
CHAPTER 5

**SURFACE PROCESSES, WEATHERING
HISTORY AND PALAEOCLIMATE**

5.1 Introduction

It is widely accepted that several intracrustal processes such as weathering, metamorphism, sorting (grain size effect) and recycling can significantly influence the chemical composition of clastic sedimentary rocks. Although lithological characteristics of source terrain essentially controls the chemical records of the clastic sedimentary rocks, some surface processes such as chemical weathering and sorting process during transportation may greatly modify the provenance memory (McLennan, 1989; Nesbitt and Young, 1996; Nesbitt et al., 1996). In addition, sediment recycling is a common process which produces a buffering effect where a small amount of new input can go unnoticed. Therefore, to identify the provenance of sedimentary sequences it is important to consider first the effect of these processes on the overall composition of sediments.

5.2 Hydraulic Sorting, Recycling and Quartz Dilution

It is a well known fact that hydraulic sorting and quartz dilution can significantly influence the chemical composition of terrigenous sediments. In this regard the sorting may be of particular importance in modifying the mineral abundances and consequently the concentration of specific elements. During hydraulic sorting, the clay minerals which are enriched in most of the trace elements are preferentially concentrated in finer fraction and thus produce higher abundances of many trace elements in pelitic rocks relative to associated sandstones. If mature weathered material (quartz + clays) and immature rock debris (separate minerals + lithic fragments) are mixed, the result is arenites (enriched in immature rock debris) and pelites (enriched in mature weathered materials). This preferential sorting can lead to REE fractionation.

The chemical composition of sedimentary rocks can be effectively used to evaluate the influence of sedimentary sorting. In studies of coarser elastic sedimentary rocks the assessment of sorting and concentration of accessory minerals, such as zircon, monazite, sphene and apatite, is very important because it may considerably affect the distribution of some trace elements (Cullers, 1994; 2000). Some authors (Cullers et al., 1987; 1988; Cullers, 1994) have shown that fine grained sediments are more likely to have mineralogy and chemical composition similar to their source than do coarser sand fraction. In the following paragraph, chemical compositions of quartzites and metapelites of the Alwar basin are discussed to evaluate effects of sorting on the chemical composition of these rocks.

The increasing trend of textural maturity in sandstones leads an increase in amount of quartz at the expense of primary clay size material. As a result, the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios are increased and concentrations of other elements are decreased due to quartz dilution which leads to decrease in all other elements and an increase in SiO_2 . Therefore, the textural maturity of sandstone can be assessed by using $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios (McLennan et al., 1993). The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio is sensitive to sediment recycling and weathering processes and can be used as signal of sediment maturity, increasing as quartz survives preferentially to feldspar, mafic minerals and lithic grains (Roser and Korsch, 1986; Roser et al., 1996). Average values of $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio in unaltered igneous rock range from ~ 3 in basic rocks to ~5 in acidic rocks. The values ranging from >5 to 6 in sediments are an indication of progressive maturity. $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios in our samples are generally very high and show a large of variation (6 - 319). Very high values as shown by some samples (e.g. S25, S26 and S27) are due to extremely low concentration of Al_2O_3 (<1 %). The overall high values

of $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios displayed by Alwar basin quartzites indicate high maturity. Strong negative correlation of SiO_2 with Al_2O_3 ($r = -0.94$), Sc ($r = -0.57$), Ga ($r = -0.90$), Rb ($r = -0.67$), Zr ($r = -0.79$), Th ($r = -0.63$) and LREE such as La ($r = -0.62$) and Ce ($r = -0.60$) indicates that quartz dilution should have considerable influence over the chemical composition of these rocks. Hence, the fact that quartzites are depleted in some major and trace elements against AUCC (Figure 4.5) is largely due to quartz dilution. Despite differing REE contents, most of the quartzites and metapelites of Alwar basin have similar shape of REE patterns (Figure 4.7). It has been observed that during physical fluvial sorting, REE and other elements such as Fe, Mg, Mn, Ni Cr, tend to be more concentrated in finer than in coarser particles (Singh, and Rajamani, 2001).

Hydraulic sorting may also play a major role in favouring accumulation of plagioclase in sand fraction which results in a decrease of Eu anomaly (McLennan et al., 1993). This preferably occurs in sands which are derived from active tectonic settings where Eu anomalies in sands differ by as much as 0.1 from those in associated muds (McLennan et al., 1990). In the absence of abundant plagioclase, there is no systematic Eu enrichment in sands over associated muds (Nathan, 1976; Bhatia and Crook 1986). In Alwar basin the average values of Eu/Eu^* in different units of quartzites show a range of variation from 0.51 to 0.68 and averages at 0.68. On the other hand the average values of Eu/Eu^* in different units of metapelites show a range of variation from 0.57 to 1.02 with an average of 1.08. Thus the Eu/Eu^* ratios in metapelites of Alwar basin are higher than those of associated quartzite units and thus indicate the absence of plagioclase concentration due to sand sorting.

The HFSE, REE, Sc and Th concentrations in sedimentary rocks are useful tools for determining occurrence of mineral sorting during transport and deposition. In particular, ratios of incompatible elements having similar hydrodynamic behavior are more useful because these ratios are not altered during the processes of sedimentation and deposition. The invariance rule does not apply if the immobile elements have different hydrodynamic behavior. For example, Zr and Sc which may fractionate during sedimentary processes due to concentration of zircon. The poor correlation of Zr/Sc with Sc ($r = 0.15$) does not indicate significant zircon enrichment in Alwar basin quartzites.

