GEOLOGY OF THE WORLD'S MAJOR GOLD DEPOSITS AND PROVINCES

A Webinar on SEG Special Publication, No. 23

February 18, 2021
WELCOME

Halley Keevil
Webinar Moderator
SUBMIT A QUESTION

• Find the Q&A button on the control bar and type a question

• Logistical questions will be answered in Zoom

• Questions on the presentation will be answered during the Q&A Session following the presentation (time permitting)
Speakers

Richard H. Sillitoe  Richard J. Goldfarb  François Robert  Stuart F. Simmons
AGENDA

Richard H. Sillitoe – *Introduction*
Stuart F. Simmons - *Porphyry-Epithermal*
Francois Robert - *Carlin & Archean Orogenic*
Richard J. Goldfarb - *Young Orogenic & Others*
Stuart Simmons - *Gold Deposition*

Q & A Panel Discussion
Geology of the World’s Major Gold Deposits and Provinces

Richard H. Sillitoe, Richard J. Goldfarb, François Robert, and Stuart F. Simmons, Editors

Special Publication Number 23
Commemorating the 100th Anniversary of
The Society of Economic Geologists, Inc.
Gold deposit types

- Placer Au
- Reduced Intrusion-Related Au (± Skarn)
- Carlin-Type Au
- Porphyry Cu-Au/Au
- Carlin-Type Au
- Possible Skarn/CRD Au
- Inferred felsic intrusion
- Greenstone
- Turbidite
- Reduced felsic equigranular intrusion
- Shear zone
- Orogenic Au
- GRANITOID
- HS Epithermal Au
- LS Epithermal Au
- VMS Au
- Seawater
- Volcanic rocks
- Carbonate rocks
- Porphyry intrusion
- Inferred felsic intrusion
- IOCG
Gold deposits

[Diagram showing global distribution of gold deposits, with labels for locations such as Hemlo, Timmins, Cripple Creek, Peñasquito, Yanacocha, Paracatu, Loulo, Obuasi, Geita, Kibali, Kisladag, Muruntau, Olympiada, Sukhoi Log, Hishikari, Grasberg, Lihir, Porgera, Telfer, Kalgoorlie, Boddington, and Cadia. Each location is marked with a specific color indicating its type: light blue for orogenic, purple for epithermal, yellow for reduced intrusion related, red for porphyry, and green for Carlin-type. A legend at the bottom identifies these colors and states that disputed deposits are shown in white.]
Gold provinces

- Nevada Carlin-Type
- Abitibi
- Birimian
- Witwatersrand
- Eastern Goldfields
- Jiaodong Peninsula
- Kolyma Placers
Kışladağ  
Grasberg  
Cadia  
Brucejack  
Peñasquito  
Cripple Creek  
Porgera  
Lihir  
Yanacocha  
Pueblo Viejo  
Round Mtn  
Fruta del Norte  
Hishikari

West Tethyan Magmatic Belt  
Irian Fold & Thrust Belt  
Macquarie Arc  
Canadian Cordillera-Golden Triangle  
Sierra Madre Occidental  
Front Range Rocky Mtns  
Papuan Fold Belt  
Tabar-Feni Island Chain  
Peruvian Andes  
Greater Antilles Arc  
Southern Great Basin Ignimbrite Province  
Cordillera del Cóndor  
Ryukyu Arc

Intrusion-related: Porphyry to Epithermal Deposits

Hishikari

Fruta del Norte

Brucejack

Pueblo Viejo

Yanacocha

Round Mountain

Peñasquito

Kısladağ

Grasberg

Cadia

Brucejack - Golden Triangle

Peñasquito - Sierra Madre Occidental

Cripple Creek - Front Range Rocky Mtns

Porgera - Papuan Fold Belt

Lihir - Tabar-Feni Island Chain

Yanacocha - Peruvian Andes

Pueblo Viejo - Greater Antilles Arc

Round Mtn - Southern Great Basin Ignimbrite Province

Fruta del Norte - Cordillera del Cóndor

Hishikari - Ryukyu Arc

Porphyry

Hybrid

Alkaline

High sulfidation

Low sulfidation
Porphyry to Epithermal Deposits: Age & Period
Alteration, Mineralization, and Age Relationships at the Kışladağ Porphyry Gold Deposit, Turkey

