Geochemistry of Sandstones from the Upper Cretaceous Sillakkudi Formation, Cauvery Basin, Southern India: Implication for Provenance

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Abstract: Major, trace and rare earth elements (REE) composition of sandstones from the Upper Cretaceous Sillakkudi Formation, Ariyalur Group, Cauvery Basin were studied to decipher their weathering and provenance history. Texturally, these sandstones are immature, poorly sorted and grain supported. Abundance of feldspars especially, plagioclase indicates rapid deposition of sediments from a nearby source rocks. Using the geochemical classification diagram the Sillakkudi sandstones are classified as fe-sand, quartz arenite, litharenite, sub-litharenite, sub-arkose, arkose, and wacke types, which is also supported by the petrography study. The transition trace elements like Co, Ni, and V are higher in the Sillakkudi sandstones than upper continental crust (UCC) values. However, the Sillakkudi sandstones are lower in Cr (mean ~21) content than average UCC value (~ 35). The poor correlation between Cr and Ni (r = 0.08, number of samples n = 20) imply that these sandstones were derived from felsic source rocks. Similarly, the Eu/Eu* (0.35-1.73), La/Sc (1.93-9.36), Th/Sc (0.41-6.57), Th/Co (0.14-5.01), Th/Cr (0.23-2.94), and Cr/Th (0.34-4.28) ratios support a felsic source for the Sillakkudi sandstones. The significant enrichment of Zr, Hf, and Th in fe-sand, sub-arkose and litharenite could be related to the presence of heavy minerals, especially zircon. However, the zircon geochemistry did not affect the REE distribution and its patterns in the Sillakkudi sandstones. The Chondrite normalized REE patterns of Sillakkudi sandstones are characterized by relatively flat HREE (Gd/Yb$_{CN}$ = ~ 0.73-2.41; subscript $_{CN}$ refers to chondrite normalized value), enriched LREE (La/Sm$_{CN}$ = ~ 3.39-5.82) and negative Eu anomaly (mean value Eu/Eu* = 0.80). The Gd/Yb$_{CN}$ ratios (~0.73-2.50) are less than 2.5, which suggest that these Sillakkudi sandstones were derived from the less HREE depleted source rocks. The comparison of REE patterns and its Eu anomalies to the source rocks reveals that the Sillakkudi sandstones received a major contribution of sediments from Dharwar craton.

Keywords: Geochemistry, Zircon, sandstones, Upper Cretaceous, Sillakkudi, Cauvery Basin.

INTRODUCTION

The composition of detrital sediments is primarily controlled by the source rock composition followed by weathering and diagenetic processes to a minor extent (e.g., Armstrong-Altrin, 2009). Compositional characteristics of source rocks are generally well recorded in sedimentary products and provide valuable information about nature of source rocks and the tectonic setting of their emplacement (van de Kamp and Leake, 1995; Joo et al. 2005; Armstrong-Altrin et al. 2004; Armstrong-Altrin and Verma, 2005; Liu et al. 2007; Sinha et al. 2007; Nagarajan et al. 2007a,b; Wanas and Abdel-Maguid, 2006; Maravelis and Zelilidis, 2009). Geochemical data on sandstones of un-metamorphosed sedimentary sequences deposited in intracratonic or epicratonic basins also provide vital clues on paleoweathering conditions and variations in provenance composition and tectonics (Condie et al. 2001; Khudoley et al. 2001; Armstrong-Altrin et al. 2004; Chakrabarti et al. 2007, 2009; Carranza-Edwards et al. 2009; Araújo et al. 2010). Similarly, many studies have used the major, trace and rare earth elements (REE) geochemistry as a tool to characterize source-rock weathering, and climatic variability from the terrigenous sediments (Nesbitt and Young 1982; Cox et al. 1995; Nagarajan et al. 2007a, b; Dey et al. 2009; Ranjan and Banerjee, 2009). Thus distribution of these elements in sandstones provides clues to the geological

processes, provenance, and tectonic settings of their respective sources (McLennan et al. 1993; Cullers et al. 1988; Umazano et al. 2009; Fanti, 2009). However, the rare earth elements contribute more to decipher the provenance than major and trace elements, since their concentration is not affected during erosion, sedimentation and diagenesis, and thus represents a homogenized average source composition (e.g. Sinha et al. 2007).

The purpose of the present study is to investigate the source rock characteristics of the Sillakkudi sandstones exposed in the Cauvery basin, southern India, using major, trace, and rare earth elements geochemistry. To identify the source rocks, the geochemical data of these sandstones are compared with granites, charnockites, and gneisses from areas located relatively close to the study area (Dharwar craton and Kerala Khondalite belt). Furthermore, the compositional changes made by the heavy minerals will be also addressed in this paper.

GEOLOGICAL SETTING

The Cretaceous succession of Cauvery basin consists of a shallow marine sequence with a very rich faunal succession of Albian - Maastrichtian age. The Cauvery basin is considered to be a rift basin (Rangaraju et al. 1993), which developed by extension during the Mesozoic break up of the Gondwana land (Prabhakar and Zutshi, 1993). Blankford (1862) carried out detailed and systematic study on this succession and divided it into three major groups as Uttatur, Trichinopoly and Ariyalur on the basis of lithology. The Ariyalur group is more widely exposed than the other two groups. Sastry et al. (1972) divided the Ariyalur group into four formations, namely Sillakkudi, Kallankurichchi, Ottakkovil and Kallamedu in upward succession. The Ariyalur Group unconformably rests over the Trichinopoly Group (Table 1). The sediments of this basin are well exposed on the coastal plain of Tamil Nadu, along the Ariyalur, Virdhachalam and Pondicherry districts. Of these, the Ariyalur area provides the most complete representation of the Mesozoic succession and afforded many works on stratigraphy, palaeontology, paleoclimate and tectonic evolution of the succession (Banerji, 1979; Ramanathan, 1979; Sundaram and Rao, 1986; Ramasamy and Banerji, 1991; Ramasamy et al. 1995; Govindan et al. 1996; Madhavaraju and Ramasamy, 1999a, b; 2001; Madhavaraju et al. 2002; Ayyasami, 2006). All the formations constituting the Ariyalur Group, except Kallamedu Formation, were deposited in the marginal marine environments (Sundaram and Rao, 1986; Madhavaraju and Ramasamy, 1999b; Madhavaraju and Lee, 2009).

Table 1. Lithostratigraphy of Ariyalur Group (modified after Sastry et al. 1972)

Group	Formation	Lithology	Age
A R I Y A L U R	Niniyur		Danian
	Kallamedu	Unfossiliferous fine to coarse grained sandstones interbedded with siltstone, sandy clay, ferruginous clay and marl	Maastrichtian
	Ottakovil	Fossiliferous calcareous sandstone interbedded with sandy clay	
	Kallankurichchi	Fossiliferous calcareous conglomeratic sandstone interbedded with sandy clay, sandy fossiliferous limesone, fossiliferous limestone and marl	
	Sillakkudi	Unfossiliferous calcareous sandstone, Fossiliferous calcareous gritty sandstone, Fossiliferous calcareous andstones interbedded with sandy clay and thin band of sandy limestone	Campanian
Trichinopoly			Late Turonian to Santonian

