

Origin and tectonic setting of Precambrian greywacke of Ribandar-Chimbel, Goa, India: Petrological and geochemical evidences

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Abstract:

The Precambrian greywacke of Ribandar-Chimbel belonging to the Sanvordem Formation of the Goa Group, India, have been studied for petrography and analyzed for major, trace elements. The greywacke is characterized by angular to sub-round grains of quartz, feldspar, biotite, chlorite and clay minerals. The abundance of clayey matrix seems to have influenced the Al₂O₃ content and the K₂O/Al₂O₃ ratio. The variation diagrams indicate a decreasing trend of TiO₂, Al₂O₃, Fe₂O₃ and MgO; whereas Na₂O and CaO exhibit a scatter which could be a result of the variable presence of feldspar within the sediments. The immobile elements, vanadium (25 to 144 ppm), nickel (up to 107 ppm) and chromium (up to 184 ppm), reflects the abundance of clay minerals. The greywacke shows strongly fractionated REE patterns with La_N/Yb_N = 8 to 26 and with higher total REE abundances (up to 245 ppm). The low REE enrichment and depletion in heavier REE with prominent negative Eu anomaly (Eu/Eu* = 0.54 to 0.79) suggest derivation of the greywacke from an old upper continental crust composed chiefly of felsic components. Petrological evidences and geochemical data suggest that the deposition of the greywacke largely took place in a deep to shallow basin that progressively changed from that of a continental island arc to an active continental setting.

Key words: greywacke, petrochemistry, origin, diagenesis, active continental setting, Goa, Dharwar Craton

1 Introduction

It is well recognized that the crustal evolution and the tectonic setting can be indicated from the geochemistry of clastic sedimentary rocks (Lahtinen, 2000). The geochemical composition of terrigenous sedimentary rocks is a function of the complex interplay of variables, such as provenance, weathering, transportation, and diagenesis. The framework mineralogy, provenance and the tectonic setting of their sedimentary basins are interrelated (Bhatia, 1983; Crook, 1974; Schwab, 1975; Potter 1978; Dickinson and Suczek 1979; Dickinson, and Valloni, 1980; Valloni, and Maynard 1981). The greywacke composition is also used to decipher the origin and tectonic setting of source areas (Banerjee and Banerjee, 2010). Thus, the composition of sedimentary rocks is useful to recognize the nature of ancient continental and oceanic basins. Further the relationship between attributes of the plate tectonic setting and factors such as provenance, relief, physical sorting, and diagenesis govern the composition of clastic sedimentary rocks (Pettijohn et al., 1972; Blatt et al., 1980).

The formation process of greywacke of Goa Group is obscured due to the effect of low grade metamorphism, but a record of the geological history is possible to be derived as it is retained in the detrital sediments. Hence, detailed field work coupled with petrological examination and supported by geochemical examination are important tools to understand the formation of greywacke. Since the framework grains of greywackes are liable to be modified with burial and metamorphism, and for these reasons, it is not very reliable to infer the tectonic setting. Therefore, trace elements such as La, Ce, Nd, Y, Th, Zr, Hf, Nb, Ti and Sc which are regarded as insensitive to alteration, and due to their low mobility during sedimentary processes and low residence time in water (Holland, 1978) are well suited as diagnostic elements to decipher the origin of greywacke. Some of these elements are useful to plot various discrimination diagrams that help to characterize the tectonic setting of the formation of greywacke (Bhatia and Crook, 1986). Similarly, the rare earth elements (REE) are also very useful to determine the origin of the greywacke as these are incorporated into the sedimentary rocks during the recycling of sediments and get preserved in them as a record of the average upper crustal elemental abundances (Rashid, 2005). Widdowson (2009) studied the mineralogical and compositional changes of the laterite profile in the Merces quarry, Goa, that were formed from a greywacke parent rock. The petrology and geochemistry of the greywacke of the Dharwar-Goa sector, that occur to the south of Goa and along the Western Ghats, have being studied extensively for petrology and geochemistry by Devaraju et al. (2010). These are the only studies that pertain to the characteristics of the greywacke to a certain extent but so far the origin and formation mechanism of the greywacke of Goa have not been reported.

In the above background we have investigated the structural details, petrology, and petrochemistry of greywacke and the associated rocks from the quarries located at Ribandar and Chimbhel, in the capital city of Panaji, Goa, India (Fig. 1). The study involved intense field work to map the greywacke and detailed petrography and petrochemistry (major, minor and rare earth elements) of the greywacke. Using several discrimination plots, the tectonic setting of the greywacke is deciphered. Finally, we integrate the field

observations, the petrological characteristics and composition of the greywacke to understand its origin and the interplay between diagenesis and low grade metamorphism. To our knowledge this is the first detailed work that concerns the greywacke occurring in the hinterland of Goa.

2 Geologic Setting

Geologically, the state of Goa forms a part of the Indian Precambrian shield. The general stratigraphic sequence described by the Geological Survey of India (1996), consists of the Peninsular Gneissic complex (Archaean), the Goa Group of meta-volcanics and meta-sedimentary assemblage (Archaean to lower Proterozoic), mafic-ultramafic complexes and intrusive granites (lower Proterozoic), Deccan Traps (Upper Cretaceous to Eocene), laterite (Cenozoic) and beach sands and estuarine alluvium (Quaternary). It is of interest that the ultramafic-gabbro complex of Dharwar Supergroup occurring in other parts of Goa (Jena, 1985) and the Pre-Cambrian metamorphic rocks of Sindhudurg, Maharashtra (to the north of Goa) (Chari and Maggriwar, 1968, Iyer et al., 2010) host significant amount of chromites. The Goa Group is divided in the order of superposition as Barcem (lowermost), Sanvordem, Bicholim-Rivona and Vageri Formations (Gokul et al., 1985; Dessai, 2011). The general stratigraphy of Goa group is given in table 1 and figure 1. As reported by the Geological Survey of India (1996), the Sanvordem Formation consists mainly of turbidities comprised of polymictic meta-conglomerates / breccia, metagreywacke, quartz-chlorite schist and thick lenses of quartzite. The thickness of the formation is variable and is reported to be upto 400 m. Outcrops of greywacke occur in the quarries in North Goa (Fig.1).

The several dyke injections found along the coast of North Goa intruding the greywacke of Sanvordem Formation are attributed to have been emplaced during the Mesozoic rift of western India (Sinha-Roy and Radhakrishna, 1983) and the splitting of India and Madagascar at 89 Ma (Storey et al., 1995). Geological, geochemical and palaeomagnetic studies have proved that the dykes of Goa originated contemporarily to the Deccan Traps viz. 62-63 Ma (Widdowson et al., 2000, Patil and Rao, 2002). The basic intrusive followed the emplacement of mafic-ultramafic layered complex and Canacona Granite (2395±390 Ma) and thus indicate the injection of the dykes to be the last event (Dessai, 2011). These dykes could also be related to post-trappean tectonics that occurred at 63 Ma in the Seychelles, and which corresponds to the end of Deccan volcanism and/or to the initiation of rifting of the Arabian Sea (Courtillot et al., 1986, Patil and Rao, 2002).

Widdowson (2009) described in detail the mineralogical and compositional changes observed in a 40 m high laterite profile that is present at the Mercedes quarry, Goa. This profile, of probable Miocene age (Schmidt et al., 1983) overlies fresh greywacke and portrays seven weathered zones. These zones from the bottom to the top are: altered greywacke (saprolite), reddened greywacke (saprolite), saprolite with Fe-rich mottling and/or segregations, Fe-Al segregations and nodular concretions, laterite with fretworks of Fe-rich segregations, semi-indurated Fe-rich tubular textured laterite and indurated laterite cap. Below the fretworks a palaeo-water-table occurs. It is to be noted that the Mercedes quarry, of which only the laterite was studied in detail by Widdowson (2009), is the same as the Chimbhel quarry described in this paper.

3 Materials and Methods

Traverses were conducted in the Tiswadi Taluka in the quarries of Ribandar and Chimbel for the collection of samples, observations of various sedimentary features and to obtain the structural data, which includes attitude of beds. Seventeen fresh samples (15 greywacke and 2 dolerite) were collected and petrographic study was carried out and photomicrographs were obtained to determine the minerals present and the textural features. A Leica DMLP microscope was used to examine the thin sections at magnifications ranging from 25X to 630X. Of the seventeen samples, thirteen greywacke and two dolerite samples were used for geochemical studies. The samples were powdered in a carbide-tungsten mortar followed by an agate mortar. One gram of each powdered samples were made into glass pellets and analysed for major and minor elements using a Philips X-ray Fluorescence Spectrometer. The standard rocks used were gabbro, dolerite and quartz latite. Trace elements including the REE concentrations were determined with an Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) following the procedures of Balaram and Rao (2003). The standard reference material (BIR-1 and DNC-1) and replicate and blank samples were also analyzed for precision and accuracy. The REE data were normalized using the chondrite values of Sun and McDonough (1989).

4 Discussion

4.1 Petrographic Characteristics

The greywackes are fine to medium grained and show variable scales of laminations. The colour varies from light to dark grey. The thickness of greywacke exposures ranges from about 4 to 30 m and have a gentle dip of about 15°- 25° (Fig 2a). Tabular cross bedding (Fig. 2b) and micro-scale level graded bedding (Fig. 2c) is present in the greywacke.

