 inclusions.

2) Two-, three- and four-phase H$_2$O-CO$_2$-CH$_4$-NaCl-CaCl$_2$ inclusions. These primary or pseudosecondary inclusions can be divided into methane-
TYPE 1: GASEOUS
   a) CO₂
   b) CH₄
   c) CO₂ + CH₄

TYPE 2: GAS + WATER \pm DAUGHTER SALTS
   a) CO₂ + H₂O
   b) CH₄ + H₂O
   c) CO₂ + CH₄ + H₂O
   d) CO₂ + H₂O + daughter salts
   e) CH₄ + H₂O + daughter salts
   f) CO₂ + CH₄ + H₂O + daughter salts

TYPE 3: AQUEOUS
   a) H₂O_L + H₂O_V
   b) H₂O_L + H₂O_V + daughter salts

Figure 10. Compositional variability of fluid inclusion types from the Atlantic City-South Pass district
Figure 11. Histograms of freezing data, Types 1 and 2 inclusions
Figure 11 (continued)
or carbon dioxide-rich types (Fig. 10). Some inclusions with mixed gases were also observed. Inclusions were assigned to Type 2c (mixed gases) if they showed either homogenization within the gaseous phase at \( T > -56.6^\circ C \) and/or if a solid was observed to melt at \( T > -115^\circ C \). In the absence of melting or homogenization data, inclusions showing hydrate melting at \( T > 10^\circ C \) were assigned to Type 2b. Freezing data for these inclusions are given in Figure 11, and homogenization data in Figure 12. The average homogenization temperature for Type 2 inclusions is 275\(^\circ\)C.

Carbon dioxide-rich inclusions contain nearly pure CO\(_2\) (Type 2a, Fig. 10). Inclusions from the gold district show CO\(_2\) melting temperatures from \(-59.2^\circ\) to \(-56.6^\circ\)C, hydrate melting from \(-9.7^\circ\) to \(9.6^\circ\)C, and CO\(_2\) homogenization from \(-12.7^\circ\) to \(27.9^\circ\)C to liquid (Fig 11). Salinities from clathrate hydrate melting were determined using the equation of Bozzo et al. (1975), and range from 0.8 to 24.0 equiv. wt % NaCl. Carbon dioxide homogenization temperatures correspond to phase densities of 0.95 to 0.66 g/cm\(^3\). Final homogenization temperatures range from 177.8\(^\circ\) to 420.0\(^\circ\)C. Homogenization to vapor and to liquid has been observed, with homogenization to vapor the most prevalent mode. These inclusions decrepitated on or shortly after homogenization. A few inclusions which showed final homogenization to liquid were observed, and these did not decrepitate.

Carbon dioxide-rich inclusions from the US Steel iron mine melted from \(-57.4^\circ\) to \(-56.8^\circ\)C and showed hydrate melting from \(-12.4^\circ\) to \(7.2^\circ\)C, corresponding to salinities of 3.8 to >24.2 equiv. wt % NaCl. Most salinities were >24.2\%. Only three inclusions with negative clathrate
Figure 12. Histogram of homogenization data, Types 2 and 3 inclusions
hydrate melting temperatures contained a halite daughter mineral. The NaCl-CO₂-H₂O eutectic is at -10.0°C and 24.2 wt % NaCl (Bozzo et al., 1975). Hydrate melting at temperatures less than -10°C indicates the presence of an additional component in the aqueous phase, most likely CaCl₂ (R. J. Bodnar, Univ. W. Virginia, 1988, pers. comm.). Carbon dioxide homogenized to liquid from 0.4° to 29.0°C, corresponding to a phase density of 0.93 to 0.63 g/cm³. This range is similar to that obtained for Type 2a inclusions from the gold district, and to Type 1 CO₂ inclusions. Final homogenization, to liquid or to vapor, occurred in the range 230.2° to 419.7°C.

Inclusions with methane as the dominant gas component (Types 2b, e, Fig. 10) were found in quartz from the Carissa, Smith Gulch, and Alpine mines. Saline CH₄-H₂O inclusions were observed most frequently in samples from the Carissa mine. These inclusions show melting from -175.4° to -169.6°C and homogenization to liquid + clathrate hydrate in the range -111.8° to -83.6°C. Critical homogenization within the methane phase was observed in several inclusions. Since specific elevations of the critical point are associated with specific XCO₂, the amount of CO₂ equivalent dissolved in CH₄ can be calculated (Donnelly and Katz, 1954). For those inclusions showing critical homogenization, XCO₂ < 0.08, and the gaseous phase is > 92% CH₄.

Clathrate hydrate in methane-bearing inclusions (Types 2b and 2c) melts in the range of 10.4° to 22.2°C. Since pure methane hydrate melts by about 18°C, the presence of an additional component, possibly N₂, is indicated. However, N₂ as a separate phase was not observed during
freezing runs. Goldfarb et al. (1988) note that H₂S can cause clathrate hydrate melting at temperatures up to 25°C. Final homogenization occurred in the range 278.0° to 353.8°C. Homogenization to vapor was most common, but homogenization to liquid and critical homogenization were also observed.

