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Elemental geochemistry of river sediments from the Deccan Traps, India: Implications to sources of elements and their mobility during basalt–water interaction

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Abstract

The abundances of several major (Na, Ca, Mg, K, Al, Ti, Fe) and minor elements (Sr, Ba, Mn, P, V, Cr, Ni, Cu and Zn) have been measured in twenty-eight sediment samples from seventeen rivers belonging to the Krishna headwaters and west flowing Western Ghat rivers, all of which drain the Deccan Trap basalts. These results, particularly those of Na, Ca, Mg and Sr coupled with those reported for these elements in the dissolved phase of the same rivers, provide an assessment of their relative mobility and insight into the nature of chemical weathering of Deccan basalts. The sediments are heavily depleted in Na, Ca, Mg and Sr relative to parent basalts (by ~60%). The abundance ratios of these elements in sediments are roughly the same as those in basalts and in dissolved phases of these rivers [Das, A., Krishnaswami S., Sarin M. M., Pande K., 2005a. Chemical weathering in the Krishna basin and the Western Ghats of the Deccan Traps: Rates of basalt weathering and their controls. Geochim. Cosmochim. Acta 69, 2067–2084.], suggesting their near congruent release from basalts to water during chemical weathering, both at present and over the residence time of particles in the basin. K and Ba show limited mobility relative to the above four elements. The abundances of K and Ba are strongly correlated, most likely due to their association in rock forming minerals. Al, Fe and Ti, are generally enriched in the sediments, resulting from the loss of more mobile elements from basalts and their association with secondary minerals formed during weathering. The data also provide evidence for the fractionation of Fe and Al during chemical weathering and erosion. Fe and Ti exhibit significant correlation, attributable either to their co-occurrence in weathering resistant minerals and/or due to scavenging of Ti by Fe oxy-hydroxides formed during weathering of basalts. The abundance of minor elements (Mn, P, V, Cr, Ni, Cu and Zn) and their ratios with Al show significant scatter, by and large bracketing the range reported for Deccan basalts. The wide and overlapping ranges in the concentration of these elements and their ratios relative to Al, between sediments and basalts place severe constraints in assessing their mobility during weathering and erosion, and in judging the role of anthropogenic sources in contributing to their abundances. Among the minor elements, there is a hint that Zn concentration may have been influenced by anthropogenic inputs. Mn, V and Ni, analogous to Ti, show significant correlation with Fe, either due to their association with Fe–Ti minerals or their sequestration by Fe oxy-hydroxides. The mobility of elements during weathering and erosion of Deccan basalts follows the trend ($Na \approx Ca \geq Mg \approx Sr) > (K \geq Ba) > (Al \geq Fe \approx Ti$).

There is considerable spatial variability in the intensity of chemical weathering of Deccan basalts. The CIA (Chemical Index of Alteration) values for the sediment range between 42 and 92, compared to ~37 for the Deccan basalts. The lower CIA values are in sediments richer in $CaCO_3$. This may be a result of semi-arid climate of the region which facilitate $CaCO_3$ precipitation and restrict

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chemical weathering/erosion. Higher CIA values are generally associated with sediments from basins with higher runoff. Modeling the major element composition of sediment and water yields estimates of particulate abundances in water. These estimates agree with the measured values within a factor of ~2 for some of the rivers whereas in some others they differ by more than a factor of 3–4. The use of sediment composition instead of that of the suspended matter, spatial and temporal variations in sediment flux and non-steady state erosion all can contribute to this discrepancy. These factors also seem to be contributing to difference in CO_2 consumption estimated from sediment composition and that reported based on dissolved phase data.

Keywords: Deccan Traps; River sediments; Chemical weathering; Elemental mobility

1. Introduction

Rivers are the major pathways of transport of both particulate and dissolved weathered continental materials to the oceans (Martin and Meybeck, 1979). Studies on weathering of rocks are important as they inform about continental erosion and consumption of atmospheric CO_2, both of which are relevant to global change (Walker et al., 1981; Raymo and Ruddiman, 1992; Berner and Berner, 1997; Edmond and Huh, 1997; Gaillardet et al., 1999a; Krishnaswami et al., 1999; Kump et al., 2000; Amiotte-Suchet et al., 2003; Dessert et al., 2003). Major ion chemistry of dissolved load of rivers is an index of contemporary chemical weathering and erosion of the basins and the factors influencing them. In contrast, chemistry of river particulates is a measure of "time" averaged chemical weathering of the basin, the 'time' being the residence time of particulates in the river basin. Studies on chemical weathering and erosion based on riverine particulate loads are less common (Martin and Meybeck, 1979; McLennan, 1993; Gaillardet et al., 1995, 1999b; Canfield, 1997; Picouet et al., 2002) compared to those based on the dissolved load approach. In recent years, however, there have been studies of both dissolved and particulate phases together to derive better understanding of weathering and erosion and their role in global carbon cycle (Dupre et al., 1996; Gaillardet et al., 1997; Louvat and Allegre, 1997, 1998; Picouet et al., 2002; Vigier et al., 2005; Gislason et al., 2006).

The present study, based on the chemistry of river sediments, is about weathering, erosion and the relative mobility of elements during these processes, in an important basaltic province on continents, viz., the Deccan Traps. Studies on weathering of such large continental basaltic provinces are important for several reasons, including the long term global carbon cycle. In this study, sediments from rivers having their drainage almost exclusively in the Deccan Traps, such as the headwaters of the Krishna river system and several smaller rivers draining the Western Ghats and flowing into the Arabian Sea, have been analysed. These studies complement the work on the dissolved major ion chemistry of the same rivers (Das et al., 2005a) and makes an important addition to the reported river water studies from major basaltic provinces on their chemical weathering, consumption of atmospheric CO_2 and long term global carbon cycle (Bluth and Kump, 1994; Gislason et al., 1996; Louvat and Allegre, 1997, 1998; Taylor and Lasaga, 1999; Dessert et al., 2001; Das et al., 2005a).

The objectives of the present study are to: (i) determine the major and minor element composition of sediments from rivers draining the Deccan Traps, and use the data to infer the relative mobilities of various elements from the parent basalts to rivers during weathering and transportation, (ii) compare the mobilities of elements derived from the sediment composition with their contemporary mobility based on dissolved phase data (Das et al., 2005a) and assess its implications to weathering characteristics of minerals in Deccan basalts, (iii) estimate physical erosion rates of the basins based on measured elemental abundances in sediments and in water and available models, and (iv) evaluate the extent of anthropogenic influence on the minor and trace element abundances in sediments.

Prior to this work there have been a few studies on the chemistry of suspended and bed sediments of the rivers draining the Deccan Traps, the Godavari, Krishna, Narmada and the Tapti (Borole et al., 1982; Subramanian et al., 1985; Ramesh et al., 1989; Dekov et al., 1998). These studies were mainly to determine their average composition and associated fluxes to oceans, to elucidate the behaviour of various elements in particulate phases in the river-estuarine zone and to assess the impact of pollution on elemental abundances. More recently, Vigier et al. (2005) have studied the nature and time scales of erosion based on U series disequilibria in water and particulate phases of the Narmada and Tapti rivers draining the northern regions of the Deccan.

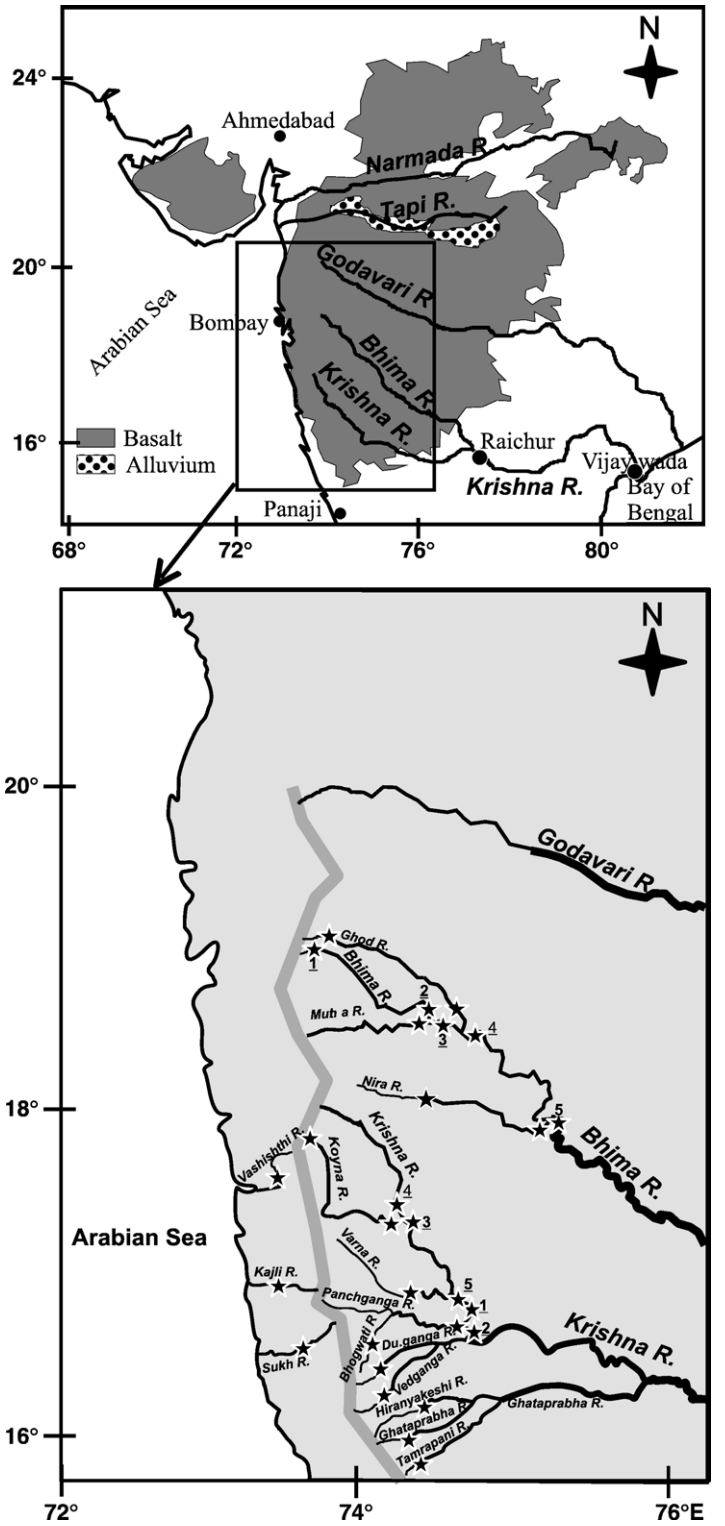

Fig. 1. The upper map shows the extent of present day aerial coverage of Deccan Traps on land and the major rivers draining it. The lower map gives the sampling locations (⋆) of river sediments. All samples are collected from the basins of the Krishna head waters and their tributaries having their drainage almost exclusively within the Deccan Traps. The Western Ghats are shown by a band parallel to the western coast. The numbers on the Krishna and the Bhima mainstream represent sample codes (e.g., #1 on Krishna is KRS-1).

2. Geohydrology of the river basins

The detailed hydrogeology of the river basins is discussed in Das et al. (2005a). Briefly, the Deccan basalts cover an area of $\sim 5 \times 10^5$ km^2 in the west-central India, and have an estimated volume of $\sim 10^6$ km^3 (Courtillot et al., 1986). The thickness of these Traps varies from ~200 m to ~2000 m (Courtillot et al., 1986) and consists of a series of lava sequences the bulk of which erupted around ~65 Ma ago (Courtillot et al., 1986; Venkatesan et al., 1993; Allegre et al., 1999; Courtillot et al., 1999; Pande, 2002). These lava sequences or "Formations" have characteristic chemical and isotopic composition (e.g., Cox and Hawkesworth, 1985; Beane et al., 1986; Devey and Lightfoot, 1986; Mahoney, 1988; Subbarao and Hooper, 1988; Mitchell and Widdowson, 1991; Peng et al., 1998) which allows their identification through the Deccan province. The Deccan Traps consist of twelve such Formations (Subbarao and Hooper, 1988; Mitchell and Widdowson, 1991).

