Geochemical constraints on the evolution of mafic and felsic rocks in the Bathani volcanic and volcano-sedimentary sequence of Chotanagpur Granite Gneiss Complex

ASHIMA SAIKIA^{1,*}, BIBHUTI GOGOI¹, MANSOOR AHMAD² and TALAT AHMAD¹

¹*Chatra Marg, Department of Geology, University of Delhi, Delhi 110 007, India.*

²*Rajabazar, Patna 800 020, India.*

**Corresponding author. e-mail: ashima.saikia@gmail.com*

The Bathani volcanic and volcano-sedimentary (BVS) sequence is a volcanic and volcano-sedimentary sequence, best exposed near Bathani village in Gaya district of Bihar. It is located in the northern fringe of the Chotanagpur Granite Gneiss Complex (CGGC). The volcano-sedimentary unit comprises of garnet-mica schist, rhyolite, tuff, banded iron formation (BIF) and chert bands with carbonate rocks as enclaves within the rhyolite and the differentiated volcanic sequence comprises of rhyolite, andesite, pillow basalt, massive basalt, tuff and mafic pyroclasts. Emplacement of diverse felsic and mafic rocks together testifies for a multi-stage and multi-source magmatism for the area. The presence of pillow basalt marks the eruption of these rocks in a subaqueous environment. Intermittent eruption of mafic and felsic magmas resulted in the formation of rhyolite, mafic pyroclasts, and tuff. Mixing and mingling of the felsic and mafic magmas resulted in the hybrid rock andesite. Granites are emplaced later, cross-cutting the volcanic sequence and are probably products of fractional crystallization of basaltic magma. The present work characterizes the geochemical characteristics of the magmatic rocks comprising of basalt, andesite, rhyolite, tuff, and granite of the area. Tholeiitic trend for basalt and calc-alkaline affinities of andesite, rhyolite and granite is consistent with their generation in an island arc, subduction related setting. The rocks of the BVS sequence probably mark the collision of the northern and southern Indian blocks during Proterozoic period. The explosive submarine volcanism may be related to culmination of the collision of the aforementioned blocks during the Neoproterozoic (1.0 Ga) as the Grenvillian metamorphism is well established in various parts of CGGC.

1. Introduction

The Chotanagpur Granite Gneiss Complex (CGGC), a high grade terrain in the eastern part of the Central Indian Tectonic Zone (CITZ), covers an area of 80,000 km² having a ENE–WSW trend. It consists predominantly of amphibolite to granulite facies rocks juxtaposed between two low

grade mobile belts, namely the North Singhbhum mobile belt in the south and the Mahakoshal mobile belt in the north (figure 1). The evolution of CGGC has been marked by multiple episodes of magmatism, metamorphism and deformation over a geological history spanning from Proterozoic till about 65 Ma (Mukherjee and Ghose 1998). Several attempts were made to classify

Keywords. Chotanagpur Granite Gneiss Complex (CGGC); Munger–Rajgir belt; Bathani volcanic and volcano-sedimentary (BVS) sequence; volcanic arc; subduction; magma mixing.

Figure 1. Geological map of the Chotanagpur Granite Gneiss Complex (CGGC) and adjoining areas after GSI 1998 (reproduced after Chatterjee and Ghosh 2011). The tectonic features are marked after Sastri *et al.* (1971), Rao (1973), Valdiya (1976), GSI (2000) and Chatterjee *et al.* (2010). Marked in the map in black open square is the study area of present work. In the inset is the map of India showing the relative position of CGGC with respect to various Proterozoic complexes of the Indian shield. **Abbreviations.** ADMB: Aravalli–Delhi Mobile Belt, BuC: Bundelkhand Craton, BC: Bastar Craton, CGC: Chotanagpur Gneissic Complex, CITZ: Central Indian Tectonic Zone, DC: Dharwar Craton, EGB: Eastern Ghats Belt, EITZ: Eastern Indian Tectonic Zone, grp: Group, MB: Mahakoshal Belt, NSMB: North Singhbhum Mobile Belt, SB: Satpura Belt, SC: Singhbhum Craton, SMGC: Shillong–Meghalaya Gneissic Complex, SONA: Son–Narmada Graben.

the CGGC by various researchers. Ghose (1983) and Banerji (1991) have based their classification on lithostratigraphic units, viz., crystalline basement, older metasediments, and later intrusives associated with the Chotanagpur, Satpura, and Munger orogenic phases. Singh (1998) classified the CGGC based on lithodemic groups and placed the CGGC lithodemic group as the oldest followed by the Kodarma Group and the Rajgir Group. Mahadevan (2002) classified the CGGC into five east–west divisions based on the Damodar and the Koel river Gondwana basins as reference frames. However, Sanyal and Sengupta (2012) have argued that geological information is too less from this terrain to attempt any robust classification of CGGC.

Available radiometric age dates obtained by various methods like U–Pb zircon, whole rock Rb–Sr, K–Ar, and monazite chemical dates have been used to infer four magmato-metamorphic events, viz., >2.5, 1.6–1.5, 1.2–1.0, and 0.9 Ga in this crustal block (Chatterjee *et al.* 2008; Maji *et al.* 2008; Singh and Krishna 2009; Chatterjee *et al.* 2010; Karmakar *et al.* 2011; Mukhopadhyay *et al.* 2011 and references therein; Sanyal and Sengupta 2012). Most of these ages are from the metamorphosed basement lithology of the eastern part of the high grade terrain. The protolith of the high grade metamorphic rocks for this terrain which were part of the proto-crust are difficult to recognize following multiple metamorphic episodes. Thus, the evolutionary history of CGGC has remained speculative

to build a meaningful stratigraphy due to absence of lithological, structural, petrological and precise geochronological constraints from various basins of the terrain.

We present new geochemical, petrological and mineral chemical data for the volcanic and volcano-sedimentary sequence in juxtaposition with Rajgir metasediments best exposed near Bathani village in the Gaya district of Bihar (Ahmad and Wanjari 2009; Ahmad and Dubey 2011) located on the northern fringe of the CGGC.

The exposed areas at the northern margin of CGGC comprise of the Bihar Mica Belt (BMB), Munger Group, and the Rajgir–Gaya sub-basins. The BMB has a basement cover relationship with the CGGC as is evident from the occurrence of Inderwa Conglomerate (Mukherjee and Ghose 1998; Ghose and Mukherjee 2000). The Munger Group and the Rajgir–Gaya metasediments comprise of folded phyllite–quartzite sequence with sporadic occurrences of mafic–ultramafic and granitic intrusives (Das 1967; Mazumdar 1988). Based on their lithological and structural similarities, these metasediments have been correlated with the folded synclinal sequences of the Son–Narmada Valley (Das 1967).

The Bathani volcanic and volcano-sedimentary sequence (BVS sequence) occurring within the graben is flanked by CGGC to the south and flat alluvial country with occasional granitic inselberg to the north. A fault trending north–east along the eastern boundary of the Rajgir–Gaya basin (Das 1967; Srivastava and Sengupta 1967) has been correlated with the NE–SW Monghyr–Saharsa Ridge Fault (MSRF) on the northwestern edge of the CGGC (Sastri *et al.* 1971; Rao 1973; Valdiya 1976; Raiverman *et al.* 1983; Goswami *et al.* 2009). Bouger gravity anomaly map (Das and Patel 1984) shows anomalous NE–SW trending gravity high to the north of Bodh Gaya suggesting the probability of the presence of a regional fault (continuation of Son–Narmada Lineament) along with intrusive basic igneous material beneath. The plutonic rocks reported from the northwestern side of MSRF in association with schists, phyllites, quartzite have been correlated with the Mahakoshal Group of the Son–Narmada graben (Chatterjee and Ghosh 2011).

Reported occurrence of the BVS sequence by Ahmad and Wanjari (2009) and Ahmad and Dubey (2011) presents the Munger–Rajgir belt in an entirely novel lithostratigraphic perspective. Extensive magmatic activity in the area has been established beyond doubt. It is important to understand how and under which tectonic regime this magmatic activity took place. Constraining the geochemical signatures of BVS sequence will add to our understanding of Proterozoic magmatism in the eastern Indian shield.

2. Geological background

The BVS sequence is extended over known ~40 km aerial distance from Bathani (24°59.5'N, 85°16'E), Gaya District (Toposheet 72H/5) to Churi–Jaganaathpur (24°47'6.6"N, 84°59'24.8"E), Gaya District, Bihar (Toposheet 72D/13) on the northern fringe of CGGC. Three litho-domains have been discerned so far for the Munger–Rajgir belt based on field relationship, viz., (a) granitoids with occurrences of xenoliths of anorthosite and mafic rocks like gabbro and hornblende, (b) the volcanic and volcano sedimentary sequence exposed in Bathani village (BVS) and to the south of it is the (c) Rajgir metasediments (figure 2).

The volcano-sedimentary unit comprises of garnet-mica schist, rhyolite, tuff, banded iron formation (BIF) and chert bands with carbonate rocks as enclaves within the rhyolite unit whereas the differentiated volcanic sequence comprises of rhyolite–andesite (figure 3a, b), pillow basalt (figure 3c), massive basalt (figure 3d), tuff (figure 3e) and mafic pyroclasts. There is no remarkable break between the two sequences but on the basis of primary sedimentary and volcanic structures it may be established that the volcano-sedimentary sequence is overlain by the differentiated volcanic sequence. The Mesoproterozoic Rajgir metasediments comprise stratigraphically of two distinct quartzite horizons underlain and overlain by phyllites. Volcano-sedimentary sequences as well as the lower unit of Rajgir metasediments are intruded persistently by concordant ultramafic bodies of gabbro–pyroxenite suite. However, only few ultramafics are exposed in antiformal valley portion formed as a consequence of the second phase of deformation, but subsurface probe in the area revealed that various concordant ultramafic intrusions of variable thickness are present (personal communication). Granitic bodies (figure 3f) are seen at places overlying or cross cutting these units suggesting a late stage felsic magmatic activity in the area. Ahmad and Wanjari (2009) suggested bimodal volcanism in the area based on the occurrence of felsic volcanic rhyolite and mafic pillow basalt. The thrust contact between the overlying volcano-sediments and granitoids with underlying rhyolite of differentiated volcanics at Mirzapur–Gere, suggests that the rocks of the area had experienced large scale brittle deformation (Ahmad and Paul 2013).

Mixing and mingling of mafic and felsic magmas is collaborated by the presence of felsic clasts within mafic ground mass (figure 4a), rapakivi feldspars in andesite (figure 4b), hybrid zones at mafic and felsic flow contacts resulting in andesite (figure 4c), felsic ocelli in mafics (figure 4d),

Figure 2: Geological map of the Bathani volcano-sedimentary (BVS) sequence showing various lithological units along with their trends modified after Ahmad and Dubey (2011), Ahmad and Paul (2012). The chronological order suggested for the BVS sequence is based on field relations with the Munger-Rajgir Group of Mesoproterozoic age (GSI 2000). Locations of the samples presented in the study have been marked in the map with different symbols. Solid diamond (◆) for basalt, solid square (■) for andesite, filled triangle (▲) for rhyolite, filled circles (●) for granite and plus sign (+) for tuff. These symbols will be henceforth used to mark these rocks in all the plots used for illustration of mineral chemistry and geochemistry in the present study.