A number of heavy minerals (particularly zircon, allanite and monazite) are dominated by trace elements, and thus their accumulation in high concentration may significantly influence trace element concentrations in sedimentary rocks (McLennan et al., 1993). Potential sedimentary recycling, resulting in the addition of heavy minerals such as zircon, can be inferred from prominently high Zr/Sc ratio (McLennan et al., 1990; Floyd et al., 1991). The Th/Sc ratio of sedimentary rocks is particularly sensitive to overall bulk composition of the provenance. The Th/Sc ratio of sedimentary rocks characterizes the average composition of source terrain, whereas, an increase in Zr/Sc ratio alone indicates significant reworking consistent with zircon enrichment. Th/Sc ratios of sedimentary rocks greater than 1 reflect inputs from fairly evolved crustal igneous rocks (Taylor and McLennan, 1985). Th/Sc ratios less than 0.8 are an indication of sources other than typical continental crust, probably mafic sources or input from mature or recycled sources if coupled with higher Zr/Sc ratio (>10). A positive linear correlation between these ratios expresses the igneous differentiation trend. The Zr/Sc ratio for Alwar quartzite is higher (22.75 - 281.37; avg. 109.87) than the associated metapelites (7.29 - 58.49; avg. 25.55). However both

of these rock types show linear correlation between these ratios (quartzite: $r = 0.57$; metapelites: $r = 0.84$).

Sedimentary sorting and recycling can be monitored by Th/Sc vs Zr/Sc diagram (McLennan *et al.*, 1993) that is a useful measure to assess the contribution of pre-existing sedimentary sources. First-order sediments show a simple positive correlation between these ratios, whereas recycled sediments show a substantial increase in Zr/Sc with far less increase in Th/Sc. An addition of zircon by recycling and sorting to the sediments would result in an increase in Zr/Sc ratio as exemplified by an arrow in (Figure 5.1). Value of Zr/Sc less than 10 reflect the differentiation related compositional variations in igneous rocks. An addition of zircon by the process of sorting and recycling to sedimentary deposits would result in an increase in Zr/Sc ratio exemplified by trend shown in Figure 5.1. The trend of increased Zr/Sc and almost constant Th/Sc can also be exhibited by first-cycle sediments if they are derived from largely plutonic sources, as described by Roser and Korsch (1999). In this diagram most of our samples follow a linear trend that is consistent with provenance- dependent compositional variation (McLennan *et al.*, 1993). Plotting of samples along a linear trend, representing provenance- dependent compositional variation, may be due to enrichment of zircon from source terrain.

As discussed in the previous chapter zircon preferentially incorporates HREE relative to LREE and its accumulation leads to HREE enrichment and decrease in $(La/Yb)_n$ ratio, as a result negative correlation between Zr and $(La/Yb)_n$ ratio is expected. But no such relationship exists in quartzite ($r = 0.47$) and metapelites ($r = 0.16$). Samples of this study thus indicate that the enrichment can be considered to represent transport of REE enrichment from the provenance region (e.g. McLennan *et al.*, 1993).

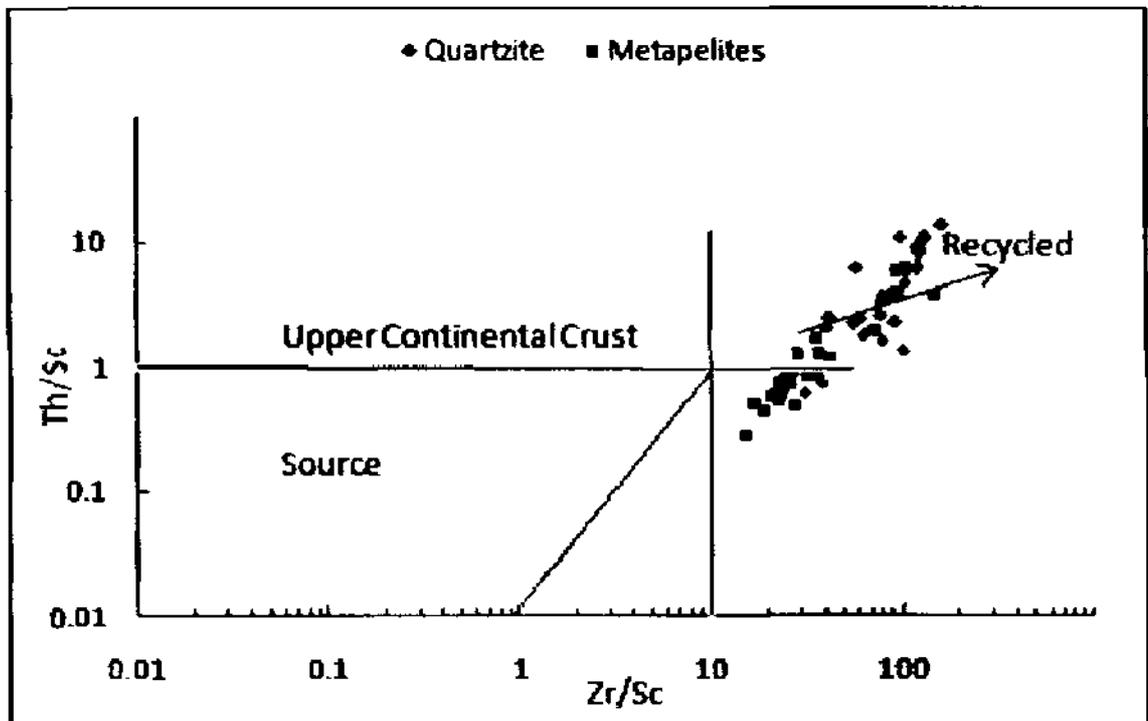


Figure 5.1 Th/Sc vs. Zr/Sc plot for quartzites and metapelites of Delhi Supergroup of Alwar basin (after McLennan et al., 1993).