The rivers sampled for this study are the headwaters of the Krishna river system, which include the main river Krishna, and its tributaries; the Bhima, Koyna, Varna, Panchganga, Dudhganga and the Ghataprabha (Fig. 1). In addition, the major tributaries of the Bhima, the Ghod, Mutha and the Nira and a number of west flowing small rivers and streams of the Western Ghats (Fig. 1) were also sampled. The Krishna river basin has a total drainage area of ~258,948 km^2, of which ~25% lie in Deccan Traps (Rao, 1975). The rivers of the Krishna system flow eastwards and drain into the Bay of Bengal, whereas the small Western Ghat streams (WFWG rivers, Vashishthi, Kajli and Sukh; Fig. 1) flow west into the Arabian sea.

The drainage basins of the rivers sampled are composed mainly of three Formations, the Ambenali, the Poladpur and the Mahabaleshwar with minor exposures of the Bushe, Bhimashanker and Thakurwadi. The Ambenali Formation is the most voluminous and widespread among all the Formations (Kisakurek et al., 2004). Representative chemical compositions of these Formations are given in Table 1. These are compiled by Subbarao et al. (2000) from available data (e.g. Cox and Hawkesworth, 1985; Beane et al., 1986; Devey and Lightfoot, 1986). The average major elemental abundances among the various Formations in Table 1 are similar, suggesting that their compositional range is limited.

The Deccan Trap basalts are predominantly tholeiitic lavas composed primarily of plagioclase, pyroxene and olivine. There are reports of zeolites in the cavities and as crystalline specimens in the basalt (James and Walsh, 1999) and mention of opaque phases and altered glass in the groundmass (e.g., Cox and Hawkesworth, 1985; Devey and Lightfoot, 1986; Mahoney, 1988). Mineralogical studies suggest that olivines have 77% to 88% forsterite (Sen, 1980, 1986; Beane, 1988) and plagioclase phenocrysts have 61% to 82% anorthite (Sen, 1986). Among pyroxenes, augite and pigeonite are more common (Sethna and Sethna, 1988). There are reports of occurrences of calcium carbonate in the basin as a component of bed sediments (Das et al., 2005a) and as calcretes and calcareous tufas in the upland Bhima basin (Pawar et al., 1988; Patil and Surana, 1992; Pawar and Kale, 2006). In addition, calcites are present as a minor

Table 1
Average elemental abundances[a] in selected formations of the Deccan Traps

Formation		Fe	Al	Ca	Mg	Na	K	Ti	Mn	P	Sr	Ba
Poladpur (n=4)	Average	10.4	7.0	7.7	3.71	1.78	0.16	1.26	0.16	0.07	224	104
	(σ)	1.1	0.3	0.4	0.49	0.20	0.04	0.18	0.01	0.01	13	20
Ambenali (n=3)	Average	11.6	7.4	7.9	3.67	1.84	0.19	1.48	0.16	0.09	227	74
	(σ)	1.7	0.5	0.4	0.43	0.12	0.08	0.31	0.01	0.02	3	23
Mahabaleshwar (n=3)	Average	11.4	7.4	7.7	3.35	1.96	0.29	1.64	0.16	0.17	228	135
	(σ)	1.1	0.6	0.8	0.13	0.19	0.11	0.69	0.03	0.09	14	33
Bushe (n=3)	Average	8.2	7.9	7.1	3.82	2.00	0.68	0.71	0.13	0.06	172	170
	(σ)	0.3	0.5	0.4	0.95	0.19	0.27	0.06	0.00	0.02	55	104
Thakurwadi[b] (n=9)	Average	9.7	7.2	7.0	3.91	1.63	0.44	1.35	0.14	0.10	249	149
	(σ)	1.3	0.3	1.1	0.86	0.20	0.29	0.31	0.02	0.02	10	65
Bhimashanker (n=3)	Average	10.4	7.3	7.0	3.59	2.36	0.55	1.53	0.14	0.12	254	146
	(σ)	0.4	0.5	0.3	0.05	0.11	0.10	0.20	0.01	0.02	3	57
Overall average (n=25)		10.1	7.3	7.3	3.74	1.85	0.39	1.33	0.15	0.10	228	133
(σ)		1.5	0.5	0.8	0.66	0.3	0.26	0.4	0.02	0.04	32	60

Data source: Compiled by Subbarao et al. (2000) from data of Cox and Hawkesworth (1985); Beane et al. (1986), Devey and Lightfoot (1986).
[a] In wt.%, except Sr and Ba which are ppm wt.
[b] n=6 for Sr.

Table 2
$CaCO_3$, major and trace element concentrations[a] in sediments from rivers draining the Deccan Traps

Sample	River	Na	K	Mg	Al	Ca	$CaCO_3$	Ca_{sil}	Fe	Ti	Mn	Sr	Ba	Ni	Cr	V	Cu	Zn	P
Krishna mainstream																			
KRS-1	Krishna	0.75	0.21	2.38	6.35	5.02	2.28	4.11	17.4	5.45	0.22	240	168	100	176	990	291	223	535
KRS-2	”	0.52	0.36	1.38	8.85	2.21	0.23	2.12	13.6	2.28	0.20	104	186	97	138	512	287	164	1006
KRS-3	”	0.63	0.26	1.86	7.13	3.59	0.12	3.54	13.6	2.65	0.17	210	164	95	151	560	263	170	728
KRS-3R	”	0.72	0.28	2.13	7.95	3.83	0.13	3.78	13.3	2.49	0.17	234	185	99	144	524	253	172	720
KRS-4	”	1.20	0.27	2.84	6.35	8.93	9.13	5.28	13.0	2.73	0.21	260	163	88	206	695	206	191	736
KRS-5	”	0.71	0.26	1.99	7.78	4.16	2.48	3.17	14.0	3.51	0.22	248	209	93	138	617	271	173	666
Bhima mainstream																			
BHM-1	Bhima	0.47	0.58	1.68	8.81	1.89	0.10	1.85	13.0	1.46	0.17	146	273	112	195	425	211	156	917
BHM-2	”	0.91	0.55	2.31	6.81	5.72	5.70	3.44	9.89	1.99	0.15	238	230	88	188	431	169	129	649
BHM-3	”	0.90	0.60	2.39	7.12	5.00	5.93	2.63	8.12	1.41	0.11	219	228	81	161	322	142	113	762
BHM-4	”	0.86	0.55	2.15	6.93	5.73	6.65	3.07	8.86	1.53	0.15	251	252	81	171	343	161	137	913
BHM-4R	”	0.83	0.58	2.24	7.21	5.80	nd	–	8.88	1.56	0.16	241	245	80	171	349	158	131	887
BHM-5	”	0.95	0.57	2.62	6.42	6.56	10.3	2.45	7.88	1.35	0.27	287	254	80	105	299	188	188	907
Tributaries of Bhima																			
GHOD-1	Ghod	1.03	0.57	2.81	7.46	4.69	0.38	4.54	11.6	1.83	0.19	235	245	106	306	441	167	146	722
GHOD-2	”	0.61	0.54	2.03	6.08	8.11	16.9	1.36	5.85	0.94	0.16	248	188	68	100	242	126	101	952
MTH-1	Mutha	0.85	0.53	2.30	6.97	4.61	2.55	3.59	9.41	1.77	0.15	220	241	91	248	422	221	214	1804
NIRA-1	Nira	1.07	0.23	3.10	5.92	9.39	12.9	4.25	10.2	2.11	0.15	340	140	80	165	513	202	144	470
NIRA-2	”	1.05	0.27	2.74	5.84	8.78	11.9	4.04	10.9	2.54	0.19	298	175	82	154	540	219	155	482
Tributaries of Krishna																			
KYN-1	Koyna	0.69	0.32	1.89	7.87	3.58	1.03	3.17	14.6	2.75	0.20	160	168	97	156	592	299	192	879
KYN-2	”	0.54	0.30	1.64	9.78	2.57	0.10	2.53	16.4	2.42	0.22	132	205	126	295	651	297	186	1014
KYN-2R	”	0.56	0.30	1.72	10.0	2.70	0.10	2.66	16.9	2.48	0.23	138	215	128	303	651	299	190	1030
VRN-1	Varna	0.59	0.30	1.22	7.76	2.10	0.04	2.09	13.9	2.95	0.23	122	183	90	119	531	303	161	845
PGN-1	Panchganga	0.59	0.25	1.24	7.61	2.15	0.10	2.11	17.7	5.18	0.23	131	172	96	148	927	324	205	773
GTP-1	Ghataprabha	0.10	0.55	0.60	10.4	0.34	0.15	0.28	14.6	2.66	0.21	40	198	141	246	540	204	147	759
HRN-1	Hiranyakeshi	0.22	0.51	0.89	9.12	0.89	0.20	0.81	13.2	2.40	0.21	57	199	110	174	503	247	143	1036
HRN-1R	”	0.22	0.53	0.95	9.65	0.95	nd	–	14.0	2.39	0.23	62	210	122	188	568	260	151	957
TPN-1	Tambrapani	0.13	0.41	0.52	9.78	0.37	0.10	0.33	16.3	3.51	0.17	46	194	127	212	620	268	164	998
DDG-1	Dudhganga	0.37	0.21	1.13	7.09	1.67	0.35	1.53	18.9	6.55	0.23	74	138	92	171	1059	334	238	672
VDG-1	Vedganga	0.18	0.36	0.75	9.35	0.74	0.13	0.69	16.0	3.12	0.18	54	193	123	185	616	316	166	855
BGW-1	Bhogwati	0.29	0.28	0.87	8.88	1.12	0.13	1.07	16.6	3.16	0.21	64	181	99	151	627	327	187	1005
BGW-1R	”	0.27	0.30	0.90	9.18	1.10	nd	–	17.0	2.65	0.23	64	175	103	156	657	332	192	902
West flowing Western Ghat rivers																			
SUKH-1	Sukh	0.35	0.18	1.04	8.57	1.52	0.11	1.48	16.5	2.46	0.20	73	135	119	146	662	329	161	816
KJL-1	Kajli	0.36	0.15	2.08	6.80	2.20	0.00	2.20	30.2	7.62	0.30	61	79	162	235	2165	568	398	503
VAT-1	Vashishthi	0.50	0.23	1.95	8.19	2.98	0.05	2.96	16.9	3.40	0.21	103	144	113	199	760	328	212	738

R repeat analysis.
[a] Concentrations of Na to Mn in wt.%; Sr to P in μg g^{-1}.

phase in some of the basalts (Sukeshwala et al., 1972; Jeffery et al., 1988; Das et al., 2005b). Black coloured vertisols and laterites dominate the soils of the basins (Krishnan, 1982; Deshpande, 1998). The black soils are fine textured with abundant smectite (Bhargava and Bhattacharjee, 1982; NRSA, 1998). Some of these soils are salt affected containing chlorides, bicarbonates, and carbonates of Na in different proportions (Bhargava and Bhattacharjee, 1982). Laterite soils occur in low-lying coastal areas between Ratnagiri and Bombay and also in patches on the summits of the Western Ghats (Widdowson and Cox, 1996). These soils are deficient in Ca, Na, Mg and several trace elements resulting from continuous leaching of parent basalts (Widdowson and Gunnell, 2004).

The climate of the Deccan Province is subtropical, with semi-arid to arid climate in the Bhima and in some parts of the upper Krishna river basins. The rainfall in the study area is highly variable, averaging ~700 mm y^{-1} in the rain shadow region east of the Western Ghats and

~2500 mm y^{-1} in west of the Western Ghats. About 85% of the annual rainfall occurs during July to October, the period of southwest monsoon. The rainfall pattern is also reflected in the river discharge, as >80% of their flow is during monsoon (UNESCO, 1993). The runoff of the Krishna basin in the Deccan Traps is ~476 mm y^{-1}, much lower than that in the basins of the west flowing rivers ~1685 mm y^{-1} (Das et al., 2005a). The Bhima and its tributaries, the Ghod and the Nira, have dams upstream of sampling locations, which restrict their water flow even during monsoon. The surface air temperature of the region ranges from 10 °C to 14 °C in winter and between 31° to 37 °C in summer with a mean annual temperature of ~25 °C.

3. Sampling and analyses

Twenty-eight samples of river sediments from seventeen rivers draining the south-western Deccan Traps were collected during 2001 (Fig. 1). The details of sampling are given in Das et al. (2005a). The sampling locations were away from cities and towns to minimize the influence of domestic and industrial contributions. The sediments were collected with a pre-cleaned plastic scoop, stored in plastic bags, and brought to the laboratory. In the laboratory, part of the sediments was transferred to glass beakers and dried at ~90 °C. The dried samples were powdered to <100-μm size and stored in plastic containers. Care was taken to avoid metal contacts during powdering and sieving. A known weight of the powdered sediments was taken in quartz crucibles and combusted at ~450 °C for 6 h to oxidize organic matter in them. The ashed samples were transferred quantitatively to teflon dishes and digested repeatedly with HF–HCl–HNO_3 acid mixture to bring them to solution. The solutions were made to known volume and diluted suitably for various measurements.