Figure 3. Field photographs of various rock types reported from the Bathani volcano-sedimentary (BVS) sequence. (a) An outcrop of rhyolite showing its banded nature ($24^{\circ}58'39''\text{N}$, $85^{\circ}17'55.1''\text{E}$). (b) An outcrop of andesite with prominent felsic ocelli ($24^{\circ}58'40.6''\text{N}$, $85^{\circ}17'57.5''\text{E}$). (c) A pillow basalt outcrop from Churi village of Gaya district with prominent radial cracks and chilled margin ($24^{\circ}47'6.6''\text{N}$, $84^{\circ}59'24.8''\text{E}$). (d) A basaltic flow outcrop from Ghansura area ($24^{\circ}58.753'0''\text{N}$, $85^{\circ}18.432'0''\text{E}$). (e) A tuff layer in midst of a weathered terrain ($24^{\circ}58'42.3''\text{N}$, $85^{\circ}17'3.4''\text{E}$). (f) Granitic rock outcrop ($24^{\circ}58'50''\text{N}$, $85^{\circ}17'20''\text{E}$).

rhyolite flow bands occurring in association with the basaltic flows (figure 4e) and mafic clots within andesitic rocks (figure 4f). In the BVS sequence, rhyolite and basalt are observed as alternate flows in contact with each other. Andesites are mostly

concentrated in the hybrid contact zones between the two. This indicates that the basaltic and the rhyolitic eruptions occurred concomitantly over a period of time. The formation of the andesite in the contact zone would at least require the two

Figure 4. Field photographs showing various mixing and mingling structures and textures in rocks of BVS sequence. (a) Rhyolitic clasts in basalts ($24^{\circ}58'39''\text{N}$, $85^{\circ}17'55.1''\text{E}$). (b) Growth of rapakivi feldspar in andesite suggestive of the changing melt composition ($24^{\circ}58'40.6''\text{N}$, $85^{\circ}17'57.5''\text{E}$). (c) Hybrid andesitic zone at mafic flow and felsic flow contact ($24^{\circ}58'39.5''\text{N}$, $85^{\circ}17'56''\text{E}$). (d) Occurrence of felsic ocelli in basalt ($24^{\circ}58.753'\text{N}$, $85^{\circ}18.432'\text{E}$). (e) Rhyolite flow occurring with basaltic flows ($24^{\circ}58'40.6''\text{N}$, $85^{\circ}17'57.5''\text{E}$). (f) Mafic clots within hybrid andesite indicative of entrapment of mafic magma in felsic magma due to mingling ($24^{\circ}59.323'\text{N}$, $85^{\circ}15.627'\text{E}$).

magma types to be in contact in fluid state for a definite interval of time for chemical interactions to occur. Though rhyolitic magma can be generated by fractional crystallization of basaltic magma, in the given scenario the basaltic and the rhyolitic magmas do not seem to be genetically related.

Southwest of our study area, Wanjari *et al.* (2012) have reported pillow basalts around Churi,

Jagannathpur, and Gulni villages and rhyolite occurrences from the Gere and Mirzapur villages within the Gaya district of Bihar. The Rb–Sr whole rock dating of the Mirzapur rhyolites show a crystallization age of 1044 ± 35 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.8734 ± 0.0088 (Wanjari *et al.* 2012). The researchers remarked that the crystallization age of Mirzapur rhyolites coincides with the global Grenvillian event (1000 Ma) which

had a major bearing in the tectono-thermal evolution of Neoproterozoic rocks and emplacement of acid volcanic and peraluminous granite plutons (Wanjari *et al.* 2012). The age of these rhyolites is similar to the whole rock isochron age of 1020.5 ± 45.5 Ma of Meromako granite pluton of the BMB and the tonalitic gneisses (995.5 ± 31.1 Ma) of Canary Hill of Hazaribagh town which is believed to retain record of the fourth tectono-thermal event in CGGC (Mallick 1993).

This paper discusses the geochemical characteristics of these diverse volcanic rocks of BVS sequence along with the granite exposed in and around the Bathani village and proposes a model for their evolution. These are the first pre-Mesoproterozoic magmatic rocks reported from the CGGC terrain. Geochemical characterization of the magmatic rocks of the BVS sequence will indeed augment our understanding of the tectono-magmatic events accountable for the evolution of CGGC.

3. Petrography

Petrographic study has been carried out on representative samples of basalt, andesite, rhyolite, tuff, and granite from the study area.

3.1 Basalt

The major mineral constituents of the basalt are augite and plagioclase feldspar while accessory phases include titanite, chlorite, iron oxides and alkali feldspar. Texturally, the basalts are holocrystalline and porphyritic in nature with phenocrysts of augite and plagioclase. Ophitic to subophitic texture (figure 5a) has been observed where plagioclase laths are partially or wholly engulfed within augite grains. Alteration of pyroxene to amphibole (figure 5b) is observed in basalts. In few samples pyroxenes have been totally replaced by amphiboles. Biotite at places is also altered to chlorite. Presence of secondary amphibole and chlorite may be attributed to low grade metamorphism setting in.

3.2 Andesite

Andesites appear holocrystalline, hypidiomorphic, and porphyritic with phenocrysts of quartz, plagioclase, and biotite in a fine-to-medium grained groundmass of quartz, feldspar, biotite, calcite, and iron oxide. Oscillatory zoning in plagioclase feldspar (figure 5c), quartz ocelli, presence of resorbed plagioclase grains (figure 5d) and acicular apatite (figure 5e) have been observed which are indicative of hybrid nature of the andesites. In

some andesites, mafic clots (figure 5f) are also found preserved.

3.3 Tuff

The tuffs are fine grained with abundant broken fragments of euhedral to anhedral muscovite (figure 5g) set in a matrix of subrounded quartz and fine grained alkali feldspar embedded in a devitrified glass (figure 5h). Tourmaline is also observed in some tuffs. Uneven distribution of broken crystals is characteristic of rocks derived from explosive environments. The glassy component occurs concentrated along irregular bands.

3.4 Rhyolite

The major constituent phases of the rhyolites are alkali feldspar, quartz, muscovite, and iron oxides. They are fine grained and holocrystalline. The grain shapes vary from subhedral to anhedral. The rhyolites show quartz-rich and muscovite-rich layers, thus giving the rock a banded appearance (figure 5i). This bandings are probably because of deformation undergone by the rocks.

3.5 Granite

The major phases in granites are feldspar, biotite, and quartz. Chlorite, muscovite, sericite, epidote, titanite, and iron oxide occur as accessory phases (figure 5j). Texturally, these are coarse-to-medium grained, holocrystalline, and leucocratic rocks with grain shapes varying from subhedral to anhedral. The vermicular intergrowth of quartz and feldspar (figure 5k) in the granite provides textural evidence of late stage simultaneous growth of quartz and feldspar in an extremely differentiated magma source. Perthitic exsolution (figure 5l) is common in granites.

4. Mineral chemistry

Mineral chemical analyses of various minerals in the basalt, andesite, rhyolite, tuff, and granite were determined using a CAMECA SX 100 electron microprobe with acceleration voltage of 15 kV and beam current of 10 nA at the Electron Microprobe Analyzer Laboratory, Geological Survey of India, Faridabad. Analyses were carried out with a beam diameter on 1 μm . Standards used include Wollastonite for Si and Ca, Periclase for Mg, Rhodonite for Mn, Albite for Na, Corundum for Al, Hematite for Fe, Orthoclase for K, Apatite for P, Metallic Cr and Ti for Cr and Ti, Halite for Cl, Metallic Zn for Zn, Fluorite for F, and Barite for Ba. The correction applied to the data is that of PAP (Pouchou and Pichoir 1987).

4.1 Basalt

In basalts, the feldspar is of plagioclase composition. The chemical composition of feldspar represents a solid solution between albite and anorthite. The X_{Na} content varies from 0.45–0.64 (figure 6a) and X_{Ca} varies from 0.34–0.54 (table 1).

The pyroxene data shows a solid solution between enstatite, ferrosilite and wollastonite. The EPMA data of pyroxene from basalts have been documented in table 1. The end member calculation of pyroxene has been done on the basis of six oxygen (Cawthorn and Collerson 1974) and ferrous and ferric Fe content has been calculated

Figure 5. Photomicrographs of various rock types illustrating textural features of different rocks from BVS sequence. (a) Basalt showing ophitic texture with plagioclase laths enclosed in augite (sample no. R01). (b) A pyroxene grain in basalt with alteration rim of amphibole at its grain boundary (sample no. RD30). (c) Andesite with oscillatory zoned plagioclase indicating disequilibrium growth (sample no. R04). (d) Resorbed plagioclase grain in andesite formed due to disintegration of an earlier formed plagioclase grain getting re-equilibrated in the new hybrid melt (sample no. RJ24). (e) Growth of acicular apatite in andesite due to quenching of hot mafic magma by relatively colder felsic magma (sample no. R04). (f) Mafic mineral clot in hybrid rock (sample no. RJ22B). (g) A fine grained tuff showing broken fragments of muscovite in a devitrified glassy matrix suggests an explosive eruption (sample no. R07). (h) Tuff showing subrounded grains of K-feldspar and quartz and broken fragments of muscovite embedded in a devitrified glassy matrix (sample no. R07). (i) Rhyolite showing alternating bands of mica and quartz rich layers. Such bands may develop as a result of deformation (sample no. R04). (j) Granite showing euhedral biotite grains occurring with euhedral to subhedral plagioclase and quartz grains (sample no. RD29). (k) Myrmekite texture in granite (sample no. RD28). (l) Perthitic intergrowth in granite (sample no. RD34).

Figure 5. (Continued.)

according to Droop (1987). The chemical data of pyroxene of the basalts show a restricted end member composition ($Wo_{40-43}En_{36-38}Fs_{18-22}$). Figure 6(b) shows the composition of clinopyroxene grains of the basalts in terms of end member compositions. Almost all data plot within the augite field.

Micas of the present area have been classified based on classification given by Deer *et al.* (1992). Mica minerals have been further subdivided on the basis of Si, Al and (Mg, Fe) value of atoms per formula unit. Basalts have biotite as the mica mineral showing a solid solution between annite and siderophyllite end members (Speer 1984). The Si content of biotite grains vary from 5.43–6.10 and total Al varies from

2.29–3.47 (figure 6d). The Fe+Mg value ranges from 3.91–5.45 mol fractions (22O) and Ti content varies from 0.04–0.28. Low total observed for the biotite is because of the alteration of the biotite to chlorite.

Chlorite is mostly occurring as secondary phase. The Si content for chlorite varies from 6.59–5.30 with Al content of 5.69–3.88.

Amphibole is reported only from the basalts of the study area. Mineral formula calculation for the amphibole has been carried out following Leake *et al.* (1997). Amphibole is commonly actinolite and magnesium hornblende with Mg percentage varying from 12–14 wt% and with low Ti content of <1 wt% (figure 6f). Amphibole chemistry could not be used for the purpose of estimating the

pressure–temperature conditions of the magma chamber as the amphibole compositions plot within the metamorphic field of the calcic amphibole

discrimination diagram of Fleet and Barnett (1978). They are probably crystallized due to metamorphic equilibration.

Figure 6. (a) A triangular plot showing the composition of the feldspars of the various rock types of BVS sequence Deer *et al.* (1992). (b) Composition of pyroxene grains of the basalt samples of the BVS sequence. The end member calculations of the pyroxene have been done on the basis of 6 oxygen (Cawthorn and Collerson 1974). (c) Compositional profile of an oscillatory zoned plagioclase grain of andesite (sample no. R04). The compositional variability shown as a function of X_{Ca} content marks the disequilibrium growth of the mineral (see table 2). (d) (i) Classification of biotite from basalt, andesite and granite of BVS sequence based on the nomenclature of Spear (1984). (ii) A plot showing the Mg–Fe compositional variation of biotite in mafic, felsic and intermediate rocks of the BVS sequence. (e) Plot showing the total range of Phengitic substitution in the muscovite grains of tuff, rhyolites and granites of the BVS sequence Deer *et al.* (1992). (f) Classification plot of amphibole from basalt of the BVS sequence after Leake *et al.* (1997).

