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A tenfold increase in the Orange River mean Holocene mud flux: implications for soil erosion in South Africa

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Abstract: Soil erosion poses a major threat to sustainable agriculture in southern Africa but is difficult to quantify. One measure of soil erosion is the sediment flux of rivers. The Orange River is the principal source of sediment to the western margin of South Africa with an estimated mean mud flux over the last 11 500 years (the Holocene epoch) of 5.1 (3.2–7.4) million metric tons/year (Mt/yr). A total of 43 gigatons (Gt; 10^{15} g) representing 72% of the Holocene mud flux has accumulated on the shelf in the Orange River prodelta and mudbelt, a clayey fine-silt deposit focused on the inner to middle shelf. Only 8% (5 Gt) of the mud flux occurs in Holocene calcareous ooze on the slope. Comparison of the clay to mud ratio of offshore deposits with Orange River suspended sediment and catchment soils indicates that 20% (11 Gt) of the Holocene mud flux has been lost as clay beyond the margin. The Orange River mud flux prior to the building of large dams (1930–1969) is ten times greater than the mean Holocene mud flux and is reconciled with estimates of soil erosion within the catchment. A tenfold increase in the Orange River mud flux implies up to a hundredfold increase in total soil erosion depending on the extent of mud storage over periods of decades to centuries within the catchment. Erosion has shifted from areas of high relief and rainfall of the Drakensberg escarpment during the Holocene to intensely cultivated lands of low relief having moderate to high rainfall in the eastern catchment and to a lesser extent, grazing areas of the southern Orange River catchment.

Key words: Soil, erosion, Orange River, South Africa, continental margin, Holocene.

Introduction

Soil erosion is a major environmental threat globally and in South Africa is highly variable and linked to past land-use change (Garland *et al*., 1999) and likely to be influenced by future climate change (eg, Lobell *et al*., 2008). A pre-dam (1930–1969) sediment discharge of 60 million metric tons/year (Mt/yr), of which 50 Mt/yr is mud, makes the Orange River the most turbid in Africa and the fourth most turbid river in the world (Bremner *et al*., 1990). Most rainfall and erosion occur in the eastern portion of the 0.9 million km^2 catchment (Figure 1). The suspended mud load of rivers can provide a useful measure of accelerated soil erosion, but requires an estimate of river fluxes prior to human impacts. Anthropogenic increases in river fluxes can be estimated by quantifying terrigenous mud accumulation offshore adjacent to rivers, and in the case of South Africa indicate a 12-fold increase since the Pliocene for the east coast (Martin, 1987) and a 13-fold increase since the Neogene for the west coast (Dingle and Hendey, 1984). However, deriving natural background rates of erosion over long, million-year timescales is complicated by tectonic and climatic variations, which may have significantly altered river drainage, sediment discharge and dispersal (Partridge and Maud, 2000). Therefore, it is desirable to compare modern river discharge with that of the Holocene, a period during which tectonism and climate were largely similar to today. Here, we estimate the mass of terrigenous mud on the western continental margin to derive the mean Holocene mud flux of the Orange River and reconcile the large increase in the modern flux with soil erosion within the Orange River catchment.

