Banded Magnetite Quartzite in Southern Granulite Terrain (SGT) – A Case Study from Tirthamalai Region, Tamil Nadu, Southern India

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ABSTRACT

The Banded Magnetite Quartzite (BMQ) formations of the Tirthamalai region, Dharmapuri District, Tamil Nadu, represent important Precambrian iron formations within the Southern Granulite Terrain (SGT) of southern India. This study investigates their geological occurrence, mineralogical characteristics, geochemical composition, and petrogenetic evolution through systematic geological mapping of approximately 40 km² at 1:50,000 scale, supported by petrographic and whole-rock geochemical analyses of representative samples. Field investigations identified four distinct BMQ bands associated with charnockite, granulite, gneiss, and granitic rocks. The formations are predominantly composed of magnetite and quartz, with minor grunerite, hypersthene, hematite, and accessory minerals. Geochemical analyses indicate Fe_2O_3 contents of 43.87–58.25 wt.%, SiO_2 of 41.41–54.82 wt.%, and Al_2O_3 of 0.06–0.48 wt.%. The enrichment of iron and silica, coupled with low alumina and relatively low concentrations of trace elements, suggests a predominantly chemical sedimentary origin with limited terrigenous input. Mineralogical and textural features indicate subsequent recrystallization, high-grade metamorphism, and deformation. The combined geological, petrographic, and geochemical evidence therefore supports the interpretation that the Tirthamalai BMQ formations originated as chemical sediments precipitated in a sedimentary basin and were subsequently modified by regional metamorphic processes. This study provides insights into the origin and geological evolution of Precambrian iron formations in the Southern Granulite Terrain of southern India.

Keywords - Banded Magnetite Quartzite (BMQ), Mineralogy, Geochemistry, Southern Granulite Terrain (SGT), Southern India

INTRODUCTION

Globally, iron ore deposits are closely associated with schist belts, gneisses, and granulite terranes of Archaean age. In India, the iron ore deposits are found as Banded Hematite Quartzite (BHQ) and Banded Magnetite Quartzite (BMQ) in parts of Jharkhand, Karnataka, Chattisgarh, Maharashtra, Orissa and Tamil Nadu state occur as bands, enclaves, veins in the districts of Salem, Dharmapuri, Tiruchirappalli and South Arcot (Dubey and Karunakaran,1943; Krishnan and Aiyengar 1944; Majumder *et al.,* 1982; Rajendran 1996; Rajendran and Chandrasekaran, 2000; Rajendran *et al.,* 2007). These are banded magnetite quartzite, differentiated on the basis of enriched magnetite and quartz, with an iron content of 35-40%, classified as low-grade iron ores (Radhakrishna *et al.,* 1986; Raja *et al.,* 2010; Thirunavukkarasu *et al.,* 2016). These are distinct types of iron formations that are highly folded, metamorphosed, and confined to the granulite facies, called the Tamil Nadu type (Prasad et al., 1982; Radhakrishna et al., 1986; Thirunavukkarasu *et al.,* 2015; Radhika, 2021). These iron ore deposits are a group of pre-Cambrian iron formations occurring as narrow, highly deformed and metamorphosed belts within Archaean granulite terrain (Prasad *et al.,* 1982). These rocks are older than >3,000 m.y. represented by oxide iron formations (Radhakrishna *et al.,* 1986). Although many workers have studied this banded iron formation in detail, the Tirthamalai iron ore deposit has not received much attention. So, the present study is an attempt to describe in detail the field, mineralogy, and geochemistry of the BIF and associated

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granulites; their origin, source, and environment of iron formations; and their similarities and differences with other Precambrian banded iron formations (BIFs).

MATERIALS AND METHODS

Systematic geological mapping of the study area was conducted by the author at a scale of 1:50,000 using Survey of India (SOI) Toposheet No. 58 L/12. The study area covers approximately 40 km² and encompasses several iron ore outcrop samples within the Tirthamalai belt. During the field investigations, approximately 70 representative iron ore samples were collected from fresh, accessible outcrops for subsequent mineralogical and geochemical analyses. Forty representative iron ore samples were selected for petrographic investigation. The collected rock-chip samples were submitted to Continental Instruments (Lab Crystals, Thin Section Preparations), Lucknow, Uttar Pradesh, India, for the preparation of thin sections and polished sections. Petrographic examinations were performed using a Leica DM-720 P optical microscope under transmitted and reflected light. These investigations aimed to identify the constituent mineral assemblages, textural characteristics, mineral associations, and microstructural relationships in the iron ore samples.

A total of 40 representative iron ore samples were selected for whole-rock geochemical analysis to determine their major element, trace element, and rare earth element (REE) compositions. The samples were processed in two batches following the respective laboratory preparation requirements. The first batch, comprising 20 samples, was crushed and pulverized to approximately 230 µm using steel and agate mortars at the National Centre for Earth Science Studies (NCESS), Thiruvananthapuram, Kerala, India. The remaining 20 samples, collected from fresh rock outcrops, were separately crushed and pulverized using steel and agate mortars to meet the particle-size specifications of Activation Laboratories Ltd. (Actlabs), Canada. The samples were prepared to achieve a particle-size distribution in which 95% of the pulverized material passed through a 105 µm sieve. Subsequently, approximately 10–20 g of each homogenized and pulverized sample was packaged and submitted to Activation Laboratories Ltd. (Actlabs), Canada, for whole-rock geochemical analysis. The concentrations of major elements, trace elements, and REEs were determined using the laboratory's specified analytical procedures, including Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for the appropriate elemental groups. The analytical results were used to evaluate the geochemical characteristics and compositional variations of the BMQ samples and to investigate their petrogenetic significance.

1. Geological Settings and Field Relations

The study area in and around Tirthamalai (latitudes N 12° 03' to 12° 06' and longitudes E 78° 35' to 78° 38') forms part of the Archaean Peninsular complex that has undergone high-grade regional metamorphism, with folding, faulting, and shearing structures (Santosh et al., 2009; Tsunogae and Santosh, 2011). The key rock types of the study area are banded magnetite quartzite, charnockite, and epidote hornblende gneisses (Fig. 1). There are four bands of magnetite quartzite on this hill, separated by gneisses and other rock types. The first band is observed on the western slope of the hill and runs for about 11 km. The second band lies a short distance east of the first and is nearly 10 km long. In the southern part, it is roughly parallel to the first band and separated by granite. The average thickness is 30 m. The third band appears to be merely an offshoot of the second band and forms a prominent ridge NNE for over 0.8 km. The fourth band is seen at the southeastern base of Tirthamalai, 0.8 km south of Andiyur.