5.3 Source Area Weathering

The degree of weathering is controlled by climate and rates of tectonic uplift (Wronkiewicz and Condie, 1987). Increased chemical weathering intensity may reflect the decrease in tectonic activity and /or the change of climate towards warm and humid conditions which are more favourable for chemical weathering in the source region (Jacobson et al., 2003). Therefore weathering indices of sedimentary rocks may provide useful clues to investigate climatic conditions and tectonic activity in the source terrain during the sedimentation.

Chemical weathering tends to modify the major and trace element composition of rocks and sediments. Labile cations including Na, K, Ca and Rb are leached in preference to insoluble hydrolysates such as Ti and Al (Roy et al., 2008). Thus the Ti/Na and Al/Na ratios are gradually increased with increasing chemical weathering. Similarly K/Na ratio reflects the abundance of K- Feldspar compared to that of Na-Plagioclase. Because K- Feldspar is relatively less resistant to weathering compared to Ca-Na feldspars, higher K/Na ratio mirrors higher chemical weathering vice-versa (Roy et al., 2008). K_2O/Na_2O ratio of Alwar basin quartzite ranges from 0.005 to 95.00 with an average of 17.48 and those of associated metapelites ranges from 0.91 to 54.00 and averages at 32.70, indicating higher degree of weathering in their source region.

The degree of weathering in source area can be effectively assessed by using alkaline earth element contents of terrigenous sediments (Nesbitt et al., 1980; Schau and Henderson, 1983; Reimer, 1985). Cations with large ionic radius as Ba and Rb remain fixed in weathering profile by preferential exchange and adsorption on clays,

whereas smaller cations such as Ca, Na, Sr are selectively leached from weathering profile (Nesbitt et al., 1980). These chemical trends may be transferred to the sedimentary records (e.g. Nesbitt and Young, 1982; Wronkiewicz and Condie, 1987; Fedo et al., 1996), thus provide a useful tool for monitoring source area weathering conditions. This relationship is demonstrated in an AUCC normalized spider plot (Figure 4.4). CaO, Sr and Na₂O are strongly depleted both in quartzites and associated metapelites of Alwar basin whereas Ba, Rb and K are enriched. Similar pattern has been identified in Torongo granodiorite weathering profile (Nesbitt, 1980), indicating high chemical weathering of source area. In most of our samples the CaO contents are below 0.25 %, so that no carbonate correction is necessary for the calculation of weathering indices. As stated in previous section, a positive linear correlation between Al₂O₃ and TiO₂ ($r = 0.84$) in metapelites also supports chemical weathering of source rock (Young and Nesbitt, 1998; Sreenivas and Srinivasan, 1994).

The chemical index, most commonly used to investigate and quantify the degree of source area weathering is Chemical Index of Alteration (CIA; Nesbitt and Young, 1982; 1984). This index gives a practical approach to the measurement of feldspar transformation to clay minerals, and the influence of weathering increases with increasing values of CIA. The index is a dimensionless number, defined in molecular proportions as: $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O) \times 100]$, where CaO* represent Ca in silicate minerals as opposed to phosphate and carbonates. This index provides a practical approach to the measurement of feldspar transformation to clay minerals, and the influence of weathering increases with increasing value of CIA. The CIA values of sedimentary rocks are widely used as an indicator of the intensity of weathering of sedimentary provinces (Nesbitt and Young, 1982). CIA values

between 50 and 60 indicate a low value of chemical weathering, between 60 and 80 moderate chemical weathering, with values >80 indicating extreme chemical weathering (Fedo et al., 1995). The CIA is also considered as powerful tool to estimate a quantitative assessment of palaeoweathering in the source region because a large amount of aluminous clay minerals generally forms by intensive chemical weathering under tropical conditions and give CIA values of 80- 100. Contrary to it, under glacial conditions where abrasion dominates over chemical weathering CIA values are 50 to 70 (Nesbitt and Young, 1982).

The CIA values of quartzite and metapelites of Alwar basin are shown in tables 4.1 and 4.2. All the samples of quartzite except samples S19, S26 and S27, show CIA values >40. These three samples have extremely low values (7-21) therefore, are not considered for palaeoweathering interpretations. Similarly all samples of metapelites except samples S30, have CIA values >50. Very low value of CIA (15) for this sample is due to abnormally high content of CaO (15.46 %). CIA value of this sample is also not included in calculation of mean CIA values. The CIA values of our samples of quartzite range from 40 to 89 (avg. 63) and those of metapelites from 51 to 76 (avg. 69), which suggests that the parent rocks of both these rocks were subjected to same weathering conditions. Collectively, these values are between unweathered clastic rocks (<50) and average standard shales (70-75; McLennan et al., 1993) suggesting that the source area of these sediments had only moderately weathered. K-metasomatism of the sedimentary rocks is considered to be a common process during geological history (Condie, 1989; Fedo et al., 1995), which would change K₂O concentrations of the sedimentary rocks to be higher than their original concentrations during deposition. This leads to the wrong estimation of the intensity of weathering.

