

Tracking Precambrian Crustal Sources through Heavy Mineral and Bulk Geochemistry: Cauvery River Sediments, Dharwar Craton–Southern Granulite Terrain, India

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ABSTRACT

Provenance and chemical weathering studies of river sediments usually work at one scale, either the bulk sample or a single mineral, and the two rarely meet. Here we combine bulk geochemistry and detrital ilmenite chemistry for bed sediments of the Cauvery (Kaveri) River, which drains the Dharwar craton and the Southern Granulite Terrain of peninsular India. We analysed 15 bed-load samples from Mettur dam to the river mouth by XRF, and detrital ilmenite from eight sites along the Tamil Nadu reach by electron probe. We then compared the results with published data for sand, clay and suspended sediment from major Indian and world rivers. The bulk sands are silica-rich (SiO₂ 64.9–84.6 wt%) and their chemical index of alteration (CIA 41.7–61.4; mean 53.7) is close to that of the upper continental crust. CIA is controlled almost entirely by the amount of Ca-bearing plagioclase and mafic minerals (CIA–CaO, $r = -0.89$), not by weathering intensity. Seen at grain scale, the same bed load is equally fresh. Ilmenite is 84–97 mol% FeTiO₃, no grain exceeds the stoichiometric TiO₂ of ilmenite, and its Fe³⁺ is held in primary ilmenite–hematite solid solution (TiO₂–Fe₂O₃, $r = -0.99$) rather than produced by alteration to pseudotile. Both scales point to a mixed source. Bulk chemistry identifies Ca–Mg-rich sands from charnockite and gneiss in the upper reach, quartz-rich felsic sands in the middle reach and a heavy-mineral concentrate at the mouth. Ilmenite separates Mg-bearing grains from mafic granulites and Mn- and Fe³⁺-rich grains from felsic or metamorphic rocks, which are concentrated in the middle reach. Compared with other rivers, the Cauvery bed load resembles bed sediments of large Tibetan–Himalayan rivers (CIA 46.5–69.6). It is about 28 CIA units less weathered than the river's own clay (81.6) and far below the world mean for suspended sediment (72.1). Cauvery ilmenite is also fresher and lower in TiO₂ than altered beach-placer ilmenite on the Indian coast. We argue that bulk indices from bed load describe sorting and source mineralogy rather than climate, and that single-grain chemistry, checked first for alteration, is needed to read provenance reliably. We close with a practical framework for future river-sediment studies.

Keywords: Cauvery (Kaveri) River; river bed sediments; sediment provenance; chemical weathering; chemical index of alteration (CIA); mineral sorting; detrital ilmenite; Mn/Mg ratio; Southern Granulite Terrain; Peninsular India

1. INTRODUCTION

River sand is an archive of the rocks it came from and of everything that happened to it on the way. Geochemists have long used it to study source composition, weathering, erosion, tectonic setting and the evolution of the continental crust (Nesbitt and Young, 1982; Taylor and McLennan, 1985; McLennan et al., 1993; Gaillardet et al., 1999; Singh, 2009; Garzanti et al., 2011; Lupker et al., 2012; Maharana et al., 2018). The difficulty is that a single sample mixes several signals at once. Source lithology, the intensity of weathering, sorting during transport and post-depositional change all leave their mark on bulk chemistry (Taylor and McLennan, 1985; Nesbitt et al., 1996; Singh and Rajamani, 2001).

Two approaches have grown up to deal with this, and they are rarely used together. The first works at the bulk scale. Indices such as the chemical index of alteration (CIA; Nesbitt and Young, 1982) are quick to calculate and easy to compare, but recent work shows they can mislead. Across world drainage basins, the CIA reflects the integrated weathering history of the basin rather than present-day weathering (Li and Yang, 2010). In Taiwan river sands, weathering indices depend mainly on how much mobile element the source rocks contained in the first place (Garzanti and Resentini, 2016). Grain size matters as well. Channel sands and suspended sediments of the same river can record different weathering intensities and different sources (Maharana et al., 2018; Kaotekwar et al., 2019).

The second approach works at the scale of a single mineral. Detrital ilmenite (FeTiO₃) is well suited to this.

It forms in a wide range of igneous and metamorphic rocks (Ramdohr, 1980), makes up a large share of the opaque heavy fraction of many sands (Pettijohn et al., 1987; Basu and Molinaroli, 1989), and its Mn, Mg and Fe³⁺ contents vary with the host rock (Darby, 1984; Darby and Tsang, 1987; Grigsby, 1992). Its weak point is alteration. During weathering ilmenite loses iron and passes through hydrated ilmenite to pseudorutile and leucoxene (Mücke and Chaudhuri, 1991), which is well documented in Indian beach placers (Suresh Babu et al., 1994; Bernstein et al., 2008; Rao and Sengupta, 2014). Before its chemistry can be used for provenance, the analyst has to show that the grains are unaltered (Basu and Molinaroli, 1991).

Each approach can check the other. Bulk chemistry shows how sorting and weathering have shaped the whole sediment, but it blurs sources together. Single-grain chemistry resolves individual sources, but only for one mineral. Used side by side on the same river, they can show which bulk signals are real provenance signals and which are artefacts of sorting.

The Cauvery River is a good place to test this. Its basin has been studied for sediment transport (Vaithianathan et al., 1992), floodplain geochemistry (Singh and Rajamani, 2001), weathering of charnockites and lower crustal rocks (Sharma and Rajamani, 2001; Rajamani et al., 2009), solute-based weathering rates (Pattanaik et al., 2013), tectonic controls on drainage (Kale et al., 2014), heavy-mineral control of rare earth elements in the delta (Ahmad and Singh, 2020) and the clay mineralogy of its fine sediment (Babu et al., 2021). Seasonal changes in the geochemistry of Cauvery sediment in Tamil Nadu have been described by Vybhav et al. (2020). Heavy minerals of the upper reaches and of the Kabini tributary are also known (Prakash Narasimha et al., 2018), spinel in the river sediment has been traced to both felsic and meta-ultramafic sources (Mujumdar et al., 2019), and the composition of detrital ilmenite along the Tamil Nadu reach was first reported by Vybhav et al. (2018). What is still missing is a combined, downstream record of the bed load at both scales.

In this paper we (1) characterise the bulk chemistry of Cauvery bed load from Mettur dam to the mouth, (2) characterise detrital ilmenite along the same reach and test it for alteration, (3) compare the two scales to separate weathering, sorting and provenance, (4) place the Cauvery among major Indian and world rivers using sediment of the same type, and (5) propose a simple framework that other workers can apply to river sediments.

2. STUDY AREA

The Cauvery rises in the Brahmagiri range of the Western Ghats at about 1350 m and flows east across Karnataka and Tamil Nadu to the Bay of Bengal, where it builds a delta near Poompuhar (Fig. 1). Its catchment covers about 81,155 km² (Singh and Rajamani, 2001), and its main tributaries are the Kabini, Hemavathi, Lakshmanatheertha, Bhavani and Amaravathi. On its way the river crosses the Dharwar craton, the Southern Granulite Terrain and younger sedimentary cover. The Southern Granulite Terrain is a high-grade metamorphic belt formed during the assembly of Gondwana (Collins et al., 2014).

Rock types along the course are varied. They include granitoids, gneisses, charnockites and pyroxene granulites, gabbro and ultramafic bodies, and ancient supracrustal belts with meta-igneous, meta-sedimentary and carbonate units (Ramakrishnan and Swaminath, 1981, 2009; Ramakrishnan, 1993; Prakash Narasimha et al., 2009). Downstream of Mettur dam the river first cuts through charnockite and pyroxene granulite, then granitoid and hornblende-biotite gneiss, and finally reaches the coastal tract, which is underlain by Cretaceous sedimentary formations including phosphatic limestones, sandstones and clays (Babu et al., 2021). In the upper reaches the heavy-mineral assemblage is dominated by garnet and zircon, with subordinate rutile and amphibole (Prakash Narasimha et al., 2018).



Fig. 1. Geological map of the Cauvery River basin showing bulk-sediment sampling sites C1–C15 (numbered 1–15) from Mettur dam to the Bay of Bengal. [Authors: add the ilmenite sampling sites I-1 to I-8 to this map.]

3. MATERIALS AND METHODS

The study has two sampling strands that share field methods but differ in spacing and in the fraction analysed (Fig. 2).

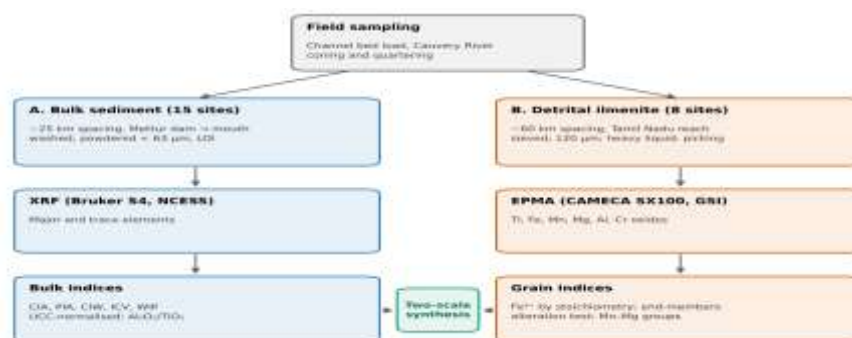


Fig. 2. Workflow of the two-scale approach. Strand A characterises the bulk bed load; strand B characterises single grains of detrital ilmenite. Both are combined in the synthesis.

