Source of the suspended load of the upper Orange River, South Africa

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ABSTRACT

The Orange River is one of the World's most turbid; delivering 60 million tons of sediment each year to the western margin of South Africa. Much of this sediment is believed to be from soil erosion, an increasing environmental threat to sustainability in southern Africa. This study focuses on the upper reaches of the Orange River above the Caledon River confluence, because it is here that high rainfall and topographic relief of the Drakensberg Mountains produce most of the Orange River's suspended load. Comparison of grain size, mineralogy and geochemistry of the suspended sediment load with catchment bedrock soils provides an estimate of the source of the suspended sediment. Major and trace element ratios indicate that the suspended sediment load is primarily derived from Karoo (upper Beaufort and Stormberg groups) sedimentary rocks rather than Drakensberg basalt. The Caledon River carries the largest fine-mud suspended load primarily from the erosion of Karoo sedimentary rock soils. The organic carbon content of the suspended load ranges from 1.0 to 1.3 weight % with $\delta^{13}C$ values that range from -19.7 to -16.9$^0/_{00}$ PDB. The $\delta^{13}C$ values of the organic fraction of soils is highly variable (-21.5 to -12.7$^0/_{00}$ PDB) and reflect the mix of C3 and C4 vegetation in the catchment area.

Introduction

Since the break up of Gondwana, the Orange River has delivered large amounts of sediment to the western continental margin of South Africa. The vast majority of the Orange River's terrigenous sediment was delivered during the warm and humid climates of the middle and late Cretaceous (Dingle and Hendey, 1984; de Wit, 1999). Terrigenous sedimentation on the margin has tapered off during the increasingly arid climates of the late Cenozoic so that now most runoff from the 0.9 million km^2 Orange River catchment area is derived from the high-rainfall areas of the Upper Orange River with only 1.8% derived from below the Orange/Vaal confluence (Kriel, 1972; Benade, 1988). Although the mean annual runoff of 11 km^3/year is small in comparison with most other major rivers, the Orange River carries a relatively large suspended sediment load and ranks as the most turbid river in Africa and the fourth most turbid in the World (Bremner *et al.*, 1990).

The Orange River originates in the Drakensberg Mountains of Lesotho and flows west for 2300 km across an increasingly arid interior plateau (Figure 1). Most of the sediment delivered by the Orange River to the Atlantic Ocean ends up widely dispersed across the western continental margin. The sand fraction of the Orange River sediment load is transported north to the Namib Desert by longshore drift driven by high-energy waves and strong southerly winds (Rogers, 1977; Rogers and Bremner, 1991; Rogers and Rau, 2006), while the mud fraction is transported offshore and south by a poleward undercurrent to form the mudbelt (Mabote *et al.*, 1997). The depositional history of deposits such as the mudbelt on the western margin is related, in part, to the input of Orange River sediment (Herbert and Compton, 2007). The Orange River suspended load is therefore important in understanding the source of offshore deposits and linkages between the terrestrial and marine realms.

Land degradation, in the loss of valuable topsoil and deep erosional gullies (dongas) which scour sediment-filled valleys and bedrock, is an increasingly large threat to sustainable development in southern Africa (Garland *et al.*, 1999). This study includes regions documented to have experienced high erosional activity in the recent past (Rooseboom, 1975; Seuffert *et al.*, 1999). Determining the source of the suspended sediment load can help in land management and the development of effective land use policies (Conley and van Niekerk, 2000). For example, variations in the clay mineralogy of the suspended load have been used to infer the source area of specific Orange River flood events (Bremner *et al.*, 1990). In this paper the texture, mineralogy and geochemistry of the suspended river sediment and the soils of the major bedrock types of the catchment area are compared to determine the source of the suspended load of the upper Orange River above the confluence with the Caledon River.

Geological setting

The Orange River catchment receives primarily summer rainfall, which varies from 700 to 800 mm/year in the far eastern catchment to less than 100 mm/year in the far western catchment. Higher rainfall in the eastern catchment is explained by orographic rainfall resulting from the high elevation of the region. The high rainfall area also corresponds to areas of high sediment production (Rooseboom, 1975; Seuffert *et al.*, 1999) which occur primarily in the Upper Orange River above the confluence with the Vaal (Wellington, 1958). The focus of this paper is on the uppermost reaches of

