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# Geology and Mineralization of the Wyoming Province

by W. D. Hausel, B. R. Edwards, and P. J. Graff

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Reprint No. 52 • 1992

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Laramie, Wyoming

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Reprint of 400 copies by Wyoming Department of Administration and Information, Central Printing Section, Cheyenne, Wyoming.

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Box 3008, University Station  
Laramie, Wyoming 82071-3008  
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Originally published as Preprint 91-72 of the Society for Mining, Metallurgy, and Exploration, Inc., and presented at the 1991 SME Annual Meeting, Denver, Colorado, February 25-28, 1991.

# SOCIETY FOR MINING, METALLURGY, AND EXPLORATION, INC.

P.O. BOX 625002 • LITTLETON, COLORADO • 80162-5002

PREPRINT  
NUMBER

91-72



## *GEOLOGY AND MINERALIZATION OF THE WYOMING PROVINCE*

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Denver, Colorado - February 25-28, 1991*

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PREPRINT AVAILABILITY LIST IS PUBLISHED PERIODICALLY IN  
MINING ENGINEERING



## Abstract

The Wyoming Province is an Archean craton which underlies portions of Idaho, Montana, Nevada, Utah, and much of Wyoming. The cratonic block consists of Archean age granite-gneiss with interspersed greenstone belts and related supracrustal terranes exposed in the cores of several Laramide uplifts. Resources found in the Province and in the adjacent accreted Proterozoic terrane include banded iron formation, Au, Pt, Pd, W, Sn, Cr, Ni, Zn, Cu, and diamonds.

The Province shows many similarities to the mineral-rich cratons of the Canadian shield, the Rhodesian and Transvaal cratons of southern Africa, and the Pilbara and Yilgarn blocks of Western Australia, where much of the world's precious and strategic metal and gemstone resources are located.

## Introduction

The Wyoming Province comprises a craton of Archean age (> 2.5 Ga) metamorphic and crystalline rocks exposed in the cores of several mountain ranges of Wyoming and in portions of adjoining states to the north and west (Engel, 1963; Condie, 1976; Houston and Karlstrom, 1979; Houston, 1983). The boundary of this Archean block is not well known except on the southern limit where it is exposed in northern Utah and southern Wyoming. It was first recognized by Houston as the limits of the Penokean orogen in southeastern Wyoming where the boundary is exposed in the Medicine Bow Mountains and Sierra Madre and known locally as the Mullen Creek-Nash Fork shear zone. The boundary was later determined to be the expression of a continental-arc collision zone (Graff, 1978) and renamed the Cheyenne Belt (Hills and Houston, 1979). This suture separates Archean Wyoming Province basement rocks to the north from the Proterozoic volcanogenic arc assemblages to the south (2.2 to 1.6 Ga). This boundary extends from the Medicine Bow Mountains and the Sierra Madre eastward to the Laramie Range then under the sedimentary sequences of the high plains to where it intersects the southward extension of the Trans-Hudsonian orogen (Williams and others, 1986).

The eastern boundary is not exposed and has in the past been extended to include the Black Hills, but geochronologic data show that the ages of the basement rocks in the Black Hills and in western North and South Dakota (Goldich and others, 1966) have been largely reset to Proterozoic values of the Trans-Hudsonian event. Ages greater than 2.5 Ga recognized in the Black Hills represent the envelopes of an Archean basement which were thermally insulated and not strongly enough affected during the Trans-Hudsonian event to reset the isotopic composition.

The western limits of the Province are now extended into the Basin and Range region of north-

eastern Nevada where relict Archean ages are reported (Art Snoke, pers. comm. to P.J. Graff, 1990) in the core of the Eastern Humbolt Range of Nevada, and extend to the north through Idaho into southwestern Montana. Here information is masked by younger thermal and structural events, and by younger sedimentary and metasedimentary cover which extends to the north and west. Reed (1987) shows the Archean terrane extending into Canada to presumably join Archean rocks of the northwest Canadian Shield.

The Wyoming craton consists of vast region of relatively unmineralized Early Archean gneiss (maximum 3.4 Ga) and Late Archean granite (2.5 to 2.7 Ga) with interspersed fragments of Middle to Late Archean greenstone belts (2.7 to > 2.8 Ga), mafic complexes (2.7 Ga), and supracrustal terranes dominated by metasediments, gneiss, and amphibolite (2.75 to 3.2 Ga). Much of the significant mineralization in the craton is confined to these metamorphosed sedimentary and igneous belts while intervening gneiss-granite terranes are comparatively unmineralized.

Windley (1979) separated the supracrustal belts of the World's cratons into greenstone belts and high-grade supracrustal terranes. However, Houston (1983) separated the Wyoming Province supracrustal terranes into greenstone belts in the southern portion of the Province, and transitional terranes in the northwestern portion of the craton. The transitional terranes were described by Houston (1983) to exhibit transitional characteristics between greenstone belts and Early Proterozoic metasedimentary successions.

Most greenstone belts and other supracrustal terranes in the Province represent fragments of larger, supracrustal terranes hidden under thousands of feet of Phanerozoic sedimentary rock in the adjacent basins. The term "greenstone" refers to low metamorphic grade (greenschist facies), and "greenstone belt" refers to supracrustal successions of low grade metamorphosed sedimentary and volcanic rock which exhibits a, lower, komatiitic and tholeiitic volcanic sequence overlain by a sedimentary sequence dominated by metagreywacke (Anhaeusser, 1971). The Wyoming Province greenstone belts are of low metamorphic rank ranging from upper greenschist facies to middle amphibolite facies, and contain rock with well-preserved primary textures and structures (Houston, 1983).

