Primary gold production in India is only up to 4 tons per annum, barely 0.4% of its annual gold consumption. However, India holds 9% of the available global gold reserves that is estimated at about 14,000 tons (IGCP-540 Report 2011). Currently, in India, primary gold is produced mainly from the world class orogenic-type Hutti gold deposit in the Archaean Hutti-Maski greenstone belt in the eastern Dharwar Craton (EDC). The world famous Kolar gold deposit in the Kolar greenstone belt had produced about 800 tonnes of gold before its closure in 1998. Other gold-hosting greenstone belts in the EDC include Sandur, Ramagiri, Jonnagiri, Kushtagi, Magalur, Gadag, Kadiri, and south Kolar belts. All of these deposits fall into a single type deposit called ‘orogenic’ gold deposits. These are epigenetic, structurally controlled, shear zone-hosted lode gold quartz-carbonate vein systems associated with regionally metamorphosed and deformed terranes.

Orogenic gold deposits collectively account for significant amount of world gold (more than 25000 tons gold) production. There have been worldwide intense studies on these deposits, for the past three decades, on various aspects of regional-and mine-scale structures, host rock metamorphism, ore mineralogy, alteration geochemistry and physico-chemical conditions pertaining to nature and evolution of the ore fluid, and transport-precipitation mechanisms of gold. Ore fluid compositions in orogenic gold deposits are very well understood from wide range of fluid inclusion, petrological and geochemical studies. A comprehensive review shows that the nature of ore fluids responsible for Archaean lode-gold systems are generally neutral to weakly alkaline, low–moderate-salinity aqueous-gaseous with high CO$_2$ (+CH$_4$) (0.05–0.25 X$_{CO2}$) for deposits ranging from sub-greenschist to upper-amphibolite facies conditions, capable of carrying Au, Ag, As and Sb but with limited capacity to transport base metals. In spite of all these studies the source of gold-carrying fluids and controls on its composition still remain potential unknowns.
Ore Fluid Characteristics of Orogenic Gold Deposits: An Overview

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Gold-only Deposits in Metamorphic Terrains

- Geographical terms: Motherlode-, Homestake-, Korean-types
- Host rock terms: Turbidite-, Slate-, BIF-, Greenstone-hosted
- Depth & temperature terms: Mesothermal
- Mineralization style terms: Vein-type, Stockwork, Replacement
- Shear zone-hosted
- Archaean lode gold

‘Orogenic Gold deposits’ (Groves et al. 1998 Ore Geol Rev)

Epigenetic, structurally controlled lode gold quartz-carbonate vein systems associated with regionally metamorphosed/deformed terrenes

‘Mesothermal’ (Lindgren, 1933) deposits formed at about 1.2–3.6 km, is more applicable to sedimentary rock-hosted ‘Carlin-type’ deposits and the gold porphyry skarn environment (Poulsen, 1996)
Along convergent margins → terrain accretion or collision related to subduction and/or lithosphere delamination (Groves et al 2003: Econ Geol), late in the metamorphic-magmatic evolution of the orogen (Groves et al 2000: Ore Geol Rev)
Crustal Continuum Model (Groves 1993, Min Dep)

(Goldfarb and Groves 2015, Lithos)
Zoned alteration halos

DEPOSIT
wallrock reactions
Au deposition

CONDUIT

FLUID
FOCUSING

SOURCE ROCK

(< a few km)

10's of metres

Quartz vein / lode

(Modified from Ridley et al 1996, Ore Geol Rev)
Orogenic Gold deposits: Key components

Tectonic Setting
Convergent plate margins-subduction zones (Oceanic-Continental plate interaction)- Accretionary orogens

➢ Structural style
On regional scales association with first-order trans-crustal structures ← in district/ mine scales the gold deposits are hosted in subsidiary geometrically related second- or higher-order splays such as brittle-ductile or brittle faults reflecting regional stress orientations → ore localization dictated by brittle-ductile shear structures, frequently producing more than two generations of veins, such as D₂/D₃ in a D₁ to D₄ sequence. HENCE, which vein(s)?