Figure 6. (Continued.)

4.2 Andesite

Andesites have feldspars of both plagioclase and alkali feldspar compositions. The andesite plagioclase composition is rich in Ca content with X_{Ca} value varying from 0.71–0.85 with a corresponding X_{Na} value of 0.14–0.28. However, in the plagioclase grains with oscillatory zones, composition ranges from albite-rich rims to anorthite-rich cores. A zoning profile of X_{Ca} content for a plagioclase grain illustrating disequilibrium growth is shown in figure 6(c) (see table 2). For the alkali feldspar of andesite, the X_K content ranges from 0.69–0.95. Andesites have biotite as the mica mineral. According to the nomenclature of biotite based on Speer (1984), biotite of the andesites is solid solution of annite and siderophyllite end members with a Si value varying from 6.23–6.49 and total Al = 1.65–1.96 (figure 6d).

4.3 Tuff

Alkali feldspar compositions are observed for tuff with X_K content of 0.93–0.94. Mica in the tuff is muscovite with Si content of 6.29–6.63 p.f.u., Mg+Fe content of 0.29–0.38 p.f.u and Al content of 4.96–5.36 p.f.u and X_K varies from 0.95–0.97 (figure 6e).

4.4 Rhyolite

The alkali feldspar of rhyolite shows X_K content of 93–95 mol%. Muscovite grains are observed in rhyolites with X_K varying from 0.93–0.98. Si vs. total Al plot clearly shows that they are ideal muscovite with a limited phengitic substitution (figure 6e). Ilmenite grains are also observed in the rhyolite. Cation calculation for the ilmenite has been done on the basis of 3O as given in table 1.

Table 1. Representative major oxide analyses of various mineral phases present in the representative samples of basalts, andesites, rhyolites, granites and tuffs from Bathani volcano-sedimentary sequence.

Basalt											
Plagioclase Feldspar				Pyroxene				Biotite			
SiO ₂	56.65	54.68	55.88	56.85	52.55	SiO ₂	50.14	50.08	49.72	48.06	48.72
TiO ₂	0.00	0.00	0.00	0.00	0.08	TiO ₂	1.17	0.83	1.21	1.56	1.37
Al ₂ O ₃	26.79	28.83	27.13	28.86	30.95	Al ₂ O ₃	2.45	3.11	3.36	7.14	5.12
FeO	0.42	0.61	0.37	0.08	0.68	FeO	12.95	13.05	12.98	11.14	11.97
MgO	0.01	0.05	0.03	0.00	0.21	MgO	12.26	12.60	12.16	12.33	12.29
CaO	9.40	11.37	10.19	7.11	9.80	CaO	19.20	18.62	18.81	19.14	19.35
Na ₂ O	6.42	5.23	5.95	6.91	5.28	Na ₂ O	0.33	0.30	0.31	0.35	0.37
K ₂ O	0.06	0.05	0.06	0.09	0.33	K ₂ O	0.00	0.01	0.01	0.00	0.00
MnO	0.03	0.00	0.00	0.00	0.00	MnO	0.33	0.29	0.33	0.14	0.30
Total	99.76	100.83	99.60	99.90	99.87	Total	98.83	98.88	98.90	99.87	99.49
Calculation based on 8 oxygen											
Si	2.56	2.45	2.53	2.54	2.38	Si	1.92	1.91	1.90	1.80	1.85
Ti	0.00	0.00	0.00	0.00	0.00	Ti	0.03	0.02	0.03	0.04	0.04
Al	1.42	1.53	1.45	1.52	1.65	Al	0.11	0.14	0.15	0.32	0.23
Fe	0.02	0.02	0.01	0.00	0.03	Al ^{iv}	0.08	0.09	0.10	0.20	0.15
Mg	0.00	0.00	0.00	0.00	0.01	Al ^{vi}	0.03	0.05	0.05	0.12	0.08
Ca	0.45	0.55	0.49	0.34	0.48	Fe	0.41	0.42	0.41	0.35	0.38
Na	0.56	0.46	0.52	0.60	0.46	Fe ³⁺	0.01	0.01	0.00	0.02	0.04
K	0.00	0.00	0.00	0.01	0.02	Fe ²⁺	0.41	0.40	0.41	0.33	0.34
Mn	0.00	0.00	0.00	0.00	0.00	Mg	0.70	0.72	0.69	0.69	0.69
Total	5.02	5.01	5.01	5.00	5.03	Ca	0.79	0.76	0.77	0.77	0.79
X _{Na}	0.55	0.45	0.51	0.63	0.48	Na	0.02	0.02	0.02	0.03	0.03
X _{Ca}	0.45	0.54	0.48	0.36	0.50	K	0.00	0.00	0.00	0.00	0.00
X _K	0.00	0.00	0.00	0.01	0.02	Mn	0.01	0.01	0.01	0.00	0.01
						Total	4.00	4.00	4.00	4.01	4.01
						Wo%	41.57	40.49	41.04	42.95	43.12
						En%	36.95	38.14	36.93	38.50	38.09
						Fe%	21.48	21.37	22.03	18.54	18.79
						Q	1.90	1.88	1.88	1.79	1.82
						Aeg	0.03	0.04	0.02	0.04	0.06
						Jd	0.13	0.16	0.17	0.34	0.26
Andesite											
Plagioclase Feldspar				Pyroxene				Biotite			
SiO ₂	56.65	54.68	55.88	56.85	52.55	SiO ₂	50.14	50.08	49.72	48.06	48.72
TiO ₂	0.00	0.00	0.00	0.00	0.08	TiO ₂	1.17	0.83	1.21	1.56	1.37
Al ₂ O ₃	26.79	28.83	27.13	28.86	30.95	Al ₂ O ₃	2.45	3.11	3.36	7.14	5.12
FeO	0.42	0.61	0.37	0.08	0.68	FeO	12.95	13.05	12.98	11.14	11.97
MgO	0.01	0.05	0.03	0.00	0.21	MgO	12.26	12.60	12.16	12.33	12.29
CaO	9.40	11.37	10.19	7.11	9.80	CaO	19.20	18.62	18.81	19.14	19.35
Na ₂ O	6.42	5.23	5.95	6.91	5.28	Na ₂ O	0.33	0.30	0.31	0.35	0.37
K ₂ O	0.06	0.05	0.06	0.09	0.33	K ₂ O	0.00	0.01	0.01	0.00	0.00
MnO	0.03	0.00	0.00	0.00	0.00	MnO	0.33	0.29	0.33	0.14	0.30
Total	99.76	100.83	99.60	99.90	99.87	Total	98.83	98.88	98.90	99.87	99.49
Calculation based on 8 oxygen											
Si	2.56	2.45	2.53	2.54	2.38	Si	1.92	1.91	1.90	1.80	1.85
Ti	0.00	0.00	0.00	0.00	0.00	Ti	0.03	0.02	0.03	0.04	0.04
Al	1.42	1.53	1.45	1.52	1.65	Al	0.11	0.14	0.15	0.32	0.23
Fe	0.02	0.02	0.01	0.00	0.03	Al ^{iv}	0.08	0.09	0.10	0.20	0.15
Mg	0.00	0.00	0.00	0.00	0.01	Al ^{vi}	0.03	0.05	0.05	0.12	0.08
Ca	0.45	0.55	0.49	0.34	0.48	Fe	0.41	0.42	0.41	0.35	0.38
Na	0.56	0.46	0.52	0.60	0.46	Fe ³⁺	0.01	0.01	0.00	0.02	0.04
K	0.00	0.00	0.00	0.01	0.02	Fe ²⁺	0.41	0.40	0.41	0.33	0.34
Mn	0.00	0.00	0.00	0.00	0.00	Mg	0.70	0.72	0.69	0.69	0.69
Total	5.02	5.01	5.01	5.00	5.03	Ca	0.79	0.76	0.77	0.77	0.79
X _{Na}	0.55	0.45	0.51	0.63	0.48	Na	0.02	0.02	0.02	0.03	0.03
X _{Ca}	0.45	0.54	0.48	0.36	0.50	K	0.00	0.00	0.00	0.00	0.00
X _K	0.00	0.00	0.00	0.01	0.02	Mn	0.01	0.01	0.01	0.00	0.01
						Total	4.00	4.00	4.00	4.01	4.01
						Wo%	41.57	40.49	41.04	42.95	43.12
						En%	36.95	38.14	36.93	38.50	38.09
						Fe%	21.48	21.37	22.03	18.54	18.79
						Q	1.90	1.88	1.88	1.79	1.82
						Aeg	0.03	0.04	0.02	0.04	0.06
						Jd	0.13	0.16	0.17	0.34	0.26
Granite											
Plagioclase Feldspar				Pyroxene				Biotite			
SiO ₂	56.65	54.68	55.88	56.85	52.55	SiO ₂	50.14	50.08	49.72	48.06	48.72
TiO ₂	0.00	0.00	0.00	0.00	0.08	TiO ₂	1.17	0.83	1.21	1.56	1.37
Al ₂ O ₃	26.79	28.83	27.13	28.86	30.95	Al ₂ O ₃	2.45	3.11	3.36	7.14	5.12
FeO	0.42	0.61	0.37	0.08	0.68	FeO	12.95	13.05	12.98	11.14	11.97
MgO	0.01	0.05	0.03	0.00	0.21	MgO	12.26	12.60	12.16	12.33	12.29
CaO	9.40	11.37	10.19	7.11	9.80	CaO	19.20	18.62	18.81	19.14	19.35
Na ₂ O	6.42	5.23	5.95	6.91	5.28	Na ₂ O	0.33	0.30	0.31	0.35	0.37
K ₂ O	0.06	0.05	0.06	0.09	0.33	K ₂ O	0.00	0.01	0.01	0.00	0.00
MnO	0.03	0.00	0.00	0.00	0.00	MnO	0.33	0.29	0.33	0.14	0.30
Total	99.76	100.83	99.60	99.90	99.87	Total	98.83	98.88	98.90	99.87	99.49
Calculation based on 8 oxygen											
Si	2.56	2.45	2.53	2.54	2.38	Si	1.92	1.91	1.90	1.80	1.85
Ti	0.00	0.00	0.00	0.00	0.00	Ti	0.03	0.02	0.03	0.04	0.04
Al	1.42	1.53	1.45	1.52	1.65	Al	0.11	0.14	0.15	0.32	0.23
Fe	0.02	0.02	0.01	0.00	0.03	Al ^{iv}	0.08	0.09	0.10	0.20	0.15
Mg	0.00	0.00	0.00	0.00	0.01	Al ^{vi}	0.03	0.05	0.05	0.12	0.08
Ca	0.45	0.55	0.49	0.34	0.48	Fe	0.41	0.42	0.41	0.35	0.38
Na	0.56	0.46	0.52	0.60	0.46	Fe ³⁺	0.01	0.01	0.00	0.02	0.04
K	0.00	0.00	0.00	0.01	0.02	Fe ²⁺	0.41	0.40	0.41	0.33	0.34
Mn	0.00	0.00	0.00	0.00	0.00	Mg	0.70	0.72	0.69	0.69	0.69
Total	5.02	5.01	5.01	5.00	5.03	Ca	0.79	0.76	0.77	0.77	0.79
X _{Na}	0.55	0.45	0.51	0.63	0.48	Na	0.02	0.02	0.02	0.03	0.03
X _{Ca}	0.45	0.54	0.48	0.36	0.50	K	0.00	0.00	0.00	0.00	0.00
X _K	0.00	0.00	0.00	0.01	0.02	Mn	0.01	0.01	0.01	0.00	0.01
						Total	4.00	4.00	4.00	4.01	4.01
						Wo%	41.57	40.49	41.04	42.95	43.12
						En%	36.95	38.14	36.93	38.50	38.09
						Fe%	21.48	21.37	22.03	18.54	18.79
						Q	1.90	1.88	1.88	1.79	1.82
						Aeg	0.03	0.04	0.02	0.04	0.06
						Jd	0.13	0.16	0.17	0.34	0.26
Diorite											
Plagioclase Feldspar				Pyroxene				Biotite			
SiO ₂	56.65	54.68	55.88	56.85	52.55	SiO ₂	50.14	50.08	49.72	48.06	48.72
TiO ₂	0.00	0.00	0.00	0.00	0.08	TiO ₂	1.17	0.83	1.21	1.56	1.37
Al ₂ O ₃	26.79	28.83	27.13	28.86	30.95	Al ₂ O ₃	2.45	3.11	3.36	7.14	5.12
FeO	0.42	0.61	0.37	0.08	0.68	FeO	12.95	13.05	12.98	11.14	11.97
MgO	0.01	0.05	0.03	0.00	0.21	MgO	12.26	12.60	12.16	12.33	12.29
CaO	9.40	11.37	10.19	7.11	9.80	CaO	19.20	18.62	18.81	19.14	19.35
Na ₂ O	6.42	5.23	5.95	6.91	5.28	Na ₂ O	0.33	0.30	0.31	0.35	0.37
K ₂ O	0.06	0.05	0.06	0.09	0.33	K ₂ O	0.00	0.01	0.01	0.00	0.00
MnO	0.03	0.00	0.00	0.00	0.00	MnO	0.33	0.29	0.33	0.14	0.30
Total	99.76	100.83	99.60	99.90	99.87	Total	98.83	98.88	98.90	99.87	99.49
Calculation based on 8 oxygen											
Si	2.56	2.45	2.53	2.54	2.38	Si	1.92	1.91	1.90	1.80	1.85
Ti	0.00	0.00	0.00	0.00	0.00	Ti	0.03	0.02	0.03	0.04	0.04
Al	1.42	1.53	1.45	1.52	1.65	Al	0.11	0.14	0.15	0.32	0.23
Fe	0.02	0.02	0.01	0.00	0.03	Al ^{iv}	0.08	0.09	0.10	0.20	0.15
Mg	0.00	0.00	0.00	0.00	0.01	Al ^{vi}	0.03	0.05	0.05	0.12	0.08
Ca	0.45	0.55	0.49	0.34	0.48	Fe	0.41	0.42	0.41	0.35	0.38
Na	0.56	0.46	0.52	0.60	0.46	Fe ³⁺	0.01	0.01	0.00	0.02	0.04
K	0.00	0.00	0.00	0.01	0.02	Fe ²⁺	0.41	0.40	0.41	0.33	0.34
Mn	0.00	0.00	0.00								