Houston's (1983) transitional terranes are belts dominated by intercalated quartzofeldspathic gneiss and amphibolite with metasedimentary packages of banded iron formation (BIF), quartzite, metapelite, and minor metadolomite. These belts are intensely deformed and metamorphism is of relatively high-rank such that primary textures and structures are rarely preserved. Metamorphic grade ranges from lower amphibolite to lower granulite facies and is dominated by middle amphibolite facies.

Many of these belts exhibit similarities to Windley's high-grade supracrustal terranes.

Some belts in the Province are not characteristic of either greenstone belts or high-grade supracrustal terranes. The Hartville uplift near the southeastern edge of the craton, for example, includes thick low-rank metadolomites and well preserved stromatolitic dolomites, with hematite schist, some metapelite, and metabasalt. This belt is more similar to the Proterozoic miogeosynclinal terranes that unconformably overlie the Archean basement in the Medicine Bow Mountains and Sierra Madre. But the relative abundance of metavolcanics compared to metasediments, and the lack of thick sequences of mature quartzites and basal metaconglomerates characteristic of the miogeoclinal terranes are noticeable. The Hartville uplift is more typical of an eugeoclinal terrane.

In general, the Archean rocks of the Wyoming Province consist of relatively unmineralized potassium feldspar-poor gneisses, migmatites, and granitic plutons and batholiths with interspersed isolated greenstone terranes and high-grade supracrustal terranes. The greenstone terranes and related supracrustal belts are generally thought to represent primitive back-arc basins, intracratonic basins, or rifts, and, compared to the gneissic basement, are relatively enriched in metal deposits.

### Greenstone belts

Greenstone belts in the Wyoming craton typically consist of synformal belts of metamorphosed sedimentary, volcanic, and plutonic rocks. The metavolcanics include ultramafic and mafic schists in the lower portions of the belts, and progressively lesser amounts of mafic schists in the upper portions. Metasedimentary rocks are dominated by turbidites and BIF with subordinate argillaceous rock.

The metamorphic rank of the greenstone belts is generally higher than similar terranes in the Western Australia, southern Africa, and Canada, but the rank is still relatively low such that primary textures are preserved. Pillow basalt, amygdaloidal basalt, spinifex basalt, cumulus peridotite, porphyritic andesite, and graded, cross-bedded, and channeled greywacke have all been identified in the Wyoming Province greenstone belts. These belts are dominated by amphibolite facies mineral assemblages with subordinate upper greenschist facies rocks.

Structurally, the greenstone belts are complex, and the various episodes of deformation are difficult to correlate (Hull, 1988; Hausel and Hull, 1990). The belts have been subjected to an early Archean episode of isoclinal folding accompanied by regional metamorphism, followed by a later Archean buckle-type open refolding event, and by a much later brittle event during the Laramide orogeny. In their simplest form, the greenstone belts are tightly folded, doubling

plunging, deep synformal basins, with isoclinal fold axes, foliation, bedding, and Archean shears paralleling the axis of the synform or synclinorium (Graff and others, 1982).

Ultramafic rocks in the greenstone belts include serpentinite, talc-chlorite-tremolite schist, and actinolite schist. Primary textures in many ultramafic rocks have been destroyed, although cumulate textures are preserved in the South Pass and the Seminoe Mountains greenstone belts, and spinifex-textured komatiites are relatively common in the Seminoe Mountains greenstone belt (Snyder and others, 1989). Bulk rock compositions indicate these rocks are similar to aluminum-undepleted peridotitic komatiites from Kambalda, Western Australia. Compositionally, they have CaO/Al<sub>2</sub>O<sub>3</sub> ratios below unity (some of the high-MgO serpentinites have very low ratios interpreted to be due to CaO loss during serpentinitization), and Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> ratios near 20. MgO contents vary from 18 to 38%, with a maximum of 10,100 ppm Cr, and 2,500 ppm Ni (Table 1).

Table 1. Comparison of komatiitic rocks from the South Pass, Seminoe Mountains, and Elmers Rock greenstone belts, Wyoming.

Description	MgO% (ppm)	Cr (ppm)	Ni (ppm)	CaO/Al <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub> /TiO <sub>2</sub>
<u>South Pass greenstone belt</u> Serpentinites	26.6-38	1,700-10,100	860-2,500	0.35	21
Tremolite-talc-chlorite schists	21-32.7	1,400-4,000	289-1,890	0.76	23
<u>Seminoe greenstone belt</u> Serpentinites	26-37	1,900-6,200	810-1,600	0.41	27
Spinifex tremolite schists	7-28.4	150-6,000	60-1,400	0.86	23
<u>Elmers Rock greenstone belt</u>	11-28.4	713-4,900	---	1.25	21

Mafic rocks in the greenstone belts include hornblende-plagioclase amphibolite, tremolite-chlorite schist, metabasalt, metagabbro, chlorite schist, greenstone, and greenschist. Compositionally, these include two suites of metaigneous rock: basaltic komatiites and metatholeiites.

Rocks with basaltic komatiite affinity include tremolite-chlorite schist and hornblende-plagioclase amphibolite. Primary textures are generally overprinted by schistosity, although some of these samples retain spinifex and aphyric textures. These metabasalts are magnesian-rich and compositionally vary from 9 to 18% MgO with relatively high Cr and Ni. CaO/Al<sub>2</sub>O<sub>3</sub> ratios are close to unity (Table 1).

Rocks with metatholeiite affinity include plagioclase-hornblende amphibolite, mica schist, chlorite schist, greenstone, greenschist, and

metabasalt. Locally, plagioclase phenocrysts, amygdules, and pillows are preserved. Chemically, they have tholeiitic affinity and vary from high-Mg basalts to high-Fe basalts. Typically, Ti/V ratios are varied, but average around 25. They are not cogenetic with the komatiite suite, however they share the characteristically low  $TiO_2$  content relative to other incompatible elements, suggesting a Ti-depleted source for both the komatiites and tholeiites (Klein, 1981; Snyder and others, 1989; Hausel, 1991).