➢ Metamorphism of the host rocks vis-à-vis granitoid emplacement
Timing of fluid focusing and mineralization
   Syn- to post-metamorphism and post granitoid (gold-hosting) emplacements

Alteration geochemistry (gain/loss of elements + changes in mass/volume of the shear zones)
   Depends on the host rock composition and temperature (of alteration)

Source of water, carbon, sulfur and gold
   Fluid source - metamorphic lower crustal (?) ; S & Au: Mantle (Contradictory). However, Inexplicable consistency in the compositions of ore fluid and sulfur isotopes in all deposits

Nature of ore fluid and its evolution, with emphasis on transport and deposition of gold
   $\text{H}_2\text{O-NaCl-CO}_2\pm\text{CH}_4\pm\text{N}_2$, Low-moderate salinity
Fluid Characteristics

Two sources of information:

1. Direct analysis of Fluid Inclusions in minerals
   Microthermometry, Raman Spectrometry
   LA-ICP-MS

2. Calculations from chemical and isotopic analysis of the coexisting hydrothermal minerals in veins and proximal zones
Fluid Characteristics

Fluid Inclusion Assemblages (FIA) or Group of Synchronous Inclusions (GSI)

- Single or multiple ore forming/deformation events
- Although primary inclusions are examined, secondary inclusions also important for bulk gold forming event at later stage

**Ore Fluid: H₂O-NaCl-CO₂-CH₄ Low saline**

- $X_{\text{CO}_2} = 0.10$ to $0.25$ with minor CH₄ and trace to minor N₂
- Salinity: 3–7 wt.% NaCl equivalent
- Salinity generally is defined by Na>K>Ca and Mg, although precipitation of muscovite or K-feldspar from such a fluid will be favored over paragonite or albite because of the greater super saturation of K relative to Na
- Near-neutral pH of about 5.5 at moderate (ore-forming) temperatures.
Fluid Characteristics

Ore fluid compositions from different gold deposits types with respect to molar proportions of $\text{H}_2\text{O}$, $\text{CO}_2$ and salinity (wt% NaCl equiv, expressed as molar proportion). Ridley and Diamond (2000) Rev. Eco. Geol
Fluid Characteristics

Significant amounts of $\text{H}_2\text{S}$ are main carriers of the gold and varies from 0.01 and 0.36 mol%.

Reduced state of sulfur is consistent with an ore-fluid redox state that is normally more reducing than the Hem-Mt buffer.

Hydrogen, ethane, propane etc are reported rarely. Up to 6 mol% $\text{H}_2$. These products are reaction between C-O-H volatiles within the FI due to drop in P-T during uplift of ore fluid.

Various studies of orogenic gold deposits around the world have shown enormous variability from almost pure $\text{H}_2\text{O}$ to almost pure $\text{CO}_2$ to very $\text{CH}_4$-rich fluid inclusions.
Stable Isotopes

To define sources for oxygen, hydrogen, carbon, sulfur, and nitrogen → Source of fluid

However, interpretation of stable isotope data has a number of problems.

(1) fluid–rock interaction along the flow path

(2) fluid–rock interaction at the sites of ore formation

(3) overlap of isotopic values for different source areas

(4) uncertainties in permissive isotopic ranges for specific source areas.

As orogenic gold deposits are generally associated with massive fluid flow along a fault conduit, the first problem is significant during early fluid release at depth and initial hydro fracturing. Once fluids are channelized along main faults, the hydrothermal system is highly fluid-dominant and significant exchange along the flow path is unlikely. Thus, fluid $\delta^{18}O$ ratios are unlikely to undergo significant modification along the pathway.
## Stable Isotopes

<table>
<thead>
<tr>
<th></th>
<th>Archean</th>
<th>Proterozoic</th>
<th>Phanerozoic</th>
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<tr>
<td>$\delta^{18}\text{O}$</td>
<td>+6 to +11‰</td>
<td>+6.5 to 12‰</td>
<td>+7 to +13‰</td>
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<tr>
<td>$\delta^{13}\text{C}$</td>
<td>-11 to +2‰</td>
<td>+1.5 to 10‰</td>
<td></td>
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<tr>
<td>$\delta^{15}\text{N}$</td>
<td>+10 to +24‰</td>
<td>+1.5 to 10‰</td>
<td></td>
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<tr>
<td></td>
<td>(Neoarchean)</td>
<td>(Paleoproterozoic)</td>
<td></td>
</tr>
<tr>
<td>$\delta^{34}\text{S}$</td>
<td>Varying (-20 to +25‰)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta\text{D}$</td>
<td>Varying (-20 to -80‰)</td>
<td></td>
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</table>
Source Models

1. **Magmatic-hydrothermal model**: Magmatic fluid originating from extensive regional or specific granitic associations.