3.1 Bulk sediment (strand A)

Bed load was collected at 15 sites (C1–C15) at intervals of about 25 km, depending on access, from Mettur dam to the river mouth (Fig. 1). Samples were reduced by coning and quartering, oven-dried at 50 °C, washed with distilled water to remove salts and powdered to < 63 µm in an agate mortar. For loss on ignition (LOI), powders were dried at 110 °C for about 6 h and heated at 950 °C for 1 h. Major and trace elements were measured by XRF (Bruker S4) at the National Centre for Earth Science Studies (NCESS), Thiruvananthapuram. More than 15 international reference materials, including MAG-1, SGR-1 and SCo-1, were used for calibration. [Authors: add precision, accuracy and detection limits.] Zn values reported as zero are treated as below detection.

3.2 Detrital ilmenite (strand B)

About 500 g of channel sand was collected at each of eight sites (I-1 to I-8) spaced about 60 km apart along the Tamil Nadu reach. Each sample was reduced by coning and quartering, dried and sieved into 60, 120 and 180 µm fractions. The 120 µm fraction was separated in heavy liquid, and ilmenite grains were hand-picked under a stereo binocular microscope, mounted in epoxy and polished. Grains were analysed with a CAMECA SX100 electron probe microanalyser at the PPOD laboratory, Geological Survey of India, Bengaluru. [Authors: add accelerating voltage, beam current, standards and the number of grains analysed per site.] One representative analysis per site is reported. These ilmenite analyses were first published by Vybhav et al. (2018). Here they are recalculated (Section 3.3) and reinterpreted alongside the bulk data. [Authors: state whether any of the bulk samples overlap with those of Vybhav et al. (2020).]

3.3 Data treatment

For the bulk samples, weathering indices were calculated from molar proportions. $CIA = 100 \times Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)$ (Nesbitt and Young, 1982), where CaO^* is CaO in silicates, corrected here for apatite

using P_2O_5 (McLennan et al., 1993). A carbonate correction was not needed because LOI is low (0.35–3.34 wt%). PIA follows Fedo et al. (1995), CIW follows Harnois (1988) and WIP follows Parker (1970). The index of compositional variability, $ICV = (Fe_2O_3^T + K_2O + Na_2O + CaO + MgO + MnO + TiO_2) / Al_2O_3$, follows Cox et al. (1995). Concentrations were normalised to the upper continental crust (UCC) of Rudnick and Gao (2003). Calculated in the same way, UCC has a CIA of 51.4 and an ICV of 1.20, and post-Archaeon Australian shale (PAAS; Taylor and McLennan, 1985) has 70.4 and 0.89.

For ilmenite, EPMA reports total iron as FeO (FeO). Ferric iron was estimated from charge balance with the equation of Droop (1987), assuming two cations per three oxygens. End-members were calculated as $FeTiO_3$ (ilmenite), Fe_2O_3 (hematite), $MgTiO_3$ (geikielite) and $MnTiO_3$ (pyrophanite). Stoichiometric $FeTiO_3$ contains 52.65 wt% TiO_2 and 47.35 wt% FeO. Correlations are reported as Pearson r for the bulk data ($n = 15$) and as Pearson r and Spearman ρ for the ilmenite data ($n = 8$). Al_2O_3 and Cr_2O_3 in ilmenite are close to EPMA detection limits and were not interpreted.

4. RESULTS

4.1 Bulk chemistry of the bed load

Bulk compositions are listed in Table 1 and the derived indices in Table 2 (both at the end of the paper). SiO_2 ranges from 64.86 to 84.63 wt% (mean 75.18) and Al_2O_3 from 8.24 to 14.60 wt% (mean 10.98). $Fe_2O_3^T$ varies between 1.78 and 7.69 wt%, and CaO between 1.28 and 6.44 wt%. The other oxides follow the order $CaO > Na_2O > K_2O > MgO > TiO_2 > P_2O_5 > MnO$. Ba (110–782 ppm) and Cr (54–223 ppm) are the most abundant trace elements.

Against UCC, the sediments are richer only in SiO_2 ($1.13 \times$ UCC) and TiO_2 ($1.11 \times$ UCC). All other major oxides are depleted (0.50 – $0.78 \times$ UCC), K_2O and MgO the most. Among trace elements, only Cr ($1.31 \times$ UCC on average, above UCC in 10 of 15 samples) and Cu ($1.07 \times$ UCC) are enriched. Ni sits close to UCC (0.91) and Rb, Nb, Ba, La, Ce, Sm and Co are depleted (0.66 – $0.85 \times$ UCC) (Fig. 3). In the classification of Herron (1988) most samples fall in the litharenite, wacke and Fe-sand fields (Fig. 4a).

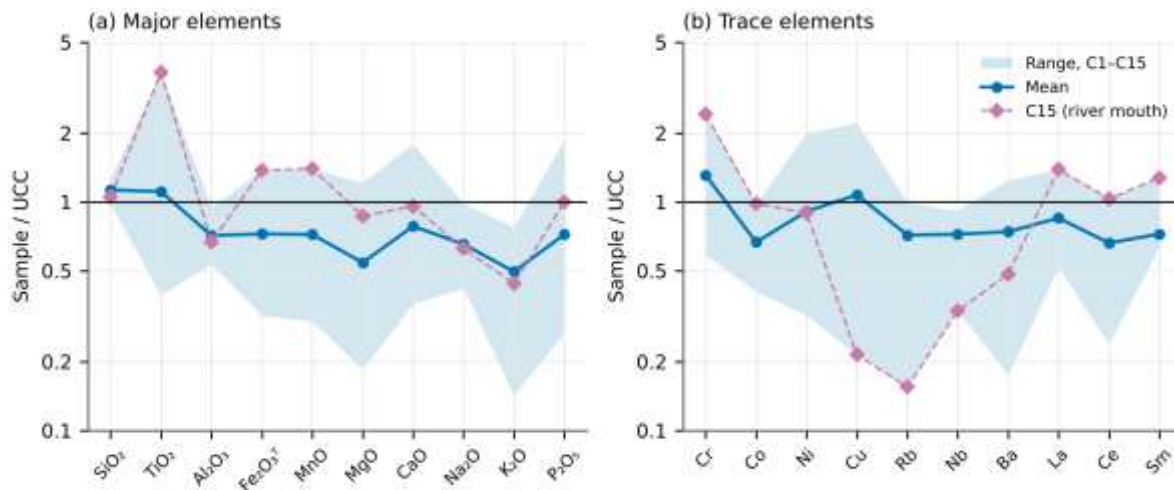


Fig. 3. Bulk bed-load (a) major- and (b) trace-element concentrations normalised to UCC (Rudnick and Gao, 2003). The band is the range of all samples, the solid line the mean and the dashed line sample C15 from the river mouth.

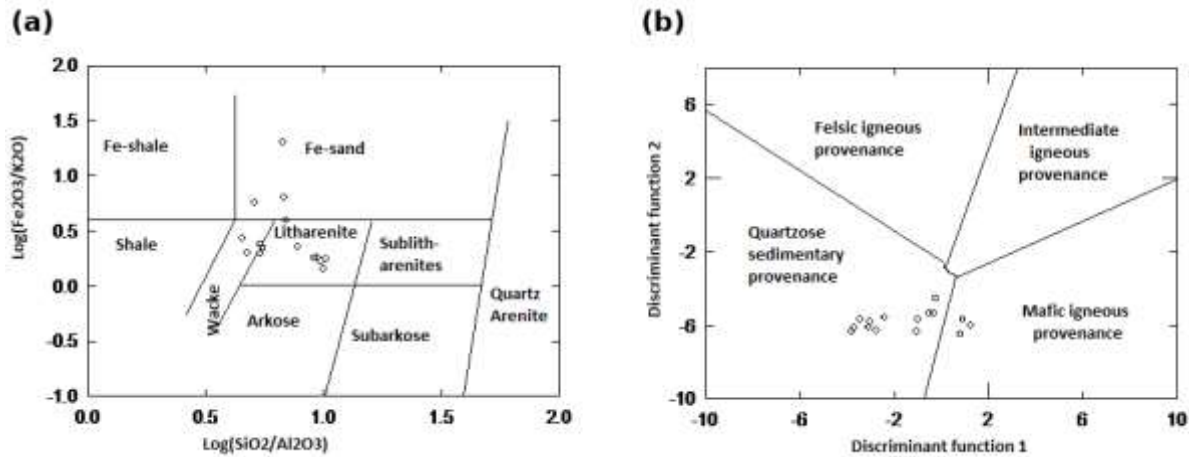


Fig. 4. (a) Chemical classification of the bulk bed load (after Herron, 1988). (b) Provenance discriminant-function diagram (after Roser and Korsch, 1988). [Authors: redraw both panels at 300 dpi.]

Quartz dilution is the main control on bulk chemistry. SiO_2 is negatively correlated with Al_2O_3 ($r = -0.87$), MgO (-0.86), Co (-0.85), CaO (-0.84), Ce (-0.84), MnO (-0.82), Fe_2O_3^T (-0.80), Cr (-0.79) and La (-0.78), but shows no relationship with Rb (0.04) or Nb (0.07). Fe_2O_3^T in turn correlates very closely with Co (0.99) and Cr (0.95), and also with MnO (0.88), MgO (0.84) and TiO_2 (0.83).

