JOURNAL INDIAN ASSOCIATION OF SEDIMENTOLOGISTS ISSN NO 2582 – 2020
Vol. 38, Issue 2, 2021, pp. 49-62
DOI: https://doi.org/10.51710/jias.v38i2.134

Geochemistry and tectonic setting for the deposition of IOG siliciclastics at the western margin of Bonai Granite, Singhbhum-Orissa Craton, India

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Abstract

Bagiyabahal and Birtola areas are located in the south-western extension of the Noamundi-Koira Iron Ore Group (IOG) basin. Rock types exposed in the area comprises of siliciclastics and volcanics which occurs unconformably over the basement tonalite-trondhjemite granite-gneiss (Bonai Granite Phase-I). The cover rocks show sheared contact with the porphyritic Bonai Granite Phase-II. The IOG basin margin is suggested to be a part of a 'volcanic passive margin' as indicated by the geochemical behaviour of the siliciclastics as well as massive emplacements of mafic intrusives (doleritic sill, dyke and gabbro) and extrusives (basaltic lava flow) along faulted continental blocks. The siliciclastics comprise of U and Au bearing quartz-pebble conglomerate (QPC) and quartzite succession. It was deposited along the western margin of the Bonai granite (phase I) in anoxic conditions as indicated by their low Th/U ratios and presence of detrital uraninite grains. Repeated cycles of sedimentation and volcanism led to the formation of alternate layers of siliciclastics and basic bodies in the area. Major, trace and rare earth elements (REE) geochemical data suggests a semi-humid to humid palaeo-climatic environment of during the deposition in the passive continental margin setting characterized by fault-controlled sedimentation over a rift related faulted continental crust and shelf. Geochemical data suggests chemically weathered provenance dominated by clay minerals. Higher content of U, Th, Au, Cr, REE, platinum group of elements (PGE) and other geochemical ratios suggest a mixed provenance for the deposition of the siliciclastics comprising a predominantly acidic/granitic source possibly from the Bonai Granitic Complex (BGC) along with granite derived reworked quartzose sediments, minor basic and ultrabasic sources of Older Metamorphic Group (OMG). This paper attempts to characterize the geochemical behaviour, tectonic setting and provenance of the siliciclastics of Birtola and Bagiyabahal areas by analyzing drill core and surface samples.

Keywords: Siliciclastics, Provenance, QPC, Diagram, Tectonic

INTRODUCTION

Geochemistry is a useful tool for determination of the provenance and tectonic setting for the deposition of sedimentary rocks (Bhatia, 1983; Bhatia and Crook, 1986, Roser and Korsch, 1986, 1988, Nesbitt et al., 1996). The Singhbhum Orissa Craton hosts several granite-greenstone assemblages with overlying metasediments as IOG rocks (Saha, 1994). The Noamundi-Koira IOG rocks are situated at the western part of the Singhbhum Orissa Craton. The geology and stratigraphy of the area to the north-west of BGC have been studied by several workers (Mahalik, 1987; Sengupta et al., 1991; Sarkar and Saha, 1992; Chakrabarti et al., 2001, Naik, 2001, Saha et al., 2004, Kundu and Matin, 2007; Kumar et al., 2009). The Noamundi-Koira IOG is also favourable for U-Au-Ag-PGE-REE bearing QPC lithounits at the base of IOG (Kumar et al., 2009, Kumar et al., 2011, Jana et al., 2016) in the Singhbhum-Orissa Craton. The geochemical characteristics as well as the tectonic setting for deposition of QPC and quartzite lithounits of the Noamundi-Koira IOG basin in this part of Singhbhum-Orissa Craton around Bagiyabahal and Birtola areas have remained the least studied so far. In this study we have carried out geochemical analysis of drill core and surface samples of Makarchua-Balisura tract (comprises of Bagiyabahal sector and Birtola sector) in order to understand the geochemical characteristics, provenance of the siliciclastics and establish the tectonic model for its deposition along the basin margin.

Regional Geology

Geologically the study area of entire Makarchua-Balisura tract is situated along the western margin of Bonai Granite in the western part of Singhbhum-Orissa Craton and it is thought to be the south-western extension of the Noamundi-Koira IOG basin. The IOG rocks rest unconformably over the Archaean basement of tonalite-trondhjemite (migmatitic at places) variety of Bonai Granite Phase-I (3369±57 Ma) (Sengupta et al., 1991) and intruded by porphyritic granite/granodiorite variety of Bonai Granite Phase-II (3163±126 Ma) (Sengupta et al., 1991, Sarkar and Saha, 1992) which is evidenced by the presence of large enclaves of IOG quartzite, pelitic metasediments, meta-lava and amphibolite within the porphyritic Bonai Granite (Saha, 1994).The volcano-sedimentary succession of IOG is unconformably overlain by the Darjing Group of rocks in the north

(Mahalik, 1987). The 2.8 Ga old Tamperkola Granite intruded both the Darjing and IOG rocks (Bandyopadhyay et al., 2001). U–Pb LA-ICPMS age from the acid volcanics of western IOG suggests an age of 3.29 Ga (Basu et al., 2008). The IOG rocks are whereas the few enclaves of Bonai Granite Phase-I are exposed as small patches within the Bonai Granite Phase-II.

IOG Siliciclastics

The IOG siliciclastic rocks of Bagiyabahal and Birtola area consist of intermittently exposed polycyclic, matrix supported, oligomictic, radioactive QPC bands hosted in matured quartzite (Jana et al., 2016) (Fig. 2). Apart from the radioactive basal QPC band (which is prominently exposed and comparatively thicker), several thin interlayered radioactive QPC layers and lenses of varying dimensions have also been located within the IOG quartzite suggesting a palaeochannel controlled cyclic deposition of sediments. The thickness of the QPC bands varies from 30cm to 3m. The QPC is matrix supported, oligomictic, comprising slightly stretched, sub-rounded to well-rounded clasts of vein quartz, greyish black coloured smoky quartz pebbles with iron oxide stains (Fig. 4a, b). Matrix is mostly siliceous and micaceous (sericite, chlorite, fuchsite, biotite and muscovite) with goethite at places and with pyrite. Sericite and chlorite are the most dominant flaky minerals in matrix along with quartz exhibiting crude schistosity (S_1) which is parallel to the strike of the