A more useful way of evaluating the chemical weathering trend than simple comparison of numerical values of chemical index of alteration (CIA Index) is to employ a ternary plot with Al_2O_3 at the top apex $\text{CaO}^*+\text{Na}_2\text{O}$ at the bottom left and K_2O at the right apex of the bottom as shown in Figure 5.2. This triangle, that is also known as A-CN-K ternary plot (Nesbitt and Young, 1984), permits the identification of 'anomalous' samples and trends that deviate (because of metasomatic alteration) from the expected trends as established both by theoretical consideration and empirical observations on modern weathering profiles (Nesbitt and Young, 1984; Fedo et al., 1995). Molar proportions of Al_2O_3 (A), $\text{CaO}^*+\text{Na}_2\text{O}$ (CN) and K_2O (K), in the samples of Alwar basin are plotted in the ACNK space in (Figure 5.2) after Nesbitt and Young (1984). To estimate chemical weathering, metasomatism and source rock composition weathering trends may be predicted to be parallel to the A-CN join during the initial stage because Na and Ca are removed by chemical weathering of plagioclase as shown by solid arrows in (Figure 5.2).

The theoretical background of this diagram (Nesbitt and Young, 1982, 1984; Fedo et al., 1995) is that the weathering of bed rock produces Al-rich sediments, that results in the movement of plots of weathered samples sub-parallel to A-CN join from their unweathered source composition on the feldspar join. CIA values for average shales ranges from 70 to 75 which reflects composition of muscovite, illites and smectites. Intensely weathered rock yields mineral compositions trending towards kaolinite or gibbsite and a corresponding CIA that approaches to 100. CIA values of unweathered rock is about 50. An additional advantage of A-CN-K diagram is that it enables to estimate the source rock composition by back ward projection of the line passing through the weathered samples to a point on the feldspar line.

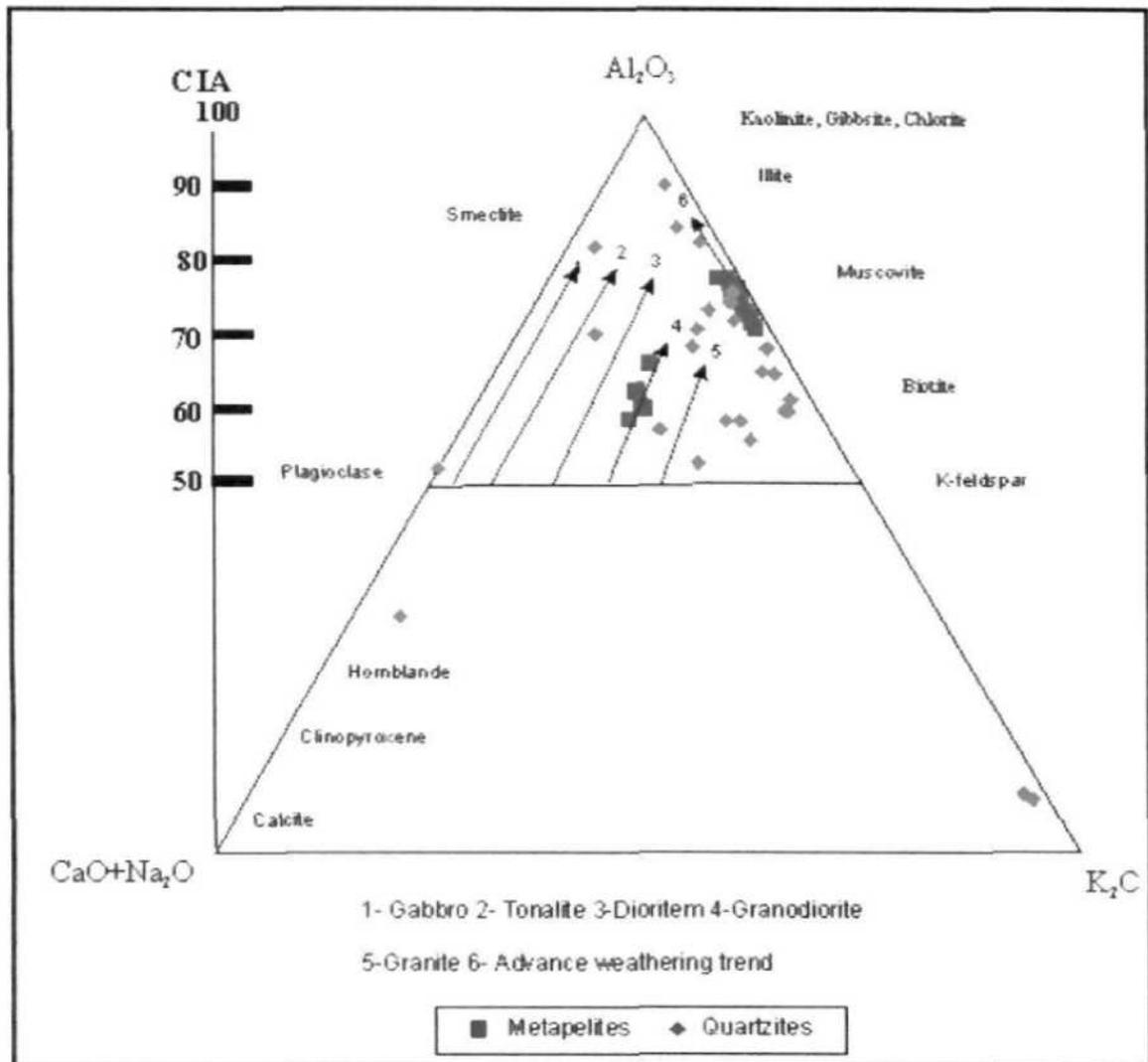


Figure 5.2 A-CN-K (in molecular proportion) ternary plot (Nesbitt and Young, 1984) for metasedimentary rocks of Delhi Supergroup, of the Alwar basin. CaO^* is the silicate fraction of rocks. Nos. 1 to 6 denote Compositional trend of initial weathering profile of various rock types, 1- Gabbro, 2- Tonalite, 3- Diorite, 4- Granodiorite, 5- Granite and 6- compositional trend for advance weathering profile, $CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$.