The analytical techniques used for elemental concentration measurements are: Flame AAS (for Na, K, Fe, Mn, Cu and Zn) and ICP-AES (for Ca, Mg, Al, Ti, Sr, Ba, V, Cr and Ni). Phosphorous was measured by spectrophotometry of its molybdenum blue complex at 885 nm. In addition, carbonate content of the sediments and basalts was also determined by coulometry.

Five samples were digested in duplicate and analysed to determine the overall precision of measurements. The accuracy of measurements was checked by analysing the USGS standard W-1. The concentrations of major elements in reagent blanks were very low compared to the samples; and for most of the trace elements the concentrations were found to be at or below detection limits.

4. Results and discussion

The measured concentrations of major and minor elements in sediments and their carbonate contents are given in Table 2. The carbonate content is expressed as $CaCO_3$; calculated assuming that all the measured carbonate is $CaCO_3$. The elemental concentrations in Table 2 are either in wt (%) or μg g^{-1} in oven dried (~90 °C) samples. The results of analysis of W-1 show that the measured concentrations of various major elements agree on average within ±~2% of their reported values (http://www.geoanalyst.org), while the agreement is within ±~5% on average for trace elements (Das, 2005). The precision of measurements for various elements, based on their coefficient of variation derived from the five sets of duplicate measurements, is better than ±3%.

The $CaCO_3$ content of samples range between ~0% to ~16.9%, the high concentrations (>0.5 wt.%) are in sediments from the Bhima tributaries and from the Bhima and Krishna mainstream. Many of these rivers, particularly the Bhima and its tributaries and some of the Krishna waters are supersaturated w.r.t. calcite (Das et al., 2005b) indicating that a potential source of $CaCO_3$ in these sediments can be its precipitation from river water (Das et al., 2005b). Further, some of these regions are semi-arid and the wetting and drying cycles can facilitate calcite precipitation as has been observed in the Ganga plains (Sarin et al., 1989). The occurrences of $CaCO_3$ as calcretes and tufas in soils and colluvial deposits of these regions has also been reported (Patil and Surana, 1992; Pawar and Kale, 2006). It is suggested that the calcretes and tufas are formed by their precipitation from soil/groundwater rich in Ca and HCO_3, during drier season following the loss of CO_2. Patil and Surana (1992), in their extensive studies of carbonates of the region observed that they occur in several forms (e.g., nodular, powder, laminar) and more importantly are often associated with minor amounts of dolomite. These calcretes can be a source of carbonates in the sediments.

The major element composition of the sediments are presented in two ternary diagrams (Fig. 2a,b). On the Al_2O_3, (CaO*+Na_2O) and K_2O (A–CN–K) ternary diagram, the points lie evenly spread along the mixing line between A–CN apices (* denotes CaO from silicates; Fig. 2a) bound by two end members with composition of average Deccan basalt and average laterites (Subbarao et al., 2000; Widdowson and Gunnell, 2004). The spread of the points along the mixing line suggests that the bed sediments have been subject to different degrees of weathering. The extensively weathered samples, with

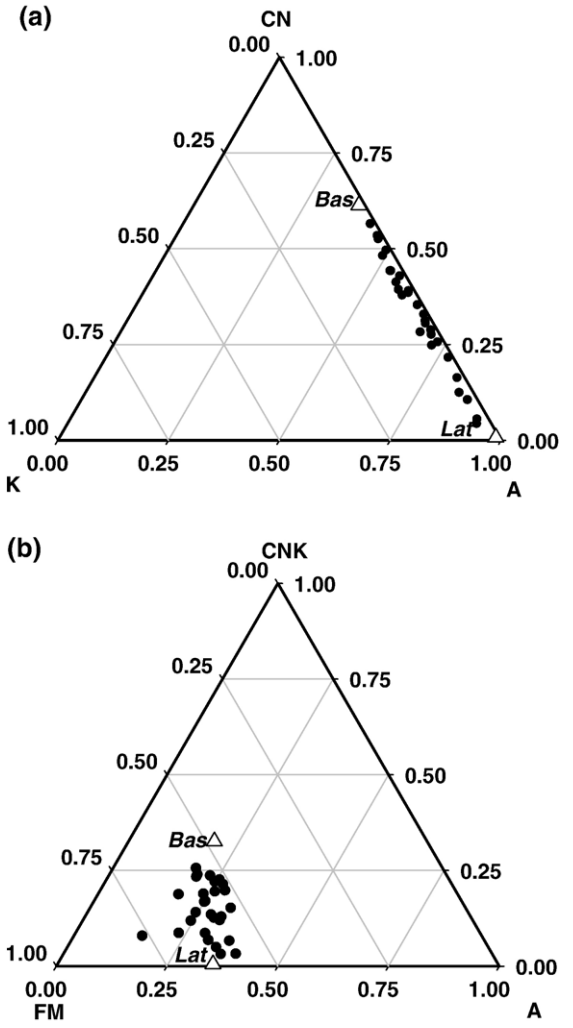

Fig. 2. Ternary diagrams of sediment composition. In the A–CN–K diagram (a), the data plot along a line bound by the parent rock, Basalt (Bas) and the end product of weathering, laterites (Lat) indicating the varying degrees of chemical weathering undergone by the sediments. In the A–FM–CNK plot (b), the points scatter around the line joining basalts and laterites.

their composition close to that of laterites, are mostly from the east and west flowing smaller rivers, which are associated with higher rainfall. The dispersion of data in the Al_2O_3, ($CaO^* + Na_2O + K_2O$) and ($Fe_2O_3 + MgO$) [A–CNK–FM] ternary plot suggests that the sediment composition is dominated by contributions from the A and FM end members (Fig. 2b). This, as discussed later, is expected as chemical weathering of basalts in near tropical climate releases Ca, Na, Mg and Si to solution resulting in the formation of a residue with kaolinite/smectite clays and Al and Fe hydrous oxides. Comparison of the composition of the sediments with those of unaltered Deccan basalts, and laterites (plotted in Fig. 2a,b) shows that many of the data points cluster around the line connecting them. However, some samples plot away from the mixing line, towards the FM apex. This could arise for reasons such as fractionation between Fe and Al during weathering, contribution of Fe from weathering resistant minerals and precipitation of oxides, (oxy)-hydroxides of Fe.

Compared to average basalts (Table 1), the sediments are significantly depleted in Na, Mg, Ca and Sr, and enriched in Al, Fe and Ti (Table 2). This depletion/enrichment in elemental abundances is a measure of the intensity of alteration of Deccan basalts by chemical weathering and subsequent removal of various elements by rivers. These are discussed in some detail in the following sections. In these discussions, it is, however, recognized that river sediments are subject to size and mineral sorting during transportation and deposition which can influence their mineralogical and chemical composition (Pettijohn, 1975).

4.1. Sodium, magnesium, calcium and strontium

These four elements are grouped together, as all of them are depleted in sediments relative to basalts (Tables 1 and 2). The frequency distributions of Na, Mg, Ca_{sil} and Sr abundances in sediments are shown in Fig. 3(a–d). Ca_{sil} is Ca from silicates; it is calculated by subtracting from the total Ca, the Ca contribution from carbonates (assuming that all measured carbonate is $CaCO_3$). The average concentrations of Na, Mg and Ca_{sil} in the sediments are a factor of ~3 lower than their average abundances in Deccan basalts (Table 1). Further, the concentrations of all these three elements in *all* the sediment samples analysed are less than their average abundances in basalts (Fig. 3a–c) and also in all the six Deccan Trap Formations present in the river basins. These results suggest that Na, Mg and Ca are very mobile during chemical weathering and erosion of the Deccan basalts. The decrease in the concentration of Na and Mg in sediments relative to basalts would be more pronounced if only $CaCO_3$ poor sediments (<0.5 wt.%) are considered for comparison. The sediments from the Krishna and Bhima mainstream and the Bhima tributaries which contain >0.5 wt.% $CaCO_3$ (Table 2) also seem to have marginally higher Na and Mg (Table 2). (Average Na and Mg concentrations in sediments with <0.5% $CaCO_3$ are 0.43 and 1.35 wt.% respectively, ~25% lower than the average of all the samples analysed). A likely cause for this is that these $CaCO_3$ rich sediments have been subject only to limited extent of chemical weathering and erosion. Further, in sediments with >0.5% $CaCO_3$, both Na and Mg show a significant correlation with $CaCO_3$ abundance

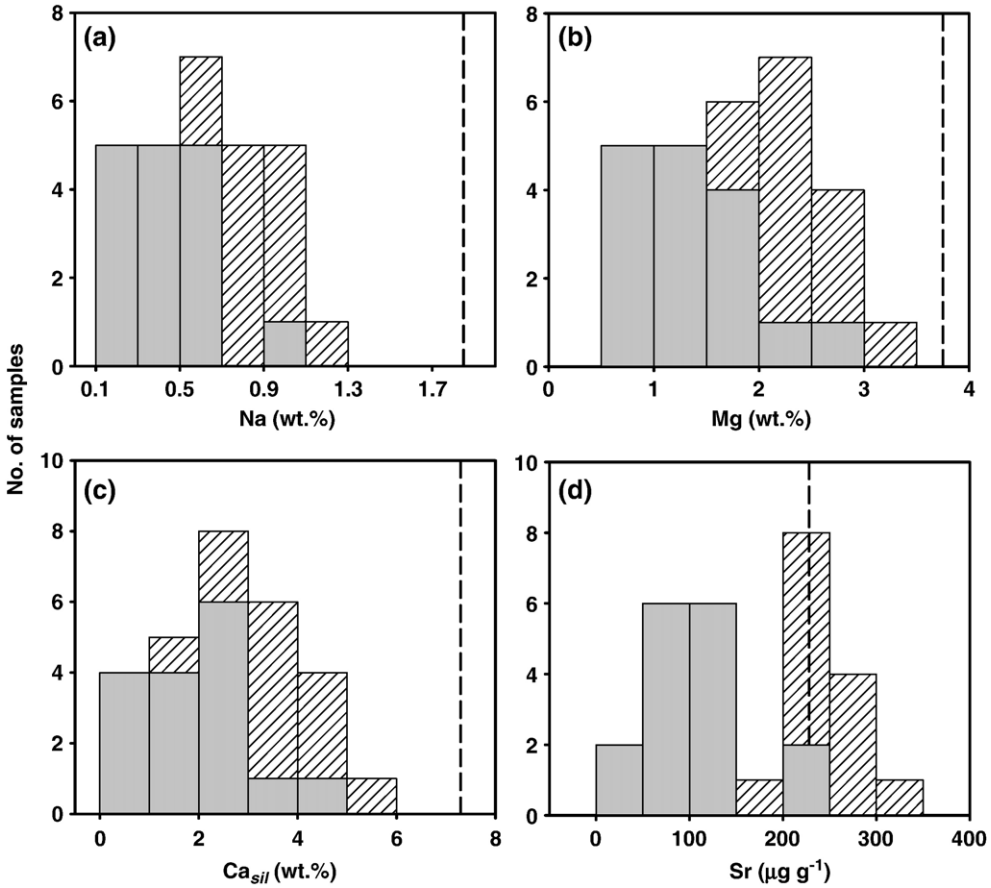

Fig. 3. (a–d). Frequency distribution of abundances of Na, Mg, Ca_{sil} (all in wt.%) and Sr (μg g^{-1}) in sediments. The samples are divided into two groups: (▭) samples with <0.5% $CaCO_3$ and (▨) >0.5% $CaCO_3$. The dashed vertical lines are the average abundances in basalts (Table 1). The concentrations of Na, Mg, and Ca_{sil} in all samples are less than the average in basalts.

(except for GHOD-2). This can result if the abundances of all these three sediment constituents are influenced by a common variable such as climate. The arid/semi-arid climatic condition of the region may facilitate $CaCO_3$ precipitation while restricting the chemical weathering/erosion of basalts. In case of Mg, the observation of Mg–$CaCO_3$ correlation (in sediments with >0.5% $CaCO_3$) coupled with the findings of Patil and Surana (1992) that calcretes of the region often contain minor amounts of Mg as dolomites hints at the possibility that part of Mg in these sediments may also be associated with carbonates. The primary mineral hosting Na in basalts is plagioclase (and also interstitial glass in the groundmass), for Mg it is pyroxenes and olivines, and for Ca it is plagioclase and pyroxenes. The groundmass in basalts is also made of these minerals along with altered glass (Devey and Lightfoot, 1986). The high mobility of Na, Mg and Ca from the Deccan basalts, therefore, suggests that all these primary silicate minerals are undergoing intense chemical weathering.