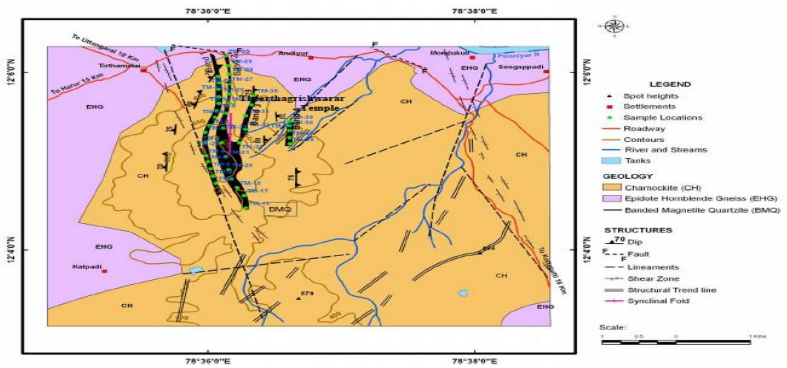

Fig. 1. Geological map of the study area

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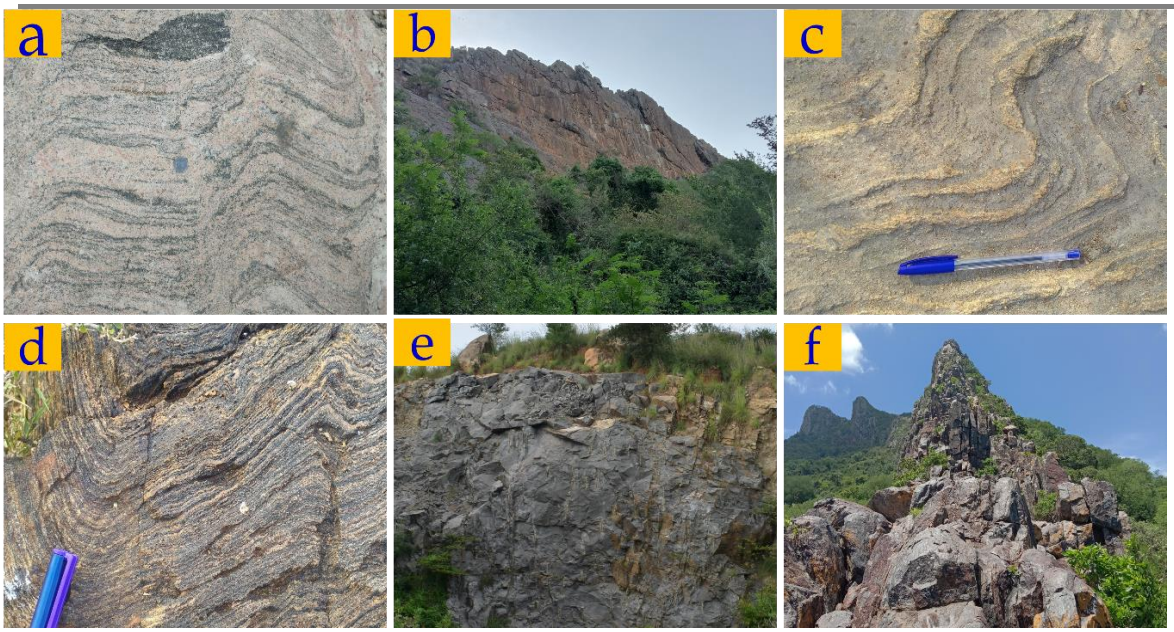

Fig. 2. a) Field photograph shows the epidote hornblende biotite gneiss exposures in the study area, b) Field Photograph shows magnetite quartzite iron ore bands occurring as linear ridges more than 90 m in height, c) Field photograph shows the occurrences of fold in the friable nature with rugged surface of magnetite quartzite exposure, d) Field Photograph shows the occurrences of fold in the magnetite quartzite iron ore formation. e) Field Photograph shows the charnockite exposures in the study area, f) Field Photograph shows the occurrence of fractures in the magnetite quartzite iron ore formations.

The granulite and charnockite are younger in age (<3,000 m.y.). These are occurring within the banded magnetite quartzite formations. This is also equivalent to the Supracrustal rock types of Sathyamangalam. These are followed by hornblende-biotite gneiss (Fig. 2a) that occurs in force throughout most of the regions. In the field, the iron formations are exhibited as highly metamorphosed sediments with characteristic banding. These are exposed as very hard, linear ridges with a vertical wall almost 90 m in height (Fig. 2b). There is no evidence of igneous origin, and they are preserved as friable, with rough surface characteristics. The friable nature and banding with rugged surfaces (Fig. 2c) are characteristic of the meta-sedimentary rocks. The presence of folds, joints, and fractures (Fig. 2d, e, and f) is the result of later forces, suggesting a higher grade of deformation and metamorphism.

The geological succession of rock types of the iron formations of the granulite region of Tamil Nadu has been proposed by several authors (Krishnan and Aiyengar, 1944; Saravanan, 1969; Anjanaeya Sastry and Krishna Rao, 1970) through different studies. The succession proposed here is based on views proposed by earlier workers. The oldest member in the region is the older banded magnetite quartzite, which is equivalent to the Supracrustals of Sathyamangalam (Gopalakrishnan *et al.,* 1975). Its age is over 3000 m.y. (Radhakrishna *et al.,* 1986). The stratigraphic sequence of pre-Cambrian rocks of the region and available age data are given in Table 1.

Table 1. The stratigraphic sequence of the study area

Lithological units	Age (Million Years)
Dolerite	2100-1000
Ultramafic rocks (dunite-serpentinised magnesite)	2500-3000
Gabbro	>3000
Hornblende biotite gneiss	

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Granulite Charnockite Magnetite quartzite (equivalents of Sathyamangalam supracrustals)	

2. Mineralogy

Mineralogically, the BIFs are composed mostly of magnetite and quartz, are coarse- to fine-grained, have high hardness and specific gravity, are compact, dark-coloured, and strongly banded. A thin-section study of magnetite quartzites shows the presence of magnetite and quartz, predominantly, with minor amounts of grunerite (Fig 3a-f), hypersthene (Fig. 4a-f) in this banded iron formation. Magnetite and quartz occur in both granular and banded forms, with alternating layers of magnetite and quartz. Under the microscope, magnetite is isotropic and sometimes exhibits brushed extinction. The quartz minerals exhibit wavy extinction in aggregates of thin lamellae separated by laminae of Fe-silicates, magnetite, or both.