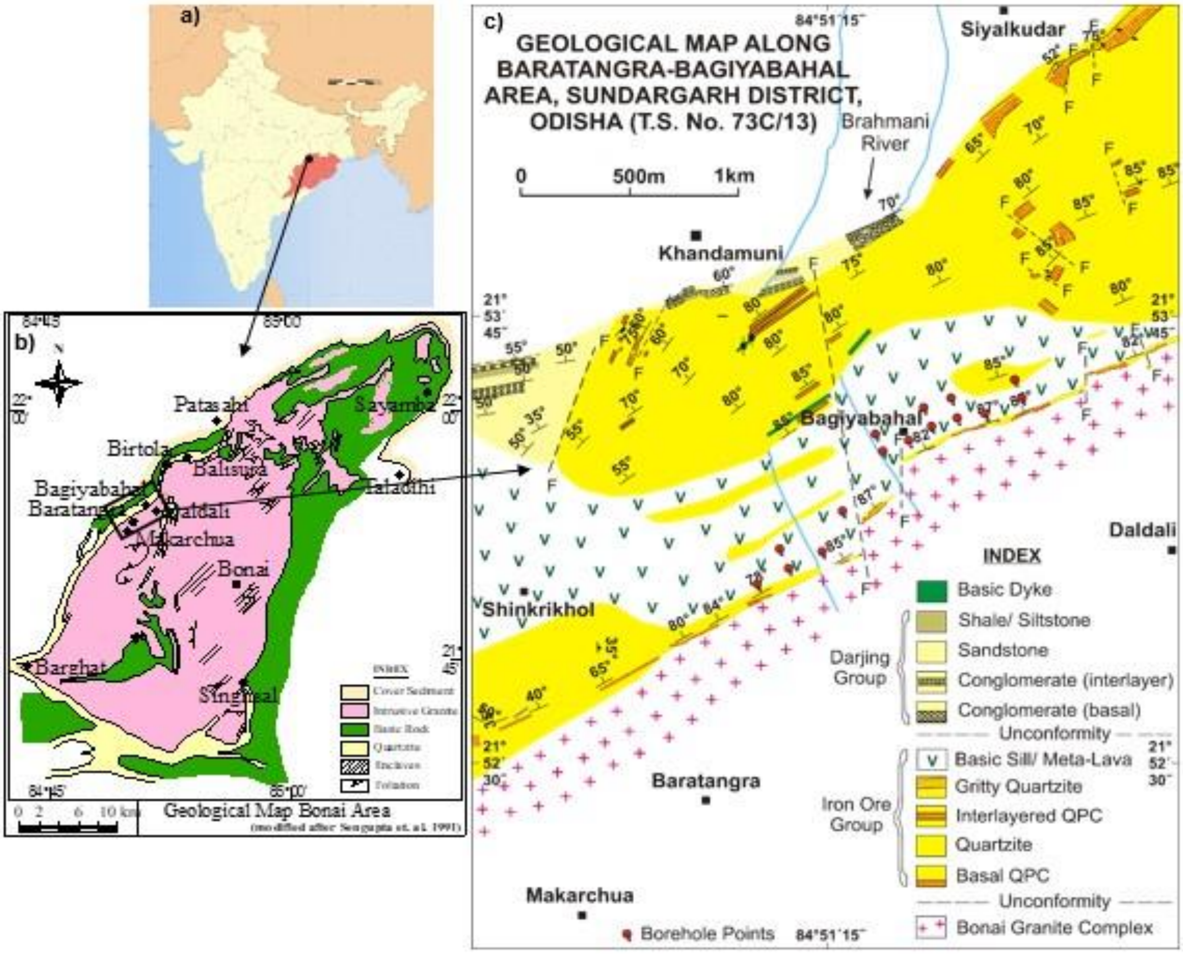

Fig. 1a)- Study area shown in India map, b) Geological Map along entire Makarchua- Balisuratract and c) along Makarchua – Daldali tract showing borehole points around Bagiyabahal, Baratangra areas, Sundargarh district, Odisha

devoid of iron ore and mostly represented by QPC, quartzite, quartz-sericite schist and intercalated meta-basic lavas exposed in a series of hills trending in NE-SW to ENE-WSW direction with dips 40º-80º due NW/NNW all along the western margin of BGC. The IOG metasediments are intruded by several younger basic dykes and sills (Fig. 1a, b, c, Table. 1). The QPC-quartzite succession is exposed over a strike length of approximately 8km from Makarchua in the west to Balisura in the east over the BGC (Kumar et al., 2009, Jana et al., 2016) (Fig. 1b). The QPC-quartzite succession of the Makarchua-Balisura tract is displaced by a regional N-S fault along the Birtola-Daldali section which bifurcates the entire succession into two parts (i) Bagiyabahal sector (Makarchua-Bagiyabahal-Daldali tract) and (ii) Birtola sector (Birtola-Balisura tract) (Fig. 1b, c). Darjing Group is represented by Birtola, Kumakela and Jalda Formation (Mahalik, 1987). Bonai Granite Phase-II covers the vast area of the terrain

Table. 1- Stratigraphic succession of Baratangra-Bagiyabahal area (after Sarkar and Saha, 1992)	
Birtola Formation (Darjing Group)	Feldspathic quartzite and conglomerate
	Green schist conglomerate and greenish quartzite
	Conglomerate and quartzite
Unconformity	
Dolerite dykes, basic sills, ultrabasics, aplite and pegmatitic veins	
Bonai Granite II (Potassic porphyritic granite, 3.16 Ga)	
Iron Ore Group (Conglomerate, quartzite and metabasic lava)	
Unconformity	
Bonai Granite I (Tonalitic grey gneiss, 3.3 Ga)	

QPC-quartzite bedding (S_0). Pebble-matrix ratio is approx. 1:4 (by volume). Reduction in clast size (7.5cm to 0.3cm) and increase in the content of vein quartz clast are observed from the basal QPC to interlayered QPC lithounit towards the top of the succession. Sub-rounded, detrital uraninites are associated with other subrounded to rounded heavy minerals, viz. monazite, magnetite, pyrite, rutile, ilmenite and zircon in the QPC matrix as palaeoplacers (Jana et al., 2016) (Fig. 4c).

Fig: 2- Radioactive basal QPC exposed in Brahmani riverbed near Baratangra

Fig: 3- Trough cross-stratified quartzite of IOG exposed near Khandamuni

Quartzite is the major siliciclastics of the 'iron ore barren' IOG which is exposed in a series of hills of Bagiyabahal and Birtola areas trending in NE-SW to ENE-WSW direction with dip of 40º-88º due NW/NNW. The quartzite shows steep dipand shearing near the contact zone with granite but dip decreases towards the centre of the basin. Quartzite occurs in

Fig. 4a, b: Stretched smoky quartz pebble in the radioactive QPC core samples, Baratangra and c: Detrital, broken uraninite grains (U) in QPC, Bagiyabahal. TL, 1N, 10X different varieties e.g. fuchsitic sericitic, pure massive, fine grained, gritty and also as fine layers/bands at places. Deformation and higher amount of chlorite and mica (sericite and fuchsite) minerals often turned the quartzite to quartz-chlorite-sericite schist and quartz-sericite schist (± fuchsite). These two varieties are dominantly exposed at the surface as well as intercepted in the drill cores. Foliation parallel to the regional strike of the formation (S_0) (N65°E- S65°W) is present in quartzite.In Bagiyabahal - Baratangra sector, the quartzite is massive near the lower part of the succ-

Major Oxides

The major elemental parameters of QPC and quartzite have been used to understand the tectonic settings of different sedimentary environments (Bhatia, 1983, Roser and Korsch, 1986). The QPC drill core samples have been sub-divided into two categories according to matrix composition (especially on the content of phyllosilicate minerals as well as Al_2O_3) e.g. i) QPC with sericitic matrix and ii) QPC with siliceous matrix.

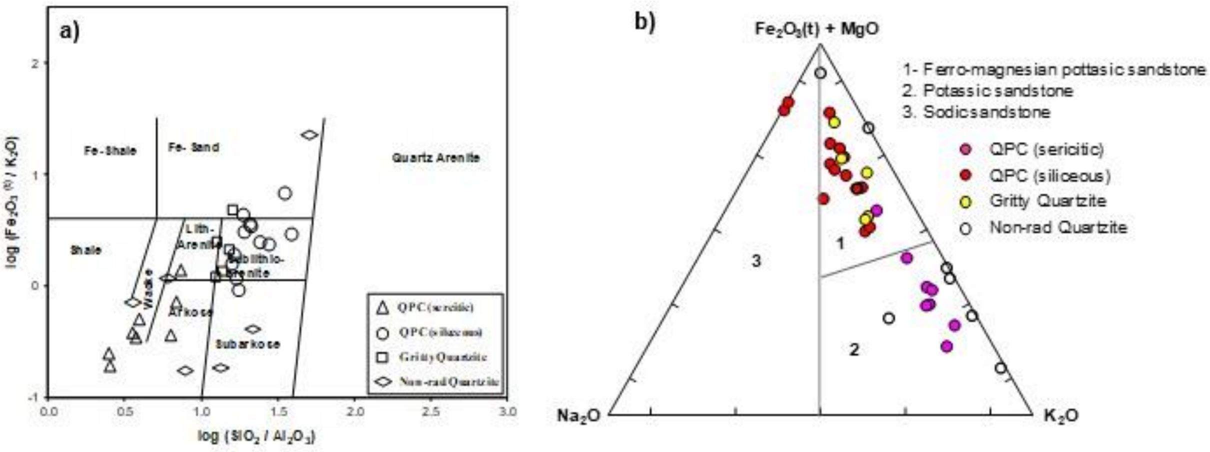

Fig. 5 Classification diagrams a) - log(Fe_2O_3(t)/K_2O) vs log(SiO_2/Al_2O_3) diagram of radioactive QPC (with siliceous and sericitic matrix), gritty quartzite and non-radioactive quartzite of Bagiyabahal and Birtola Blocks (after Heron, 1988) and b)- Fe_2O_3(t)+MgO vs Na_2O vs K_2O ternary diagram for classification of radioactive QPC (with siliceous and sericitic matrix), gritty quartzite and non-radioactive quartzite of Bagiyabahal and Birtola Blocks (after Blatt, 1972)

ession and almost devoid of any primary sedimentary feature due to intense silicification. Few crudely developed plane bedding, low angle planar cross bedding in quartzite and crude graded bedding in basal QPC band have been observed at places indicating high energy flow regime. From middle to upper part of the succession massive to mostly trough cross bedded quartzite was deposited with scattered palaeoflow directions in the braided streams with thin interlayered pebbly quartzite/conglomerates near Khandamuni area (Fig. 3). Quartzites are mostly non-radioactive in nature.