The behaviour of Sr during weathering by and large seems to follow that of Na, Mg and Ca_{sil}. The Sr concentrations in some of the sediment samples, however, are more than the average basalt value (Fig. 3d), unlike that of Na, Ca_{sil}, and Mg all of which are less abundant in all sediment samples relative to basalts. It is also seen that sediments with higher $CaCO_3$ have higher Sr concentration (see later discussion). In samples with $CaCO_3$ < 0.5%, the Sr ranges from 40 to 235 μg g^{-1} with a mean of 103 μg g^{-1}, a factor of ~2 lower than the average Sr in basalts 228 ± 32 μg g^{-1} (Table 1; Subbarao et al., 2000). Major Ca-rich mineral such as plagioclase is the primary host of Sr in basaltic rocks. Among accessory minerals, apatite could be an important source for Sr. The factor of ~2 lower concentration of Sr in sediments relative to parent basalt, would suggest intense solution of plagioclase consistent with the inference derived earlier from Na and Ca_{sil} data.

The high mobility of Na, Ca_{sil}, Mg and Sr during weathering and transportation is also borne out from the

relation of their concentrations to that of Al (Fig. 4a–d). The abundances of all these four elements in sediments decrease as Al increases, suggesting their contrasting geochemical behaviour during weathering and transport. As weathering progresses Na, Ca_{sil}, Mg, Sr and other more labile elements of rocks are released to solution, thereby continuously depleting them in the residual solid phases. This results in a concomitant increase in the concentrations of the more weathering resistant elements (Al, Ti, Fe) in sediments and hence in an anti-correlation in the abundances of these two groups of elements (Fig. 4a–d). Al is generally used as a normalizing element as it is one of the least mobile elements during chemical weathering (Garrels and Mackenzie, 1971; Nesbitt and Wilson, 1992; Gislason et al., 1996). Its concentration in sediments shows a factor of ~2 variation, from a low value of 5.8 wt.% to a high of 10.4 wt.% (Table 2). These are on either side of its average concentration in basalts (7.3±0.5 wt.%, Table 1). Al in basalts is mainly associated with plagioclase, and in sediments it is a major constituent of clay minerals. The average Al content of lateritic soils from Deccan basalts can be quite high, ~18 wt.% (Widdowson and Gunnell, 2004).

Lower Al concentrations in sediments, as compared to the mean basalt value, can be interpreted in terms of particle sorting and/or dilution with Al poor phases such as carbonates. Indeed, sediments with low Al, from the Bhima tributaries and mainstreams of the Bhima and Krishna, have high $CaCO_3$ (Table 2), highlighting the importance of $CaCO_3$ in diluting their Al content. Calculation of Al concentration on a $CaCO_3$ free basis narrows down its range from 6.5 wt.% to 10.4 wt.%, with all but three samples having values in excess of

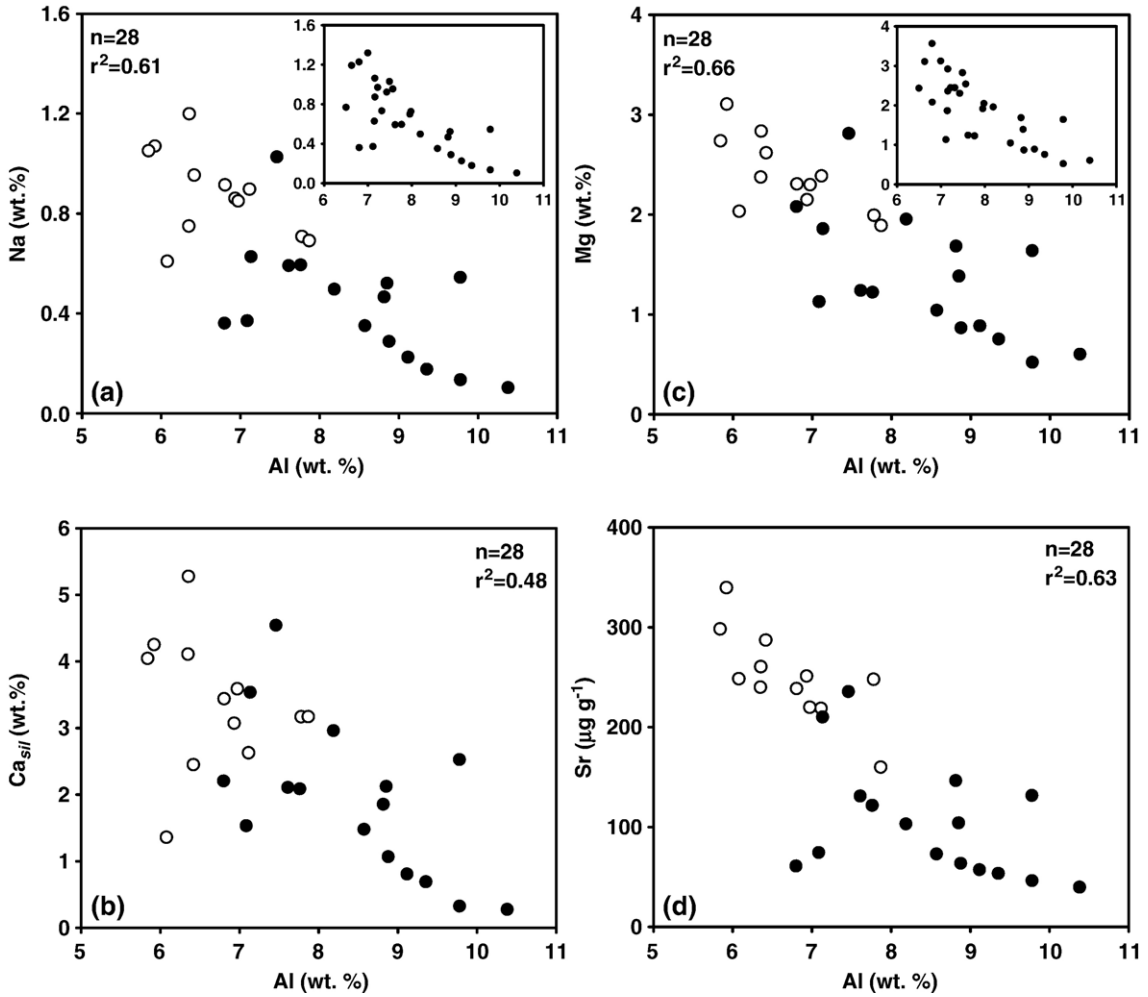

Fig. 4. (a–d). Scatter plots of Na, Ca_{sil}, Mg and Sr vs. Al. The data show an inverse correlation, resulting from the loss of Na, Mg, Ca_{sil} and Sr and other mobile elements from basalts to rivers during chemical weathering and concomitant increase of Al in the residue. Open circles are samples with >0.5% $CaCO_3$. The inset shows the plot on a $CaCO_3$ basis. The trend in both the plots, as evident, is similar.

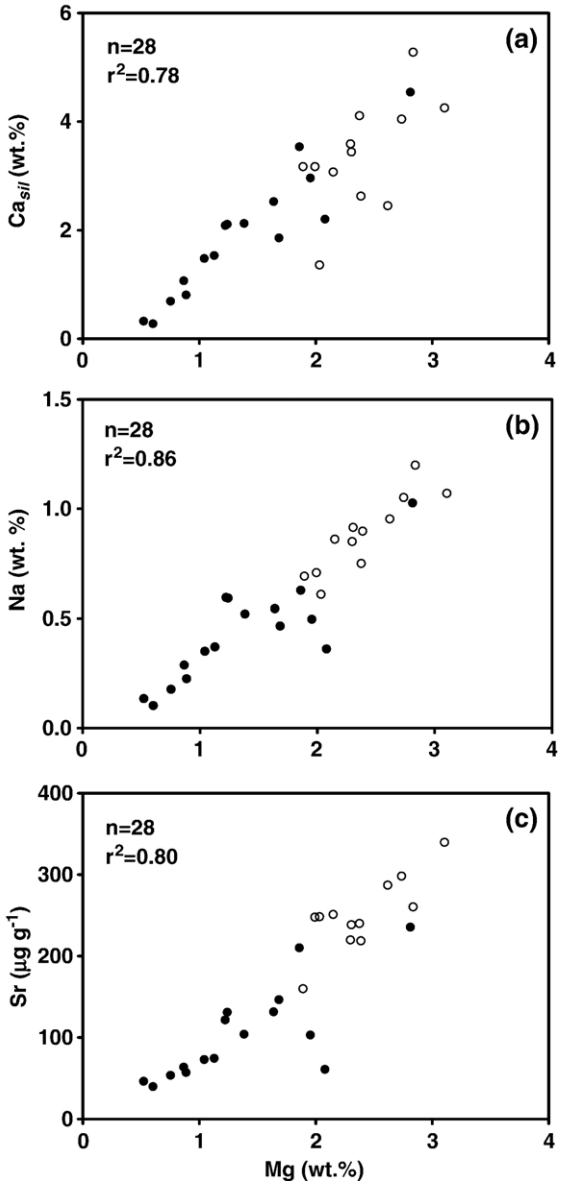

Fig. 5. (a–c). Scatter plots of Ca_{sil}, Na and Sr vs. Mg. The plots show strong linear trends. The element/Mg ratios of sediments are similar within errors to that in basalts and river waters, indicating near congruent release of all these elements during chemical weathering. Open circles are samples with >0.5 wt.% of $CaCO_3$.

7.0 wt.%. Even the three low Al-samples have Al concentration within $\pm 2\sigma$ of mean Al in basalts. The trend in Fig. 4 for Mg and Na would remain roughly the same if $CaCO_3$ corrected data are used in the plot. It is, however, to be noted that the role of $CaCO_3$ and/or an associated phase in hosting part of Mg (and Sr) of sediments is not well understood and hence difficult to quantify. The enrichment of Al in sediments can result from: (i) the loss of more mobile major elements such as Ca, Mg, Na and Si from parent rocks to solution accompanied by the formation of secondary minerals which sequester Al (and other elements, e.g., Stefansson and Gislason, 2001) such as zeolites, smectites/kaolinites and their precursors, Al enriched laterites and/or (ii) particle sorting, contributing to higher abundance of plagioclase in sediments. The lower abundances of Ca, Mg and Na in sediments relative to parent basalts, the occurrence of zeolites in basalts (James and Walsh, 1999) and smectite rich clays in particulates of the Krishna river and other Deccan Trap derived sediments (Naidu et al., 1985; Raman et al., 1995; Kessarkar et al., 2003) and lateritised soils rich in Al along the coastal tracts and summits of the Western Ghats (Widdowson and Cox, 1996; Widdowson and Gunnell, 2004) all favour the first alternative to be more prevalent in the basins sampled.

The abundance ratios of Na, Mg, Ca and Sr in sediments and in waters relative to that in Deccan basalts is a measure of their relative mobility. The composition of river water represents contemporary weathering dictated by the residence time of river waters whereas the sediment composition provides an integrated weathering signal averaged over the residence time of sediments in the drainage basin. Estimates of chemical erosion time scales of particulate matter in the Narmada and Tapti rivers of the northern Deccan basin, based on U series disequilibrium studies (Vigier et al., 2005) suggest that it is variable and can be upto 100 ka. If such time scales are applicable to the basins sampled in this work, it would lead to infer that the sediment composition represents elemental mobility over several thousands of years. Fig. 5a is a plot of Ca_{sil} vs. Mg (wt.%), which shows a strong positive correlation ($r^2 = 0.79$) with a slope of 1.58 ± 0.16 (Table 3) similar to the arithmetic mean Ca_{sil}/Mg wt. ratio of 1.34 ± 0.38. These ratios though seem to be lower than the average Ca/Mg (wt. ratio) of 1.95 ± 0.28 in basalts they overlap within errors. The similarity in all these ratios within errors can be interpreted in terms of near stochiometric release of Ca and Mg from Deccan basalts, however, the possibility that on an average Ca may be slightly more mobile ($\sim 25\%$) relative to Mg cannot be ruled out. (The calculation of these ratios in sediments assumes that there is no contribution of Mg from carbonates.) If, however, some of the Mg is of carbonate origin, it has to be accounted for to derive Mg content of silicate phases. Such a correction would enhance the Ca/Mg in silicate component of the sediments from those derived above (Fig. 5a) and bring it closer to the basalt ratio, strengthening the hypothesis of near stochiometric release of both Ca and Mg during chemical weathering.