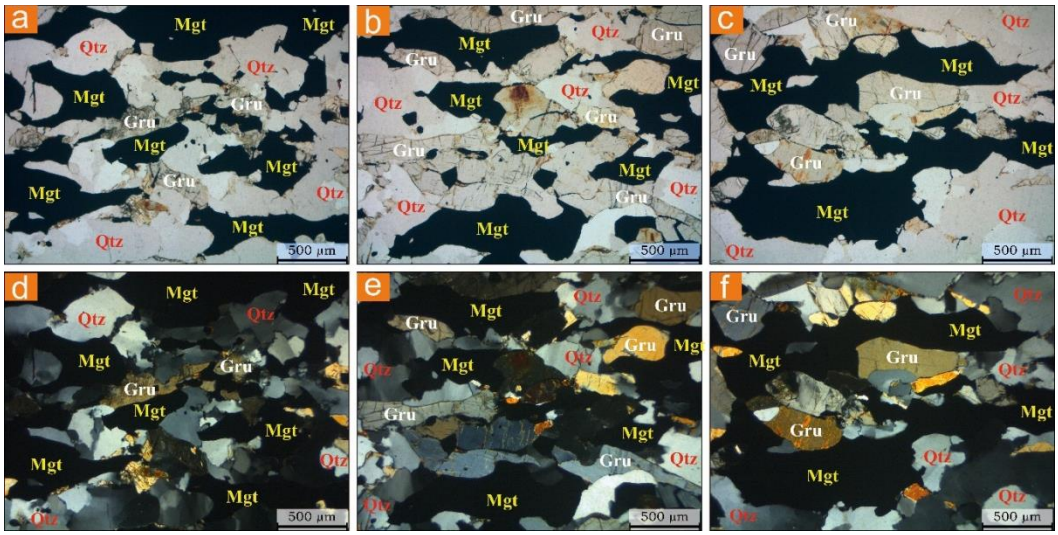

Fig. 3. Microphotograph shows the grunerite grains occurring between quartz and magnetite. a-c (PPL) & d-f (XPL)photomicrographs show an interlocking assemblage of magnetite, quartz, and grunerite. Grunerite occurs as subhedral to anhedral grains intergrown between quartz and magnetite, indicating equilibrium crystallization during regional metamorphism. Quartz forms recrystallized polygonal grains, whereas magnetite occurs as opaque anhedral to subhedral grains distributed throughout the rock.

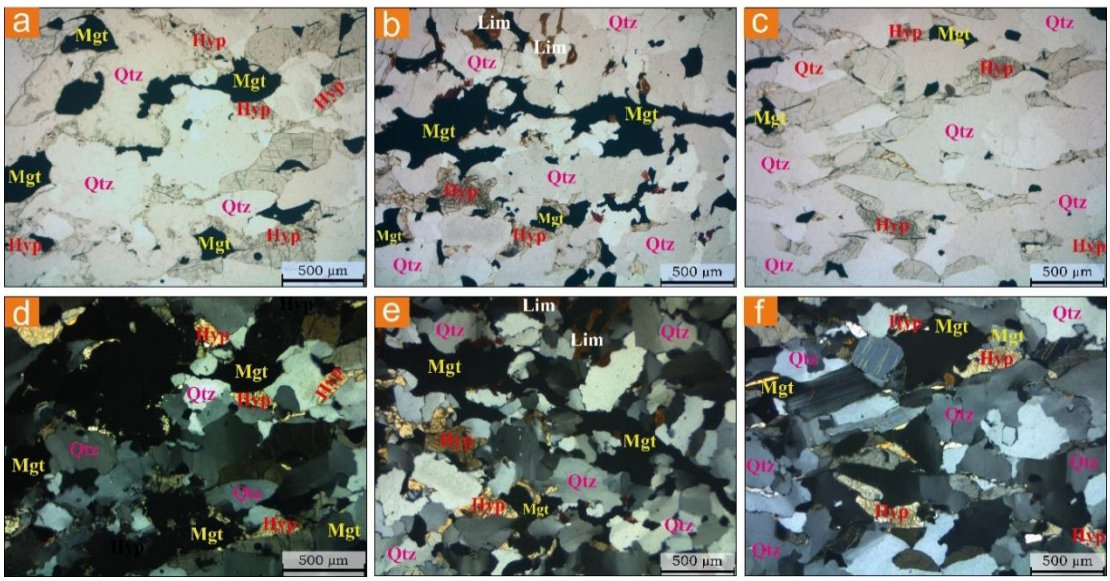

Fig. 4. Photomicrographs show the medium-grained porphyroblasts texture of iron silicate minerals, with hypersthene and limonite, under transmitted light. a-c (PPL) & d-f (XPL) photomicrographs show coarse-grained

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hypersthene porphyroblasts within a recrystallised matrix composed of quartz and magnetite. The magnetite minerals are seen as anhedral to subhedral grains, while the quartz minerals appear as polygonal recrystallised grains exhibiting first-order interference colours under XPL. Small amounts of limonite are observed as a secondary alteration mineral that replaces magnetite.

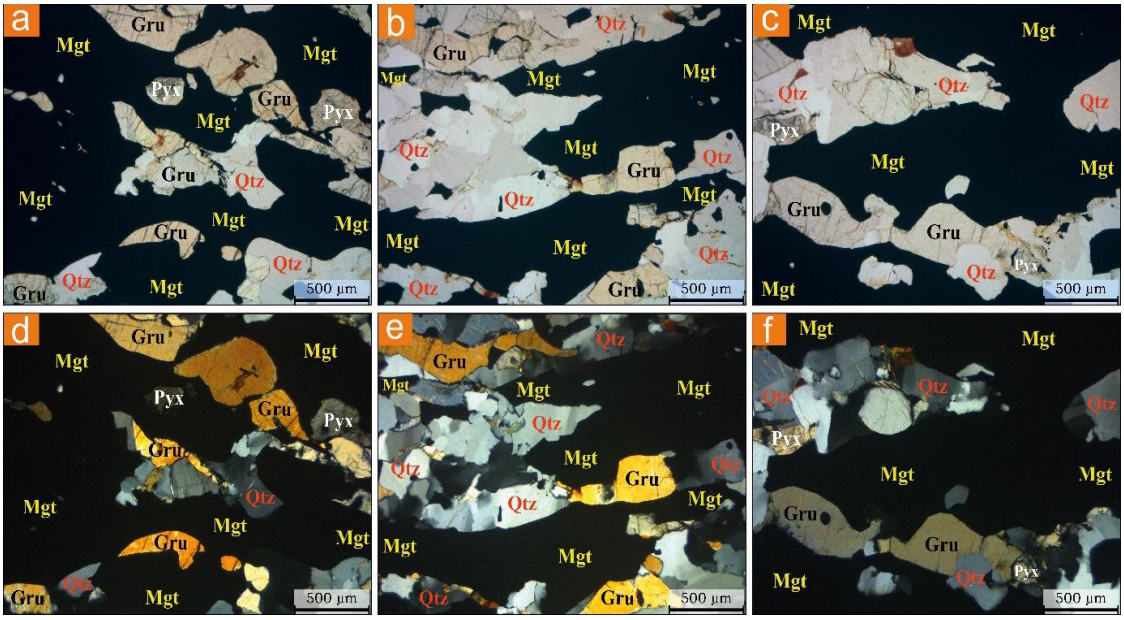

Fig. 5. Microphotograph shows the quartz mineral contains inclusions of magnetite with fibrous and needle texture of grunerite. a-c (PPL) & d-f (XPL) photomicrographs show fine-grained magnetite and quartz minerals, which exhibit first-order interference, while the grunerite shows a yellowish interference colour. The magnetite boundaries and cleavage planes are altered to hematite minerals.

