Gold mobility during hydrothermal and supergene alteration of BIF (Itabirites), Ouro Fino syncline, Brazil

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Abstract: The Precambrian banded iron formation from the Quadrilatero Ferrifero and from the Ouro Fino syncline (Minas Gerais, Brazil) display some gold showings as quartz veins, and some gold anomalies in the surficial alteration facies. Fresh and altered rocks as well as quartz veins crosscutting the Ouro Fino series have been sampled in order to understand the factors controlling gold mobility in the itabirite series during hydrothermal vein formation, and during laterite formation. Fresh itabirites display rather high gold concentrations which range from 30 to 40 ppb. In laterites, the gold content remains relatively high but may vary significantly from the bottom to the top of the hills, and within the different horizons from 20 to 60 ppb. Thus, fresh and altered itabirites may have constituted significant source rocks for gold. Systematic fluid inclusion studies by using microthermometry and Raman spectrometry analysis have been carried out on different types of quartz veins. At the hydrothermal stage, gold deposition seems to be restricted to the veins characterized by the presence of C-H-O-S fluids characterized by rather low fO2 (around that fixed by the Ni-NiO oxygen buffer) whilst no gold was found in the quartz-specularite veins characterized by high fO2 (fO2 greater than that fixed by the Hematite-magnetite buffer) and sulfate rich solutions.

1. INTRODUCTION

The Quadrilatero Ferrifero (Iron Quadrangle) of Minas Gerais (Brazil) owes its name to an almost rectangular arrangement of huge banded iron-formations or BIF (Dorr, 1969; Hoppe et al., 1987). The Quadrilatero Ferrifero is an area of about 7000 km² of central Minas Gerais located approximately 450 km north of Rio De Janeiro (Fig. 1). The area is rich in mineral deposits of iron-formations or BIF, and the BIF itself shows gold anomalies in the lateritic weathering profile. There are two types of quartz veins. The first type cut the itabirites and contain specularite but no gold. The second type are from the Batala formation (Caraca group) and contain rare native gold particles. Systematic fluid inclusion studies using microthermometry and Raman spectrometry analyses have been carried out on different quartz veins crosscutting the Ouro Fino syncline series, in order to characterize the P-V-T-X conditions of the fluid circulation in the fault network.

2. THE OURO FINO SYNCLINE: GEOLOGICAL SETTING AND WEATHERING OF THE BIF

The Ouro Fino syncline is a small perched syncline, in which refolding has resulted in an acute axial flexure (Fig. 1). The Caraca and Itabira groups (lower and middle units of the Minas Supergroup) form the skeletal structure of the Serra do Ouro Fino (Table 1). The lower unit (Caraca group) consists of Moeda and Batala formations. The middle unit (Itabira group) is represented by the Caue formation. These formations are the only units preserved in the syncline. The Moeda formation is composed largely of a clean white fine-grained quartzite and minor amounts of sericite phyllite (Maxwell, 1972). The Batala formation is a homogeneous dark-gray graphitic argillite (Maxwell, 1972). The Caue formation (lower Itabira group) is composed of itabirites (or BIF), bedded metasedimentary rocks with alternating hematite/magnetite and quartz layers. The itabirites are deeply weathered (down to as much as 200 m) and the different weathering horizons (Table 2) have been studied in detail (Ramanaidou, 1989). The first weathering stages (Soft Itabirite, SI and Hematite B, HB) are isovolumetric; their desilicification is progressive but important, and geothitisation is moderate. When desilicification is almost complete in the Hematite A horizon (HA), the primary oxides (hematite and magnetite) are destabilized. An epigenetic replacement of the preexisting minerals occurs in...
"clay-like red product" a product consists of sma hematite and goethite. It horizon (HGH) the goethite induration is strong lead destruction of the primary goethite-rich "cuirasse", of weathering column. The plateau shows a rest canga caps the HB or HA are marked by a deep and with a HGH horizon well

3. GEOCHEMISTRY  PROFILE

3.1. Raw data

Atomic absorption analysis was used for the determination. Fresh itabirites di concentrations which ran laterites, the gold content level as in the BIF but m the bottom to the top of the horizons. Near the surface horizon, 30 to 40 ppb are values are obtained in the ("clay-like red product") e

3.2. Corrected data

Using the density of the possible to compute the gr of rocks in the different 3. On the plateau, an en the HB horizon and in weathering effect is not leached. On the other profile, when HGH horizon gold level seems erratic compared to the bed rock product, where the wealth gold is the lowest.