(Indeed, if samples with $CaCO_3 > 0.5\%$ are excluded from the regression analysis, the slope of Ca_{sil}–Mg line increases to 1.76 ± 0.18; $r^2 = 0.88$). The gross similarity in the mobility of Ca and Mg derived from the sediment data is also consistent with the conclusions based on dissolved Ca and Mg in these rivers. The Ca/Mg wt. ratios (after correcting for atmospheric contribution) for the Krishna river and its tributaries and for the WGWF rivers are 2.28 ± 0.35 and 2.1 ± 0.13 respectively. These ratios overlap within errors with the average Ca/Mg wt. ratio of 1.95 ± 0.28 in basalts, though the water values seem marginally higher. These results have been interpreted (Das et al., 2005a) in terms of similar mobility of Ca and Mg or a slight preferential mobility of Ca relative to Mg from basalts to rivers. Similar to Ca, Na also shows a strong positive correlation with Mg in sediments ($r^2 = 0.86$; Fig. 5b; Table 3) with a slope of 0.39 ± 0.03 as compared to Na/Mg (wt. ratio) of 0.51 ± 0.13 in basalts. The slope in sediments seems ~20% lower than the ratio in basalts, though they overlap within errors. This would imply either that Na is slightly more mobile than Mg or that the mobilities of both Na and Mg are grossly similar. The latter interpretation is consistent with inferences drawn from their dissolved concentrations (Das et al., 2005a).

Fig. 5c is a plot of Sr with Mg, which also shows strong positive correlation. In samples with <0.5% $CaCO_3$, the slope of the Sr–Mg line is 73 ± 16 (Table 3), overlapping with their ratio in basalts (μg g^{-1}/wt%). This indicates that Sr and Mg are released from basalts to waters nearly congruently, consistent with the conclusion drawn from their dissolved phase data (Das et al., 2006). In $CaCO_3$ rich sediments ($CaCO_3 > 0.5$ wt.%), Sr, analogous to Na and Mg, also shows a significant correlation with $CaCO_3$. Further, in some of these sediments Sr abundance and Sr/Al exceed the average value in basalts. These observation though hint at the possibility that $CaCO_3$ or an associated phase may be a carrier for Sr, it is difficult to justify this from the known very low Sr partition coefficient into calcite ($K^{Sr-Ca} \ll 1$; Jacobson et al., 2002) and typical Sr/Ca molar ratio measured in the Krishna river waters. Therefore, similar to Na and Mg, the higher Sr concentration in these samples is likely to be more of a result of less intense chemical weathering and erosion of basalt due to prevailing arid/semi-arid climate which also promotes $CaCO_3$ precipitation. Variability in Sr and Sr/Al of source rock, therefore, may have to be invoked to explain the high Sr and Sr/Al measured in some of the $CaCO_3$ rich samples.

Thus, the strong inter-element correlation among Na, Ca, Mg and Sr in sediments and their ratios suggest that all these elements are released from Deccan basalts to rivers grossly in the same proportion (±~25%) as their abundances in basalts though there is a hint of marginal preferential release of Ca and Na over Mg and Sr. The Deccan Trap basalts, therefore, are weathering roughly congruently with respect to these four elements, a conclusion consistent with that arrived based on major ion chemistry of the Krishna river and its tributaries (Das et al., 2005a). The sediment and water data also indicate that on average the ratios of release of these four elements during the residence time of sediments in the various basins have been nearly the same as their contemporary supply ratios, both of which are roughly the same as in Deccan basalts.

4.2. Potassium and barium

Potassium is generally hosted in feldspar minerals in basalts. K though is known to be mobile element; the solid phase remaining after weathering is generally rich in K (Nesbitt et al., 1980). The K content in sediments is regulated by the abundance of K-rich minerals in it and exchange/adsorption of dissolved K on clay minerals (Nesbitt et al., 1980; Banfield et al., 1991). K concentration in sediments analysed vary from ~0.15 to 0.6 wt.% (Table 2) with an average of (0.37 ± 0.15)

Table 3
Regression parameters of co-variation of Ca_{sil}, Na and Sr with Mg

Pair (Y–X)		r^2	Intercept	Slope	Average ratio [a]	R_{bas}
Ca_{sil}–Mg	(n=28)	0.79	−0.3±0.3	1.58±0.16	1.34±0.38	1.95±0.28
	(n=16[#])	0.88	−0.5±0.3	1.76±0.18	1.29±0.41	
Na–Mg	(n=28)	0.86	−0.07±0.06	0.39±0.03	0.34±0.08	0.51±0.13
	(n=16[#])	0.71	−0.0003±0.08	0.32±0.05	0.31±0.09	
Sr–Mg	(n=28)	0.80	−32±21	110±11 [b]	89±22 [b]	61±13
	(n=16[#])	0.61	5±23	73±16	77±20	

[#]Samples with $CaCO_3 < 0.5$ wt.%.
[a] Arithmetic mean of individual ratios, R_{bas} is the ratio in basalts.
[b] Sr/Mg in μg g^{-1}/wt.%.

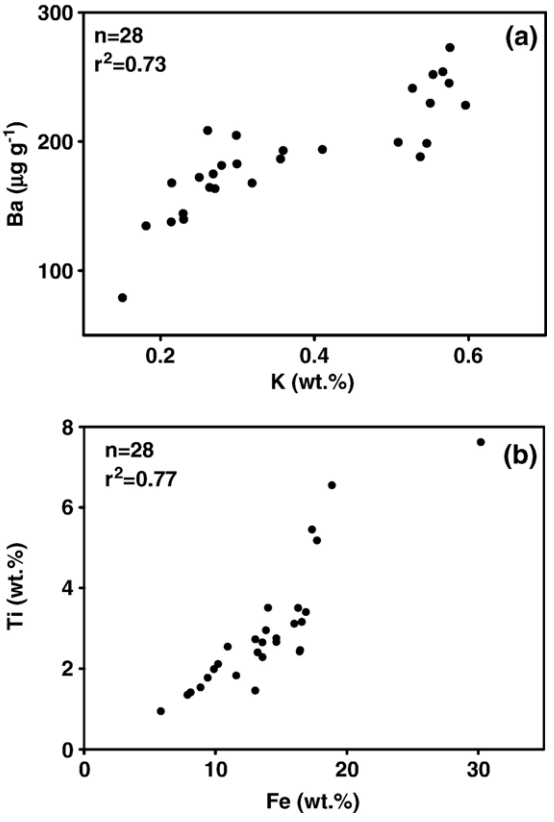

Fig. 6. (a) Scatter diagram of Ba vs. K in sediments. The data show that Ba and K co-vary, either attributable to incorporation of Ba in K minerals and/or their sequestration in solid residues, (b) Scatter plot of Ti with Fe. The data show strong linear trend, a cause for which can be presence of Fe–Ti weathering resistant minerals in sediments.

wt.%, overlapping with its abundance in Deccan basalts ~0.39±0.26 wt.% (Table 1). The distribution of K in sediments also does not show any significant correlation with other major elements. The similarity in average K abundance between basalts and sediments and its wide and overlapping range in them makes it difficult to assess the extent of its mobility during weathering of Deccan basalts. These results, seem to indicate that on average the mobilization of K from Deccan basalts is lower than that of Na, Ca, and Mg consistent with its distribution in weathering profiles from the Deccan (Wilkins et al., 1994) and the observations of Gaillardet et al. (1999b) that the weathering index of K in many large global rivers is several times lower that that of Na. Studies on the weathering of volcanics (Banfield et al., 1991) have demonstrated that smectites pick up K released to solution. One of the end products of chemical weathering of Deccan Traps is smectites, which may be trapping K and thereby contributing to its limited mobility.

Ba, though is a member of the alkaline earth group, its relation with Ca shows a significant scatter. This can be a cumulative effect of variability in Ba/Ca in basalts, and their different geochemical behaviour during weathering and transport. The range in Ba concentration in sediments, 79 to 273 μg g^{-1}, is similar to the range, 48–285 μg g^{-1} in basalts. The average Ba in sediments (189±43 μg g^{-1}) and its ratio with Al (25±7; μg g^{-1}/wt.% and hereafter) seem to be marginally higher than the corresponding values in basalts (133±60 μg g^{-1} and 18±8) though they overlap within errors.

Das and Krishnaswami (2006) observed that the Ba/Al of sediments with $CaCO_3$ <0.5 wt.% (21±5) overlaps with the average basalt value whereas in sediments with $CaCO_3$ in excess of 0.5%, the Ba/Al was higher (30±5). This led to the suggestion of a potential association of Ba with $CaCO_3$. Analysis of the data, however, does not show any significant correlation of Ba with $CaCO_3$. Gaillardet et al. (1999b) reported that the world average weathering index of Ba is about an order of magnitude lower than that of Na. Such low weathering index for Ba, coupled with the wide range in its concentration both in parent rocks and in sediments, makes it difficult to assess its depletion/enrichment in sediments and therefore the extent of its mobility during weathering. In contrast to the solid phase data, the dissolved concentration of Ba and associated Ba/Mg ratio allow better assessment of its mobility during the weathering of Deccan basalts. These results (Das and Krishnaswami, 2006) show that the Ba/Mg ratios in water are of 2–3 times lower than that in basalts; suggesting limited mobility of Ba relative to Mg. Ba is generally hosted in feldspars, mainly K-feldspars (Prinz, 1967). Due to similar ionic radius, Ba can substitute for K in many K-bearing minerals (Wedepohl, 1972). The association between Ba and K in the sediments is evident from their strong correlation (r^2=0.73; Fig. 6a), similar to that observed in basalts (r^2=0.65). Dalai et al. (2004) also reported strong coupling between Ba and K in sediments of the Yamuna river system in the Himalaya. Another mechanism for the sequestration of Ba in sediments is its retention in clays and Fe-oxides/hydroxides. Smectites and its precursors and oxides/hydroxides of Fe, formed during weathering of Deccan basalts, can serve as traps for Ba and thus restrict its mobility.

The lesser mobility of K and Ba relative to Ca, Na and Mg is also evident from their abundance in laterites of Deccan Traps (Widdowson and Gunnell, 2004). The average concentrations of K and Ba in laterites are similar to their average abundance in basalts whereas Ca, Na and Mg are 1–2 orders of magnitude lower. The

trend remains the same even if the data are normalized to Al attesting to the lesser mobility of these two elements.

4.3. Iron and titanium

Iron and titanium, analogous to Al, are two other elements, which because of their geochemical properties are known to be least mobile during weathering of basalts and therefore retained in the solid phase (e.g., Gislason et al., 1996).

In basalts, Fe occurs in ferromagnesium silicates and weathering resistant minerals, magnetite, titanomagnetite, and ilmenite; the latter two also hosting Ti. The dominant minerals of Ti in Deccan basalts are titanomagnetite, ilmenite and rutile (De, 1974). These are some of the highly weathering resistant minerals and hence are expected to be retained in sediments contributing to the enrichment of Fe and Ti in them relative to basalts.

Fe abundance in sediments varies widely, from a low 5.85 wt.% to a high of 30.2 wt.% (Table 2). Fe/Al ratios in the samples range from 0.96 to 4.4, with many of them having ratios in excess of 1.8 (average Fe/Al in basalt = 1.4 ± 0.24). These data suggest that Fe is enriched over Al in many of these sediments relative to basalts. Chemical weathering can contribute to fractionation between Al and Fe (Banfield et al., 1991). The primary silicate phases hosting Fe in basalts are pyroxenes and olivines, in these minerals Fe occurs in divalent state (Fe^{+2}). During chemical weathering of these silicates, Fe^{+2} is released to solution, the subsequent fate of which depends on the redox state of the solution. In oxic environments Fe^{+2} is oxidized to Fe^{+3}, which because of its 'reactive nature' and low solubility in natural sediment–water system is precipitated as hydroxide/hydrous oxides (e.g. goethite) and retained in sediments. Distribution of Fe in soil profiles of Deccan provides evidence for such mobilization of Fe (Kisakurek et al., 2004). In these profiles, the abundance of Fe_2O_3 increases from 13.5% in the unaltered bedrock to ~80% in the laterite attesting to the enrichment and retention of Fe in the laterites. Mineralogical analysis of these samples shows that augitic clinopyroxene in the parent basalt is broken down to hematite, goethite and clay minerals. In the Deccan, laterites are distributed in the western coast and in the Koyna river basin (Widdowson and Cox, 1996). These laterites can be a source of high Fe to sediments of rivers draining them. In addition to chemical weathering, size sorting and mineral differentiation in sediments can also bring about Fe–Al fractionation. Part of Fe (or Ti) in sediments is known to be associated with the coarser size fractions whereas Al is more concentrated in the finer fraction, clay minerals. As a result, Al and Fe (Ti) can be fractionated in solid phases of rivers depending on the energy carried by the stream. Many samples, such as the KJL-1 and DDG-1 show higher Fe/Al ratios than others; these samples also have higher concentration of Ti. This co-variation is attributable to the presence of weathering resistant Fe–Ti minerals.