The laminae probably represent a relic of micro banding. In some sections, magnetite is associated with hypersthene and grunerite, which are interstitial grains that occur between quartz and magnetite. In some cases, the magnetite occurs as thin bands, and quartz is found crushed near the contact with the magnetite laminations. It is concentrated in bands, and the grains are irregularly intergrown with each other. In a few sections, quartz contains numerous small inclusions of apatite and magnetite. The grunerite is a typical ferromagnesian silicate mineral, occurring as rounded grains and needles, and sometimes cutting across magnetite and quartz (Fig. 5a-f).

This variety of grunerite is probably of retrograde origin, as noted by Immega and Klein (1976). It is a ubiquitous mineral phase that shows a typical golden colour and a silky look. In some samples, hypersthene occurs in minor amounts. It occurs as coarse, subhedral grains rimmed by extremely fine-grained, asbestiform grunerite.

RESULT AND DISCUSSION

Interpretation of Major Elements

Chemical analysis of magnetite-quartzite of the Tirthamalai area is given in Tables 2a and 2b. In Table 3, their average chemical composition is compared with other iron formations of Kanjamalai iron formations (Rajendran 1996; Yellappa *et al.,* 2016; Gopinathan *et al.,* 2020). Tiruvannamalai (Subba Reddy and Sashidhar, 1989), Superior Lake (Gross and Mcleod, 1980), quartz magnetite of Isua iron formations (Dymek and Klein, 1988). These iron formations are similar to other banded iron formations worldwide. To distinguish the iron formations of the study area from post-Precambrian and Precambrian iron formations, the ternary plot of Al_2O_3-SiO_2-Fe_2O_3 (Govett, 1966) has been plotted: the BIF of the Tirthamalai area clearly fall within the Precambrian field (Fig. 6).

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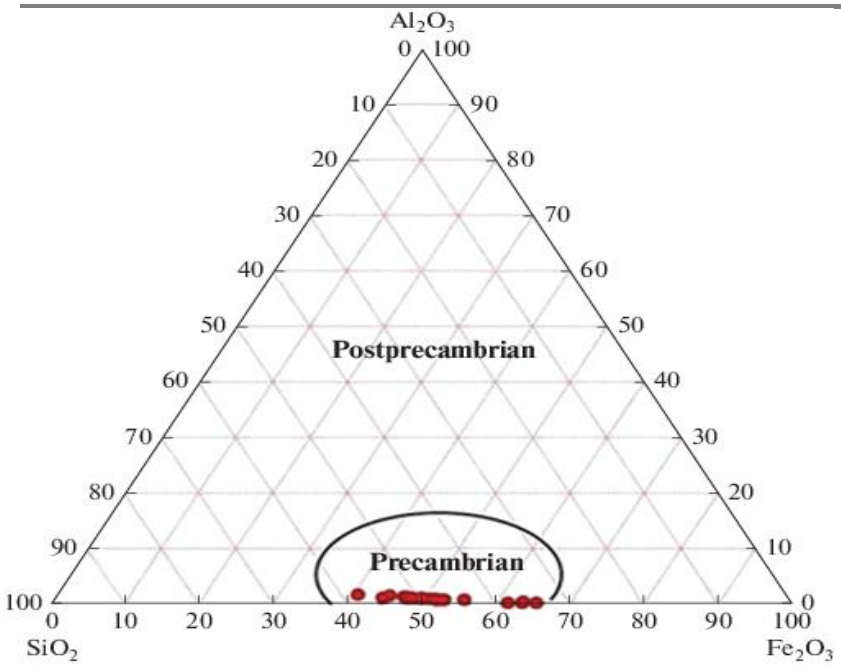

Fig. 6. Composition of Tirthamalai BIF (after Govett, 1966)

The average major element composition of the Tirthamalai region is compared with other iron formations of Kanjamalai, Superior Lake, quartz magnetite of Isua and Godumalai iron formations (Rajendran 1996; Rajendran *et al.,* 2007; Dymek and Klein, 1988; Gross and Macleod, 1980) and given in Table 3 and fig. 7. It can be observed that the iron formations of the study area are similar to other banded iron formations of the world.

Table 2a. Result of major elements (in wt. %) and trace elements (in ppm) analysis of BIF in the Study area

Elements	TM1	TM2	TM23	TM4	TM5	TM6	TM7	TM8	TM9	TM10	TM11	TM12	TM13	TM14	TM15	TM16	TM17	TM18	TM19	TM20
SiO_2	44.85	44.98	49.96	47.85	46.79	45.85	49.17	48.69	48.43	49.3	48.33	49.18	48.15	49.63	46.43	48.96	45.04	45.34	47.55	48.56
Al_2O_3	0.12	0.19	0.23	0.11	0.06	0.41	0.22	0.26	0.29	0.21	0.12	0.15	0.09	0.23	0.26	0.22	0.24	0.14	0.13	0.17
Fe_2O_3	54.01	54.34	48.42	50.03	50.55	52.43	49.78	48.72	47.96	48.72	49.11	47.69	51.02	49.43	52.2	47.73	53.31	51.64	51.62	49.96
MnO	0.014	0.054	0.07	0.12	0.041	0.13	0.022	0.063	0.014	0.029	0.067	0.018	0.013	0.016	0.019	0.09	0.03	0.02	0.06	0.06
MgO	0.29	0.56	0.24	0.63	0.24	0.44	0.58	0.37	0.54	0.63	0.46	0.49	0.53	0.43	0.34	0.66	0.65	0.52	0.64	0.42
CaO	0.39	0.32	0.34	0.21	0.39	0.32	0.25	0.63	0.47	0.46	0.72	0.31	0.36	0.26	0.39	0.49	0.32	0.38	0.31	0.24
Na_2O	0.07	0.06	0.08	0.09	0.22	0.06	0.03	0.09	0.23	0.02	0.05	0.05	0.03	0.08	0.03	0.06	0.07	0.03	0.04	0.06
K2O	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.026	0.22	0.04	0.01	0.02	0.04	0.09	0.02	0.02	0.04	0.02	0.01	0.01
TiO_2	0.016	0.024	0.019	0.013	0.022	0.021	0.04	0.019	0.021	0.036	0.025	0.019	0.01	0.024	0.022	0.023	0.05	0.021	0.014	0.011

