CHAPTER 8

CRUSTAL EVOLUTION AT ARCHAEAN - PROTEROZOIC BOUNDARY

8.1 Introduction

Geochemical compositions of Sedimentary rocks have been widely used as tool to constrain the average composition of the continental crust exposed at the time of deposition (e.g., Condie, 1993; McLennan et al., 1995). Much of our present understanding about the composition and evolution of continental crust comes chiefly from geochemical and isotopic data gathered on sedimentary rocks (for e.g. Taylor and McLennan, 1985, 1995; Wronkiewicz and Condie, 1987, 1990; Naqvi et al., 1988, 2002; Condie, 1993,1997; Lahtinen, 2000; Condie et al., 2001; Bhat and Ghosh, 2001; Saha et al., 2004). It is generally accepted that sediments preserve the 'memory' of the composition of contemporary upper continental crust, much of which is eroded from geological record; so this approach provides a window to look through the compositional evolution of continental crust. Several geochemical parameters like K_2O/Na_2O ratio, Ni-Cr content, europium anomaly and REE fractionation are found to be distinctive in Archaean and Proterozoic sedimentary rocks (Reference above cited). The Archean-Proterozoic boundary (A/P boundary) is recognized as a fundamental benchmark in the chemical evolution of the upper continental crust. Extensive studies of clastic sedimentary rocks from Precambrian shields in wide geographic areas such as North America, Western Europe, Australia, India and Southern Africa have shown that the Archean upper crust is generally different in chemical composition from post-Archean upper crust (Condie, 1993; Taylor and McLennan, 1985). The chemical differences between Archean and post- Archean upper crust are recorded in trace elements of sedimentary rocks (Taylor and McLennan, 1985; McLennan and Hemming, 1992; Condie, 1993). These include: (1) a change in REE patterns in clastic sedimentary rocks involving a significant depletion in Eu-anomalies in chondrite - normalized REE patterns (Figure 8.1). There is also a tendency for the total REE abundances to increase, as well as a relative enrichment in the LREE. (2) a decrease in $(Gd/Yb)_n$ ratio from >2.0 to 1.0 – 2.0. Condie (1993) has, however, indicated that unlike Archean graywackes, Archean shales lack HREE depletion, (3) a decrease in Sm/Nd ratio from about 0.21 to 0.19, (4) a decrease in the Cr/Th ratio from about 20 to 5.7, (5) a decrease in Cr/ Sc ratio from about 13 to 4.1, and (6) Parallel to the change in REE patterns is a significant increase in the Th/Sc ratio from about 0.5 to 1.0 (possibly only in continental sediments). These two elements are particularly useful indices because both are insoluble with short residence time in sea water. During igneous processes Th is incompatible and thus enriched in residual silicate melts. While Sc is compatible and is concentrated in nearly crystallizing phases such as pyroxene. Therefore the abundances of these two elements provide an index for the relative proportions of acidic to basic material in the sources of sediments.

The changes from Archaean to post-Archaean upper continental crust are interpreted as due to a massive intracrustal melting event which produced an upper crust dominated by K - rich siliceous igneous rocks. It is a well known fact that the formation of the Archaean crust was dominated by greenstone tectonics which produced a crust predominantly mafic in nature. At Archaean - Proterozoic transition large intrusion of high-K intracrustal granite emplaced resulting in production of voluminous upper crust. The Archaean sedimentary rocks display flat REE patterns with no europium anomaly and high Ni-Cr content in comparison to their Proterozoic counterpart; which shows fractionated REE patterns with significant negative europium anomaly and low Ni-Cr content. Large scale production of high-K intracrustal granites and widespread crust formation at 2.5 Ga has been suggested for above mentioned geochemical changes in expense of komatiitic magmatism of greenstone association of the Archaeans. However, this has been challenged by several workers (Gao and Wedepohl, 1995; Gibbs et al., 1986; Condie, 1993, 1997) who have suggested tectonic setting artifacts for such geochemical changes. These authors emphasized that comparison should be made on rocks of similar tectonic associations. Condie (1993, 1997) suggested that the observed upper crustal compositional changes at the APB can be related to four evolutionary changes of earth history viz. i) komatiite effect, ii) TTG effect, iii) subduction effect, iv) weathering effect. Out of these, first three changes are direct consequence of cooling of mantle through time. Komatiite effect is preserved in sedimentary record in term of high Ni-Cr content and flat REE pattern with moderate positive Eu anomaly in Archaean sediments relative to those of Proterozoic. The voluminous production of TTG in Archaean is related to TTG effect. During the late Archaean-Early Proterozoic the operation of subduction process resulted in production of huge amounts of granitic magma due to partial melting of metasomatised mantle wedge with distinct subduction geochemical component i.e LILE enrichment over Nb and Ta. These changes are recorded in terms of HREE and Y depletion in Archaean TTG and LILE enrichment in Proterozoic granites. The Archean TTG is characterized by steep fractionated REE pattern and LILE depletion in comparison to Proterozoic granite and TTG. Some geochemical changes across APB seem to be related to palaeoweathering effects since intensity of chemical weathering decreased after the Archaean.