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Grasberg Copper-Gold-(Molybdenum) Deposit: Product of Two Overlapping Porphyry Systems

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Grasberg Copper-Gold-(Molybdenum) Deposit: Product of Two Overlapping Porphyry Systems
Grasberg Copper-Gold-(Molybdenum) Deposit: Product of Two Overlapping Porphyry Systems
Geologic Evolution of Late Ordovician to Early Silurian Alkaline Porphyry Au-Cu Deposits at Cadia, New South Wales, Australia

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[Diagram with geological features and legends: Tertiary basalt, Wauigoolo Group (Silurian), Cadia Intrusive Complex, Ridgeway intrusive complex, Weemalla Formation, Volcaniclastic rocks, basaltic anesites, Magnetite skarn, Feldspathic laminated siltstones/basalt, Faults, Bedding]
The Brucejack Au-Ag Deposit, Northwest British Columbia, Canada: Multistage Porphyry to Epithermal Alteration, Mineralization, and Deposit Formation in an Island-Arc Setting

Warwick S. Board,¹ Duncan F. McLeish,² Charles J. Greig,³ Octavia E. Bath,¹ Joel E. Ashburner,¹ Travis Murphy,¹ and Richard M. Friedman⁴

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The Peñasquito Gold-(Silver-Lead-Zinc) Deposit, Zacatecas, Mexico

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Epithermal Gold Deposits Related to Alkaline Igneous Rocks in the Cripple Creek District, Colorado, United States

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Geology of the Porgera Gold Deposit, Papua New Guinea

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Lihir Alkalic Epithermal Gold Deposit, Papua New Guinea

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Gold Deposits of the Yanacocha District, Cajamarca, Peru

Richard Pilco† and Sean McCann

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The Pueblo Viejo Au-Ag-Cu-(Zn) Deposit, Dominican Republic

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Map and diagram showing geological features and timelines relevant to the Pueblo Viejo deposit. The map includes labeled points such as Monte Negro pit, Moore pit, and Cumbe fault. The diagram illustrates timelines for various geological events, including subduction of oceanic crust, formation of the calc-alkaline arc, and metamorphism ages. The diagram also marks specific mineral deposits such as Pyrite, Enargite, and PV.
Geology of Round Mountain, Nevada: A Giant Low-Sulfidation Epithermal Gold Deposit

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Figure 3B, view NW, toward 310 azimuth

Au mineralization outlines
- >0.04 Oz/t (1.13 g/t)
- 0.015-0.04 Oz/t (0.43-1.13 g/t)

16.8 g/t 8.4 g/t
Geology of the Fruta del Norte Epithermal Gold-Silver Deposit, Ecuador

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Geology of the Hishikari Gold Deposit, Kagoshima, Japan

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Porphyry to Epithermal Deposits: *Footprints of Ore Bodies*

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<td>Round Mountain</td>
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<td>Yanacocha</td>
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Porphyry to Epithermal Deposits: Depth & Interval
Carlin & Archean Orogenic

Francois Robert
Carlin deposits in Nevada (Muntean)

Prolific N Central Nevada
- **250 Moz** in 250 x 300 km
- Major production center: ~4.5 Moz/y

Well-known characteristics
- Replacements & breccias in silty carbonate
- Au in As-pyrite rims; As-Hg-Sb-Tl-Ba
- Eocene, low-T and shallow crustal depth

Unique regional setting
- Precambrian deep crustal architecture
- Favorable Eocene tectonics

Large deposits along 4 Trends
- Deep structures and magma conduits in J, K, E
- Eocene Carlin and Miocene epithermal

Link with deep processes, heat source and gold source?
Goldstrike (Dobak et al.)

58 Moz @ 6 g/t Au
- Largest and type example
- 4.5 x 2 km within 20 x 40 km thermal anomaly

Unique pre-mineral structural confluence
- Trend-parallel J lamprophyre dike swarm
- Intersection of swarm with reef
- J stocks at intersection

Favorable sedimentary units
- Debris flows shedding from exposed reef
- Reactive rocks with elevated available Fe

Deep Post - 27 g/t
Screamer – 11 g/t

North Carlin trend

Goldstrike 58 Moz
Debris flow apron
Reef
Apron

3 kilometers
Cortez district (Bradley et al.)