The Sillakkudi Formation at the base of the Ariyalur Group has been selected for this study (Fig.1). It overlies the Trichinopoly Group unconformably (Ayyasamy, 2006). This formation comprises of unfossiliferous calcareous sandstone, fossilifereous calcareous gritty sandstone, fossiliferous calcareous sandstone and interbedded arenaceous limestone with sandy clay. The basal unit of the Sillakkudi Formation consists of unfossiliferous calcareous sandstone, which is thin in the northern part of the study area, whereas it is well developed in the central and southern parts. A thick band of oolitic ironstone, sandwiched between the fossiliferous calcareous sandstone and arenaceous limestone has been reported from well sections (Madhavarju, 1996). Major part of this Sillakkudi Formation consists of sandstone and thus this study is concentrated on sandstones of this formation. The Kallankurichchi Formation unconformably overlies this Sillakkudi Formation. The Sillakkudi Formation (Fig.1) is well exposed in Mettol railway cutting (lat. 11°04'54.9"N and long. 79°02'3.1"E), Nochikkulam (lat. 11°07'55.8"N and long. 79°03'01"E), and Vayalpadi (lat. 11°20'2.5"N and long. 79°07'9.1"E).
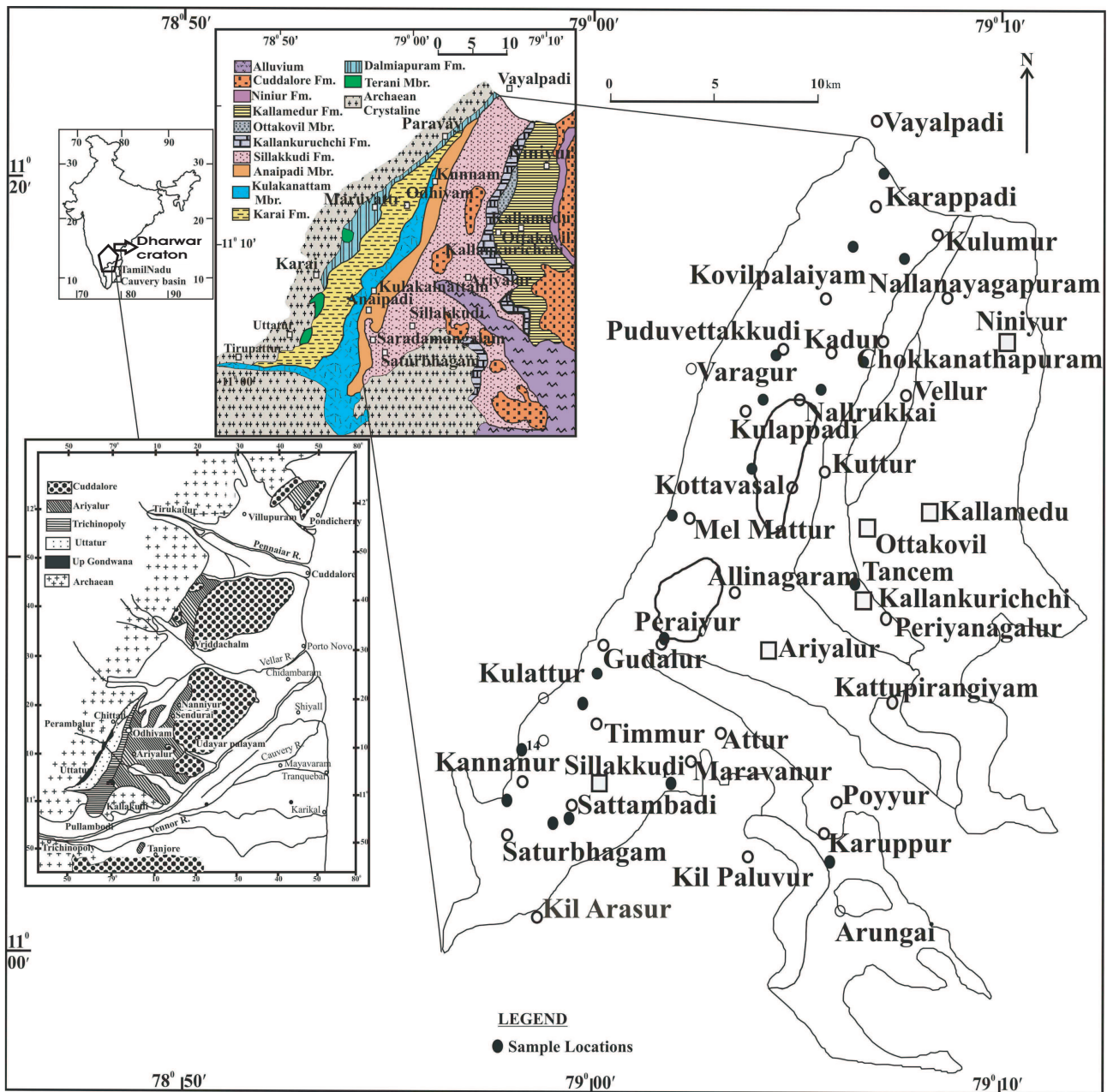
Fig.1. Geology and location map of the study area (modified after Sundaram et al. 2001).

MATERIALS AND METHODS

Thirty fresh, least weathered sandstone samples were chosen from the Sillakkudi Formation and they were washed thoroughly in distilled water to remove contamination. A detailed petrographic study was carried out for about twenty thin sections. For modal analysis, a minimum of three hundred framework grains were counted from each thin section, except matrix and cement. The point counts were done using Gazzi-Dickinson (Gazzi, 1966, Dickinson, 1970) and traditional methods. The samples were then analyzed

for their major element geochemistry. The samples were digested using NaOH solution (solution A) and are analyzed for the major elements SiO_2 and Al_2O_3. Later, the samples were digested in a $HNO_3+HF+HClO_4$ solution and were analyzed for other major elements (Fe_2O_3, CaO, MgO, Na_2O, K_2O and P_2O_5). Twenty of them were analyzed for trace and rare earth elements by Inductively Coupled Plasma–Maas Spectrometry (ICP-MS-ELAN). 0.05 g of each of the samples was digested with mixture of 7 ml of HF, 3 ml of HNO_3 and 1 ml of $HClO_4$ for 24 hours in a tightly closed

Teflon vessel on a hot plate at temperature < 150°C. Later, the solution was evaporated to dryness and extracted with 10 ml of 1% HNO_3. An internationally recognized standard reference material (SRMs) viz., GSR 4 was used for reference. Replicate analyses of samples indicate that error for major elements is better than 1%, whereas the precision for other elements varies between 1 and 9%. Based on these standards, the accuracy and precision of the analysis were within ±2% for the elements like Ni, Cu, Rb, Sr, Y, Nb, Cs, Ba, Ta, Pb, Th, U, Eu, Gd, Tb, Dy, Ho, Yb and Lu; ±5% for Cr, Co, Zn, Ga, Zr and Er; and ±10% for Sc, V, Sm, and Tm. The REE data were normalized relative to the Chondrite values (Taylor and McLennan, 1985). In order to quantify the degree of weathering, the chemical Index of Alteration (CIA) was used (Nesbitt and Young, 1982) and this index was calculated using the molecular proportions as shown in the equation below:

$$CIA = [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$$

where, CaO^* is the amount of CaO incorporated in the silicate fraction of the rock. Correction for CaO from carbonate contribution was not done in this study due to the absence of CO_2 value. Thus, to compute for CaO^* from the silicate fraction, the assumption proposed by Bock et al. (1998) was adopted. In this regard, CaO values were accepted only if $CaO < Na_2O$; consequently, when $CaO > Na_2O$, it was assumed that the concentration of CaO equals to that of Na_2O. This procedure provides measure of the ratio of the secondary aluminous mineral to feldspar, and forms a basis for the measure of intensity of weathering.

RESULTS

Petrography

Most of the sandstones from the Sillakkudi Formation show grain supported fabric (sub-angular to sub-rounded). Generally, these sandstones consist of quartz, feldspar, rock fragments, biotite, glauconite, heavy minerals, opaque minerals and calcite cement. The main framework grains are non undulatory monocrystalline quartz, undulatory monocrystalline quartz, polycrystalline quartz, plagioclase feldspar, K-feldspar, and rock fragments. Quartz mostly in the form of monocrystalline grains, constitute on average, 76.64% of the rock volume. Some of the quartz grains show multiple deformation fractures. In polycrystalline quartz, the 2-3 crystal unit per grain variety is dominant than the >3 crystal unit per grain variety and some of the grains rarely shows up to 5 crystal unit per grain. Mostly quartz grains show a straight extinction and some of them show undulose extinction. Quartz with abundant vacuoles is

present in many samples. The feldspars are orthoclase, plagioclase, microcline, and some perthite. K-feldspar and plagioclase are present in varying proportions among the samples and feldspars are significantly altered on the boundary and inner part of the grain. Quartz – feldspar intergrowth and perthite is also seen in some of the samples. On average, feldspar constitutes about 16.94%. Lithic fragments are comparatively less abundant, which are mostly sedimentary and some are metamorphic. These rock fragments are clearly seen in the litharenite type with an overall average of about 6.13%. Mica, particularly biotite, is more abundant than white mica in some samples. These sandstones contain substantial amount of calcite both as shell fragments and as calcite cement. Heavy minerals such as zircon and garnet, and more opaque minerals (magnetite and hematite) were observed. Glauconites are common in some sandstones. Calcite cement is present both in the form of micrite and spar calcite. The calcite cement constitutes 15 to 25% and matrix constitutes 5 to 15%. Early formed calcite cement is masked by iron oxide materials and coated over the framework grains.