3) Two- and three-phase H₂O_L-H₂O_v ± solid NaCl inclusions. These are secondary inclusions. They show initial melting phenomena in the range -67° to -27°C and final melting from -50.2° to -8.2°C (Fig. 13), corresponding to total salinities of 11.95 to -31 equiv. wt % NaCl, with approximate CaCl₂ contents of 9.2 to 29 wt. % (Yanatieva, 1946; Hall et al., 1988). Homogenization temperatures of 52.4° to 301°C have been obtained, although most of these inclusions homogenize at temperatures less than 190°C (Fig. 12).

As indicated by the shaded boxes in Figures 11 to 13, data for all inclusion types for the gold district and the iron mine overlap. Average phase transition temperatures for Type 2a inclusions for the district were calculated and used to model a bulk fluid composition. Figure 14 shows estimated P-T conditions for formation of the Atlantic City-South Pass lode gold deposits. Bulk fluid composition for Type 2a inclusions was calculated using FLINCOR (Brown, 1989) and the equation of state for H₂O-CO₂-NaCl of Brown and Lamb (1989). The fluid has XH₂O=0.8039, XCO₂=0.1615, and XNaCl=0.0346, a bulk molar volume of 24.111 cm³/mol, and a bulk density of 0.9750 g/cm³. A solvus for this composition was estimated from the data of Bowers and Helgeson (1983). For the bulk fluid homogenizing on the solvus at the average T_hTOT of
Figure 13. Histogram of freezing data, Type 3 inclusions
Figure 14. P-T conditions for formation of Atlantic City-South Pass lode gold deposits. Solvus for XCO₂=0.16 and XNaCl=0.35 estimated from the data of Bowers and Helgeson (1983). Isochore for bulk fluid calculated using FLINCOR (Brown, 1989) and the equation of Brown and Lamb (1989)
287°C, pressure at trapping was ~3 kb. For the modal $T_{\text{HOT}}$ of 275°C, a correction for ~0.7 kb is required, and the estimated temperature of trapping is 350°C. Trapping pressures of 3-4 kb are in agreement with those determined by Brown and Lamb (1986), who indicated that pressures of trapping estimated for most Archean lode gold deposits (e.g., Smith et al., 1984) are too low.
DISCUSSION

Studies of Archean greenstone-hosted gold deposits worldwide have revealed a number of common geological and geochemical characteristics. The deposits occur as gold-quartz veins which, although spatially associated with major structures, are usually hosted by secondary structures (Keays et al., 1989). Major structures provided access for mineralizing fluids, which were derived from a source external to the environment of deposition (Colvine et al., 1984; Keays, 1984). Alteration and mineralization occurred relatively late in the sequence of events affecting the mineralized areas, and postdates sedimentation, volcanism, episodes of intrusion, some metamorphism, and at least one episode of deformation (Colvine et al., 1984). In most districts, only minor deformation and/or intrusive activity postdates mineralization (Colvine et al., 1984).

Unique geochemical characteristics of Archean lode gold deposits include the addition of large amounts of CO₂ and K, and introduction and remobilization of significant quantities of Si, S, and Na. The chemical signature is independent of host rock type. Trace element enrichments typically include Au, As, Sb, W, Mo, and to a lesser extent Ag, Te, Se, B, Ba, Bi, and Cr (Colvine et al., 1984; Boyle, 1979). H₂O-CO₂ fluids of low salinities (<5 NaCl equiv. wt. %) are indicated by fluid inclusion studies, although fairly saline fluids have been reported for some deposits (Guha et al., 1979; Guha et al., 1986; Krupka et al., 1977; Macdonald, 1984; Macdonald and Hodgson, 1986; Robert and Kelly, 1987). Temperatures of formation are typically in the range 200°-500°C.
Minor CH$_4$ and N$_2$ may be present in the inclusions.

Alteration associated with mineralization typically forms narrow haloes around the veins, and is controlled by host rock composition. Movement of large volumes of hydrothermal fluid through the system is indicated (Colvine et al., 1984; Kerrich et al., 1977). Light stable isotope data for a number of Archean lode gold deposits worldwide are summarized by Colvine et al. (1988, 1984), Lambert et al. (1984), Golding et al. (1987), and Golding and Wilson (1987) and characteristic ranges of isotopic values of -2.5 to 4.0 $\delta$ for C, 1.0 to 6.0 $\delta$ for S, and 5.0 to 12.0 for O have been obtained. A plot of $\delta^{18}O$ vs temperature of deposition shows that fluids responsible for Archean deposits are distinct from those which produced gold mineralization of younger age (Colvine et al., 1984). The worldwide uniformity of light stable isotopic composition of the fluids has been taken to indicate that Archean gold mineralization is the result of a process common to all deposits, which operated on a shield-wide scale, and which was unique to the Archean (Colvine et al., 1984).