8.2 Geochemical Changes across APB in Aravalli Craton

In order to determine whether changes in composition of the continental crust at the A/P boundary was a worldwide phenomena, we test the proposed model of compositional change at the A/P boundary on the chemical data of clastic sedimentary rocks of the Aravalli craton, which is located in a less studied part of Indian shield. The geochemical data of Alwar basin clastic sedimentary rocks generated during present study, in combination with available geochemical data of about 2800 Ma old Achaeans quartzite (Naharmagra Quartzite: Raza et al., 2010a) and about 1600 Ma old Vindhyan sandstones (Raza et al., 2010b) of the Aravalli craton are used to determine the geochemical changes in composition of sedimentary rocks across Archaean – Proterozoic transition. The average REE patterns of these three are shown in (Figure 8.2). The geochemical data and detailed discussion presented in the present work have important implication on change of upper crustal composition from Mesoarchaean to Late Palaeoproterozoic period in north western part of the Indian shield. As evidenced from the geochemistry of Archean Naharmagra quartzites from this terrain (Raza et al., 2010a), the Archean crust was dominated by TTG and possibly with a low K-Archean granite component (50 % TTG, 40 % granite, and 10 % basalt). The mixing modeling of REE data of Alwar basin clastics rocks, presented in chapter six of the present thesis indicates that the Palaeoproterozoic upper crust was consisting of, 50% high-K granites (~2.5 Ga) 30 % TTG and 20 % mafic rocks.

The geochemical data of Alwar clastics suggest a significant contribution from high K-granitic rock which was intruded into an Archaean crust at about 2.5 Ga, as well as a contribution from TTG. The Late palaeoproterozoic Lower Vindhyan sandstone geochemistry points (Raza et al., 2010b) towards a dominantly high-K granitic (~2.5 Ga) upper crust. The data indicate upper crust evolved from TTG dominated composition at Archean (~2.9Ga) to granite dominated composition during the Palaeoproterozoic. This phenomenon can be explained simply by erosion.