Geochemistry

The major (wt%), trace (ppm) and rare earth element (ppm) concentrations of the Sillakkudi sandstones are reported in the Table 2. The major element compositions of the Sillakkudi sandstones are quite variable. Using the geochemical classification diagram (Herron, 1988) the Sillakkudi sandstones are classified as different rock types (Fig.2). Slight enrichment in SiO_2 (wt%) content is observed in fe-sand (the mean with one standard deviation value being 75.71 ± 14.43; n = 8), quartz arenite (74.68 ± 9.26; n = 6), and sub-arkose (71.48 ± 4.86; n = 7) as compared to litharenite (66.00 ± 3.13; n = 4), arkose (62.28 ± 0.65; n = 2), wacke (61.27 ± 0.96; n = 2), and sub-litharenite (68.45), which can be attributed to the variation in quartz content among these sandstone types. Al_2O_3 content is relatively high in wacke (10.32 ± 0.53), arkose (9.75 ± 0.19), and litharenite (7.50 ± 1.94), but low in fe-sand (4.03 ± 1.55), sub-arkose (3.10 ± 1.25), and quartz arenite (1.10 ± 0.27). The K_2O content is higher in arkose and sub-arkose (3.24 ± 0.30 and 3.24 ± 0.70, respectively) than other rock types. This variation in K_2O content is probably due to the differences in K-feldspar content among these sandstone types. Similarly, the Na_2O content is higher in arkose (2.73 ± 0.02) than litharenite (1.50 ± 0.64), sub-arkose (1.28 ± 1.01), wacke (1.16 ± 0.17), and quartz arenite (1.12 ± 1.36). Low Na_2O content is recorded in fe-sand (0.21 ± 0.29). The wide variation in K_2O/Na_2O ratio (0.44 - 34.3) may be due to the low and erratic concentrations of Na_2O. K_2O and Na_2O

Table 2. Major (wt %), trace (ppm), and rare earth element (ppm) concentrations of Sillakkudi sandstones

Rock type	Fe Sand								Quartz arenites					
Sample #	Sk-III	SK-IV	SK-V	PR-II	PR-II.1	PR-III	PR-IV	PR-V	SK-II	SK-VI	Sk-XI	PR-I	PV	KP
SiO$_2$	60.41	55.01	60.57	84.06	88.27	89.93	81.59	85.81	73.71	75.61	71.15	90.46	75.34	61.82
TiO$_2$	1.15	0.92	1.16	1.41	1.17	1.19	1.00	1.01	1.61	1.07	1.56	1.32	1.07	0.47
Al$_2$O$_3$	2.59	4.67	1.81	5.26	5.44	6.12	3.08	3.25	1.44	1.10	0.81	1.24	0.76	1.24
Fe$_2$O$_3$	14.93	14.91	14.40	7.84	3.48	1.28	12.04	8.90	0.08	0.12	0.76	4.98	2.62	2.88
MnO	0.006	0.031	0.045	0.004	0.004	0.004	0.004	0.007	0.031	0.013	0.818	0.004	0.601	0.207
MgO	0.22	0.20	0.26	0.03	0.02	0.02	0.02	0.01	0.19	0.19	0.25	0.04	0.29	0.27
CaO	13.40	14.10	13.10	0.86	0.98	0.80	0.78	0.70	11.90	13.50	11.50	0.70	8.65	18.05
Na$_2$O	0.31	0.72	0.55	0.01	0.04	0.01	0.02	0.01	0.48	0.53	0.75	0.04	3.80	1.16
K$_2$O	2.61	2.13	2.60	0.02	0.06	0.23	0.10	0.03	2.18	1.98	2.78	0.12	1.97	3.99
P$_2$O$_5$	0.32	0.30	0.33	0.11	0.11	0.11	0.17	0.11	0.28	0.27	0.29	0.11	0.13	0.17
LOI	4.29	6.81	6.10	0.35	0.85	0.43	0.49	0.19	8.45	6.54	8.83	0.87	5.11	10.03
Total	**100.23**	**99.80**	**100.93**	**99.95**	**100.43**	**100.12**	**99.29**	**100.03**	**100.34**	**100.93**	**99.49**	**99.88**	**100.33**	**100.28**
Sc	-	7.08		8.88	10.52	12.23	-	-	14.71	-	-	-	15.32	4.90
V	-	75.15		83.64	94.95	134.97	-	-	92.65	-	-	-	91.11	39.65
Cr	-	16.44		17.93	29.31	22.46	-	-	19.52	-	-	-	19.03	9.87
Co	-	8.27		10.62	5.87	11.84	-	-	15.1	-	-	-	14.98	7.15
Ni	-	25.73		29.31	22.61	29.22	-	-	31.48	-	-	-	32.32	30.27
Cu	-	27.09		29.64	26.09	30.56	-	-	21.56	-	-	-	22.16	22.91
Zn	-	33.79		50.72	41.84	57.96	-	-	61.89	-	-	-	63.28	21.06
Ga	-	18.20		20.17	18.13	21.50	-	-	16.7	-	-	-	16.90	5.47
Rb	-	81.43		14.91	16.47	28.38	-	-	100.87	-	-	-	102.72	20.71
Sr	-	318.52		29.93	26.03	35.98	-	-	406.47	-	-	-	405.93	1170.80
Y	-	32.89		33.00	20.26	16.30	-	-	92.8	-	-	-	94.64	12.42
Zr	-	2981.73		3312.93	2991.59	1084.17	-	-	404.11	-	-	-	403.28	93.18
Nb	-	11.25		17.32	31.10	42.60	-	-	13.98	-	-	-	14.13	3.74
Cs	-	2.00		1.48	1.59	2.41	-	-	2.42	-	-	-	2.39	0.80
Ba	-	2114.54		198.32	111.08	221.10	-	-	2971.7	-	-	-	2988.19	842.07
Hf	-	86.28		93.60	85.54	154.77	-	-	12.5	-	-	-	12.45	2.82
Ta	-	0.91		1.01	1.81	2.40	-	-	0.69	-	-	-	0.75	0.23
Pb	-	38.70		32.32	22.86	22.75	-	-	36.13	-	-	-	39.40	20.38
Th	-	14.73		11.03	15.58	25.66	-	-	41.75	-	-	-	42.20	6.24
U	-	2.28		2.25	2.27	3.09	-	-	2.43	-	-	-	2.75	1.37
La	-	46.77		22.73	26.62	37.78	-	-	123.12	-	-	-	127.85	17.01
Ce	-	81.12		49.08	48.01	72.74	-	-	219.89	-	-	-	232.58	31.80
Pr	-	9.29		5.58	6.49	7.96	-	-	20.65	-	-	-	28.92	3.87
Nd	-	34.15		20.77	23.37	28.08	-	-	90.76	-	-	-	107.44	13.97
Sm	-	5.69		4.13	4.11	4.50	-	-	15.12	-	-	-	19.24	2.42
Eu	-	1.60		0.69	0.50	0.50	-	-	3.81	-	-	-	4.69	0.63
Gd	-	5.69		4.29	3.76	4.14	-	-	14.96	-	-	-	18.24	2.42
Tb	-	0.89		0.93	0.71	0.64	-	-	1.46	-	-	-	2.83	0.36
Dy	-	5.18		6.68	4.50	3.67	-	-	12.73	-	-	-	15.47	2.07
Ho	-	0.93		1.28	0.82	0.64	-	-	2.2	-	-	-	2.67	0.35
Er	-	2.87		4.08	2.70	2.10	-	-	6.38	-	-	-	7.99	1.19
Tm	-	0.36		0.59	0.39	0.30	-	-	0.77	-	-	-	0.91	0.15
Yb	-	2.66		4.79	3.16	2.40	-	-	4.72	-	-	-	6.24	1.07
Lu	-	0.34		0.58	0.40	0.32	-	-	0.61	-	-	-	0.76	0.13
Th/U	-	6.46		4.91	6.87	8.32	-	-	17.18	-	-	-	15.36	4.55
La/Th	-	3.18		2.06	1.71	1.47	-	-	2.95	-	-	-	3.03	2.73
La/Co	-	5.66		2.14	4.54	3.19	-	-	8.15	-	-	-	8.54	2.38
Th/Co	-	1.78		1.04	2.65	2.17	-	-	2.76	-	-	-	2.82	0.87
La/Sc	-	6.61		2.56	2.53	3.09	-	-	8.37	-	-	-	8.35	3.47
Th/Sc	-	2.08		1.24	1.48	2.10	-	-	2.84	-	-	-	2.75	1.27
Th/Cr	-	0.90		0.62	0.53	1.14	-	-	2.14	-	-	-	2.22	0.63
Rb/Sr	-	0.26		0.50	0.63	0.79	-	-	0.25	-	-	-	0.25	0.02
Cr/Th	-	1.12		1.63	1.88	0.88	-	-	0.47	-	-	-	0.45	1.58
LREE/HREE	-	8.63		4.28	6.41	10.28	-	-	9.98	-	-	-	8.63	8.27
ΣREE	-	197.54		126.16	125.53	165.75	-	-	517	-	-	-	575.81	77.42
(La/Yb)$_{cn}$	-	11.89		3.21	5.69	10.65	-	-	17.63	-	-	-	13.84	10.78
(La/Sm)$_{cn}$	-	5.17		3.47	4.08	5.29	-	-			-		4.18	4.43
(Gd/Yb)$_{cn}$	-	1.73		0.73	0.96	1.40	-	-	2.57	-	-	-	2.37	1.84
Eu/Eu*	-	0.86		0.50	0.38	0.35	-	-	0.77	-	-	-	0.77	0.79

Table 2 Contd....