The Atlantic City-South Pass district is geologically more similar to the turbidite-hosted type of gold deposits than to the greenstone-hosted type. Lithologically, the area contains metagreywackes, chert, graphitic schist, iron formation, and metavolcanic rocks of ultramafic to intermediate composition, but metasedimentary rocks are volumetrically dominant. Metaturbidites of the Atlantic City-South Pass
district were estimated to be on the order of 1600 to 3300 m thick (Bayley et al., 1973). In the Ballarat Slate Belt of Australia, 730 m of Cambrian turbidites occur in the Stawell Province, and 1800 m of Ordovician turbidites in the Bendigo province, with a combined thickness of 2530 m (Sandiford and Keays, 1986). The Cambrian-Ordovician Meguma Group of Nova Scotia contains 5400+ m of greywacke and 3500 m of slate (Haynes, 1986), while the Cretaceous Valdez Group of the Chugach terrane, Alaska, contains 3 to 5 km of turbidites (Goldfarb et al., 1986).

Goldfarb et al. (1988) distinguish two types of turbidite-hosted gold deposits in the Pacific Border Ranges and Coast Mountains of Alaska. Metaturbidites of the Alexander terrane, host of the Juneau Gold Belt, contain abundant intercalated volcanic rocks, and have been metamorphosed to greenschist-amphibolite facies. Rocks of the Chugach terrane consist of greenschist-facies trench-fill turbidites that were accreted onto and subducted below the continental margin during late Cretaceous times. In addition to the differences in host lithology, mineralization style and fluid inclusion compositions differ as well.

Geological, structural, and chemical factors are important in providing a favorable site for mineralization in any type of ore deposit. The association of gold deposits with metaigneous rocks at or near the igneous-sedimentary interface has been reported in a number of Archean and younger sediment-hosted gold districts and is not unique to the South Pass Supracrustal Belt. Deposits of the Slave Province, Northwest Territories (Padgham, 1986), the Juneau Gold Belt, Alaska...
(Goldfarb et al., 1988; Leach et al., 1987), and the Mother Lode, California (Weir and Kerrick, 1987) also have a similar association. In the Alaska-Juneau district of the Juneau Gold Belt, orebodies are spatially associated with small bodies of metagabbro, metadiorite, or metamorphosed mafic to intermediate volcanics within the turbiditic Perseverence Slate, and sections lacking intercalated metaigneous rocks also lack extensive veining (Leach et al., 1987). Only a few mines of the Atlantic City-South Pass district (nos. 6, 7, 19, Fig. 3) are located 0.5 km or more from the Miners Delight Amphibolite Belt.

Bayley (1968) first proposed structural causes for the close spatial association of gold deposits of the Atlantic City-South Pass district with rocks of the MDAB. Goldfarb et al. (1988) suggested that preferential brittle fracture of more competent metagabbro and metadiorite sills in the Juneau Gold Belt may locally have controlled much of the quartz veining. Since pelitic sedimentary rocks commonly respond to shear in a ductile fashion, hydrothermal fluids may be focussed through adjacent, more competent rocks such as basalts or iron formation. These rock types are more favorable geochemical sites for mineralization as well. Colvine et al. (1988) reported that well-developed vein systems are observed to terminate abruptly against argillaceous units, indicating that the physical characteristics of some sedimentary rocks may deter fluid flow.

The presence of iron formation, graphitic schists, cherts, and turbidites in the Atlantic City-South Pass district is important, but perhaps somewhat misleading as to genetic implications. Sediments such
as iron formation, chert, and graphitic shales are a normal part of Archean marine sedimentation (Ojakangas, 1985). Iron formation occurs only in the older Goldman Meadows Formation, not in the Miners Delight Amphibolite Belt. Although the iron formation is locally sulfide-bearing, only one historic gold mine, the Lone Star, was developed in the Goldman Meadows Formation, and the site was later buried by tailings from the US Steel iron mine (Hausel, 1986). Graphitic schists and cherts actually occur as interbeds in the MDAB. Ojakangas (1985) divides Archean clastic sedimentation into turbidite and pelagic facies. The distal part of the submarine fan (turbidite) facies commonly grades outward into the pelagic facies, which contains graphitic schist, iron formation, and chert. Although the pelagic facies was presumably deposited in relatively deep water, it could be found in any marine environment where coarse clastic sedimentation was subdued and only fine clastic deposits and chemical sedimentation occurred. The graphitic schists and cherts of the MDAB record lulls in deposition of coarser clastic material. The cherts may be observed in outcrop to interfinger with turbidites and/or graphitic schists. Their unusually high REE content (Section I) suggests contamination, perhaps from a fine, tuffaceous component.

The ultimate source of the gold in Archean deposits is controversial. Some workers have argued that mafic or ultramafic rocks are important (Boyle, 1961; Keays, 1984; Pyke, 1976; Viljoen et al., 1970), since they often have enhanced levels of Au relative to other rock types. Recently, lamprophyres have been considered important by
some workers (e.g., Rock et al., 1989). However, where present, these rocks were emplaced at the same time gold mineralization occurred. The metaigneous rocks of the MDAB are mostly volcanic and were deposited prior to gold mineralization. The high precious metal content of ultramafic rocks such as komatiites is related to their high temperature of magma generation and subsequent late-stage saturation with respect to immiscible sulfide liquids. Most mafic magmas are sulfur-saturated at the source or become saturated before extrusion, and therefore lose most of their Au and chalcophile elements to scavenging by immiscible sulfide melts. Since komatiites are erupted at higher temperatures, they have a greater sulfur capacity than most mafic magmas and do not become sulfur-saturated until a late stage. Keays (1984) estimates the Au content of disseminated sulfides in komatiites, subvolcanic dunites, and high-Mg basalts to be 280 times greater than those of the parental komatiitic melts. Anhaeusser et al. (1975), however, found that komatiitic rocks of the Barberton greenstone belt in South Africa did not contain anomalous background levels of gold, and argued against the need for particular source rocks.