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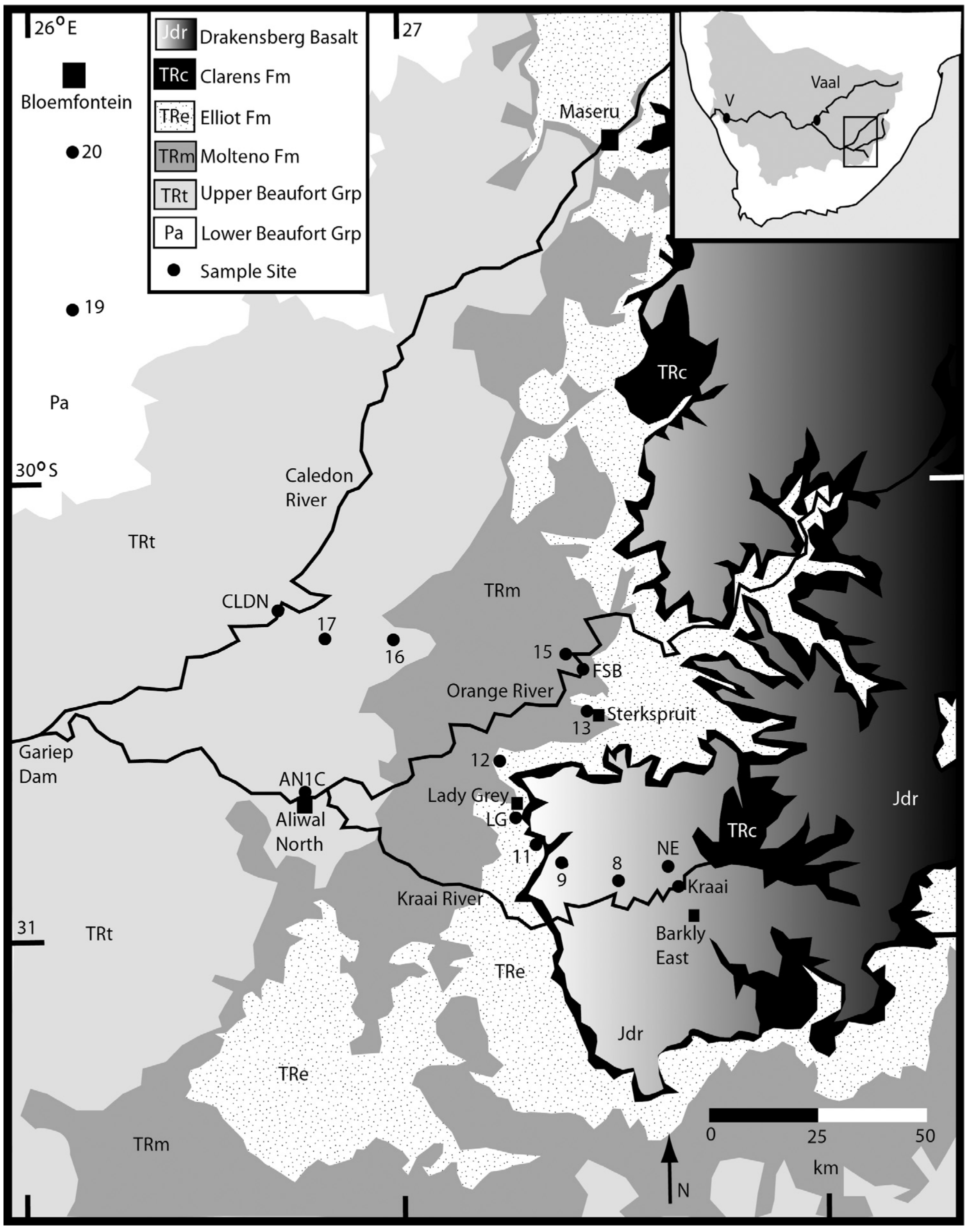

Figure 1. Geological map of the study area (modified after the Council for Geosciences 1:1 000 000 map) showing location of sample sites and major river courses. Inset of southern Africa shows catchment area of the Orange River shaded in grey and sample sites on the lower Vaal River and Orange River at Vioolsdrif (V).

the Orange River above the confluence with the Caledon River (Gariep Dam; Figure 1) because most Orange River suspended sediment is produced upstream of the Caledon-Orange river confluence (Bremner *et al.*, 1990). In addition, no major dams occur above the Caledon confluence with the exception of the Katse Dam in the Lesotho Highlands, completed in 1997.

The Orange River catchment above the Caledon confluence includes continental sedimentary rocks of the Beaufort Group, as well as the Molteno, Elliot and Clarens formations of the Stromberg Group. These sedimentary rocks are capped by the Drakensberg Group succession of flood basalts (Figure 1). Together, these rocks constitute the upper portion of the Karoo Supergroup. Beaufort Group sediments were deposited in the Late Triassic in an intracratonic basin, with the sediments derived from a volcanically active source located to the south and west (Turner, 1978; 1990). The Beaufort Group primarily consists of sandstones, siltstones and mudstones as well as some lenticular limestone and abundant calcareous concretions (Tankard *et al.*, 1982). The sediments of the Molteno Formation are an intracratonic, bedload-dominated fluvial wedge derived from a tectonically active source

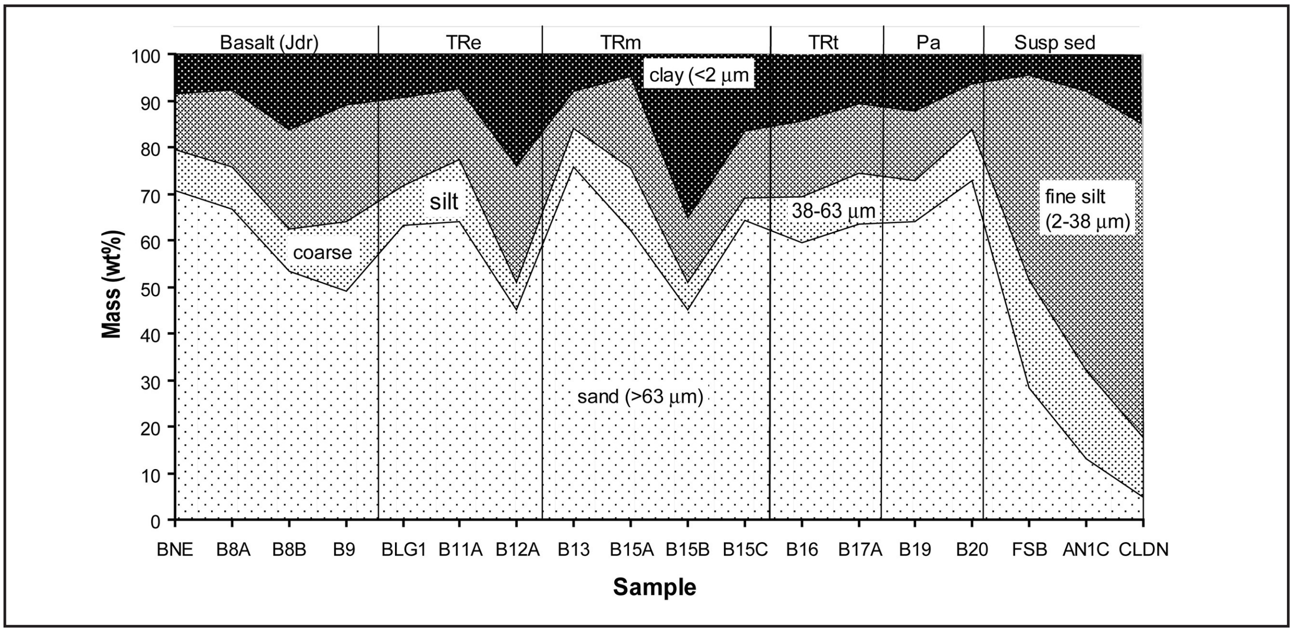

Figure 2. Grain size distribution of soil and river suspended sediment samples. Samples were collected in February 2006 and their location in relation to bedrock type is indicated in Figure 1.