P_2O_5	0.21	0.17	0.14	0.13	0.44	0.15	0.021	0.021	0.031	0.002	0.001	0.001	0.001	0.11	0.15	0.025	0.22	0.21	0.35	0.32
Total	99.98	100.70	99.50	99.19	98.77	99.83	100.14	98.87	98.20	99.44	98.89	97.92	100.24	100.30	99.86	98.27	99.97	98.32	100.72	99.81
Sc (ppm)	0.4	0.6	1.0	0.2	0.8	0.7	1.6	2.1	1.5	1.2	1.6	0.5	1.9	1.7	0.6	1.3	1.2	0.4	1.5	0.2
Cr	20.3	20.3	20.2	19.8	19.75	19.9	19.6	20.8	20.3	20.1	19.7	20.1	20.1	20	20.2	20.2	19.8	19.98	19.86	19.01
Co	1	1.65	1.05	2.85	4.98	1.93	2.03	2.1	1.96	0.99	1.97	0.92	0.99	1.01	11.86	1.95	0.97	1.03	1.01	1.75
Ni	20.11	20.05	19.6	19.5	19.8	19.8	19.8	20.4	20.1	20.6	19.68	19.8	20.7	19.8	20	50.1	20.3	19.8	19.7	20
Cu	9.7	9.8	9.7	9.8	10	10.1	10	9.9	9.7	10.1	10.3	10.2	10.4	10.1	10	10.2	9.8	9.9	70	10
Zn	30	29.7	29.7	30	30.5	30.4	30.2	30.2	30.2	30	29.9	29.9	29.7	29.8	30.1	30.1	30	30.2	29.8	29.8
Ba	6	11	8	21.23	17.36	35	10.02	9.03	24	5	20.2	5	12.1	3	17.01	5.01	6	6	12	39.36
V	4.86	9.9	7.03	16.9	6.01	6	4.92	5	4.94	5	6	5.95	5	6.89	9.67	17.56	4.95	5.05	6.89	9.01
Zr	3.87	4.95	4.9	7.01	3.96	3.87	4.07	4.03	4.01	4.02	3.98	3.96	3.94	4.03	7.01	4.99	4.96	5.82	5.25	6.36
Sr	12	7	2	23	6	5	5	5	2	5	4	6	5	2	5	5	3	7	3	7
Y	4	4	3	4	8	3	4	4	7	10.96	6	3	5	6	2	1.98	2	1.96	3	5
Rb	2.1	2.3	2	2..1	2.1	2.4	2.2	2	2.3	2.3	2.4	2.2	2.1	2.1	2	2	2.2	2.1	2.3	1

Table 2b. Result of bulk analyses of geochemical elements of BIF in the Study area

Elements	**TM 21**	**TM 22**	**TM 23**	**TM 24**	**TM 25**	**TM 26**	**TM 27**	**TM 28**	**TM29**	**TM30**	**TM 31**	**TM 32**	**TM 33**	**TM 34**	**TM 35**	**TM 36**	**TM 37**	**TM 38**	**TM 39**	**TM 40**
SiO_2	50.25	52.7	42.98	42.02	46.19	49.63	48.39	49.51	49.99	41.89	54.82	50.41	43.84	51.15	46.85	44.37	43.51	52.49	51.96	41.41
Al_2O_3	0.12	0.35	0.22	0.23	0.48	0.17	0.19	0.34	0.22	0.08	0.17	0.21	0.09	0.09	0.15	0.12	0.09	0.19	0.15	0.16
Fe_2O_3(T)	50.04	48.03	55.05	55.19	52.19	48.51	51.84	51.45	49.68	58.25	43.87	49.18	51.12	48.81	49.36	53.06	55.05	47.27	46.16	55.56
MnO	0.047	0.038	0.066	0.032	0.047	0.029	0.046	0.051	0.036	0.078	0.026	0.046	0.077	0.036	0.048	0.035	0.081	0.04	0.033	0.026
MgO	0.17	0.15	0.22	0.74	0.18	0.06	0.09	0.29	0.07	0.07	0.06	0.2	1.76	0.08	1.29	1.33	1.21	0.15	0.04	1.54
CaO	0.21	0.21	0.14	0.73	0.27	0.12	0.1	0.23	0.13	0.1	0.11	0.27	2.03	0.06	0.57	0.48	1.05	0.08	0.08	0.72

Na_2O	0.06	0.08	0.09	0.08	0.11	0.08	0.06	0.09	0.07	0.04	0.06	0.07	0.05	0.07	0.11	0.07	0.07	0.089	0.05	0.06
K_2O	< 0.01	0.01	0.04	0.06	0.05	< 0.01	0.02	0.01	< 0.01	0.04	< 0.01	0.06	0.01	< 0.01	0.04	< 0.01	0.04	0.04	0.04	0.01
TiO_2	0.013	0.035	0.022	0.022	0.074	0.018	0.021	0.037	0.022	0.009	0.018	0.022	0.01	0.01	0.054	0.046	0.012	0.014	0.013	0.013
P_2O_5	0.15	0.04	0.15	0.18	0.1	0.09	0.05	0.06	0.16	0.13	0.11	0.15	0.24	0.04	0.07	0.27	0.26	0.06	0.17	0.3
LOI	-1.63	-0.69	-0.46	0.39	0.22	0.62	-0.21	-1.47	0.39	-0.63	0.27	-1.43	-0.35	-1.29	0.18	0.22	-1.22	-1.4	0.53	-0.75
Total	99.43	100.9	98.53	99.66	99.9	99.3	100.6	100.6	100.7	100.1	99.53	99.17	98.89	99.05	98.72	99.99	100.2	99.02	99.23	99.04
Sc(ppm)	< 1	1	< 1	< 1	1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	2	< 1	< 1	< 1	< 1
Be	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
V	< 5	10	7	17	6	6	< 5	< 5	< 5	< 5	6	6	< 5	7	10	17	< 5	< 5	7	9
Ba	6	11	8	21	17	35	10	9	24	5	20	5	12	< 3	17	5	6	6	12	40
Sr	7	5	2	12	6	5	2	5	5	5	4	7	7	< 2	5	5	6	3	3	23
Y	3	11	3	4	2	3	4	4	7	< 2	< 2	3	5	4	< 2	5	6	8	4	6
Zr	< 4	5	< 4	< 4	4	< 4	< 4	4	< 4	< 4	5	< 4	6	5	< 4	7	7	< 4	< 4	7
Cr	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Co	< 1	2	1	3	5	2	2	2	2	1	2	1	< 1	< 1	12	2	< 1	< 1	1	< 1
Ni	< 20	< 20	< 20	50	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20	< 20
Cu	< 10	< 10	< 10	< 10	< 10	< 10	70	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Zn	< 30	< 30	< 30	30	< 30	< 30	< 30	< 30	< 30	< 30	< 30	< 30	< 30	< 30	30	< 30	< 30	< 30	< 30	< 30
Ga	< 1	< 1	1	3	12	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	4	1	< 1	< 1	< 1	< 1
Ge	7	2	3	4	3	2	2	2	2	2	2	7	4	2	4	4	4	2	2	4
As	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	21	< 5	< 5	< 5	23	< 5	< 5	< 5
Rb	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Nb	1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Mo	< 2	< 2	< 2	< 2	< 2	< 2	2	< 2	2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ag	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<	<

