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ISSN : 2455-1953
JGSR
Journal of Geosciences Research
Vol. 7, No.1, January, 2022, pp. 81-85

Gold from Auriferous Iron Ore of Goa, India

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Abstract

In view of the closure of the 65 years old Iron ore industry in Indian state of Goa due to complex techno-legal and environmental issues, lack of systematic geochemical evaluation of the mineral wealth have led to the wastage of precious auriferous resources. Goa falling under the Western Dharwar Craton (WDC), is one of Asia's major metallogenic province having Banded Iron Formation (BIF) of late Archean and Paleoproterozoic periods which provided the backbone of the local Iron ore industry since 1946. There is lack of knowledge on the systematic geochemical evaluation of Iron ore of Goa area. Iron ore centered mining and export strategy had completely overlooked Gold mineralization of economic importance which is mainly restricted to Archean greenstone terrains of the WDC. The samples were analyzed from the BIF belt of Goa area using SEM-EDX with the quantification of the gold using ICP-AES to clear the global ambiguity over auriferous nature of Goa's Iron Ore.

Keywords: Goa, India, Western Dharwar Craton (WDC), Metallogenic Province, Auriferous Resources

Introduction

Goa is situated in the northwestern part of the Western Dharwar Craton (WDC) which is Asia's major metallogenic province (Dessai, 2011). The WDC offers unique opportunities to study mineral deposits (Mahantesha *et al.*, 2021). The Banded Iron Formation (BIF) in addition with being large repositories of iron ore also hosts many gold deposits (Dessai, 2018). There are various techniques which can be used for detection and quantification of gold such as Fire Assay and Instrumental neutron activation (INAA) (Vargas and Reyes, 2021). Modern laboratory techniques such as Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES), Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) offer the advantages of rapid determination of small concentrations of gold in a number of samples (Vargas and Reyes, 2021). Environmental Scanning Electron Microscope equipped with an Energy Dispersive Spectrometer (SEM-EDS) allows combined analysis of mineral morphology and composition (Bi *et al.*, 2011). Occurrence of gold in sulphidic Banded Iron Formation (BIF) range from 0.7 to 3.2 g/t (Sawkar *et al.*, 1995). Gold occurs (0.06 to 0.16) ppm in laterite and powdery ore of Keri and Kalne village of Maharashtra. There is also report of occurrence of < 0.1 ppm gold in laterite and iron ores in Sindhudurg District (Umathay, 1993). Geological Survey of India has reported the presence of gold in schist belt of Chitradurga District and Shimoga (Devaraju *et al.*, 2004; Ganguly *et al.*, 2016). These formations shows the characteristics similar to the iron ores occurring within the Ponda Group of Goa which include Vageri, Bicholim and Sanvordem formations(Dessai, 2011).This work was initiated because there was no knowledge of the presence of gold in Goa region.

Occurrence of Gold

Gold is a precious metal that is valued for its beauty as well as being conductive and malleable. These properties make gold valued both in industry and in economics. Gold occurs in free elemental form as well as nuggets or grains interlocked in rocks, veins and in alluvial deposits. Gold occurs in solid solution series with silver and naturally alloyed with copper and palladium. Primary form of gold occurs in the biosphere widely and in various rocks such as in case of igneous, sedimentary, and metamorphic rocks (Oludare, 2017). Under Earth surface conditions, primary gold is progressively transformed by mechanical and (bio) geochemical processes, ultimately resulting in secondary grains and nuggets, which commonly occur in eluvial and alluvial deposits, so called placers (Southam *et al.*, 2009; Reith *et al.*, 2013).

Exports of Iron Ore

Present day mining in Goa resumed in 1947 which marks the beginning of modern day mining and export of iron ore. The exports of iron ore have steadily increased from 4,36,400 tonnes (1951) to 38 MMT (2008-09) and has exported 800 MMT of Iron ore (1951-2011) (Anon, 2011a, source: Department of Industries and Mines, Govt. of Goa). The Goan Iron Ore is exported to Peoples Republic of China (PRC), Japan, Taiwan, South Korea and Eastern European Countries (Directorate of Mines and Geology-Goa) (Dessai, 2011). Table 1 gives the total export of ores from Goa.