to the south and south east (Rust, 1962; Turner, 1970) and are somewhat coarser grained compared to those of the upper Beaufort Group. The Elliot Formation was deposited in a fluvio-lacustrine environment within a long-established internal drainage basin, remote from any marine shoreline. Fine-grained red beds and lenticular yellow sandstones make up the Elliot Formation, and represent a reduction in fluvial energy and bed load in comparison to the underlying Molteno Formation (Tankard *et al*., 1982). The Clarens Formation is made up of quartzose aeolian sands, derived in general from the preceding fluvial deposits of the Molteno and Elliot formations. Drakensberg volcanism terminated Karoo sedimentation approximately 182 million years ago and heralded the break up of Gondwana. Flood basalts produced vast lava fields, of which the 140 000 km^2 Drakensberg plateau is an erosional remnant (Tankard *et al.,* 1982). In addition to flood basalts, the region is cut by numerous dolerite dykes and sills (not shown in Figure 1).

Methods

River water samples were collected from the Orange River upstream of the bridge at Aliwal North (AN1C) and upstream of the bridge at the Free State Border (FSB) in February 2006 (Figure 1). The Caledon River (CLDN) was sampled upstream of the N6 bridge between the towns of Rouxville and Smithfield. The Kraai River was sampled downstream of the R58 bridge north of Barkly East (Kraai) and a tributary to the Kraai River was sampled at the town of Barkly East (BE). River water samples were collected from the edge of the riverbank by submerging, in one rapid and continuous motion, 5-10 litre plastic buckets to a depth of approximately 30 cm below the surface of the river. River water suspended sediment was collected by settling in the field and filtration through a 0.45 micrometre (µm) filter in the laboratory. Collected suspended sediment was dried under vacuum (<100 mtorr) in a VirTis freeze drier at -85°C at the University of Cape Town (UCT). Soil samples were collected from road cut or riverbed exposures of the major rock types in the catchment area. The suspended sediment load (but no other data) was determined for a second set of river water samples collected in January 2007 from the Aliwal North site and Caledon River site as well as from the Vaal River 25 km upstream of the town of Douglas and at Vioolsdrif near the mouth of the Orange River (Figure 1; Table 1).

Table 1. Suspended sediment load of river samples in milligrams/litre.

Location	mg/l	Date	mg/l	Date
Barkly East	50	Feb 2006		
Kraai	220	Feb 2006		
FSB	3400	Feb 2006		
AN1C	2600	Feb 2006	460	Jan 2007
CLDN	3000	Feb 2006	520	Jan 2007
Vaal			<20	Jan 2007
Vioolsdrif			60	Jan 2007

The settled suspended river samples and bulk soil samples were wet sieved into sand (>63 µm) and coarse silt (38 to 63 µm) size fractions. The mud was separated into fine silt (2 to 38 µm) and clay (<2 µm) size fractions by allowing the suspended mud fraction to settle for 20 minutes and assuming that the fine silt particles follow Stoke's law (spherical grains with a density of quartz). Mineralogy was determined by petrography of thin sections of bedrock, sand and silt size fractions

Table 2. Major oxide composition of soil and river suspended sediment (Susp sed) samples by XRF.

Sample	BNE	B8A	B8B	B9	BLG1	B11A	B12A	B13	B15A	B15B	B15C	B16	B17A	B19	B20	FSB	AN1C	CLDN
Type	Top soil	Top soil	Subsoil	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil	Subsoil	Top soil	Top soil	Top soil	River bank	River bank	Susp sed	Susp sed	Susp sed
Bedrock	Jdr	Jdr	Jdr	Jdr	TRe	TRe	TRe	TRm	TRm	TRm	TRm	TRt	TRt	Pa	Pa	Water	Water	Water
SiO_2	51.61	45.41	50.85	49.55	77.71	75.92	59.91	78.88	55.88	73.45	79.30	76.51	74.14	72.69	78.94	62.47	65.64	62.47
TiO_2	1.83	1.05	1.43	1.11	0.53	0.53	0.41	0.60	0.95	0.63	0.53	0.61	0.65	0.64	0.66	0.78	0.80	0.97
Al_2O_3	13.91	13.97	13.51	13.51	9.85	8.00	16.81	8.01	13.38	9.95	7.57	8.56	9.63	8.92	7.94	13.58	13.10	16.32
Fe_2O_3	12.63	10.93	10.22	10.65	3.60	2.17	5.82	3.40	9.38	4.29	3.20	3.71	4.24	3.21	2.50	6.14	5.51	5.80
MnO	0.21	0.16	0.15	0.16	0.04	0.15	0.08	0.07	0.16	0.05	0.09	0.09	0.09	0.07	0.06	0.12	0.11	0.12
MgO	4.68	6.12	3.37	6.22	0.83	0.86	2.04	1.48	4.25	1.13	0.73	1.08	1.16	1.29	0.87	3.03	2.45	1.60
CaO	5.55	7.00	3.76	7.47	0.30	2.90	1.08	1.85	5.49	1.90	0.90	1.22	0.99	2.49	1.50	3.68	2.78	0.99
Na_2O	2.28	2.03	1.75	2.11	0.71	1.69	0.51	1.68	2.25	0.81	0.83	1.27	1.61	1.93	1.86	1.35	1.25	0.51
K_2O	0.87	0.89	1.17	0.82	1.55	1.97	1.51	1.51	1.10	1.57	1.36	1.32	1.54	2.17	1.94	1.11	1.34	2.21
P_2O_5	0.08	0.20	0.12	0.13	0.05	0.05	0.04	0.05	0.10	0.05	0.04	0.08	0.07	0.12	0.07	0.10	0.09	0.09
SO_3	0.02	0.01	0.01	0.03	0.00	0.03	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.05	0.03	NM	NM	NM
Cr_2O_3	0.06	0.05	0.06	0.07	0.02	0.01	0.02	0.03	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.05	0.04	0.05
NiO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01
H_2O-	1.67	3.24	4.13	2.59	2.27	0.95	3.03	0.98	2.62	1.87	1.28	1.82	1.84	1.44	0.88	NM	NM	NM
LOI	4.65	9.53	9.87	6.41	2.59	4.55	8.55	2.29	4.72	4.82	3.56	2.78	4.22	5.79	2.72	10.51	7.02	8.96
Total	100.06	100.60	100.40	100.83	100.05	99.79	99.82	100.85	100.35	100.56	99.42	99.08	100.23	100.82	99.99	99.98	100.13	100.09
Mg+Na/K	8.02	9.20	4.38	10.17	0.99	1.29	1.69	2.10	5.91	1.24	1.15	1.78	1.80	1.48	1.41	3.95	2.76	0.95