GEOCHEMISTRY

Major oxides, trace elements and REE data have been utilized in the interpretation of the tectonic setting of sedimentary rocks. The surface as well as borehole core samples of QPC and quartzite of the Birtola and Bagiyabahal sectors have been analysed. Trace elements and REE analysis of core and surface samples have been carried out by Flame-AAS and ICP-AES at Chemistry Laboratory, AMD, Jamshedpur. The procedures are normalised and validated by analysing certified reference materials. Major oxides and some of the trace elements of core samples have been analysed by XRF Spectrometry at AMD, Nagpur.

The quartzite samples also have been categorised into two, based on their radio-elemental concentration e.g. i) radioactive gritty quartzite and ii) non-radioactive massive quartzite. A total of 35 samples have been analysed, viz. radioactive QPC with siliceous matrix (n=14), QPC with sericitic matrix (n=8), gritty quartzite (n=5) and massive quartzite (n=8) (Table. 2).

The binary plot of log(Fe_2O_3(t)/K_2O) vs log(SiO_2/Al_2O_3) (Heron, 1988, Fig. 5a) shows a wide distribution of siliciclastics in different fields. QPC having sericitic matrix mostly falls in wacke field (>60% sample) as well as arkose fields with a solitary sample in the lith-arenite field. QPC having siliceous matrix (Fig. 5a) falls mostly in sub-lithic arenite field (>70% sample) with very few samples in Fe-sandstone and sub-arkose fields. The radioactive gritty quartzite samples too mostly fall in the sub-lithic arenite field with a few samples distributed in the boundary regions of lith-arenite and Fe-sandstone with sub-lithic arenite field. The non-radioactive massive quartzite samples show a scattered distribution in arkose, sub-arkose, wacke and Fe-sandstone fields indicating their variation in composition and a probable mixed provenance (Fig. 5a). The geochemistry of the siliciclastics broadly varies from sub-lithic arenite to wacke to arkosic category.

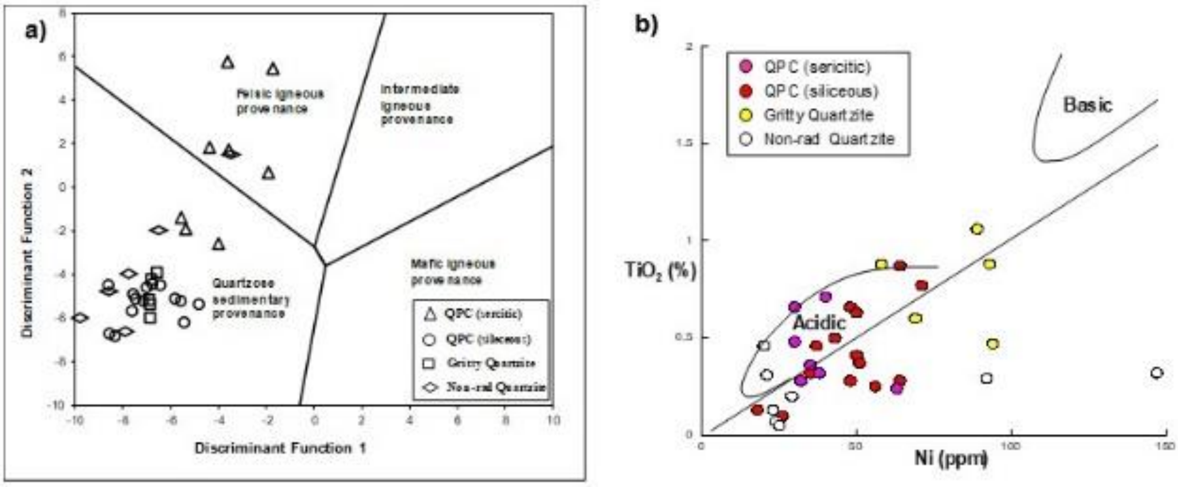

Fig. 6 Provenance diagrams a)- Provenance study of radioactive QPC (with siliceous and sericitic matrix), gritty quartzite and non-radioactive quartzite of Bagiyabahal and Birtola Blocks (after Roser and Korsch, 1988) through discriminant functions and b)- TiO_2 vs. Ni sedimentary provenance discriminant diagram of radioactive QPC (with siliceous and sericitic matrix), gritty quartzite and non-radioactive quartzite of Bagiyabahal and Birtola Blocks for fields for acidic and basic source materials (after Floyd et al. 1989)