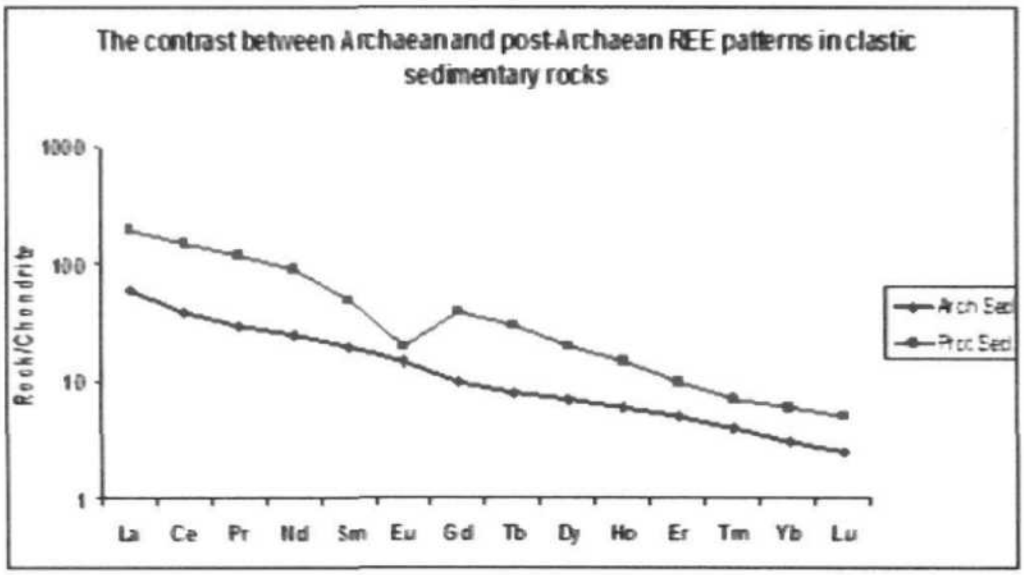

Figure 8.1 The contrast between Archaean and Post-Archaean REE patterns in clastic sedimentary rocks (Taylor, 1987).

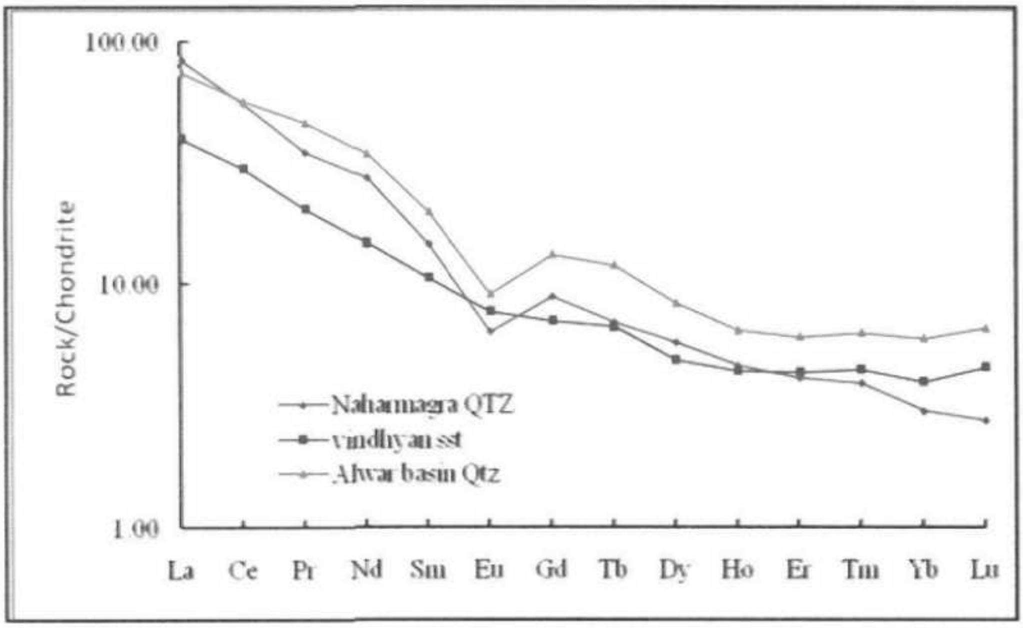

Figure 8.2 Chondrite–normalized REE patterns of avg. quartzites/sandstones of Aravalli craton ranging in age from Meso-Archaean to late Palaeoproterozoic. Source of data; Naharmagra Quartzite- Raza et al. (2010a); Vindhyan sandstone- (2010b); Alwar Basin Quartzite- Present Study.

It is suggested that most of the upper crust comprising TTG was extensively eroded during the Palaeoproterozoic and entered in the sedimentary record of that period. The erosion of upper TTG cover exposed the deep level granite batholiths which significantly contributed detritus to Alwar basin. By the end of Paleoproterozoic the crust of same composition existed and provided debris to the Lower Vindhyan basin resulting deposition of Lower Vindhyan group of south eastern Rajasthan.

Therefore the compositional changes of upper crust at APB in Aravalli craton is characterized by evolution from TTG dominated crust of Mesoarchean to a granitic crust during the Paleoproterozoic. In summary following parameters signifies the change and illustrated in (Figure 8.3).