NM=not measured

Table 3. Trace element composition of soil and river suspended sediment (Susp sed) samples by XRF.

Sample	BNE	B8A	B8B	B9	BLG1	B11A	B12A	B13	B15A	B15B	B15C	B16	B17A	B19	B20	FSB	AN1C	CLDN
Type	Top soil	Top soil	Subsoil	Top soil	Top soil	Top soil	Top soil	Top soil	Top soil	Subsoil	Top soil	Top soil	Top soil	River bank	River bank	Susp sed	Susp sed	Susp sed
Bedrock	Jdr	Jdr	Jdr	Jdr	TRe	TRe	TRe	TRm	TRm	TRm	TRm	TRt	TRt	Pa	Pa	Water	Water	Water
Nb	11.6	8.5	11.5	6.6	8.1	9.3	14	9.7	8.7	9	9	8.1	10.9	8.7	7.6	1	3	8
Zr	186	86	164	114	333	375	138	321	163	282	362	289	330	248	299	183	232	203
Y	16	17	17	16	19	22	37	17	18	22	23	20	22	19	16	28	28	33
Sr	107	121	101	130	33	80	42	74	127	60	39	77	70	162	136	133	120	88
Rb	16	12	21	13	46	50	56	36	23	53	45	39	43	53	45	31	38	80
Pb	<4.7	<4.7	<4.7	<4.7	5.9	7.1	21.4	<4.7	<4.7	<4.7	6.8	4.8	5.3	9	<4.7	4	57	20
Zn	81	153	92	96	35	30	73	28	86	48	30	42	44	39	20	57	58	71
Cu	83	106	87	86	32	25	34	34	83	40	34	38	39	32	27	11	10	11
Ni	97	122	130	116	57	48	51	62	109	59	59	58	63	54	51	77	67	64
Co	44	40	41	45	8	7	10	12	38	11	15	14	14	10	8	32	28	28
Mn	1603	1235	1220	1258	196	1199	559	456	1205	329	631	648	665	447	347	NM	NM	NM
Cr	330	299	365	379	99	66	76	134	265	110	99	118	118	103	99	125	114	101
V	364	224	246	273	74	44	57	80	203	82	65	81	87	72	54	106	90	84
Ba	281	234	323	236	358	440	624	346	336	330	398	367	417	525	480	279	268	473
Sc	41.8	32.7	34.2	37.8	9.9	7.4	10.6	10.3	37.4	13.2	9	10.5	11.5	9.2	7.6	NM	NM	NM
S	350	554	452	298	454	233	164	115	73	103	142	177	281	718	645	NM	NM	NM
(Rb+Ba)/(Ni+Cr+V)	0.38	0.38	0.46	0.32	1.76	3.10	3.70	1.38	0.62	1.53	1.99	1.58	1.72	2.52	2.57	1.01	1.13	2.22

NM=not measured

and X-ray diffraction (XRD) analysis of the fine silt and clay size fractions mounted as wet slurries on glass slides. Bulk soil and settled river water samples were freeze dried and powdered for elemental analysis by X-ray fluorescence (XRF) and organic carbon analyses at UCT. The three suspended river sediment samples were analysed by XRF at the University of Stellenbosch. The results are assumed to be representative of the long-term erosion of the catchments sampled because of the high discharge and sediment load of the three river waters sampled in February 2006. This assumption will be tested by the future sampling and analysis of the suspended sediment load at the three sites.

Carbonate carbon (mostly present as $CaCO_3$) in freeze-dried samples was removed by reaction with a buffered 0.5M acetic acid-sodium acetate solution with a pH of five for a minimum of five hours. Samples were rinsed three to four times with distilled water, until the pH was neutral. The carbonate-free samples were run on a Thermo Finnigan Delta Plus XP stable light isotope mass spectrometer at UCT to determine the organic carbon content and isotope composition. Uncertainty in the carbon isotope measurements is ± 0.1‰ and $\delta^{13}C$ values are reported corrected to in-house reference materials calibrated against the PDB (Pee Dee Belemnite) international standard.