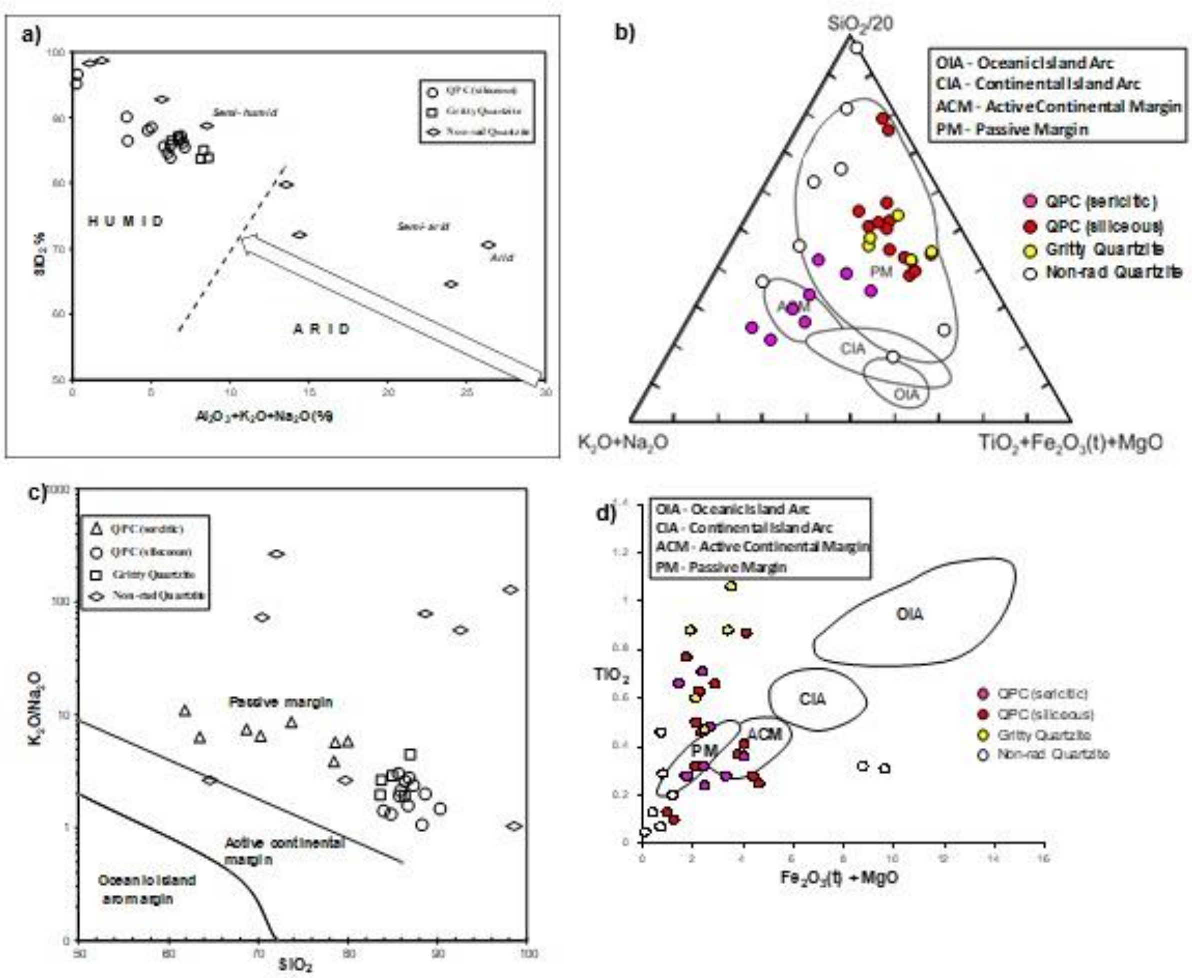

Fig. 7 Climate diagram a)- SiO_2 (%) vs Al_2O_3+K_2O+Na_2O (%) diagram of radioactive QPC (with siliceous and sericitic matrix), gritty quartzite and non-radioactive quartzite of Bagiyabahal and Birtola Blocks (after Suttner and Dutta, 1986) and Tectonic Setting Diagrams b)- SiO_2/20 vs K_2O+Na_2O vs TiO_2+Fe_2O_3(t)+MgO ternary diagram for tectonic setting of radioactive QPC (with siliceous and sericitic matrix), gritty quartzite and non-radioactive quartzite of Bagiyabahal and Birtola Blocks (after Kroonenberg, 1994), c)- K_2O/Na_2O vs SiO_2 diagram for tectonic setting of radioactive QPC (with siliceous and sericitic matrix), gritty quartzite and non-radioactive quartzite of Bagiyabahal and Birtola Blocks (after Roser and Korsch, 1986) and d)- Fe_2O_3(t)+MgO vs TiO_2 plot on tectonic setting discrimination diagram of radioactive QPC (with siliceous and sericitic matrix), gritty quartzite and non-radioactive quartzite of Bagiyabahal and Birtola Blocks (after Bhatia, 1983)

Table. 2- Analysis of major oxides and 'Ni' of the drill-core samples of the QPC and quartzite of Bagiyabahal and Birtola areas (all values are in percentage except 'Ni' which is in 'ppm' and the ratios are unitless)

Sample No.	Lithology	SiO_2	TiO_2	Al_2O_3	FeO(T)	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5	Ni	SiO_2/Al_2O_3	MgO/Al_2O_3	K_2O/Al_2O_3	K_2O/Na_2O
BGL-1/B2/9	QPC (siliceous)	85.50	0.66	5.28	2.63	0.25	0.02	0.16	0.45	1.37	0.08	48	16.19	0.047	0.259	3.044
BGL-1/B2/10		85.64	0.41	4.14	3.83	0.21	0.02	0.18	0.54	1.05	0.07	50	20.69	0.051	0.254	1.944
BGL-1/B2/11		84.65	0.87	4.01	3.88	0.25	0.02	0.19	0.85	1.13	0.11	64	21.11	0.062	0.282	1.329
BGL-2/B2/10		87.19	0.77	5.04	1.15	0.59	<0.01	0.13	0.52	1.26	0.07	71	17.30	0.117	0.250	2.423
BGL-2/B2/14		83.93	0.25	4.47	4.31	0.32	<0.01	0.12	0.71	1.00	0.05	56	18.78	0.072	0.224	1.408
BGL-3/B2/26		88.52	0.46	3.68	2.13	0.23	0.02	0.19	0.43	0.87	0.08	37	24.05	0.063	0.236	2.023
BGL-4/B1/16		86.21	0.63	5.50	1.65	0.61	0.02	0.22	0.40	1.05	0.09	50	15.67	0.111	0.191	2.625
BGL-2A/B2/34		86.68	0.28	5.11	1.43	0.27	<0.01	0.12	0.44	1.22	0.03	48	16.96	0.053	0.239	2.773
BGL-2A/B2/35		88.09	0.50	3.18	1.86	0.27	<0.01	0.12	0.74	0.79	0.05	43	27.70	0.085	0.248	1.068
BGL-2A/B2/36		90.16	0.32	2.33	1.88	0.20	<0.01	0.12	0.43	0.64	0.04	35	38.70	0.086	0.275	1.488
BGL-2A/B2/37		85.73	0.37	4.49	3.51	0.28	<0.01	0.14	0.53	1.14	0.05	51	19.09	0.062	0.254	2.151
BGL-4/B2/22		95.23	0.13	<0.01	0.88	0.10	<0.01	0.21	0.21	<0.01	0.03	18	-	-	-	-
BGL-4/B2/23		96.60	0.10	<0.01	1.14	0.11	<0.01	0.19	0.23	<0.01	0.03	26	-	-	-	-
BGL-4/B2/24		86.56	0.28	2.48	4.26	0.14	<0.01	0.31	0.39	0.62	0.12	64	34.90	0.056	0.250	1.590
BGL-1/B2/12	QPC (sericitic)	63.49	0.28	25.07	1.30	0.48	0.01	0.16	1.06	6.79	0.06	32	2.533	0.019	0.271	6.41
BGL-2/B2/19		70.21	0.24	18.84	1.73	0.75	0.01	0.16	0.78	5.06	0.05	63	3.727	0.040	0.269	6.49
BGL-2/B2/31		68.71	0.28	19.38	2.09	1.24	0.02	0.18	0.75	5.58	0.05	32	3.545	0.064	0.288	7.44
BGL-2A/B3/4		78.44	0.36	10.57	3.59	0.45	<0.01	0.16	0.68	2.62	0.06	35	7.421	0.043	0.248	3.85
BGL-2A/B3/5		61.77	0.48	24.57	1.90	0.77	0.02	0.18	0.70	7.68	0.08	30	2.514	0.031	0.313	10.97
BGL-3/B2/25		80.00	0.66	12.70	1.06	0.39	<0.01	0.15	0.51	2.96	0.07	30	6.299	0.031	0.233	5.80
BGL-4/B2/21		78.58	0.71	11.48	1.96	0.42	<0.01	0.42	0.48	2.77	0.11	40	6.845	0.037	0.241	5.77
BGL-4/B2/25		73.68	0.32	18.77	2.16	0.28	<0.01	0.22	0.50	4.31	0.04	38	3.925	0.015	0.230	8.62
BGL/B1/13	Gritty Quartzite	86.42	1.06	5.35	2.94	0.58	0.05	0.17	0.33	0.62	0.09	89	16.15	0.108	0.116	1.88
BGL/B1/17		86.94	0.88	5.68	1.76	0.15	0.05	0.16	0.19	0.83	0.09	58	15.31	0.026	0.146	4.37
BGL-2/B2/30		84.98	0.47	6.16	2.16	0.32	0.01	0.18	0.56	1.60	0.08	94	13.80	0.052	0.260	2.86
BGL-2A/B1/30		83.81	0.60	6.76	1.65	0.47	0.07	0.19	0.53	1.38	0.07	69	12.40	0.070	0.204	2.60
BGL-3/B1/22		83.58	0.88	6.66	2.53	0.88	0.06	0.20	0.52	1.01	0.12	93	12.55	0.132	0.152	1.94
BRT-1/72.55	Massive Quartzite	79.71	0.20	10.16	0.42	0.78	<0.01	0.29	0.96	2.44	0.08	29	7.85	0.077	0.240	2.54
BRT-1/133.25		70.43	0.46	21.42	0.22	0.51	<0.01	0.16	0.07	4.96	0.04	20	3.29	0.024	0.232	70.86
BRT-4/30.25		72.05	0.32	11.84	2.98	5.77	<0.01	1.02	0.01	2.57	0.09	147	6.09	0.487	0.217	257.00
BRT-5/65.1		64.58	0.31	17.91	3.10	6.54	0.02	0.34	1.76	4.42	0.10	21	3.61	0.365	0.247	2.51
BRT-4/6		92.60	0.29	4.26	0.55	0.25	<0.01	0.13	0.025	1.35	0.04	92	21.74	0.059	0.317	54.00
BRT-3/11		88.62	0.07	6.60	0.35	0.36	<0.01	0.17	0.025	1.92	0.03	24	13.43	0.055	0.291	76.80
BRT-1/29		98.16	0.13	0.49	0.23	0.18	<0.01	0.19	<0.01	0.62	0.03	23	200.33	0.367	1.265	-
BRT-1/30		98.55	0.05	1.92	0.11	<0.01	<0.01	0.11	<0.01	<0.01	0.02	25	51.33	-	-	-

The presence of higher Al_2O_3 and K_2O in QPC having sercitic matrix indicates an acidic provenance. In Fe_2O_3(t) + MgO vs Na_2O vs K_2O diagram (Blatt, 1972, Fig. 5b), QPC with siliceous matrix mostly falls under ferromagnesian potassic sandstone and few samples in sodic sandstone field, whereas QPC with sericitic matrix mostly shows potassic nature with a few samples having ferromagnesian potassic characteristics. The gritty quartzite samples fall in ferromagnesian potassic sandstone whereas the massive quartzites are widely distributed both in the ferromagnesian potassic sandstone and potassic sandstone category indicating its mixed provenances. So, the siliciclastics can be categorized in an overall ferromagnesian potassic to potassic sandstone field (Fig. 5b).