	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
In	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Sn	< 1	9	< 1	1	< 1	< 1	< 1	< 1	< 1	7	< 1	4	1	< 1	< 1	4	< 1	2	1	1

Table 3. Comparison of average major elements of iron formations (wt %) with other world iron formations

Elements	Kanjamalai	Lake Superior	Isua	Godumalai	Tirthamalai
SiO_2	45.06	57.66	61.99	45.42	48.00
Al_2O_3	2.45	0.28	0.54	0.37	0.19
Fe_2O_3	39.64	38.29	19.95	41.14	51.00
MgO	2.24	0.01	1.84	1.28	0.04
CaO	1.61	0.02	1.13	0.58	0.38
MnO	0.16	0.06	0.14	0.25	0.04
Na_2O	0.14	0.01	0.04	0.29	0.07
K_2O	0.06	0.02	0.16	0.19	0.03
P_2O_5	0.15	0.05	0.18	0.28	0.14

1. Average Kanjamalai iron-formation (Rajendran, 1996)
2. Average Lake Superior silicate facies iron-formation fromNorth America (Gross and Macleod, 1980)
3. Average Quartz-Magnetite IF of Isua (10 analyses) Dymekand Klein (1988)
4. Average Godumalai iron-formation (Rajendran et al, (2007)
5. Average Tirthamalai iron formation (oxide facies), N=40 (thisstudy).

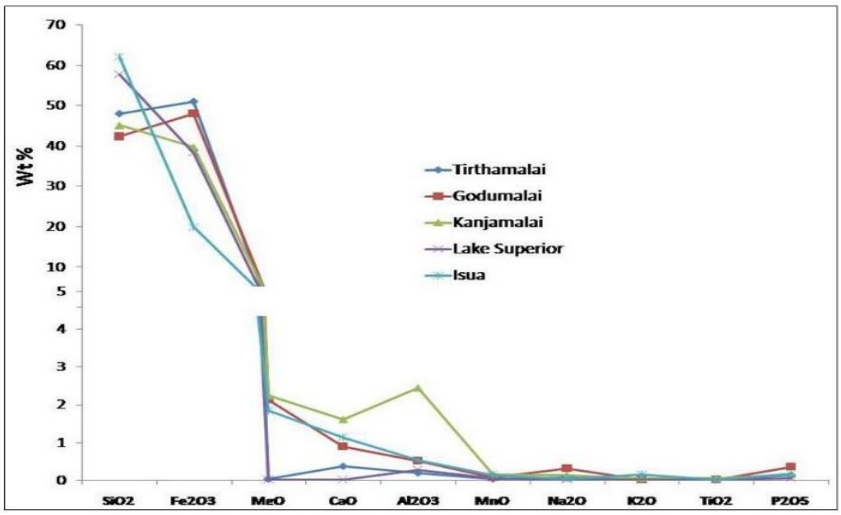

Fig. 7. Average major elements of Tirthamalai iron formations are compared with those of other iron formations of the world.

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Wang *et al.,* 2016; Barrote et al., 2017, showed a positive correlation between oxides pairof TiO_2-Al_2O_3 in the analyses of iron formation samples of Hammersly Basin, Australia. They interpreted that the increasing concentration of TiO_2 and Al_2O_3 reflects the contribution of higher amounts of a clastic 'contaminant' to the iron formation. Fig. 8 shows a corresponding plot of samples from iron formations in the Tirthamalai and Isua regions. In which the samples of Tirthamalai iron formations show positive correlation, and an increase in Al_2O_3 and TiO_2 values indicates the contribution of higher amounts of clastic contaminants. However, the clastic contaminants are relatively less abundant in the Tirthamalai iron formation than in the clastic metasediments and amphibolites of the Isua region (Dymek and Klein, 1988).

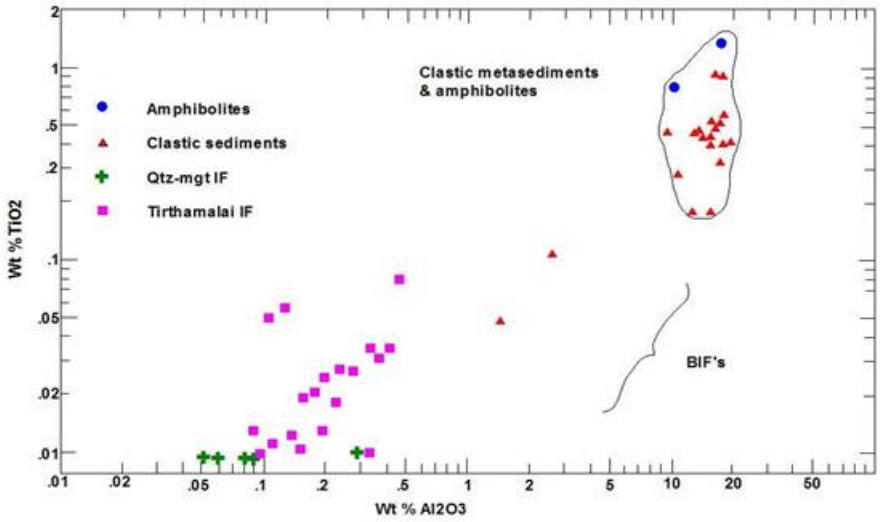

Fig. 8. Plot of wt.% TiO_2 vs. wt. % Al_2O_3 in analysed samples of Tirthamalai iron formations. Data for clastic metasediments (triangular red) and amphibolites (circle blue) are taken from Boak and Dymek (1982). Data for Qzt-mag IF of Isua are taken from Dymek and Klein (1988). The samples of Tirthamalai iron formations show an increasing trendand contribution of 'clastic' contamination.

Interpretation of Ferride Group Elements

The analyses of ferride group elements of Tirthamalai iron formations are interpreted with other iron formations of northern districts of Tamil Nadu state. The concentrations of ferride group elements, namely Mn, Ni, Ti, Co, Cr and V. The Minimum, maximum and average values of such elements in the iron formations of Tirthamalai, Godumalai, Tattayyangarpettai, Vellalakundam and Kanjamalai regions of the northern districts of Tamil Nadu state, India, are given in Table 4. The samples of the Tirthamalai region show the ranges as Mn (201 - 627 ppm); Ni (20 - 50 ppm); Ti (54 – 444 ppm); Co (1 - 12); Cr (20 -20 ppm) and V (5 - 17 ppm).