The greywacke exhibits immature and poorly sorted texture. The framework components consisting of quartz, feldspar, biotite, chlorite and epidote are angular to sub-rounded in shape. Relict detrital rock fragments are also common while apatite is rare. Disseminated pyrite occurs in a few samples. Quartz grains exhibit monocrystalline to polycrystalline nature. The greywacke is characterized by an abundance of matrix of clay to silt-sized detrital matter (Fig. 2d-f). Prominent laminations occur at the microscopic scale and are distinct from the parallel alignment of grains. It is observed that biotite grains are altered to chlorite due to chloritization. The most conspicuous feature is the alternate bands of light grey and dark grey which shows a variation in mineralogy. Schistosity in greywacke is defined by alignment of biotite streaks, which sometimes exhibits bending of grains (Fig. 2 e, f). Detrital quartz shows fused, serrated and sutured grain boundaries. A band of chlorite and biotite exhibits pinch and swell texture, due to deformation (Fig. 3a). Quartz veins are seen at the megascopic scale (Fig. 3b) in the outcrops as well as microscopic scales (Fig. 3c)

Greywacke is intruded by dolerite dyke, composed of augite, plagioclase and chlorite (Fig 3d). Porphyritic texture within phenocrysts of plagioclase set in a groundmass of augite and plagioclase (Fig. 3e) and ophitic to sub-ophitic textures are commonly seen. The dolerite dyke and greywacke is seen to be deformed, fractured and criss-crossed by veins of chert/quartz, which has led to dissipation of silica in greywacke at the contact of

quartz vein (Fig. 3f).

4.2 Geochemical Characteristics

The geochemistry of Archaean sedimentary rocks has been studied by many workers to understand its mode of origin (Condie, 1967; Condie et al., 1970; Naqvi and Hussain, 1972; Wildeman and Condie, 1973; Nance and Taylor, 1977; Bavinton and Taylor, 1980; Jenner et al., 1981; Bhatia and Crook, 1986). The analytical data of major, minor as well as trace elements of the 13 greywacke and 2 dolerite samples are presented in table 2. The major element composition of greywacke is as follows: SiO₂ 54.73-78.57%, Al₂O₃, 10.56-18.46%, K₂O 1.30- 4.54%, CaO 2.86-0.57%, TiO₂ 0.29-0.73%, Fe₂O₃^t 3.11- 10.04%, MgO 1.12-4.48%, MnO 0.03-0.12%, Na₂O 2.72- 4.59% and P₂O₅ 0.04-0.16%. The average of the major element data is comparable to that of Archaean greywacke of Fig Tree, Barberton (South Africa) (Toulkeridis et al., 1999), Late Archaean (3.5-2.5 Ga) greywacke (Condie, 1993) and greywacke with biotite, greywacke with chlorite-sericite and fine-grained greywacke of Goa-Dharwar sector (Devaraju et al., 2010) (Table 3).

Variable trends observed on the variation diagrams (Fig. 4) result from mixing of the different constituents of the sediments and indicate a poor mineralogical maturity. Increase in SiO₂ suggests an increase in the quartzose content and it exhibits a decreasing content against TiO₂, Al₂O₃, Fe₂O₃ and MgO; whereas Na₂O and CaO are scattered which may result from the presence of variable feldspar proportions within the sediments. The decrease in SiO₂ and a systematic increase in Al₂O₃ indicates significant occurrence of clayey matrix in the fine to medium grained greywacke (Cullers, 1995). The presence of secondary weathering products such as clay is indicated by enhanced Al₂O₃ content (10.56 to 18.47%) (Cox et al., 1995; Rashid, 2005) and K₂O/ Al₂O₃ (0.12 to 0.24).

Major element and trace element data have been used to classify the sandstones (Pettijohn, et al., 1972; Herron, 1988; Marston, 1978; Le Maitre et al., 1989; Bhatia and Crook, 1986). Binary variation diagram of SiO₂/Al₂O₃ vs K₂O/Na₂O (after Wimmenauer, 1984) (Fig. 5a), indicates that 9 of our samples correspond to 'greywacke,' one sample plot in 'quartz-rich greywacke', whereas 3 samples plots in the 'pelitic greywacke' field. The greywacke from Mercedes (Widdowson, 2009), greywacke with biotite, greywacke with chlorite-sericite and fine-grained greywacke from Goa-Dharwar sector (Devaraju et al., 2010), Late Archaean (3.5-2.5 Ga) greywacke (Condie, 1993), Archaean greywacke of Fig Tree, Barberton (Toulkeridis et al., 1999) also plot in the 'greywacke' field. The plot of log (Na₂O/K₂O) against log (SiO₂/Al₂O₃), (after Pettijohn et al., 1972) (Fig. 5b) emphasizes the 'greywacke' field except a greywacke with biotite from Goa-Dharwar sector (Devaraju et al., 2010) which reflects 'litharenite' field.

Pettijohn et al.'s (1972) variation diagram as modified by Herron (1988) (Fig. 5c) is a binary plot of log (Fe₂O₃/K₂O) against log (SiO₂/Al₂O₃). On this plot 7 samples fall in the field of 'shale,' 5 samples plot in the field of 'wacke' along with greywacke with biotite from Goa-Dharwar sector (Devaraju et al., 2010) and greywacke from Mercedes (Widdowson, 2009). One sample plots in the field of 'litharenite' and the average of Archaean greywacke of Fig Tree, Barberton (Toulkeridis et al., 1999) plots in the 'Fe- sand.' On the ternary

diagram of $\text{Fe}_2\text{O}_3+\text{MgO}-\text{Na}_2\text{O}-\text{K}_2\text{O}$ (after Marston, 1978), a majority of the samples plot in the field of 'greywacke' and one sample plots in the field of 'sodic sandstone'. The average of Archaean greywacke of Fig Tree, Barberton (Toukeridis et al., 1999) and the average of greywacke with biotite from Goa-Dharwar sector (Devaraju et al., 2010) plots in the 'Fe-Mg potassic sandstone' (Fig. 5d). Hence, from the plots it is evident that our samples show a range of sandstone types but mostly they plot in the greywacke field.

The greywacke is enriched in Rb, Sr, Zr, La, Ce, and Nd contents. Ba values are significantly high and range from 264 to 909 ppm (Table 2). The average contents of Sc, Co, Ni and Pb are lower than those of Archaean greywacke of Fig Tree, Barberton (Toukeridis et al., 1999), Late Archaean greywacke (Condie, 1993) and greywacke with biotite (Devaraju et al., 2010) except Ni which is higher than greywacke with chlorite-sericite of Goa-Dharwar sector (Devaraju et al., 2010). While the average of Rb, Sr, Nb, Ba, La, Ce, Nd and Yb is higher than Archaean greywacke of Fig Tree, Barberton (Toukeridis et al., 1999) and Late Archaean greywacke (Condie, 1993) and greywacke with biotite and greywacke with chlorite-sericite of Goa-Dharwar sector (after Devaraju et al. 2010) (Table 3). The most immobile element during metamorphism is vanadium (Condie, 1976) which in our greywacke ranges from 25 to 144 ppm (avg 106 ppm). The high content of V primarily reflects the abundance of clay minerals and presence of hydrous oxides of Fe and Mn. Archaean sedimentary rocks are known to be enriched in Ni and Cr than those of Post-Archaean time (Taylor and McLennan, 1983). Ni and Cr of our greywacke show an overall enrichment ranging from 12 to 107 ppm (avg 47 ppm) and 29 to 184 ppm (avg 113 ppm) respectively. Cr and Ni are components which constitute clay minerals and also occur in chlorite and ferromagnesian minerals.

The REE are generally immobile and undergo only minor changes during sedimentary processes. The factors controlling the REE abundance in sedimentary rocks are their abundance in the source rocks, the weathering conditions as well as the syn-deposition and post-deposition processes such as exchange reactions during transportation (Cullers et al., 1979; Chaudhuri and Cullers, 1979; Bhatia, 1985). The presence of heavy minerals and clay minerals in sedimentary rocks could also leads to enrichment in the REE concentrations (Taylor and McLennan, 1983; McLennan et al., 1983; Rashid, 2005). The greywacke of Ribandar and Chimbel show a strong fractionated REE patterns with $\text{La}_N/\text{Yb}_N = 8$ to 26 and with higher total REE abundances ranging from 75 to 246 ppm. A prominent negative Eu anomaly is exhibited with $\text{Eu}/\text{Eu}^* = 0.539$ to 0.785. Chondrite normalized REE patterns of our greywacke (Fig. 6a) have similar trends except for one sample (GA-10) that shows lower contents of REE but with a similar pattern as the other samples. Overall, the samples show light REE (LREE) enrichment, depletion in heavy REE (HREE) and a negative Eu anomaly.

The geochemical data of the dykes (Table 3) and plots of the total alkalis-silica diagram (TAS after Le Maitre et al., 1989) (Fig. 6b), reveal that sample GA-04 falls in the 'trachybasalt' field whereas GA-14 along with the average of the dykes of Goa (Widdowson et al., 2000) plots in the 'basalt' field. The greywacke samples were also plotted on the TAS diagram. The data show that most are chemically comparable to dacite whereas three samples (GA-06, GA-07, GA-08) are akin to trachyandesite and two samples (GA-06B, GA-13) plot in

the rhyolite field. Both the dolerite samples exhibit a similar chondrite normalized REE pattern (Fig. 6c) wherein GA-04 has lower REE values compared to GA-14. Similar to greywacke they also show LREE enrichment, HREE depletion pattern and a weak negative Eu anomaly. All these facts indicate a felsic source for the studied greywacke.

On the basis of megascopy, microscopy and geochemical study, various features of greywacke from the quarries of Ribandar-Chimbel are discussed. Several primary depositional structures were distinctly identified. The presence of tabular cross bedding indicates a change in the depositional current patterns in a shallow basin while the micro-scale graded bedding indicates the greywacke deposition as turbidities. Dissolution and reaction of the grains with the matrix have occurred during metamorphism as indicated by detrital quartz that show fused, serrated and sutured grain boundaries. Deformation of the greywacke is manifested in the form of pinch and swell feature of the chlorite-biotite band. Generally, the chemical composition of greywacke is related to the mineral constituents but the observed trends suggest that the chemical composition also depends on grain size of the host minerals. The mineralogy of the greywacke has been significantly altered due to burial and low grade metamorphism, which is inferred from the presence of biotite, chlorite and epidote. The REE patterns exhibit significant enrichment of LREE and a relatively flat depleted HREE pattern of Archaean greywacke and suggest its derivation from an old upper continental crust composed chiefly of felsic components (cf. Rashid, 2005). The disseminated pyrite that occur within the greywacke and present along the joint and bedding planes, indicates their formation in a reducing chemical environment in the basin. In summary, the petrological study of the framework composition of the hinterland greywacke of Goa suggests that they belong to the green schist facies of metamorphism. The structural features (graded and cross beddings) indicate the turbidite nature of deposition of sediments in a progressively shallow basin, which also underwent local reducing conditions. The strongly fractionated REE patterns, with an enrichment of LREE and a relatively flat depleted HREE suggest the derivation of greywacke from an old upper continental crust composed chiefly of felsic components. An examination of the discrimination diagrams corroborates that the greywacke was deposited in a deep to shallow basin that progressively changed from a continental island arc to an active continental setting.