Sediments have been proposed as the most likely source of gold in the turbidite-hosted type of deposit since clastic sediments such as greywackes, conglomerates, and sandstones commonly contain higher than normal background levels of gold, and the black pyritiferous shales and argillites intercalated with these rocks are invariably enriched in all the trace elements found in turbidite-hosted deposits (Boyle, 1986).

In the Atlantic City-South Pass district, iron formation and
graphitic schists had the highest overall gold content, with values of up to 37 and 140 ppb, respectively, but gold concentration was highly variable among samples of a particular rock type. The higher gold contents of these rock types may simply be related to their chemical favorability as sites of gold deposition. Hausel (1987) postulated a correlation between gold values in some of the mines and the presence of a thin unit of tremolite-actinolite schist nearby. Bow (1986) reported 0.005-0.07 ppm Au in basaltic amphibolites and 0.02-0.43 ppm Au in ultramafic amphibolites of the MDAB, and that greater thicknesses of tremolite-actinolite schist in the Carissa mine correlated with higher gold values in the adjacent shear zones. The meta-komatiites of the MDAB are thin units, and probably do not constitute a sufficient volume of source material for all the gold-quartz veins. It seems more probable that gold was derived from the entire sedimentary pile, and the tenor of particular veins enhanced by the proximity of meta-komatiites.

Although the scale of mineralization in turbidite-hosted deposits is typically smaller than in greenstone-hosted deposits (Kerrich, 1987), the apparent absence of major, throughgoing structures may have been a factor in limiting the size of the Atlantic City-South Pass gold deposits. Major structures are important in providing channels for fluid access, but these structures themselves are not necessarily mineralized (Keays et al., 1989; Colvine et al., 1988; Nesbitt and Muehlenbachs, 1988). All mines of the geologically similar Juneau Gold Belt are located within a few kilometers of the Coast Range Megalineament, but the lineament continues for 500 km south of the
southernmost gold deposit of the Juneau Gold Belt with only a few insignificant prospects along its length (Goldfarb et al., 1988). Given the fragmentary nature of the South Pass Supracrustal Belt, major structures may no longer be well-preserved. The Roundtop Fault, separating the Roundtop Mountain Greenstone Formation from the Miners Delight Formation, may be the remnant of such a structure. Development of this fault preceded and possibly overlapped the foliation-parallel shearing which localized the gold-bearing veins. The largest shears, the Carissa and the Miners Delight, were also the most productive.

Isotopic and fluid inclusion data provide evidence for the nature of the ore fluids and conditions of mineralization. Sulfur isotope data for Archean gold deposits do not form a unique group relative to other types of deposit such as epithermal vein ores or massive sulfide deposits. Possible sources of sulfur in the Archean environment include: 1) direct derivation from magmatic fluids; 2) leaching of sulfide minerals in the underlying rock column; 3) sedimentary marine sulfate; and 4) seawater sulfate. In terms of size and availability of reservoirs, only the first two are likely (Colvine et al., 1984). Archean gold deposits worldwide show similar distributions of sulfur isotope values. The negative \( \delta^{34}S \) values found in some deposits (e.g., Golden Mile, Hemlo, Lakeshore, Canadian Arrow) may reflect relatively oxidizing hydrothermal fluids (Cameron and Hattori, 1987), but most Archean gold deposits are believed to have been formed from fluids dominated by reduced S species (Colvine et al., 1984).

A \( \delta^{34}S \) of about 0 o/oo for the total dissolved sulfur in the ore
fluid is capable of yielding the observed $\delta^{34}S$ values in Archean gold deposits, depending on the $f_{O_2}$ conditions at the depositional site. This magmatic sulfur may have entered the fluid as a direct contribution from magmatic sources, or by dissolution of juvenile sulfide minerals by metamorphic fluids.

Sulfur isotope data for the Atlantic City-South Pass district show a limited range of -1.0 to 3.6 o/oo, suggesting precipitation from fluids having fairly constant $SO_2/H_2S$ (Ohmoto and Rye, 1979). Although two pyrite samples had $\delta^{34}S < 0$, the bulk of the data are positive, suggesting that the fluids were reduced in nature (Ohmoto and Rye, 1979). The samples with negative $\delta^{34}S$ are both from the US Steel iron mine, and may reflect locally more oxidizing depositional conditions. The possibility that some of the sulfur in the gold mines was leached from sulfides in the older Goldman Meadows Formation cannot be ruled out. Sulfide minerals precipitated from a fluid that acquired sulfur by leaching of pre-existing sulfide minerals should have a small isotopic variation, but could have $\delta^{34}S$ values up to 5 o/oo higher than that of the leached material (Grinenko and Grinenko, 1972). A log $f_{O_2}$-$pH$ diagram for estimated depositional conditions of the ore fluids at Atlantic City-South Pass is shown in Figure 15. Pressure-temperature conditions were estimated from fluid inclusion studies. The contours for $\delta^{34}S$ (light solid lines) are relative to $\delta^{34}$total $S=1$. Coexisting pyrrhotite and arsenopyrite were found in vein margins. Adjacent to the veins, sericite is the stable potassium phase, while K-feldspar is stable in the wallrocks. Neither potassium metasomatism nor sulfidation
Figure 15. $f_O^2$-pH diagram for 350°C, 3.75 kb. Thermodynamic data from Barton (1969), Helgeson (1969), Murray and Cubicotti (1983), Ohmoto (1972), and Shenberger and Barnes (1989).
of wallrocks was extensive, and values of total sulfur and $a_k^+$ were chosen accordingly. The depositional field is defined by the coexistence of pyrrhotite, arsenopyrite, and sericite, and by $d^{34}S$ of 0.1 to 1.7 o/oo for pyrite from the gold district. The most likely carrier of gold is bisulfide complexes.