Discriminant function analysis (Roser and Korsch, 1988, Fig. 6a) using the major oxides reveals a quartzose sedimentary provenance for most of the siliciclastics of Bagiyabahal and Birtola areas. However, a few QPC samples with sericitic matrix and a solitary massive quartzite sample plot in felsic igneous provenance.

The TiO_2vs Ni binary provenance discriminant diagram (Floyd et al., 1989, Fig. 6b) shows the concentration of all the samples in the field of the acidic source. Thus, two sources of provenance for the siliciclastics consisting of granite and granite derived reworked quartzose sediment especially for QPC is suggested based on geochemical characteristics.

The implication of climatic conditions on the chemical maturity of the siliciclastics was also inferred. The siliciclastics of Bagiyabahal and Birtola areas were deposited under a semi-humid to humid paleo-climate as indicated by a plot of SiO_2 vs Al_2O_3 + K_2O + Na_2O (Suttner and Dutta, 1986, Fig. 7a). The siliciclastics of Bagiyabahal and Birtola areas were deposited in a passive continental margin setting as inferred from the SiO_2 vs K_2O/Na_2O binary diagram. A solitary massive quartzite sample falls in the boundary of passive and active continental margin setting (Roser and Korsch, 1986, Fig. 7c). SiO_2 vs K_2O + Na_2O vs TiO_2 + Fe_2O_3 (t) + MgO diagram (Kroonenberg, 1994, Fig. 7b) also shows the same passive marginal setting for all the samples except a few QPC samples with sericitic matrix and a solitary massive quartzite sample which falls in active continental margin setting. Similarly, Fe_2O_3(t) + MgO vs TiO_2 binary diagram on tectonic setting discrimination diagram (Bhatia, 1983, Fig. 7d) shows that the majority of samples spread over passive continental margin setting with a few QPC samples with both sericitic and siliceous matrix falling within active continental margin tectonic setting. Thus, it can be suggested that the siliciclastics of Bagiyabahal and Birtola were deposited broadly in a passive continental margin setting. This is supported by the quartzose sedimentary source rock and quartz-rich nature of the sediments which were deposited in close proximity to the provenance.

Critical ratios of certain major oxides have also been studied to understand the source rock chemistry and nature of weathering (Table. 2). TiO_2 content in QPC ranges from 0.10 to 0.87 whereas in quartzite, it varies from 0.05-1.06, which may be due to the presence of more titanium bearing minerals in the siliciclastics such as rutile, ilmenite and anatase. These minerals have also been identified by petrographic study.

The K_2O/Al_2O_3 ratio is an indicator to identify the original composition of terrigenous sediments (Cox et al., 1995). The low ratios (<0.3) of K_2O/Al_2O_3 in both the QPC (avg. 0.253, n=21) and quartzite (avg. 0.22, n=21) (Table. 2) suggests the dominance of clay minerals (illite and chlorite) in the siliciclastics. Granite derived quartz clasts formed the siliceous matrix of the QPC and the reworking of clasts led to attaining the high chemical maturity whereas QPC with sericitic matrix showed low SiO_2/Al_2O_3 ratio (2.51-7.42, n=8) (Table. 2) indicating the presence of alumina-rich sediments dominated by clay minerals (Naqvi et al., 1988). Gritty quartzite shows a moderate SiO_2/Al_2O_3 ratio (12.40-16.15) (Table. 2) whereas the massive quartzites show varying ratio. K_2O/Na_2O ratio in sandstones is another important chemical parameter that depends on both the composition of source and intensity of weathering (Lindsey, 1999). A high K_2O/Na_2O ratio (>1) in all the siliciclastics suggests a chemically weathered provenance with presence of clay minerals (e.g. illite).

Trace Elements

The trace element of QPC surface samples (n=30) indicates high Th content ranging from 32 ppm to 330 ppm (avg. 108 ppm) and Cr content ranging from 195 ppm to 1900 ppm (avg. 818 ppm) compared to the average crustal concentration of 8.5 ppm and 126 ppm respectively (Wedepohl, 1995) (Table. 3, Fig. 8). Th and Cr are high mainly due to the presence of monazite and fuchsite in the matrix respectively. Higher Cr/Th ratio (range: 0.95 - 32.91; avg: 10.98) indicates the ultramafic provenance. Pb (5 to 1175 ppm) is also high. Earlier, Au was reported up to 2250 ppb in QPC (Jana et al., 2016). Similarly, 1527 ppb Au and 692 ppb Pt were also reported in quartzite (Kumar et al., 2011). Rh and Ru contents have now been analysed up to 102 ppb and 100 ppb respectively in QPC (Table. 4). QPC is also reported to contain up to 0.34% U_3O_8 with detrital uraninite grains (Jana et al., 2019). Quartzite is mostly non-radioactive except few gritty layers within the quartzite.

Radioactive core samples of gritty quartzite and QPC contain 68ppm to 375ppm U and 31ppm to 146ppm Th. Th/U ratios in the lithounits ranged from 0.186 to 1.515 which is lower in comparison to crustal

Table. 3- Analysis of trace elements of the surface samples of radioactive QPC of Bagiyabahal and Birtola areas (values are in ppm)

Location	Li	Cu	Cr	Zn	Pb	Co	Ni	Sr	V	Th	Cr/Th
Baratangra	5	79	865	20	751	11	<5	10	27	67	12.91
	9	43	1574	57	195	36	<5	17	50	165	9.54
	9	20	1362	100	272	26	7	26	60	93	14.65
	8	34	1100	32	275	17	5	20	27	134	8.21
	6	19	1060	8	988	7	<5	18	23	101	10.50
	13	24	1590	18	425	13	<5	42	64	194	8.20
	12	9	1900	48	362	19	<5	26	67	153	12.42
	11	27	650	34	689	7	<5	19	38	92	7.07
	7	48	1053	73	1175	14	5	28	35	32	32.91
	21	28	900	28	375	13	<5	14	35	78	11.54
	5	43	790	78	117	11	5	15	25	48	16.46
	8	10	195	12	53	<5	<5	51	5	206	0.95
	<5	24	1080	27	99	21	<5	15	49	68	15.88
Bagiyabahal	<5	11	735	9	99	<5	<5	8	24	104	7.07
	<5	15	855	10	50	7	<5	8	30	49	17.45
	<5	18	1095	<5	117	<5	<5	3	18	161	6.80
	<5	<5	650	<5	168	<5	<5	7	19	69	9.42
	<5	14	530	<5	89	<5	<5	12	14	48	11.04
	<5	<5	465	<5	68	<5	<5	9	12	35	13.29
	<5	6	370	<5	74	<5	<5	11	17	75	4.93
	5	64	1050	13	45	12	39	18	25	102	10.29
	6	74	1122	20	55	16	51	19	28	330	3.40
	5	46	980	19	1140	14	8	42	26	111	8.83
	<5	42	840	<5	320	6	<5	10	10	85	9.88
	<1	62	520	<1	130	<1	12	8	46	N.A.	N.A.
	<1	2	482	<1	36	<1	4	<1	12		
Birtola	<5	13	131	<5	5	<5	34	<5	5		
	<5	32	234	13	31	8	38	<5	18		
	<5	26	208	82	55	5	29	<5	22		
	<1	14	158	10	116	<1	20	<1	<1		

rocks (average Th/U ratio ~4) and indicate deposition under anoxic conditions.