Results

The Karoo sedimentary rocks consist mainly of quartz, feldspar, mica, calcite and rock fragments. Quartz and feldspar are dominant (70 to 80%), whereas mica, calcite and rock fragments occur in subordinate to minor quantities. The basalt bedrock consists of plagioclase, orthopyroxene, olivine, and clinopyroxene, and zeolite-filled amygdales are common. Soil samples of Karoo sedimentary rocks are predominantly made up of quartz and feldspar, with lesser amounts of mica and calcite. The clay-size fraction of Karoo sedimentary rock soils is dominated by illite and smectite and by smectite in the basalt soils.

The grain size distributions of most soils sampled are similar and are dominated by 50 to 70% sand (Figure 2). The suspended sediment load in February 2006 was 3.4 grams/litre (g/l) at the Free State Border (FSB), 2.6 g/l at Aliwal North (AN1C) and 3.0 g/l for the Caledon River (CLDN) at the N6 bridge (Table 1). The suspended load of the Kraai River was 0.22 g/l and 0.05 g/l for a tributary of the Kraai River sampled at the town of Barkly East. Rainfall and suspended sediment loads were significantly less in January 2007 (Table 1). The suspended river sediments are dominated by 40 to 60 weight % fine silt with sand, coarse silt and clay each varying between 10 and 20% (Figure 2). Suspended river sediments contain quartz, feldspar and clay minerals. Smectite dominates over illite in the clay-size fraction.

The major oxide and trace element composition of Karoo sedimentary rock soils is distinct from basalt soils. River suspended sediment elemental compositions tend to be intermediate between the two. Basalt soils have similar or higher major oxide contents than Karoo sedimentary rock soils, except for silica and potassium (Table 2) and basalt soils have similar or higher trace element contents than Karoo sedimentary rock soils, except for Ti, Rb, Zr, Pb and Ba (Table 3). The major oxide ratio of (Mg + Na)/K has a mean value of 7.9 for basalt soils and 1.4 for Karoo sedimentary rock soils (excluding sample B15A) (Figure 3) and the trace element ratio (Rb + Ba)/(Ni + Cr + V) has a mean value of 0.4 for basalt soils and 2.0 for Karoo sedimentary rock soils (excluding sample B15A) (Figure 4).

The organic carbon content of the soil samples ranges from 0.2 to 2.9% and for the suspended river sediment from 1.0 to 1.3% (Table 4). The percentage of organic carbon in basaltic soils (1.3 to 2.9 weight %) is higher than in Karoo sedimentary rock soils (0.2 to 1.6 weight %). The organic carbon content is reported on a carbonate-free basis, but the carbonate content of these samples is low, ranging from 0.5 to 5 weight %. The $\delta^{13}C$ values of the organic carbon in the soil samples range from -21.5 to -12.7‰ PDB and from -19.7 to -16.9‰ PDB for the suspended river sediment samples. Duplicate $\delta^{13}C$ analyses can vary by up to 20% and reflect inhomogeneity of the small (2 mg) sample size, as well as analytical error.

Table 4. Organic carbon (OC) content on a carbonate-free basis and organic matter isotope composition of soil and river suspended sediment (Susp sed) samples.

Sample	Soil bedrock	OC (weight %)	$\delta^{13}C$ (‰ PDB)
BNE	Basalt (Jdr)	2.00	-13.31
B8A	Basalt (Jdr)	2.65	-18.40
B8A(D)		2.90	-18.51
B8B	Basalt (Jdr)	2.45	-12.66
B9	Basalt (Jdr)	1.34	-16.15
BLG1	Elliot (TRe)	0.74	-15.25
BLG1(D)		0.73	-14.90
B11A	Elliot (TRe)	0.63	-21.45
B11A(D)		0.65	-21.41
B12A	Elliot (TRe)	0.91	-12.98
B13	Molteno (TRm)	0.33	-18.38
B15A	Molteno (TRm)	0.28	-16.17
B15B	Molteno (TRm)	0.24	-17.81
B15C	Molteno (TRm)	0.43	-15.10
B16	Beaufort (TRt)	0.51	-15.04
B17A	Beaufort (TRt)	0.86	-14.26
B17A(D)		0.90	-14.63
B19	Beaufort (Pa)	1.57	-17.53
B20	Beaufort (Pa)	0.43	-19.89
B20(D)		0.38	-19.80
FSB	Susp sed	1.34	-18.57
FSB(D)	Susp sed	1.24	-19.15
AN1C	Susp sed	1.28	-19.47
AN1C(D)	Susp sed	1.09	-19.74
Caledon	Susp sed	0.98	-16.88
Caledon(D)	Susp sed	1.18	-17.05