Ti in sediments varies from 0.94 to 7.6 wt.% (Table 2) compared to an average of 1.3 wt.% in basalts (Subbarao et al., 2000). Analogous to Fe, Ti also shows an enrichment w.r.t. Al in some of these sediments. The highest abundance of Ti is in KJL-1 (Table 2), which also is most abundant in Fe (30.2%). In general, Ti shows a tight correlation with Fe ($r^2 = 0.77$; Fig. 6b), indicating a strong association between them in sediments.

4.4. Depletion/enrichment of elements

The percentage depletion or enrichment (PD or PE respectively) of an element in sediment is a measure of its loss (or gain) from the parent rocks due to chemical weathering and subsequent mobilization. It is calculated using the relation (Canfield, 1997);

$$(\text{PD or PE}) = [\{(X/Al)_{sed} - (X/Al)_{bas}\}/(X/Al)_{bas}] \times 100 \quad (1)$$

where X = Na, Mg, Ca, Sr etc. and $(X/Al)_{bas}$ is the element to Al ratio in basalts. The calculations of PD (PE) should in principle be based on element to Al ratios of sediments and basalts from the same river basins. As data on the aerial exposures of various Deccan Formations in individual river basins are unavailable, in this work the average composition of Deccan basalts is used for these calculations. Both these approaches are expected to yield similar PD/PE values as the average elemental concentrations (particularly Ca, Mg, Na and Sr) among the various Formations ((Table 1) vary only within a limited range and they match within errors reasonably well with the overall average composition of Deccan basalts). It is however recognized that the accuracy and precision of calculated PD (PE) values would depend on better knowledge of the elemental abundances and associated uncertainties in the parent basalts in individual river basins. The percentage depletion or enrichment of Ca, Mg, Na and Sr is reported in Table 4.

Na is depleted in the sediments from 26 to 96% with an average of ~65%. This implies that on average about two-thirds of Na is lost from basalts to dissolved phase in rivers over the residence time of sediments. The average depletion of Mg and Ca_{sil} are also similar

Table 4
Average percent change[a] of Na, Mg, Ca_{sil} and Sr in sediments

Element	n	% change	
		Range	Mean ± 1σ
Na	28	−26 to −96	−65±20
	16	−46 to −96	−79±13
Mg	28	+3 to −90	−51±26
	16	−26 to −90	−67±18
Ca_{sil}	28	−17 to −97	−65±22
	16	−39 to −97	−76±16
Sr	28	+85 to −88	−24±50
	16	+2 to −88	−59±26

+ indicates enrichment, − depletion.
n=28 (all samples) and n=16 (samples with $CaCO_3$<0.5 wt.%).
[a] PD/PE, calculated based on Eq. (1). See text.

to that of Na, 51% and 65% respectively. Sr shows both depletion and enrichment. The depletion varies from 1 to 88% (average: 58%; n=17). If these calculations are made by excluding sediment samples with $CaCO_3$>0.5 wt.%, the average percent depletion of Mg and Sr becomes 67 and 59 respectively (n=16). The similarity in the average depletion factors of Na, Mg, Ca and Sr further attests to the conclusion arrived earlier that all these four elements are mobilized from Deccan basalts to river waters nearly congruently.

Distribution of PD (PE) values among the various sub-basins shows significant differences, suggestive of spatial variability in mobilization of elements. The basins of the small east flowing tributaries of the Krishna and those of WFWG rivers generally have higher depletion of elements indicating the occurrence of more intensely weathered sediments in these basins. The poor availability of the easily weatherable elements, Na, Ca and Mg in these sediments is also reflected in their relatively low dissolved concentrations in many of these rivers (Das et al., 2005a).

Analogous to Na and Ca, Sr also shows maximum depletion in sediments of the east flowing smaller tributaries of the Krishna and of the WFWG rivers. In sediments from the Krishna, Bhima mainstreams and the Bhima tributaries, Sr behaviour is inconsistent. For example, in sediments of the Bhima tributaries, there is an enrichment of Sr. This can result if part of Sr is contained in $CaCO_3$ and/or in an authigenic phase associated with $CaCO_3$ and which is present in the Bhima system sediments (Table 2). This hypothesis, as mentioned earlier, is difficult to validate in light of very low partition coefficient of Sr in calcite and known Sr/Ca ratio in waters.

Weathering profile studies by Wilkins et al. (1994) from the Deccan basalts to a bole also suggest the depletion of Ca (~60%) and Na (~75%) from basalts. K behaviour in this profile is highly variable and shows little apparent change. Fe and Al abundances though exhibit depth variation; there is no discernible trend within the profile. The results borne out of the present study are consistent with the findings based on the weathering profiles.

The relative mobilities of elements during chemical weathering of Deccan basalts in the river basins investigated are (Na ≈ Ca ≥ Mg ≈ Sr) > (K ≥ Ba) > (Al ≥ Fe ≈ Ti). Earlier investigations on chemical weathering of continental and island basalts have brought out the importance of factors such as (i) their age and composition, (ii) rainfall (runoff) and mechanical erosion of the basin and (iii) the formation of secondary minerals, in determining the relative mobilities of elements and their depletion in sediments. Chesworth et al. (1981) in their studies of basalts from Belbex (France), and Gislason et al. (1996) on Iceland basalts observed that the age of the basalts has a significant influence on the relative mobilities of elements. In 'young' basalts from Iceland (Gislason et al., 1996) Na is far more mobile than Ca and Mg, with mobility decreasing as Na > K ≥ Ca > Mg > Sr, compared 'older' basalts in which the mobility trend is Na > Ca ≈ Mg ≈ K > Sr. This change in the trend between the young and old basalts was attributed to decrease in the deposition of alteration products during weathering in 'older' basalts due to limited availability of easily weatherable glass and enhanced solution of plagioclase. Chadwick et al. (2003) in their investigations on the impact of climate on biogeochemical processes in Hawaiian volcanics observed that rainfall is a key factor determining mineral weathering and secondary mineral formation. Their results also showed that these volcanics weather rapidly and congruently and that the leaching losses of Ca, Na, K and Mg all follow grossly similar trend with rainfall. Study of contemporary denudation rates on Reunion Island (Louvat and Allegre, 1997) shows that the intensity of basalt weathering is low due to dominance of mechanical over chemical erosion. This low chemical weathering intensity of basalts coupled with variability in the basalt composition constrains the estimation of the extent of depletion of Na, Ca, Mg and Sr and other mobile elements from them. Deccan basalts, as mentioned earlier, were all emplaced about 65 Ma ago; there are no 'young' Deccan basalts. These basalts are subject to tropical climate and monsoon rains. The present day intensity of chemical weathering and erosion of these basalts has been shown to be dependent on rainfall, the WFWG river basins which receive higher rainfall are eroded more intensely than the interior basins of the Krishna river system (Das et al., 2005a). The relative mobilities of groups of elements in these river basins during chemical

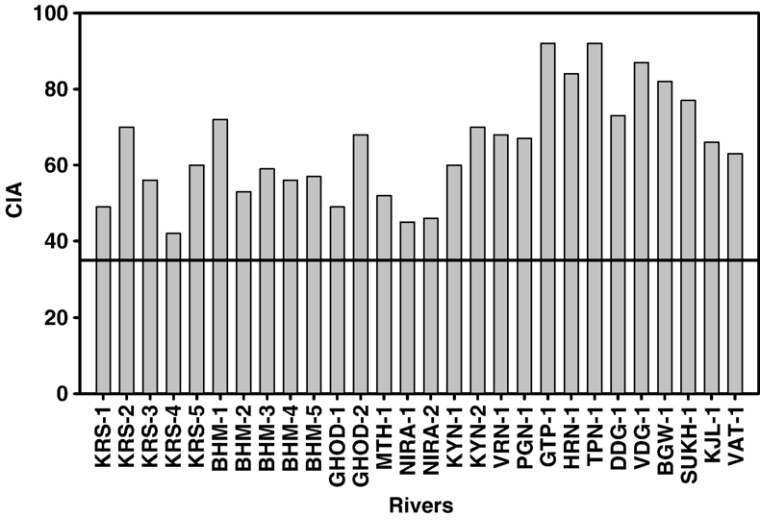

Fig. 7. CIA (Chemical Index of Alteration; see Section 4.5) values of individual river sediments. The line parallel to *X*-axis is the average CIA for un-altered Deccan basalts. The height of the bars above the line is a measure of the extent of alteration of sediments relative to basalts. The CIA values range from 42 to 92 and suggest that there is spatial variability in weathering intensity among the various sub-basins of the Krishna system.

weathering of the Deccan basalts, viz., the high mobility of (Na, Ca, Mg and Sr) and nearly immobile nature of (Fe, Al and Ti) are grossly similar to those reported for some of the other basaltic regions. There, however, are differences in the trends of relative mobilities of various elements within the group among the various basaltic regions, this is not unexpected considering the number of factors which govern them.

4.5. Chemical Index of Alteration (CIA)

One approach to quantify the extent of chemical weathering is through the calculation of chemical index of alteration, CIA, (Nesbitt and Young, 1982) defined as

$$\mathrm{CIA} = [\mathrm{Al_2O_3}/\mathrm{Al_2O_3} + \mathrm{Na_2O} + \mathrm{K_2O} + \mathrm{CaO^*}] \times 100. \quad (2)$$

The CIA values are calculated using the molar concentrations of the oxides. As weathering progresses, the more labile cations (e.g., Na, Ca) would be released from the source rocks, thereby depleting their concentrations in the residual material. In contrast, the less mobile elements such as Al, Fe and Ti concentrations would increase in the residue. Thus, with increase in silicate weathering, the CIA values would increase, ultimately reaching the limiting value of 100. The average CIA value of Deccan basalts, based on their average composition (Table 1) is ~37 and ranges from 35 to 44 for the various Formations. In contrast, the CIA values of laterites from the coastal regions of the Western Ghats (Widdowson and Gunnell, 2004) can be calculated to be ~100. The high CIA value for laterites is expected as the abundances of Ca, Na and K in them are quite low.

Fig. 7 is a bar diagram of CIA values of sediments analysed in this study with the reference line that of the un-weathered basalt. The height of the bars above the "basalt line" indicates the extent of chemical alteration of the sediments. It shows that the least altered sediment is KRS-4 (CIA=42) and the most altered is TPN-1 (CIA=92). The frequency distribution of CIA shows that it is fairly evenly distributed in the range of 40–80 indicating varying degrees of alteration. This is consistent with the observations made earlier from the distribution of sample data in the ternary plots (Fig. 2). Average CIA of the two large river systems, the Krishna and the Bhima, are roughly the same with values of 55± 11 and 59±7 respectively. In contrast, the smaller tributaries of the Krishna and the WFWG river sediments have higher CIA values of 75±11. These higher CIA values suggest more weathered sediments, which can result from higher rainfall and runoff in the region. The samples with high $CaCO_3$ (>0.5 wt.%) also have relatively low CIA values, 42–60, with an overall decreasing trend with increase in $CaCO_3$. This suggests that these sediments are poorly weathered and that $CaCO_3$ precipitation and low intensity chemical weathering are coupled, probably, through an environmental condition, arid/semi-arid climate. This finding attests to the earlier discussion on inter elemental association. Fig. 8 shows plots of PD with CIA (for samples having <0.5 wt.% $CaCO_3$). The plots of Ca_{sil}, Na, Mg and Sr show roughly similar, systematic and

continuous decreasing trend of PD with CIA, similar to that reported for the Baynton profile, Australia (Nesbitt and Wilson, 1992). These results confirm the earlier inferences that the mobility of these elements is roughly similar during chemical weathering. Further, there seems to be an indication from the trends in Fig. 8 that the magnitude of decrease in PD (Percent Depletion) is higher during the early stages of weathering relative to that during the later stages. A likely cause for this can be more rapid weathering of relatively "pristine" Deccan basalts. In contrast, to Ca, Na, Mg and Sr, Fe and Ba show enrichment with no discernible trend with CIA. The association of Fe and Ba with weathering resistant minerals, their limited mobility and their incorporation in secondary minerals formed during chemical weathering all can regulate their abundances and distribution in sediments and contribute to the observed scatter with CIA.