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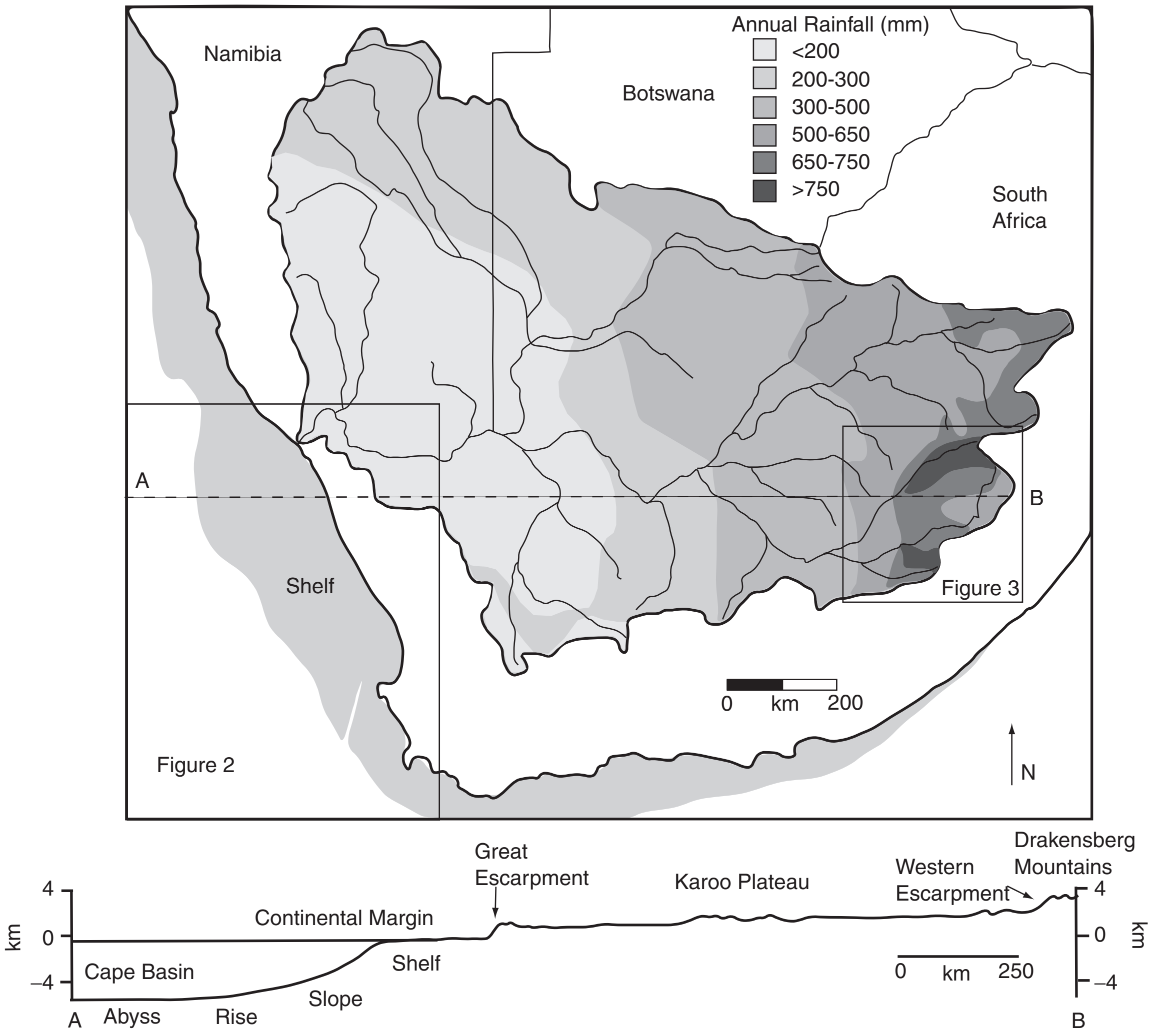

Figure 1 Orange River catchment and rainfall distribution (South African Weather Bureau). Topographic cross-section from Cape Basin (A) to Drakensberg Mountains (B) showing the coastal plain escarpment (Great Escarpment), the Karoo plateau and the Drakensberg escarpment

Holocene terrigenous mud on the offshore margin

This study focuses on the accumulation of terrigenous mud (<63 µm; silt and clay). In part this is because the mud fraction constitutes, along with organic matter, the most valuable components of soil for sustainable agriculture. Mud is also the sediment most easily transported in the suspended load of rivers and, in the case of the western margin of South Africa, most mud has accumulated during the Holocene in an offshore mudbelt deposit where it can be quantified from marine geophysical and coring surveys. Sand carried by the Orange River is separated from the mud fraction by the high-energy wave climate at the coast. Sand is transported north by longshore drift and southerly winds to the Namib Desert whereas the mud is carried out onto the delta and south by a poleward undercurrent to form the mudbelt (Shannon and Nelson, 1996; Rogers and Rau, 2006). Additional sources of terrigenous mud to the western margin include wind blown dust (Shannon and Anderson, 1982), erosion of older deposits (eg, Wigley and Compton, 2006) and discharge from the Olifants and Berg rivers. These are all considered to be relatively negligible sources of mud in comparison to the Orange River (Herbert and Compton, 2007).