Table 1. (Continued.)

Andesite														
Plagioclase feldspar					Alkali feldspar					Biotite				
SiO ₂	50.27	50.60	62.30	54.83	48.33	SiO ₂	60.89	63.84	61.57	SiO ₂	35.02	35.83	34.72	36.04
MgO	0.05	0.00	0.00	0.03	0.13	MgO	0.06	0.00	0.00	MgO	8.88	9.18	8.95	9.15
FeO	1.02	0.30	0.04	0.07	0.90	FeO	0.09	0.00	0.00	FeO	20.03	20.65	20.03	20.15
Al ₂ O ₃	31.06	30.10	22.85	28.28	32.01	Al ₂ O ₃	19.07	18.47	18.30	Al ₂ O ₃	17.56	15.85	18.15	16.57
CaO	13.11	14.03	4.94	11.60	13.72	CaO	0.26	0.04	0.00	CaO	0.04	0.00	0.04	0.00
Na ₂ O	3.71	3.49	8.56	5.18	2.13	Na ₂ O	1.83	3.33	0.52	Na ₂ O	0.14	0.07	0.04	0.04
K ₂ O	0.10	0.05	0.08	0.06	1.59	K ₂ O	11.98	11.76	15.18	K ₂ O	9.30	9.17	9.04	9.52
P ₂ O ₅	0.04	0.15	0.03	0.08	0.14	P ₂ O ₅	0.00	0.00	0.03	P ₂ O ₅	0.00	0.00	0.00	0.04
TiO ₂	0.02	0.00	0.02	0.00	0.01	TiO ₂	0.03	0.01	0.02	TiO ₂	1.52	1.69	1.37	1.69
Cr ₂ O ₃	0.10	0.06	0.00	0.00	0.00	Cr ₂ O ₃	0.00	0.02	0.00	Cr ₂ O ₃	0.00	0.05	0.00	0.00
MnO	0.00	0.00	0.00	0.00	0.00	MnO	0.00	0.00	0.00	MnO	0.28	0.37	0.30	0.29
BaO	0.07	0.05	0.01	0.01	0.03	BaO	1.73	0.01	1.75	BaO	0.44	0.36	0.16	0.09
Cl	0.04	0.03	0.00	0.00	0.07	Cl	0.01	0.00	0.01	Cl	0.11	0.17	0.14	0.11
F	0.00	0.00	0.07	0.00	0.00	F	0.00	0.00	0.00	F	0.49	0.33	0.31	0.45
Total	99.567	98.864	98.905	100.125	99.063	Total	95.95	97.47	97.39	Total	93.80	93.70	93.25	94.12
Calculation based on 8 oxygen														
Si	2.77	2.79	3.22	2.93	2.72	Si	3.37	3.42	3.39	Calculation based on 22 oxygen				
Mg	0.00	0.00	0.00	0.00	0.01	Mg	0.01	0.00	0.00	Mg	2.38	2.44	2.42	2.43
Fe	0.05	0.01	0.00	0.00	0.04	Fe	0.00	0.00	0.00	Fe	2.99	3.06	3.01	2.89
Al	1.01	0.98	0.70	0.89	1.06	Al	0.62	0.58	0.59	Al ^{iv}	1.74	1.64	1.75	1.63
Ca	0.77	0.83	0.27	0.66	0.82	Ca	0.02	0.00	0.00	Al ^{vi}	0.11	0.01	0.18	0.11
Na	0.20	0.19	0.43	0.27	0.12	Na	0.10	0.17	0.03	Ca	0.01	0.00	0.01	0.00
K	0.00	0.00	0.00	0.00	0.06	K	0.42	0.40	0.53	Na	0.02	0.01	0.01	0.01
P	0.00	0.00	0.00	0.00	0.00	P	0.00	0.00	0.00	K	1.06	1.04	1.04	1.07
Ti	0.00	0.00	0.00	0.00	0.00	Ti	0.00	0.00	0.00	P	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	Cr	0.00	0.00	0.00	Ti	0.20	0.23	0.18	0.22
Mn	0.00	0.00	0.00	0.00	0.00	Mn	0.00	0.00	0.00	Cr	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	Ba	0.04	0.00	0.04	Mn	0.04	0.06	0.05	0.04
Cl	0.00	0.00	0.00	0.00	0.01	Cl	0.00	0.00	0.00	Ba	0.03	0.02	0.01	0.01
F	0.00	0.00	0.01	0.00	0.00	F	0.00	0.00	0.00	Cl	0.03	0.05	0.04	0.03
Total	4.82	4.81	4.64	4.76	4.84	Total	4.58	4.58	4.59	F	0.28	0.18	0.18	0.23
										Total	15.16	15.11	15.12	15.10
Calculation based on 8 oxygen														
X _{Na}	0.20	0.18	0.61	0.29	0.12	X _K	0.79	0.70	0.95					
X _{Ca}	0.79	0.81	0.39	0.71	0.83	X _{Na}	0.18	0.30	0.05					
X _K	0.00	0.00	0.00	0.00	0.06	X _{Ca}	0.03	0.00	0.00					

Table 1. (Continued.)

Tuff											
Alkali feldspar						Muscovite			Tourmaline		
SiO ₂	47.45	45.85	46.96	47.85	46.34	SiO ₂	47.53	46.99	46.18	46.87	48.57
MgO	0.50	0.45	0.74	0.45	0.65	MgO	0.53	0.63	0.39	0.81	0.87
FeO	0.93	1.00	1.17	0.93	1.01	FeO	1.06	0.92	0.82	1.21	1.16
Al ₂ O ₃	36.19	35.82	34.15	36.41	35.31	Al ₂ O ₃	36.15	35.15	35.35	33.76	34.54
CaO	0.00	0.00	0.00	0.03	0.09	CaO	0.05	0.05	0.00	0.05	0.00
Na ₂ O	0.40	0.48	0.38	0.38	0.43	Na ₂ O	0.31	0.37	0.41	0.39	0.39
K ₂ O	10.50	10.75	10.48	10.64	10.38	K ₂ O	8.66	9.09	10.43	10.24	10.34
P ₂ O ₅	0.63	0.33	0.04	0.38	0.13	P ₂ O ₅	0.10	0.00	0.00	0.00	0.01
TiO ₂	1.42	4.32	3.92	2.11	2.94	TiO ₂	0.43	0.45	0.45	0.13	0.10
Cr ₂ O ₃	0.07	0.08	0.02	0.05	0.04	Cr ₂ O ₃	0.06	0.23	0.03	0.00	0.00
MnO	0.03	0.00	0.04	0.00	0.07	MnO	0.00	0.03	0.03	0.00	0.01
BaO	0.65	0.00	0.68	0.17	0.53	BaO	0.12	0.18	0.26	0.08	0.10
ZnO	0.00	0.04	0.00	0.06	0.06	ZnO	0.00	0.00	0.00	0.00	0.00
F	0.11	0.00	0.19	0.00	0.08	F	0.00	0.20	0.00	0.12	0.24
Total	98.88	99.12	98.77	99.47	98.04	Total	95.00	94.28	94.35	93.65	96.33
Calculation based on 8 oxygen											
Si	2.22	2.14	2.21	2.22	2.19	Si	6.24	6.26	6.19	6.33	6.37
Mg	0.03	0.03	0.05	0.03	0.05	Mg	0.10	0.12	0.08	0.16	0.17
Fe	0.04	0.04	0.05	0.04	0.04	Fe	0.12	0.10	0.09	0.14	0.13
Al	1.99	1.97	1.90	1.99	1.97	Al	5.59	5.52	5.59	5.38	5.34
Ca	0.00	0.00	0.00	0.00	0.00	Al ^{iv}	1.76	1.74	1.81	1.67	1.63
Na	0.04	0.04	0.03	0.03	0.04	Al ^{vi}	3.84	3.78	3.78	3.71	3.71
K	0.63	0.64	0.63	0.63	0.63	Ca	0.01	0.01	0.00	0.01	0.00
P	0.02	0.01	0.00	0.01	0.01	Na	0.08	0.10	0.11	0.10	0.10
Ti	0.05	0.15	0.14	0.07	0.10	K	1.45	1.54	1.78	1.77	1.73
Cr	0.00	0.00	0.00	0.00	0.00	P	0.01	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	Ti	0.04	0.04	0.05	0.01	0.01
Ba	0.01	0.00	0.01	0.00	0.01	Cr	0.01	0.02	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	Mn	0.00	0.00	0.00	0.00	0.00
F	0.02	0.00	0.03	0.00	0.01	Ba	0.01	0.01	0.01	0.00	0.01
Total	5.05	5.04	5.06	5.03	5.06	Zn	0.00	0.00	0.00	0.00	0.00
						F	0.00	0.08	0.00	0.05	0.10
X _K	0.945	0.937	0.948	0.947	0.934	Total	13.66	13.82	13.91	13.95	13.96
X _{Na}	0.055	0.063	0.052	0.051	0.059						
X _{Ca}	0.000	0.000	0.000	0.002	0.007						

Calculation based on 31 oxygen

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Fe

Al

Ca

Na

K

P

Ti

Cr

Mn

Ba

Zn

F

Total

Si

Mg

Table 1. (Continued.)