4.3 Tectonic setting of greywacke

Goa, located at the northwestern part of the western Dharwar craton, forms a part of the Shimoga-Goa supracrustal belt that probably extends upto the Narmada beneath the Deccan Traps, which terminates at the Narmada-Son lineament (Dessai, 2011). This supracrustal belt extends NNW-SSE for a length of over 250 km and the maximum width of 120 km is seen at Dharwar. The Dharwarian schist belt can be designated as the older Bababudan and younger Chitradurga schist belts (Group) (Dessai, 2011). The Barcem Formation of Goa (Fig. 1) is equivalent to the Bababudan group whereas the Sanvordem, Bicholim and Vageri formations are comparable to the Chitradurga Group (Dessai, 2011). The Goa Group has undergone three stages of folding. The first cycle of folding is observed to the SW of Goa, which is developed with an E-W trend. The

second cycle of folding was the most powerful, which resulted in the NW-SE trend of the rocks. The third cycle of folding had resulted in a major syncline in the north-eastern part of Goa (Gokul et al., 1985).

Diagnostic geochemical signatures are useful to unravel the tectonic setting of the provenances and depositional basins of the siliciclastic sedimentary rocks (Bhatia and Crook, 1986). Diagenesis also influences the bulk composition of sandstones, but the nature of diagenesis itself depends on the tectonic setting of the basin (Siever, 1979; Bhatia, 1983). Immobile trace elements such as La, Ce, Nd, Y, Th, Zr, Hf, Nb, Ti and Sc are most appropriate to help discriminate the tectonic setting which is in turn influenced by parameters such as provenance, relief, weathering, physical sorting and diagenesis (Bhatia, 1983; Bhatia and Crook, 1986).

Ti/Zr v/s La/Sc binary plot (after Bhatia, and Crook, 1986) (Fig. 7a) indicates the deposition of the Ribandar-Chimbel greywacke essentially in a continental island arc tectonic setting with subordinate tectonic setting of active continental margin. The ternary discrimination diagram of CaO-Na₂O-K₂O, La-Th-Sc and Th-Sc-Zr/10 (cf. Bhatia, and Crook, 1986) (Figs. 7b to d) attest to the fact that an overwhelming deposition of the greywacke occurred in a continental island arc setting. Interestingly, the plot of CaO-Na₂O-K₂O (Fig. 7b) exhibits that the sediments were not only deposited in a continental island arc set-up but also in an active continental margin setting. The data of other workers (Condie, 1993; Toulkeridis et al., 1999; Widdowson et al., 2000; Widdowson, 2009; Devaraju et al., 2010) also corroborate our findings. Turbidite structures found in greywacke are common in Archaean clastic sequences and generally the framework mineralogy of these clastic rocks is greatly altered due to burial and metamorphism (Bhatia and Crook, 1986). Studies in the future of the coastal greywacke would help to corroborate this finding.

5 Conclusions

(1) Petrological and structural data of the hinterland (Ribandar-Chimbel quarries) greywacke of Goa, suggest that the detrital rock fragments and polycrystalline quartz grains were derived from the weathering of pre-existing felsic rocks. The presence of feldspar and abundant clay-sized matrix indicates the immaturity and poor sorting of the sediments.

(2) The graded bedding is a typical turbidities feature that perhaps formed due to gravitational deposition from a turbidity flow and points to a deep basin environment. The tabular cross bedding indicates a change in the depositional current that occurred in a shallower basin. These features could be integrated to form a part of the Bouma sequence, which is an ideal turbidite depositional sequence.

(3) The greywacke probably represents a turbidite deposit and in turn underwent low grade metamorphism resulting in an assemblage of biotite-chlorite-epidote. The presence of schistosity and bending of biotite grains are also evidences of metamorphic effects.

(4) The emplacement of the dolerite dyke resulted in the formation of several quartz veins within the greywacke and resulting in silicification at their contact.

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References

- Banerjee, A., Banerjee, D. M., 2010. Modal analysis and geochemistry of two sandstones of the Bhandar Group (Late Neoproterozoic) in parts of the Central Indian Vindhyan basin and their bearing on the provenance and tectonics. *Journal of Earth System Science*, 119:825–839
- Balaram, V., Rao, T.G., 2003. Rapid determination of REEs and other trace elements in geological samples by microwave acid digestion and ICP-MS. *Atomic Spectroscopy*, 24:206-212
- Bavinton, O.A., Taylor, S.R., 1980. Rare earth element abundances in Archean metasediments from Kambalda, Western Australia. *Geochimica et Cosmochimica Acta*, 44: 639-648
- Bhatia, M.R., 1983. Plate tectonics and geochemical composition of sandstones. *Journal of Geology* 91: 611-627.
- Bhatia, M.R., 1985. Rare earth element geochemistry of Australian Palaeozoic greywacke and mud rocks: provenance and tectonic control. *Sedimentary Geology*, 45: 97-113.
- Bhatia, M.R., Crook, K.A.W., 1986. Trace element characteristics of greywacke and tectonic setting discrimination of sedimentary basins. *Contribution to Mineralogy and Petrology*, 92: 181-193.
- Blatt, H., Middleton, G.V., Murray, R., 1980. *Origin of sedimentary rocks*. Englewood Cliffs, NJ, Prentice-Hall, pp. 782.
- Chari, C.N, Maggirwar, C.N., 1968. Occurrence of chromite deposits associated with ultrabasic rocks in the Maharashtra State. Directorate of Geology and Mines, *Mineral Research*, 1: 17-20.
- Chaudhuri, S., Cullers, R.L., 1979. The distribution of rare earth elements in deeply buried Gulf Coast sediments. *Chemical Geology*, 24: 327-328.
- Condie, K.C., 1967. Geochemistry of early Precambrian greywacke from Wyoming. *Geochimica et Cosmochimica Acta*, 31: 2135-2149.
- Condie, K.C., 1993. Chemical composition and evolution of the upper continental crust: Contrasting results from surface samples and shales. *Chemical Geology*, 104: 1-37.
- Condie, K.C., 1976. Plate tectonics and crustal evolution. *Pergamon Press*, New York, pp. 288.
- Condie, K.C., Mackie, J.E., Reimer, T.O., 1970. Petrology and geochemistry of Early Precambrian greywacke from the Fig Tree Group, South Africa. *Geological Society of American Bulletin*, 81: 2759-2776.
- Courtillot, V., Besse, J., Vandamme, D., Montigny, R., Jaeger J.J., Cappetta, H., 1986. Deccan flood basalts at the Cretaceous/ Tertiary boundary? *Earth and Planetary Science Letters*, 80: 361–374.

- Cox, R., Low, D.R., Cullers, R.L., 1995. The influence of sediment recycling and basement composition on evolution of mudrock chemistry in the South Western United States. *Geochimica et Cosmochimica Acta*, 59: 2919-2940.
- Crook, K.A.W., 1974. Lithogenesis and geotectonics: the significance of compositional variations in flysch arenites (greywacke), In: Modern and ancient geosynclinal sedimentation Dott, R.H. and Shaver, R.H. (eds), *SEPM Special Publication*, 19: 304-310.
- Cullers, R.L., 1995. The controls on the major- and trace- elements evolution of shales, siltstones and sandstones of Ordovician to Tertiary age in the Wet Mountains region, Colorado, USA. *Chemical Geology*, 123: 107-131.
- Cullers, R.L., Chaudhuri, S., Kilbane, N., Koch, R., 1979. Rare earths in size fractions and sedimentary rocks of Pennsylvanian-Permian age from the mid-continent of the U.S.A. *Geochimica et Cosmochimica Acta*, 37: 1499-1512.
- Devaraju, T.C., Sudhakara, T.L., Kaukonen, R.J., Viljoen, R.P., Alapiett, T.T., Ahmed, S.A., Sivakumar, S., 2010. Petrology and geochemistry of greywackes from Goa-Dharwar sector, Western Dharwar craton: implications for volcanoclastic origin. *Journal of Geological Society of India*, 75: 465-487.
- Dessai, A.G., 2011. The Geology of Goa: Revisited. *Journal of Geological Society of India*, 78: 233-242.
- Dickinson, W.R., Suczek, C.A., 1979. Plate tectonics and sandstone compositions. *American Association of Petroleum Geological Bulletin*, 63: 2164-2182.
- Dickinson, W.R., Valloni, R., 1980. Plate settings and provenance of sands in modern ocean basins. *Geology*, 8: 82-86.
- Geological Survey of India, 1996. *Geological and Mineral map of Goa*, Government of India.
- Gokul, A.R., Srinivasan, M.D., Gopalkrishnan, K., Viswanathan., L.S., 1985. Stratigraphy and structure of Goa. In: *Seminar volume on Earth Resources for Goa's Development*, Panaji, Goa, 1-13.
- Herron, M.M., 1988. Geochemical classification of terrigenous sands and shales from core or log data. *Journal of Sedimentary Petrology*, 58: 820-829.
- Holland, H. D., 1978. The chemistry of the atmosphere and oceans. Wiley, New York, pp. 351.
- Jena, B.K., 1968. Usgaon ultramafic-gabbro complex, Goa. *Journal Geological Society of India*, 26: 492-495.
- Jenner, G.A., Fryer, B.J., McLennan, S.M., 1981. Geochemistry of the Archean Yellowknife Supergroup. *Geochimica et Cosmochimica Acta*, 45: 1111-1129.
- Iyer, S.D., Babu, E.V.S.S.K., Mislankar, P.G., Gujar, A.R., Ambre, N.V, Loveson, V.J., 2010. Occurrence and emplacement of chromite ores in Sindhudurg District, Maharashtra, India. *Acta Geologica Sinica*, 84: 515-527.
- Lahtinen, R., 2000. Archaean-Proterozoic transition: geochemistry, provenance and tectonic setting of metasedimentary rocks in central Fennoscandian Shield, Finland. *Precambrian research*, 104:147-174.
- Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Woolley, A.R., Zanettin, B., 1989. *A classification of igneous rocks and glossary of terms*, Blackwell, Oxford.
- Marston, R.J., 1978. The geochemistry of the Archaean clastic metasediments in relation to crustal evolution, northeastern Yilgarn Block, Western Australia. *Precambrian Research*, 157-175.
- McLennan, S.M., Taylor, S.R., Kroner, A., 1983. Geochemical evolution of Archean shales from South Africa. I. The Swaziland and Pongola Supergroups. *Precambrian Research*, 22: 93-124.
- Nance, W.B., Taylor, S.R., 1977. Rare earth element patterns and crustal evolution II: Archean sedimentary rocks from Kalgoorlie, Australia. *Geochimica et Cosmochimica Acta*, 41: 225-231.
- Naqvi, S.M., Hussain, S.M., 1972. Petrochemistry of early Precambrian metasediments from the central part of the Chitradrug Schist Belt, Mysore, India. *Chemical Geology*, 10: 109-135.