The calculated $d^{13}C$ for total dissolved C in the hydrothermal fluid under the conditions postulated for Canadian and Australian Archean gold deposits (graphite absent, sericite stable, 300°-500°C) is about -7 to 0 o/oo with a median value of -3.5 o/oo (Colvine et al., 1988). Colvine et al. (1988, 1984) argue that since the inferred $d^{13}C$ for hydrothermal carbon falls within the range for magmatic carbon (-2 to -12 o/oo), derivation from a magmatic reservoir is most likely. The average $d^{13}C$ of magmatic CO$_2$ (-5 o/oo) could be shifted to -3 o/oo by formation of about 5 mole % CH$_4$ at the expense of CO$_2$ in the fluid (Colvine et al., 1988). Carbonaceous sediments locally abundant in the Atlantic City-South Pass district are also a potential source of carbon. Carbon dioxide could be produced from such sediments either by oxidation or by hydrolysis. Both types of reactions produce isotopically light CO$_2$ (-15 to -35 o/oo), but hydrolysis generates CH$_4$ as well as CO$_2$. Methane is an important fluid constituent in inclusions from several mines of the district. The light values of $d^{13}C$ for vein carbonate at Atlantic City-South Pass suggests that the carbon was derived in part from an organic source, most likely the graphitic schists of the district. Hydrolysis of carbon in the graphitic schists could also be responsible for CH$_4$ in fluid inclusions.
Calculated $d^{18}O$ and $d$D values for water in Archean greenstone-hosted gold deposit ore fluids lie in the range 2.5 to 10.0 o/oo and 0 to -70 o/oo, respectively (Colvine et al., 1988). This restricted range indicates deposition from a single, uniform, crust-equilibrated reservoir at levels below those of groundwater infiltration (Kerrich, 1987). Fluids for some mesothermal gold deposits, such as the Mother Lode (Bohlke and Kistler, 1986; Weir and Kerrick, 1987) overlap this range. Mesothermal lode gold deposits in the Canadian Cordillera (Murowchick et al., 1987; Nesbitt et al., 1986) have similar isotopic signatures characterized by relatively heavy oxygen ($d^{18}O = 0$ to 13) but light $d$D similar to that of the local meteoric waters. The $d$D values were also found to vary with latitude. Nesbitt et al. (1986) believe the ore fluids were derived from deeply-circulating meteoric waters, while Kerrich (1987) postulates mixing of heavy, $d^{18}O$-enriched, crust-equilibrated fluids with local meteoric water in the hydrothermal conduit to produce solutions that reflect local latitude control.

The fluid field for the Atlantic City-South Pass district defined by calculated $d^{18}O$ and measured $d$D values partly overlaps the metamorphic and magmatic fluid fields, but extends to lighter oxygen and hydrogen values (Fig. 9). This data spread is more typical of evolved meteoric and/or formation waters (Taylor, 1987; Welhan, 1987). Some formational brines and geothermal systems with a significant meteoric water component may undergo extensive oxygen and limited hydrogen exchange with sedimentary rocks, and therefore evolve into the metamorphic/magmatic water field. If evolved formation brines become...
involved in a hydrothermal system, they evolve along J-shaped trajectories with increasing water-rock ratios (Field and Fifarek, 1985). Such evolved waters are saline, in contrast to the dilute (<5 NaCl equiv. wt. %) fluids responsible for most Archean and mesothermal gold deposits.