2. **Metamorphic devolatilization model**: Metamorphic devolatilization during prograde, regional metamorphism of the greenstones.
Jonnagiri- Many Questions

- Why the mineralization is exclusively localized in the granitoids?
- The challenge → to distinguish the granitoid-hosted orogenic gold with that of intrusion-related deposits
- Uncertainty on source(s) of the ore fluid-the role of magmatic fluid?
- Less known on genetic aspects ← compared to those in the greenstones
Chinnasamy and Mishra (2013) Eco Geol
Dona Shear

Sh₁: 103°/84°S
Sh₂: 168°/58°W
Borehole logs

Dona East Block

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- **S 80°W (RL - 418.987 m)** JD51
- **N 80°E**
- **RL(m)**
- **242**
- **280**
- **320**
- **360**
- **400**
- **420**

**Legend:**
- Soil
- Quartz vein
- Granodiorite
- Sheared granodiorite
- Auriferous zone

**Note:**
- **Hbl**
- **Pt**
- **Qtz**
- **Ms**
- **Py**
- **Au**

---

- **23.22m x 5.65 g/t**
- **1.06m x 7.0 g/t**
- **2.13m x 31.5 g/t**
- **5.32m x 9.98 g/t**

- **27.8m x 2.34 g/t**
- **2.50m x 19.69 g/t**
- **2.90m x 2.66 g/t**

- **24.25m x 2.92 g/t**
- **13.85m x 4.62 g/t**
- **5.54m x 1.08 g/t**

- **19.5 m x 0.37 g/t**
- **1.9 m x 1.25 g/t**

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**Notes:**
- JD42 (RL - 419.276 m)
- JD43 (RL - 419.503 m)
- JD32 (RL - 420.26 m)

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**Measurements:**
- **130.90 m**
- **193.00 m**
- **229.25 m**
Greenstones Metamorphism

Metabasite
Hornblende-plagioclase thermometry (Holland and Blundy, 1994) at 5 kbar
➢ edenite richterite → 545–560 °C
➢ edenite-tremolite → 615–645 °C

Plagioclase-hornblende thermobarometry (Plyusnina, 1982)
➢ ≥ 6 kbar/ < 500 °C
➢ 2–5 kbar/ 550–600 °C
Greenstones Metamorphism

Multi Equilibrium Thermobarometry (MET)

**THERMOCALC Results (at $X_{H2O}=1.0$)**

(Hbl + Pl + Cz/Ep + Chl+ Qtz)

\[
4.6(\pm 0.8) \text{ kbar/472}\pm21 \text{ °C} \quad 5.5(\pm 0.6) \text{ kbar/485}\pm21 \text{ °C}
\]

At lower $X_{H2O}$: increase in $\Delta T/\Delta P$.

![Diagram](chart.png)
Greenstones Metamorphism: \(\sim 5 \text{kbar and } 500^\circ \text{C}\)

Grt-Chl schist

Fe-Mg exchange \(\rightarrow\) garnet-chlorite thermometry
(at 5 kbar) \(\rightarrow 510-515^\circ \text{C}\)

THERMOCALC Result
(Grt+ Pl+ Chl + Qtz)
5.1(\(\pm 0.2\)) kbar/515\(\pm 7^\circ \text{C}\)
Chlorite Thermometry: \( \sim 300 ^\circ \text{C} \)

Empirical calibrations → Al\textsuperscript{IV} contents & amount of □\textsuperscript{VI} (Cathelineau and Nieva, 1985; Zang and Fyfe, 1995)

Proximal: 270–297 °C  Inner: 263–293 °C

Intra-crystalline exchange (Vidal et al., 2001, 2005)

Proximal: 268–324 °C  Inner: 293–323 °C
Arsenopyrite Thermometry (Kretschmar and Scott, 1976; Sharp et al., 1985)

T: 305 to 335 °C

$\log f_{S2}$: −10.9 to −8.6
Ore Mineralogy
**Sulfur Isotope**

\[ \delta^{34}S^\text{‰} = +1.42 \text{ to } +7.05 \text{ ‰} \]
\[ \delta^{34}S^\text{H}_2S = +0.2 \text{ to } +5.8 \text{ ‰} \]

Source: magmatic (± mantle) an average crustal sulfur composition
Mineralizing P-T Condition