Thus, at the super enrichments or depleted weathering of the itabirite gold loss or gain from on however difficult to concentrations (< 100 p localization of the minerals. Though the gold in the values are anomalous, at possible source of gold fi veins.

4. P-V-T-X CONDITION FORMATION

Systematic fluid incl microthermometry and R:
"clay-like red product" alumina rich pockets. This product consists of small particles of secondary hematite and goethite. In the Hardened Goethitic horizon (HGH) the goethitization is intense and the induration is strong leading sometimes to a total destruction of the primary bedding. A vesicular and goethite-rich "cuiarasse", the so called canga caps the weathering column.

The plateau shows a restricted evolution where the canga caps the HB or HA horizons, while the slopes are marked by a deep and strong weathering column with a HGH horizon well developed.

3. GEOCHEMISTRY IN THE WEATHERING PROFILE

3.1. Raw data

Atomic absorption analysis (with a graphite furnace) was used for the determination of gold content (Table 3). Fresh itabirites display anomalous gold concentrations which range from 20 to 60 ppb. In laterites, the gold content remains at about the same level as in the BIF but may vary significantly from the bottom to the top of the hills, and in the different horizons. Near the surface (cuiarasse) and in the HB horizon, 30 to 40 ppb are recorded, whereas lower values are obtained in the intermediate HA horizon ("clay-like red product") or in the HGH horizon.

3.2. Corrected data

Using the density of the different samples, it is possible to compare the gold level for a same volume of rocks in the different weathering horizons (Table 3). On the plateau, an enrichment occurs mainly in the HB horizon and in the canga. When the weathering effect is not very strong, the gold is not leached. On the other hand, on very weathered profile, when HGH horizon is well developed, the gold level seems erratic and we observe a loss compared to the bed rock. In the pockets of the red product, where the weathering effect is the highest, gold is the lowest.

Thus, at the supergene stage, some gold enrichments or depletions could occur during weathering of the itabirites. The mechanisms of the gold loss or gain from one of the lateritic horizon is however difficult to solve since the low concentrations (< 100 ppb) make impossible any localization of the mineralogical form of gold.

Though the gold in the BIF is extremely low, these values are anomalous, and are considered to be a possible source of gold found in some of the quartz veins.

4. P-V-T-X CONDITIONS OF QUARTZ VEIN FORMATION

Systematic fluid inclusion studies by using microthermometry and Raman spectrometry analysis have been carried out on different quartz veins crossing the Ouro Fino series, in order to characterize the P-V-T-X conditions of the fluid circulation in the fault network. Two vein types have been identified: -type 1- barren quartz-specularite veins which are frequent in the Ouro Fino syncline. The studied quartz vein from the Capanema mine cutcross the itabirite series and do not show any ductile deformation. They are centimetric to decimetrix in width, are partly weathered near the surface. They do not show any gold concentration. Specularite crystallizes sometimes on cores of magnetite.

Table 3: Variation in gold content (absolute and normalized at constant volume) in samples from the alteration profiles

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type</th>
<th>Au ppb</th>
<th>Density ppb/100cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Itabirites</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>145 IT</td>
<td>4</td>
<td>3,27</td>
<td>13,08</td>
</tr>
<tr>
<td>CP07 IT</td>
<td>35</td>
<td>3,49</td>
<td>122,15</td>
</tr>
<tr>
<td>IT36 IT</td>
<td>68</td>
<td>3,1</td>
<td>210,8</td>
</tr>
<tr>
<td>123 IT</td>
<td>43</td>
<td>2,92</td>
<td>128,56</td>
</tr>
<tr>
<td>IT 20 IT</td>
<td>2,79</td>
<td>55,8</td>
<td></td>
</tr>
<tr>
<td>CHBA300 IT</td>
<td>60</td>
<td>2,24</td>
<td>134,4</td>
</tr>
</tbody>
</table>