District = 47 Moz
- 3 deposits >10 Moz
- Goldrush: 11.3 Moz @ 9.5 g/t; >5 km x ~400m

Typical Carlin characteristics
- Collapse bx to passive replacements
- From compact bx pipe to long linear zones

Controls
- EQ strata to Goldstrike: units with debris flow
- Open anticlines and thrusts
- K and J stocks and metamorphic haloes

Cortez Hills Breccia - 40.7 g/t
Goldrush - 32.8 g/t
Archean deposits: paleoplacer and greenstone gold

Provinces
- Witwatersrand, Abitibi, Eastern Goldfields

Camps
- Timmins (Hollinger-McIntyre, Dome)
- Malartic (Canadian Malartic)
- Golden Mile (Mt Charlotte, Fimiston)

Deposits
- Orogenic: Hollinger-McIntyre, Dome, Geita, Kibali, Mt. Charlotte
- Atypical: Boddington, Canadian Malartic, Fimiston, Hemlo

Greenstone gold highlights
- Atypical deposits remain enigmatic
- Diversity and multiple ages recognized
- Overprinting of types in many deposits
Witwatersrand Goldfields (Frimmel and Nwaila)

Syngenetic origin proposed
- Initial fixation on microbial mats
- Reworking in fluvial channels & eolian deflation surfaces
- Subsequent local hydrothermal modification

Supporting evidence
- Sedimentologic controls across scales
- Grade vs clast size correlation
- Mechanically deformed Au micro-nuggets with secondary Au overgrowths

Uniqueness
- Exceptional preservation of possibly more widespread Mesoarchean process
Abitibi Province (Dubé and Mercier-Langevin)

New synthesis of geology, evolution and gold

- Chronostratigraphic map
- Well-constrained evolution

Documents range of deposit types and ages

- Sulfidic (Au-VMS), intrusion-associated, orogenic
- Formed over ~90 my of Abitibi evolution
Timmins-Porcupine camp (Dubé et al.)

70.5 Moz; mainly orogenic qz-cb veins
- Hollinger-McIntyre = 33 Moz @ 9.5 g/t
- Dome = 17 Moz @ 4.8 g/t

Multiple Au styles and ages
- Dominant syn-shortening orogenic qz-cb veins
- Pre-unconformity ankerite veins (low Au)
- Pre-shortening Cu-Mo-Au porphyry

Updated stratigraphic / structural framework
- Folds, competency contrasts, anisotropy
- Unconformities marking favorable erosional depth
Malartic camp (De Souza et al.)

32.5 Moz; mainly disseminated-stockwork
- Canadian Malartic = ~18 Moz @ 1 g/t

Canadian Malartic characteristics
- Sediment-hosted, monzonite-associated
- Disseminated-stockwork/sheeted
- K-spar-carbonate alt’n
- Au-Ag (+/-Te, W, Bi, Mo, Pb)

Timing constraints
- Controlled by D₂ structures, cut by orogenic qz-cb-tm veins

Interpretation
- Syn- orogenic (D₂) deposit stockwork-disseminated
Hemlo (Poulsen et al.)

26 Moz @ 4.74 g/t

Characteristics
- Marginal to felsic porphyry in clastic rocks
- Disseminated-stockwork mineralization
- Au-Mo (V, Ba, Hg, Sb, Te)
- Feldspar (K, Na) + sericite alteration
- Highly strained with deformed post-ore dikes
- Overprinted by minor orogenic qz-cb veins

Interpretation
- Deformed/metamorphosed high-level system
- From oxidized hydrothermal fluid
Kibali district (Allibone et al.)

23 Moz; ironstone replacement
- KCD = ~20 Moz @ 4.1 g/t

Characteristics
- In chert-magnetite BIF within clastic sequence
- Veinlet and replacement pyrite in BIF
- Proximal siderite-py-silica in BIF
- Broad halo of sericite-carbonate in host rocks
- Ore in hinges of stacked shallow-plunging folds
- Ore shoots +750 m down-plunge

Interpretation
- Typical BIF/Ironstone-hosted orogenic deposit
- Typical ore: py-sid-qz and ghost BIF
Geita district (Dirks et al.)