- Patil, S.K., Rao, D.K., 2002. Palaeomagnetic and rock magnetic studies on the dykes of Goa, west coast of Indian Precambrian shield. *Physics of the Earth and Planetary Interiors*, 133: 111-125.
- Pettijohn, F.J., Potter, P.E., Siever, R., 1972. *Sand and sandstone*. Springer-Verlag, New York pp 618.
- Potter, P.E., 1978. Petrology and chemistry of modern big river sands. *Journal of Geology*, 86: 423-449.
- Rashid, S.A., 2005. The geochemistry of Mesoproterozoic clastic sedimentary rocks from the Rautgara Formation, Kumaun Lesser Himalaya: Implications for provenance, mineralogical control and weathering. *Current Science*, 88: 1832-1836.
- Schmidt, P.W., Prasad, V., Ramam, P.K., 1983. Magnetic ages of some Indian laterites. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 44: 185-202.
- Schwab, F.L., 1975. Framework mineralogy and chemical composition of continental margin-type sandstone. *Geology*, 3: 487-490.
- Siever, R., 1979. Plate-tectonic controls on diagenesis. *Journal of Geology*, 87: 127-155.
- Sinha Roy, S., Radhakrishna, T., 1983. Geochemistry and petrogenesis of basic dykes of Agali area, Palghat district, Kerala. *Journal of Geological Society of India*, 24: 628-638.
- Storey, M., Mahoney, J.J., Saunders, A.D., Duncan, R.A., Kelley, S.P., Coffin, M.F., 1995. Timing of hot spot- related volcanism and the breakup of Madagascar and India. *Science*, 267: 852-855.
- Sun, S., McDonough, W.F., 1989. Chemical and isotope signatures of ocean basalts. In: Saunders AD and Norry MJ (eds.) *Magmatism in the ocean basins*. Geological Society, London, Special Publication 42: 313-345.
- Taylor, S.R., McLennan, S.M., 1983. Geochemistry of Early Proterozoic rocks and the Archean/Proterozoic boundary. *Geological Society of American Memoirs*, 161: 119-122.
- Toulkeridis, T., Clauer, N., Kroner, A., Reimer, T., Todt, W., 1999. Characterization, provenance and tectonic setting of Fig Tree greywacke from the Archaean Barberton Greenstone Belt, South Africa. *Sedimentary Geology*, 124: 113-129.
- Valloni, R., Maynard, J.B., 1981. Detrital modes of recent deep-sea sands and their relation to tectonic setting: a first approximation: *Sedimentology*, 28: 75-83.
- Widdowson, M., 2009. Evolution of laterite in Goa. In: Natural resources of Goa: a geological perspective, Mascarenhas, A. and Kalavampara, G. (eds.), *Geological Society of Goa*, Miramar, Goa, 35-68.
- Widdowson, M., Pringle, M.S., Fernandez, O.A., 2000. A post K-T Boundary (Early Palaeocene) Age for Deccan type feeder dykes, Goa, India. *Journal of Petrology*, 41: 1177-1194.
- Wildeman, T.R., Condie, K.C., 1973. Rare earths in Archean greywacke from Wyoming and from the Fig Tree Group, South Africa. *Geochimica et Cosmochimica Acta*, 37: 439-453.
- Wimmenauer, W., 1984. Das prävariskische Kristallin in Schwarzwald. *Fortschritt der Mineralogie*, 62: 69-86.

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Fig. 2 Photographs of greywacke of Ribandar-Chimbel, Goa. (a) Close up of fresh massive greywacke (3m section height) exposed at a quarry face in Ribandar. (b) Field photograph of tabular cross bedding at Chimbel. (c) Photomicrograph of graded bedding (in plane polarised light) in greywackes from Ribandar. (d) Medium grained greywacke from Chimbel with framework components of plagioclase, biotite, chlorite, rock fragments (red circle) and matrix (under crossed nicols). (e) Greywacke from Ribandar showing monocrystalline quartz (yellow circle) and polycrystalline quartz (red circle). Schistosity is indicated by red line (under crossed nicols). (f) Greywacke from Ribandar showing distinct schistosity marked by a red line (under crossed nicols).

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Fig. 4 Compositional trends of major elements. See text for explanation

Fig. 5 Classification of Ribandar-Chimbel greywacke. The legends are the same for figures.

(a) Binary plot of $\text{SiO}_2/\text{Al}_2\text{O}_3$ v/s $\text{K}_2\text{O}/\text{Na}_2\text{O}$ (after Wimmenauer, 1984) showing a majority samples to plot in the 'greywacke' field. (b) Binary plot of $\log(\text{Na}_2\text{O}/\text{K}_2\text{O})$ against $\log(\text{SiO}_2/\text{Al}_2\text{O}_3)$ (after Pettijohn et al., 1972) emphasizes the 'greywacke' field. (c) Binary plot of $\log(\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ against $\log(\text{SiO}_2/\text{Al}_2\text{O}_3)$ (after Herron, 1988) shows the samples to fall in 'shale' as well as 'wacke' fields. (d) Ternary diagram of $\text{Fe}_2\text{O}_3 + \text{MgO} - \text{Na}_2\text{O} - \text{K}_2\text{O}$ (after Marston, 1978) depicts most of the samples to fall in the 'greywacke' field except one which plots in the 'sodic sandstone' field.

Fig. 6 (a) Chondrites normalised rare earth element patterns showing the REE trends of greywacke. (b) Total alkalis vs silica diagram (after Le Maitre et al., 1989) showing plots for dolerite samples and greywacke samples. (c) Chondrites normalised rare earth element patterns showing the REE trends of dolerite.

Fig. 7 Tectonic discrimination diagrams for the Ribandar-Chimbel greywacke. A=oceanic island arc, B=continental island arc, C=active continental margin, D=passive margin. The fields are after Bhatia and Crook (1986). (a) Ti/Zr v/s La/Sc binary plot showing deposition of greywacke essentially in a continental island arc tectonic setting with subordinate tectonic setting of active continental margin. (b) Ternary discrimination diagram of $\text{CaO} - \text{Na}_2\text{O} - \text{K}_2\text{O}$, (c) ternary discrimination diagram of $\text{La} - \text{Th} - \text{Sc}$, (d) ternary discrimination diagram of $\text{Th} - \text{Sc} - \text{Zr}/10$ (after Bhatia and Crook, 1986) show an overwhelming deposition of the greywacke in a continental island arc setting.

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Table 2: Major and minor elements (in wt %) and trace elements and rare earth element (in ppm) of greywacke from Ribandar (1 to 7) and Chimbel (8 to 13) quarries. #14 is dolerite dyke from Ribandar and #15 dolerite dyke from Chimbel quarry.

Table 3: Average compositions of greywackes and related rocks from other areas for comparison. The numbers within brackets indicate the number of samples averaged. Ribandar-Chimbel quarry (RCG); dykes of Goa (GD) and greywacke (MG) from Merces (Widdowson, 2009). 1 to 3 = greywacke with biotite, greywacke with chlorite-sericite and fine-grained greywacke all from Goa-Dharwar sector (Devaraju et al., 2010). 4 = Late Archaean (3.5-2.5 Ga) greywacke (Condie, 1993), 5 = Archaean greywacke of Fig Tree, Barberton (Toulkeridis et al., 1999), * = total Fe as FeO.