Chinnasamy et al. (2009) Ore Geol Rev

Metamorphic-low salinity
$\text{H}_2\text{O-CO}_2-\text{CH}_4\text{NaCl-Au(HS)}_2^-$

Proximal (GQV) Inner (LQV)

Negligible fluid evolution  (1.4 to 2.6 kbar and 265 to 320 °C)
Formation and accretion of the Jonnagiri greenstone sequence at the subduction boundary

Chinnasamy and Mishra (2013) Econ Geol
Metamorphism, two phases of folding, shearing, metamorphic fluid advection

Chinnasamy and Mishra (2013) Econ Geol
Granodiorite intrusion, two sets of shearing $\rightarrow$ hydrothermal alteration (Hbl$\rightarrow$Chl$\rightarrow$Bt), gold pptn at 1.4 to 2.6 kbar/265 to 320 $^\circ$C by diverse mechanism with negligible fluid evolution.

Chinnasamy and Mishra (2013) Econ Geol
Emplacement of Chennampalli granite along the contact shear

Chinnasamy and Mishra (2013) Econ Geol
Pongola Basin

→ Contemporaneous to *Witwatersrand Basin*

→ Similar in age and depositional characters
The Problems

- What controls the mineralization?
  Lithology/Structure?

- Uncertainty on source(s) of the ore fluid-the role of magmatic fluid?

- Source of Au and sulfur?

- What class of deposit?
At least three deformational events (D1, D2 & D3)

D1 → NNW-thrusts, reverse faults and shear zones → ENE-tending F1 folds

D2 → NW-SE extension → emplacement of mafic dykes/sills.

D3 → NW-trending, open upright F3 folds → refolded early F1 folds to a dome-and-basin interference pattern

→ Klipwal Shear Zone is associated with D1
Post-Pongola Granitoids
~2800 Ma

Delfkom Formation: **Klipwal Shear Zone**

Mozaan Group: sedimentary
~2940 Ma

Nsuze Group: volcano-sedimentary
~3028 Ma
Basement

9.6 km
(Modified after Gold and Von Veh, 1995)
Lodes - Reefs

Section across the shear zone

Mean strike orientation → 014°/50°E
Great circle girdle → 189°/40°W

(After Hilliard, 2007)
Cross-cut on a plan view

Altered siltstone
(Qtz-Chl-Car±Mus-schist)

Least-altered sandstone

Altered sandstone
(Metapsammite)
Proximal alteration
Inner alteration
Chlorite Thermometry: ~ 300°C

Empirical calibrations →

(i) Al^{IV} content & Amount of Fe^{VI} (Cathelineau and Nieva, 1985)

(ii) Al^{IV} content, corrected (Zang and Fyfe, 1995)

267–301°C.

Intra-crystalline exchange (Vidal et al., 2001, 2005)

268–312°C.
Ore mineralogy

Gold Occurrences
Arsenopyrite Thermometry: $\sim 300^\circ$C

(Kretschmar and Scott, 1976; Sharp et al., 1985)

$\log f_{S_2}: -9.9$ to $-11.7$

$T: 255 - 318^\circ$C
Mineralizing P-T Conditions
~2 kbar and 300°C

Metamorphic-low salinity
H₂O-CO₂-CH₄NaCl-Au(HS)₂⁻

Chinnasamy et al. (2015) Min Dep
Source of Fluid at Klipwal

- Age of Mineralization 2563±84 Ma (Py and Asp Re-Os data)
- Younger than the post-Pongola granites (2863–2721 Ma)
- Very Low initial Os values an initial $\text{^{187}Os}/\text{^{188}Os}=0.29±0.08$ (MSWD=0.38).
- Ore fluid is from primitive sources-interacted with mafic rocks, leaching non-radiogenic Os, the likely source being the deeper seated volcanic dominant Nsuze Group or greenstones below Pongola Super Group.
Ore Fluid Source?

Non-Aqueous volatile rich fluid → neither meteoritic water nor magmatic water

The fluid could be a crustally-derived or crustally-modified fluid that was likely slightly more CO$_2$-rich in the Precambrian than in the Phanerozoic ore-forming systems.

The consistent CO$_2$-rich nature of these fluids is likely a critical factor in providing the near-neutral pH buffering is required for high gold solubility as gold-hydrosulfide complex. (Phillips and Evans 2004)

Metamorphic devolatilization in greenschist to amphibolite facies transition
But the **Question** still remains un answered !!!