The intersection point provides an approximate ratio of plagioclase to K-feldspar in the source rocks. The best fit lines through our data points are parallel to (i) trend 4 that is parallel to A-CN line and (ii) trend 6 that is parallel to A-K join and represents high degree of chemical weathering. Plotting of our data along these trends indicates that the source of Alwar basin clastic sedimentary rocks had a granodioritic composition which had undergone moderate to high degree of chemical weathering. However many of our samples plot right side of “limit of weathering” line probably due to enrichment in K_2O . These indicate that the Alwar clastics have suffered post depositional potash metasomatism, which accounts for their low CIA values. Our samples followed the predicted weathering path for granodioritic composition until virtually all Na and Ca were removed (Trend 4, Figure 5.2). At some later time, the samples suffered K-metasomatism as a result of which their compositions shifted toward K_2O apex. It is possible to assess the pre-metasomatised CIA values of the sediments in A-CN-K space when K is introduced in aluminous clays to form illite (Fedo et al., 1995). The effect of K-metasomatism can be corrected for by projection of tie line between the K- apex through the data point to the ideal weathering trend lines shown as solid arrows (Fedo et al., 1995). Using this principle, premetasomatic CIA values obtained for Alwar quartzites ranges from ~ 60 to ~90 and those of metapelites from ~58 to ~78. This is in conformity with the observation of moderate to severe weathering of source rocks during their sedimentation.

Three of our samples i.e. S25, S15, and S9. are plotted to the left side of predicted weathering trend, that could be due to varied source or mobility during the metamorphism. The scatter in the data point may be related to (i) uplift of the source area leading to exposures of source rocks of different composition (ii) variability in

the degree of weathering of the source rocks, (iii) mixing of sediments from a weathered and unweathered rocks. There is a possibility that the samples, displaced towards CN apex in A-CN-K diagram, were probably derived from a source dominated by tonalite and trochilite components. La/Sc, Th/Sc, Th/Co, and Th/Cr ratios of samples S25 favour its derivation from mafic sources (Cullers, 1994, 2000; Table 6.1). These ratios of samples S9 and S15 are within the range of felsic sources (Table 6.1). However, their $(La/Yb)_n$ ratios are high (17.85 - 31.24). There is a possibility that some of the samples, displaced towards CN apex, were probably derived from a source dominated by tonalite and trochilite components.

The intense nature of chemical weathering can also be portrayed by Chemical Index of Weathering (CIW, Harnois, 1988) and Plagioclase Index of Alteration (PIA, Fedo et al., 1995). The CIW index eliminates affect of K-metasomatism and defined as: $CIW = Al_2O_3 / (Al_2O_3 + CaO * Na_2O) \times 100$ where the elements are represented in mole proportion. The calculated CIW values of our samples ranges from 40 - 97 with an average of 83 (except sample S19) in quartzites and 62 - 98 with an average of 90 (except sample S30) in metapelites, indicating high degree of weathering. But CIW is as much as a function of source rock composition as it is a function of weathering intensity, thus could not be used strictly where basement compositions vary (Fedo et al., 1995).

Plagioclase Index of Alteration (PIA, Fedo et al., 1995) is better index, as it portrays weathering of plagioclase feldspars, which are abundant in Archaean basement terrains. The PIA is defined by the equation: $PIA = [(Al_2O_3 - K_2O) / (Al_2O_3 + CaO * Na_2O - K_2O)] \times 100$, where all elements are in molecular proportions and CaO* represent CaO in silicate fractions. The maximum PIA value is 100 (kaolinite,

gibbsite) and unweathered plagioclase has PIA value of 50. PIA values of our samples of quartzites ranges from 40 to 96 with an average of 77, (except samples S19, S26, S27 and MR6) and those of metapelites from 51 to 97 with an average of 86 (except sample S30). The high PIA values of Alwar basin clastic rocks indicate strong chemical weathering as depicted by severe depletion of CaO, Na₂O and Sr in AUCC normalized spider plot (Figure 4.4) and strong Al₂O₃-TiO₂ correlation ($r = 0.84$) shown by metapelites. The average CIA, PIA and CIW values of Alwar Group are 67, 79, 87 respectively and those of Ajabgarh group are 64, 85, and 88 respectively. These values indicate almost same intensity of weathering throughout the sedimentation of Delhi Supergroup in Alwar basin.

Molar proportions of Al₂O₃ (minus Al associated with K), CaO* and Na₂O are plotted in the (A-K)- C- N diagram of Fedo et al, (1997), in order to understand and monitor the evolution of plagioclase weathering in the Alwar clastic sedimentary rocks (Figure 5.3). The vertical dimension on the (A-K)- C- N triangle corresponds to the plagioclase index of alteration (PIA; Fedo et al., 1997). The PIA values of around 50 for fresh rocks and values corresponding 100 indicate significant production of secondary aluminous clay minerals (Fedo et al., 1997). Distribution of plots in (A-K)- CN-K plot suggests that primary plagioclase of varying compositions were present in source terrain of Delhi Supergroup of Alwar basin. However the rocks containing albite were more dominant.