Calc-alkaline metavolcanics are less common in the Wyoming greenstone belts, but are present in the upper levels of the belts. At South Pass, these distinctly porphyritic rocks include meta-andesite porphyry and trachyte porphyry.

Turbidites are ubiquitous at South Pass and both proximal and distal facies metagreywacke are present. Bedding in fine-grained metagreywacke is often overprinted by foliation, and fine- to medium-grained proximal facies metagreywacke locally preserves graded bedding, cross-stratification, and channels. Bulk rock compositions for these rocks vary from basaltic to granitic, but average quartz dioritic suggesting derivation from a uplifted ancient felsic terrane (Condie, 1967a; Hausel, 1987). BIF in the greenstone belts consists of alternating layers of magnetite and quartz with grunerite, hornblende, and chlorite. These are typically oxide facies metasediments of probable exhalative genesis. Other less common rocks include quartzite, and metapelite.

Gold and iron are important in the Archean greenstone belts of the Wyoming Province, although other mineral resources are present. Tertiary paleoplacers within and along the flanks of the greenstones enclose giant low-grade gold resources derived from the greenstone terranes. Gemstones are found locally and include aquamarine, ruby, jade, and possibly diamond. In the Deer Creek area and in the Casper Mountain and Elmers Rock greenstone terranes, chromite and asbestos occurs in serpentinite and ultramafic schist. Other metals in the Wyoming greenstone terranes include tungsten, silver, and copper.

### High grade and transitional supracrustal terranes

Some supracrustal successions within the Wyoming Province include thick successions of quartzofeldspathic gneiss and amphibolite with subordinate amounts of quartzite, BIF, metadolomite, and metapelite. Primary rock textures in these terranes have been destroyed by intense deformation and metamorphism, and these appear to be characteristic of Windley's (1979) high-grade supracrustal belts.

Additionally, there are terranes in the Province where rock textures are preserved, and the supracrustal succession is not typical of greenstone terranes. Houston (1983) introduced the term

"transitional terranes" to describe low-rank supracrustal belts with transitional characteristics between Archean greenstone belts and Proterozoic miogeoclinal terranes.

*High-grade terranes.* Due to intense deformation in the high-grade terranes, relict rock textures are seldom preserved. Metamorphism ranges from upper greenschist facies to lower granulite facies but middle to upper amphibolite facies sequences prevail. The protoliths of the thick layered gneiss-amphibolite successions are not readily apparent. In the Copper Mountain district of the Owl Creek Mountains, intercalated quartzofeldspathic gneiss and amphibolite represent a metamorphosed bimodal volcanic suite with associated sediments. The amphibolites include para- and ortho-amphibolites interpreted as metamorphosed greywacke (Condie, 1967b) and LREE-depleted tholeiitic basalts and LREE-enriched basaltic andesites (Mueller and others, 1985). Quartzofeldspathic gneisses of dacitic affinity (Hausel and others, 1985) represent strongly LREE-enriched dacites (Mueller and others, 1985).

In the Tobacco Root Mountains, > 2.75 Ga quartzofeldspathic gneiss is intercalated with amphibolite. The gneiss has calc-alkaline affinity and is chemically equivalent to granite. The presence of rounded accessory zircon leads to the interpretation that some of these rocks represent para-gneiss and are metamorphosed feldspathic sandstones interstratified with minor basalt and rhyolite flows. The amphibolites are tholeiitic (Wilson, 1981).

The central metasedimentary unit of the Copper Mountain supracrustal belt in the Owl Creek Mountains is lithologically diverse. The age of this unit in relationship to the adjacent gneisses and amphibolites is unknown. Structurally, the "metasedimentary unit" lies between two successions of interlayered gneiss-amphibolite and gives the appearance of a steeply dipping homocline. But, the belt is isoclinally folded, and possibly the metasedimentary unit occupies the core of a synform.

This package includes para- and ortho-amphibolite; BIF, fuchsitic quartzite, orthoquartzite, and metapelite, with subordinate gneiss. The BIF includes both grunerite schist and banded magnetite-quartz-amphibole gneiss. Similarly, supracrustals in the Tobacco Root, Ruby, Gravelly, and Madison ranges of Montana include a "metasedimentary sequence" termed the "Cherry Creek Group" by early mappers. Although there is no evidence that the units correlate from one range to another, the metasediments in these ranges are similar and include tonalite gneiss, garnet gneiss, quartzite, schist, BIF, amphibolite, and a thin dolomitic marble (James, 1981).

All of these high-grade gneiss-amphibolite terranes include BIF. The BIF is oxide- and silicate-facies. BIF in the Copper Mountain district of the Owl Creek Mountains varies from 20 to 37 % Fe, but individual units are relatively thin compared to

those in the greenstone terranes. Iron formation in the Tobacco Root Mountains is comprised of magnetite, quartz, orthopyroxene, clinopyroxene, and garnet. The units are relatively thin (< 100 ft). Chemical analyses show values range from 33 to 38 % Fe (James, 1981).

*Transitional belts.* The South Snowy Range block of the southwestern Beartooth Mountains includes a sedimentary package which differs strongly from the high-grade belts in the northern Wyoming Province. Thurston (1986) suggests the belt to be similar to the South Pass greenstone belt in the southern Province based on the anomalous Cr, Ni, and Mg in the metasedimentary rocks. But the lack of tholeiitic and komatiitic metaigneous rocks in the Snowy Range block makes such a comparison tenuous.