4.2 Downstream pattern in the bulk sediment

Bulk chemistry changes along the river in steps rather than smoothly (Fig. 5). Three domains and one outlier stand out:

- **Upper reach (C1–C4).** Between Mettur dam and the Bhavani confluence, SiO_2 is relatively low (64.86–75.12 wt%), CaO and MgO are high, ICV is high (1.13–1.83) and CIA is the most variable of the whole river (41.7–61.4). Sample C1 is unusually poor in K_2O (0.40 wt%) and Rb (40 ppm).
- **Middle reach (C5–C9).** Here the sands are quartz-rich (SiO_2 82.28–84.63 wt%; $\text{SiO}_2/\text{Al}_2\text{O}_3$ 9.14–10.19) and poor in Fe_2O_3^T (1.78–2.77 wt%) and Cr (54–72 ppm, below UCC). ICV is below 1 (0.78–0.96), $\text{Al}_2\text{O}_3/\text{TiO}_2$ is high (19.9–34.2) and CIA is uniform (56.1–58.9).
- **Delta (C10–C14).** Al_2O_3 rises (10.15–14.60 wt%), $\text{SiO}_2/\text{Al}_2\text{O}_3$ falls (4.60–7.75), ICV stays close to 1 (0.90–1.08) and Ba is high (515–782 ppm).
- **River mouth (C15).** This sample has the highest TiO_2 (2.36 wt%), Fe_2O_3^T (7.69 wt%), Cr (223 ppm), La (43 ppm), Ce (65 ppm) and Sm (6 ppm) of the whole set, the lowest $\text{Al}_2\text{O}_3/\text{TiO}_2$ (4.35), and very little Rb (13 ppm) or Nb (4 ppm).

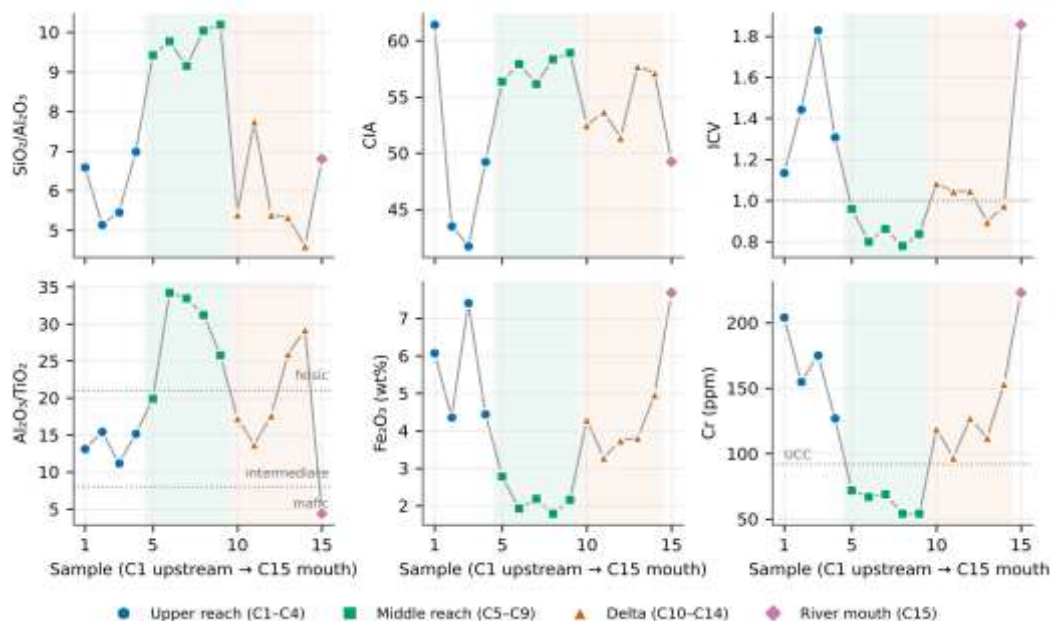


Fig. 5. Downstream variation of bulk $\text{SiO}_2/\text{Al}_2\text{O}_3$, CIA, ICV, $\text{Al}_2\text{O}_3/\text{TiO}_2$, Fe_2O_3^T and Cr from C1 (Mettur dam) to C15 (river mouth). Shaded bands mark the middle reach (green) and the delta (orange). Dotted lines show ICV = 1, $\text{Al}_2\text{O}_3/\text{TiO}_2 = 8$ and 21 (Hayashi et al., 1997) and Cr in UCC (Rudnick and Gao, 2003).

4.3 Ilmenite chemistry

Ilmenite contains 46.42–52.18 wt% TiO_2 (mean 49.82) and 46.35–50.68 wt% FeO_t (mean 48.24), with 0.14–1.91 wt% MnO and 0.07–0.85 wt% MgO (Table 3). Recalculated Fe_2O_3 ranges from 0.93 wt% (I-1) to 12.10 wt% (I-4), and totals are 99.3–100.9 wt%. On a three-oxygen basis the grains carry 0.884–0.990 Ti, 0.843–0.969 Fe^{2+} and 0.018–0.230 Fe^{3+} atoms per formula unit, with Mg and Mn below 0.05 (Table 4). This corresponds to 84.3–97.0 mol% FeTiO_3 , 0.9–11.5 mol% hematite, 0.3–4.1 mol% pyrophanite and 0.3–3.2 mol% geikielite.

Table 3. EPMA analyses (wt%) of detrital ilmenite. FeO and Fe_2O_3 are calculated from FeO_t by stoichiometry (Droop, 1987).

Oxide	I-1	I-2	I-3	I-4	I-5	I-6	I-7	I-8	Mean
MgO	0.7 2	0.2 8	0.0 7	0.2 2	0.1 4	0.8 5	0.4 8	0.7 5	0.44
Al_2O_3	0.0 1	0.0 2	0.0 2	0.0 3	0.0 5	0.0 3	0.0 1	0.0 4	0.03
Cr_2O_3	0.0 8	0.0 2	0.0 2	0.0 2	0.0 3	0.0 3	0.1 0	0.0 2	0.04
MnO	0.1 4	0.7 1	1.9 1	1.5 5	0.2 5	0.2 9	0.3 5	0.8 0	0.75
TiO_2	52. 18	48. 15	49. 08	46. 42	51. 28	49. 48	50. 36	51. 58	49.82
FeO_t (measured)	46. 35	49. 31	49. 01	50. 68	47. 40	48. 29	48. 08	46. 77	48.24
FeO (calc.)	45. 51	42. 10	42. 09	39. 80	45. 63	42. 70	44. 09	44. 25	43.27
Fe_2O_3 (calc.)	0.9 3	8.0 2	7.6 9	12. 10	1.9 7	6.2 1	4.4 3	2.8 0	5.52
Total (recalc.)	99. 57	99. 29	10 0.8 8	10 0.1 3	99. 35	99. 59	99. 82	10 0.2 4	99.86

FeO_t = total iron as FeO. Totals recalculated with iron split into FeO and Fe_2O_3 .

Table 4. Ilmenite cations per formula unit (3 O, 2 cations) and end-member proportions (mol%).

	I-1	I-2	I-3	I-4	I-5	I-6	I-7	I-8	Mean
Ti	0.9 90	0.9 23	0.9 27	0.8 84	0.9 80	0.9 40	0.9 57	0.9 73	0.947
Fe^{2+}	0.9 60	0.8 97	0.8 84	0.8 43	0.9 69	0.9 02	0.9 31	0.9 28	0.914
Fe^{3+}	0.0 18	0.1 54	0.1 45	0.2 30	0.0 38	0.1 18	0.0 84	0.0 53	0.105
Mg	0.0 27	0.0 11	0.0 03	0.0 08	0.0 05	0.0 32	0.0 18	0.0 28	0.017

	I-1	I-2	I-3	I-4	I-5	I-6	I-7	I-8	Mean
Mn	0.0 03	0.0 15	0.0 41	0.0 33	0.0 05	0.0 06	0.0 07	0.0 17	0.016
FeTiO ₃ (Ilm)	96. 1	89. 7	88. 4	84. 3	97. 0	90. 3	93. 2	92. 9	91.5
Fe ₂ O ₃ (Hem)	0.9	7.7	7.3	11. 5	1.9	5.9	4.2	2.6	5.3
MgTiO ₃ (Gk)	2.7	1.1	0.3	0.8	0.5	3.2	1.8	2.8	1.7
MnTiO ₃ (Pyr)	0.3	1.5	4.1	3.3	0.5	0.6	0.7	1.7	1.6
Mn/Mg (atomic)	0.1 1	1.4 4	15. 5	4.0 0	1.0 2	0.1 9	0.4 1	0.6 1	-
Group	A	B	B	B	A	A	A	A	-

Al and Cr (≤ 0.002 apfu) omitted. Ilm = ilmenite, Hem = hematite, Gk = geikielite, Pyr = pyrophanite. Calculated Fe₂O₃ falls as TiO₂ rises along an almost perfect straight line (Pearson $r = -0.99$; Spearman $\rho = -0.98$, $p < 0.001$), and every analysis lies on the ilmenite–hematite mixing line (Figs. 6 and 7). MnO increases with Fe₂O₃ ($\rho = 0.74$, $p = 0.04$). MgO varies largely on its own, and MnO and MgO are inversely related ($r = -0.58$), although not significantly so with eight samples.