D = duplicate

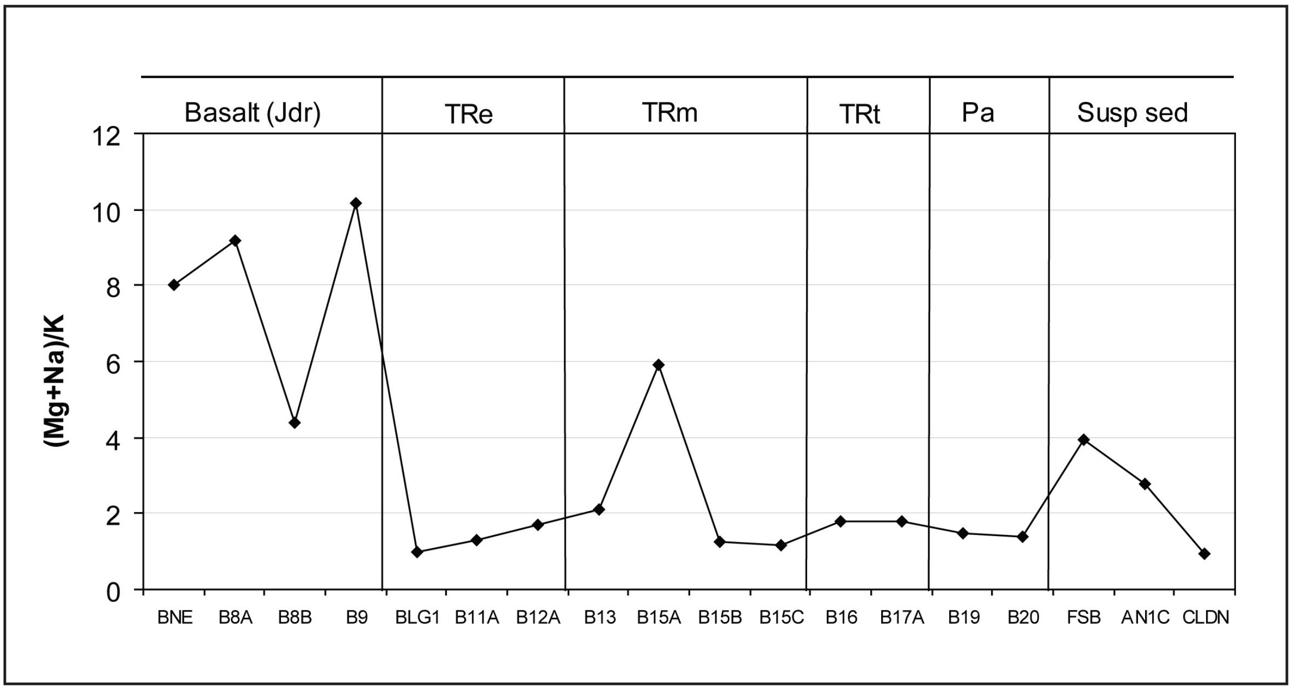

Figure 3. Ratio of major elements (Mg + Na)/K determined by XRF (Table 1) for soil and river suspended sediment samples. Samples were collected in February 2006 and their location in relation to bedrock type is indicated in Figure 1.

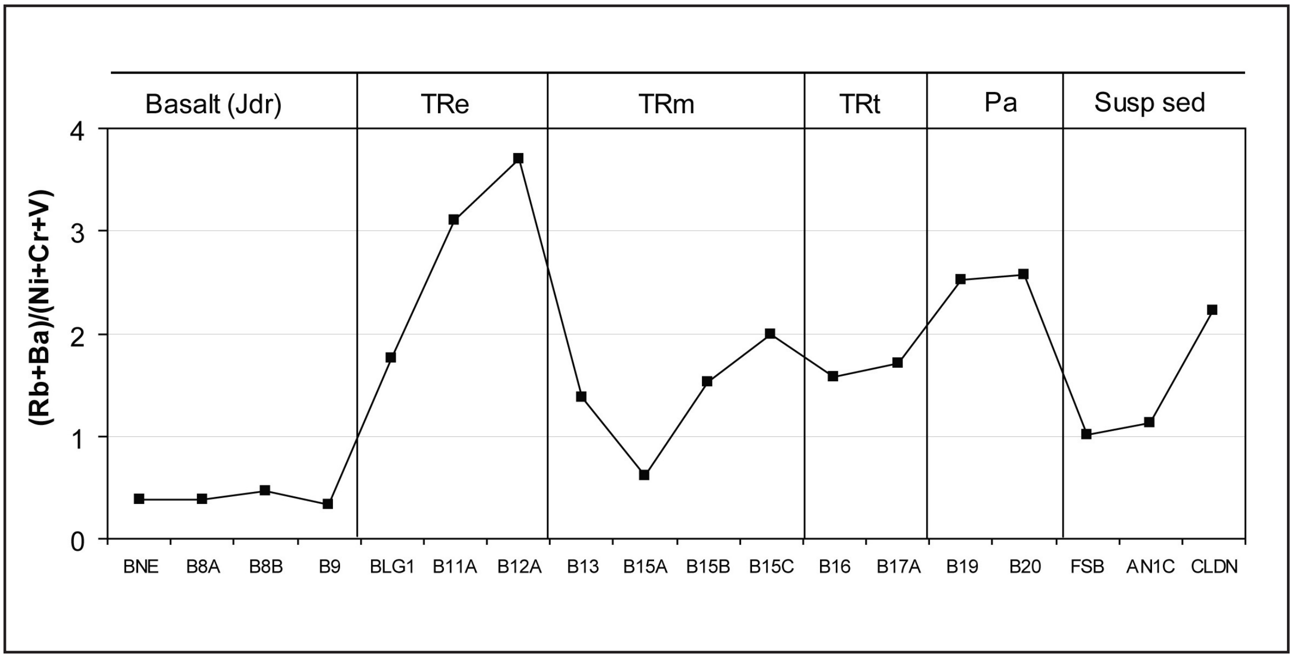

Figure 4. Ratio of trace elements (Rb + Ba)/(Ni + Cr + V) determined by XRF (Table 2) for soil and river suspended sediment samples. Samples were collected in February 2006 and their location in relation to bedrock type is indicated in Figure 1.

Discussion

Suspended sediment load

The suspended sediment load varies significantly among the rivers sampled in this study (Table 1). Rivers draining the basalt bedrock of the Drakensberg Mountains have a low suspended sediment load compared to those draining Karoo sedimentary rocks. In the field, clear river water was observed flowing over the bare basalt bedrock surfaces of Orange River tributaries. The banks of these basalt bedrock tributaries had dark clayey soils tightly bound by abundant plant roots. It therefore appears that the dense vegetation cover (mostly grasses) and hard basalt bedrock limit suspended sediment production, despite steep slopes and rapid flow rates. The suspended sediment load increases after the rivers cut into the generally softer and, therefore, more easily eroded underlying Karoo sedimentary rocks (Bremner *et al.*, 1990; and references therein).