Rhyolite											
Alkali feldspar				Muscovite				Ilmenite			
SiO ₂	56.88	61.78	52.12	65.90	SiO ₂	50.36	47.82	48.25	48.19	SiO ₂	0.04
MgO	0.65	0.71	0.68	0.55	MgO	0.94	0.77	1.06	0.79	MgO	0.09
FeO	1.05	1.15	1.11	0.86	FeO	1.50	1.32	1.68	1.27	FeO	42.72
Al ₂ O ₃	27.65	25.42	32.82	22.08	Al ₂ O ₃	31.98	33.66	34.89	34.44	Al ₂ O ₃	0.05
CaO	0.00	0.00	0.05	0.21	CaO	0.00	0.09	0.00	0.04	CaO	0.00
Na ₂ O	0.25	0.18	0.28	0.17	Na ₂ O	0.18	0.20	0.26	0.33	Na ₂ O	0.00
K ₂ O	8.79	8.39	10.57	6.64	K ₂ O	9.91	10.64	10.29	10.58	K ₂ O	0.06
P ₂ O ₅	0.17	0.01	0.20	0.11	P ₂ O ₅	0.00	0.04	0.00	0.04	P ₂ O ₅	0.00
TiO ₂	2.62	0.32	1.39	1.03	TiO ₂	0.31	0.22	0.41	0.41	TiO ₂	52.08
Cr ₂ O ₃	0.00	0.06	0.02	0.05	Cr ₂ O ₃	0.00	0.00	0.01	0.00	Cr ₂ O ₃	0.03
MnO	0.00	0.00	0.01	0.00	MnO	0.09	0.00	0.00	0.08	MnO	1.49
BaO	0.22	0.00	0.23	0.47	BaO	0.00	0.01	0.14	0.06	BaO	0.60
ZnO	0.00	0.00	0.00	0.00	ZnO	0.00	0.00	0.00	0.06	ZnO	0.00
F	0.29	0.12	0.18	0.07	F	0.00	0.35	0.03	0.18	F	0.08
Total	98.56	98.13	99.65	98.13	Total	95.27	95.11	97.02	96.46	Total	97.23
Calculation based on 8 oxygen				Calculation based on 22 oxygen				Calculation based on 3 oxygen			
Si	2.60	2.80	2.40	2.95	Si	6.64	6.38	6.29	6.33	Si	0.00
Mg	0.04	0.05	0.05	0.04	Mg	0.19	0.15	0.21	0.15	Mg	0.00
Fe	0.04	0.04	0.04	0.03	Fe	0.16	0.15	0.18	0.14	Fe	0.92
Al	1.49	1.36	1.78	1.16	Al total	4.97	5.29	5.36	5.33	Al	0.00
Ca	0.00	0.00	0.00	0.01	Al ^{iv}	1.36	1.62	1.71	1.67	Ca	0.00
Na	0.02	0.02	0.03	0.01	Al ^{vi}	3.60	3.67	3.66	3.67	Na	0.00
K	0.51	0.48	0.62	0.38	Ca	0.00	0.01	0.00	0.01	K	0.00
P	0.01	0.00	0.01	0.00	Na	0.05	0.05	0.07	0.08	P	0.00
Ti	0.09	0.01	0.05	0.03	K	1.66	1.81	1.71	1.77	Ti	1.01
Cr	0.00	0.00	0.00	0.00	P	0.00	0.00	0.00	0.00	Cr	0.00
Mn	0.00	0.00	0.00	0.00	Ti	0.03	0.02	0.04	0.04	Mn	0.03
Ba	0.00	0.00	0.00	0.01	Cr	0.00	0.00	0.00	0.00	Ba	0.01
Zn	0.00	0.00	0.00	0.00	Mn	0.01	0.00	0.00	0.01	Zn	0.00
F	0.04	0.02	0.03	0.01	Ba	0.00	0.00	0.01	0.00	F	0.01
Total	4.86	4.78	5.00	4.64	Zn	0.00	0.00	0.00	0.00	Total	1.99
X _K	0.96	0.97	0.96	0.94	F	0.00	0.15	0.01	0.07	Total	2.00
X _{Na}	0.04	0.03	0.04	0.04	Total	13.70	14.02	13.88	13.96		
X _{Ca}	0.00	0.00	0.00	0.02							

Table 1. (Continued.)

Granite													
Plagioclase feldspar							Alkali feldspar						
SiO ₂	60.91	66.12	69.19	64.00	64.58	66.89	SiO ₂	65.59	65.20	65.06	64.93	64.68	64.86
MgO	0.01	0.00	0.00	0.00	0.01	0.00	MgO	0.03	0.00	0.00	0.00	0.00	0.02
FeO	0.23	0.00	0.04	0.00	0.09	0.00	FeO	0.05	0.00	0.01	0.00	0.00	0.00
Al ₂ O ₃	23.99	21.70	19.19	22.30	23.15	21.12	Al ₂ O ₃	17.76	17.93	18.00	18.01	18.30	18.08
CaO	6.37	1.32	0.19	3.71	2.58	1.93	CaO	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	8.04	10.11	10.82	8.96	9.22	9.87	Na ₂ O	0.63	0.59	0.51	0.39	0.26	0.49
K ₂ O	0.08	0.10	0.08	0.08	0.26	0.11	K ₂ O	15.68	15.76	15.89	16.10	16.17	15.92
P ₂ O ₅	0.02	0.00	0.00	0.00	0.03	0.01	P ₂ O ₅	0.06	0.00	0.00	0.00	0.02	0.00
TiO ₂	0.00	0.00	0.01	0.03	0.00	0.02	TiO ₂	0.02	0.00	0.02	0.00	0.00	0.00
Cr ₂ O ₃	0.09	0.00	0.00	0.02	0.03	0.01	Cr ₂ O ₃	0.00	0.00	0.00	0.07	0.00	0.00
MnO	0.00	0.00	0.05	0.01	0.08	0.00	MnO	0.00	0.03	0.05	0.02	0.00	0.00
BaO	0.00	0.01	0.00	0.00	0.01	0.00	BaO	0.00	0.00	0.01	0.04	0.01	0.00
Cl	0.00	0.00	0.01	0.01	0.09	0.03	Cl	0.00	0.10	0.11	0.08	0.00	0.17
F	0.00	0.00	0.22	0.00	0.00	0.08	F	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.73	99.42	99.83	99.13	100.09	100.06	Total	99.81	99.62	99.71	99.71	99.74	99.71
Calculation based on 8 oxygen							Calculation based on 8 oxygen						
Si	2.72	2.91	3.02	2.84	2.84	2.93	Si	3.03	3.02	3.01	3.01	3.00	3.01
Mg	0.00	0.00	0.00	0.00	0.00	0.00	Mg	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.01	0.00	0.00	0.00	0.00	0.00	Fe	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.26	1.12	0.99	1.17	1.20	1.09	Al	0.97	0.98	0.98	0.98	1.00	0.99
Ca	0.30	0.06	0.01	0.18	0.12	0.09	Ca	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.70	0.86	0.92	0.77	0.78	0.84	Na	0.06	0.05	0.05	0.04	0.02	0.04
K	0.00	0.01	0.00	0.00	0.01	0.01	K	0.92	0.93	0.94	0.95	0.96	0.94
P	0.00	0.00	0.00	0.00	0.00	0.00	P	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	Ti	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	Cr	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00	Mn	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	Ba	0.00	0.00	0.00	0.00	0.01	0.00
Cl	0.00	0.00	0.00	0.00	0.01	0.00	Cl	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.03	0.00	0.00	0.01	F	0.00	0.01	0.02	0.01	0.00	0.02
Total	5.00	4.96	4.97	4.96	4.97	4.96	Total	4.98	5.00	5.00	5.00	4.99	5.01
X _{Na}	0.69	0.93	0.99	0.81	0.85	0.90	X _K	0.94	0.95	0.95	0.96	0.98	0.96
X _{Ca}	0.30	0.07	0.01	0.19	0.13	0.10	X _{Na}	5.71	5.36	4.62	3.55	2.35	4.49
X _K	0.00	0.01	0.00	0.00	0.02	0.01	X _{Ca}	0.00	0.00	0.00	0.00	0.00	0.00
Biotite													
SiO ₂	34.22	33.29	34.22	33.29	34.22	33.29	SiO ₂	34.22	33.29	34.22	33.29	34.22	33.29
MgO	6.57	6.58	6.57	6.58	6.57	6.55	MgO	6.57	6.58	6.57	6.58	6.57	6.55
FeO	24.70	23.72	24.70	23.72	24.70	22.90	FeO	24.70	23.72	24.70	23.72	24.70	22.90
Al ₂ O ₃	18.23	21.12	18.23	21.12	18.23	22.12	Al ₂ O ₃	18.23	21.12	18.23	21.12	18.23	22.12
CaO	0.00	0.01	0.00	0.01	0.00	0.06	CaO	0.00	0.01	0.00	0.01	0.00	0.06
Na ₂ O	0.05	0.10	0.05	0.10	0.05	0.10	Na ₂ O	0.05	0.10	0.05	0.10	0.05	0.10
K ₂ O	9.24	8.99	9.24	8.99	9.24	9.11	K ₂ O	9.24	8.99	9.24	8.99	9.24	9.11
P ₂ O ₅	0.03	0.00	0.03	0.00	0.03	0.05	P ₂ O ₅	0.03	0.00	0.03	0.00	0.03	0.05
TiO ₂	1.71	1.26	1.71	1.26	1.71	1.26	TiO ₂	1.71	1.26	1.71	1.26	1.71	1.26
Cr ₂ O ₃	0.00	0.05	0.00	0.05	0.00	0.05	Cr ₂ O ₃	0.00	0.05	0.00	0.05	0.00	0.05
MnO	0.16	0.20	0.16	0.20	0.16	0.20	MnO	0.16	0.20	0.16	0.20	0.16	0.20
BaO	0.25	0.13	0.25	0.13	0.25	0.13	BaO	0.25	0.13	0.25	0.13	0.25	0.13
Cl	0.04	0.05	0.04	0.05	0.04	0.05	Cl	0.04	0.05	0.04	0.05	0.04	0.05
F	0.94	0.74	0.94	0.74	0.94	0.58	F	0.94	0.74	0.94	0.74	0.94	0.58
Total	96.13	96.25	96.13	96.25	96.13	95.52	Total	96.13	96.25	96.13	96.25	96.13	95.52
Calculation based on 22 oxygen							Calculation based on 22 oxygen						
Si	5.38	5.17	5.38	5.17	5.38	5.08	Si	5.38	5.17	5.38	5.17	5.38	5.08
Mg	1.54	1.53	1.54	1.53	1.53	1.52	Mg	1.54	1.53	1.54	1.53	1.53	1.52
Fe	3.25	3.08	3.25	3.08	3.25	2.99	Fe	3.25	3.08	3.25	3.08	3.25	2.99
Al	2.62	2.83	2.62	2.83	2.62	2.83	Al ^{iv}	2.62	2.83	2.62	2.83	2.62	2.83
Al ^{vi}	0.76	1.04	0.76	1.04	0.76	1.15	Al ^{vi}	0.76	1.04	0.76	1.04	0.76	1.15
Ca	0.00	0.00	0.00	0.00	0.00	0.01	Ca	0.00	0.00	0.00	0.00	0.01	0.01
Na	0.01	0.03	0.01	0.03	0.01	0.03	Na	0.01	0.03	0.01	0.03	0.01	0.03
K	1.85	1.78	1.85	1.78	1.85	1.81	K	1.85	1.78	1.85	1.78	1.85	1.81
P	0.00	0.00	0.00	0.00	0.00	0.01	P	0.00	0.00	0.00	0.00	0.01	0.01
Ti	0.20	0.15	0.20	0.15	0.20	0.13	Ti	0.20	0.15	0.20	0.15	0.20	0.13
Cr	0.00	0.01	0.00	0.01	0.00	0.00	Cr	0.00	0.01	0.00	0.01	0.00	0.00
Mn	0.02	0.03	0.02	0.03	0.02	0.03	Mn	0.02	0.03	0.02	0.03	0.02	0.03
Ba	0.02	0.01	0.02	0.01	0.02	0.01	Ba	0.02	0.01	0.02	0.01	0.02	0.01
Cl	0.01	0.01	0.01	0.01	0.01	0.01	Cl	0.01	0.01	0.01	0.01	0.01	0.01
F	0.47	0.36	0.47	0.36	0.47	0.29	F	0.47	0.36	0.47	0.36	0.47	0.29
Total	16.13	16.02	16.13	16.02	16.13	15.97	Total	16.13	16.02	16.13	16.02	16.13	15.97
Muscovite													
SiO ₂	45.59	46.25	44.16	45.26	45.97	45.97	SiO ₂	45.59	46.25	44.16	45.26	45.97	45.97
MgO	0.64	0.82	0.80	1.24	1.11	1.11	MgO	0.64	0.82	0.80	1.24	1.11	1.11
FeO	2.02	2.61	2.23	3.93	3.70	3.70	FeO	2.02	2.61	2.23	3.93	3.70	3.70
Al ₂ O ₃	33.96	33.10	36.06	32.85	32.56	32.56	Al ₂ O ₃	33.96	33.10	36.06	32.85	32.56	32.56
CaO	0.00	0.00	0.00	0.00	0.00	0.00	CaO	0.00	0.00	0.00	0.00	0.00	0.00
Na ₂ O	0.51	0.31	0.45	0.33	0.26	0.26	Na ₂ O	0.51	0.31	0.45	0.33	0.26	0.26
K ₂ O	10.79	10.79	10.51	10.81	11.03	11.03	K ₂ O	10.79	10.79	10.51	10.81	11.03	11.03
P ₂ O ₅	0.00	0.00	0.00	0.07	0.02	0.02	P ₂ O ₅	0.00	0.00	0.00	0.07	0.02	0.02
TiO ₂	1.24	1.03	1.22	0.50	0.79	0.79	TiO ₂	1.24	1.03	1.22	0.50	0.79	0.79
Cr ₂ O ₃	0.00	0.06	0.00	0.00	0.02	0.02	Cr ₂ O ₃	0.00	0.06	0.00	0.00	0.02	0.02
MnO	0.01	0.00	0.00	0.05	0.05	0.05	MnO	0.01	0.00	0.00	0.05	0.05	0.05
BaO	0.30	0.31	0.34	0.39	0.17	0.17	BaO	0.30	0.31	0.34	0.39	0.17	0.17
ZnO	0.00	0.00	0.00	0.03	0.00	0.00	ZnO	0.00	0.00	0.00	0.03	0.00	0.00
F	0.32	0.50	0.08	0.46	0.00	0.00	F	0.32	0.50	0.08	0.46	0.00	0.00
Total	95.37	95.77	95.87	95.88	95.68	95.68	Total	95.37	95.77	95.87	95.88	95.68	95.68