Profile 14 (upper slope)

| CHB91 SI | 20 | 2,76 | 55,2 |
| CHB92 SI | 25 | 2,93 | 75,25 |
| CHB93 HB | 17 | 2,44 | 41,48 |
| CHB94 HB | 35 | 2,5 | 87,5 |
| CC95 C | 40 | 2,61 | 104,4 |

Profile 10 (slope)

| S1 HA | 45 | 2,06 | 92,7 |
| S2 HA | 45 | 3,02 | 135,9 |
| S3 HA | 20 | 2,17 | 43,4 |
| S5 HA | 35 | 3,08 | 107,8 |
| S6 HGH | 25 | 2,4 | 60 |
| S7 HGH | 33 | 3,13 | 103,29 |
| CC58 C | 32 | 2,57 | 82,24 |

Profile 4 (slope)

| 131 HA | 8 | 2,99 | 23,92 |
| 132 HA | 39 | 1,92 | 74,88 |
| 133 HGH | 10 | 2,41 | 24,1 |
| 134 HGH | 11 | 2,96 | 32,56 |
| 135 HGH | 28 | 1,49 | 41,72 |
| 136 HGH | 16 | 2,95 | 47,2 |
| 137 HGH | 11 | 2,9 | 31,9 |
| 138 HGH | 14 | 3,71 | 37,94 |
| 139 C | 10 | 2,12 | 21,2 |

Red products

| 400 RP | 6 | 1,7 | 10,2 |
| 103 RP | 5 | 1,7 | 8,5 |
- type 2- quartz veins containing rare native gold particles, mostly located in metamorphic series surrounding the itabirites. Small and old scrapes attest of local investigations for gold. The weathering makes difficult the identification of the primary sulphide assemblages which are partially totally transformed into iron oxides and/ or hydroxides.

Type 1 veins display three kind of inclusions. Most inclusions are scattered within the quartz and no chronology could be established. No definite planes of fluid inclusions have been recognized. This suggest that most fluids are contemporaneous of the crystallization or recrystallization of the quartz.

a) two-fluid phase aqueous inclusions: the Tm H2O are mostly in the -8.5; -10.5°C, whilst the temperature of first melting is low around -60°C. The Th (L-V) range from 63 to 157°C.

b) sulfate rich inclusions

Two types are distinguished:
- hypersaline CO2-rich inclusions: they are multiphase and contain:
  - one or more solids: a solid hexagonal in shape representing about 10% of the total volume of the inclusion, identified by Raman spectroscopy as a sulphate (barite, or celestite, ?). Other solids are difficult to identify. Tm of the hexagonal solid is around 140 ± 15°C.
- a vapour phase dominated by CO2 accompanied by small amounts of N2. ThCO2(L or V) is in the 1°-17.8°C range with a maximum between 7° and 14°C. Tm CO2 in the -56.6°-56.8°C range indicate the presence of dominating CO2, which is confirmed by Raman spectroscopy;
- a liquid phase where SO4 2- is the dominant ion identified by Raman spectroscopy, while HS04- ions are detected but in much lower concentrations. TmH2O is in the -4.3°, -5.7°C range.

All studied inclusions decrepitated at temperatures ranging from 160 to 280°C.

- bisulfate rich inclusions, are two-fluid phase inclusions characterized by the presence of an unidentified small solid. Most Tm H2O ranges from -1.5 to -4.5°C. Some Th (L-V) are recorded around 230°C whilst most inclusions decrepitate at temperatures up to 290°C.

Considering the polyatomic species which can be identified by Raman spectroscopy, the liquid phase contains both SO4 2- and HS04- ions in rather similar concentrations.