Th/U ratios of sedimentary rocks are expected to increase with increasing weathering due to oxidation and loss of uranium with a resultant increase in this ratio (Taylor and McLennan 1985). Although highly reduced sedimentary environments can have enriched uranium leading to low Th/U ratio, weathering tend to result in

oxidation of insoluble U_4^+ to soluble U_6^+ (McLennan and Taylor, 1991), with loss of solution and elevation of Th/U ratio. Th/U ratios above 4 are thought to be related to weathering history (McLennan et al., 1995). The Th/U ratios of sedimentary rocks of the Alwar basin range from 0.22 to 11.32 with mean value of 5.13 in quartzites and from 0.69 to 11.08 with mean value of 3.24 in pelites. These values are close to the UCC value of 3.8. In this sense these sedimentary rocks might have been derived from a source subjected to low to moderate weathering in their source terrain.

Ga/Rb ratio can also be used to assess the intensity of weathering in the source terrain of sedimentary rocks (Roy and Roser, 2013). Ga/Rb ratio of Alwar basin clastic rocks is variable. In quartzite it ranges from 0.03 to 1.13 with an average of 0.14. In associated metapelites it ranges from 0.06 to 0.17 and averages at 0.12. It has been suggested that Ga/Rb ratio <0.25 indicates weak to moderate weathering in the source of clastic rocks (Roy and Roser, 2013). Therefore the Ga/Rb ratios of our samples indicate that their source terrain suffered weak to moderate weathering at the time of deposition. However, due to mobile nature of Rb, the Ga/Rb ratios are not considered reliable.

The Rb/Sr ratios of sedimentary rocks also monitor the degree of the source-rock weathering (McLennan et al., 1993). The quartzites and metapelites of Alwar basin have average ratios of 2.95 and 2.83 respectively, significantly higher than that of the average upper continental crust (0.32) and average post-Archean Australian shale (0.80; McLennan et al., 1983). The Rb/Sr ratios of the Alwar basin sediments (quartzites and metapelites) therefore indicate significant weathering in their source area.

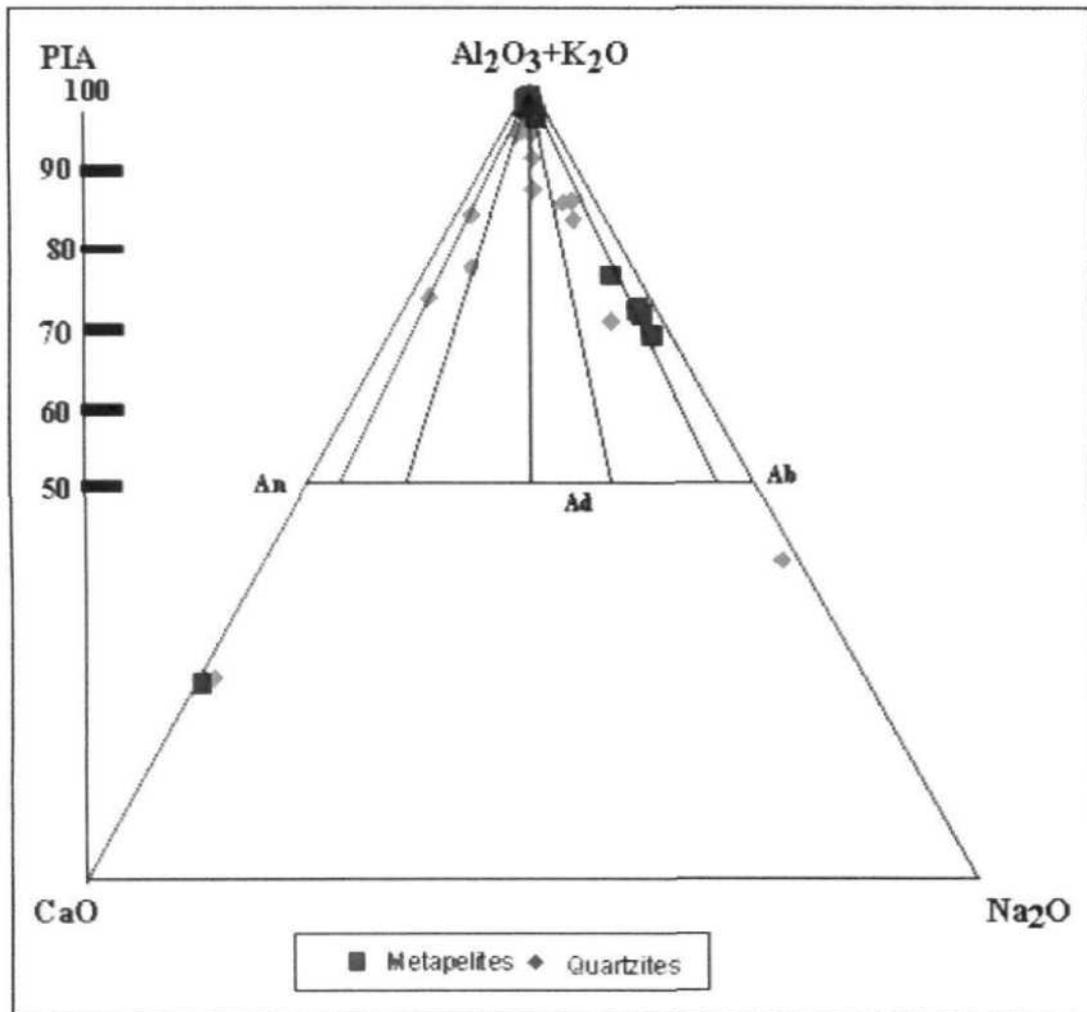


Figure 5.3 AK-C-N (in molecular proportion) ternary plot (Fedo et al., 1995) for KCB clastics. $PIA = [(Al_2O_3-K_2O)/(Al_2O_3+CaO+NaO-K_2O)] \times 100$. An (Anorthite), Ab (Albite), Og (Oligoclase), Ad (Andesine).