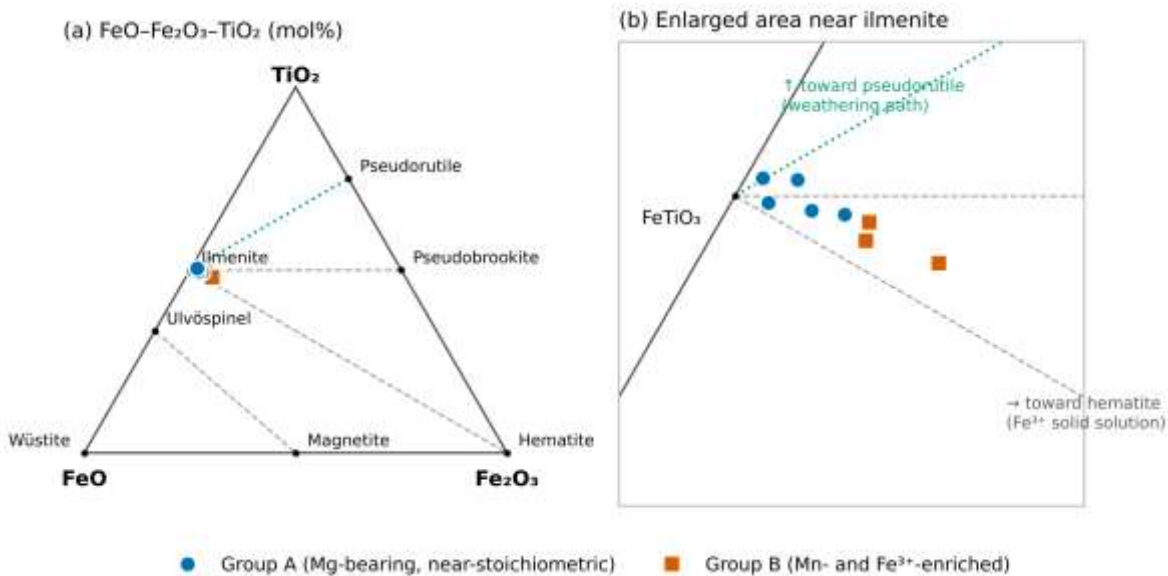


Fig. 6. (a) Molar FeO–Fe₂O₃–TiO₂ diagram for detrital ilmenite, showing the ilmenite–hematite, ulvöspinel–magnetite and ilmenite–pseudobrookite joins and the ilmenite → pseudorutile weathering path (dotted green). (b) Enlarged area near FeTiO₃. All grains lie on or just below the ilmenite–hematite join; none follow the weathering path.

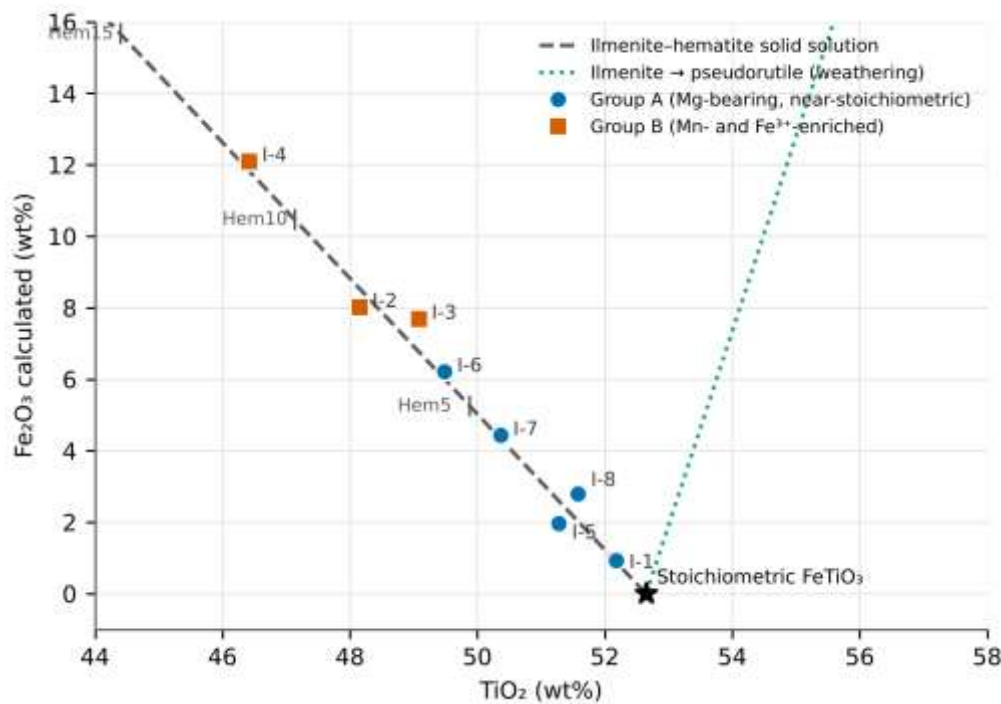


Fig. 7. Calculated Fe_2O_3 versus TiO_2 in ilmenite. The dashed line is the ilmenite–hematite series (ticks at 5, 10 and 15 mol% hematite); the dotted green line runs from stoichiometric ilmenite to pseudorutile and represents iron loss during weathering (Mücke and Chaudhuri, 1991).

4.4 Two ilmenite populations

The ilmenite falls into two groups (Figs. 8 and 9). Group A (I-1 and I-5 to I-8) is close to stoichiometric (49.48–52.18 wt% TiO_2 , ≤ 6.2 wt% Fe_2O_3), carries the most MgO (up to 0.85 wt%) and has atomic Mn/Mg of 0.1–1.0. Group B (I-2 to I-4) has the lowest TiO_2 (46.42–49.08 wt%) and the highest Fe_2O_3 (7.7–12.1 wt%). Its MnO (0.71–1.91 wt%) is high relative to MgO (≤ 0.28 wt%), giving Mn/Mg of 1.4–15.5. Group B occupies the stretch about 60–180 km downstream of I-1. Group A compositions occur both upstream and downstream of it.

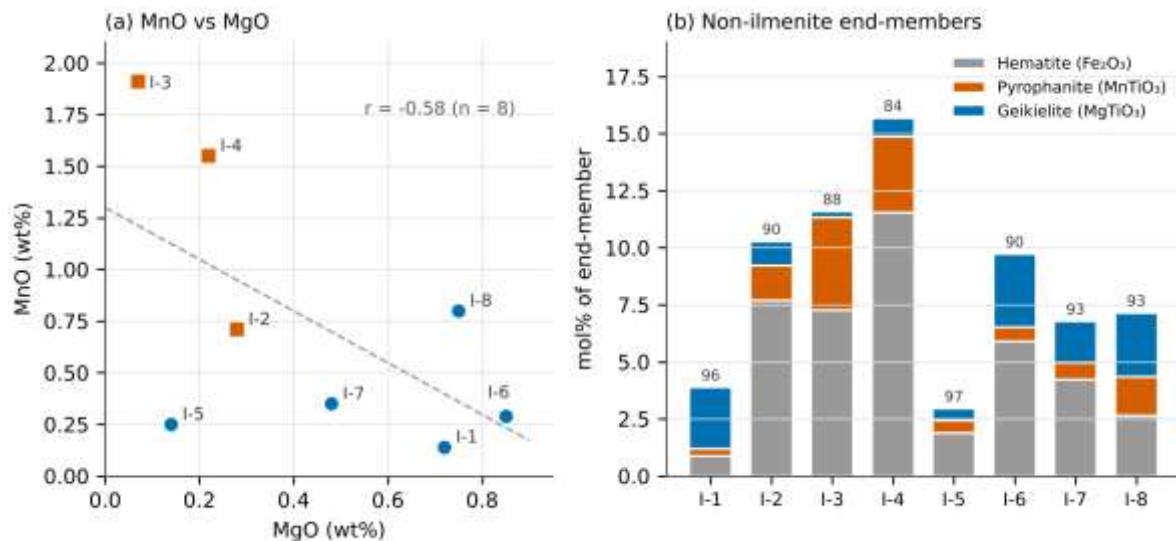


Fig. 8. Detrital ilmenite: (a) MnO versus MgO with a least-squares fit ($r = -0.58$); (b) non-ilmenite end-members for each site, with FeTiO_3 mol% above each bar.

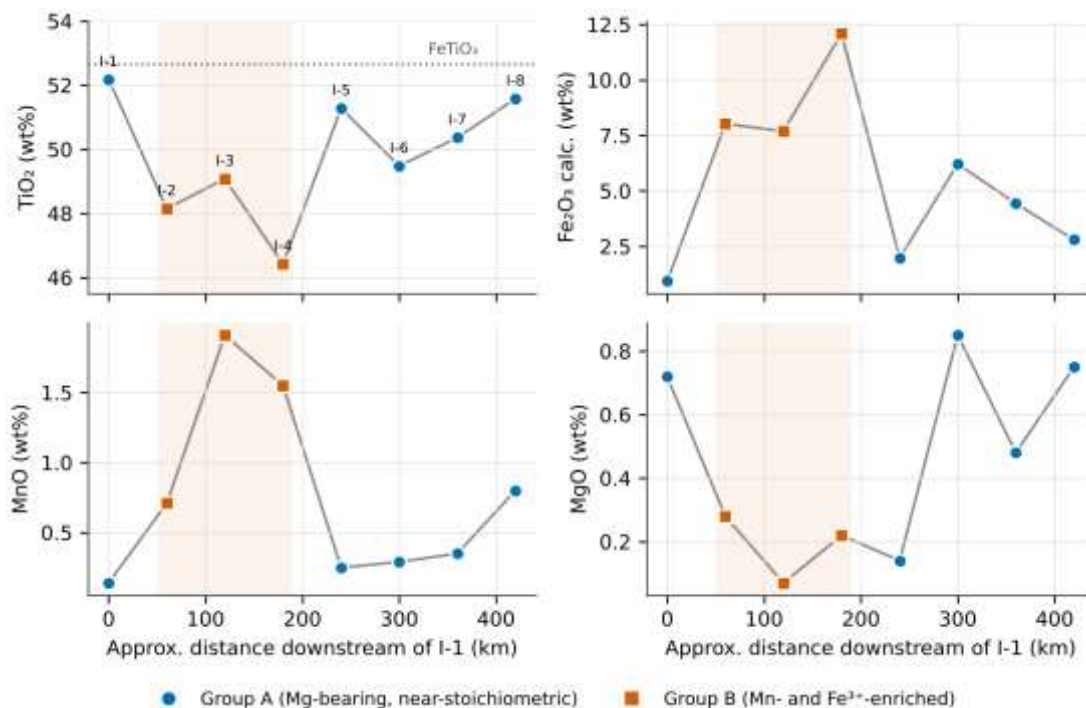


Fig. 9. Downstream variation of ilmenite TiO₂, calculated Fe₂O₃, MnO and MgO (sites about 60 km apart). The shaded band marks Group B (I-2 to I-4). The dotted line in the TiO₂ panel is stoichiometric FeTiO₃ (52.65 wt%).