Thanks to a calibration by using experimental solutions (Moisette et al., 1990), (SO4 2-) was estimated to be around 0.32 ± 0.05 molal, and pH around -0.3 ± 0.2 at 25°C in such inclusions. It is probably the first occurrence of such acid fluids in natural fluid inclusions.

-c) aqueous vapours: the vapour phase occupies around 80-90% of the inclusion. No volatile species has been identified by Raman spectroscopy. No TH could be obtained due to decrepitation. The salinity of the vapours is estimated to be very low from the rare observation of ice melting near 0°C in some inclusions.

The fluid compositions, especially in type c inclusions are rather unusual: low pH at room temperature, sulfate rich aqueous solutions, some of them being mixed with volatiles (CO2). The coexistence of aqueous vapours together with hypersaline fluids are probably indicative of boiling process which probably lead the crystallization of the quartz -hematite assemblage. The observed compositions reveal highly oxidizing conditions, and temperatures around 200-300°C. It is actually difficult to propose any source for such fluids (evaporates?).

Type 2 quartz veins contain volatile rich fluids mostly borne by fluid inclusion trails. Each trail is characterized by rather homogeneous phase relationships at room temperature. Especially, the water filling which varies from nearly 0 up to 70% in the largest inclusions, is nearly constant within a given fluid inclusion plane. Textural relationships suggest repeated fracturing, with the trapping of fluids characterized by increasing amounts of water.

Tm CO2 ranges from -56.7 to 57.2°C with a maximum at -56.8°C. Tm H2O when H2O is present is in the -1.5°; -11.5°C range with a maximum around -2.7°C. ThCO2 (L-V) shows rather constant values within a given trail, but varies greatly from trail to trail: it ranges from -11.5°C to +39°C, with maxima at -7°C, +3°C, +17°C, and +27°C. Most inclusions decrepitate at temperatures ranging from 180 to 320°C. Some global homogenization to the vapour phase have been obtained in the 320-400°C range. Raman spectroscopy reveals the presence of CH4, H2S, (C2H6 and N2) in the volatile phase. The presence of CH4 reveals much lower Tm than for type 1 veins.

5. CONDITIONS OF GOLD MOBILITY IN THE URO FINO SERIES AT THE HYDROTHERMAL STAGE

Itabirites constitute the most probable source rocks for gold anomalies encountered in this area. At the hydrothermal stage, gold deposition seems to be restricted to the veins characterized by the presence of carbonic fluids (type2) characterized by rather low fO2 and moderate pH, whilst no gold deposition characterizes the studied quartz-pyrite-carbonatite veins which are characterized by high fO2 (IO2 greater than that fixed by the Hematite-magnetite buffer) and nearly neutral pH at 250-300°C.

Consideration of thermodynamical data on gold solubility gives a relatively good explanation to the different behaviour of gold in such contrasted conditions. Gold was probably easily transported in highly saline and oxidizing solutions and could not be deposited before any changes in the surrounding conditions. Gold was probably easily transported in such contrasted conditions.

REFERENCES

ated to be very low from the melting near 0.0°C in some aqueous solutions, some of which may be very low from the volatiles (CO₂). The observed simulacrum. The observed.

JUS my source for such fluids contain volatile rich fluids inclusion trails. Each trail is increasing amounts of water. 'C range with a maximum, +17°C, and -300°C. Most compositions characterize the barren and mineralized veins cropping the Ouro Fino series. The barren quartz-specularite veins (type 1) display different kinds of fluids, with, especially, unusual compositions such as hypersaline, sulfate rich and CO₂ rich fluid inclusions. The physical-chemical conditions (T min. = 200-300°C, pH nearly neutral (when recalculated at such temperatures, high FO₂, sulfate rich solutions) seem to have been incompatible with gold transport or deposition.

However, the two successive lateritic horizons above the itabirite, noted HB, HA, which are overlain by the ferruginous cuirassé so-called "canga" display gold contents have gold contents which remain within the 8-45 ppb range. It is highly probable that further process than the lateritization is necessary to get higher grade concentrations, such as for instance a mechanical reworking of the weathered profiles by surficial waters followed by a differential sedimentation by gravity of the transported products. The study of such process would need specific investigations which were not carried out in our study.