Table 1 Stratigraphy of Goa Group after Gokul et al., 1985

Late Cenozoic to Recent		Sand, alluvium, lateritic soil and laterite	
Upper Cretaceous to Lower Eocene		Deccan Trap volcanics and dolerite dykes	
Early Proterozoic (<2500Ma)		Acidic and basic intrusive including granites, gabbro, dolerite dykes and ultramafics	
Archean	(Dharwar Supergroup) Goa Group (3000-2500Ma)	Vageri Formation	Detrital metasediments (quartzite, metagreywacke and argillite) with some metavolcanics
		Bicholim Formation	Mainly chemogenic sediments (phyllites with banded-hematite-quartzite and limestone)
		Sanvordem Formation	Detrital metasediments including meta-conglomerates, quartzites, metagreywackes and argillites
		Barcem Formation	Mainly metavolcanics and metabasites with few metasediments
	(>3000Ma)	Basement Trondhjemite Gneiss	

Table 2 Major and minor elements (in wt %) and trace elements and rare earth element (in ppm) of greywacke from Ribandar (1 to 7) and Chimbel (8 to 13) quarries. #14 is dolerite dyke from Ribandar and #15 dolerite dyke from Chimbel quarry

Sample	1 GA - 01	2 GA - 1B	3 GA - 02	4 GA - 05	5 GA - 06	6 GA - 06B	7 GA - 07	8 GA - 08
SiO ₂	62.83	78.57	64.43	64.36	65.01	59.87	56.34	74.92
Al ₂ O ₃	15.35	10.56	14.93	14.00	14.01	16.55	17.48	11.66
TiO ₂	0.70	0.29	0.62	0.60	0.68	0.73	0.71	0.41
Fe ₂ O ₃	7.57	3.11	6.85	7.43	7.50	7.99	10.04	3.94
MnO	0.08	0.03	0.11	0.11	0.09	0.08	0.12	0.03
MgO	3.02	1.12	2.37	2.69	2.70	3.36	3.85	1.81
CaO	0.99	0.82	1.34	2.86	1.94	1.61	1.46	0.73
Na ₂ O	3.78	3.87	4.59	3.71	3.86	3.97	2.72	3.26
K ₂ O	3.02	1.30	2.23	1.77	2.10	2.99	3.97	1.94
P ₂ O ₅	0.14	0.06	0.17	0.13	0.16	0.14	0.14	0.08
Sum	97.48	99.73	97.62	97.65	98.03	97.29	96.82	98.78
Li	47.31	19.99	34.97	30.17	34.02	53.83	56.35	20.92
Be	12.70	13.82	12.50	11.00	10.81	12.48	12.78	8.51
Sc	17.21	5.89	14.40	14.64	15.08	18.39	17.68	9.09
Cr	135.30	29.73	87.54	163.10	184.40	146.60	152.60	58.98
Co	22.61	6.36	24.67	19.30	20.30	24.96	19.61	10.94
Ni	57.01	12.74	39.33	53.68	51.62	57.04	57.92	21.99
Cu	41.51	9.32	108.50	64.98	68.11	47.25	35.69	60.31
Zn	77.19	28.93	81.58	66.29	76.70	56.62	85.10	23.02
Ga	48.63	21.16	39.42	31.06	32.99	37.44	54.70	31.13
Rb	168.60	86.79	128.30	81.11	99.77	177.00	207.60	57.33
Sr	131.00	117.30	157.00	233.20	212.50	154.70	130.10	108.80
Y	23.50	25.32	23.22	23.93	23.16	22.32	21.51	21.45
Zr	146.30	150.70	171.30	141.40	144.30	160.40	147.10	91.68
Nb	18.51	12.29	18.88	13.33	16.05	18.78	16.26	13.79
Sn	2.56	1.68	2.06	1.77	1.80	2.03	2.52	2.02
Sb	0.19	0.25	0.31	0.45	0.25	0.23	0.09	0.17
Cs	7.78	4.38	7.86	5.30	6.56	11.89	12.79	1.75
Ba	846.60	264.50	675.60	405.10	460.20	516.70	909.80	519.40
Pb	2.97	7.37	4.41	4.30	3.47	5.06	4.48	3.00
Th	7.61	6.79	8.07	7.31	7.50	8.56	6.39	5.57
U	3.24	2.78	3.40	3.47	3.40	3.58	2.69	2.29
La	36.83	41.81	46.01	44.36	56.73	43.68	34.17	32.21
Ce	84.22	103.00	100.70	91.73	111.40	90.35	72.44	66.22
Pr	7.60	9.44	9.34	8.73	10.37	8.96	7.08	6.52
Nd	31.36	39.46	38.68	36.96	44.56	38.44	30.46	27.78
Sm	4.30	4.76	4.79	4.86	5.40	5.26	4.48	3.81
Eu	1.05	0.86	1.20	1.24	1.34	1.33	1.17	0.90
Gd	4.33	4.94	4.72	5.02	5.65	5.31	4.54	3.93
Tb	0.61	0.68	0.65	0.69	0.74	0.71	0.63	0.54
Dy	3.40	3.68	3.51	3.85	3.86	3.70	3.43	2.98
Ho	0.72	0.77	0.74	0.80	0.77	0.74	0.70	0.64
Er	2.26	2.47	2.37	2.48	2.29	2.20	2.10	1.98
Tm	0.35	0.40	0.38	0.39	0.35	0.34	0.31	0.31
Yb	2.18	2.75	2.45	2.48	2.13	2.07	1.91	2.00
Lu	0.33	0.46	0.38	0.38	0.32	0.32	0.29	0.30

Table 2 (contd)

Sample	9 GA - 09	10 GA - 10	11 GA - 12	12 GA - 13	13 GA - 15	14 GA - 04	15 GA - 14
SiO ₂	54.73	69.30	68.93	66.38	66.85	49.02	50.20
Al ₂ O ₃	18.47	13.56	13.81	14.56	13.89	12.23	12.98
TiO ₂	0.72	0.49	0.54	0.57	0.72	1.37	2.95
Fe ₂ O ₃	8.92	5.38	5.22	6.29	6.15	17.00	15.49
MnO	0.12	0.08	0.09	0.04	0.09	0.27	0.17
MgO	4.48	2.62	2.40	3.07	2.86	5.70	3.87
CaO	1.36	0.77	0.86	0.57	1.54	8.12	5.89
Na ₂ O	3.70	3.30	3.64	2.90	3.32	2.88	3.18
K ₂ O	4.54	3.01	2.48	3.49	2.64	0.88	2.18
P ₂ O ₅	0.12	0.08	0.11	0.04	0.13	0.20	0.86
Sum	97.15	98.58	98.07	97.91	98.19	97.66	97.77
Li	64.83	38.89	31.13	49.38	40.52	18.70	25.09
Be	17.24	10.09	11.45	11.92	10.53	4.42	8.61
Sc	16.98	11.24	11.81	12.76	15.23	37.97	31.41
Cr	108.70	75.59	85.68	95.98	143.30	88.76	25.07
Co	29.53	15.68	16.37	16.79	51.94	78.35	52.57
Ni	55.09	30.14	31.59	34.15	107.80	84.13	52.68
Cu	89.46	65.91	39.83	33.96	69.37	49.98	41.01
Zn	107.50	87.16	54.16	44.98	126.00	93.56	112.10
Ga	57.92	37.15	37.10	43.34	36.06	30.51	46.19
Rb	225.80	138.00	92.79	148.30	131.50	31.39	78.19
Sr	220.30	117.80	143.70	125.40	110.50	257.00	428.20
Y	26.26	13.51	20.88	17.81	25.34	31.47	67.94
Zr	150.80	105.30	115.20	137.80	202.30	117.10	200.50
Nb	31.37	19.14	20.11	17.73	29.51	8.54	28.77
Sn	3.56	2.23	2.28	2.62	2.94	1.37	2.63
Sb	0.22	0.21	0.35	0.16	0.21	0.10	0.38
Cs	11.58	5.68	4.23	5.85	6.87	0.62	5.69
Ba	784.70	629.50	628.90	757.30	585.70	436.60	768.80
Pb	4.70	3.02	2.20	1.67	4.70	3.19	5.15
Th	10.92	7.04	8.09	7.62	20.73	2.67	2.41
U	5.80	2.66	3.94	3.82	10.48	1.27	0.91
La	37.00	15.18	32.61	18.72	47.13	13.52	50.50
Ce	73.67	30.38	69.77	43.63	99.66	33.46	115.50
Pr	7.33	3.31	7.20	4.41	10.69	4.02	14.40
Nd	31.60	14.35	31.14	19.26	46.72	17.47	70.92
Sm	4.52	2.17	4.55	3.13	6.48	3.97	12.36
Eu	1.04	0.55	1.09	0.81	1.49	1.19	3.40
Gd	4.69	2.22	4.51	3.27	6.26	4.76	13.86
Tb	0.67	0.32	0.63	0.47	0.83	0.81	1.96
Dy	3.75	1.95	3.42	2.69	4.58	4.89	10.63
Ho	0.81	0.45	0.70	0.59	0.93	1.06	2.15
Er	2.54	1.54	2.12	1.84	2.89	3.23	6.04
Tm	0.41	0.28	0.35	0.30	0.49	0.50	0.86
Yb	2.76	1.89	2.25	2.00	3.31	3.10	5.12
Lu	0.45	0.30	0.33	0.32	0.49	0.48	0.75

Table 3 Average compositions of greywackes and related rocks from other areas for comparison. The numbers within brackets indicate the number of samples averaged. Ribandar-Chimbel quarry (RCG); dykes of Goa (GD) and greywacke (MG) from Merces (Widdowson, 2009). 1 to 3 = greywacke with biotite, greywacke with chlorite-sericite and fine-grained greywacke all from Goa-Dharwar sector (Devaraju et al., 2010). 4 = Late Archaean (3.5-2.5 Ga) greywacke (Condie, 1993), 5 = Archaean greywacke of Fig Tree, Barberton (Toulkeridis et al., 1999), * = total Fe as FeO