Rock type	Litharenites				Sublith arenite	Subarkoses							Arkose		Wacke	
Sample #	VP-I	KN	KR	TM	SB	SK-I	Sk-VII	SK-IX	SK-X	SK-XII	KD	KK	MM	MM-I	KL	KY
SiO_2	63.49	69.37	67.94	63.19	68.45	77.18	70.38	79.21	70.24	68.97	65.79	68.61	62.74	61.82	60.59	61.95
TiO_2	1.06	0.98	0.97	0.97	0.98	1.38	1.36	1.31	1.06	1.17	0.72	0.99	0.91	0.91	0.97	0.96
Al_2O_3	5.20	8.91	9.29	6.59	4.65	4.34	4.67	1.86	2.27	3.67	1.46	3.40	9.89	9.62	9.94	10.70
Fe_2O_3	5.91	1.72	1.36	2.15	1.82	0.37	0.08	0.61	0.12	1.04	2.90	1.70	1.68	1.52	2.01	1.53
MnO	0.012	0.027	0.077	0.181	0.097	0.008	0.033	0.015	0.612	0.814	0.015	0.133	0.099	0.088	0.209	0.081
MgO	0.16	0.29	0.28	0.25	0.24	0.26	0.27	0.20	0.26	0.27	0.19	0.29	0.21	0.21	0.23	0.36
CaO	14.70	10.21	11.90	16.61	10.55	8.30	13.70	7.60	13.90	13.10	15.32	11.86	12.64	12.43	13.93	12.32
Na_2O	0.61	1.52	2.11	1.77	1.21	0.31	1.63	0.37	0.63	1.29	1.53	3.20	2.74	2.72	1.28	1.04
K_2O	1.53	0.72	0.95	0.77	1.39	2.66	2.35	2.67	3.26	3.83	3.66	4.21	3.03	3.45	1.02	0.74
P_2O_5	0.31	0.25	0.39	0.26	0.26	0.15	0.29	0.16	0.29	0.31	0.13	0.35	0.24	0.29	0.17	0.31
LOI	8.21	7.13	6.02	8.21	8.97	5.13	6.14	5.10	6.98	6.01	8.27	6.20	6.21	6.07	8.76	10.08
Total	**101.19**	**101.13**	**101.28**	**100.95**	**98.62**	**100.09**	**100.90**	**99.11**	**99.62**	**100.47**	**99.97**	**100.95**	**100.38**	**99.13**	**99.10**	**100.07**
Sc	7.54	20.75	19.19	12.46	18.80	8.95	8.50	-	-	9.12	9.76	-	11.29	11.09	12.03	18.03
V	74.49	90.81	121.71	66.76	125.84	105.14	90.60	-	-	91.33	105.13	-	82.48	82.54	80.73	87.84
Cr	28.43	26.06	28.79	24.03	33.01	19.71	18.96	-	-	18.51	20.34	-	20.81	20.67	17.99	18.32
Co	9.25	7.38	8.92	6.30	29.43	12.35	11.14	-	-	10.82	37.46	-	9.35	9.72	6.81	17.67
Ni	29.08	21.23	25.26	23.39	43.80	32.46	24.97	-	-	24.32	51.43	-	20.75	19.42	21.18	30.06
Cu	26.63	21.90	20.68	15.34	25.66	26.16	25.49	-	-	25.23	18.40	-	16.03	16.38	16.47	21.56
Zn	35.50	50.42	73.62	31.88	57.84	48.03	46.19	-	-	45.47	30.55	-	38.20	37.9	35.20	45.55
Ga	17.32	19.84	24.30	16.65	17.40	18.83	19.70	-	-	18.90	10.32	-	23.80	22.76	14.38	18.58
Rb	55.75	44.11	71.90	99.43	38.86	80.44	83.85	-	-	80.32	23.12	-	148.42	148.1	80.56	91.55
Sr	291.31	501.87	530.81	406.39	447.25	234.13	229.43	-	-	222.43	254.67	-	451.15	450.8	281.56	232.95
Y	37.30	20.30	37.94	33.40	68.23	41.27	41.27	-	-	40.53	90.44	-	15.57	16.02	37.07	40.13
Zr	2775.36	292.74	506.35	248.29	319.92	2676.02	5892.03	-	-	5709.84	172.09	-	204.17	202	386.19	324.98
Nb	9.08	11.30	28.01	11.91	11.11	14.79	24.43	-	-	22.69	4.17	-	7.96	6.47	14.75	16.73
Cs	1.87	0.38	1.20	0.97	0.50	1.93	2.11	-	-	2.03	0.56	-	1.55	1.09	0.74	1.25
Ba	3843.43	1577.22	1501.02	2962.48	1553.25	4170.94	950.27	-	-	931.15	1720.16	-	1822.48	1797	1772.33	1455.00
Hf	80.75	8.96	15.50	0.77	10.19	75.59	83.64	-	-	80.46	5.31	-	5.54	5.21	11.06	9.38
Ta	0.33	1.28	1.88	0.85	0.65	1.06	1.50	-	-	1.50	0.10	-	0.46	0.54	1.10	1.37
Pb	33.92	25.46	32.39	21.01	28.02	34.59	24.45	-	-	27.16	24.12	-	45.65	30.87	19.74	24.41
Th	8.35	36.15	38.53	14.25	7.71	30.63	55.81	-	-	50.32	5.29	-	7.24	7.65	23.85	19.20
U	2.16	1.83	2.49	1.04	0.88	3.04	3.36	-	-	3.56	1.16	-	1.15	1.26	1.82	2.32
La	31.23	58.69	82.92	39.28	36.34	76.21	79.59	-	-	77.71	58.83	-	36.17	33.23	53.90	45.30
Ce	55.38	104.45	160.39	75.00	58.90	142.26	155.09	-	-	151.60	80.74	-	65.02	60.38	103.43	89.58
Pr	6.71	11.44	19.85	8.58	8.22	17.66	18.04	-	-	17.47	10.81	-	7.10	6.14	12.16	9.95
Nd	25.86	39.35	71.55	30.71	32.63	64.51	65.50	-	-	63.55	42.72	-	24.11	23.86	43.67	35.59
Sm	4.71	6.35	12.07	5.56	6.75	10.77	10.45	-	-	10.17	8.29	-	4.03	4.12	7.52	6.14
Eu	1.67	1.69	2.49	2.18	2.38	2.63	1.44	-	-	1.42	2.74	-	2.21	1.67	1.68	1.65
Gd	5.13	5.91	10.64	5.72	7.92	10.03	9.51	-	-	9.04	9.47	-	3.67	4.12	7.07	6.45
Tb	0.88	0.81	1.47	0.90	1.47	1.46	1.34	-	-	1.32	1.65	-	0.55	0.88	1.10	1.06
Dy	5.56	4.05	7.80	5.57	9.88	7.96	7.30	-	-	7.23	11.05	-	3.16	3.56	6.46	5.68
Ho	1.04	0.66	1.27	0.97	1.84	1.38	1.25	-	-	1.19	2.08	-	0.52	0.65	1.11	1.22
Er	3.13	2.18	4.09	3.08	5.70	4.23	3.83	-	-	3.91	6.38	-	1.62	1.13	3.53	4.05
Tm	0.40	0.27	0.50	0.39	0.72	0.53	0.48	-	-	0.45	0.75	-	0.21	0.29	0.45	0.55
Yb	2.89	1.99	3.89	2.81	5.00	3.98	3.67	-	-	3.45	5.24	-	1.67	1.89	3.41	4.15
Lu	0.38	0.26	0.47	0.35	0.65	0.49	0.46	-	-	0.44	0.66	-	0.20	0.28	0.42	0.54
Th/U	3.86	19.73	15.48	13.77	8.75	10.06	16.60		-	14.14	4.57	-	6.28	6.07	13.08	8.27
La/Th	3.74	1.62	2.15	2.76	4.72	2.49	1.43		-	1.54	11.12	-	4.99	4.34	2.26	2.36
La/Co	3.38	7.95	9.29	6.23	1.23	6.17	7.15		-	7.18	1.57	-	3.87	3.42	7.91	2.56
Th/Co	0.90	4.90	4.32	2.26	0.26	2.48	5.01		-	4.65	0.14	-	0.77	0.79	3.50	1.09
La/Sc	4.14	2.83	4.32	3.15	1.93	8.51	9.36		-	8.52	6.03	-	3.20	3.00	4.48	2.51
Th/Sc	1.11	1.74	2.01	1.14	0.41	3.42	6.57		-	5.52	0.54	-	0.64	0.69	1.98	1.06
Th/Cr	0.29	1.39	1.34	0.59	0.23	1.55	2.94		-	2.72	0.26	-	0.35	0.37	1.33	1.05
Rb/Sr	0.19	0.09	0.14	0.24	0.09	0.34	0.37		-	0.36	0.09	-	0.33	0.33	0.29	0.39
Cr/Th	3.41	0.72	0.75	1.69	4.28	0.64	0.34		-	0.37	3.84	-	2.87	2.07	0.75	0.95
LREE/HREE	5.88	12.36	10.63	7.24	4.02	9.53	11.23	-	-	11.27	5.04	-	9.87	8.83	8.75	7.36
ΣREE	144.97	238.09	379.40	181.10	178.38	344.10	357.94	-	-	348.96	241.38	-	150.25	142.20	245.90	211.89
$(La/Yb)_{cn}$	7.29	19.90	14.40	9.45	4.91	12.94	14.65			15.23	7.59		14.65	14.56	10.68	7.38
$(La/Sm)_{cn}$	4.17	5.82	4.33	4.45	3.39	4.46	4.79			4.81	4.47		5.65	5.58	4.51	4.65
$(Gd/Yb)_{cn}$	1.44	2.40	2.22	1.65	1.28	2.04	2.10		-	2.12	1.46	-	1.79	1.62	1.68	1.26
Eu/Eu*	1.04	0.84	0.67	1.18	0.99	0.77	0.44		-	0.45	0.94	-	1.76	1.67	0.70	0.80
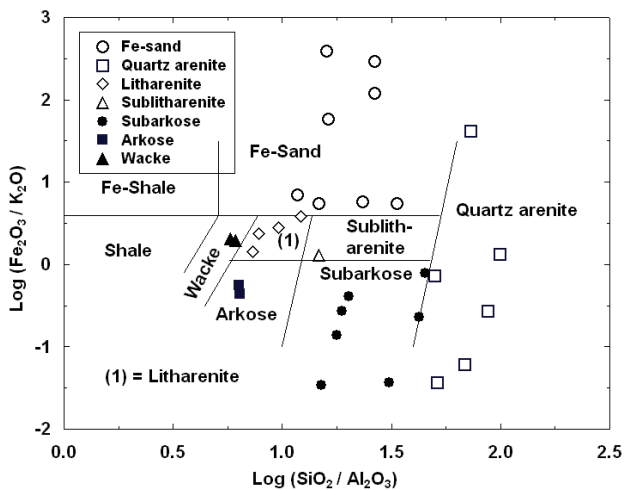
Fig.2. Geochemical classification of Sillakkudi sandstones using log(SiO$_2$/Al$_2$O$_3$)-log(Fe$_2$O$_3$*/K$_2$O) diagram (*after* Herron, 1988).