High U and Th in QPC indicate a granitic source more specifically the Bonai Granite Complex. The presence of higher Cr and PGE indicates an ultrabasic provenance component. Higher Au content suggests basic sources which probably might be the amphibolite suites of OMG. So, the geochemical characteristic of the siliciclastics suggests an overall mixed provenance.

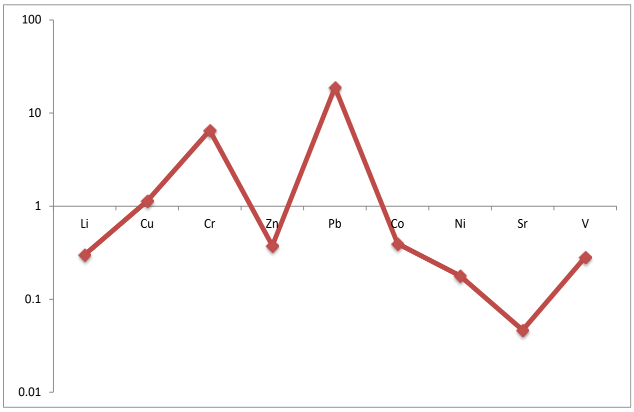

Fig. 8- Average value of trace elements of radioactive QPC of Bagiyabahal and Birtola with respect to continental crust

Table-4: Analysis of PGE of core QPC samples of Bagiyabahal-Baratangra tract (values are in ppb)

Sample No.	Pd	Rh	Ru
BGL-2/B-2/10	15	58	100
BGL-2/B-2/19	<10	95	84
BGL-2A/B-2/34	<10	88	70
BGL-2A/B-2/35	<10	102	92
BGL-2A/B-3/4	<10	23	41
BGL-2A/B-3/5	<10	<10	<10
BGL-2A/B-3/33	<10	<10	<10
BGL-4/B-2/21	<10	<10	<10
BGL-4/B-2/22	<10	<10	<10
BGL-4/B-2/23	<10	<10	<10
BGL-4/B-2/24	<10	<10	<10
BGL-4/B-2/25	<10	<10	<10
BGL-2A/B-1/30	<10	79	52

Rear Earth Elements

REE content of the surface QPC samples of Bagiyabahal area ranges from 303.50 ppm to 2680 ppm with a very high LREE/HREE (31.09) ratio (Table. 5, Fig. 9) and for core QPC samples, it ranges from 254 ppm to 999 ppm with moderately high LREE/HREE (18.30) ratio (Table. 6, Fig. 10). LREE enrichment in QPC are also reflected by their high values of $(La/Sm)_{CN}$ with an average value of 5.04 in surface QPC and 4.86 in core QPC samples. HREE depletion is reflected in surface QPC samples by $(Gd/Yb)_{CN}$ value of 6.60 whereas a nearly flat HREE pattern is observed in core QPC samples with $(Gd/Yb)_{CN}$ value of 2.50. QPC show fractionated
REE pattern with $(La/Yb)_{CN}$ value varying from 16.78 to 52.31 from the core to surface QPC samples. The Eu anomaly in sedimentary rocks is usually interpreted as being inherited from igneous source rocks (McLennan and Taylor, 1991, Taylor and McLennan, 1985). Strong negative Eu anomaly (Eu/Eu*: 0.30) characterises both the surface and core QPC samples. Negative Eu anomaly has been attributed to the presence of plagioclase depleted felsic igneous rocks in the provenance such as granites. Higher content of total REE and negative Eu anomaly is characteristic of QPC. QPC samples yield higher concentration LREE mainly due to the presence of monazite in the matrix which have been derived from the pegmatite and granite sources. LREE fractionation, HREE depletion, higher LREE/HREE and strong negative Eu anomaly indicate derivation of sediment from the highly evolved granitic source.
REE were also used by different workers to decipher provenance study and tectonic setting of the sedimentary rocks (Taylor and McLennan, 1985, Cullers, 1994, Cullers, 2000, McLennan 1989, McLennan and Taylor, 1991). On La-Th-Sc ternary diagram (Bhatia and Crook, 1986, Fig. 11), the radioactive QPC surface samples plot near passive and active continental margin fields along the La-Th line, mostly towards La. REE concentration with trace element signatures such as high Th/Sc (25.45), La/Sc (60.54) ratio also supports granitic provenance for QPC samples (Condie, 1993). High REE and Th concentrations and low Sc (2–10 ppm) indicate derivation of QPC from felsic igneous

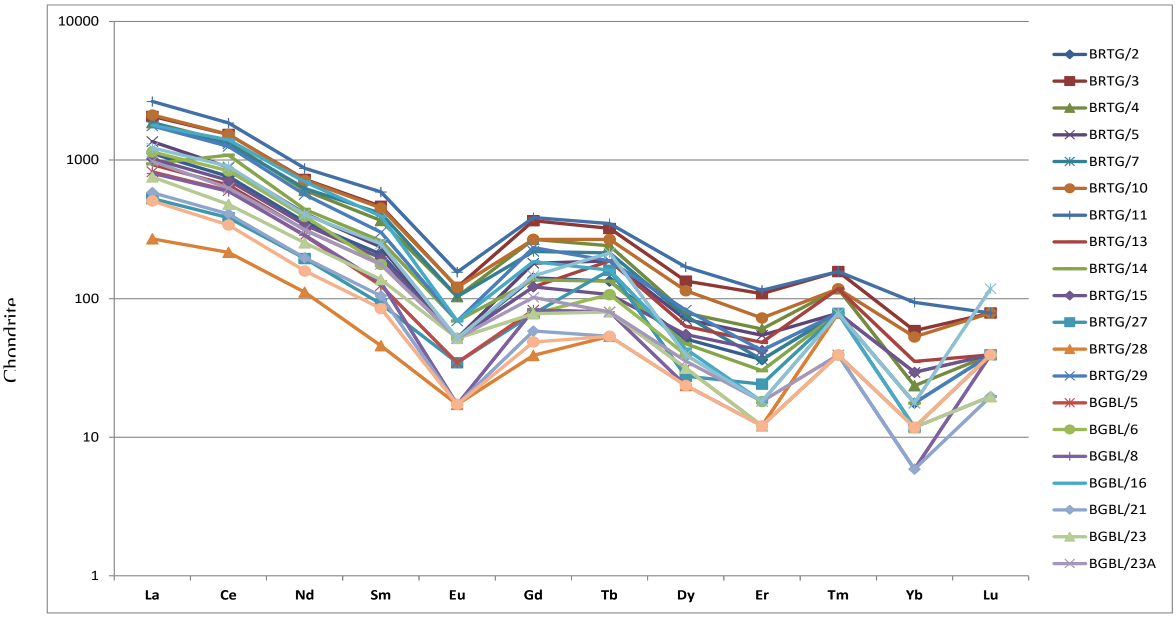

Fig. 9- REE distribution pattern of radioactive QPC surface samples (chondrite normalized)

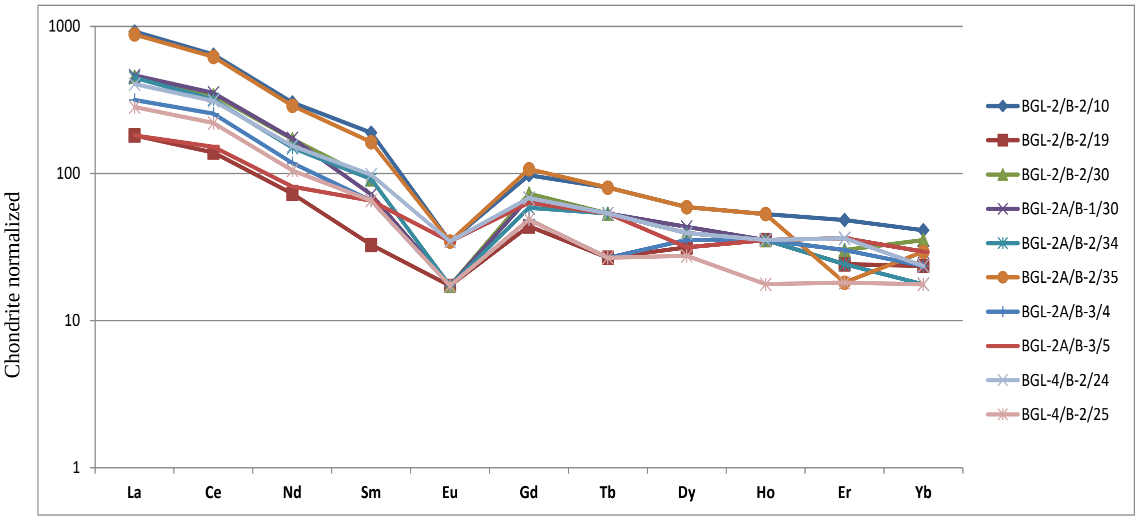

Fig. 10- REE distribution pattern of radioactive QPC core samples (chondrite normalized)