Sample	Ribandar (7)	Chimbel (6)	RCG(13)	Dyke(2)	GD(7)	MG Goa
SiO ₂	64.49	66.85	65.88	49.61	49.26	67.77
Al ₂ O ₃	14.70	14.33	14.53	12.61	13.90	14.65
TiO ₂	0.62	0.58	0.60	2.16	2.32	0.56
Fe ₂ O ₃	7.21	5.98	6.64	16.25	14.51	6.08
MnO	0.09	0.08	0.08	0.22	0.20	0.13
MgO	2.73	2.87	2.80	4.79	5.93	3.07
CaO	1.57	0.97	1.30	7.01	10.40	0.95
Na ₂ O	3.79	3.35	3.59	3.03	2.56	3.31
K ₂ O	2.48	3.02	2.73	1.53	0.47	3.68
P ₂ O ₅	0.13	0.09	0.11	0.53	0.26	0.12
Sum	97.80	98.11	97.95	97.72		
Li	39.52	40.95	40.18	21.90		
Be	12.30	11.62	11.99	6.52		
Sc	14.76	12.85	13.88	34.69	31.40	14
Cr	128.47	94.71	112.88	56.92	106	108
Co	19.69	23.54	21.47	65.46	59.57	
Ni	47.05	46.79	46.93	68.41	71.29	33
Cu	53.62	59.81	56.48	45.50	186.71	41
Zn	67.49	73.80	70.40	102.83	106.14	109
Ga	37.91	40.45	39.08	38.35	23.1	
Rb	135.60	132.29	134.07	54.79	12.86	118
Sr	162.26	137.75	150.95	342.60	225	114
Y	23.28	20.88	22.17	49.71	36.14	15
Zr	151.64	133.85	143.43	158.80	146	191
Nb	16.30	21.94	18.90	18.66	11.43	13
Sn	2.26	2.61	2.31	2.00		
Sb	0.25	0.22	0.24	0.24		
Cs	8.08	5.99	7.12	3.16	0.27	
Ba	582.64	650.92	614.15	602.70	133.43	721
Pb	4.58	3.22	3.95	4.17	2.40	12
Th	7.46	10.00	8.63	2.54	1.14	16
U	3.22	4.83	3.96	1.09	0.35	6
La	43.37	30.48	37.42	32.01	8.96	
Ce	93.41	63.89	79.78	74.48	22.77	
Pr	8.79	6.58	7.77	9.21	2.95	
Nd	37.13	28.48	33.14	44.20	15.11	
Sm	4.84	4.11	4.50	8.17	3.90	
Eu	1.17	0.98	1.08	2.30	1.28	
Gd	4.93	4.15	4.57	9.31	4.13	
Tb	0.67	0.58	0.63	1.39	0.71	
Dy	3.63	3.23	3.44	7.76	4.27	
Ho	0.75	0.69	0.72	1.61	0.85	
Er	2.31	2.15	2.24	4.64	2.29	
Tm	0.36	0.36	0.36	0.68	0.35	
Yb	2.28	2.37	2.32	4.11	2	
Lu	0.35	0.37	0.36	0.62	0.34	

Table 3 (contd)

Sample	1 (6)	2 (13)	3 (8)	4 Archaean	5 (12)
SiO ₂	67.31	63.03	63.13	65.00	63.41
Al ₂ O ₃	12.13	14.16	15.18	15.20	11.85
TiO ₂	0.79	0.59	0.61	0.61	0.54
Fe ₂ O ₃	7.67	7.06	7.19	5.90*	8.15*
MnO	0.08	2.93	3.27		0.18
MgO	3.90	0.11	0.11	3.30	6.16
CaO	1.37	2.83	2.22	2.60	2.48
Na ₂ O	2.10	3.51	2.65	3.10	1.68
K ₂ O	3.30	1.92	3.17	2.10	1.85
P ₂ O ₅	0.11	0.14	0.16	0.14	0.09
Li					
Be					
Sc	17	14	14	15	14
Cr	152	108	108	175	539
Co	38	25	28	30	30
Ni	58	52	54	75	336
Cu	64	47	69		31
Zn	58	78	91		90
Ga					
Rb	106	80	161	70	94
Sr	90	292	390	265	77
Y	24	23	27	25	16
Zr	166	215	271	160	111
Nb	9	9	14	11	7
Sn					
Sb					
Cs					
Ba	356	419	713	390	291
Pb	7	12	14	20	15
Th	8	10	13	8	5
U	2	3	5	2	1
La	25.70	30.94	35.10	26	16.21
Ce	57.98	72.12	85.16	52	31.76
Pr	4.83	6.38	7.09		3.55
Nd	20.07	24.74	23.70	22	14.08
Sm	3.69	4.58	3.11	3.90	2.86
Eu	1.02	1.28	0.69	1.10	0.68
Gd	3.76	4.27	4.95	3.69	2.59
Tb	0.61	0.60	0.44	0.58	0.47
Dy	4.32	3.40	4.27		2.85
Ho	0.76	0.65	0.49		0.61
Er	2.27	1.83	0.01		1.77
Tm	0.35	0.26	0.22		0.28
Yb	2.20	1.71	1.33	1.40	1.67
Lu	0.33	0.24	0.19	0.25	0.26