contents and their ratios (K$_2$O/Na$_2$O ≥ 1 or <1) are also consistent with the petrographic observations, according to which K-feldspar dominates over plagioclase feldspar and K$_2$O/Na$_2$O < 1 in some samples indicate predominance of plagioclase over K-feldspar.

Concentrations of trace elements in Sillakkudi sandstones (Table 2) are generally lower than the average upper continental crust (UCC) concentrations and near to 1 (Fig. 3). The Large ion lithophile elements (LILE) like Rb, Ba, and Sr are compared with UCC in which Ba is higher in all sandstone types. However, Sr is higher in sub-litharenite, quartz arenite, and wacke types than sub-arkose and fe-sands. The reverse trend is observed in Rb concentration, which is higher in wacke than the other sandstone types. The transition trace elements Co, Ni, V are higher and Cr is lower in the Sillakkudi sandstones than UCC. The significant enrichment of Zr, Hf and Th in sub-arkose, sub-litharenite, fe-sand and
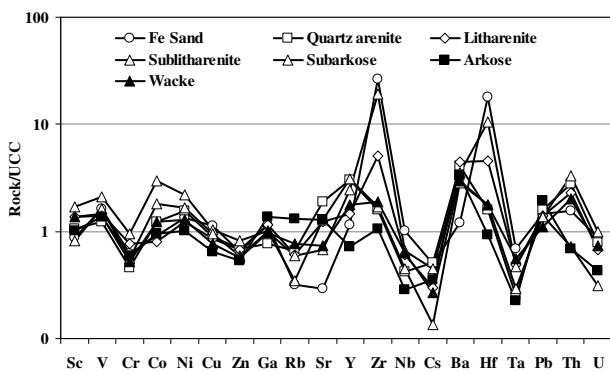
Fig.3. Multi-element normalized diagram for the Sillakkudi sandstones, normalized against average upper continental crust values (UCC; Taylor and McLennan, 1985).
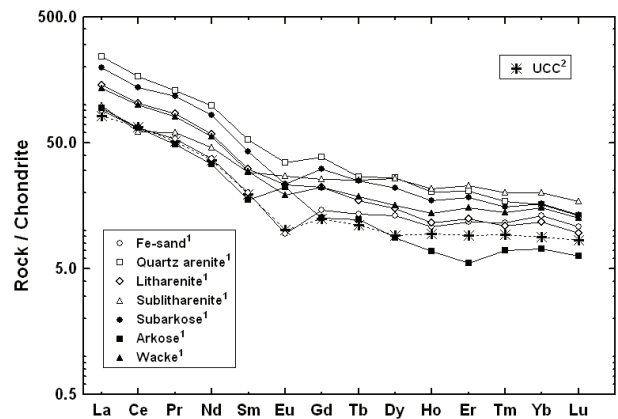
Fig.4. Chondrite normalized rare earth elements plot for the Sillakkudi sandstones. Chondrite normalization and upper continental crust values are from Taylor and McLennan (1985) [1]This study, [2]Taylor and McLennan (1985).

quartz arenite could be related to the amount of heavy minerals (especially zircon) present in them. The high abundance of Zr (93–5892 ppm) in the Sillakkudi sandstones indicate that they may be derived from zircon enriched source rocks such as massif charnockites and granitoids from Dharwar Craton.

The REE concentrations of the Sillakkudi sandstones are also given in the Table 2 and are shown as chondrite normalized patterns in Fig.4. Total REE concentrations vary widely in Sillakkudi sandstones (77-576; mean = 247 ppm). The wide variations are also identified in individual rock types, e.g., fe-sand (~126-197 ppm; n = 4) quartz arenite (77-573; n = 3) and litharenite (~145- 379; n = 4). The average ΣREE concentrations are higher in the Sillakkudi sandstones than the UCC value (~ 143; Taylor and McLennan 1985). The lower REE content in quartz arenite (77 ppm; sample no. KP; Table 2) than other sandstone types highlight a possible paucity of clays and/or quartz dilution effect caused by sedimentary sorting. The REE patterns (Fig. 4) of the Sillakkudi sandstones are with enriched LREE (La$_{CN}$/Sm$_{CN}$ = 4.6 ± 0.6; n = 20), relatively flat HREE (Gd$_{CN}$/Yb$_{CN}$ = 1.74 ± 0.50) and a negative Eu anomaly (Eu/Eu* = 0.80 ± 0.33).

DISCUSSION

Based on the petrographic study the Sillakkudi sandstones are classified as quartz arenite, litharenite, arkose, sub-arkose, wacke and iron rich sandstone (ferrugenous sandstone) types. The average contents of different quartz grains in these sandstones show granitic and/or gneissic source. This has been confirmed by overall variation in the relative abundance of different types of quartz grains

[monocrystalline (undulatory and non undulatory) and polycrystalline]. The greater abundance of alkali feldspar than plagioclase further supports for granitic and/or gneissic source. Glauconites are common in some sandstone types, which indicate shallow marine environments. Several authors (Pettijohn et al. 1972; Blatt et al. 1980; Herron, 1988) have proposed the geochemical classification diagrams for terrigenous sedimentary rocks using major elements. However, the modified classification diagram proposed by Herron (1988) facilitates arkoses to be more successfully classified than Pettijohn et al. (1972) diagram and it is also a measure of mineral stability as the ferromagnesian minerals tend to be amongst the least stable minerals during weathering. Using the geochemical classification diagram of Herron (1988) the Sillakkudi sandstones are classified as fe-sand, quartz arenite, litharenite, sub-litharenite, sub-arkose, arkose, and wacke types (Fig.2). This classification is supported petrographically in which fe-sands are classified as ferruginous sandstone.