Table. 5- REE content of the surface samples of QPC of Bagiyabahal and Baratangra areas (values are in ppm)																	
QPC	LREE								HREE								
	Sc	La	Ce	Pr	Nd	Sm	Eu	Gd	Y	Tb	Dy	Ho	Er	Tm	Yb	Lu	La/Sc
BRTG/2	4	264	466	13	167	32	3	29	48	5	13	2	6	2	3	1	66.0
BRTG/3	8	489	936	34	339	71	7	75	121	12	34	6	18	4	10	2	61.1
BRTG/4	8	441	829	20	282	56	6	55	64	9	20	4	10	3	4	1	55.1
BRTG/5	5	322	543	18	192	36	3	37	68	7	18	3	9	2	5	1	64.4
BRTG/7	6	443	803	19	292	63	6	45	53	8	19	3	6	2	3	1	73.8
BRTG/10	10	501	939	29	334	69	7	55	112	10	29	6	12	3	9	2	50.1
BRTG/11	10	627	1133	43	407	90	9	79	187	13	43	8	19	4	16	2	62.7
BRTG/13	4	220	403	16	146	27	3	25	84	7	16	4	8	3	6	1	55.0
BRTG/14	2	223	665	12	206	40	4	28	14	5	12	2	5	2	3	1	111.5
BRTG/15	5	242	436	14	159	30	3	25	60	4	14	2	7	2	5	1	48.4
BRTG/27	4	125	235	7	91	14	2	16	25	6	7	1	4	2	2	1	31.3
BRTG/28	3	64	132	6	52	7	1	8	18	2	6	1	2	2	2	<1	21.3
BRTG/29	5	418	768	21	263	46	4	48	68	7	21	2	7	2	3	1	83.6
BGBL/5	4	195	368	8	133	19	2	17	23	3	8	<1	2	1	2	1	48.8
BGBL/6	5	271	512	10	183	27	3	16	34	4	10	<1	3	1	2	1	54.2
BGBL/8	3	190	364	6	134	20	1	17	18	3	6	<1	2	1	1	1	63.3
BGBL/16	4	423	856	11	325	60	4	38	26	6	11	<1	3	2	2	<1	105.8
BGBL/21	2	138	250	6	92	16	1	12	17	2	6	<1	2	1	1	<1	69.0
BGBL/23	4	179	293	8	118	21	3	16	25	3	8	<1	2	1	2	<1	44.8
BGBL/23	4	232	384	9	147	27	3	21	31	3	9	<1	3	1	2	1	58.0
BGBL/66	3	290	551	10	189	38	3	30	33	8	10	1	3	2	3	3	96.7
DLDL/67	3	120	208	6	74	13	1	10	25	2	6	<1	2	1	2	1	40.0
Average	4.82	291.68	548.82	14.82	196.59	37.36	3.59	31.91	52.45	5.86	14.82	2.23	6.14	2.00	4.00	1.14	62.04
∑REE	303.5 - 2680																

Table. 6- REE content of the drill-core samples of QPC of Bagiyabahal and Baratangra areas (values are in ppm)																
QPC	LREE								HREE							
	Sc	La	Ce	Pr	Nd	Sm	Eu	Gd	Y	Tb	Dy	Ho	Er	Tm	Yb	Lu
BGL-2/B-2/10	1	219	394	38	142	29	2	20	116	3	15	3	8	1	7	1
BGL-2/B-2/19	2	43	85	<10	34	<10	1	9	50	<2	8	2	4	<1	4	<1
BGL-2/B-2/30	1	108	209	20	80	14	1	15	61	2	10	2	5	<1	6	<1
BGL-2A/B-	2	110	216	22	81	11	1	14	290	2	11	2	6	1	5	<1
BGL-2A/B-	1	106	195	19	70	14	1	12	43	2	10	2	4	<1	3	<1
BGL-2A/B-	1	209	380	35	135	25	2	22	92	3	15	3	3	<1	5	1
BGL-2A/B-3/4	2	75	156	16	55	10	1	10	56	<2	9	2	5	<1	4	<1
BGL-2A/B-3/5	3	43	93	<10	38	10	2	13	71	2	8	2	6	<1	5	<1
BGL-4/B-2/24	1	96	191	18	72	15	2	14	51	2	10	2	6	<1	4	<1
BGL-4/B-2/25	2	67	135	13	49	10	1	10	41	<2	7	<2	3	<1	3	<1
Average	1.6	107.6	205.40	19.10	75.60	14.30	1.40	13.90	87.1	1.9	10.3	2.1	5	-	4.6	-
∑REE	254 - 999															

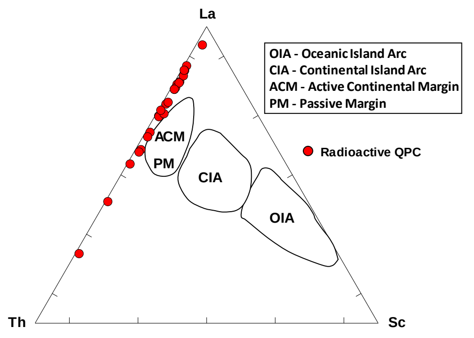

Fig. 11- La-Th-Sc ternary diagram for tectonic setting of radioactive QPC of Bagiyabahal and Birtola (after Bhatia and Crook, 1986)

source rocks. Higher La/Sc and Th/Sc relative to the well-known Archaean sediments suggest derivation from the fractionated and evolved crustal sources as well.

TECTONIC SETTING

The overall geochemical behaviour shows the siliciclastics of Bagiyabahal and Birtola were deposited mostly in a passive continental margin setting with an indication of the active regime of the continent in a few samples (inferred from SiO_2 vs K_2O/Na_2O diagram, SiO_2 vs $K_2O + Na_2O$ vs $TiO_2 + Fe_2O_3$ (t) + MgO diagram, Fe_2O_3(t) + MgO vs TiO_2 diagram and La vs Th vs Sc diagram). This is supported by the quartzose sedimentary source rock along with granite derived reworked quartz clasts which were deposited in close proximity to the provenance. So, the western part of the Noamundi-Koira IOG basin around the Bagiyabahal and Birtola area is probably a part of ancient 'volcanic rifted passive margin' indicated by the massive emplacements of mafic extrusive and intrusive rocks along the series of faulted continental crust and the geochemical behaviour of the metasediments (Fig. 12a, b, c, d). Passive continental margins are generally developed when the continental blocks are separated by continental rift systems (Frisch et al., 2010) and this is evidenced by the repeated downthrown blocks of siliciclastics towards the WNW direction due to rift related parallel normal faults (slightly oblique to the basin margin) along Daldali-Bagiyabahal-Khandamuni tract (Fig. 12c). In volcanic rifted passive margin, rifting is accompanied by significant mantle melting with volcanism occurring before and/or during the continental breakup and the volcanism is characterized by a huge volume of basaltic lava flows and numerous emplacements of doleritic sill, dykes and gabbro which are present all along the Gurundia-Baratangra-Bagiyabahal tract and Birtola-Balisura tract within the subsided continental crust (Fig. 12a, b, c, d). The passive basin margins are also characterized by thick accumulations of sediments over the continental shelf. The deposition of thick sediments over the relatively thin continental crust led to the gradual subsidence of the crust and increases the slope of the basin margin.Repeated cycles of sedimentation and volcanism led to the formation of alternate layers of basic bodies in the area (Fig. 12a, b, c, d). So, it can be suggested that the deposition of sedimentary succession was controlled by fault-controlled sedimentation over the faulted continental siliciclastics and crust and shelf.