In Th/U - Th plot (Figure 5.4), our samples follow the weathering trend thus suggesting that weathering has affected the compositions. This result is consistent with interpretation drawn from CIA values.

Chemical weathering condition, as indicated by clastic rocks of the Alwar basin is in conformity with worldwide humid and warm climate during the Palaeoproterozoic period (Eriksson et al., 1998). The positive correlation between $\text{FeO}^{(\text{T})}$ and TiO_2 as shown by studied Alwar basin quartzites ($r = 0.73$) indicates that the iron was retained in palaeoweathering profiles. The conservative behavior of Fe suggests that Fe was chiefly in ferric oxidation state and will require oxygenated atmosphere. Evolution of atmospheric oxygen from <1 to ~15 % of the present-atmosphere level (PAL) between 2.2 and 1.9 Ga is indicated by the geochemical studies of iron retention in the Palaeoproterozoic paleosols (Holland et al., 1989; Holland and Beukes, 1990; Macfarlane et al., 1994; Rye and Holland, 1998).

However, lower degree of weathering as shown by some samples may be due to tectonic instability during the deposition. The type of weathering trend as shown by clastic sedimentary rocks of Alwar basin usually results from mixing sources of different compositions or weathering histories (McLennan et al., 1993). The distribution of plots of Alwar basin clastic rocks in A-CN-K diagram in combination with CIA, PIA, CIW and Th/U values suggest an over all moderately to highly weathered mixed source.

5.4 Palaeoclimate

The weathering indices of clastic sedimentary rocks are helpful in deciphering the tectonic setting and climatic conditions in the source terrain. Increase in the degree of chemical weathering may signify a decrease in the tectonic activity and or change in climate towards warm and humid conditions. (e.g. Jacobson et al., 2003).

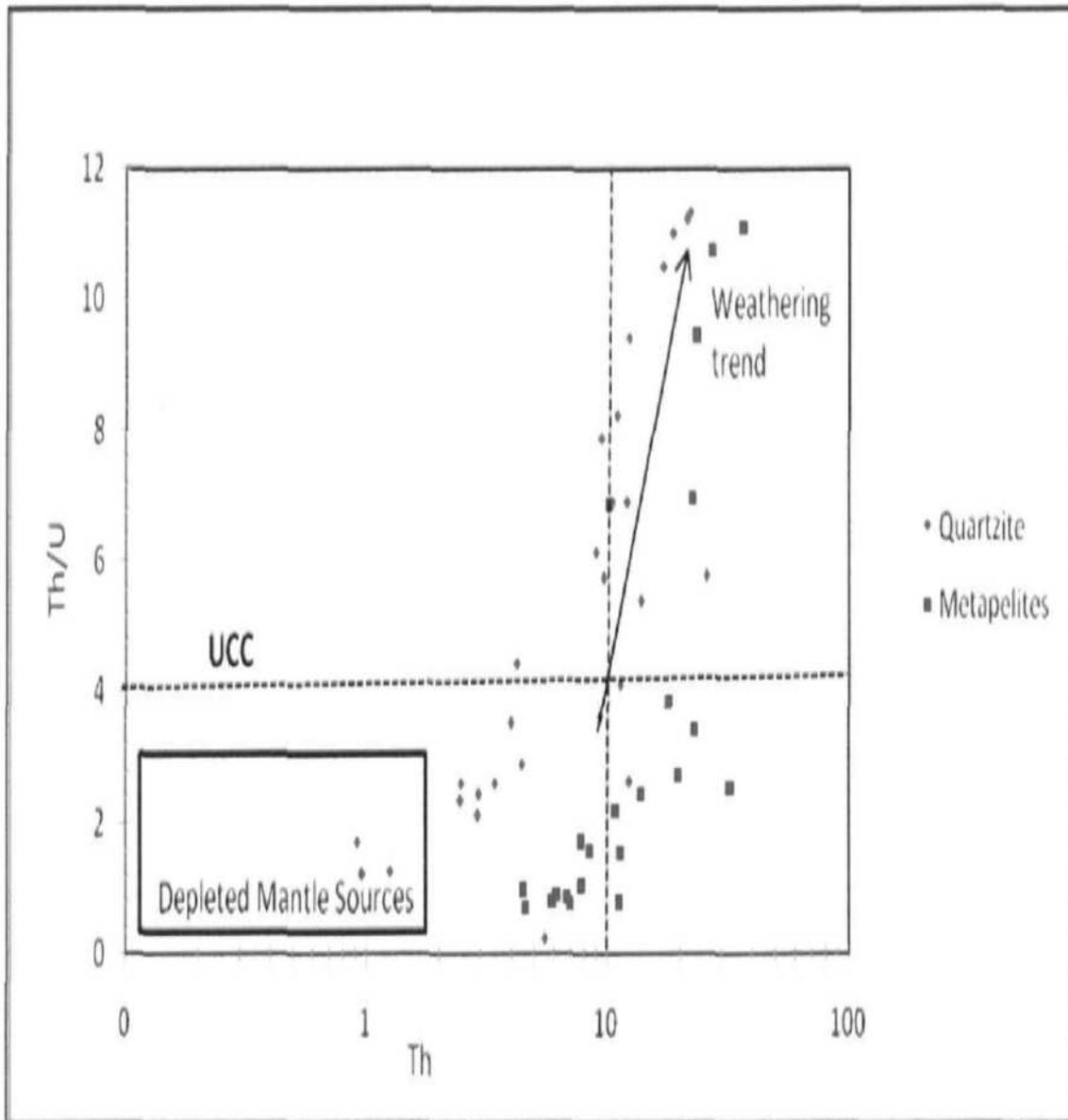


Figure. 5.4 Th/U- Th plot (Gu et al., 2002) of metasedimentary rocks of Delhi Supergroup from Alwar basin.