Table 2. Representative mineral chemistry data of plagioclase grain of andesite sample (R04) for a rim to rim chemical profile.
Data of rim to rim profile of oscillatory zoned plagioclase grain presented in figure 3(c)

SiO ₂	62.15	53.41	52.56	50.52	51.45	50.64	49.25	49.89	50.54	50.51	49.82	52.24	51.90	53.00	62.94
MgO	0.01	0.00	0.00	0.04	0.07	0.09	0.10	0.05	0.05	0.03	0.04	0.07	0.03	0.02	0.00
FeO	0.24	0.18	0.37	0.39	0.38	0.36	0.41	0.45	0.47	0.52	0.37	0.16	0.36	0.25	0.03
Al ₂ O ₃	24.18	29.89	30.07	31.18	30.15	30.43	31.11	31.05	30.78	30.88	31.76	28.70	30.23	29.90	23.62
CaO	5.24	12.18	12.80	14.38	13.67	13.65	14.85	14.20	14.23	13.82	14.96	11.70	13.25	12.17	4.52
Na ₂ O	8.56	4.56	4.33	2.97	3.77	3.69	2.95	3.28	3.56	3.54	3.03	4.74	4.17	4.66	9.10
K ₂ O	0.20	0.03	0.04	0.58	0.11	0.10	0.15	0.11	0.22	0.19	0.08	0.13	0.09	0.12	0.06
P ₂ O ₅	0.05	0.00	0.00	0.03	0.08	0.00	0.00	0.04	0.00	0.10	0.00	0.00	0.00	0.00	0.00
TiO ₂	0.02	0.00	0.10	0.10	0.00	0.00	0.03	0.00	0.08	0.00	0.03	0.00	0.00	0.06	0.06
Cr ₂ O ₃	0.09	0.02	0.00	0.09	0.02	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.03	0.00
MnO	0.00	0.03	0.03	0.00	0.02	0.00	0.00	0.05	0.02	0.00	0.03	0.03	0.00	0.03	0.05
BaO	0.01	0.00	0.03	0.05	0.15	0.00	0.11	0.05	0.04	0.10	0.00	0.00	0.10	0.00	0.00
Cl	0.05	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.01	0.03	0.03
F	0.00	0.00	0.00	0.10	0.28	0.00	0.00	0.10	0.00	0.11	0.22	0.05	0.00	0.19	0.00
Total	100.78	100.28	100.32	100.43	100.13	98.97	98.99	99.29	99.97	99.81	100.35	97.85	100.13	100.45	100.41
Si	2.74	2.41	2.38	2.30	2.34	2.33	2.28	2.29	2.31	2.31	2.26	2.42	2.36	2.39	2.77
Mg	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Fe	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00
Al	1.26	1.59	1.60	1.67	1.62	1.65	1.70	1.68	1.66	1.66	1.70	1.56	1.62	1.59	1.23
Ca	0.25	0.59	0.62	0.70	0.67	0.67	0.74	0.70	0.70	0.68	0.73	0.58	0.65	0.59	0.21
Na	0.73	0.40	0.38	0.26	0.33	0.33	0.26	0.29	0.32	0.31	0.27	0.43	0.37	0.41	0.78
K	0.01	0.00	0.00	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00
P	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.00	0.00	0.00	0.01	0.04	0.00	0.00	0.01	0.00	0.02	0.03	0.01	0.00	0.03	0.00
Total	5.00	5.00	5.01	5.01	5.02	5.01	5.01	5.01	5.02	5.02	5.02	5.02	5.02	5.02	5.00
X _{Na}	0.74	0.40	0.38	0.26	0.33	0.33	0.26	0.29	0.31	0.31	0.27	0.42	0.36	0.41	0.78
X _{Ca}	0.25	0.60	0.62	0.70	0.66	0.67	0.73	0.70	0.68	0.68	0.73	0.57	0.63	0.59	0.21
X _K	0.01	0.00	0.00	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00

Ilmenite shows $Ti = 1.01$ and $Fe^{2+} = 0.92$ mol fraction per formula unit.

4.5 Granite

The granite has feldspars of both plagioclase and alkali feldspar composition (figure 6a). The plagioclase feldspars are enriched in albite component with X_{Na} varying from 0.69–0.98. The granite has an alkali feldspar composition with X_K ranging from 0.94–0.97. Biotite and muscovite are present in the granite. Biotite is a solid solution of annite and siderophyllite having a Si value varying from 5.52–5.69 and total Al varying from 3.13–3.55 (figure 6d). The Fe+Mg values range from 4.16–4.47. The muscovite show limited phengitic substitution.

The general trend of decreasing X_{Ca} content of plagioclase feldspar composition from the basalt to the granite indicates fractional crystallization of basaltic magma to produce granitic magma. Biotite composition from the basalt to the granite shows a decrease in Mg content with a corresponding increase in Fe/Fe+Mg content, pointing towards fractionation of granites from the basalts. However, the biotite from the andesite plots as a distinct composition group from the granite and basalt. It can be inferred that this might be due to mixing of felsic and mafic melts.

5. Geochemistry

5.1 Geochemical analytical methods adopted

A total of 18 bulk rock samples (5 basalts, 4 andesites, 3 rhyolites, 1 tuff, and 5 granites) were analysed for major oxides, trace elements and rare earth elements (tables 3 and 4). Major oxides and trace elements were analysed using XRF (Bruker S8 Tiger Sequential X-ray Spectrometer with Rh excitation source) following the procedure of Saini *et al.* (1998, 2000) and rare earth elements (REEs) were analysed using ICP-MS (PerkinElmer made SCIEX quadrapole type ICP-MS, ELAN DRC-e), at the Wadia Institute of Himalayan Geology, Dehradun (India).

Operating conditions for the major oxides were: no filter, vacuum path, 20/40 kV; for trace elements: no filter, vacuum path, 55/60 kV. The overall accuracy in relative standard deviation percentage is <5% for major and minor oxides and <12% for the trace elements. The average precision is better than 2.0% (Purohit *et al.* 2006; Saini *et al.* 2007).

Sample solutions were introduced for rare earth element analysis into the argon plasma using a peristaltic pump and a cross flow nebulizer.

Table 3. Representative major oxide analyses of the mafic and felsic rocks from Bathani volcano-sedimentary sequence.

Sample no.	Basalt				Andesite				Rhyolite				Tuff	Granite				
	R01	R12	R16	R17	RJ25C	RJ22A	RJ05	RJ24	R04	R03	RJ23C	RJ25A	R07	RJ45	RJ48E	RJ48F	R10	R13
SiO ₂	45.18	49.43	47.34	48.29	43.92	55.42	52.39	53.87	55.81	73.91	80.79	81.31	53.92	66.61	63.48	67.91	68.85	66.63
TiO ₂	1.56	0.83	1.07	2.29	2.02	1.13	1.27	0.99	0.88	0.91	0.38	0.70	0.75	0.32	0.66	0.25	0.25	0.31
Al ₂ O ₃	13.8	11.84	12.38	11.33	14.56	12.18	13.55	14.11	15.41	13.25	9.19	8.48	26.21	15.76	16.24	15.62	15.12	15.65
Fe ₂ O ₃	13.98	11.63	14.42	16.62	15.14	9.44	9.70	9.31	8.39	4.55	2.26	3.01	6.27	3.94	5.12	3.28	3.58	4.46
MgO	8.23	10.02	9.35	5.21	7.40	7.21	7.17	5.19	6.16	1.45	0.50	0.43	1.22	0.68	1.59	0.63	0.55	0.83
CaO	9.31	12.16	9.58	11.9	8.18	12.41	12.04	6.40	5.74	0.68	1.80	0.71	0.09	2.35	2.96	2.03	1.72	2.17
Na ₂ O	2.47	1.51	1.93	1.86	0.87	0.89	1.68	1.84	2.25	1.59	2.46	0.51	0.38	3.34	2.78	3.22	3.06	3.09
K ₂ O	0.57	0.11	0.13	0.55	3.83	0.84	1.76	4.05	4.01	3.74	0.99	2.14	6.88	5.00	4.20	5.32	5.4	5.12
P ₂ O ₅	0.28	0.07	0.06	0.24	0.42	0.05	0.13	0.36	0.37	0.02	0.03	0.02	0.02	0.14	0.12	0.14	0.1	0.14
MnO	0.19	0.18	0.2	0.21	0.24	0.20	0.18	0.14	0.12	0.04	0.03	0.03	0.01	0.08	0.04	0.08	0.09	0.11
LOI	2.75	0.55	2.06	0.62	1.56	1.88	1.25	2.88	2.31	1.42	0.83	0.95	4.45	1.11	1.14	0.96	0.77	0.70
Sum	98.32	98.33	98.52	99.12	98.14	101.65	101.12	99.14	101.45	101.56	99.26	98.29	100.2	99.33	98.33	99.44	99.49	99.21

Table 4. Representative trace element analyses of the mafic and felsic rocks from Bathani volcano-sedimentary sequence.