District = 15 Moz; ironstone replacement

Characteristics
- In chert-ironstone units & intruding diorite complex
- Py-qz veinlets/replacements in ironstone & diorite
- Biot-carb alteration in clastics; K-spar-Fe carbonate in diorite
- Controls: shear-BIF intersections, fold hinges

Interpretation
- Classic ironstone-hosted (late) orogenic deposit
Eastern Goldfields Province (Tripp et al.)

Updated synthesis - Kalgoorlie district as example
- 2 unconformities separating 3 sets of folds
- Improved framework for gold setting

Diversity of deposit styles and ages
- “Early” high-level: Kanowna Belle, Binduli, Golden Mile
- “Late” orogenic veins: Kundana, Mt Charlotte

Importance of unconformities
- Depth and time markers for gold
Kalgoorlie gold camp (McDivitt et al.)

~75 Moz; Golden Mile = 57 Moz produced

Fimiston / Oroya lodes:
- Carb-qz-py veins & breccias; crustiform-colloform
- Accessory sulfosalts, anh, mt, hm
- Au-Te-Ag (Hg, Mo, Sb, As), +V in Oroya

Mt Charlotte
- Late quartz-carbonate veins; Au-Ag only

Interpretation
- Fimiston/Oroya: oxidized magmatic-hydroth
- Mt Charlotte: typical late-stage orogenic
Boddington Au-Cu deposit (Turner et al.)

30.4 Moz @ 0.74 g/t (~0.10% Cu)

Characteristics
• Mainly diorite-hosted
• Fracture/veinlet stockworks – multiple stages
• Cu-Ag-Mo +/- Bi, W, Te
• Orogenic veins also present

Interpretation
• Protore of early Mo-Cu “dioritic” porphyry
• Orogenic veins
• Bulk of Au-Cu: late-orogenic high-T, magmatic-hydrothermal

Early quartz-molybdenite in biotite-albite alteration

Late chlorite-sulfide – bulk of Au-Cu

Orogenic quartz vein
Archean greenstone gold summary

Orogenic deposits
• Coherent group of deposits
• Well-defined characteristics
• Localization controls well understood

Atypical deposits
• Disparate group but...many show
  – Stockwork-disseminated ore & proximal feldspar alteration
  – Te, Mo, Cu, V, Hg, Sb; +/- sulphates, mt, he
  – Multiple hydrothermal stages
  – Overprinting strain and orogenic veins
• Formed early and preserved? “oxidized” Associated with pre-shortening intrusions
• Recurring “oxidized” flavor

Exploration considerations
• Camp-scale framework critical for targeting
• Unconformities important markers
• Range ore styles, signatures and controls
• Hydrothermal overprinting & complexity
• Supergiants can be unique and freaks
Young Orogenic & Others

Rich Goldfarb
GOLD DEPOSITS IN METASED TERRANES: PROTEROZOIC & PHANEROZOIC
GOLD IN METASEDIMENTARY TERRANES
(extroverted & introverted oceans)

2.15-1.75 Ga
700-30 Ma
KEY FEATURES OF METASED. GOLD
METAMORPHIC SETTING
(Rarely Metamorphosed)

Greenschist facies
$\text{CO}_2$, $\delta^{18}$O rich
3-15 km, 220-450°C

PHYSICAL & CHEMICAL TRAPS

Mod. from Newberry & Brew, 1986
• Ca. 2160 Ma; Tarkwa source?
• Jogs, intersections, contacts (2110-2095 Ma)
• Tectonic switch: Contraction, basin inversion, mm & fault reactivation; then transpression (SW Ghana)
• Post collision K-magmatism, thermal aureole Au (Morila, Loulo; 2060 Ma)
OBUASI
(Oliver et al)

- 70 Moz; 8 km long, >2.5 km depth
- 2135-2115 Ma gwk & carb. phyll
- Inverted basin margin faults (plumbing)
- 2095 Ma Au & mm
- Early deformation & Au
- Mm model (but strange flincs)
- Carbonaceous material (fertility)--S, As, Au source
- Multiple Au events: D2, D4, D5 (and/or remobilization from early aspy)
LOULOU DISTRICT (Allibone et al)