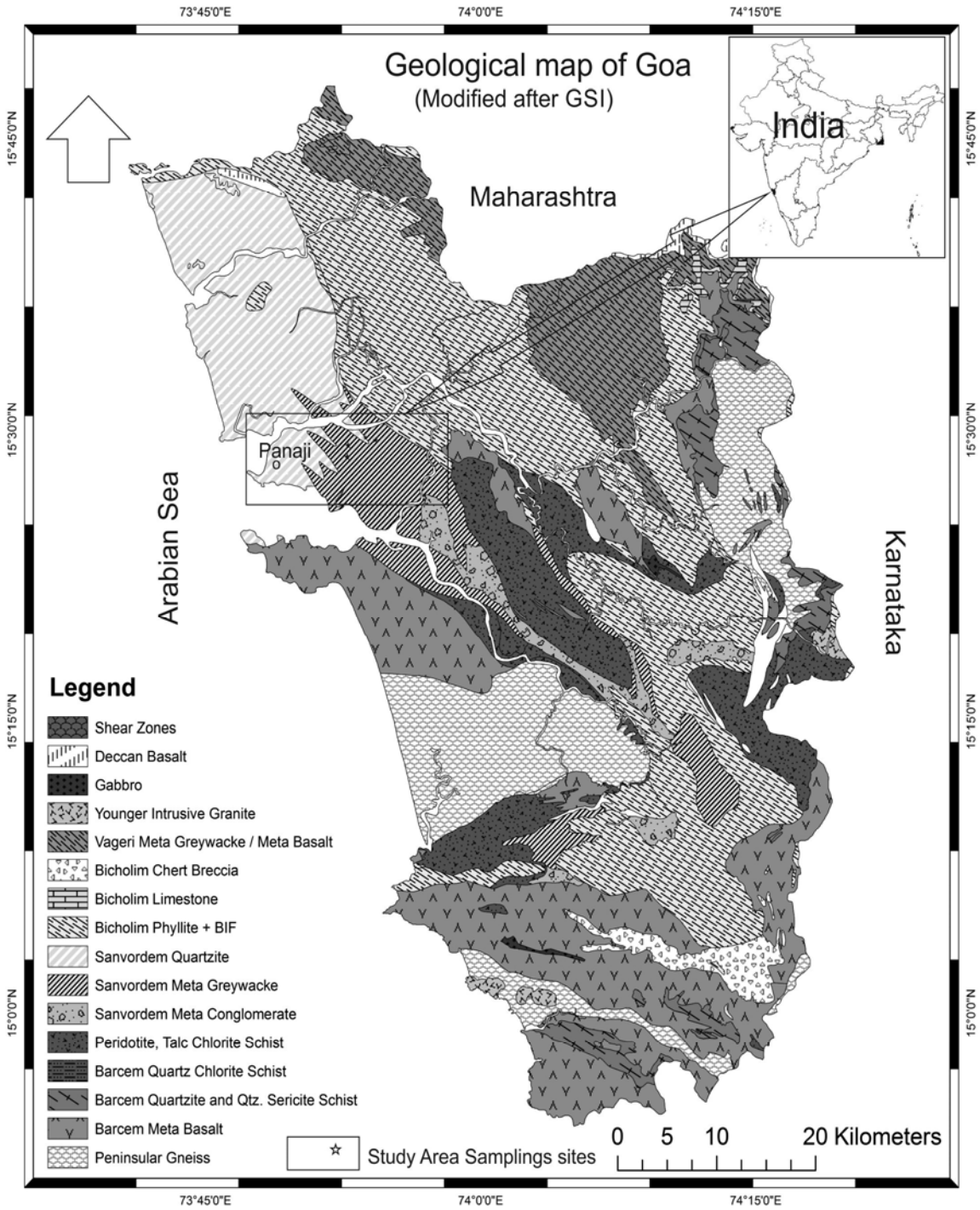


Fig.1

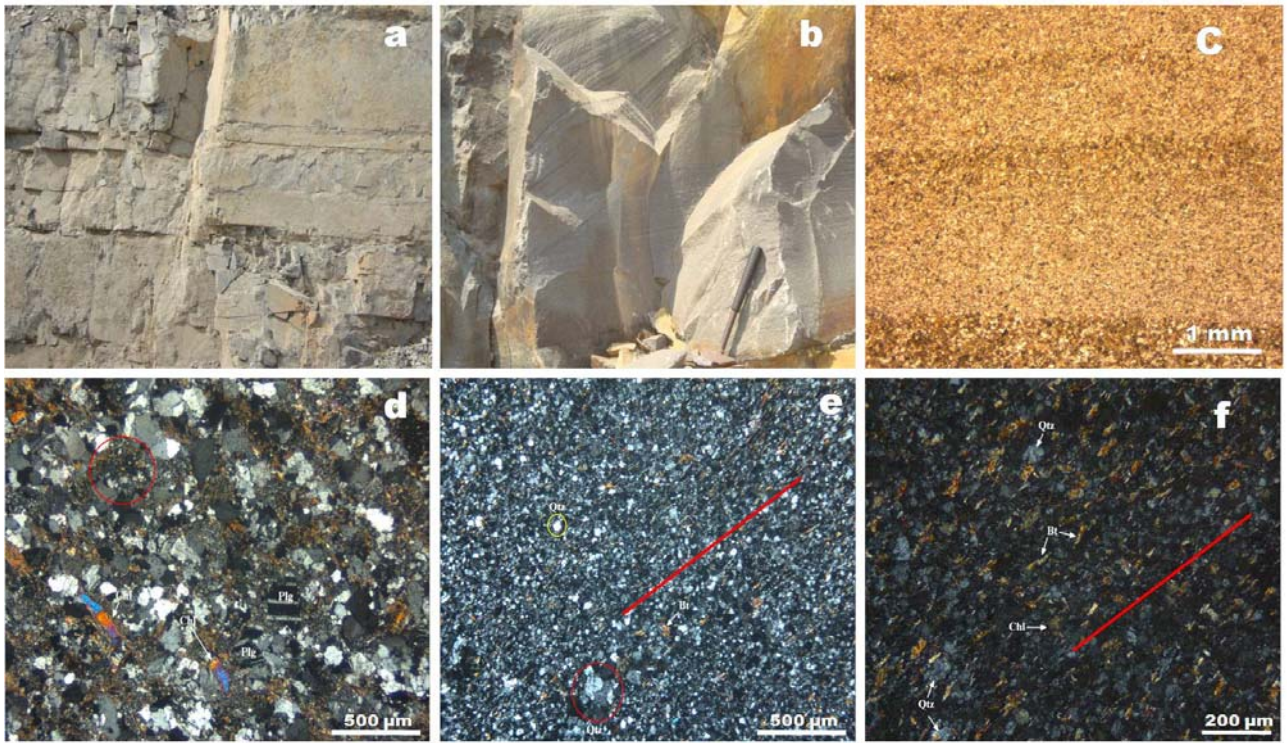


Figure 2

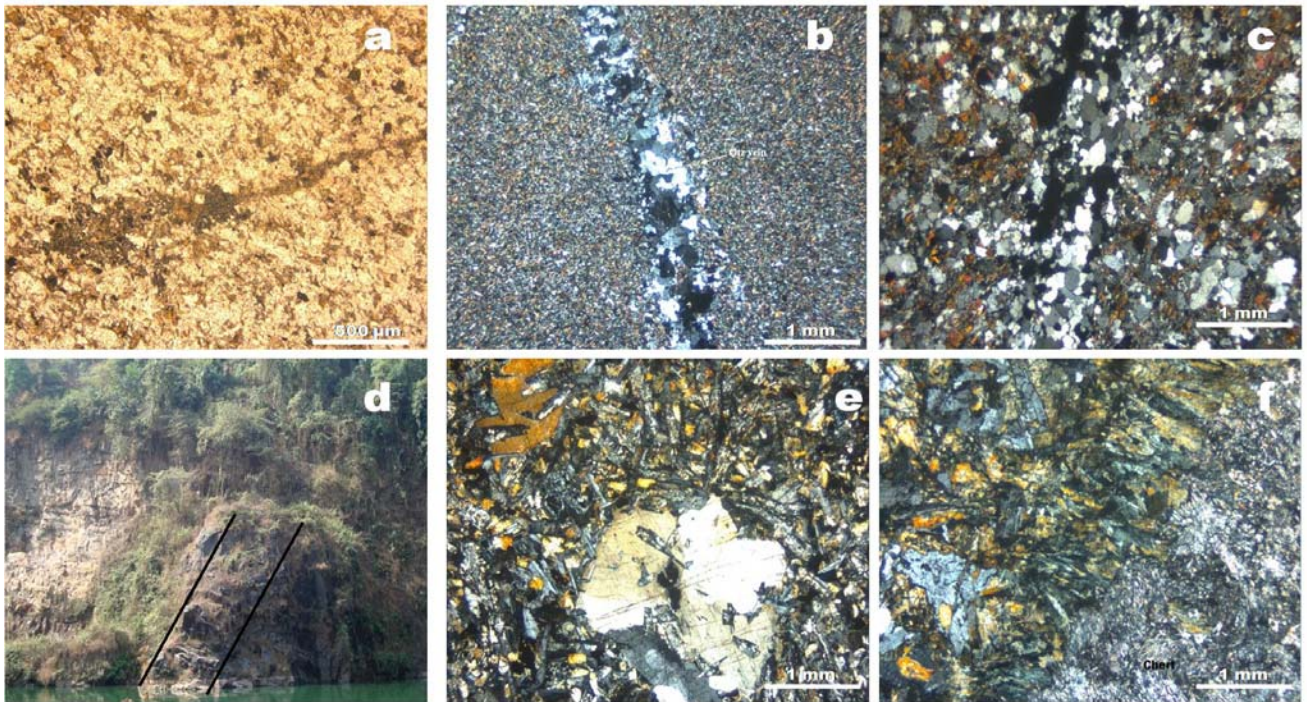


Figure 3

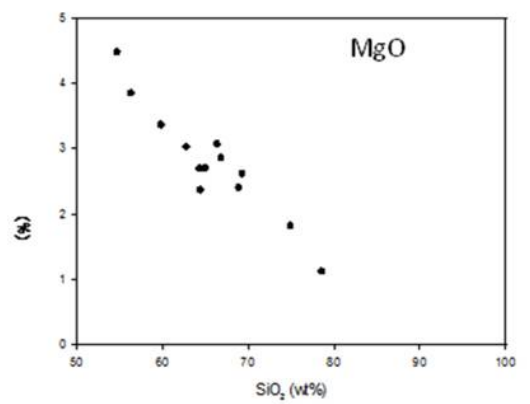
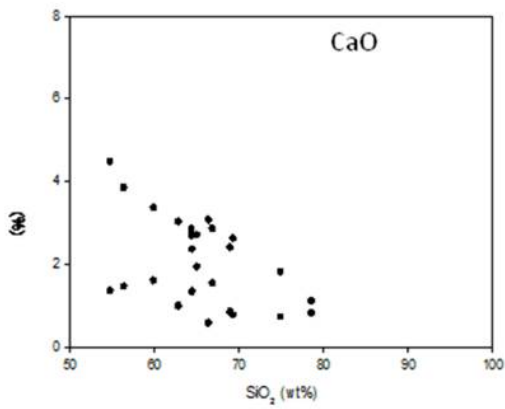
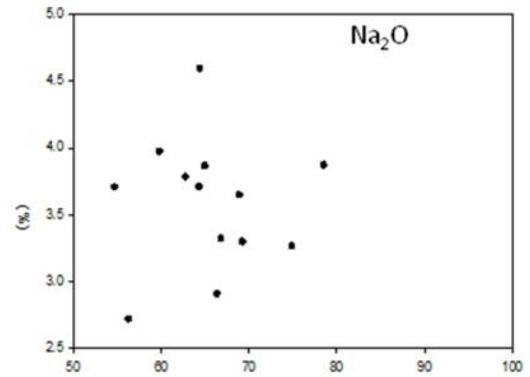
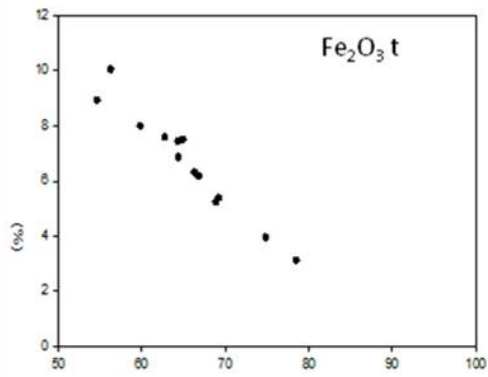
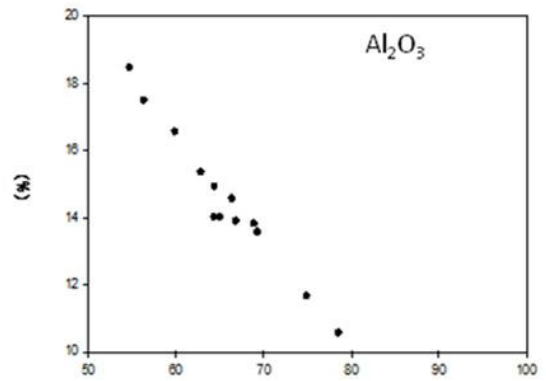
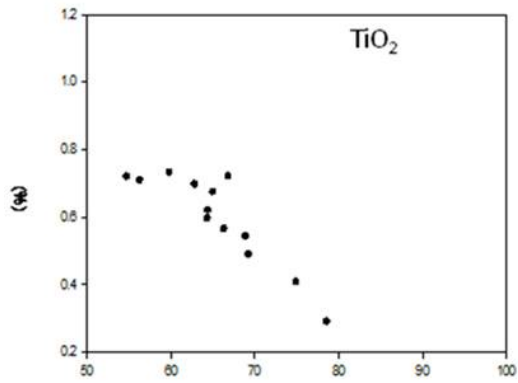
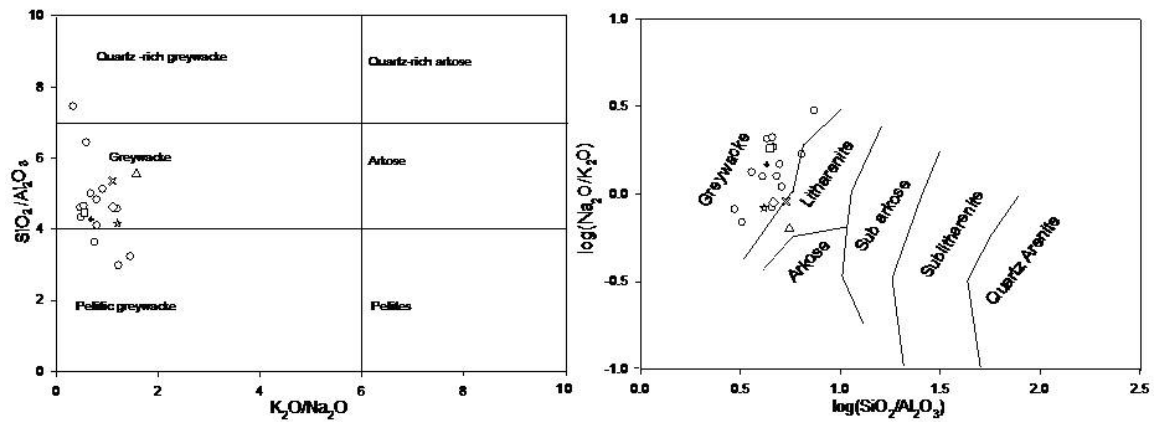
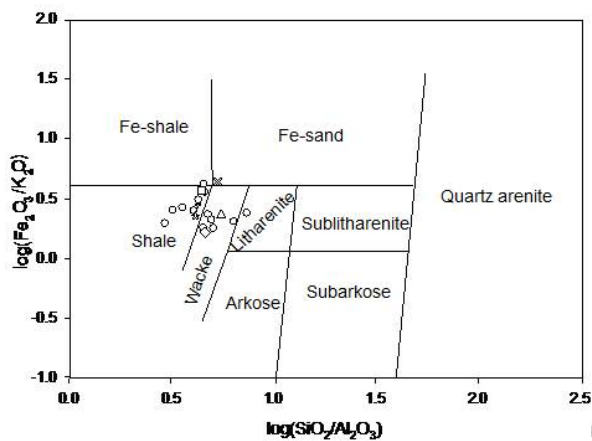