Sample	Basalt			Andesite				Rhyolite			Tuff	Granite					
	R01	R12	R16	R17	RJ25C	RJ22A	RJ05	RJ24	R04	R03	RJ23C	RJ25A	RJ45	RJ48E	RJ48F	R10	R13
Ba	206	41	75	145	319	86	156	746	714	151	343	384	746	1206	571	673	728
Cr	228	61	349	253	328	264	356	63	140	1311	72	74	4	21	9	284	179
V	223	252	246	407	388	280	284	181	159	132	103	80	21	51	21	14	22
Co	51	59	60	49	99	99	109	52	20	14	162.8	126.9	146.7	74	120.6	7	8
Ni	96	264	112	80	98	65	73	16	17	35	21	12	1	9	1	5	4
Cu	39	9	33	18	61	9	38	114	81	23	32	48	8	8	2	7	7
Zn	106	74	96	128	122	59	70	106	90	35	15	24	51	83	36	50	57
Ga	20.87	13.35	16.82	17.64	20	15	15	20	17	14	13	12	18	19	18	18	18
Pb	10.78	4.8	221.13	8.05	48	11	24	16	15	7	61	40	37	22	36	42	35
Th	3.52	<5.0	<5.0	2.12	<1.0	<1.0	0.4	14.5	21	5	8	4	33	37	23	40	38
Rb	24	3	9	15	59	10	21	181	200	46	17	35	293	210	338	319	295
Sr	272	186	279	204	90	89	155	322	291	25	81	17	183	238	161	140	171
Y	30	13	16	37	38	11	18	38	23	8	11	12	30	24	33	39	32
Zr	147	51	53	156	90	59	66	170	158	60	45	32	167	294	105	151	155
Nb	12.81	2.49	6.8	14.11	9	6	6	14	13	8	6	6	18	27	17	16	16
Sc	28	39	33	44	62	53	55	41	18.5	11.6	13	8	7	8	6	5	5
U	0.4	0.1	0.2	0.4	0.9	1.1	1.0	1.2	4.9	1.2	1.2	2.3	6	3.8	5.6	6.4	3.4
La	14.8	3.8	5.8	16.1	12.4	4.7	7.4	37.4	37.8	12.7	12.7	8.8	67.3	134	65.1	41.3	43.5
Ce	34.7	9.3	12.4	37.8	30.6	11.5	17	76.7	77.7	24.9	23.3	16.9	129.2	264.8	120.3	78.6	80
Pr	4.9	1.5	1.7	5.3	4.5	1.7	2.5	9.3	8.8	2.6	2.4	1.7	12.9	27.3	11.9	8.4	8.9
Nd	20.8	6.6	7.5	22.8	20.7	7.3	11.4	34.3	36.3	9.9	9.4	6.3	47.7	102	41.9	32	34.6
Sm	5.09	2	2.11	5.88	5.66	2.03	3.15	6.75	6.99	1.61	1.94	1.29	6.79	15.31	5.45	5.54	5.62
Eu	1.82	1.02	1.11	2.13	1.72	0.89	1.1	1.66	0.79	0.27	0.54	0.25	0.92	1.95	0.74	0.54	0.52
Gd	5.37	2.36	2.48	6.59	6.47	2.22	3.58	6.55	5.32	1.26	1.52	1.04	5.37	11.76	4.11	4.16	4.02
Tb	0.88	0.43	0.43	1.11	1.02	0.38	0.6	0.86	0.79	0.19	0.22	0.17	0.75	1.46	0.53	0.62	0.51
Dy	5.12	2.61	2.63	6.59	6.02	2.24	3.64	4.64	4.93	1.25	1.2	0.97	4.37	6.53	2.88	4	2.9
Ho	1.06	0.56	0.56	1.41	1.21	0.47	0.76	0.9	0.81	0.22	0.26	0.22	0.76	0.95	0.51	0.67	0.44
Er	2.84	1.49	1.47	3.7	2.96	1.21	1.9	2.41	2.24	0.67	0.69	0.56	1.81	1.75	1.15	1.93	1.21
Tm	0.42	0.23	0.22	0.56	0.42	0.18	0.28	0.36	0.34	0.11	0.09	0.08	0.31	0.21	0.19	0.32	0.18
Yb	2.7	1.48	1.45	3.59	2.56	1.24	1.75	2.38	2.35	0.76	0.63	0.53	2.12	1.26	1.35	2.26	1.25
Lu	0.41	0.22	0.22	0.52	0.38	0.18	0.26	0.37	0.4	0.13	0.1	0.08	0.35	0.2	0.23	0.39	0.21

The procedures adopted for sample digestion and preparation of solutions were that of Balaram *et al.* (1990). USGS (BHVO-1, AGV-1) and JGS (JG-2, RGM-1) samples were used as rock standards to minimize matrix effect. RSD for most of the samples is better than 10%.

5.2 Geochemical results and interpretations

5.2.1 Major oxides

Major oxide data for the studied samples of the different rock types are presented in table 3. The SiO₂ content for basalt ranges from 43.92–49.43 wt%, for granite 63.48–68.85 wt%, for andesite from 52.39–55.81 wt%, and for rhyolite 73.91–81.31 wt%. Basalts contain 1.62–4.7 wt% K₂O+Na₂O, 11.63–16.62 wt% Fe₂O₃, 5.21–10.02 wt% MgO, 0.83–2.29 wt% TiO₂, and 0.06–0.42 wt% P₂O₅. Basaltic andesites have K₂O+Na₂O content of 1.73–6.26 wt%, total Fe₂O₃ of 8.39–9.44 wt%, and MgO content of 5.19–7.21 wt%. For the rhyolite, K₂O+Na₂O content varies from 2.65–5.33 wt%, Fe₂O₃ content varies from 2.26–4.55 wt%, and the MgO content varies from 0.43–1.45 wt%. The granites are characterized by 6.98–8.54 wt% K₂O+Na₂O, 3.28–5.12 wt% Fe₂O₃, 0.25–0.66 wt% TiO₂, 0.55–1.59 wt% MgO, and 0.10–0.14 wt% P₂O₅.

Secondary minerals like chlorite, epidote and amphibole have been observed optically in rock thin sections. Their formation from pre-existing minerals by alteration may be attributed to low grade metamorphism/deformation and are thus considered to be isochemical.

Figure 7 displays Harker variation diagrams for the rocks of the BVS sequence. Here the major oxide wt% has been plotted against SiO₂ wt% in order to understand the evolution of magma through element partitioning. Significant linear relationships have been observed among the basalts, andesites and granites for most of the major oxides. On the contrary, the rhyolite lacks such linear relationships with the other rock types.

Negative correlation of SiO₂ with CaO, Fe₂O₃, MnO and TiO₂ exists for the basalt, andesite, and granite samples indicating fractionation of plagioclase, clinopyroxene, and ilmenite. A weak positive correlation is observed between Na₂O and SiO₂ for these samples. Scattering of data plots of SiO₂ with Al₂O₃, P₂O₅, and K₂O probably indicate the mobile nature of these elements during post-crystallization processes. Harker plots show that most of the major oxides have not been affected by the post-crystallization secondary processes.

The volcanic rocks of the BVS sequence were classified based on the total alkali *versus* silica

(TAS) plot with subdivisions after Middlemost (1994) (figure 8). On this classification scheme, five samples (R01, R12, R16, R17, and RJ25C) plot in the basalt field, four samples (RJ22A, RJ05, RJ24, and R04) plot in the fields of basaltic trachy-andesite and basaltic andesite, three samples (R03, RJ23C, and RJ25A) plot on the rhyolite field, and one sample (R07), which is a tuff, plots in the trachy-andesite field. In the QAP diagram (figure 9), the felsic samples plot in the granite field. Molar A/CNK for the granites ranges between 1.04 and 1.12, suggesting weak peraluminous character of these rocks (figure 10).

In the AFM plot of Irvine and Baragar (1971) (figure 11), the basalts display tholeiitic trend. The other rock types like rhyolite, andesite, and granite show calc-alkaline affinities consistent with their generation in an island arc, subduction related setting.

In the CaO/Na₂O *vs.* Al₂O₃/TiO₂ diagram (figure 12a), the granites of the study area plot on the mixing line between the pelite and basalt derived melts. The Rb/Sr *vs.* Rb/Ba plot (figure 12b) indicates that the granites formed from a plagioclase-rich and clay-poor source. Moreover, high Al₂O₃/TiO₂ ratios point to the fact that they were generated at a higher temperature and pressure regime. The metapelitic derived melts generally have higher Al₂O₃/(MgO+FeO (t)) and lower CaO/(MgO+FeO (t)) ratios than those derived from meta-igneous rocks. The granites of the study area have Al₂O₃/(FeO (t)+MgO)<2, suggesting metabasaltic and metatonalitic derived melts for these rocks.

5.2.2 Trace and rare earth elements

Basalt: Rare earth element (REE) data for the five basalt samples are documented in table 4 and the chondrite-normalized REE diagram for these samples is displayed in figure 13(a).

Chondrite-normalized REE trends for basalts can be clubbed into two groups; one with moderate enrichment in LREE relative to HREE and no negative Eu anomaly (Eu/Eu* = 0.87–1.06) and the other with a relatively less enrichment of LREE in comparison to HREE with positive Eu anomaly (Eu/Eu* = 1.44–1.49) indicating plagioclase accumulation. The subparallel REE patterns for the basalts suggest that the crystal fractionation is dominant in the evolution of the compositional variations, with plagioclase being a dominant fractionate. However, the possibility of varying degrees of partial melting cannot be ruled out for the samples.

Primitive mantle normalized trace element abundance patterns for the basalt samples show enrichments in large ion lithophile elements (LILE)

Figure 7. Harker plot showing the variation of major oxides as a function of SiO_2 content for basalt, andesite, rhyolite, granite and tuff of BVS sequence.

Figure 8. Total alkalis *vs.* silica diagram with subdivisions from after Middlemost (1994) showing the volcanic rock classification of the samples from BVS sequence.

and Pb compared with high field strength elements (HFSE) (figure 13b). An overall trend of HFSE depletion and LILE enrichment is a characteristic subduction signature. An island arc setting is further corroborated by the depletion of Nb and Ti.

The sample RJ25C shows a distinctive pattern from the rest of the four basalt samples. It shows marked negative anomalies for Sr, Th, Nb, and Zr and positive anomalies for K and Pb. The negative Sr anomaly is thought to be caused by plagioclase fractionation while negative Th and Zr anomalies may be related to fractionation of minor phases like zircon and/or allanite. Moreover, the observed positive anomaly for K may be attributed to K-feldspar accumulation.

Figure 9. QAP plot (after Le Maitre *et al.* 1989) showing the felsic rocks of the BVS sequence all falling on the granite field.