1- K_2O/Na_2O ratio increased dramatically from Archaean to Proterozoic. K_2O/Na_2O ratio of ~1 at 2800 Ma during Archaean increased to around ~5 at 1800 Ma and ~9 at 1600 Ma during the Proterozoic.

2- A decrease in the $(Gd/Yb)_n$ ratio from 2. 97 in Archaean to 2. 22 and then 1.77 in Proterozoic.

3- The $(La/Yb)_n$ ratio mimics the $(Gd/Yb)_n$ ratio, and show similar change in upper crust. The average $(La/Yb)_n$ of Archaean Naharmagra quartzite is 28 which evolved to a value of 12.46 for Alwar basin quartzites , and changed eventually to a value of 9.99 in Vindhyan sediments. The temporal evolution of REE pattern is exactly opposite to that reported by Taylor and Mclennan, (1985) i.e. flat REE pattern with no europium anomaly for Archaean and fractionated REE patterns with significant negative europium anomaly for Proterozoic sedimentary rocks.

4- Sm/Nd ratio increases from 0.53 in Archaean to 0.58 and than 0.78 in Proterozoic.

5- Th/Sc ratio increases from 2.35 in Archaean 4.11 and then 1.22 in Proterozoic. Generally, LILEs along with Th are enriched in Proterozoic sediments compared to those of Archaean sediments. This signifies the importance of intra-crustal granite during Proterozoic. The metasomatic addition of LILEs is governed by "subduction effect" where excess LILEs are introduced in metasomatised mantle wedge.

6- La/Th ratio also changed temporally (Figure 8.3), the Archaean Naharmagra quartzites are characterized by higher values (avg.3.11) that declines with increase in Th content in Proterozoic (Avg. Alwar basin quartzite 1.90 , Avg. Vindhyan Sandstone, 1.94). The data indicate systematic unrooling of granite batholiths during the Proterozoic by upliftment and erosion of upper TTG cover.

7- Cr/Sc ratio varies from 57.87 in the Archaean to 18.11 and 16.68 in the Proterozoic.

8- The Rb/Sr ratio does not show any significant variation. It increased from 1.29 during Archaean to 2.8 at 1800 Ma but again decreased at 1600 Ma.

9- Eu/Eu* value does not show any significant change as it varies from 0.64 in Artchaean to 0.66 and 0.65 in Proterozoic rocks. However the total REE content does not show any significant change from Archaean Naharmagra quartzite (77.85 ppm) to Proterozoic Alwar basin quartzites (84.59 ppm) and late early Proterozoic Vindhyan sandstones (43.52). The trends shown by values of Eu/Eu* anomalies and total REE abundances are not similar to those reported by

Taylor and McLennan, (1985) and indicate early evolution of continental crust including formation of granite in the northwestern part of Indian shield.

10- Similarly Cr/Th varies from 24.60 in the Archaean to 4.41 and 14.85 in the Proterozoic.

The geochemical data of Archaean and Proterozoic sedimentary rocks of Aravalli craton, as presented and discussed above are in accordance with the modern concepts regarding evolution of early continental crust. Recently Lopez et al. (2006), have suggested that the petrogenetic evolution of Archaean crust initiated by large scale production of progressive TTG magma. The melts for this magma were produced by melting of down going plate at relatively shallower depth ($P < 10$ kbar) without extraction with the mantle during ascent. Further cooling of the earth favoured an increase in the angle of dip of subducting slab. This phenomenon favored partial melting of basaltic rocks at higher depth ($P < 10$ kbar) and interaction of TTG magma with the overlying mantle wedge. At Archean Proterozoic boundary, the interaction between hydrous sanukitoid magma and tonalitic crust resulted in production of large amount of K-granite magma. The TTG with positive Eu anomalies in their REE patterns and sanukitoid signatures in Berach Granite of Aravalli craton have been recently identified by Mondal and Raza, A. (2013). From the foregoing discussion it may be visualized that at least northern part of Indian shield evolved from a TTG dominated crust during Archean to granitic dominated crust during late Palaeoproterozoic / Mesoproterozoic.