5. DISCUSSION

5.1 How weathered is the bed load? Two scales, one answer

At the bulk scale the bed load looks barely weathered. Its CIA (41.7–61.4; mean 53.7) is close to UCC (51.4) and well below PAAS (70.4), and PIA (40.8–62.0) and CIW (44.0–65.1) tell the same story. In the A–CN–K diagram the samples sit near the plagioclase–K-feldspar join, beside UCC and far from the clay minerals (Fig. 10a). Unaltered material has a CIA of about 50, whereas values near 100 indicate intense weathering to kaolinite and gibbsite (Nesbitt and Young, 1982; Fedo et al., 1995).

It would be easy to read these numbers as a climate signal. We think that would be wrong, for two reasons. First, CIA tracks CaO almost perfectly ($r = -0.89$; Fig. 11b). The two lowest values, at C2 and C3 (CIA < 44), come from the samples richest in CaO (≥ 5.97 wt%) and MgO. These sites lie just below Mettur dam and near the Bhavani confluence, where charnockites and pyroxene granulites dominate the catchment (Fig. 1). These rocks shed sediment full of fresh plagioclase and ferromagnesian minerals (Sharma and Rajamani, 2001; Rajamani et al., 2009). Second, CIA rises with SiO₂ ($r = 0.66$) and is highest and steadiest in the quartz-rich middle reach. There, abrasion and hydraulic sorting have stripped out Ca-bearing grains and pushed the CIA up without any extra weathering. In other words, the bulk CIA of this bed load measures how much plagioclase and mafic material each sample contains. This fits the view that weathering indices in sands are set by source mineralogy and sorting (Nesbitt et al., 1996; Garzanti and Resentini, 2016), and the finding in the Ganga basin that mineral sorting is the first-order control on the chemistry of river sediment (Lupker et al., 2012). It is also consistent with earlier work on Cauvery floodplain sediments, which found low CIA values and abundant unweathered primary minerals and linked them to recent uplift exposing fresh Archaean rock (Singh and Rajamani, 2001). It also explains why the samples lie on the plagioclase side of the feldspar join, since plagioclase tends to be concentrated in fluvial sand relative to its weathered source (Nesbitt et al., 1996; Singh and Rajamani, 2001).

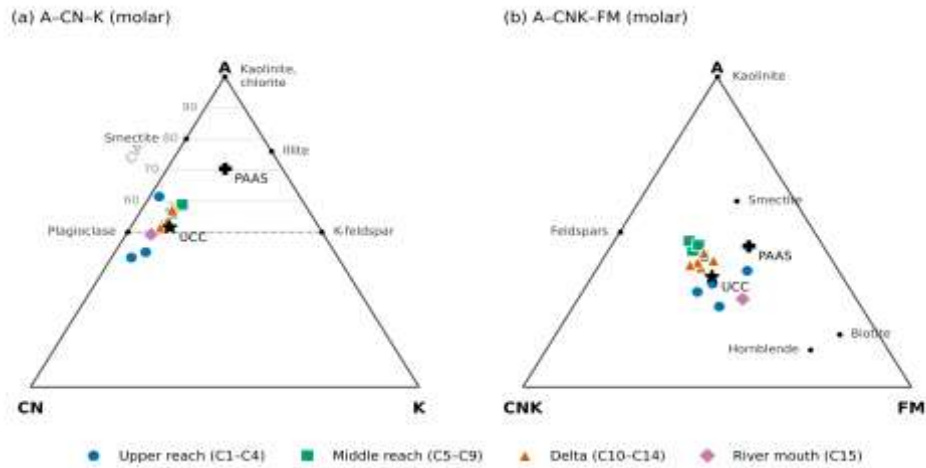


Fig. 10. Bulk bed load in (a) A-CN-K and (b) A-CN-K-FM ternary diagrams (molar; Nesbitt and Young, 1982, 1989). A = Al_2O_3 , C = CaO^* , N = Na_2O , K = K_2O , F = FeO^T , M = MgO . UCC (Rudnick and Gao, 2003) and PAAS (Taylor and McLennan, 1985) are shown for reference.

The grain-scale data give an independent check, and they agree. Weathering drives ilmenite towards pseudorutile: Fe^{2+} is oxidised, iron is leached and TiO_2 rises above the stoichiometric value (Mücke and Chaudhuri, 1991; Suresh Babu et al., 1994). Not one Cauvery grain shows this. Every analysis has TiO_2 at or below 52.65 wt%, and the Fe^{3+} rises as TiO_2 falls (Figs. 6 and 7). That is the signature of ilmenite-hematite solid solution, in which two Fe^{3+} replace $\text{Fe}^{2+} + \text{Ti}$. It is the opposite of supergene alteration, which adds Fe^{3+} while raising TiO_2 . The Fe^{3+} in these grains is therefore inherited from their source rocks. There is one caveat. Stoichiometric Fe^{3+} (Droop, 1987) assumes a full cation site and cannot detect the vacancies that appear early in hydration, so direct measurement of $\text{Fe}^{3+}/\Sigma\text{Fe}$ on a few grains would be worthwhile.

So the two scales give one answer: the Cauvery bed load is chemically fresh. This matters for anyone using river sand from a tropical craton, because the bed load here is not a record of how intensely the basin weathers. It is a record of what the source rocks were and how the river sorted their debris.

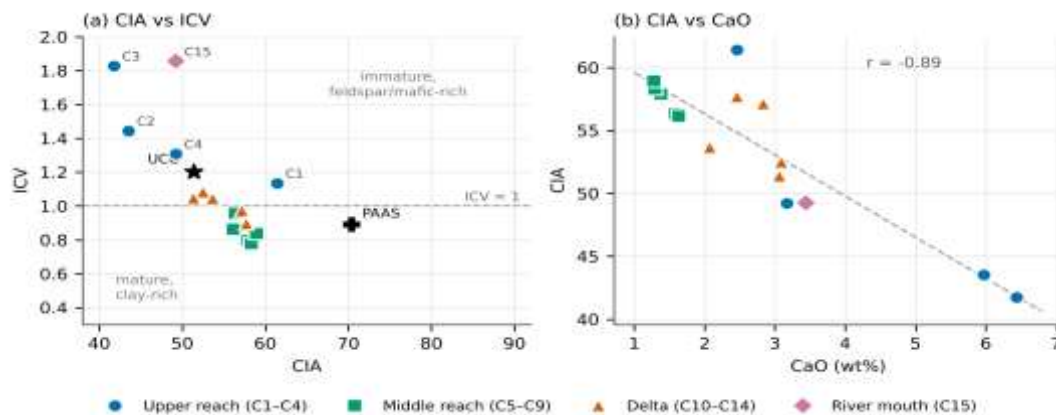


Fig. 11. Bulk bed load: (a) CIA versus ICV (after Cox et al., 1995) and (b) CIA versus CaO. UCC and PAAS as in Fig. 10.

5.2 Maturity, and the Cauvery among other rivers

Compositional maturity follows the same logic. $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios (4.60–10.19; mean 7.20) are higher than those of UCC (4.32) and PAAS (3.32), pointing to quartz enrichment (McLennan et al., 1993). ICV (0.78–1.85; mean 1.12) is above PAAS (0.89). ICV above 1 marks sediment rich in rock-forming silicates, and values below 1 mark clay-rich or quartz-rich sediment (Cox et al., 1995). The upper reach and C15 plot as immature, while the middle reach drops below ICV = 1 only because quartz dilutes everything else (Fig. 11a). $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ is low (0.04–0.17), so plagioclase outweighs K-feldspar and mica (Cox et al., 1995).

How does the Cauvery compare with other rivers? The answer depends on what is being compared (Table 5;

Fig. 12). Bed sediments of six large rivers draining the Tibetan Plateau and Himalaya (the Jinsha/Yangtze, Lancang/Mekong, Nuijiang/Salween, Huang He, Indus and Yarlung Tsangpo/Brahmaputra) have CIA values of 46.5–69.6, close to their catchment bedrocks (Wu et al., 2012). The Cauvery bed load (41.7–61.4) overlaps the lower half of that range. This is striking, because the Cauvery drains a stable tropical to subtropical craton rather than a rapidly eroding mountain belt.

Fine sediment tells a very different story. The < 4 µm clay of the lower Cauvery has a CIA of 81.6. East-coast Indian river clays average 81.6 for Precambrian-terrain rivers, 75.5 for the Deccan-basalt rivers (Krishna and Godavari) and 79.4 for mixed-lithology rivers such as the Mahanadi (Babu et al., 2021). Suspended loads of major world rivers run from 61.3–66.3 (Indus) and 65.7–66.1 (Ganges) up to 89.9 (Congo), averaging 72.1 (Li and Yang, 2010). Clay from the Ganga in Bangladesh has a CIA of 84 ± 2 (Garzanti et al., 2011), close to the Cauvery clay value. The gap between Cauvery sand and Cauvery clay, about 28 CIA units, is wider than most of the gaps between entire rivers.