The supracrustals are isoclinally folded biotite schist, quartz-biotite schist, metapelite, metaconglomerate, felsic metavolcanics, and BIF metamorphosed to greenschist to middle amphibolite facies at about 2.8 Ga (Thurston, 1986; Stanley, 1988). Later open folds are superimposed on the earlier structures. The metasediments have retained primary sedimentary structures including graded bedding, cross-bedding and cut and fill channels (Thurston, 1986). The BIF is predominantly silicate facies with lesser oxide and sulfide facies and is described as hornblende-cummingtonite-garnet iron formation with quartz stringers, arsenopyrite, and subordinate pyrrhotite and pyrite similar to the Homestake Formation (Seager, 1944; Stanley, 1988). The deposit is interpreted as a folded stratiform deposit (Cuthill and others, 1989).

The Homestake Formation in the Black Hills is Proterozoic (2.0 Ga) and consists of sideroplesite to cummingtonite schist (Nelson, 1986; Redden and French, 1989). The gold mineralization, is stratabound associated with pyrrhotite, arsenopyrite, minor pyrite and chlorite, and concentrated in fold closures. And at least two isoclinal folding events have been recorded (Caddy and Bachman, 1990). The age of mineralization is interpreted as Proterozoic (Caddy and Bachman, 1990; Redden and French, 1990), however, Rye and Rye (1974) reported the mineralization to be approximately 1.6 Ga remobilized from a 2.5 Ga source terrane. More recent lead isotope models would place the 2.5 Ga date closer to 2.0 Ga (Redden and French, 1990).

Another supracrustal belt which includes low-rank metamorphics is in the Hartville uplift along the southeastern flank of the Province. This belt is more typical of the Proterozoic metasedimentary wedges that lie on the Archean basement in the Medicine Bow Mountains and Sierra Madre. The Hartville uplift includes thick successions on metabasalt, metapelite, hematite schist and metadolomite. The belt is tightly refolded by open to isoclinal folds (Snyder and others, 1989; 1990).

More than 11,000 ft of stratified rock are included in four formations in the uplift (Snyder, 1980). The lowermost unit is a 2,700 to 4,500 ft succession of metacarbonate with tremolite dolomite and interlayers of metagreywacke and quartzite. It is overlain by 360 to 4,500 ft of amphibolite, chlorite schist, metabasalt, and pillow metabasalt that are compositionally Mg-tholeiites. Lying on top of the metabasalt is 3,600 to 6,300 ft of schist containing minor interbeds of metagreywacke. The uppermost unit consists of 1,300 ft of siliceous stromatolite dolomite and dolomite containing interlayers of pelitic schist and amphibolite (Snyder and others, 1989).

### Layered mafic complexes

The only major layered mafic complex in the Wyoming craton is the Stillwater complex in the Beartooth Mountains located in the northern Wyoming Province. The complex is 2.7 Ga old and outcrops over an area of 29 miles by 3.6 miles (McCallum, 1988). Magnetic and gravity data suggest the complex continues to the north and east under Phanerozoic sediments (Mogk, 1988). At least two other small complexes intrude the craton in the Bighorn Mountains and in the Laramie Range, but no mineralization is known in these later two layered complexes.

Other layered complexes lie along the southern edge of the craton but within Proterozoic volcanogenic schists and gneisses of the Green Mountain terrane of the Medicine Bow Mountains and Sierra Madre. These complexes (Lake Owen, and Mullen Creek) have potential for Pt-Pd-Au-Cr mineralization and are interpreted to have intruded the Green Mountain schists at 1.8 Ga (Houston and others, 1968).

The Stillwater complex is a major layered mafic intrusion with similarities to the Bushveld complex, South Africa. Zientek and others (1985) divide the Stillwater complex into the Basal, the Ultramafic, and the Banded Series. Each of these series have been further subdivided into compositional layers. The Basal Series is subdivided into a Basal Norite Zone and a Basal Bronzite Cumulate Zone. The Ultramafic Series is subdivided into a Peridotite Zone and a Bronzite Zone. And the Banded Series is subdivided into Lower, Middle, and Upper Banded Zones.

The Basal Series is dominated by bronzite and consists of bronzite cumulates and bronzite plus plagioclase cumulates (Naldrett, 1990). Disseminated and massive sulfides occur in both zones (Page and others, 1985). In the Peridotite Zone of the Ultramafic Series, olivine cumulates usually mark the base of each cycle, and these cumulate layers include chromite-cumulates (chromitite) (Naldrett, 1990). The lower part of the series contains disseminated and massive sulfides (Page and others, 1985). The Banded Series is marked by the ap-

pearance of plagioclase cumulates, and consists of a series of norites, gabbro-norites, and anorthosites. Five separate olivine-bearing zones occur in the Banded Series, and the J-M Reef (PGE deposit) occurs in the lowest olivine-bearing zone of the Lower Banded Zone. The Picket-Pin PGE deposit occurs in the Middle Banded zone (Page and others, 1985).

## Mineralization

### *Gold shears and lodes*

Worldwide, greenstone belts are known for their gold mineralization, such that in many cratons, "greenstone belt" is synonymous with "gold belt". In the South Pass greenstone belt of the Wind River Mountains, the principal Archean gold deposits occur in shears associated with quartz, pyrite, pyrrhotite, and arsenopyrite. Alteration assemblages include chlorite and hematite, with lesser carbonate, sericite, and tourmaline.

The principal Archean gold event is temporally associated with regional metamorphism (Hausel, 1991). Host rocks include metagreywacke, hornblende-plagioclase amphibolite, graphitic schist, meta-andesite, tremolite-actinolite schist, greenschist, and greenstone. Auriferous veins are less common, and occur in metagreywacke, actinolite schist, greenstone, and metatonalite porphyry.

The auriferous shears parallel isoclinal fold axes, lithologic contacts, and regional foliation and vary in thickness from less than 1 ft to as much as 200 ft, and strike lengths vary from tens of feet to more than 11,000 ft. The depths of the shears has not been adequately assessed, and the deepest gold mine is only 400 feet deep and has been drilled to a depth of only 970 ft. At that depth, however, the shear is continuous and carries ore grade mineralization (deQuadros, 1989).