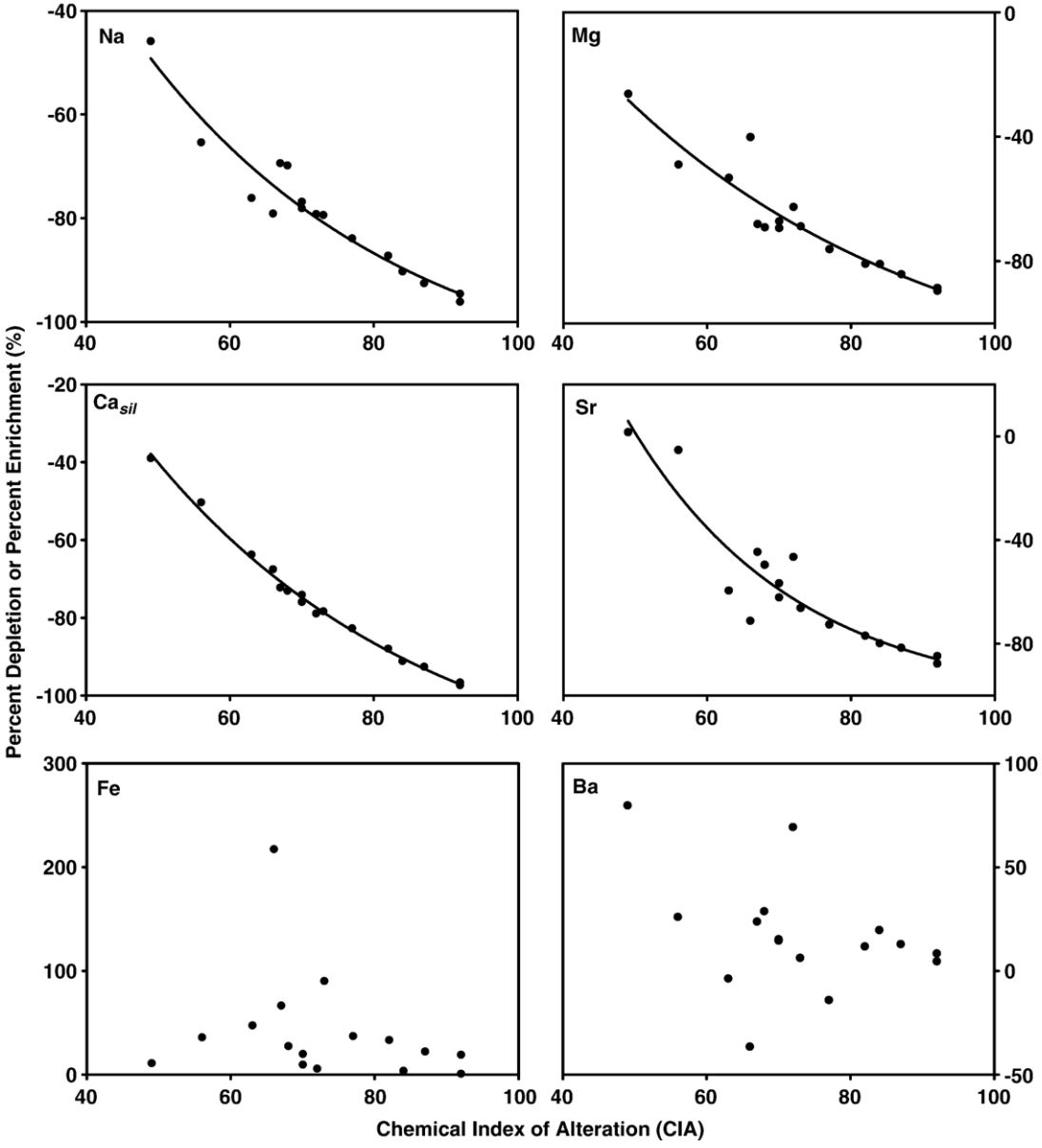

Fig. 8. Percent depletion (PD) of various elements in sediments vs. CIA values. The data show that the PD values decrease nearly similarly and continuously as a function of CIA for Ca_{sil}, Na, Mg and Sr. The lines are exponential fit for the data. The data suggest near congruent release of these elements during weathering and erosion of Deccan basalts. There is also a hint that the depletion of these elements during early stages of weathering may be more rapid. Fe and Ba are enriched in sediments and show scatter without any discernible systematic trend. Only samples with $CaCO_3 < 0.5$ wt.% are plotted.

4.6. Sediment composition and physical erosion

The concentrations of elements in particulate and dissolved phases, coupled with that of bedrock composition, have been used to estimate physical erosion of river basins (Martin and Meybeck, 1979; Stallard, 1995; Gaillardet et al., 1995, 1999b; Louvat and Allegre, 1997). This approach is based on a steady state erosion model which assumes that the amount of sediment produced in a drainage basin equals the amount exported by rivers. The model is a material balance between the amount of bedrock eroded and the amounts of solutes and solid residue produced. If $C_{bas}(i)$, $C_{sed}(i)$ and $C_r^{sil}(i)$ denote the concentration of element (i) in basalt, in solid residue and dissolved in rivers (derived from silicates) respectively, then the steady state material balance equation can be written as:

$$M_{bas}C_{bas}(i) = M_{sed}\cdot C_{sed}(i)\cdot\phi + C_r^{sil}(i)\cdot\phi \quad (3)$$

where M_{bas} is the mass of basalts eroded per year, M_{sed} is the mass of solid residue per unit volume of river water (g l^{-1}) and ϕ is the annual water discharge (l y^{-1}). For a weathering resistant element (e.g. Al), with almost no contribution from the dissolved phase to its budget, Eq. (3) reduces to

$$M_{bas}C_{bas}(Al) \approx M_{sed}\cdot C_{sed}(Al)\cdot\phi \quad (4)$$

Combining Eqs. (3) and (4) will yield an equation, which relates the weathering index of element (i), WI (i), to its concentration in rivers, in the solid residue and M_{sed}

$$WI(i) = 1 + C_r^{sil}(i)/M_{sed}\cdot C_{sed}(i). \quad (5)$$

The weathering index is defined as the Al-normalized ratio of the concentration of an element in basalts to that in the solid residue; $WI(i)=[C_{bas}(i)/C_{bas}(Al)]/[C_{sed}(i)/C_{sed}(Al)]$.

M_{sed} can be calculated from Eq. (5) and using the abundances of Na, Ca and Mg in dissolved phases and in the solid residue. Following Das et al. (2005a), in this work the abundances of Mg in rivers have been used as a proxy of silicate weathering and therefore to estimate M_{sed}.

The solid weathering residue formed during chemical weathering of rocks though includes both suspended and bed loads transported by rivers generally in these models only the abundance of suspended load and its composition are used to represent M_{sed} and C_{sed} respectively. In this work, the elemental abundances in river sediments were used for C_{sed} as composition of suspended matter was not measured. The major difference between suspended matter and river sediments is in their particle size and the extent of chemical weathering they have undergone. The suspended sediments are generally finer and more intensely weathered than sediments (cf. Louvat and Allegre, 1998). Therefore, WI(i) calculated based on sediment data is expected to be lower than that derived from suspended matter composition.

The calculated M_{sed} values show a wide range, 11–236 mg l^{-1}. The suspended matter concentrations of many of these rivers were determined by filtering ~300–500 ml of surface water collected away from the bank of rivers (towards mid-stream) through 0.4 μm Nucleopore filters. The ratio of calculated M_{sed} to that of measured suspended matter concentration varies over an order of magnitude, from 0.3 to 4.9. (In many samples the weight of suspended matter recovered by filtering 300–500 ml water was quite low. To avoid uncertainties arising from such measurements, only samples with >30 mg l^{-1} measured suspended matter concentrations are used for comparison). Of the eight samples available for comparison, in four the calculated and measured values agree within a factor of ~2, in two the calculated values are 3–4 times lower than measured and in the other two the calculated values exceed the measured concentration by factor of ~4. Different factors could be contributing to these discrepancies. One can be the use of sediment composition instead of that of suspended matter in the model. The suspended matter, as mentioned earlier, is expected to be more intensely weathered than the sediments and hence the concentration of Mg in them is likely to be less than that in sediments, whereas the trend for Al is likely to be the opposite. The effect of these will be to make the calculated M_{sed} values lower. In samples where the calculated M_{sed} exceed the measured values, this could be a determining factor. Another cause could be temporal and spatial variations in suspended sediment abundance. In the rivers sampled, which are fed by monsoon, there can be significant variations in sediment abundance and flux over short time intervals along the course of the river. Further, as the sediment concentration can vary from mid-stream to banks and from surface to bottom, determination of particulate concentration based on single sampling can be prone to more uncertainties. As a result, the representativeness of the one time sampling carried out in this work to determine the annual sediment flux can be in doubt. The presence of dams across some of the rivers could be another controlling factor. Further the model calculations rely on steady state assumptions, which have been shown to be questionable for the Narmada and Tapti

river basins draining the northern Deccan Traps (Vigier et al., 2005).

The physical erosion rates (PER) calculated from the model based M_{sed} values varies from ~5 to ~100 t km^{-2} y^{-1} (for eastern river basins) and ~140 to ~400 t km^{-2} y^{-1} (for the WFWG river basins). The area weighted PER for the entire Deccan Traps, with fractional areas of 94% and 6% respectively for the eastern and western river basins, is ~52 t km^{-2} y^{-1}. These rates are a few times the average chemical erosion rates obtained for these river basins (Das et al., 2005a). The average PER values are comparable to those reported for the north western region of the Deccan based on U isotope data for the Narmada-Tapti river systems and a steady state erosion model (Vigier et al., 2005). These authors, however, observed that the contemporary PER based on measured particle fluxes are about an order of magnitude higher than the calculated values, which they attributed to a non-steady weathering regime. Some of the sub-basins of the Krishna system also show significant difference between measured and calculated M_{sed} values, a cause for which could be non-steady state erosion. The difference in these values, however, could also be due to various other factors discussed earlier. The calculated M_{sed} for the Krishna and the Narmada-Tapti basins (Vigier et al., 2005) seem to suggest that the average PER in different regions of the Deccan could be similar, however, more representative sampling are needed to quantitatively estimate their magnitudes and variability.

4.7. Major element abundances and CO_2 budget

One of the objectives of studying chemical weathering in river basins is to derive CO_2 consumption rates and its impact on global CO_2 budget. Conventionally, this is done through measurements of dissolved major ions in river water which provide information on the contemporary weathering. An alternate approach to obtain chemical erosion rates of basin is by comparing major elemental abundance in parent rock with that of the river particulate load exiting the basin (McCauley and DePaolo, 1997). The erosion rate based on sediments is expected to be a time-averaged value as it would depend on the residence time of sediments in the basin.

It is shown from the results in Table 2 and ensuing discussions in earlier sections that the abundances of Na, Ca and Mg in sediments of the Krishna river are significantly lower than that in Deccan basalts. If the sediments analysed are representative of particulate matter exiting the rivers, then estimate of cation loss from the parent rock resulting from weathering can be derived using Al as a normalizer. The total cation (Na+K+Ca+Mg) loss (in equivalent units) per unit volume of water can be written as:

$$\sum \text{Cat loss} = \sum[\{(X/Al)_{bas} - (X/Al)_{sed}\} \times [Al]_{sed} \times Z_X \times \phi_{sed}] \quad (6)$$

where X (=Ca, Mg, Na and K), Z is the valence of individual cation, ϕ_{sed} is the particulate matter concentration, the elemental concentrations are in molar units.

Using the above equation and the measured data for KRS-2 (KRS-2 is nearest to the outflow of the Krishna river from the Deccan Traps); the total cation loss can be calculated to be ~370 μE. The calculation uses 55 mg l^{-1} for particulate matter concentration, the measured value in the present study. This estimate of ~370 μE is a factor of ~2 lower than the HCO_3 concentration measured in KRS-2 (Das et al., 2005a). Temporal variation in erosion, the use of sediment abundance and composition from single sampling as representative of particulate matter exiting the system, all could contribute to this discrepancy. Vigier et al. (2005) observed that the contemporary physical erosion of the Narmada and Tapti derived from measured particulate matter concentration is much higher than the model based values. Such high physical erosion can also contribute to enhanced chemical erosion as both are coupled (Gaillardet et al., 1999a,b; Millot et al., 2002). This study, however, brings out the potential of river particulates to derive estimates of total cation loss and associated CO_2 consumption during weathering. Such studies would provide an independent estimate of CO_2 consumption rates during chemical weathering in river basins and their relation to present day CO_2 drawdown based on chemistry of river water.