The grain size of the river suspended load varies in relation to elevation and bedrock type. The greatest amount of sand and highest total suspended load occurs at the Free State Bridge (FSB), where the gradient is steepest. The least amount of sand occurs at the Caledon River (CLDN), which has a low topographic gradient (Figure 2). The large decrease in grain size between the suspended river sediment and the bulk soil samples reflects the preferential erosion of finer grained material from soils and the sampling of the surface flow of the river with much of the sand carried near or on the river bed. The amount of suspended sediment load is mostly related to the amount of runoff as seen in the much greater load during the high rainfall of 2006 compared to 2007 (Table 1). Previous studies have shown that most sediment is transported during Orange River floods and that the Caledon River carries the largest proportion of fine mud (Bremner *et al.*, 1990; and references therein).

The low suspended load of the lower Vaal River (most of which was living green algae and not sediment) is related to the low topographic gradient of the Vaal catchment and the large dams upstream, so that the modern Vaal River resembles a linear lake more than a flowing river. The generally rocky, sediment-starved river bed and banks, and small palaeoflood deposits indicate a low sediment load of the Vaal River. Prior to the building of dams, the Vaal River contributed 22% of the mean total water discharge, but carried less than 5% of the total sediment load of the Orange River based on Department of Water Affairs data collected between 1928 and 1943 (Rogers, 1977). The sediment load of the Orange River has been greatly reduced by sediment trapping in dams as reflected in the low sediment load at the border crossing at Vioolsdrif. Mean sediment discharge has dropped from 60 million t/year between 1929 and 1969 to 17 million t/year after the building of major dams since 1970 (Bremner *et al.*, 1990). The reduction in total sediment load of 72% is similar to the mean sand and coarse silt content of 70.5% of soils from this study (Figure 2) and suggests that most of the sand and coarse silt grains of eroded catchment soils is trapped by dams.

Geochemistry of the suspended load

Sediment derived from Karoo sedimentary rock soils can be differentiated from basalt soils from their greater abundance of quartz, K-feldspar and illite. X-ray diffraction profiles provide a qualitative estimate of these mineralogical differences but variations in the amount of clay minerals is difficult to quantify by XRD alone. Differences in mineralogy lead to differences in major and trace element geochemistry that are more easily quantified by XRF. The catchment area bedrock can be divided into two geochemical end members. The Drakensberg Group basalts and dolerite dykes have a mafic igneous rock composition and the Karoo sedimentary rocks have a predominately sialic continental crust composition. Element ratios can be used to differentiate between these two bedrock sources because the suspended load generally provides an integrated, homogeneous sampling of the eroded catchment bedrock and soil. The major oxide ratio (Mg + Na)/K is high (mean value of 7.9) for the basalt soil end member whereas the Karoo sedimentary rock soil end member has a low mean value of 1.4 (Figure 3). Sample B15A was excluded from calculating the mean for the Karoo sedimentary rocks because it was derived largely from local dolerite dykes rather than from the Molteno Formation. The trace element ratio (Rb + Ba)/(Ni + Cr + V) also discriminates between basalt (mean of 0.4) and Karoo sedimentary rock soils (mean of 2.0, excluding sample B15A) (Figure 4). The major oxide ratio shows more variability in basalt than in Karoo sedimentary rock soils and vice versa in the case of the trace element ratio.

The difference in the element ratios between the river sampled at the Free State Border and Aliwal North is small but indicates an increasing Karoo sedimentary rock soil contribution (Figures 3 and 4). The difference in the element ratios is most pronounced in the Caledon River sample which shows a predominantly Karoo sedimentary rock soil signal. The geochemical trend among the river water samples is consistent with the percentage of basalt and Karoo sedimentary rock within their catchment areas. A relatively small percentage of Caledon River tributaries above the sample site CLDN drain basalt terrains in comparison to tributaries upstream from Aliwal North (Figure 1). The Caledon River drains mostly Karoo sedimentary rocks, which make up approximately 89% of its catchment area, and contain abundant illite and K-feldspar rich in the elements K, Rb and Ba. The Orange River catchment above the Free State Border primarily drains basalt bedrock with only 28% of the catchment having upper Karoo sedimentary bedrock. The slightly greater Karoo sedimentary rock soil signal at Aliwal North reflects an increased proportion of Karoo sedimentary rocks (35%) in the catchment above Aliwal North.

Therefore, the Caledon River contributes a significant amount of the suspended fine mud carried by the Orange River sourced from the erosion of Karoo sedimentary rocks. Previous workers have argued the same (Harmse, 1974; Rooseboom and Harmse, 1979) relating the large increase in the sediment load of the Caledon River to the easily eroded Elliot Formation and, in particular, upper Beaufort Group (TRe and TRt on Figure 1, respectively). The question still remains as to whether the suspended load of the Caledon River is derived primarily from bedrock or topsoil erosion. Erosional features in the landscape clearly indicate that both bedrock and soil erosion are active (Figure 5) and the study area lies within a region, identified from aerial photographs, to have experienced significant erosion (Seuffert *et al.*, 1999). In the case of deeply scoured out bedrock (dongas and gullies), the volume of bedrock eroded is far greater than that of topsoil (Figure 5). But in the study area, few dongas of the dimensions shown in Figure 5 were observed. Therefore, topsoil

Figure 5. (**A**) A major erosional gully (donga) outside the town of Sterkspruit (Figure 1) showing sources of eroded topsoil (ploughed orange fields and uppermost, dark coloured soils on gully banks) and bedrock sediment (light colour rock of the Molteno and Elliot formations exposed below topsoil). The Clarens Formation (light colour rocks) and overlying Drakensberg basalt are exposed in the mountains in the background. Note eroded out vertical cement weir 2 m in height in river channel on the right hand side of photograph. (**B**) Same erosional gully as in (**A**) but photographed approximately one kilometre down stream showing slumping of vertically-cut river channel walls. Road in foreground is the R726 north of Sterkspruit.

erosion may be less obvious but more widespread than bedrock erosion. We do not have sufficient geochemical data to use elemental ratios to differentiate between Karoo bedrock and soil sources of the suspended sediment load of the Caledon River, but the relative contributions of bedrock and soil to the suspended load can be addressed to some extent by the organic carbon data (Table 4).