The values of weathering Indices (CIA, PIA and CIW) may be influenced by tectonism, as higher and more uniform values should be produced in stable tectonic conditions undergoing steady state weathering (Nesbitt et al., 1997). Contrary to it, uplift of the source terrain produces highly variable values in the derived sediments as all zones of weathering profile in the source terrain are eroded during the non-steady state weathering. Large variation of weathering indices values shown by Alwar basin quartzites (CIA = 60-90, avg. 61; CIW = 40-97, avg. 83; PIA = 40-96, avg. 76; Th/U = 0.22 to 11.32, avg. 5.13) and associated metapelites (CIA = 51-76, avg. 69; CIW = 62-9, avg. 90; PIA = 51-97, avg. 86, Th/U = 0.69 to 11.08, avg. 3.24) indicates that they were derived from sources experiencing steady state weathering and active tectonism. These values indicate moderate to intense weathering. Metapelites have higher average values of CIA (70), CIW (86,) and PIA (92) than associated quartzites 61, 79, 84 respectively, indicating that secondary aluminous clay minerals concentrated in the pelitic rocks.

The distribution and relative abundances of some trace elements in elastic sedimentary rocks may reveal the climatic conditions and environment prevailed at the time of their deposition (Worash, 2002). It has been observed that Fe, Mn, Cr, V, Ni and Cr are relatively enriched during moist conditions. On the other hand some elements such as Ca, Mg, K, Na, Sr and Ba are concentrated under arid conditions due to strengthening of water alkalinity due to evaporation. Due to contrast behavior of these two groups of elements, their ratio is proposed to reflect a parameter of climate change. For example the ratio of \sum (Fe, Mn, Cr, V, Ni and Cr)/ \sum (Ca, Mg, K, Na, Sr and Ba), referred to as C- value (Zhao et al., 2007; Cao et. al., 2012) have been used to study the ancient palaeoclimate. The C-values of Alwar basin quartzite show a

range of variation from 0.02 to 2.76 and averaging at 0.51. In associated metapelites the C-values show a range of variation from 0.08 to 1.03 with an average of 0.30 reflecting a generally semiarid to semi moist palaeoclimate.

5.5 Palaeo-redox conditions

Palaeo-redox conditions during sedimentation of siliciclastic rocks can be deciphered from their chemical composition. U/Th ratio are widely used to evaluate the redox conditions of the sediments (Wignall and Twitchet 1996; Kimura and Watanabe, 2001). U/Th ratio of quartzites and metapelites of the Alwar basin vary from 0.09 to 0.84, avg. 0.29 (except 4.63 in sample S14) and from 0.09- 1.45, avg. 0.67 respectively. Relatively high U/Th ratios displayed by our samples of metapelites reflect less oxygenating atmosphere during their deposition. (Taylor and McLennan, 1985). V is considered to be more enriched under anoxic conditions (Calvert and Pederson, 1993). $V/(V+Ni) > 0.6$ and $V/Cr > 2$ indicate anoxic conditions (Wignall, 1994; Jones and Manning, 1994; Rimmer, 2004). $V/(V+Ni)$ ratios of our quartzite samples vary from 0.19 to 0.43, avg. 0.47, indicating oxic conditions for quartzite deposition. Metapelites show $V/(V+Ni)$ ratios ranging from 0.77 to 0.95, avg. 0.93, indicating anoxic conditions for deposition of pelites. V/Cr values of Alwar quartzites and metapelites are 0.16- 1.11, avg. 0.56 (except S12 and MR8 having values > 2) and 0.67- 5.23, avg. 3.07 Indicating oxic conditions for quartzite and anoxic conditions for metapelitic rocks. These values indicate fluctuating oxic and anoxic conditions.

Palaeoredox conditions during sedimentation of siliciclastic rocks can also be evaluated by using their Ni/Co ratios. Jones and Manning (1994) have suggested that Ni/Co values of siliciclastic rocks less than 5 indicate oxic environment and more

than 5 indicate oxic conditions. Ni/Co ratios of Delhi quartzites of the Alwar basin range from 0.34 to 3.71, avg. 0.92 indicating oxic conditions. The Ni/Co ratio of associated pelitic rocks shows a range of variation from 0.91 to 13.26 and averages at 5.53 indicating anoxic conditions during deposition. Although the $V/(V+Ni)$, V/Cr and Ni/Co ratios overwhelmingly suggest that the quartzite of the Alwar basin deposited under oxic conditions the associated pelites were deposited under unoxic conditions. It has been observed that lower redox conditions occur in lagoonal environment (Nath et al., 2000). However, the highly variable values of these geochemical parameter indicate that the element compositions have complex controlling factors and should be used with caution for interpretation of redox conditions (Lin et al., 2008).

In view of the above discussion, it is proposed that the quartzites of Delhi Supergroup of Alwar basin probably occurred in an oxygenated transgressive beach environment. Contrary to it, the metapelites were deposited under anoxic conditions probably in a costal complex environment including lagoonal basins.