Figure 10. Variation of $\text{Al}/(\text{Na} + \text{K})$ vs. $\text{Al}/(\text{Ca} + \text{Na} + \text{K})$ with fields (after Maniar and Piccoli 1989; Pearce *et al.* 1984) with divisions based on Shand index (1943) showing the peraluminous nature of the granites of BVS sequence.

Figure 11. AFM diagram after Irvine and Baragar (1971) used for deciphering nature of magma for rocks of BVS sequence.

The remaining four samples (R01, R12, R16, and R17) are characterized by marked positive anomalies for Th and Pb indicating crustal involvement in their evolution. Samples R12 and R16 show positive Sr and Eu anomalies showing plagioclase accumulation. No such anomalies are observed in samples R01 and R17.

Andesite: On the chondrite normalized REE diagram (figure 13c), the andesitic samples show moderate to strongly fractionated REE patterns characterized by a relatively enriched LREE and nearly flat HREE ($\text{La}_N/\text{Yb}_N = 2.56\text{--}10.84$, $\text{La}_N/\text{Sm}_N = 1.46\text{--}3.49$, $\text{Gd}_N/\text{Yb}_N = 1.43\text{--}2.19$). The andesitic samples are characterized by variable

Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.4\text{--}1.28$). The less fractionated samples (RJ22A, RJ05) show slightly positive to no Eu anomalies. While the more fractionated samples (R04, RJ24) are characterized by negative Eu anomalies.

On the primitive mantle normalized spider diagram (figure 13d), the andesitic samples show moderate to highly fractionated patterns characterized by Nb depletion and Pb enrichment. The relatively more fractionated samples (R04, RJ24) are characterized by negative anomalies for Ba, Sr, Eu, and Ti indicating feldspar and ilmenite fractionation. The observed negative Ba anomaly may also be attributed to biotite and/or hornblende

Figure 12. (a) $\text{CaO}/\text{Na}_2\text{O}$ – $\text{Al}_2\text{O}_3/\text{TiO}_2$ plot after Sylvester (1998) showing the composition of the source for generation of the granites of BVS sequence. (b) Rb/Sr vs. Rb/Ba plot after Patino-Douce and Harris (1998) constraining the granite forming melt to be of clay poor and plagioclase rich composition.

fractionation. The observed negative Nb anomaly in the andesitic samples may have been caused by ilmenite fractionation.

Rhyolite and Tuff: On the chondrite-normalized REE diagram (figure 13e), all the calc-alkaline rhyolite together with the tuff samples are characterized by a strongly fractionated REE pattern ($\text{La}_N/\text{Yb}_N = 9.05 - 13.59$), a fractionated LREE ($\text{La}_N/\text{Sm}_N = 3.42 - 4.96$) pattern, flat to negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.44 - 0.96$), and flat HR-EE distribution patterns ($\text{Gd}_N/\text{Yb}_N = 1.32 - 1.92$).

On primitive mantle normalized trace element abundance diagram (figure 13f), the rhyolite and the tuff samples exhibit strongly negative Nb, Sr, Eu and P anomalies and positive Pb anomaly. The negative Sr, Eu and P anomalies may be explained by the plagioclase and apatite fractionation, either in the solid residuum left by partial melting or fractional crystallization. The negative Nb anomaly together with the positive Pb anomaly is indicative of crustal signature.

Granite: The rare earth element (REE) trends (figure 13g) confirm that the granite samples have REE enriched patterns ($\text{La}_N/\text{Yb}_N = 12.22 - 71.11$), a fractionated LREE ($\text{La}_N/\text{Sm}_N = 4.60 - 7.37$) pattern, negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.32 - 0.46$), nearly flat HREE distribution patterns and depletion of MREE relative to the HREE ($\text{Gd}_N/\text{Yb}_N = 1.47 - 7.44$). The depletion of the MREE relative to the HREE reflects fractionation of hornblende and/or clinopyroxene during petrogenesis whereas the negative Eu anomaly indicates plagioclase fractionation.

The primitive mantle normalized trace element variation trends (figure 13h) depict large ion lithophile elements (LILE) enriched pattern and negative anomalies for Ba and Sr. There is also significant depletion of three high field strength elements (HFSE) involving Nb, P, and Ti, with Zr showing slight negative anomaly. The observed Ba negative anomaly may be either due to alteration or fractionation of K-feldspar, hornblende and/or biotite during genesis of these rocks as Ba substitutes for K in K-feldspar, hornblende, and biotite. Similarly, Sr concentration may be influenced by the plagioclase fractionation. The normalized plot also shows negative anomalies for P, Ti and Zr which may suggest early fractionation of apatite, zircon, and Ti-bearing phases like titanite, rutile and ilmenite. The negative anomaly for Nb may be attributed to crustal signature or a subduction environment. In the subduction zone tectonic settings or in an island arc environment, due to the presence of fluid, entire Nb tends to go into Ti-bearing phases like titanite, rutile and ilmenite. In our samples, negative Nb anomaly is probably due to its fractionation into Ti-bearing phases.

5.2.3 Geotectonic classification of the rocks

On the Th/Yb vs. Nb/Yb plot after Pearce (2008), the basalts clearly show a volcanic arc setting of eruption (figure 14a). This suggests a subduction zone environment for their formation. In the tectonic discrimination Nb–Y plot of Pearce *et al.* (1984) the granite samples show slight affinity towards VAG and Syn-COLG (figure 14b) suggesting volcanic arc setting.

Figure 13. Chondrite normalized REE and primitive mantle normalized trace element abundance patterns of the felsic, volcanic and intermediate rocks of the BVS sequence. Chondrite normalizing values are after Boyton (1984); primitive mantle normalizing values after Sun and McDonough (1989).

Figure 13. (*Continued.*)

Figure 14. (a) Plot of Th/Yb vs. Nb/Yb after Pearce (2008) for the basalts of BVS sequence points towards a volcanic arc setting for the tectonic environment of their eruption. The mantle array extends from mid-ocean ridge basalts (MORB) to within-plate ocean island basalts (OIB). TH, CA, and SHO are respectively fields for tholeiitic, calc-alkaline, and shoshonitic basaltic rocks from convergent margins. S, C, W, and f are vectors for subduction component, crustal contaminant component, within plate processes, and fractional crystallization respectively. (b) Nb vs. Y tectonic discrimination diagram (after Pearce *et al.* 1984) for the granites show their tectonic origin to be of volcanic arc setting. Field labels: Volcanic Arc Granite (VAG), Within Plate Granite (WPG), Ocean Ridge Granite (ORG), Syn-collision Granite (Syn-COLG).

6. Concluding remarks

Emplacement of diverse felsic and mafic rocks in the BVS sequence together probably testifies for

a multi-stage and multi-source magmatism for the area in an island arc setting. The presence of pillow basalt suggests that the volcanic eruption was under shallow marine/subaqueous environment. Mafic pyroclasts and tuffs are formed by intermittent explosive eruptions of basic and acidic magmas respectively. Presence of hybrid rocks like basaltic andesite and andesite, and phenomenon of mixing and mingling supported by structures and textures in the volcanic rocks suggest that the two magmas, mafic and felsic, co-existed for sufficient time before eruption. Tholeiitic trend for basalt and calc-alkaline affinities of andesite, rhyolite, and granite indicate their generation in an island arc, subduction related setting. In the Nb/Yb vs. Th/Yb discrimination diagram, basalts plot in the alkaline oceanic arc array suggesting their generation in the subduction zone. Granites show affinity towards VAG and Syn-COLG. HFSE depletion and LILE enrichment of the basalts is also a characteristic of subduction zone environment. Island arc setting is further corroborated by depletion of Nb and Ti. $\text{Al}_2\text{O}_3/\text{TiO}_2$ vs. $\text{CaO}/\text{Na}_2\text{O}$ and Rb/Sr vs. Rb/Ba plots denote granitic magma generation from plagioclase rich and clay poor metabasalt and metatonalite protolith. Low grade of metamorphism probably to greenschist facies condition is indicated by the presence of secondary amphibole and chlorite in basalt. However, well preserved igneous texture in basalt and rhyolite undoubtedly restricts the metamorphic effect to low grade only. Low grade metamorphism of volcano-sedimentary sequence along with the pervasive subsurface mafic-ultramafic bodies is characteristic of greenstone belt. This low grade metamorphosed volcano-sedimentary sequence may be correlated with extension of Mahakoshal folded mobile belt of central India, presently situated between north and south Son-Narmada faults.

It seems that various rock types of volcanic and volcano-sedimentary sequence and their associated rocks exposed in the Bathani area are manifestation of collision of northern and southern Indian blocks during Proterozoic period. The explosive submarine volcanism may be related to the culmination of the collision of the aforementioned blocks during Neoproterozoic (1.0 Ga) as the Grenvillian metamorphism is well established in various parts of CGGC. The granitoids around Gaya-Rajgir area, north CGGC of Central Indian Tectonic Zone (CITZ) might have originated at different times corresponding to collision of the north and the south Indian blocks.

6.1 Plausible magmatic model

Inferences from the field, petrological, mineral chemical and geochemical data allow us to propose

a plausible magmatic model for the generation of the Bathani suite of rocks as discussed below. A schematic cartoon for the suggested model is shown in figure 15.

Figure 15. Schematic representation of the magma generation model suggested for the volcanics of the BVS sequence. (a) Generation of mafic magma in an arc environment due to volatile induced partial melting of the subducting slab. (b) Lithospheric thinning, subsidence and rifting by underplating of mafic magma beneath lithospheric slab. Effusive eruption of mafic magma occurred through the rifts forming pillow basalts. (c) Interception of mafic magma by pre-existing felsic rhyolitic sill resulting in hybrid andesitic rocks due to mixing of the magmas. Volcanic eruptions ensued resulting in intermittent eruption of rhyolitic and basaltic magmas along with mafic pyroclasts.

Mafic magmas are probably generated by volatile-induced partial melting of the mantle wedge in a subduction zone setting. The mafic magmas then ascended as a network of dykes. During their ascent, mafic magma pooled and underplated the lithosphere and got entrapped and may also have formed dyke swarms of mafic-ultramafic composition. The probability of subsurface intrusive basic igneous rocks was highlighted by the Bouguer gravity anomaly map (Das and Patel 1984) representing anomalous NE–SW trending gravity high to the north of Bodh Gaya. Such kind of magma entrapment is known to cause thermal erosion at the base of the lithosphere. Thinning of the lithosphere by thermal erosion gave way to lithospheric subsidence and subsequently to the formation of sedimentary basin. Accumulation of sediments developed rift system in the basin through which effusive eruption of basalt forming pillows occurred.

However, the rhyolitic magma was originally derived from some deeper zones totally unrelated to the basaltic magmatism. The ascending rhyolitic magma may have got accumulated in sill-like isolated chambers and shortly before eruption, were intruded by the ascending mafic magma. Interaction of the hotter, volatile-rich mafic magma with the rhyolitic magma reduced the rhyolite magma viscosity, thereby triggering rhyolitic volcanism. The intermediate tuffs may possibly have formed due to explosive eruption in the same environment. Presence of hybrid rocks like andesite and basaltic andesite suggests that the two magmas, mafic and felsic, interacted for sufficient time for mixing to take place. Later on, both the magmas erupted simultaneously as evidenced by the presence of rhyolite clasts in basaltic flows. Granitic plutonism succeeded this event and is the result of fractional crystallization of mafic magma.

In the given scenario we can infer that the basaltic extrusions ascended through a laterally extensive subsurface dyke system. Pillow basalts erupted *via* sutures developed due to rifting developed by lithospheric subsidence while some basic magma was intercepted by an already existent rhyolite magma chamber causing magma mixing and mingling and then finally making their way to the surface as volcanic eruptions.

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