Table 1: Total export of iron ore from BIF mining zone from Goa and its value (source- Dessai, 2018; www.indexmundi.com)

Year	Export of iron ore from BIF (MMT)	Price in US$ per metric tone
2002-03	19	12.68
2003-04	22	13.82
2004-05	23	16.39
2005-06	26	28.11
2006-07	31	33.45
2007-08	33	36.63
2008-09	38	60.80
2009-10	46	72.51
2010-11	47	125.91
2011-12	38	179.63

Geological Setting

Goa is situated in the north western part of the metallogenic Archean WDC. The Dharwar Craton is divided into Eastern and Western Cratons wherein Goa is situated in the north western part of the WDC which includes Sanvordem, Bicholim, and Vagheri Formations (Dessai 2011). The Iron Ore of Goa are associated with greenstone belt and occurs as bands, reefs and lenses of the Banded Hematite Quartzite (BHQ) and the Banded Magnetite Quartzite (BMQ) (Dessai, 2018). The Banded Iron Formation (BIF) consists of two subfacies- the haematite sub-facies which predominates in the northwestern and central part (from Advalpal to Dharbadora) of the State and the magnetite sub-facies which is largely confined to the central and the southeastern part (Costi to Barazana-Villiena) (Dessai, 2011). The Bicholim Formation consists of amphibole schists, ferruginous and manganiferous phyllites, limestones and the Banded Ferruginous Quartzites (BFQ) that occur as intercalations within the phyllites. The BHQs serve as the protores for the Iron Ore deposits that are extensively developed in this formation.

Methodology

Sampling

The exploration and collection of natural auriferous samples from the BIF region in North and South Goa under the WDC of Goa was carried out. In particular four representative samples from VIF were selected as shown in Table 2. Field

Fig. 1. Mining sites in North Goa and South Goa under BIF region (www.earth.google.com)

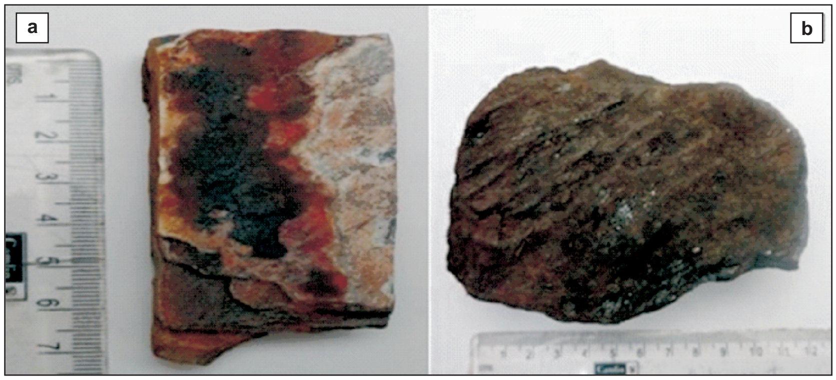

Fig. 2(a-b). The representative samples of Banded Hematite Quartzite (BHQ) and Banded Magnetite Quartzite (BMQ)

photo documentation and labelling of the samples was carried out. The collection of representative samples was done from the Auriferous region of the BIF in North and South Goa (Fig. 1-2).

Sample Preparation

Collected samples were dried, powdered using mortal and pestle (Panda *et al.*, 2011). The recovered sample was concentrated by panning method (Southam *et al.*, 2009) and subjected to magnetic separation using 2 Tesla neodymium magnet (deOliveira and Larizzatti, 2006) and sieved into different fractions with the sieve size of 250, 150, 106, 53µm.

ICP-OES Studies

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) is an analytical technique used for the detection of chemical elements (Pyrzyńska, 2005; Tang *et al.*, 2020). Quantification of gold was carried out using Agilent 5110 ICP-OES (Cera Laboratories Mumbai).10 grams of each samples was dried completely at 105°C (Panda *et al.*, 2011). 106 micron size sieved fraction of each sample was sent for the analysis.