Gold distribution is erratic. Generally, the shears are weakly mineralized with trace Au, with sporadic, structurally controlled, ore shoots that have yielded some exceptional ore. One shoot in the Hidden Hand mine in the South Pass region produced some tonnage yielding as much as 3,100 opt Au. The average ore grades based on historic reports and recent sampling range from 0.06 opt to 2.0 opt (Hausel, 1991).

Additionally, some primary shears are enclosed by low-grade mineralized envelopes. The Carissa shear for example, has widths of 5 to 50 ft with an average grade of 0.3 opt. This shear is enclosed by an 100 to 200 foot wide envelope of fractured and rehealed metagreywacke with abundant quartz veinlets parallel to the primary shear and to regional foliation. A 97 ft wide composite chip sample collected in this envelope assayed 800 ppb Au. Another 30 ft composite averaged 2.4 ppm Au (Hausel, 1989a).

Gold is the principal metal of economic interest in the shears. The noble metal has high Au/Ag, thus Ag is of little importance except in some arsenopyrite-rich zones where Au/Ag is low in favor of Ag. Chalcopyrite occurs in some shears, but appears to represent a later epoch of mineralization. Scheelite is an accessory in some quartz veins, and is also found disseminated in metagreywacke. The tungsten may represent a separate mineralizing event.

Auriferous veins vary from less than 1 ft to more than 50 ft wide. They consist of quartz veins, quartz-carbonate veins, and quartz-carbonate breccia veins. Mineralization varies considerably in the veins, and ore shoots appear to be structurally controlled in fold closures, and in pinches. More than one type of vein is present, and includes veins with high Au/Ag, veins with low Au/Ag, and veins with low Au/Ag and high Cu/Au.

In the Seminoe Mountains greenstone belt, Au occurs in narrow quartz-carbonate veins associated with a broad zone of chlorite-carbonate-quartz-sulfide alteration (Klein, 1981). The gold veins are hosted by metagabbro and chlorite schist of tholeiitic affinity.

In the Tobacco Root Mountains, significant gold mineralization is hosted by Archean rock, although the mineralization was introduced during the emplacement of the Tobacco Root batholith (Cretaceous-Tertiary). Most deposits in this region occur near the contact of the batholith with Precambrian rock and with Paleozoic sediments. A rough zonal distribution of metals is evident. Adjacent to the batholith, is the only significant copper deposit, and lode deposits have relatively high Au/Ag ratios. Farther away from the batholith, deposits generally show lower Au/Ag with Pb and Zn although reversals in the general zonation patterns are present (Lorain, 1937). Some W and Ag veins cut the batholith.

Along the margins of some supracrustal terranes, are widespread Tertiary age fanglomerates and fluvial conglomerates containing vast resources of low-grade detrital gold. For example, in the vicinity of the South Pass greenstone belt are several auriferous conglomerates including one that is estimated to contain a minimum of 28.5 million ounces of gold (Love and others, 1978).

### *Iron deposits and auriferous BIF*

Iron resources occur in many supracrustal terranes in the Wyoming Province in the form of oxide facies BIF. Prior to 1983, the Province was a significant contributor of iron ore in the United States. More than 90 million tons of iron ore were recovered from the Atlantic City mine in the South Pass greenstone belt, and more than 45 million tons were mined from the Sunrise, Chicago, and Good Fortune mines in the Hartville uplift. Auriferous silicate and carbonate facies iron formation have

also been important sources of gold in the Province as well as North America. More than 36 million ounces of gold have been recovered Proterozoic iron formation along the edge of the craton at the Homestake mine (Woodfill, 1983), and more than 200,000 ounces have been recovered from Archean iron formation in the Jardine area (Koschmann and Bergendahl, 1968).

BIF is an important constituent of several metasedimentary successions in the Province. Particularly sizable resources of iron ore occur in the South Pass and Seminoe Mountains greenstone belts, the Ruby Mountains supracrustal belt, and the Hartville terrane. Significant BIF is also found in several other supracrustal belts (Copper Mountain, Barlow Gap, Elmers Rock, Sellers Mountain, Tobacco Root, Madison, Gravelly). For the most part, these rocks consist of finely laminated quartz-rich layers alternating with magnetite-rich layers that generally contain more than 25% Fe. In the amphibolite facies BIF, grunerite, hornblende, and chlorite occur in addition to magnetite and quartz. In granulite facies BIF, pyroxene, garnet and amphibole are common in the mineral assemblage. In the Hartville uplift, iron is contained in massive hematite in schist.

The South Pass greenstone belt has been the most productive terrane in the Province for iron. From 1962 to 1983, more than 90 million tons of taconite were mined from the Atlantic City mine in this greenstone belt. There is no data to support that gold was ever recovered from the BIF, nor is there any evidence that the deposit was ever sampled for gold prior to 1983. The magnetite-quartz BIF was reported by Bayley (1968) to have indicated reserves of 300 million tons (30 % Fe). Generally, the BIF is less than 100 ft thick with an average grade of 33.5% Fe and 50% SiO<sub>2</sub>, but has been structurally thickened fourfold along the northern margin of the belt by internal folding and plication and by repetition of beds by faulting (Bayley and others, 1973).

BIF in the Seminoe Mountains greenstone belt is banded magnetite-quartz iron formation, with lenses of jasperized iron formation, and massive hematite (oxidized BIF). Harrer (1966) outlined a 100 million ton deposit of BIF, and a 200,000 to 1.0 million ton deposit of massive hematite. Samples of hematite yielded 31.4% to 68.7% Fe and the BIF yielded from 28.0% to 44.1% Fe. Typically, the BIF is less than 100 ft thick, although beds up to 800 ft thick have been mapped (Hausel, 1989b).

In the Ruby Range of Montana, the Carter Creek iron deposit represents a sizable resource of BIF. The BIF varies from 24% to 40.2% Fe with an estimated 95 million tons averaging 28.29% recoverable Fe (James, 1990).