Saline inclusions have been reported in a number of deposits (Guha et al., 1979, 1986; Krupka et al., 1977; Macdonald, 1984; Macdonald and Hodgson, 1986; Robert and Kelly, 1987), but these are usually aqueous secondary inclusions. Bowers and Helgeson (1983) showed that a high-salinity H$_2$O-rich fluid can be produced by unmixing of a relatively low salinity H$_2$O-CO$_2$ fluid because the salt will fractionate into the H$_2$O-rich liquid phase rather than into the CO$_2$-rich vapor phase. As indicated by fluid inclusion microthermometry, high salinities in inclusions of the Atlantic City-South Pass district are not restricted to aqueous secondary inclusions. Daughter crystals were observed in both CO$_2$- and CH$_4$-H$_2$O gas-water inclusions. The average salinity for Type 2a CO$_2$-H$_2$O inclusions was 12.24 NaCl equiv. wt. %, in contrast to values of < 5 NaCl equiv. wt. % commonly reported for Archean lode gold deposits. Salinities of aqueous secondary inclusions range from about 12 to 30 NaCl equiv. wt. %. A significant CaCl$_2$ component is present in Type 3 inclusions, indicated by separation of initial melts at temperatures less than -56°C, and by final melting at temperatures from -21.6 to -50.2°C. The presence of CaCl$_2$ in Type 2 inclusions is suggested by hydrate melting at temperatures less than -10°C. High CaCl$_2$ contents have also been reported in aqueous inclusions from the
Sigma mine (Robert and Kelly, 1987) and the Pamour mine (Walsh et al., 1988). Crawford et al. (1979) indicate that it is possible to produce a fluid rich in CaCl₂ through retrograde metamorphic reactions. This may be the source of CaCl₂ in secondary inclusions from the Canadian Archean deposits, but does not explain CaCl₂ in pseudosecondary as well as secondary inclusions of the Atlantic City-South Pass district. The relatively high salinities and CaCl₂ content of the Atlantic City-South Pass ore fluids appear to be due to the involvement of evolved formation waters in the hydrothermal system. The magmatic component postulated for other turbidite-hosted gold deposits (e.g., Meguma, Kontak et al., 1990) seems unlikely at Atlantic City-South Pass due to the absence of coeval alkaline igneous activity and the CaCl₂ content of the fluids. The higher CaCl₂ contents of Type 3 inclusions may be in part due to leaching of Ca from plagioclase in the greywackes.

Carbonic fluid inclusions in vein quartz from mines of the Atlantic City-South Pass district are compositionally divided into a methane (±N₂)- and a carbon dioxide-rich group. Although the two groups were occasionally observed in the same sample, they were never observed together in a manner that could allow paragenesis to be determined. A small number of carbon dioxide-bearing inclusions contained enough CH₄ to depress the melting point of CO₂, but most CO₂-bearing inclusions contained essentially pure CO₂. Since CO₂ and CH₄ are miscible, this indicates more than one generation of carbonic fluid. Ho (1987) has suggested that a high methane content in fluid inclusions is related to proximity of carbonaceous sediments. Graphitic schists are found in
close proximity to most mines of the Atlantic City-South Pass district.

The limited fluid inclusion data available from turbidite-hosted gold deposits (Goldfarb et al., 1986, 1988; Paterson, 1986; Steed and Morris, 1986) suggests that ore-forming fluids were trapped at similar temperatures and are similar in composition to those of the Atlantic City-South Pass district. Fluid components such as CH$_4$ and N$_2$ are more common in turbidite-hosted deposits than in greenstone-hosted deposits, which typically contain only minor CH$_4$ and/or N$_2$ (Colvine et al., 1984). Gas-rich fluid compositions in the C-O-H-S-N system can be produced during metamorphism of dominantly pelitic sedimentary sequences (Crawford, 1981; Goldfarb et al., 1988). In prograde sequences, fluid composition changes with metamorphic grade, with higher hydrocarbons prevalent in unmetamorphosed rocks, CH$_4$ in weakly metamorphosed rocks, H$_2$O-dominated in medium-grade rocks, and CO$_2$-dominated above the staurolite isograd (Crawford, 1981). The methane and N$_2$ content of fluid inclusions from deposits of the Valdez Group are 1.39 and 1.12 mole $\%$ respectively (Goldfarb et al., 1986), though no CH$_4$-dominated inclusions were reported. Goldfarb et al. (1988) noted that inclusions in deposits of the Chugach terrane and most deposits of the Alexander terrane are H$_2$O-dominated with 5 to 20 mole $\%$ CO$_2$, while those of the Alaska-Juneau district contain $>$50 mole $\%$ CO$_2$. The Alaska-Juneau district is located along the greenschist-amphibolite grade boundary, while the other deposits are in greenschist-grade rocks. The bulk fluid for the Atlantic City-South Pass district, with 16 mole $\%$ CO$_2$, is more similar to the fluids of the Alexander and Chugach terranes, though
deposit setting more closely resembles that of the Alaska-Juneau district.

Several lines of evidence suggest that phase separation occurred in carbonic fluids of the Atlantic City-South Pass district. Types 1 and 2 inclusions are often found together in the same plane. Type 2 inclusions contain variable volumes of gas phase, ranging from about 15-90%. Both Type 1 and Type 2 inclusions have similar ranges of density for the gas phase, suggesting that the fluid unmixed into gaseous and gas-water types. Type 1 inclusions may simply be the most gas-rich subset of carbonic inclusions. Also, among Type 2 inclusions, final homogenization to both vapor and to liquid have been observed. These relationships occur in both CH₄- and CO₂-rich inclusions. The frequent occurrence of Types 1 and 2 inclusions in the same plane suggests that trapping on the solvus was common.