Tectonic Setting

The functioning of different tectonic setting discrimination diagrams proposed by Bhatia (1983) and Roser and Korsch (1986) using major elements have been evaluated by many studies (e.g., Armstrong-Altrin and Verma, 2005; Ryan and Williams, 2007). Armstrong-Altrin and Verma (2005) observed that the tectonic setting discrimination diagram proposed by Roser and Korsch (1986) works better than Bhatia's (1983) diagrams to determine the plate tectonic setting of sedimentary basins. K_2O/Na_2O–SiO_2 diagram (Fig.5) is used here after recalculating the analyses 100% volatile-free (Roser and Korsch, 1986). This has been done in case of those samples, which contain a considerable amount of CaO ($< 20\%$), much of it representing $CaCO_3$ in order to compare the data closely. Data in this case could not be calculated carbonate-free since CO_2 values are not available; hence it was recalculated to 100% CaO free. On this diagram, (Fig.5), the Sillakkudi sandstones plot in the passive and active continental margin fields. The shifting of samples towards the ACM field is due to their low K_2O/Na_2O ratio and high SiO_2 content (Table 2). Similarly, REE distribution in sandstones are also used to infer the tectonic settings by various authors (e.g. McLennan et al. 1990; McLennan and Taylor, 1991; Asiedu et al. 2000). According to these studies, the sediments deposited in the continental margin are characterized by LREE enrichment (high La_{CN}/Sm_{CN}) and high total rare earth elements (ΣREE), whereas sediments deposited from young, undifferentiated oceanic arcs have low (La_{CN}/Sm_{CN})
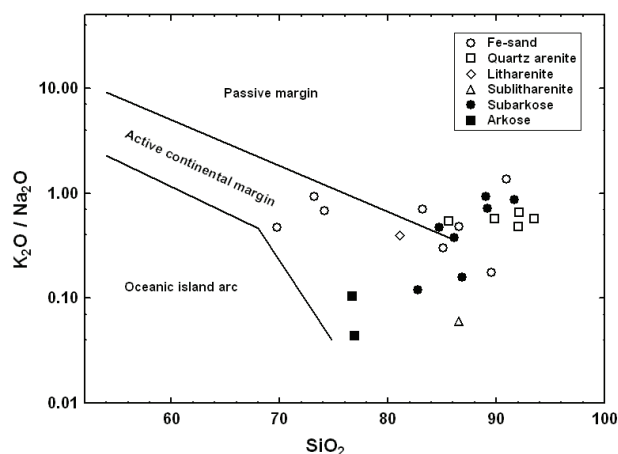
Fig.5. K_2O/Na_2O versus SiO_2 tectonic setting discrimination diagram for the Sillakkudi sandstones (after Roser and Korsch, 1986; the samples with very low K_2O/Na_2O ratio are not included).

ratio, ΣREE content, and lack of negative Eu anomaly. Passive margin provenance is typically characterized by uniform REE pattern similar to PAAS (Bhatia, 1985; McLennan, 1989), while sediments from active continental margin display intermediate ΣREE abundances with variable negative Eu anomaly in the range of 0.6-1.0 (McLennan, 1989). In this study, sandstones have relatively high La_{CN}/Sm_{CN} (5.39-9.25; 7.33 ± 1), La_{CN}/Yb_{CN} (3.21-19.90; 11.23 ± 4.34) and variable Eu/Eu^* ratios (0.35-1.73; 0.80 ± 0.33) suggesting a combination of passive and active margin settings.

Weathering and Hydraulic Sorting

Alteration of sedimentary rocks can be determined by various parameters like chemical index of alteration (CIA, Nesbitt and Young, 1982), K_2O/Na_2O (Nesbitt and Young, 1984; Lindsey, 1999; Dey et al. 2009), Rb/Sr (McLennan et al. 1993), and Th/U ratios (McLennan et al. 1993). These parameters have been successfully used in several studies (e.g. Hurowitz and McLennan, 2005; Selvaraj and Chen, 2006; van Staden et al. 2006; Varga et al. 2007; Pe-Piper et al. 2008; Zimmermann and Spalletti, 2009; Wani and Mondal, 2010) to identify the intensity of weathering.

The average CIA values are higher in fe-sands (78), wacke (76), and litharenite (65) than sub-litharenite (55), arkose (53), sub-arkose (36), and quartz arenite (31). Unweathered igneous rocks have CIA values close to 50, whereas intensely weathered residual rock forming the minerals kaolinite and gibbsite has values ~ 100 (Nesbitt and Young, 1982). However, the average CIA values are consistent with UCC value, which indicate moderate weathering in the source region. The low average CIA values

in quartz arenite, arkose and sub-arkose are due to direct input of immature continent detrital minerals in to the depositional system and do not reflect the general chemical weathering conditions in the source region, which can be inferred from other geochemical indices. Similarly, the variations in CIA values also indicate the sediment sorting effect. Physical sorting of sediments during transportation and deposition leads to concentration of quartz and feldspar with some heavy minerals in the coarse fraction and more weatherable minerals in the suspended load sediments (Garcia et al. 2004).

The average K_2O/Na_2O ratios in fe-sand (6 ± 7), quartz arenite (3.16 ± 1.39), litharenite (0.97 ± 1.03), sub-litharenite (1.14), sub-arkose (4.16 ± 2.90), arkose (1.89 ± 0.19) and wacke (0.75 ± 0.06) indicates the destruction of plagioclase is higher than the K-feldspar. Th/U ratio is also useful to study the source characteristics of clastic sedimentary rocks (e.g. Rodazz et al. 2006). The higher Th/U ratios in the sediments are due to oxidative weathering, and removal of U and Th/U increases with kaolinite content in highly weathered rocks (McLennan et al. 1980). Clastic sedimentary rocks derived from the upper crust are characterized by Th/U ratios equal to or greater than 4, whereas Th/U ratios lower than 4 have been related to mantle contribution (Roddaz et al. 2006). Figure 6 shows that the Th/U ratios in the studied samples are higher than 4 and indicates moderate intensity of weathering. Rb/Sr ratio of sediments can also monitor the degree of source rock weathering (McLennan et al. 1993). Because, chemical weathering of the source area produces higher Rb/Sr ratios in sedimentary rocks (Kimberley and Grandstaff, 1986). The average Rb/Sr ratio of Sillakkudi sandstones is 0.30, which is close to the average UCC value (0.32; Taylor and McLennan, 1985) but significantly lower than the PAAS value (0.80; McLennan et al. 1983). This suggests that the intensity of source area weathering was most probably moderate rather than intense.

Hydraulic sorting can significantly influence the chemical composition of terrigenous sediments, and have control on the distribution of some major elements (P_2O_5 and TiO_2) and trace elements (e.g., REE, Th, U, Zr, Hf and Nb). The average Zr content (1549 ppm) in Sillakkudi sandstones is higher than PAAS (210; McLennan et al., 1983) and UCC (190; Taylor and McLennan, 1985) values. Zr and Hf behave similar as attested by their positive correlation coefficient (r = 0.69, n = 20). The Zr/Hf ratio in the Sillakkudi sandstones vary from 7 to 322 and its average (51 ± 65) is slightly higher than UCC value (~ 36). Zr content does not however show any distinct correlation with HREE (r = -0.03, n = 20), indicating that, not all the

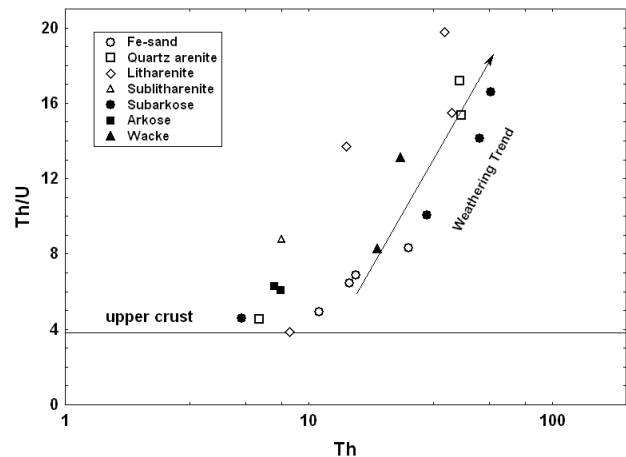**Fig.6.** Th/U versus Th plot for the Sillakkudi sandstones constructed to identify the intensity of weathering (*after* McLennan et al. 1993).