The lesson is that sediment type can outweigh climate and basin when CIA values are compared. Weathering products (kaolinite, illite and smectite; Babu et al., 2021) leave the Cauvery as fine sediment, while the bed load keeps quartz, feldspar and heavy minerals. A similar split has been found in the Peninsular tributaries of the Ganga, where channel sands carry mostly felsic material and suspended sediment mostly mafic material (Maharana et al., 2018), and in the lower Krishna, whose bulk and clay fractions are chemically fractionated (Kaotekwar et al., 2019). Comparing rivers is meaningful only when like is compared with like, and bed-load CIA should not be read as a measure of basin-scale weathering (Li and Yang, 2010; Garzanti and Resentini, 2016).

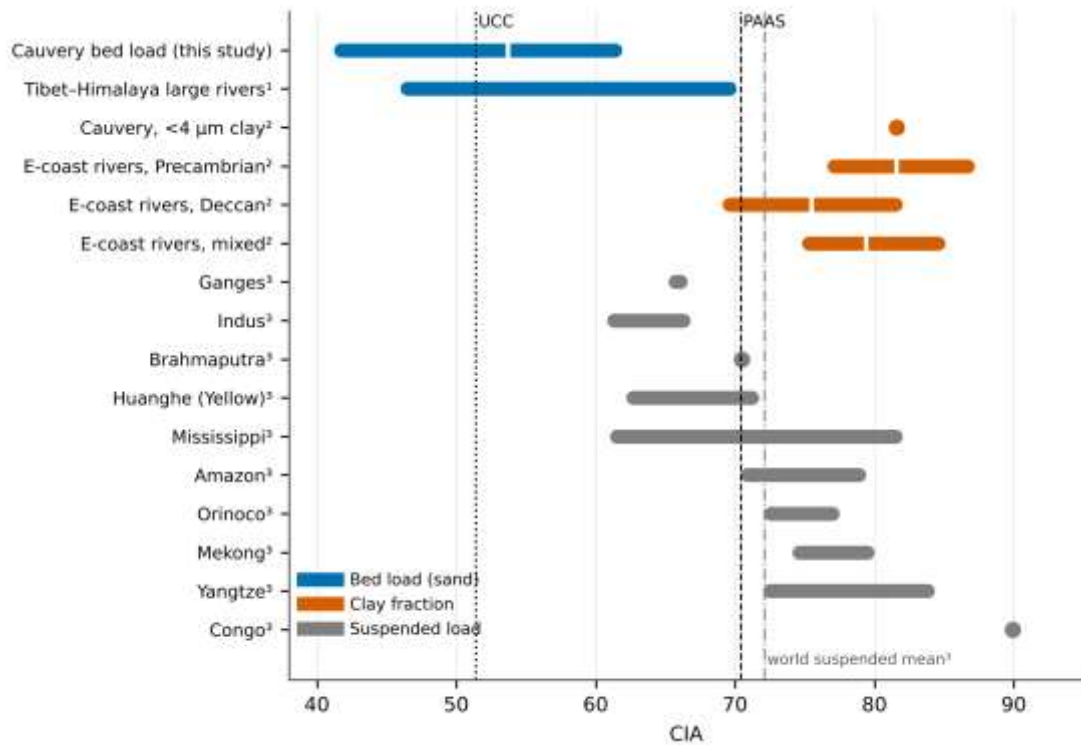


Fig. 12. CIA of Cauvery bed load compared with sediments of other rivers, grouped by sediment type. Bars show reported ranges; white ticks mark means where given. Sources: ¹ Wu et al. (2012); ² Babu et al. (2021); ³ Li and Yang (2010). UCC (Rudnick and Gao, 2003) and PAAS (Taylor and McLennan, 1985) were calculated in this study.

Table 5. CIA of Cauvery bed load compared with sediments of other rivers. Values are ranges, with

means in parentheses where reported.

River	Sediment type	CIA	Source
Cauvery, Mettur dam to mouth	Bed load (sand)	41.7–61.4 (53.7)	This study
Jinsha, Lancang, Nujiang, Huang He, Indus, Yarlung Tsangpo	Bed sediment	46.5–69.6	Wu et al. (2012)
Cauvery, lower reach	Clay (< 4 μm)	81.6	Babu et al. (2021)
Ganga, Bangladesh	Clay	84 $\pm$ 2	Garzanti et al. (2011)
East-coast rivers on Precambrian terrain (e.g., Cauvery, Palar, Pennar)	Clay (< 4 μm)	77.1–86.7 (81.6)	Babu et al. (2021)
Krishna and Godavari (Deccan basalt)	Clay (< 4 μm)	69.6–81.5 (75.5)	Babu et al. (2021)
Mahanadi and other mixed-lithology rivers	Clay (< 4 μm)	75.3–84.6 (79.4)	Babu et al. (2021)
Ganges	Suspended	65.7–66.1	Li and Yang (2010)
Brahmaputra	Suspended	70.5	Li and Yang (2010)
Indus	Suspended	61.3–66.3	Li and Yang (2010)
Huanghe (Yellow)	Suspended	62.7–71.2	Li and Yang (2010)
Yangtze	Suspended	72.5–83.8	Li and Yang (2010)
Mekong	Suspended	74.6–79.5	Li and Yang (2010)
Amazon	Suspended	70.9–78.9	Li and Yang (2010)
Orinoco	Suspended	72.6–77.0	Li and Yang (2010)
Mississippi	Suspended	61.5–81.5	Li and Yang (2010)
Congo	Suspended	89.9	Li and Yang (2010)
World rivers, average	Suspended	72.1	Li and Yang (2010)
Upper continental crust	Reference	51.4	Calculated from Rudnick and Gao (2003)
PAAS	Reference	70.4	Calculated from Taylor and McLennan (1985)

The ilmenite comparison points the same way (Table 6). Beach-placer ilmenite from Chhatrapur on the Odisha coast contains 50.25–55.41 wt% TiO_2 , partly above the stoichiometric value. It shows signs of mechanical and chemical weathering and is attributed to gneissic, granitic, basic and high-grade metamorphic rocks of the Eastern Ghats (Rao and Sengupta, 2014). Ilmenite from the South Kerala beaches and from Manavalakurichi in Tamil Nadu is Ti-enriched and partly altered to pseudorutile (Suresh Babu et al., 1994; Bernstein et al., 2008). Cauvery fluvial ilmenite has lower TiO_2 , more Fe^{3+} and no sign of alteration. Much of the alteration in beach placers seems to develop at or near the coast (Mücke and Chaudhuri, 1991; Bernstein

et al., 2008). Inland river ilmenite therefore keeps a clean source signal and makes a useful reference for provenance work on coastal deposits.

Table 6. Cauvery fluvial ilmenite compared with other Indian ilmenite occurrences.

Locality and setting	TiO ₂ (wt%)	Alteration state	Inferred source
Cauvery River, Tamil Nadu (fluvial; this study)	46.42–52.18	Unaltered; Fe ³⁺ in ilmenite-hematite solid solution	Mafic granulites (Group A); felsic or metamorphic rocks (Group B)
Chhatrapur coast, Odisha (beach placer)	50.25–55.41	Physically and chemically weathered	Gneissic, granitic, basic and high-grade metamorphic rocks of the Eastern Ghats (Rao and Sengupta, 2014)
South Kerala beaches (beach placer)	High-Ti ilmenite	Partly altered to pseudorutile	Metamorphic hinterland (Bernstein et al., 2008)
Manavalakurichi, Tamil Nadu (beach placer)	—	Altered to pseudorutile with some rutile	Suresh Babu et al. (1994)

— = not considered here.

5.3 Provenance seen at two scales

Bulk Al₂O₃/TiO₂ separates mafic (3–8), intermediate (8–21) and felsic (21–70) igneous sources (Hayashi et al., 1997). Along the Cauvery it changes systematically (Figs. 5 and 13a). The upper reach falls in the intermediate range (11.2–15.4), as expected from charnockite, pyroxene granulite and hornblende-biotite gneiss. The middle reach is clearly felsic (19.9–34.2), matching the granitoid gneiss terrain. C15 drops into the mafic range (4.35), but this is a heavy-mineral effect rather than a mafic source, as discussed below.

Cr is the only trace element consistently above UCC, and it rises and falls with Fe₂O₃^T ($r = 0.95$; Fig. 13b), as does Co ($r = 0.99$). Both elements must sit mainly in Fe-bearing detrital grains such as Fe-Ti oxides and ferromagnesian minerals, supplied from the ultramafic, amphibolite and pyroxene granulite units of the catchment (Fig. 1). Garnet, rutile and amphibole are among the river's heavy minerals (Prakash Narasimha et al., 2018), and Cr-rich spinel in Cauvery sediment has been attributed to meta-ultramafic rocks of the ancient supracrustal suite (Mujumdar et al., 2019), a likely host for part of this Cr.