Several large pods of massive hematite occur in the Silver Springs schist in the Hartville uplift near its contact with the overlying Wildcat Hills dolomite. These pods include the Sunrise, Michigan, Good Fortune, Chicago, and Central deposits. With

the exception of the Michigan deposit, all of these have been extensively mined.

The Michigan deposit consists of two separate pods of massive hematite with increasing amounts of quartz bands near the upper part of the deposit. At its contact with the overlying Paleozoics, the iron formation is cupriferous. The deposit had been divided into two minable deposits. The north ore body has an estimated 75 million tons at an average grade of 25.3 % Fe, and the south ore body has an estimated 41 million tons averaging 24% Fe (Wilson, undated). In addition to iron, samples collected by the Geological Survey of Wyoming yielded 0.76 to 1.08% Cu, and Woodfill (1987) reported anomalous gold.

South of the Michigan mine several other hematite ore bodies were extensively mined during the past 100 years. The hematite is thought to have formed by groundwater oxidation and enrichment of originally ferruginous beds (Ebbett, 1956; Bayley and James, 1973). Hematite was mined in the region for more than a century until 1981 by both open pit and underground methods. In addition to a minimum of 45 million tons of hematite some copper was also recovered. Anomalous gold (>0.02 opt) has been reported in the ore from the Sunrise and Good Fortune mines, and from numerous magnetic quartzite lenses of the Silver Springs and Muskrat Canyon Formations (Woodfill, 1987).

Essentially, all of the high-grade gneiss-amphibolite terranes in the Wyoming Province contain significant BIF. In the Copper Mountain district of the Owl Creek Mountains, BIF varies from 20 to 37 % Fe, but individual units are relatively thin (Hausel and others, 1985). Iron formation in the Tobacco Root Mountains is comprised of magnetite, quartz, orthopyroxene, clinopyroxene, and garnet. These units are relatively thin (< 100 ft wide), although they pinch and swell along strike, and vary in width from 30 ft to 400 ft. Chemical analysis of the BIF show values to range from 33 to 38 % Fe (James, 1981).

The source of gold in BIF has been described as both epigenetic and syngenetic by various researchers. Rye and Rye (1974) and Hallager (1980) described the gold in the Homestake Formation in the Black Hills and at Jardine in the Beartooth Mountains as syngenetic and to have been remobilized and concentrated in favorable structural sites during later periods of metamorphism. However, Phillips and others (1984) interpret gold in BIF in other cratons to be deposited during periods of peak metamorphic activity by mineralizing fluids of epigenetic origin.

Locally, the BIF in some supracrustal belts has concordant to crosscutting veins of quartz, calcite, and sulfides (pyrite and subordinate chalcopyrite). Few gold assays are available for BIF in the Wyoming Province greenstone belts which is an enigma considering the affinity gold exhibits for iron

(Phillips and others, 1984). Analyses of only a half-dozen sulfide-bearing BIF samples collected from the Atlantic City open pit iron mine in the South Pass greenstone belt contained no detectable gold, although, samples of the same BIF produced anomalies (1.3 ppm maximum) a short distance to the southwest (Hausel, 1987; Hausel, 1991). In the Seminoe Mountains, BIF yields local Au and Ag anomalies (Hausel, 1989a). There are unverified reports of anomalous Au associated with BIF in the Elmers Rock greenstone belt along a facies change from oxide- to carbonate-facies. And in a greenstone-like terrane of the Granite Mountains (Barlow Gap), significant gold mineralization was found in metachert by the Wyoming Geological Survey in 1981, which led to a more extensive exploration program by industry. In this region, mineralized zones were later discovered in BIF. The BIF yielded drill core with 10 ft of 0.3 opt Au. Nearby, Tertiary phonolites were also drilled and yielded 0.024 opt Au over 250 ft.

Auriferous iron formation in the Jardine and Homestake districts show similarities (Seager, 1944). These deposits consist of hornblende-cummingtonite-garnet schist with conformable quartz veins and lenses, and sulfides. The sulfides are predominantly arsenopyrite with subordinate pyrite and pyrrhotite. Gold in the lodes is closely associated with arsenopyrite (Stanley, 1988), and also occurs in quartz-biotite schist, and in quartz bands with scheelite in the Jardine district. The average ore grade of the Jardine deposit is reported as 0.2 opt (Seager, 1944).

Stanley (1988) reports BIF in the Ruby Creek area of the Gravelly Range is anomalous in gold. Based on the available data, BIF in the Wyoming Province should be considered as a high priority exploration target for gold.

#### *Platinum, palladium, chromium, nickel*

Platinum, palladium, and chromite are associated with some ultramafic rocks in the Archean terrane as well as the adjacent accreted Proterozoic terrane along the southeastern boundary of the Wyoming craton. Rocks with komatiite affinity in Archean greenstone terranes have high MgO content and may represent potential sources for anomalous Pt, Pd, Cr, and Ni. However, in the study of ultramafics in the South Pass greenstone belt, Hausel (1991) found only background Ni, Pt, and Pd in these rocks with local weak Cr anomalies. In the Bradley Peak metakomatiites of the Seminoe Mountains greenstone belt, Klein (1981) found similar background levels of Cr and Ni. But in some other greenstone terranes in the Province, weakly to strongly anomalous chromium has been reported.

Some metakomatiites in the Wyoming Province are compositionally similar to nickeliferous komatiite in Western Australia. The Western Australian nickeliferous komatiites are depleted in LREE

and  $\text{TiO}_2$ , and undepleted in alumina (Marston and others, 1981). Unfortunately, REE data are lacking for the Wyoming metakomatiites, so comparisons are limited. Smaglik (1987) reported REE data for five metakomatiites in the Elmers Rock greenstone belt. These rocks have chondrite normalized REE patterns with LREE enrichment. Although, one of two samples with peridotitic komatiite composition produced flat HREE and LREE depletion similar to the nickeliferous Kambalda, Western Australia komatiites.