- 250-km-long belt, 2nd most endowed area of W. Africa
- Loulo District=>17Moz in 2120-2110 Ma clastics±carb, evap
- D1 folding/reverse faulting; D2 transpression
- 2120-2070 Ma albite, carbonate, tourmaline pre-Au alteration

- 2090-2060 Ma batholith & Fe skarns
- Gold is late D2 (2070-2060 Ma)
- No regional Mali-Senegal shear zone
- Mm devol model BUT mixing of two fluids (contact mm Au?)
- Shoots where local shears intersect gentle folds in areas of early alteration
TELFER (Wilson et al)

- >20 Moz Au (0.75 g/t); 0.7 Mt Cu (0.12%)
- Pre-650 Ma folds (D1-D3) & doming
- 650-600 Ma transpression (D4-D6)
- 645-605 I & S reg magmatism; cp-bearing dike in deep core
- Qtz-dolo-py-cp veins and stockworks in >20 stacked reefs in dome fold hinges
- Mx in silty units between thick quartzites
- Pyrite±cp as matrix to brecciated quartz
- High salinity, 85% CO2 fluids

- High Cu, Cu:Au zonation, jasperoid, large footprint=unusual RIRGD
- Fluids exsolved over 40 m.y. from large buried batholith
PARACATU (Oliver et al)

- Brasilia fold belt; 1.0 Ga carbonaceous phyllite (gs facies) thrust over passive margin carbonates
- Ca. 630 Ma Au; predates much of ductile deformation
- Subhorizontal orebody with 15 Moz @0.4 g/t
- No igneous rocks
- “Half-way house” of elements: Si, Ca, & Sr are local
  H-O-S-C-Au-As are far-traveled
SUKHOI LOG (Vursiy et al)

- 63 Moz (>120 Moz Lena prov)
- Neoprot-Cambrian passive margin seds; E Pz terranes accrete
- 1960s=first metamorphic models
- Anticlinal dome in regional syncline
- Ores in highly carbonaceous clastics between competent carbonate along shears in axis for 5 km strike
- Many generations of auriferous pyrite with qtz rims; unique textures
- Complex genesis; ages spread from >600 Ma to 300 Ma for mm, mag, and Au; multiple events
OLYMPIADA
(Sazonov et al)

- 50 Moz@4-4.5 g/t
- Province=100s Moz
- 700 x 200 km Neoprot orogen
- Sheared anticlinal closure near major suture
- In amphib facies carbonaceous schist near carbonate contacts
- Aspy>po>>>py
- Late sulfosalts, stibnite, native Sb, aurostibite, tellurides
- 817-660 Ma mx events (150 my)?
- Mantle association?
GIANT PLACERS, NE RUSSIA (Goryachev et al)

- Upper Kolyma watershed with huge lode potential (>200 Moz lode+placer)
- 136-125 Ma strike-slip and lode Au in Kular-Nera flysch of Kolyma & Allakh-Yun of S.Verkhoyansk craton margin; reactivated Jurassic thrusts
MURUNTAU
(Seltmann et al)

- 170 Moz Au (3.5-4 g/t)
- Camb-Ord flysch deformed pre-300 Ma
- Left-lateral movement on splays and magmatism in large jog (300-275 Ma)
- Qtz-KF stockworks in large hornfels zone
- Fault intersections along plunging anticlinorium nose
- Carbonate seal?
- Bt, KF or albite, dolomite, aspy, py, po, scheelite; late Sb, Te
- Ages of mx 370-220 Ma; likely ca. 288 Ma—late defm
- MM vs TAG vs Mantle genetic models
JIAODONG (Qiu et al)

- 150 Moz (2 Moz/yr)
- Archean & Pprot blocks
- 165-145 Ma batholiths; scattered 130-122, 119-110 Ma plutons
- Gold=ca. 120 Ma along margins of Jurassic batholiths exposed as MCC
- Young Au in old terranes & Au in extensional setting
- Mm model (subduction) or magmatic model or unique decretionization model?
- Classification?
EXPLORATION CONSIDERATIONS IN METASEDIMENTARY PROVINCES