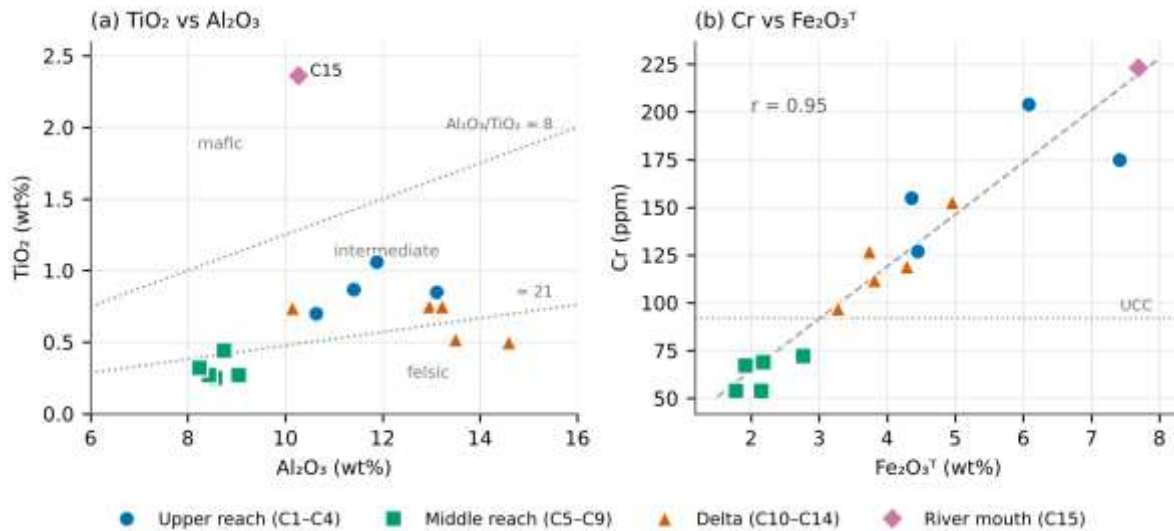


Fig. 13. Bulk bed load: (a) TiO₂ versus Al₂O₃, with Al₂O₃/TiO₂ = 8 and 21 (Hayashi et al., 1997) separating mafic, intermediate and felsic fields; (b) Cr versus Fe₂O₃^T, with a least-squares fit (dashed) and Cr in UCC (dotted).

The ilmenite adds detail that bulk chemistry cannot provide. Two published criteria are useful here. In sands from known sources, ilmenite derived from metamorphic rocks contained < 0.5 wt% MgO and clustered near 52 wt% TiO₂, whereas ilmenite from igneous rocks reached about 1.2 wt% MgO and had a wider TiO₂ range (Basu and Molinaroli, 1989). Ilmenite from mafic igneous rocks contained 50 ± 1 wt% TiO₂, against 48 ± 2 wt% for felsic igneous rocks, and grains with > 2 wt% MnO were most common in sands derived from felsic rocks (Grigsby, 1992). In Indian beach placers, the Mn/Mg ratio of ilmenite has been used in the same way: west-coast ilmenite with low Mn/Mg was traced to basic rocks, whereas higher east-coast values matched charnockite, khondalite and migmatite sources (Bhattacharyya et al., 1997). Mg enters ilmenite as the geikielite component of the solid solution (Pownceby and Fisher-White, 1999). Group A grains (49.48–52.18 wt% TiO₂; up to 0.85 wt% MgO, above 0.5 wt% in three samples) match the mafic range of Grigsby (1992) and carry more Mg than the metamorphic ilmenite of Basu and Molinaroli (1989), pointing to mafic igneous or meta-igneous (meta-basic) sources. Group B grains (46.42–49.08 wt% TiO₂) fall in the felsic range of Grigsby (1992). Their MnO (up to 1.91 wt%) is the highest in the set, although below the 2 wt% level that Grigsby (1992) found most typical of felsic sources, so we regard a felsic or metamorphic source as likely rather than proven.

The two scales line up well (Fig. 14). The Mn- and Fe³⁺-rich ilmenite (Group B) occupies roughly 60–180 km downstream of the first ilmenite site. The quartz-rich, felsic bulk sands occupy roughly 100–200 km downstream of Mettur dam. If both series begin near Mettur, these stretches overlap between about 100 and 180 km. [Authors: confirm the start point of the ilmenite series from field GPS records.] In this stretch, then, the bulk sediment and its ilmenite both carry a felsic signal. Upstream and downstream, Mg-bearing ilmenite and the higher Cr and Fe of the bulk sands both point to mafic contributions. The abrupt changes along the river, rather than gradual ones, suggest that each site mainly samples sediment from nearby bedrock and tributaries, with limited mixing over tens of kilometres. This contrasts with three large drainage basins in Virginia, where ilmenite composition stayed nearly constant over hundreds of kilometres because one dominant source swamped tributary input (Darby and Tsang, 1987). The Cauvery appears to lack such a dominant ilmenite source.

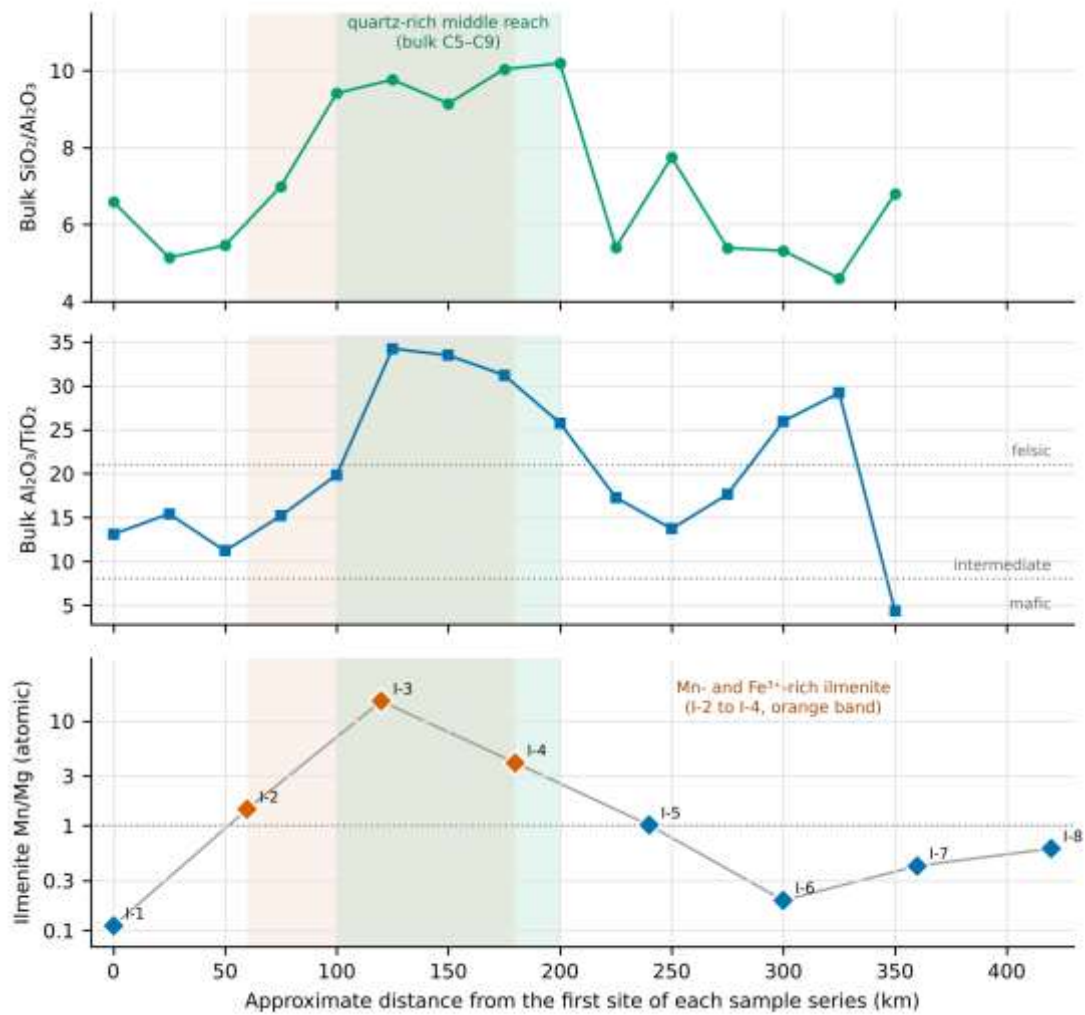


Fig. 14. Two-scale synthesis. (a) Bulk $\text{SiO}_2/\text{Al}_2\text{O}_3$ and (b) bulk $\text{Al}_2\text{O}_3/\text{TiO}_2$ for sites C1–C15, and (c) atomic Mn/Mg of detrital ilmenite for sites I-1 to I-8, plotted against distance from the first site of each series. Green band: quartz-rich bulk middle reach (C5–C9); orange band: Mn- and Fe^{3+} -rich ilmenite (I-2 to I-4). The overlap assumes both series start near Mettur dam.

5.4 Where does the titanium go?

Joining the scales also clears up the strange chemistry of C15. Its TiO_2 (2.36 wt%) is more than three times the river mean, and its $\text{Al}_2\text{O}_3/\text{TiO}_2$ (4.35) would normally suggest a basaltic source. Yet the catchment upstream is dominated by gneiss and granulite, and C15 is also the richest sample in Fe, Cr, La, Ce and Sm while being the poorest in Rb and Nb. The simplest explanation is that the river mouth concentrates dense grains. Ilmenite, the main Ti carrier in these sands, is accompanied by REE-bearing heavy minerals such as allanite, titanite and monazite, which control REE in Cauvery delta sediments (Ahmad and Singh, 2020). Micas and feldspars, which hold most of the Rb, have been winnowed away. A bulk ratio that looks like a provenance signal is in this case a sorting signal. Without the grain-scale data the C15 result could easily be misread. Titanium is listed among India's critical minerals (Ministry of Mines, 2023), so the concentration of fresh ilmenite at the river mouth also deserves attention as a resource question.