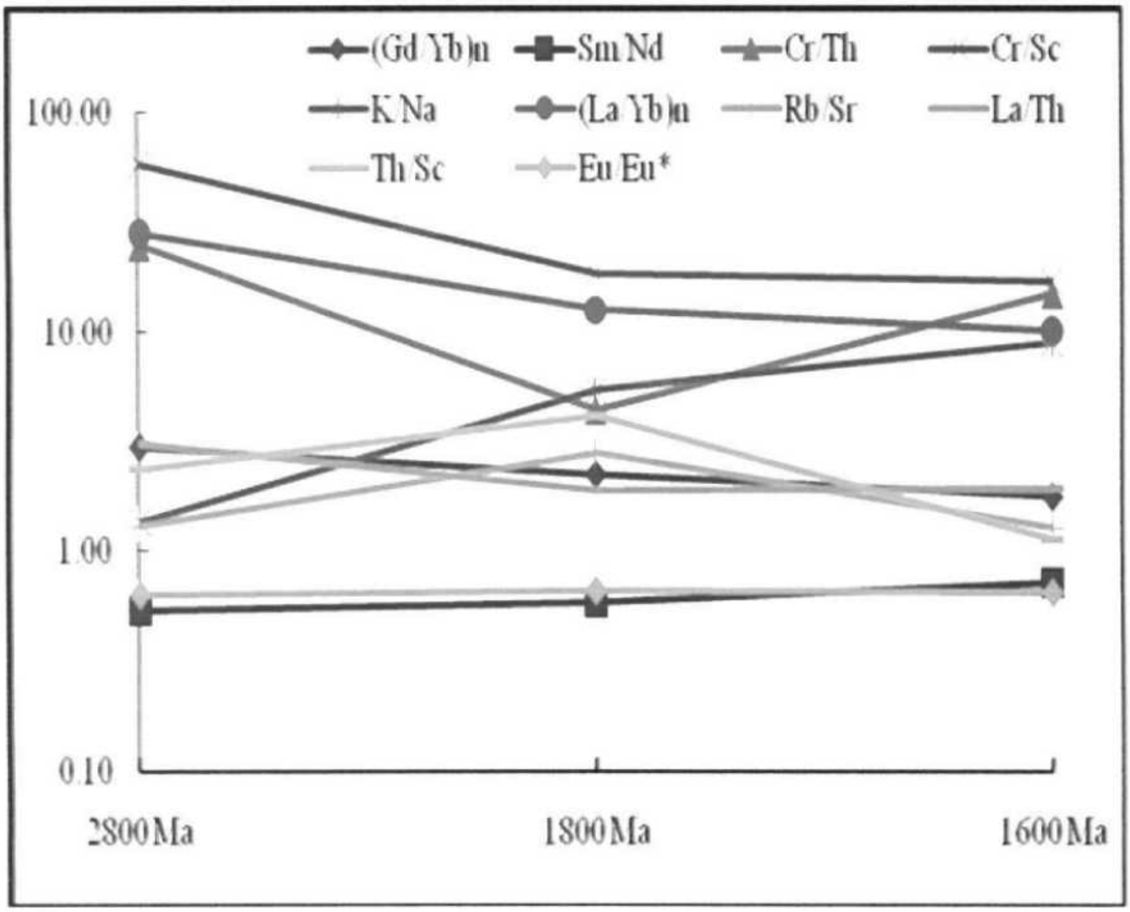

Figure 8.3: Geochemical parameters showing compositional evolution of upper continental crust of Aravalli craton of North Indian Plate during the period from 2.8 Ga and 1.6 Ga. Note systematic decreasing trends shown by $(La/Yb)_N$, $(Gd/Yb)_N$, La/Th and Cr/Sc ratios and increasing trends shown by K_2O/Na_2O and Sm/Nd ratios from Mesoarchaean to Palaeoproterozoic to late Palaeoproterozoic sedimentary rocks. Cr/Th ratio show a abrupt decrease and Rb/Sr and Th/sc ratios show abrupt increase from Archaean to Palaeoproterozoic. The temporal change shown by different ratios together suggest evolution of upper continental crust of Aravalli craton from TTG dominated composition during Mesoarchaean to granitic dominated crust during Palaeoproterozoic / late Palaeoproterozoic.