SEM-EDX Study

BHQ and BMQ were analyzed using Carl-Zeiss Scanning Electron Microscope (SEM-EDX) (USIC, Goa University). Gold is electron dense and do not require sputter coating and thus samples were analyzed without any forms of coating. The instrument is equipped with an energy dispersive spectrometer (EDXA), analysis were conducted using acceleration voltages between 15 and 20 keV. The samples were C-coated prior to analysis (Falconer and Craw, 2006).

Results and Discussion

Samples from the mining areas were collected from north Goa mines such as Shirgao Mines as well as South Goa Mines were covered. The fractions 150, 106, 53 µm showed high concentration of gold and same fraction were thus used for the further studies. There are no previous studies on the multi-elemental analysis of iron ore from the BIF of Goa (such as Au, Ag, Pt including REE). Our studies have established that the BHQ contains 12-13 ppm and BMQ 8.4 ppm, whereas the Iron Ore reject dumps contain 7.71ppm (Table 2). The presence of the elemental gold can be seen in the EDX spectra (Fig. 3a-d).

Goa is a part of the WDC which is Asia's major metallogenic province (Dessai, 2011). The Dharwar Craton is divided into Eastern and Western Cratons wherein Goa is situated in the north western part of the WDC (Dessai, 2011). Values of gold (0.98–4.72 ppm) have been reported from Gadag greenstone belt, Western Dharwar Craton, Peninsular India (Ugarkar *et al.*, 2016) and Chitradurga greenstone belt, Dharwar craton (Gupta and Jayananda, 2014; Gupta, 2013). Determination of gold (0.5 to 50 ppm) in low grade ores and concentrates by anion exchange separation followed by neutron activation have been reported (Iyer and Krishnamoorthy, 1976). Studies on the determination of gold in geological samples can be carried out by ICP-OES. The development of modern laboratory techniques such as Inductively Coupled Plasma-Optical Emission Spectrometry (ICP–OES) helps in the rapid determination of small concentrations of gold in rocks and ore samples(El-Wakil, 2015) and also has large analytical range, high sample throughput and requires Low sample volume (Wilschefski and Baxter, 2019).Our studies have established that the BHQ contains 12-13 ppm and the BMQ 8.4 ppm whereas the Iron Ore reject dumps contain 7.71ppm which is higher as compared to the earlier studies from the WDC. This is the first report on extractable gold in Goa's Iron ore and low grade

Table 2: Quantification of Gold using ICP-AES from auriferous samples

Sr. No	Sample Designation	Gold in ppm
1.	Low grade BIF ore reject, North Goa	7.71
2.	BHQ, Shirgao, North Goa	10.35
3.	BHQ, Velgeum, Surla, North Goa	12.93
4.	BMQ, Sacorda, South Goa	8.4