5.5 A caution on tectonic discrimination diagrams

In the discriminant-function diagram of Roser and Korsch (1988), the bulk samples plot mostly in the quartzose sedimentary provenance field, with a few towards the mafic igneous field (Fig. 4b). Bivariate tectonic diagrams spread them across the active continental margin and passive margin fields. These results contradict each other and the geology. The Cauvery drains a Precambrian craton and granulite terrain and reaches the sea on a passive margin, so an active-margin signature cannot be right. The quartzose signal comes from quartz enrichment by sorting in the middle reach, not from recycled sedimentary rocks. Six commonly used

discrimination diagrams performed poorly when tested on Neogene sediments from known settings (Armstrong-Altrin and Verma, 2005), and sorting and source composition strongly modify the major-element chemistry of sand (Garzanti and Resentini, 2016). We show these plots only to record where the data fall, and we do not use them to infer a tectonic setting.

5.6 A practical framework for future river-sediment studies

The Cauvery results suggest a few habits that would make river-sediment studies more reliable. We offer them as a short checklist:

1. **Match the sediment type before comparing.** Compare sand with sand, clay with clay and suspended load with suspended load. In the Cauvery, sediment type alone shifts the CIA by about 28 units (Fig. 12).
2. **Test bulk indices against mineralogy.** Plot CIA against CaO and SiO₂. Strong correlations, as here, mean the index is tracking plagioclase, mafic minerals and quartz rather than weathering.
3. **Check single grains for alteration first.** For Fe–Ti oxides, a TiO₂–Fe₂O₃ plot (Fig. 7) shows quickly whether Fe³⁺ is primary (ilmenite–hematite trend) or secondary (pseudorutile trend). Only unaltered grains should be used for provenance.
4. **Use both scales at the same sites.** Bulk chemistry shows sorting and mixing; single-grain chemistry resolves sources. Disagreements between the two, as at C15, are often the most informative results.
5. **Treat trace-element excesses as possibly natural.** In the Cauvery, Cr above UCC follows Fe-bearing heavy minerals ($r = 0.95$). Contamination indices based only on UCC would wrongly flag this geogenic Cr as pollution, so local baselines such as Table 1 are needed.
6. **Avoid tectonic interpretations of modern sorted sands** from bivariate or discriminant diagrams (Armstrong-Altrin and Verma, 2005).

Our study has limits of its own. The two strands were collected at different spacings, only one representative ilmenite analysis per site is reported, the bulk data come from sand alone, and XRF has limited sensitivity for Zn, Nb and the REE. The next steps are clear: co-located bulk and grain sampling, several tens of ilmenite grains per site so that sites can be compared statistically (Vermeesch et al., 2016), trace-element analysis of ilmenite (Darby, 1984; Darby and Tsang, 1987), automated mineralogy to quantify grain populations (Bernstein et al., 2008), separate analysis of size fractions, and radiogenic isotopes of the kind used to trace sediment sources in the Brahmaputra basin (Singh and France-Lanord, 2002).

6. CONCLUSIONS

1. Cauvery bed load from Mettur dam to the sea is silica-rich (64.9–84.6 wt% SiO₂). Relative to UCC it is depleted in all major oxides except SiO₂ and TiO₂, and in all analysed trace elements except Cr and Cu.
2. Bulk CIA (41.7–61.4; mean 53.7) is close to UCC and is controlled by Ca-bearing plagioclase and mafic minerals (CIA–CaO $r = -0.89$) and by quartz enrichment through sorting, not by weathering intensity.
3. Detrital ilmenite (84–97 mol% FeTiO₃) is unaltered. Its Fe³⁺ is held in primary ilmenite–hematite solid solution (TiO₂–Fe₂O₃, $r = -0.99$), and no grain shows the TiO₂ gain that marks weathering towards pseudorutile. Both scales therefore show that the bed load is chemically fresh.
4. Both scales record a mixed source. Charnockite and gneiss feed the upper reach, felsic granitoid gneisses dominate the middle reach in both bulk chemistry and Mn-rich ilmenite, and mafic granulites supply Mg-bearing ilmenite and Fe–Cr-rich heavy minerals. The high-Ti, low Al₂O₃/TiO₂ sample at the mouth reflects heavy-mineral concentration, not a mafic source.
5. The Cauvery bed load resembles bed sediments of large Tibetan–Himalayan rivers (CIA 46.5–69.6), is about 28 CIA units less weathered than the river's own clay (81.6), and lies well below the world mean for suspended sediment (72.1). Its ilmenite is fresher and lower in TiO₂ than coastal placer ilmenite.
6. River sediments should be compared only between matched sediment types, bulk indices should be tested against mineralogy, and single-grain chemistry should be screened for alteration before it is used for provenance.

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Data availability

All data used in this study are given in Tables 1–4.

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Table 1. Bulk major-element (wt%) and trace-element (ppm) composition of bed-load sediments of the Cauvery River (C1 upstream at Mettur dam to C15 at the river mouth).

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	Mean
SiO ₂	75.12	67.43	64.86	74.31	82.28	83.60	82.67	84.63	83.96	70.01	78.66	71.33	71.84	67.20	69.86	75.18
TiO ₂	0.87	0.85	1.06	0.70	0.44	0.25	0.27	0.27	0.32	0.75	0.74	0.75	0.52	0.50	2.36	0.71
Al ₂ O ₃	11.40	13.11	11.88	10.63	8.74	8.56	9.04	8.43	8.24	12.96	10.15	13.23	13.50	14.60	10.27	10.98
Fe ₂ O ₃ ^T	6.08	4.36	7.41	4.45	2.77	1.92	2.18	1.78	2.15	4.29	3.28	3.74	3.81	4.96	7.69	4.06
MnO	0.06	0.09	0.14	0.06	0.05	0.03	0.04	0.04	0.05	0.08	0.07	0.08	0.07	0.08	0.14	0.07
MgO	1.60	2.77	3.01	1.78	0.66	0.54	0.67	0.46	0.50	1.36	0.81	1.20	1.15	1.53	2.15	1.35
CaO	2.46	5.97	6.44	3.17	1.58	1.38	1.63	1.29	1.28	3.09	2.07	3.06	2.46	2.83	3.44	2.81
Na ₂ O	1.46	2.72	2.34	2.60	1.70	1.58	1.77	1.48	1.37	2.77	2.16	3.22	2.35	2.47	2.04	2.14
K ₂ O	0.40	2.17	1.32	1.14	1.17	1.14	1.23	1.24	1.23	1.70	1.47	1.80	1.73	1.85	1.23	1.39
P ₂ O ₅	0.06	0.28	0.17	0.13	0.07	0.05	0.06	0.04	0.07	0.12	0.06	0.12	0.13	0.11	0.15	0.11
LOI	1.00	1.10	1.45	0.40	0.38	1.02	0.47	0.90	0.35	0.57	0.83	0.94	2.50	3.34	0.73	1.07
Total	100.51	100.85	100.08	99.37	99.84	100.07	100.03	100.56	99.52	97.70	100.30	99.47	100.06	99.47	100.06	–
Cr	204	155	175	127	72	67	69	54	54	119	97	127	112	153	223	121
Co	15	12	17	13	9	8	8	7	8	12	10	11	12	14	17	12
Ni	94	66	52	53	22	17	24	17	15	43	28	41	54	73	42	43
Cu	33	27	33	45	22	25	22	39	17	27	24	31	38	62	6	30
Zn	23	21	38	26	b.d.	b.d.	b.d.	b.d.	b.d.	8	b.d.	21	17	36	31	–
Rb	40	81	47	61	68	59	59	65	61	68	64	63	70	83	13	60

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	Mean
Nb	9	11	8	10	10	8	8	9	9	9	9	8	8	10	4	9
Ba	190	110	484	470	416	407	415	452	414	782	515	739	613	668	304	465
La	24	31	27	22	22	16	18	19	18	29	27	29	29	41	43	26
Ce	29	54	58	40	30	15	29	25	35	45	47	42	46	65	65	42
Sm	3	3	4	3	3	3	3	3	3	4	3	3	3	4	6	3

$\text{Fe}_2\text{O}_3^{\text{T}}$ = total iron as Fe_2O_3 . b.d. = below detection. Trace elements in ppm.

Table 2. Weathering indices and elemental ratios of the bulk bed load.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	Mean
CIA	61.4	43.5	41.7	49.2	56.4	57.9	56.1	58.3	58.9	52.5	53.7	51.4	57.7	57.1	49.3	53.7
PIA	62.0	42.3	40.8	49.1	57.6	59.5	57.4	60.2	61.0	52.9	54.4	51.6	59.2	58.5	49.1	54.4
CIW	62.9	47.2	43.9	52.2	61.4	63.2	61.2	64.3	65.1	56.7	58.6	55.6	62.7	62.0	52.6	58.0
ICV	1.13	1.44	1.83	1.31	0.96	0.80	0.86	0.78	0.84	1.08	1.04	1.05	0.90	0.97	1.85	1.12
WIP	27.3	65.4	56.9	46.2	31.2	29.1	32.6	28.6	27.5	51.2	39.7	55.7	45.4	49.5	43.4	42.0
$\text{SiO}_2/\text{Al}_2\text{O}_3$	6.59	5.14	5.46	6.99	9.41	9.77	9.14	10.04	10.19	5.40	7.75	5.39	5.32	4.60	6.80	7.20
$\text{Al}_2\text{O}_3/\text{TiO}_2$	13.1	15.4	11.2	15.2	19.9	34.2	33.5	31.2	25.8	17.3	13.7	17.6	26.0	29.2	4.4	20.5
$\text{K}_2\text{O}/\text{Na}_2\text{O}$	0.27	0.80	0.56	0.44	0.69	0.72	0.69	0.84	0.90	0.61	0.68	0.56	0.74	0.75	0.60	0.66
$\text{K}_2\text{O}/\text{Al}_2\text{O}_3$	0.04	0.17	0.11	0.11	0.13	0.13	0.14	0.15	0.15	0.13	0.14	0.14	0.13	0.13	0.12	0.13