- the systematic fluid inclusion studies carried out by using microthermometry and Raman spectrometry analysis have shown that rather different fluid compositions characterize the barren and mineralized veins cutting the Ouro Fino series. The barren quartz-specularite veins (type 1) display different kinds of fluids, with, especially, unusual compositions such as hypersaline, sulfate rich and CO₂ rich fluid inclusions. The physical-chemical conditions (T min. = 200-300°C, pH nearly neutral (when recalculated at such temperatures, high FO₂, sulfate rich solutions) seem to have been incompatible with gold transport or deposition.

On the contrary, the quartz veins containing rare native gold particles, mostly located in metamorphic series surrounding the itabirites, are characterized by C-H-O-N-S rich fluids with varying amounts of water. These fluids indicate of relatively low FO₂, and probable equilibrium with graphite are similar to most fluids described in Au-quartz veins (Boiron et al., 1990, Alvarenga et al., 1990).

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Gold and gold deposits are one of the main focuses of pure and applied research in geological science at the present time. At the International Symposium Brazil Gold '91, participants from 23 countries and with a wide variety of research interests joined to present and discuss their latest contributions on the economics, geochemistry, geology, geochemistry and exploration of gold deposits. The proceedings of Brazil Gold '91 encompass 117 papers which are distributed in five sections: Regional studies; Petrology and geochemistry; Geology and case studies of gold deposits; Structural geology of gold deposits and districts; and Mineral exploration. They will be very useful for professional geologists, geophysicists and mining engineers concerned with precious metal deposits, whether working in research and development, industry, or mineral exploration. It will certainly also be an essential source for both undergraduate and graduate students in economic and applied geology.

FROM THE SAME PUBLISHER:


This work covers the theme gold from exploration methods to the exploitation of mines. All the papers read at the international symposium organized by the Geological Society of Zimbabwe are included in the proceedings. Many contributions are by invited lecturers from Canada, Australia, South Africa and elsewhere. They include some of the foremost research workers in this field.

Kesse, G.O. The mineral and rock resources of Ghana 1985, 25 cm, 624 pp., Hfl.245/$138.00 /£70

Importance of minerals; Ghana: Geography, physiography, geology & geohydrology; Mineral resources of Ghana: background; Metallic & non-metallic minerals; Bulk construction materials; Radioactive minerals; Petroleum & other fossil fuels; Minor minerals; Minerals in concretions; Tables of summary of mineral & rock resources in Ghana; Legislation affecting mineral concessions & mining industry; Index. Author: Director Geological Survey Department of Ghana.

Lateritisation processes

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Geomorphic & genetic aspects; Distribution in space & time, & global tectonics or paleoenvironmental controls; Geochemistry, geophysical & other exploration techniques for mineral deposits associated with laterite; Relation to agriculture, geohydrology & geotechnique. 51 papers.

Batugina, I.M. & I.M. Penukhov Geodynamic zoning of mineral deposits for planning and exploitation of mines (Russian translations series, 77) (No rights India) 1990, 25 cm, 169 pp., Hfl.95/$50.00 /£30

This book describes the principal aspects, objectives and problems, as well as the method of geodynamic zoning in areas of mineral deposits and mine fields. Data are given from investigations of the physico-mechanical properties of the rock massif and conditions of formation, nature and energy of rockbursts. The geodynamic system of blocks has been taken as the basis of stress conditions of the virgin rockmass and methods of its assessment are enumerated. Problems concerning the practical application of geodynamic zoning of mineral deposits are discussed in terms of ensuring safe working conditions in coal and metal mines.

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Mine planning & scheduling; Mine evaluation; Mineral processing; Orebody modelling/Geostatistics; Geotechnical applications; Mine transport; Monitoring; Expert systems; Mine ventilation; Exploration; Maintenance management. 88 papers.

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General hydrological conditions; Study of hydrological conditions at stage of exploitation of ore deposits; Analysis of influence of exploitation of ore deposits on changes in the geological environment.

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