Oxygen and hydrogen isotope data for Atlantic City-South Pass ore fluids suggests a metamorphic fluid reservoir which equilibrated with sedimentary rocks. The relatively high salinity and CaCl₂ content suggests evolved formational waters. Trace element data for the SPSB (Section I) is consistent with data from the Northern Wyoming Province in indicating the presence of evolved continental crust in the area during the Archean. However, data for the SPSB and the eugeosynclinal rock assemblage suggest an active continental margin tectonic setting. Fluid inclusion data for metamorphic quartz segregations in the iron mine and veins in the gold district overlap, supporting a metamorphic origin. Although sulfur isotopes do not rule out a magmatic
contribution, sulfur with similar isotopic composition could have been
derived by leaching from sulfides of the Goldman Meadows Formation, and
a direct contribution of magmatic sulfur seems unlikely in view of fluid
composition and timing of mineralization. Deposits where a magmatic
fluid component is suspected show evidence of alkaline igneous activity
contemporaneously with mineralization (Kontak et al., 1990; Rock et al.,
1989). Interaction of the ore fluids with graphitic sediments is
indicated by isotopically light carbonate minerals and by methane-
bearing fluid inclusions. In contrast to Archean lode gold deposits of
the Superior Province, which were formed in an oceanic arc setting (Card
et al., 1989), those of Atlantic City-South Pass were probably formed in
an active continental margin setting similar to that of Canadian and
Alaskan mesothermal deposits.
116

CONCLUSIONS

1. Gold mineralization at Atlantic City-South Pass occurred post-peak metamorphism, and was localized at points of competency contrast between metaigneous and metasedimentary rocks of the Miners Delight Amphibolite Belt. The apparent absence of major structures may have been a factor in limiting the extent of mineralization.

2. Thickness of Archean metasediments at Atlantic City-South Pass falls within the range reported for turbidite-hosted gold deposits, suggesting that a Proterozoic or younger age restriction as suggested by Hutchinson (1987) on this type of deposit is artificial. Formation of turbidite-hosted gold deposits is related to the tectonic setting of mineralization rather than to age. Deposits of the Atlantic City-South Pass district share geologic, isotopic, and fluid inclusion similarities to mesothermal gold deposits in accreted terranes of southern Alaska and the Canadian Cordillera. The greater salinities and high CaCl₂ of all fluid inclusions, however, suggest evolved formation waters as a fluid source. The CaCl₂ content and absence of coeval igneous activity argues against a magmatic source. Sulfur isotope and fO₂-pH data suggests reduced fluids and transport of gold by reduced sulfur complexes. Some sulfur in sulfides of the gold district may have been derived from sulfides in iron formation of the Goldman Meadows Formation.

The light d^{13}C of vein carbonate indicates an organic component to the carbon. Graphitic schists of the Atlantic City-South Pass district are the most likely source of isotopically light carbon.

3. Fluid inclusion data indicate more than one generation of
carbonic fluid. Phase separation occurred in the carbonic fluid, as suggested by the variable volumes of the gas phase in Type 2 inclusions, similar densities of the gas component in both Types 1 and 2 inclusions, and by homogenization to vapor and to liquid in Type 2 inclusions. Trapping on the solvus took place at temperatures of about 287°C and pressures of 3 kb. Fluids trapped above the solvus require a correction for -0.7 kb.

4. Data from the Atlantic City-South Pass district suggest that Archean turbidite-hosted gold deposits of the Wyoming Province were formed in a continental margin subduction-related tectonic environment similar to that responsible for younger turbidite-hosted deposits such as those of Alaska and the Canadian Cordillera. In contrast, the greenstone-hosted type of deposit was formed in a tectonic environment lacking the presence of evolved continental crust.
1. Gold mineralization at Atlantic City-South Pass occurred post-peak metamorphism, and was localized at points of competency contrast between metaigneous and metasedimentary rocks of the Miners Delight Amphibolite Belt. The apparent absence of major structures may have been a factor in limiting the extent of mineralization.

2. Rare earth element patterns for igneous rocks are similar to those of modern active continental margins, indicating evolved magmas and suggesting the involvement of thick crust during magmagenesis of the Miners Delight Amphibolite Belt.

Rare earth element patterns for metasediments of the SPSB and throughout the Wyoming Province more closely resemble the various post-Archean sediment composites and indicate that a significant source of evolved continental material existed during the Archean. A mafic volcanic component was also involved. These geochemical data corroborate dates as old as 3.8 Ga for the existence of continental crust in the Wyoming Province, and indicate that cratonization occurred relatively early. Postulated Archean/Proterozoic crustal differences are not as time-dependent as other workers have indicated.

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greenstone-hosted type of deposit was formed in a tectonic environment lacking the presence of evolved continental crust.
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APPENDIX A. SAMPLE PREPARATION AND ANALYTICAL METHODS

Fire Assay/Neutron Activation Analysis

Samples were first broken to chips using a Chipmunk crusher, then sorted by hand under a binocular microscope to remove those with weathered surfaces or staining. Samples were ground to -200 mesh powder using a Spex shatterbox with a mullite chamber and puck. Analyses were done by X-ray Assay Laboratories in Toronto, Canada, and Chemex, Nevada. Gold values with a 1 ppb detection limit were obtained by lead fire assay; other elements were determined by neutron activation analysis (NAA). One gram splits of powder were irradiated in a high-density neutron flux to produce isotopes of the elements present in the sample. Element concentrations were then determined with a multi-channel gamma spectrometer.