Table 4. Comparison of the minimum, maximum and average values (inppm) of ferride group elements of Tirthamalai iron formations with other iron formations of Tamil Nadu.

Name of Regions		Mn	Ni	Ti	Co	Cr	V
Tirthamalai	Max	627.00	20.00	444.00	12.00	20.00	17.00
	Min	201.00	50.00	54.00	1.00	20.00	5.00
	Avg	356.00	21.50	146.00	2.20	20.00	7.40
Godumalai	Max	488.00	62.00	564.00	5.00	102.00	20.00
	Min	225.00	-20.00	30.00	-1.00	20.00	-5.00

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	Avg	310.00	20.00	311.00	3.14	38.00	9.80
Tattayangarpettai	Max	705.00	138.00	1067.00	-11.00	144.00	47.00
	Min	217.00	-20.00	60.00	-1.00	-20.00	-5.00
	Avg	362.00	36.00	403.00	3.85	52.28	16.85
Vellalagundam	Max	356.00	41.00	1635.00	8.00	41.00	57.00
	Min	186.00	-20.00	60.00	-1.00	-20.00	-5.00
	Avg	252.00	-2.80	572.00	2.66	13.30	15.33
Kanjamalai	Max	140.00	72.00	500.00	21.00	202.00	32.00
	Min	31.00	8.00	10.00	4.00	41.00	16.00
	Avg	86.56	53.75	155.81	13.62	115.43	22.43

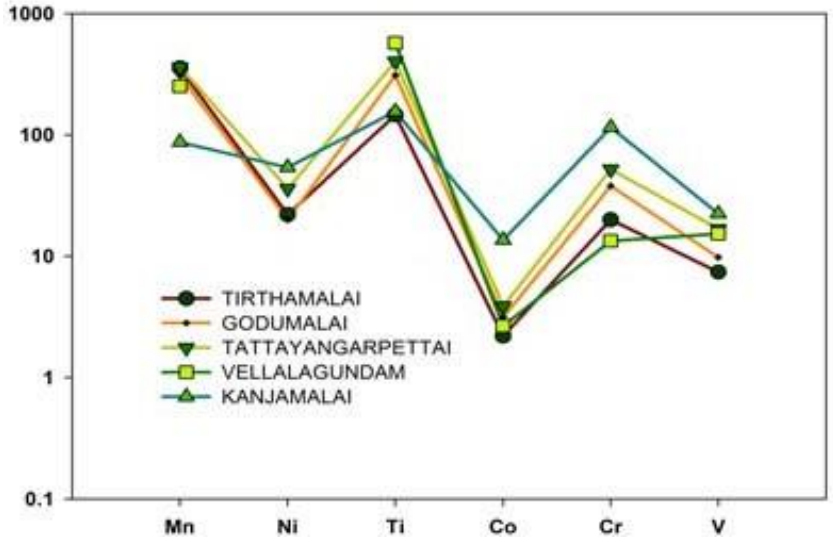

Fig. 9. Comparison of Average concentrations of ferride group of elements of iron formations of northern districts of Tamil Nadu.

The samples of the Godumalai region show the concentration of elements in the range of Mn (225-488 ppm); Ni (-20-62 ppm); Ti (30-564 ppm); Co (1-5 ppm); Cr (20-102 ppm); and V (-5-20 ppm), respectively. The results show that all samples exhibit low concentrations compared to other iron formations. The Tattayangarpettai region shows the range of concentration of ferride group elements as Mn (217-705 ppm); Ni (-20-138 ppm); Ti (60-1067 ppm); Co (-1-11 ppm); Cr (-20-144 ppm) and V (20-102 ppm), which shows a similar trend with the samples of the Godumalai region. The Vellalagundam region shows the range of concentration as Mn (186-356 (-20- 144 ppm); Ni (-20-41 (-20-144 ppm); Ti (60-1635 ppm); Co (-1-8 ppm); Cr (-20-41 ppm); and V (-5-57 ppm), respectively. The Kanjamalai region shows the concentration of such elements in the range of Mn (31-140 ppm); Ni (8-72 ppm); Ti (10-500 ppm); Co (4-21 ppm); Cr (41-202 ppm); and V (16-32 ppm) and their distributions are given in fig. 9 shows the average concentrations of ferride group elements of alliron formations of northern district of Tamil Nadu. The results of interpretation of samples of all regions show not much variation among the formations in the concentration of ferride group of elements and exhibits similar trends. The low concentrations of these elements indicate that the materials are derived from weathering of landmasses, not from volcanic sources. These iron formations are later metamorphosed. Among the elements, the Ti and Cr are enriched compared to other elements are indicating that the iron formations of the study area are of meta-sedimentary origin (Saravanan,1969; Krishna Rao

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and Kasipathi, 1991 and Rajendran 2000, 2008). LanderGren (1948) suggested that the low concentration of these elements in many iron formations of central Sweden indicating the sedimentary origin.

The average concentrations of ferride group elements of the Tirthamalai region are compared with those of iron formations of Godumalai, Tattayangarpettai, Vellalagundam, Kanjamalai, Kemmangundi, Ongole, Salem and Central Sweden (Table 5 and Fig. 10). The samples from the study region show a trend similar to that of other regions of the world and indicate a meta-sedimentary origin (Anjanaeya Sastry et al., 1970; Rama Rao, 1971; Thirunavukkarasu *et al.,* 2008).

Table 5. Comparison of average concentrations of ferride group ofelements (in ppm) with other iron formations of the world.

Name of regions	Mn	Ni	Ti	Co	Cr	V
Tirthamalai	356.00	21.50	146.00	2.20	20.00	7.40
Godumalai	310.00	20.00	311.00	3.14	38.00	9.80
Tattayangarpettai	362.00	36.00	403.00	3.85	52.28	16.85
Vellalagundam	252.00	-2.80	572.00	2.66	13.30	15.33
Kanjamalai	86.56	53.75	155.81	13.62	115.43	22.43
Kemmangundi	359.00	34.50	250.00	10.00	97.00	111.00
Ongole	228.00	10.00	40.15	10.00	63.00	11.33
Salem	238.00	10.00	30.19	10.00	222.00	38.00
Sweden	457.00	0.00	75.00	10.00	20.25	13.00