In the search for nickel anomalies in the South Pass greenstone belt, Hausel (1991) described similar peridotitic metakomatiites to the Kambalda komatiites, although LREE data are not available. The MgO/Cr and MgO/Ni ratios of these rocks indicate the presence of several weak chromium anomalies, although nickel is not anomalous. Thus the possibility of anomalous nickel outside the Stillwater complex appears to be limited.

Ultramafic rocks in the Elmers Rock greenstone belt, and in the Casper Mountain and Deer Creek supracrustal belts have anomalous Cr. In the Elmers Rock belt, disseminated and veinlet chromite was reported by Fields (1963) in serpentinite and talc-tremolite schist in a small area about 200 ft across. These rocks lie in the lower tholeiite-komatiite sequence of the greenstone belt. Samples are reported to assay 0.87%  $\text{Cr}_2\text{O}_3$ , with veinlets containing 9.3%  $\text{Cr}_2\text{O}_3$  (Fields, 1963).

In the Deer Creek supracrustal belt in the northern Laramie Range, approximately, 2,300 tons of chromitite was mined from serpentinite in Deer Creek Canyon during the early 1900s. The ore averaged 35 to 45%  $\text{Cr}_2\text{O}_3$  (Dietz, 1932; Beckwith, 1939). The serpentinite extends several hundred feet to the east and west, and is bisected by Deer Creek Canyon. The chromite occurs in a 2 to 5 ft thick layer associated with kammererite and wolchonskoite (Beckwith, 1955).

At Casper Mountain, chromite occurs as disseminations, pods and lenses in tremolite-talc-chlorite schist (Burford and others, 1979). The schist averages only 2%  $\text{Cr}_2\text{O}_3$ , and contains bands of higher grade rock with 5 to 45%  $\text{Cr}_2\text{O}_3$ . Drilling by the U.S. Bureau of Mines identified a 4.6 million ton resource averaging 2.5%  $\text{Cr}_2\text{O}_3$  to a 95 ft depth (Julihn and Moon, 1945).

A major source of Cr, Pt, and Pd is found in the Beartooth Mountains. The Stillwater complex includes the second largest deposit of platinum-group metals in the world (Stumpf, 1986), as well as 80% of the U.S. reserves of chromium (McCallum, 1988). Commercial amounts of Pt and Pd occur in the J-M Reef of the Banded Series. The reef is 3 to 15 ft thick, extends 20 to 25 miles along strike, and has an ore zone that averages 5 to 6 ppm Pt, and 20 to 24 ppm Pd. The mineralization is in the olivine-bearing troctolite portion of an anorthosite-peridotite-troctolite sequence (Irvine and Sharpe, 1986).

The J-M reef is a horizon within the thickest of the olivine-bearing members, and is relatively enriched in sulfides. The principal sulfides are chalcopyrite, pyrrhotite, pentlandite, and pyrite which texturally form blebs and an interstitial network in the lower part of the reef, and occur as fine disseminations near the top (Naldrett, 1990).

Chromite occurs as olivine-bronzite-chromite cumulates in the Peridotite Zone of the Ultramafic Series. The chromite is found as disseminations in a olivine cumulate and averages about 2% modal chromite, and is concentrated in chromitite layers having as much as 80% chromite (Radakye and McCallum, 1986; Naldrett, 1990).

Platinoids were also mined from 1900 to 1918 along the southern edge of the craton, but within the Proterozoic volcanogenic schists of the Medicine Bow Mountains. In this region are two large layered mafic intrusives of Proterozoic age (1.8 Ga) known as the Lake Owen and Mullen Creek complexes.

The Mullen Creek complex lies along the boundary between the Archean and Proterozoic terranes, and is sheared and intensely deformed. At the turn of the century, some Pt, Pd, Au, Cu, and Ag were mined from shears in hydrothermally altered mafic schist (McCallum and Orback, 1968).

By contrast, the Lake Owen complex to the east of the Mullen Creek complex, is virtually undeformed and unmetamorphosed. Cumulus sulfide mineralization has been identified in at least 12 stratigraphic horizons in the complex with a few horizons containing PGE+Au mineralization in grades greater than 1 ppm (Loucks and Glasscock, 1983).

#### Archean unconformity & massive sulfide deposits

Unconformity deposits occur in some supracrustal belts. In the northern Hartville uplift, the Silver Cliff shaft was developed on five levels on an Archean-Phanerozoic unconformity and in fault gouge of a reverse fault. Available assay reports indicate the ore contained none to 10.88 % Cu, none to 15.04 opt Ag, 0.001 to 3.39% U<sub>3</sub>O<sub>8</sub>, and anomalous gold (Wilmarth and Johnson, 1954). In the southern portion of the uplift, Kerr McGee Exploration discovered a copper-stained Archean-Paleozoic unconformity with cerargyrite, unmgangite, electrum, and native gold.

Massive sulfide deposits are also found in the Hartville uplift. In the central region of the uplift, a geophysical anomaly was detected over a gossan. The anomaly was drilled and the recovered core included 200 to 400 ft of elevated Zn with a 5 ft zone averaging 950 ppm Zn and 0.03 opt Au (Woodfill, 1987).

In the southern portion of the uplift, an extensive gossan at "gossan hill" associated with the McCann Pass fault was prospected in the 1970s. Outcrop and shallow drill holes recovered samples with elevated Cu, As, and Zn. Later drilling in the

1980s intersected 10 ft of 0.8% Zn, and 2 ft of 1.2 % Zn and 0.08 opt Au (Woodfill, 1987).