• Unlikely isolated deposit (e.g., West Africa, Lena, Baikal, So. Tien Shan, Yensei Ridge); Large h-g oxide zone (Olympiada) or favorably oriented very l-g ore body (Paracatu) may be critical for a project’s success
• Fault reactivations, basin inversions, changing stresses needed for fluid focusing
• Carbonaceous sedimentary sequences associated with giants (source?, trap?)
• Early timing (Paracatu, Obuasi) to late timing (Loulo, Kolyma) or perhaps just many tens of millions of years (Sukhoi Log? Olympiada? Muruntau?)
• Structures=jogs, fold noses, fault intersections, complex settings (Muruntau, Sukhoi Log, Jiaodong)
• Competency contrasts: Stratigraphy (Telfer), Hornfels (Muruntau), Pre-ore KF (Jiaodong), Pre-ore albite (Loulo)
• Magmatism: Almost always syn-Au but none at Paracatu
• Metamorphism: Consistent greenschist but not at Jiaodong
• Genetic model: Metamorphic? Magmatic? Maybe a local model on observed geology is always best
Gold Deposition

Stuart Simmons

Richard H. Sillitoe, Richard J. Goldfarb, François Robert, and Stuart F. Simmons, Editors

Special Publication Number 23
Commemorating the 100th Anniversary of
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Metal precipitation is the ultimate & most important event, producing ores & geochemical anomalies.

Similar thermal & chemical characteristics permit comparison of Au depositing processes across all three deposit types.

Analysis
- experimental data
- metal transport-deposition in modern hydrothermal systems
- mineralogical-geochemical-geological context of gold orebodies.
Gold solubility in sulfidic hydrothermal solutions

320 mg/kg H₂S
7000 mg/kg Cl

300°C
Gold solubility in sulfidic hydrothermal solutions

Optimal pH (near neutral)
Redox State (reduced S)

320 mg/kg H₂S
7000 mg/kg Cl
Gold deposition from sulfidic hydrothermal solutions

- Wells: 15-30 cm diameter, 50 to 150 kg/s, 1-3 km deep
- chalcopyrite scale: 60,000 ppm Au, >100,000 ppm Ag
- Solution: 1 ppb Au, 8 ppb Ag

Brown, 1986 Economic Geology
Gold deposition from sulfidic hydrothermal solutions

Orogenic quartz vein
Sigma, Quebec

Low-sulfidation epithermal
Fire Creek, Nevada
Gold deposition from sulfidic hydrothermal solutions

Champagne Pool, Waiotapu

Au deposition via chemisorption

Chloride water: 74° C
pH ~5
2000 ppm Cl
3 ppm H_2S
0.10 ppb Au
0.02 ppb Ag

Au & Ag deposit on As-Sb-S rich colloids
540 ppm Au
750 ppm Ag

Pope et al, 2005 Economic Geology
Gold deposition from sulfidic hydrothermal solutions

For Carlin ores, Au deposits on to As-rich pyrite rims due to chemisorption.

The evidence is supported by high magnification elemental maps & microbeam analyses.

Simon et al., 1999; Reich et al., 2005; Barker et al. 2009; Deditius et al., 2014.
Predominant Mechanisms of Au Deposition

Epithermal Ores
  –phase separation (boiling)
  –mixing

Carlin Ores
  –sorption of ionic Au on to the surfaces of As-pyrite

Orogenic Ores
  –phase separation
  –pyritization (sulfidation) via water-rock interaction
  –reduction via interaction with graphitic rocks
  –co-precipitation As-pyrite & arsenopyrite
Ore body geometries/dimensions
Fluid flow rates/directions
Duration of mineralization (repeated/long lived mineralization)
• Descriptive papers on 29 important deposits & 7 major provinces
• Manuscripts authored by industry & research geologists
• Mature mining districts to recent discoveries
• Exploration histories
• Geological context
• Ore body geometries
• Structural & Lithological controls
• Mineralogical & geochemical associations
• Maps, sections & field/rock/mineral photos
• Comprehensive list of references
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