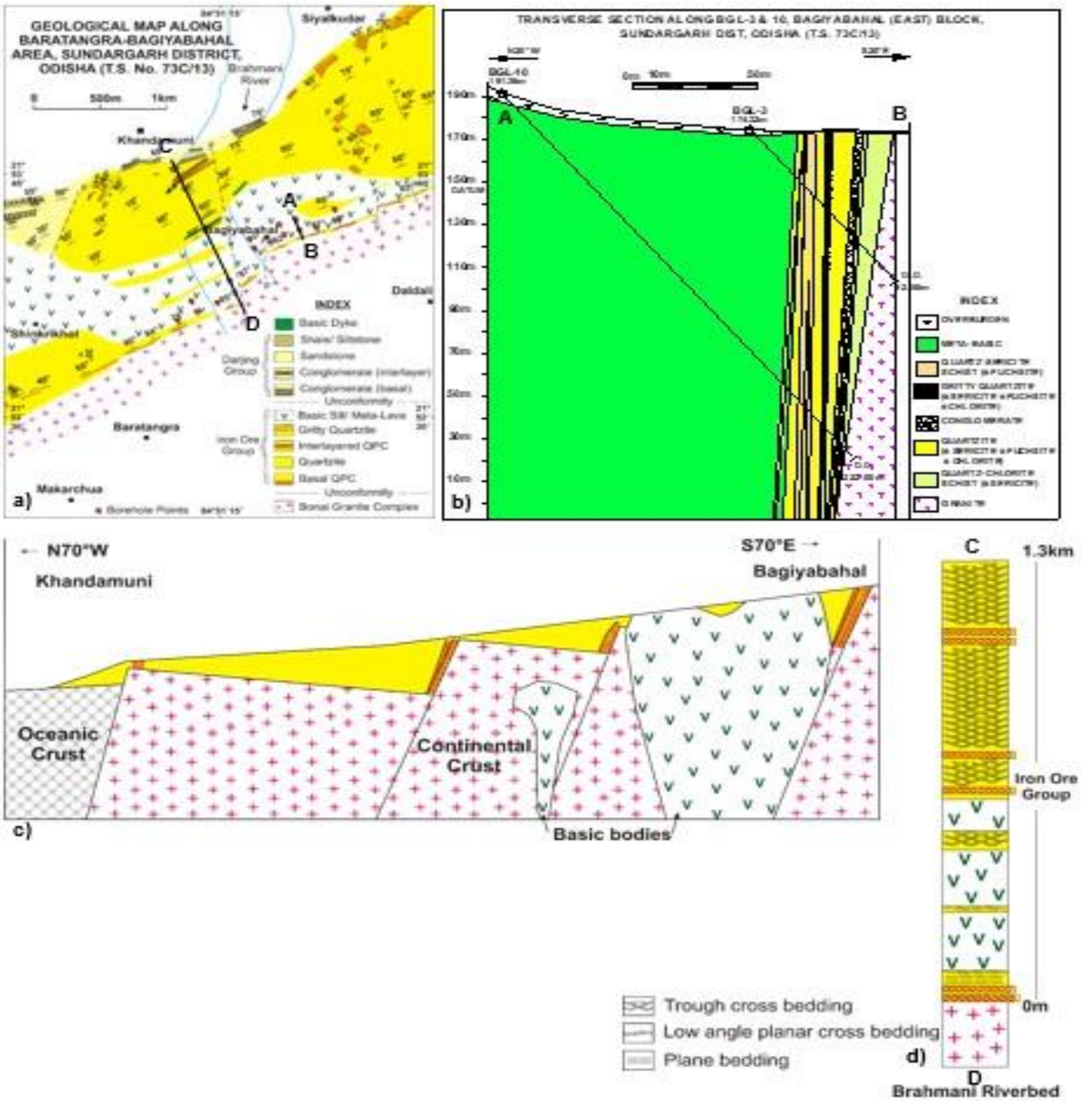

Fig. 12a)- Geological map along Makarchua – Daldali tract showing borehole points around Bagiyabahal, Baratangra areas, b) Transverse section along borehole BGL-3 and 10 of Bagiyabahal sector (along A-B line), c) Schematic diagram showing the deposition of sediments and volcanism in passive margin setting along Khandamuni – Bagiyabahal tract and d) Vertical section along Brahmani river-bed showing IOG meta-sedimentary succession (along C-D line)

The entire volcanoclastic succession has subsequently been deformed and the deformation and tilting resulted in the occurrence of higher inclination of beds (sub-vertical to vertical) near Bagiyabahal and Birtola areas. The boundary between Bonai Granite and the IOG meta-sediments is also sheared in nature as evidenced by highly sheared QPC with stretched pebbles, deformed granite and quartz-sericite schist at contact.

DISCUSSION & CONCLUSION

The geochemical parameters of the polymetallic QPC and quartzite horizon at the south-western margin of the Noamundi-Koira IOG basin have been utilized to understand the tectonic settings of different sedimentary environments. The siliciclastics were deposited along the western margin of Bonai granite in anoxic conditions as indicated by their low Th/U ratios and presence of detrital uraninite grains. Critical elemental ratio with high Th/Sc and La/Sc indicates granitic provenance for the QPC samples. The TiO_2 vs Ni diagram also indicates the acidic source. The presence of higher Al_2O_3 and K_2O in QPC with sericitic matrix indicates an acidic provenance too. However, discriminant function analysis shows a quartzose sedimentary provenance for all the siliciclastics except few QPC samples with sericitic matrix which show a felsic igneous provenance. So, a possible first cycle of granitic source and a subsequent granite derived reworked quartzose sedimentary source is suggested for the siliciclastics. A chemically weathered provenance dominated by clay minerals has been suggested for the siliciclastics from the critical ratios of major oxides like low K_2O/Al_2O_3 ratio (<0.3) and high K_2O/Na_2O ratio (>1). High SiO_2/ Al_2O_3 ratio in all the quartzite and QPCs with siliceous matrix indicates high chemical maturity of the sediments and a felsic provenance. Granite derived quartz clasts formed the siliceous matrix of the QPC and the reworking of clasts led to attaining the high chemical maturity of the lithounit. The geochemical ratios, as well as the higher contents of U, Th, Au, Cr and PGE suggest an overall mixed provenance for the deposition of the siliciclastics comprising predominantly acidic/granitic source possibly from the BGC along with some reworked quartzose sediments and minor basic and ultrabasic sources of Older Metamorphic Group (OMG). Higher content of total REE, LREE fractionation, HREE depletion, higher LREE/HREE ratio and strong negative Eu anomaly analysed in the QPC also indicate derivation of sediment from the highly evolved granitic source. The higher LREE content is due to the presence of monazite and uraninite in the matrix which have been derived from the pegmatite and granite sources. LREE enrichment in QPC is also reflected by the high values of $(La/Sm)_{CN}$ whereas near flat to depleted HREE pattern is reflected by $(Gd/Yb)_{CN}$.

The study area is suggested to be a part of an ancient volcanic passive margin where deposition of sediments was characterized by fault-controlled sedimentation over the rift related faulted continental crust and continental shelf. This has been evidenced by the presence of (i) repeated downthrown blocks of siliciclastics towards the WNW direction due to a series of rift related normal faults from Daldali to Khandamuni, (ii) huge basaltic lava flows as well as prolific emplacements of doleritic sill, dykes and gabbro due to mantle melting accompanying volcanism along the faulted and separated continental blocks and (iii) the overall geochemical behaviour of the metasediments. The huge pile of sediments over the subsided continental shelf led to the gradual subsidence of the crust and increases the slope of the basin margin. Repeated cycles of sedimentation and volcanism led to the formation of alternate layers of siliciclastics and basic bodies in the area.

Acknowledgement

The authors are highly grateful to the Director, AMD, Hyderabad for according permission to publish this paper. We are thankful to the Incharges of XRF Laboratory, AMD, Nagpur and Chemical Laboratory, AMD, Jamshedpur for the analysis of samples. We are also thankful to the Regional Director, AMD, Jamshedpur for his constant encouragement and support. We also thank the reviewers for their critical reviews and valuable suggestions for enhancing the quality of the paper.

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Received: 19th July, 2020
Revised Accepted: 5th July, 2021