Stable Isotope Ratio Analysis

Initial sample preparation was done by the author at Iowa State University. Sample selection was limited by availability of some of the minerals of interest, notably sulfides and carbonates. All samples were first broken to fragments <5 mm in size and sorted by hand under a binocular microscope. Sulfides, carbonates, and graphitic schists were ground to powder using an agate mortar and pestle. Samples from which fluids were to be extracted for d\textsuperscript{18}O and dD analyses were left as fragments, and final preparation was done by the isotope analyst. Dr. Ripley reports that due to the extremely small quantities of fluid present in the samples, long crushing times were required, and that the
procedure was reproducible. All isotope analyses were performed by Dr. E. M. Ripley at Indiana University. The following information on extraction techniques and analyses was provided by Dr. Ripley.

Sulfur isotope analyses of sulfides: sulfide powders were combusted with excess CuO at 1100°C to yield SO₂.

Carbon and oxygen isotope analyses of carbonates: CO₂ was liberated with 100% phosphoric acid at 75°C.

Oxygen and hydrogen isotope analyses of fluid inclusions:
1. Sample chips and quartz tubes were dried in a vacuum oven (T = 150°-200°C) at least overnight, and generally for several days.
2. Sample chips (1-3 g.) in the quartz tubes (9 mm. OD) were attached to a small-volume vacuum line and outgassed overnight at a relatively low temperature (50°-100°C). The vacuum line itself was heat-taped and maintained at a temperature of ~ 80°C.
3. After outgassing and attainment of high vacuum, an electrical resistance furnace was placed around the quartz tube, and sample chips heated to ~ 450°C.
4. Evolved condensible gases are collected in a liquid N₂-cooled trap. Volatiles are collected for ~ 30 minutes. Noncondensable gases are then pumped from the system.
5. The liquid N₂ trap is then exchanged for a dry ice-acetone trap, and gases such as CO₂, SO₂, etc. pumped from the system.
6. The dry ice-acetone trap is then dropped and water transferred to a small volume (~ 1 cc.) equilibration tube. An aliquot of isotopically-labeled CO₂ (usually 15-50 micromoles) is added. Water and CO₂ are
equilibrated at 25°C for 48-72 hours. CO₂ is then collected and isotopically measured using a Finnegan Delta-E stable isotope ratio mass spectrometer (MS). The CO₂-H₂O fractionation factor proposed by Friedman and O'Neil of 1.0412 at 25°C was used.

7. After collection of CO₂, the H₂O is transferred to a 6 mm pyrex tube containing ~ 100 mg zinc (~ 60 mesh). The tubes containing H₂O + zinc are heated at 500°C in a block furnace for ~ 1 hr. Hydrogen gas produced by zinc reduction is then isotopically analyzed using the Finnegan Delta-E MS. The amount of H₂ produced (and therefore H₂O abundance) is determined either manometrically or by calibration of the MS ion gauge. A series of small-volume H₂O standards (0.1 to ~ 3 mg) are used for calibration. The amount of H₂O collected from the sample chips is required to determine the CO₂/H₂O ratio used in the computation of the water d¹⁸O value.
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APPENDIX D. SELECTED MINE DESCRIPTIONS

Carissa

This mine was the major producer during the gold boom of the late 1800s. Although the Carissa is the largest lode in the district, megascopic wallrock alteration associated with the vein appears to be slight. Wallrocks near the vein contain pervasive stringers and veinlets of quartz, and may also show development of arsenopyrite haloes to a distance of several feet from the vein. The mine is 360' deep and contains five levels, the lower two of which (4 and 5) have been inaccessible due to flooding since about 1920. As of the summer of 1987, the mine had been dewatered down to the bottom level. Detailed sample traverses across the Carissa lode were obtained from levels 3 and 4. Although the main tunnel of level 5 was still flooded, a crosscut which intersected the main tunnel at the shaft was dry. Several samples were obtained from this crosscut, but they do not represent a detailed traverse. The two uppermost levels were no longer safely accessible due to extensive caving of stopes.

Snowbird

The Snowbird mine is somewhat anomalous in some respects to the other mines of the Atlantic City-South Pass district and contains two different types of mineralization. Banded quartz and carbonate veining fills a 50-60' wide shear zone in orthoamphibolite, and quartz veining on a different level of the mine (inaccessible in 1987) is hosted by metagreywacke. Surface exposures of the vein above the level of the adit consist of milky white quartz containing open-space textures
similar to those found in epithermal vein deposits. At depth, there are at least two, possibly three generations of quartz. Bluish gray quartz is present at the adit level but not on the surface. Abundant calcite is also present in the adit, and is locally host to veinlets of massive pyrite. Local malachite staining on the adit walls indicates the presence of primary copper sulfides.

Smith Gulch

The adit of the Smith Gulch mine contains exposures of actinolite schist, graphitic schist, and a 3-4" thick selvedge of massive arsenopyrite adjacent to the quartz vein.

Tornado

The Tornado mine is hosted in mafic metavolcanic rocks of the Roundtop Mountain Greenstone Formation. The Tornado vein contains abundant, dark brown siderite intergrown with quartz and minor calcite. Chalcopyrite and secondary malachite are present in the vein.