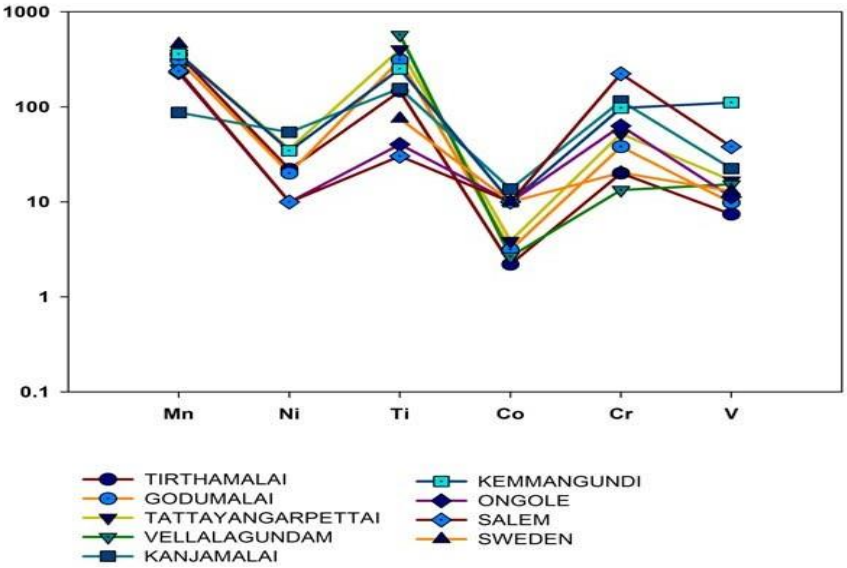

Fig. 10. Comparison of ferride group of elements of Tirthamalai iron formations with other iron formations of theworld.

Origin of Banded Iron Formations (BIFs)

The mineralogical, textural, and geochemical characteristics of the magnetite quartzites in the study area collectively suggest a meta-sedimentary origin, followed by extensive metamorphic modification under high-

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grade metamorphic conditions. The mineral assemblage, consisting predominantly of quartz, magnetite, grunerite, and hypersthene, indicates that the original iron-rich sediments underwent recrystallization and mineralogical transformation during metamorphism. The elongated quartz grains, aligned parallel to the compositional banding and containing magnetite inclusions, provide evidence of recrystallization and deformation. These textural characteristics further suggest that silica was initially deposited in a colloidal or gel-like form before undergoing diagenetic and metamorphic transformation. The development of magnetite and associated silicate minerals is therefore interpreted as a consequence of subsequent metamorphic processes rather than direct primary crystallisation.

The association of grunerite and hypersthene with magnetite and quartz provides additional evidence for metamorphic re-equilibration of the original iron-rich sedimentary assemblage. The occurrence of these minerals suggests that the precursor iron formation experienced elevated temperature conditions, potentially associated with regional metamorphism and thermal influence from the surrounding granulites and granitic gneisses. The formation of grunerite-bearing assemblages through metamorphic transformation of iron-rich quartzites has also been documented in high-grade terrains of Salem and other parts of southern India. In the present study area, the ubiquitous occurrence of grunerite, together with magnetite and quartz, supports the interpretation that the original chemical sediments were subsequently modified under high-grade metamorphic conditions. The development of the present mineral assemblage may so reflect metamorphic recrystallization and mineral reactions involving the original iron- and silica-rich sedimentary components.

The compositional banding observed in the magnetite quartzites is considered to have originated from variations in the depositional conditions of the precursor sediments. Periodic fluctuations in basin-water chemistry, sediment supply, and climatic conditions may have controlled the alternating accumulation of iron-rich and silica-rich layers. The preservation of sharp and well-defined contacts between quartz-rich and magnetite-rich bands, together with the observed cyclic nature of the banding, supports an original sedimentary layering that was subsequently modified by metamorphism. Although metamorphic recrystallization has modified the mineral textures, the compositional layering and associated clastic features indicate that the primary sedimentary character of the iron formation has been largely preserved.

The whole-rock geochemical characteristics provide further support for this interpretation. The Al_2O_3–SiO_2–Fe_2O_3 ternary relationship indicates relatively high proportions of iron and silica accompanied by low Al_2O_3 concentrations, which are characteristic of chemically precipitated iron formations. Furthermore, the magnetite quartzites exhibit low concentrations of Al_2O_3, CaO, MnO, Na_2O, and K_2O. The depletion of these elements indicates limited contributions from terrigenous aluminosilicate material and does not support a substantial volcanogenic component. The relatively low abundance of these major oxides, combined with the predominance of iron and silica, suggests that the precursor sediments were derived mainly from chemical accumulation in a sedimentary basin. The absence of convincing mineralogical and geochemical evidence for significant volcanic input further weakens a volcanogenic interpretation.

The trace-element characteristics of magnetite also provide an important constraint on the depositional origin. The relatively low concentrations of ferride-group trace elements in magnetite from the magnetite quartzites, compared with their higher concentrations in magnetite associated with pyroxene granulites, indicate differences in their respective geological origins. This distinction supports the interpretation that the magnetite quartzites represent a meta-sedimentary iron formation rather than a direct product of meta-volcanic activity. In the absence of convincing evidence for a significant volcanic contribution, the supply of iron and silica through the chemical weathering of continental landmasses provides a plausible mechanism for the formation of the precursor sediments. Intensive chemical weathering of exposed continental crust could have released substantial quantities of dissolved iron and silica, which were subsequently transported into a sedimentary basin and accumulated through chemical precipitation.

Considering the mineralogical assemblage, textural relationships, compositional banding, and major- and trace-element geochemistry, the iron formations of the study area are interpreted as metamorphosed chemical sediments of meta-sedimentary origin. Their present mineralogical characteristics reflect subsequent high-grade metamorphism, which resulted in the recrystallization of quartz, formation of magnetite, and development of grunerite- and hypersthene-bearing assemblages. The low concentrations of alumina and other major oxides,

limited evidence of volcanic contribution, and characteristic iron–silica enrichment collectively support a predominantly sedimentary precursor. So, the magnetite quartzites are interpreted to have originated through chemical precipitation of iron and silica in a sedimentary basin, potentially influenced by continental weathering and periodic variations in basin chemistry, followed by regional metamorphism and possible thermal modification associated with surrounding granulites and granitic gneisses.

CONCLUSION

The integrated geological, petrographic, mineralogical, and geochemical investigations indicate that the Tirthamalai Banded Magnetite Quartzite (BMQ) formations occur as four distinct bands associated with charnockite, granulite, epidote–hornblende gneiss, and granitic rocks. Their dominant magnetite–quartz assemblage, characteristic compositional banding, and high Fe_2O_3 (43.87–58.25 wt.%) and SiO_2 (41.41–54.82 wt.%) contents, together with low Al_2O_3 concentrations, support a predominantly chemical sedimentary origin with limited terrigenous input. The trace-element characteristics further suggest a metasedimentary rather than a direct volcanogenic origin. The formations are therefore interpreted as metamorphosed chemical sediments formed through the precipitation of iron and silica in a sedimentary basin, followed by regional high-grade metamorphism and deformation. These findings provide important insights into the origin and geological evolution of Precambrian iron formations within the Southern Granulite Terrain of Tamil Nadu.

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