In the northern Hartville uplift, the Copper Belt area is mineralized over a 1 to 15 ft thickness between the contact of hanging wall dolomite and footwall schist. Ore shoots in the mines yielded 2 to 8 % Cu. The adjacent iron-stained schist contained 0.05 to 0.58 opt Au and 2 to 5 opt Ag (Ball, 1907).

#### Gemstones

Gemstones in the craton include nephrite jade, ruby, sapphire, aquamarine, and possibly diamond. Some of the highest quality jade in the world has been recovered from the southeastern portion of the Province in the Granite Mountains. Jade has also been recovered from the southern Wind River Mountains, Seminoe Mountains, and Laramie Range. The jade is associated with altered mafic and ultramafic dikes and schists, and consists of massive nephrite.

In the same general region, poor quality ruby and sapphire are also found. Although rare, some gem quality rubies have been recovered from the southern Granite Mountains. The ruby is found in Archean mica schist enclosed in nodules of dense sericite. Gem quality aquamarine is reported from several locations including late Archean granitic pegmatite in the southern Wind River Mountains and the Copper Mountain area of the Owl Creek Mountains.

At least 15 Early Devonian diamondiferous kimberlite dikes, plugs, and blows intrude the Proterozoic basement in the southern Laramie Range along the Colorado-Wyoming state line. The diamonds recovered to date include a high percentage of gems and range up 2.5 carats in weight (M.E. McCallum, personal communication, 1990). Similar diamond deposits along the margins of cratons elsewhere in the world are generally subeconomic, whereas some intrusives within the cratons enclose commercial quantities of diamond. Within the Wyoming craton, are some unverified reports of diamond, as well as several kimberlitic heavy mineral anomalies.

#### Summary

The Wyoming Province like several other rich cratonic regions of the world, hosts a variety of mineral resources including a few world class deposits within the craton and along its margin. Many of these deposits are associated with greenstone terranes and with other supracrustal belts. Whereas, the vast sea of Archean granite-gneiss exposed between these metamorphosed sedimentary-volcanic supracrustal belts is relatively unmineralized.

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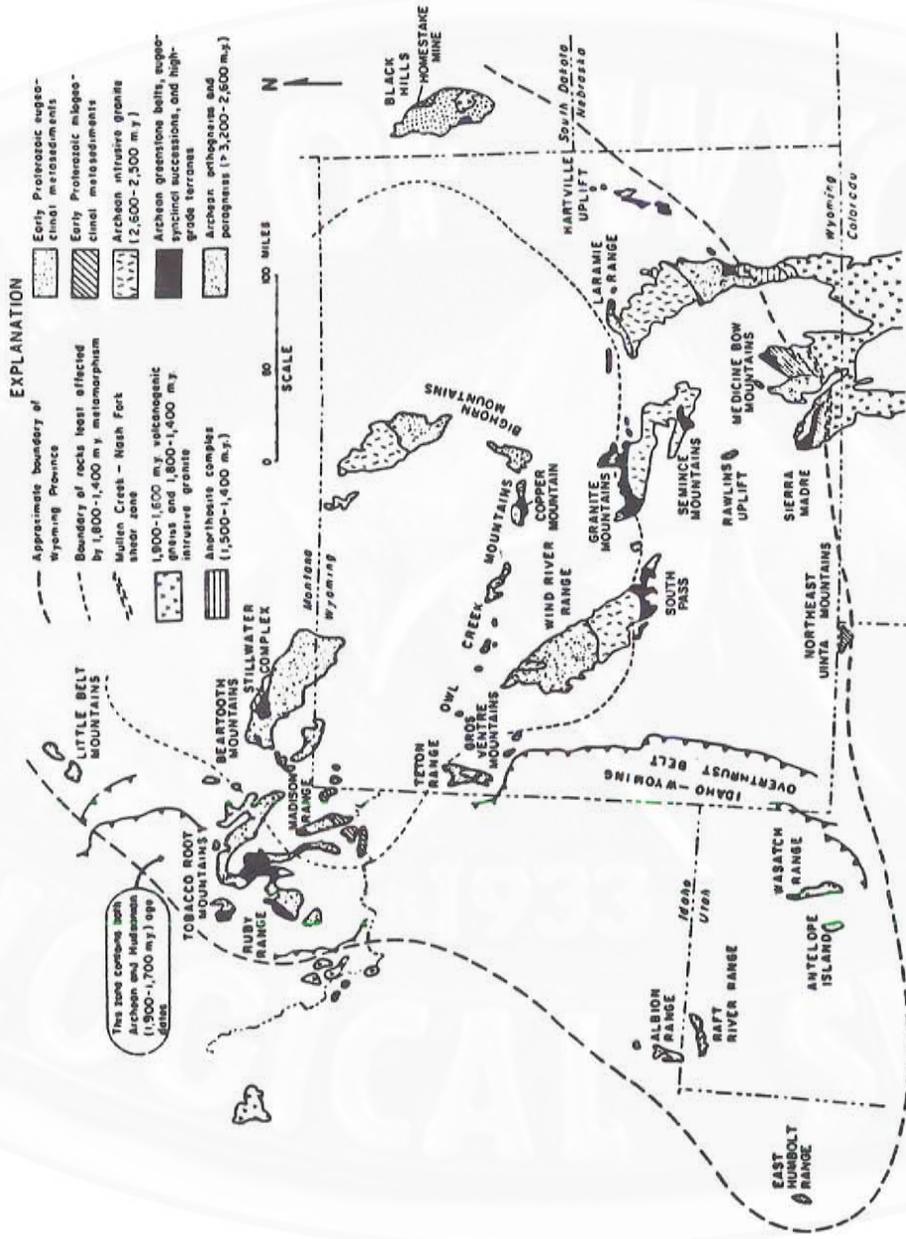


Figure 1. Generalized geologic map of the Wyoming Province (modified from Karlstrom and others (1981) and Houston (1983)).