Organic carbon

The organic carbon data include the amount of organic carbon and its isotope composition (Table 4). The amount of organic carbon in topsoil is expected to be generally higher than that in Karoo sedimentary bedrock. This is because, although thin coal seams and pockets of plant material have been reported from the Karoo sedimentary rocks of the study area (Haughton, 1969; Tankard *et al*., 1982), most are sandstones and purple and green mudstones of significantly lower organic carbon content than their grassland topsoil. The mean $\delta^{13}C$ value of organic matter eroded from Karoo bedrock is expected to be around $-26^{0}/_{00}$, the mean $\delta^{13}C$ value of plants which follow the Calvin–Benson (C3) photosynthetic pathway. This is because plants, such as grasses, which follow the Hatch-Slack (C4) pathway with mean $\delta^{13}C$ values of $-12^{0}/_{00}$ had not yet evolved at the time of Karoo sediment deposition.

The $\delta^{13}C$ value of soil organic matter from the study area shows a wide range of values from those typical of C4 plants ($-12.7^{0}/_{00}$) to values as low as $-21^{0}/_{00}$ (Table 4). Most of the study area lies within the grassland biome (Mucina *et al*, 2005) and, from the road, tall grasses appear to dominate the vegetation. However, in walking through the vegetation, significant numbers of small, low-lying woody shrubs were observed in places. Therefore, it appears that the wide spread in $\delta^{13}C$ values for soil organic carbon of this study reflects a wide range in the relative proportion of C3 woody shrubs and C4 grasses.

The mean $\delta^{13}C$ values of $-18.9^{0}/_{00}$ and $-19.6^{0}/_{00}$ for the Free State Border and Aliwal North river sites, respectively, suggests an approximately equal mixture of C3 ($-26^{0}/_{00}$) and C4 ($-12^{0}/_{00}$) plant material in their suspended loads. Yet the catchment area of the Orange River above the Free State Border site is dominated by Senqu Highland Grassland, with less extensive valley fill areas covered by Senqu Montane Shrubland (Mucina *et al*, 2005). This suggests that a greater proportion of organic matter is derived from the valley-fill areas than from the steep mountain slopes, consistent with the field observation that basalt soils are tightly bound by densely rooted grasses. In addition to greater retention of organic matter by grassland soils, C3 woody plants may have a greater resistance to degradation in the soil and are more likely than C4 plants to end up in the river suspended load.

The organic carbon (OC) content of the suspended load of the Caledon River (1.1 weight %) is significantly greater than the mean organic carbon content (0.6 weight %) of catchment soils (Table 4). In contrast, Orange River suspended load organic carbon content (1.3 weight % at FSB and 1.2 weight % at AN1C) is less than the mean for the basalt soils (2.1 weight % OC). In addition, the $\delta^{13}C$ value of organic matter from the Caledon River ($-17.0^{0}/_{00}$) is less negative than the upper Orange samples from the Free State Border ($-18.9^{0}/_{00}$) and Aliwal North ($-19.6^{0}/_{00}$) sites, which suggests that the Caledon River carries a greater percentage of eroded topsoil with significantly more C4 plant material. Therefore, the higher organic carbon content and its more positive $\delta^{13}C$ value suggests that the Caledon River suspended load has a significant eroded topsoil source, whereas the suspended load of the Orange River above Aliwal North has a significant bedrock source.

Conclusions

The source of the suspended sediment load of the Orange River can be inferred from the mineralogical and geochemical differences of the two major bedrock types of the catchment area: basalt and Karoo sedimentary rocks. Basalt soils contain abundant rock fragments, plagioclase feldspar and smectitic clay minerals, whereas Karoo sedimentary rock soils contain abundant quartz, K-feldspar and illitic as well as smectitic clay minerals. These mineralogical differences are made quantifiable by the major oxide ratio (Mg + Na)/K and the trace element ratio (Rb + Ba)/(Ni + Cr + V). These ratios clearly differentiate basalt and Karoo sedimentary rock soils and indicate that most of the Orange River suspended load is derived from erosion of Karoo sedimentary bedrock and soils. In particular, the Caledon River delivers most of the fine mud suspended load of the Orange River. Although it is difficult to determine the relative contributions of Karoo sedimentary bedrock and topsoil erosion to the suspended load, the organic carbon content and isotope composition suggest that much of the suspended load of the Caledon River is derived from the erosion of topsoil. Future, more detailed geochemical analyses will allow for a more complete evaluation of eroded sediment sources to the Orange River.

The Drakensberg Mountains receive the greatest amount of rainfall and have the steepest slopes of the Upper Orange River catchment. However, the hard basalt bedrock combined with densely rooted grassland vegetation limit the amount of erosion. The sediment load is dominated by the more easily eroded underlying Karoo sedimentary rocks where the river down cuts through the Drakensberg Mountains. It is this difference in erosion rate that makes the cliff-faced Drakensberg Mountain basalts such a prominent topographic feature of southern Africa. Therefore, most of the sediment carried to the western margin by the Orange River is derived from Karoo sedimentary rocks rather than from basalt. However, the sediment derived from Karoo sedimentary rocks is dominated by quartz sand, much of which ultimately ends up in the Namib Desert.

The terrigenous mud of the offshore mudbelt is largely derived from weathering of the upper Karoo sedimentary rocks, but will also include mud derived from the weathering of basalt. Eroded sand and silt sized basalt rock fragments can undergo further weathering downstream to produce the clay mineral smectite much of which is deposited in the mudbelt.

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