HREEs are controlled by zircon abundance, although, zircon accumulation may cause enrichment in Th and HREEs. However, the poor correlations obtained for Zr versus Th (r = 0.44) and Zr versus ΣREE (r = 0.08) indicate that zircon has little influence over the abundance of these elements. Zr enrichment in sediments is observed in the catchment areas of Cauvery River (Sharma and Rajamani, 2001) and identified that the increase in Zr content was due to the inherent heterogeneity (in granitic rocks the distribution of heavy minerals and associated trace elements are not homogeneous). If the variation of Zr concentration is not due to inherent heterogeneities with in rock, the factors other than weathering are considered for Zr enrichment (Sharma and Rajamani, 2001). The Th/Sc vs Zr/Sc plot (Fig. 7) is widely used to distinguish between the contrasting effects
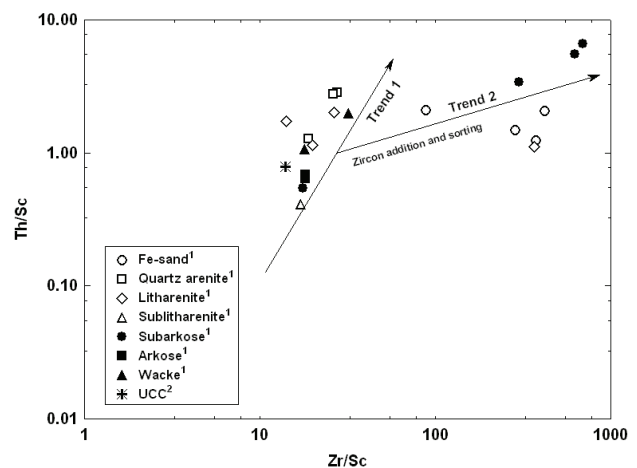

Fig.7. Th/Sc versus Zr/Sc diagram for the Sillakkudi sandstones (*after* McLennan et al. 1993). The addition of zircon due to sediment sorting and recycling is observed in Trend 2. [1]This study; [2]Taylor and McLennan (1985).

of source composition and sedimentary processes on the composition of clastic sedimentary rocks (McLennan et al. 1993). Zr/Sc ratios would increase by an addition of zircon mineral during sorting and/or recycling processes (McLennan et al., 1993). In the Th/Sc vs Zr/Sc plot (Fig. 7), trend 1 reveals the direct contribution from primary source rocks and trend 2 shows the influence of sedimentary processes. Hence, the samples which are sub-parallel to trend 1 suggests compositional homogeneity and others, which are parallel to trend 2 are indicative of heavy mineral addition during sediment recycling and sorting. Mineral sorting normally tends to increase the abundance of non-clay detrital minerals at the expense of clay minerals (Nesbitt and Young, 1984). Therefore, the relative differences in the abundance of some trace elements might have been attributed to mineral sorting (LaMaskin et al. 2008; Kasper-Zubillaga et al. 2008) and reveals that Zr does not control the distribution of REEs in Sillakkudi sandstones. Similarly, the negative correlation observed between ΣREE and P_2O_5 indicates that apatite or monazite do not control the REE distribution in Sillakkudi sandstones (Condie, 1991; Das et al. 2006).

Provenance

Geochemistry of sedimentary rocks is considerable consequence to understand the provenance of the sediments (McLennan, 1989). The high field strength elements (HFSE) such as Zr, Nb, Hf, Y, Th and U are preferentially partitioned into melts during crystallization (Feng and Kerrich, 1990) and as a result these elements are enriched in felsic sources rather than the mafic sources. Zr, Hf, and Y are thought to reflect provenance compositions as a consequence of their immobile behaviors (Taylor and McLennan, 1985).The ferromagnesian trace elements Cr, Ni, Co and V generally show similarity with the behavior of magmatic processes, but they may be fractionated during weathering (Feng and Kerrich, 1990). In the Sillakkudi sandstones, Ni is enriched whereas Cr is decreased with respect to the average UCC composition (Fig. 3). This enrichment in Ni may suggest some input of mafic minerals from the source terrain; however, the depletion of Cr (21 ± 5, n = 30), MgO (0.2 ± 0.1) contents and Cr/Th (1.57±1.22 n = 20) ratio suggests that other factors could have played a role in concentrating Ni in the sandstones. Similarly, no significant correlation is observed for Cr versus Ni (r = 0.08) and Co (r = 0.15), whereas Ni shows good positive correlation coefficient with Co (r = 0.92). Hence, the enrichment of Ni unaccompanied by Cr in Sillakkudi sandstones was due to the fractionation of garnet between the source rocks and sandstones, and not due to the mafic nature (Armstrong-Altrin et al. 2004).

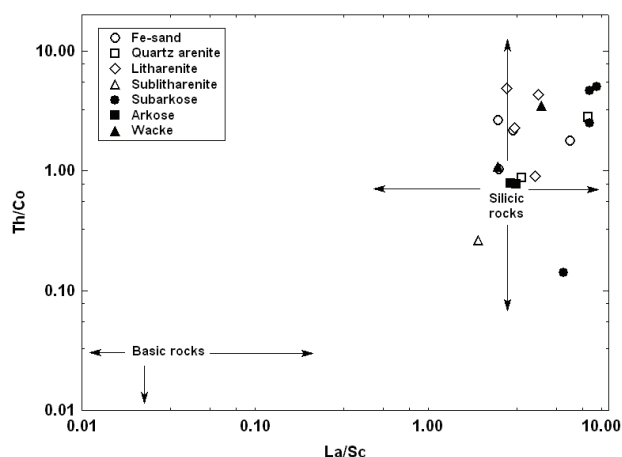The variations in Th and La (indicative of felsic) and,

Fig.8. Th/Co versus La/Sc plot showing source rock composition for the Sillakkudi sandstones (fields after Cullers, 2002).

Sc and Co (indicative of mafic) contents have been used to differentiate between felsic and mafic provenance by various authors (McLennan et al. 1980, Cullers, 2002; Nagarajan et al. 2007a, b; Kasanzu et al. 2008). Th/Co vs La/Sc bivariate and La-Th-Sc triangular diagrams can provide information regarding the source rock characteristics (McLennan and Taylor, 1991; Cullers, 2002). The Th/Co vs La/Sc plot (Fig. 8) suggests a felsic nature of the source rocks (Cullers, 2002). Similarly, La-Th-Sc triangular diagram (Fig. 9) is also used to understand the provenance characteristics. The average compositions of granite, andesite, and basalt (Condie, 1993), and UCC are used in this diagram for comparison. In this triangular diagram (Fig. 9), sub-arkose plots near to granite composition, whereas fe-sand, arkose,
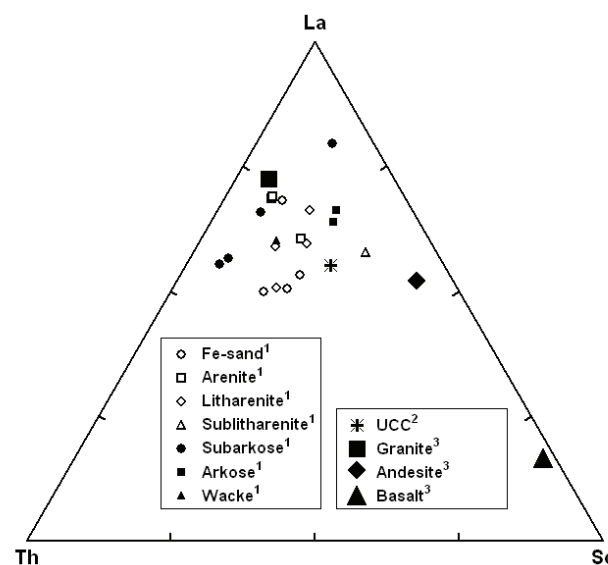

Fig.9. La-Th-Sc ternary diagram for the Sillakkudi sandstones. [1]This study; [2]Taylor and McLennan (1985); [3]Condie (1993).