Figure 4

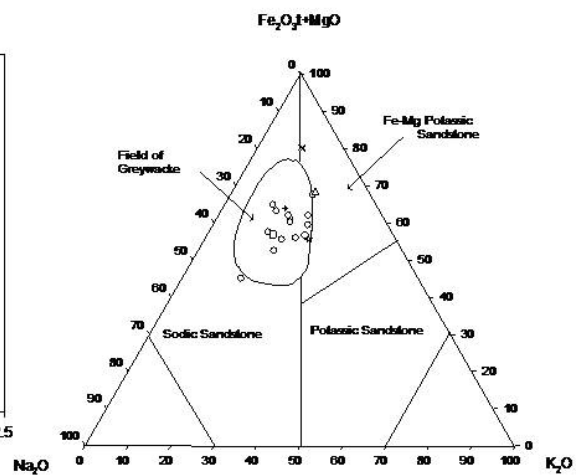


a

b



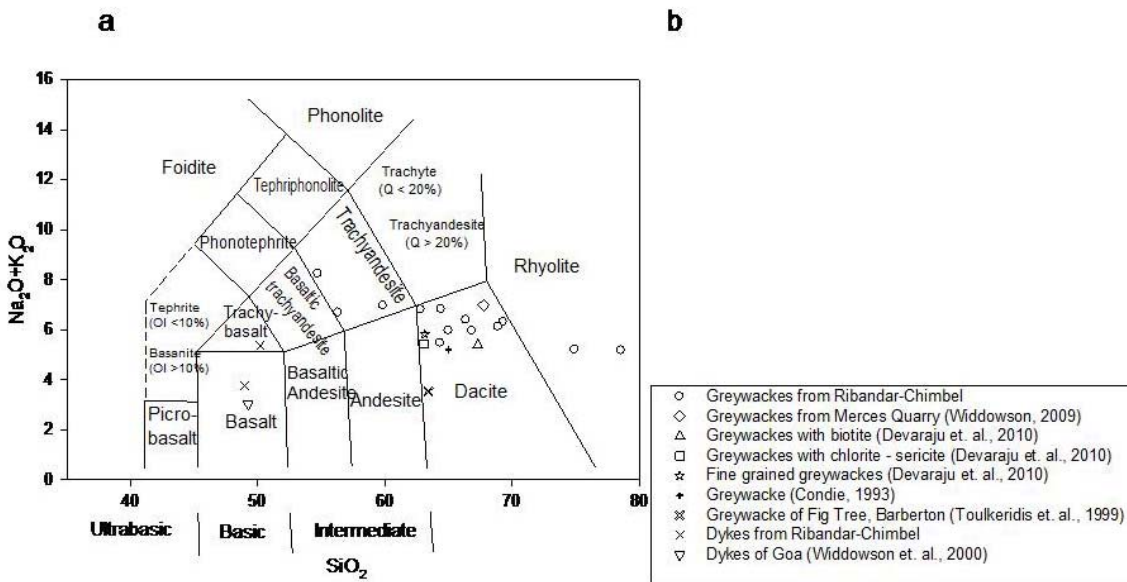
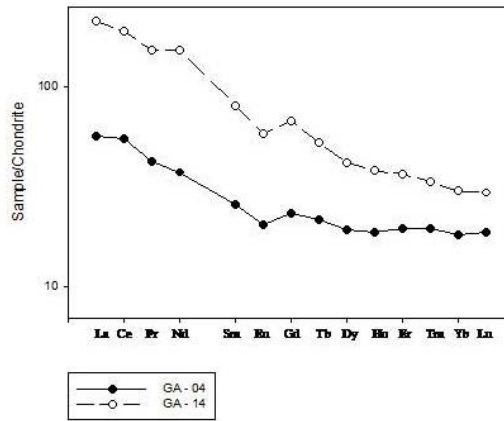
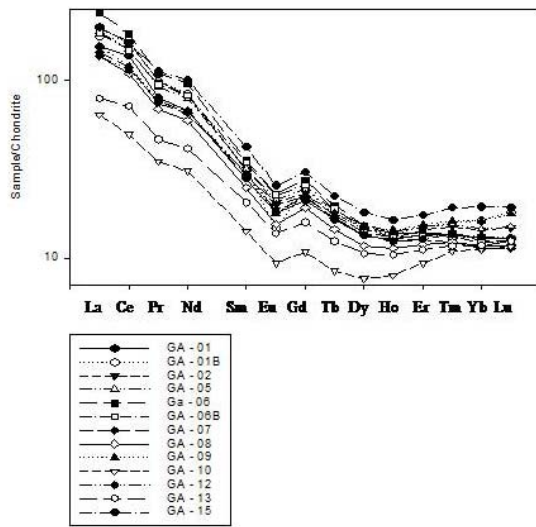
c



d

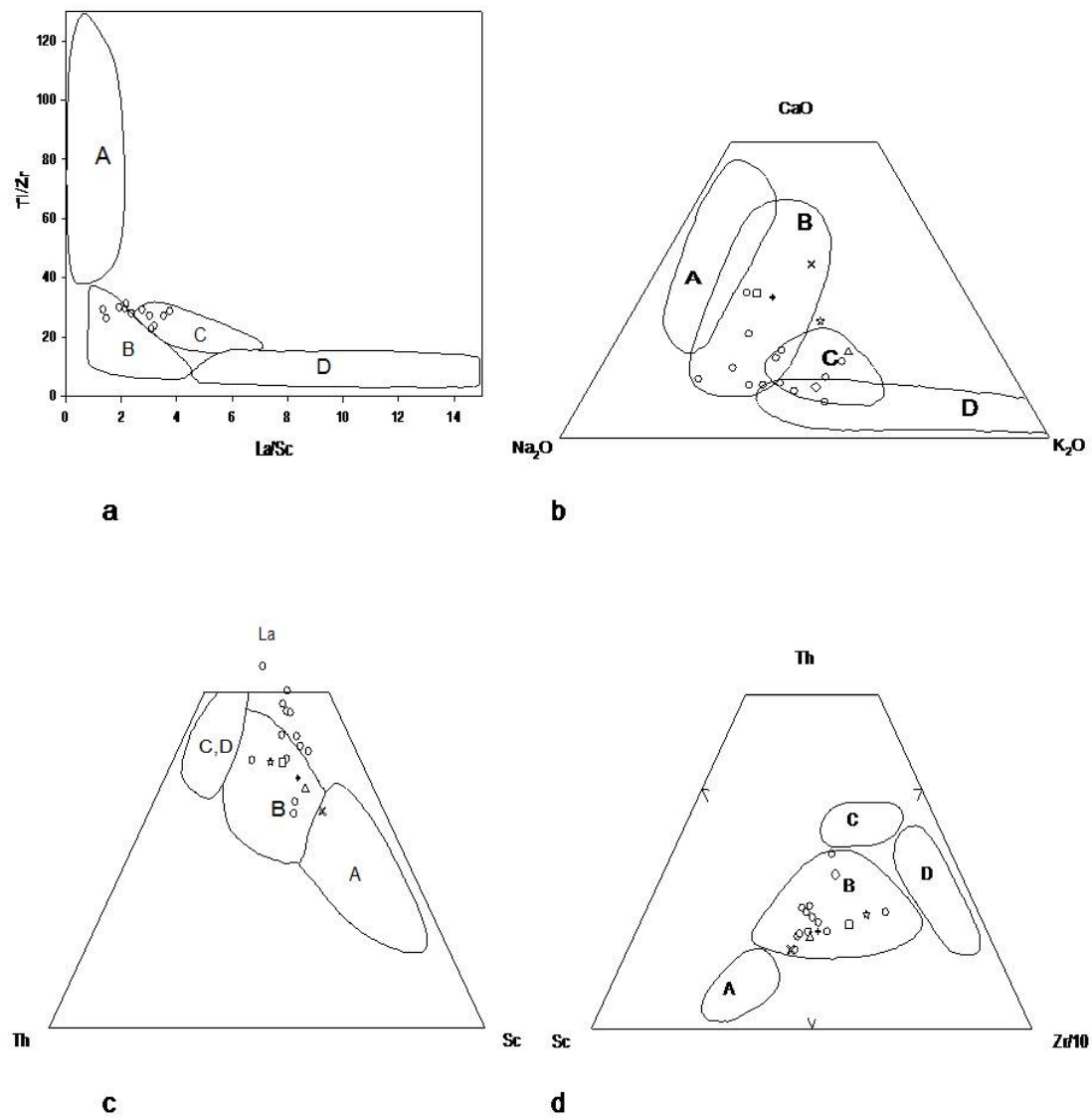
- Greywackes from Ribandar-Chimbel
- ◇ Greywackes from Merces Quarry (Widdowson, 2009)
- △ Greywackes with biotite (Devaraju et al., 2010)
- Greywackes with chlorite - sericite (Devaraju et al., 2010)
- ☆ Fine grained greywackes (Devaraju et al., 2010)
- + Greywacke (Condie, 1993)
- × Greywacke of Fig Tree, Barberton (Toulerkeridis et al., 1999)

Figure 5



c

Figure 6



A – Oceanic island arc
B – Continental island arc
C – Active continental margin
D – Passive margin

- ◊ Greywackes from Ribandar-Chimbel
- ◇ Greywackes from Merces Quarry (Widdowson, 2009)
- △ Greywackes with biotite (Devaraju et. al., 2010)
- Greywackes with chlorite - sericite (Devaraju et. al., 2010)
- ☆ Fine grained greywackes (Devaraju et. al., 2010)
- ⊕ Greywacke (Condie, 1993)
- ⊗ Greywacke of Fig Tree, Barberton (Toulkeridis et. al., 1999)

Figure 7