The advantage of using particulate matter data to derive erosion rates (particularly in multilithological terrains), is that it can provide silicate weathering rates directly, unlike from dissolved phase data, in which silicate weathering has to be derived based on forward/inverse models.

4.8. Minor elements

In addition to the major elements discussed in the preceding sections, the abundances of selected minor and trace elements were also measured in sediments to characterize their sources and behaviour during weathering and transport. These studies also provide information on the impact of anthropogenic contribution on river sediment composition, especially on selected minor/trace elements.

4.8.1. Manganese and phosphorous

The average Mn concentration in basalts is ~0.15 wt. % with Mn/Al of ~0.020±0.003 (Subbarao et al., 2000). Mn in sediments vary from ~0.11 wt.% to 0.30 wt.% with a range of values for Mn/Al, 0.016–0.043. The break down of minerals and groundmass in basalts, during their chemical weathering would release Mn to solution most likely as Mn^{+2}. The behaviour of Mn^{+2} would be determined by the redox condition of the solution, it would be oxidized to the less soluble Mn^{+4} in oxic conditions, commonly encountered in surface waters. This would result in the removal of Mn from solution to particulate phases as oxides and hydrous oxides. In this respect the geochemical behaviour of Mn follows that of Fe. Alternatively, Mn could also be adsorbed/scavenged by oxides/hydroxides of Fe. The strong positive correlation between Mn/Al and Fe/Al (Fig. 9) suggests that Mn follows Fe during weathering and transport of the Deccan Traps. This process can cause both enrichment and depletion of Mn. Enrichment of Mn can also occur due to inputs from industrial sources, such as those engaged in ferromanganese alloys. Heavy metal pollution from industrial sources, and discharge of domestic sewage and municipal wastes are reported for the Koyna and the Krishna rivers (Trivedy, 2000).

The average concentration of P in Deccan basalts is ~1010 μg g^{-1} (Subbarao et al., 2000). The concentration in sediments ranges from ~470 to ~1800 μg g^{-1} (with half of the samples having concentrations <800 μg g^{-1}, Table 2). Apatites and glass are important hosts for P in basalts (Best, 1986; Nesbitt and Wilson, 1992). The lower P content in the samples relative to average basalt value can be interpreted in terms of its loss to rivers during weathering. Evidences for progressive leaching of P from basalts have been reported from soil profile data (Nesbitt and Wilson, 1992). Among the sediments analysed only in the Mutha there is significant excess of P (Table 2). This would require additional inputs of P or its enrichment during weathering process. Co-precipitation of P with hydroxides of Fe is known (Berner and Rao, 1994). In addition, P in sediments can have contribution from land derived organic matter (Jha et al., 1990) and fertilizers.

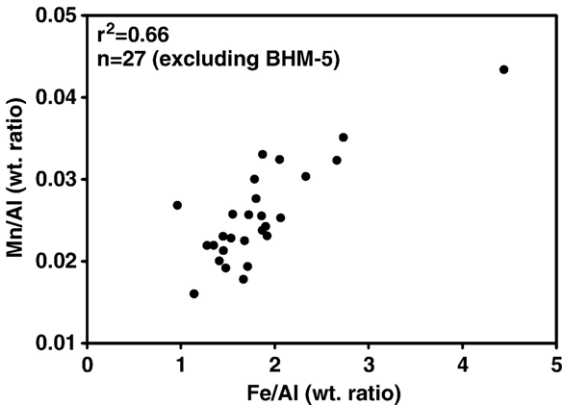

Fig. 9. Plot of Mn/Al with Fe/Al. The linear trend of the plot shows close association of Mn and Fe during weathering and erosion.

4.8.2. Vanadium, chromium, nickel, copper and zinc

The abundances of all these elements and their ratios relative to Al, both in basalts and in sediments are highly variable, making it difficult to assess their relative mobility/enrichment during weathering and transport.

Vanadium in basalts is generally contained in minerals such as pyroxenes, amphiboles and magnetites. In sediments, it is hosted in magnetite, titano-magnetite and with organic matter (Breit and Wanty, 1991; Arthur and Sageman, 1994). The average V abundance in the Ambenali Formation of the Deccan basalts is ~411± 44 μg g^{-1} (Peng et al., 1998) nearly identical to the value of 417±13 in Poladpur, with V/Al (μg g^{-1}/wt.%, hereafter Al normalized ratios of are in units of μg g^{-1}/wt.%) ratios of ~56±7. About half of the sediment samples have V in excess of 600 μg g^{-1}, indicating significant V enrichments. V shows tight correlation with both Fe and Ti in sediments (r^2=0.84, 0.82 respectively) suggesting their close association, most likely resulting from their retention in weathering resistant oxide minerals. The distribution of V in lateritic profiles from the Deccan (Borger and Widdowson, 2001; Kisakurek et al., 2004) shows about an order of magnitude enrichment in its abundance relative to the parent basalt. All these results favour restricted mobility of V during weathering and erosion of basalts.In Deccan basalts, Cr ranges from ~80 to 400 μg g^{-1} (Subbarao et al., 2000), bracketing its abundance in sediments from 100 to 306 μg g^{-1}. The minerals hosting Cr are chrome spinels (chromite) and pyroxenes (Prinz, 1967). The Cr/Al ratio in the sediments varies from 15 to 41 within the range of ~11 to ~57 in basalts. The wide range in Cr concentration and Cr/Al ratio in basalts and in sediments though makes it difficult to assess the mobility of Cr during weathering, their overall similarity is an indication that Cr, analogous to V, is not mobilized significantly during weathering and erosion. This would be expected if most of Cr in basalts reside in weathering resistant oxide minerals. The high concentration of Cr in laterites relative to parent basalts (Borger and Widdowson, 2001; Widdowson and Gunnell, 2004) further supports the inference that it is one of the least mobile elements during basalt weathering. These results corroborate the findings of Nesbitt and Wilson (1992) on the mobility of V and Cr during chemical weathering of basalts.

Similar to Cr, Ni concentration also varies significantly in basalts, from ~35 to ~220 μg g^{-1} (Subbarao et al., 2000) bracketing the range in sediments, 68 to 162 μg g^{-1} (Table 2). The Ni/Al ratios in sediments, (except in KJL-1), are also within the range in basalts. Ni shows good correlation with Fe (r=0.77), probably resulting from its incorporation in Fe-rich minerals and adsorption on oxides/hydroxides of Fe. All these observations are an indication that Ni mobility is also limited and that a significant part of it is retained in sediments during chemical weathering and erosion of Deccan basalts.

The concentration of Cu and Cu/Al ratios in sediments are similar to the average basalt value (Peng et al., 1998). The distribution of Cu in a lateritic profile from Deccan shows that its concentration increases from 177 μg g^{-1} at base (basalt) to 581 at the top of the profile, composed of verniferous laterite (Kisakurek et al., 2004) indicating its restricted mobility during weathering and its retention in the weathered residue. It has been suggested (Nesbitt and Wilson, 1992) that Cu mobility may be regulated by its adsorption/exchange on goethite and smectite, both of which are known to be weathering products of Deccan basalts. From the available data, though, it is difficult to assess the mobility of Cu because of wide variations in its concentration in both basalts and sediments; the results are consistent with its reported restricted mobility during weathering of basalts. The results also suggest that the sediments analysed are not impacted significantly by pollution inputs of Cu.

Ramesh et al. (1989) observed orders of magnitude higher particulate concentration of Zn in Krishna river, which they attributed to pollution inputs. Average Zn/Al ratio in Ambenali basalts is ~16±2, similar to values of ~14±2, calculated from composition data of Ambenali, Poladpur and Mahabaleshwar Formations (Cox and Hawkesworth, 1985). These compare with values of ~14 to ~60 (average 24±9) in sediments. The higher ratios observed in many of these river sediments can be due to supply from anthropogenic sources (Trivedy, 2000).

4.9. Conclusions

Sediments from several rivers belonging to the headwaters of the Krishna and west flowing Western Ghat (WFWG) streams all of them draining the Deccan Traps almost exclusively have been analysed to determine elemental abundances in them and their relative mobilities during weathering and erosion. The major observations and findings of this study are:

1. The sediments contain $CaCO_3$, in the range of 0.04 to 16.9 wt.%. The high $CaCO_3$ (>0.5 wt.%) are in samples from the basins of the Krishna and the Bhima mainstreams and the tributaries of the Bhima. These rivers are supersaturated w.r.t. calcite and hence its precipitation from rivers can be a source of $CaCO_3$ to the sediments. Other sources can be calcretes and tufas present in the basin.
   The abundances of Na, Ca and Mg in all the samples analysed are less than that in basalts. All sediment samples with $CaCO_3$ < 0.5 wt.% also have Sr less than that in basalts. These results coupled with the strong anti-correlation in the abundances of all these elements with Al suggest that Na, Ca, Mg and Sr are highly mobile from Deccan basalts during weathering. The Ca/Mg and Na/Mg and Sr/Mg ratios in basalts, in sediments and in river waters draining them (Das et al., 2005a) all are nearly the same within errors, indicating that these elements are released from Deccan basalts to rivers nearly congruently.
2. The abundances of Al, Fe and Ti show significant variations, with most samples having concentrations higher than that in basalts. The range in Al concentration (5.8 to 10.2 wt.%) is a result of many factors, dilution of sediments with Al poor phases (carbonates), enrichment due to loss of "mobile elements" from basalts and the formation of secondary phases rich in Al. There is an overall enrichment of Fe over Al in the sediments resulting from their fractionation during weathering and erosion. The formation of secondary phases rich in Fe and presence of highly resistant Fe minerals contribute to this enrichment. The strong correlation between Fe and Ti is also a signature of the presence of weathering resistant Fe–Ti minerals and/or sequestration of Ti in oxy-hydroxides of Fe, an end product during chemical weathering.
3. The range in K and K/Al ratios in sediments overlaps with those in basalts. This coupled with lack of any significant correlation of K with other mobile and immobile major elements suggest that K behaviour is inconsistent during basalt weathering. Ba shows a good correlation with K suggesting their similar behaviour and association in common phases such as K-feldspars. The mobility of Ba during weathering is much less than the other alkaline earth elements; Mg, Ca and Sr.
4. The abundances of trace elements (V, Cr, Ni, Cu and Zn) and their Al-normalized ratios are highly variable, however, for most of them are similar to the range reported in parent basalts. This indicates that these elements are by and large retained in the solid phases during weathering and transport. Mn correlates well with Fe, suggestive of its association

in the Fe phases (oxides, hydroxides). The impact of anthropogenic influence on the concentrations of trace elements analysed is not discernible except perhaps for Zn.

5. CIA of sediments ranges from 42–92, suggesting their variable degree of chemical alteration. The distribution of the data in the A–CN–K and A–CNK–FM ternary plots is consistent with the suggestion. The higher CIA values are in samples from basins which experiences higher rainfall and runoff. Sample rich in $CaCO_3$ generally have lower CIA values. This seems to be a result of arid/semi-arid climate which facilitates $CaCO_3$ precipitation and limit chemical weathering and erosion.
6. Comparison of the Na, Mg, Ca abundances in sediments with those in parent basalts have provided an estimate of CO_2 consumption during silicate weathering of basalts. This estimate is lower than the contemporary CO_2 drawdown derived from HCO_3 abundance in river water. Several factors could be contributing to this difference, particularly temporal variation in erosion rates and the use of sediments as representative of particulate matter exiting the basin. This approach, if improved upon to obtain representative elemental fluxes in particulate phase, can offer an independent means to derive *silicate* weathering rates of river basins, which have implications to the global CO_2 budget.
7. Overall, the study brings out the relative mobility of several major and minor elements in Deccan basalts during chemical weathering. The results obtained in this study based on alkali and alkaline earth elements in sediments converge with those reported for the dissolved phase, though different time domains are associated with these two phases, dissolved phase representing "contemporary weathering" whereas sediments integrate a much longer history. This convergence suggests that major alkali and alkaline earth elements of Deccan basalts have been released to rivers nearly congruently over the residence time of sediments. Available data on soil profiles and laterites attest to this conclusion.

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