Table 3. Range of elemental ratios of Sillakkudi sandstones in this study compared to the ratios in similar fractions derived from felsic rocks, mafic rocks and upper continental crust (UCC)

Elemental Ratio	Range of sandstones from Sillakkudi Formation[1] (n = 20)	Range of sediment from felsic sources[2]	Range of sediment from mafic sources[2]	Upper continental crust[3]
Eu/Eu*	0.35-1.73	0.40-0.94	0.71-0.95	0.63
(La/Lu)$_{cn}$	4.10-23.53	3.00-27.00	1.10-7.00	9.73
La/Sc	1.93-9.36	2.5-16.3	0.43-0.86	2.21
Th/Sc	0.41-6.57	0.84-20.5	0.05-0.22	0.79
Th/Co	0.14-5.01	0.67-19.4	0.04-1.4	0.63
Th/Cr	0.23-2.94	0.13-2.7	0.018-0.046	0.13
Cr/Th	0.34-4.28	4.00-15.0	25-500	7.76
La/Co	1.23-9.29	1.80-13.8	0.14-0.38	1.76

[1] This study; [2] Cullers (1994), (2000); Cullers and Podkovyrov (2000); Cullers et al. (1988); Armstrong-Altrin (2009); [3] McLennan (2001); Taylor and McLennan (1985)

sub-litharenite and litharenite plot between average granite, and UCC compositions, which suggests that the Sillakkudi sandstones were derived probably by the influence of felsic source rocks.

Similarly, ratios such as Eu/Eu*, La/Sc, Th/Sc, Th/Co, and Th/Cr are significantly different in felsic and mafic rocks and may allow constraints on the average provenance composition (Cullers, 1995, 2000; Cox et al. 1995). Th/Sc, Th/Co, Th/Cr, Cr/Th, and La/Sc ratios of Sillakkudi sandstones are compared with those of sediments derived from felsic and mafic rocks as well as to UCC values (Table 3). In this comparison the Sillakkudi sandstones fall within the range of felsic sediments and supports again for the felsic source rocks.

The REE pattern and Eu anomaly in the sedimentary rocks will provide important clues for the source rock characteristics (Taylor and McLennan, 1985). Higher LREE/ HREE ratios and negative Eu anomaly are generally found in felsic rocks, whereas the mafic rocks exhibit low LREE/ HREE ratio and low negative Eu anomaly (Cullers, 1994). The positive Eu anomaly was generally found in Proterozoic rocks (TTG), granodiorite and quartz diorite. The low positive Eu anomaly in TTG is resulted from hornblende melt equilibria (Cullers and Graf, 1984). In this study, the Chondrite normalized REE plots (Fig. 4) display fractionated REE patterns (La$_{CN}$/Yb$_{CN}$ = ~ 3.21 - 19.90), which are characterized by relatively flat HREE (Gd$_{CN}$/Yb$_{CN}$ = 0.73-2.57), enriched LREE (La/Sm$_{CN}$ = 3.39-5.82) and negative Eu anomaly (Eu/Eu* = 0.80 ± 0.03) similar to UCC. In addition, the Sillakkudi sandstones show enriched LREE/ HREE ratio (4.30-13.66; 9.11±2.62; n = 20), which suggests that these sandstones were mainly derived from the felsic source rocks (Taylor and McLennan, 1985).

To know the probable source rocks for the Sillakkudi

sandstones (Fig. 10) the average REE patterns are compared with those of charnockites (n = 21) and gneisses (n = 23) belongs to Kerala Khondalite Belt (Allen et al., 1985; Chacko et al., 1992), and granite (n = 6) and gneisses (n = 9) from Dharwar Craton (Jayananda et al. 1995; Stähle et al. 1987). These areas belong relatively close to the study area and are supposed to contribute sediments to the study area. The chondrite normalized REE patterns of Sillakkudi sandstones show LREE enriched, flat HREE and with significant negative Eu anomaly. However, considering the SREE (especially HREE) content and the size of the negative Eu anomaly, these sandstones are very similar to the gneisses of Dharwar Craton. This implies that the Sillakkudi sandstones received a higher contribution of sediments from Dharwar craton than Kerala khondalite belt.
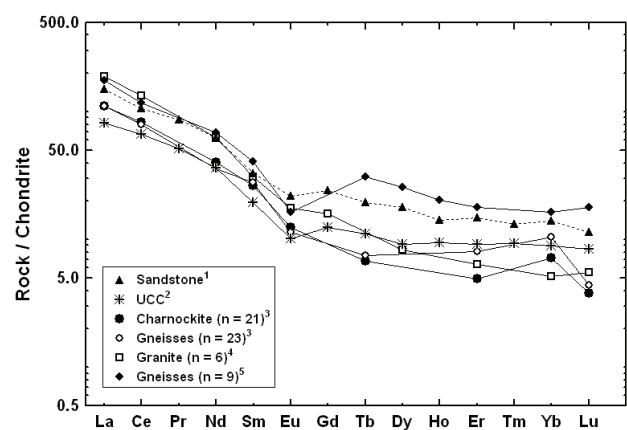

Fig.10. Chondrite-normalized REE patterns. n = number of samples; [1] This study (Sillakkudi sandstones); [2] average upper continental crust (UCC; Taylor and McLennan, 1985); [3] Kerala Khondalite Belt (Allen et al. 1985; Chacko et al. 1992); [4] Dharwar Craton (Jayananda et al. 1995); [5] Dharwar Craton (Stähle et al. 1987).
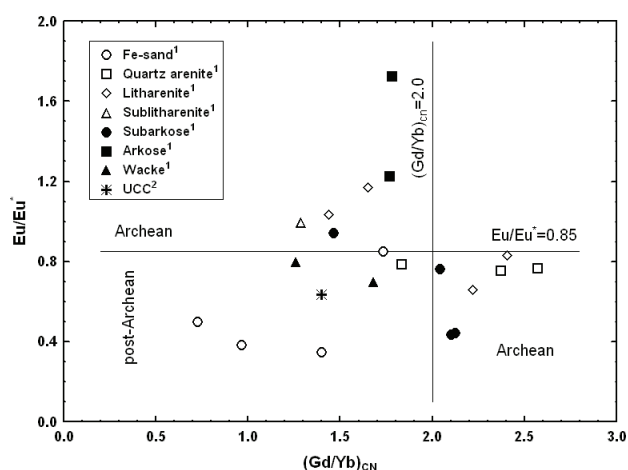
Fig.11. Plot of Eu/Eu* versus (Gd/Yb)$_{CN}$ for the Sillakkudi sandstones. Fields after McLennan and Taylor (1991). [1]This study; [2]Taylor and McLennan (1985).

The granitic rocks formed during Phanerozoic Eon have more K-feldspar rich granites and thereby reflect less depletion of Eu, and high depletion of HREE with Gd$_{CN}$/Yb$_{CN}$ ratio < 2 (McLennan 1989; Taylor and McLennan 1985). In the Eu/Eu* vs Gd$_{CN}$/Yb$_{CN}$ plot (Fig.11) the fe-sand and wacke types plot in the Phanerozoic field (K-feldspar rich granites and there by reflect less depletion of Eu), which shows Gd$_{CN}$/Yb$_{CN}$ ratio < 2.0, whereas arkose and litharenites show Gd$_N$/Yb$_N$ ratio more than 2 and low Eu/Eu* ratio. However, some arkose, sub-arkoses, and litharenite types show enriched Eu/Eu* and Gd$_{CN}$/Yb$_{CN}$ ratio < 2.0, which suggests the Archaean igneous source.

CONCLUSIONS

The Sillakkudi sandstones are classified as fe-sand,

quartz arenite, litharenite, sub-arkose, arkose, wacke and sub-litharenite based on major element geochemistry. Lower concentrations of immobile trace elements like Cr, Co, V, and Sc suggest the felsic source rock provenance, which is also supported by the Th/Sc, Th/Co, Th/Cr, Cr/Th, and La/Sc ratios. Similarly, the La-Th-Sc ternary and La/Sc vs Th/Co plots also reveal the felsic character of the source rocks. Enrichment of Zr identified from Th/Sc versus Zr/Sc plot in fe-sands and sub-arkose types suggests the influence of sedimentary processes such as sediment recycling and sorting. However, the zircon geochemistry did not affect the REE distribution and its patterns in the Sillakkudi sandstones. The comparison of REE patterns and its Eu anomalies to the source rocks reveals that the Sillakkudi sandstones received a higher contribution of sediments from Dharwar Craton than Kerala Khondalite Belt. We conclude that the REE patterns and Eu anomalies are well preserved in the Sillakkudi sandstones and are highly reliable indicator of source rocks, even though the geochemical composition can be affected by processes such as hydraulic sorting during transportation.

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