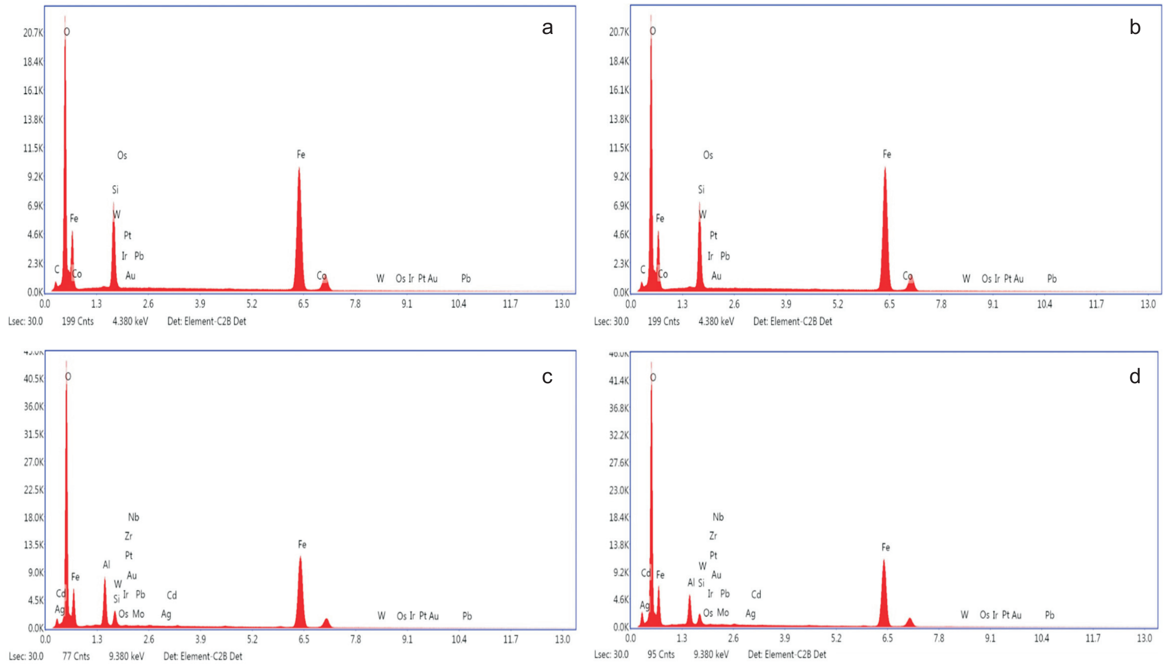

Fig. 3(a-d). SEM-EDX showing presence of gold.a-Low grade BIF ore reject, North Goa; b-BMQ, Sacorda, South Goa; c-BHQ, Velgeum, Surla, North Goa; d-BHQ, Shirgao, North Goa. The presence of the elemental gold can be seen in the spectra presented by the EDX analysis.

reject. A novel approach was suggested involving separation of auriferous fraction from ferromagnetic fraction and use of sustainable biomining techniques involving microbial bio-reduction and bio-oxidation processes (Zhao *et al.*, 2020). Lacking in knowledge of systematic geochemical evaluation, Goa's Iron Ore centered mining and export strategy had completely overlooked gold mineralization of economic importance mainly restricted to Archean greenstone terrains of the WDC. Despite endowed with chemically the most diverse and creative Archean rocks in the WDC, Goa still lacks an intensive knowledge based sustainable mining policy. There is further scope for confirmation of gold by Geological Survey of India (GSI), IIT's and other research institutes of India. Various other techniques can be used in future to carry out the gold detection. There are various reports on presence of secondary gold forms in Australia, New Zealand (Southam *et al.*, 2009). Similar studies can be carried out in India as well. There is a lot of scope to carry out the work on metallogeny of gold. Biogeochemical cycling of gold can be studied including the investigations on occurrence of vermiform gold, phytoform gold, gold from the alluvial deposits, sediments and laterites.

Conclusions

This is the first report on the detection of gold from the BHQ and the BMQ of Goa. Detection of gold in the samples have been reported. The gold concentration ranges from 7.71-13 ppm indicating auriferous nature of Goa's Iron Ore. There needs to be further research on neglected auriferous iron ore of Goa.

Authors' Contributions

Sujata Dabolkar: Investigation, Conceptualization, Methodology, Data curation, Writing- Original Draft. **Nandkumar Kamat**: Conceptualization, Visualization, Supervision, Reviewing and Editing.

Acknowledgements

First author acknowledges UGC, NF-OBC Junior Research fellowship. We thank the Chairman of Goa State Poluution Control Board Mr. Ganesh B. Shetgaonkar for his guidance in analysis. The assitance and guidance given by Late Mr. Shailesh Mhatre, Proprietor of Cera Lab, Mumbai is deeply acknowledged. We would like to thank University Science Instrumentation Centre (USIC), Goa University for providing SEM-EDX facility. We also thank School of Earth Ocean and Atmospheric Sciences for identification of ore samples and technical guidance.

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(Received: 03 July, 2021; Revised Form Accepted: 30 October 2021)