The mass of terrigenous mud is estimated from the average thickness and composition of Holocene sediment on the continental shelf and slope from the Orange River delta (28°S) to the Cape Canyon (34°S) (Table 1; Figure 2). Mud transport north of the delta is assumed to be negligible because bottom waters on the margin flow south (Shannon and Nelson, 1996) and most mud transported to the Cape Canyon is assumed to be lost from the margin. Data are compiled from the literature (Wefer *et al*., 1998; Rogers and Rau, 2006) as well as from the analysis of cores (Wigley and Compton, 2006; Compton, unpublished data, 2004) obtained from diamond exploration companies and during the scientific cruise of the RV *Meteor* (Schneider *et al*., 2003). The thickness of Holocene sediment was estimated from calibrated radiocarbon ages where available (Herbert and Compton, 2007) and down core reflectance (L*) data in combination with available seismic profiles (Schneider *et al*., 2003). Holocene sediment thickness on the slope was estimated as one half the distance down core to the first minimum (last glacial maximum) in the reflectance (L*) value, a method generally supported by available radiocarbon ages. Sediment volume was obtained by multiplying the area of the different margin depositional environments by the mean sediment thickness (see below). Measured dry bulk densities of cored samples (g dry weight/cm^3 of bulk, wet sediment) were used to convert sediment volume to dry sediment mass. The mean dry bulk density was multiplied by the mean sediment volume to obtain the mean sediment mass whereas the range in sediment mass was obtained by multiplying the minimum and maximum sediment volumes by the corresponding minimum and maximum dry bulk densities. The mean carbonate, organic matter (1.45 × organic carbon values shown in Figure 2),

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Table 1 Estimated Holocene terrigenous mud masses in gigatons (Gt) (10^{15} g) for the western margin of South Africa

Region	Area (10^4 km^2)	Sediment volume (km^3)	Dry bulk density (g/cm^3)	Sediment mass (Gt)	Terrigenous mud (wt%) (range)	Terrigenous mud mass (Gt)
Estuary	0.01	1.5 (1.2–1.8)	0.65–0.85	1.1 (0.8–1.5)	42 (37–47)	0.5 (0.3–0.7)
Delta front	0.10	19 (16–22)	0.65–0.85	14.3 (10–19)	42 (37–47)	6.0 (3.7–8.9)
Prodelta	0.10	19 (16–22)	0.55–0.75	12.4 (8.8–16.5)	80 (70–90)	9.9 (6.2–14.9)
Inner shelf	0.36					0
Mudbelt	1.26	48 (44–51)	0.55–0.65	28.8 (24–33)	75 (70–80)	21.6 (16.8–26.4)
Mid-outer shelf	8.36	33.4 (16.8–50)		27.5 (12.2–46.3)		4.6 (1.1–11)
sand	4.18	16.7 (8.4–25)	0.8–1	15.0 (6.7–25.0)	5 (0–10)	0.8 (0.0–2.5)
muddy sand	4.18	16.7 (8.4–25)	0.65–0.85	12.5 (5.5–21.3)	30 (20–40)	3.8 (1.1–8.5)
Upper slope	3.28	11.9 (7.9–14.7)		9.1 (5.4–12.4)		1.7 (0.5–2.8)
North	2.75	9.6 (6.6–10.7)	0.65–0.80	7.0 (4.3–8.6)	14 (4–18)	1.0 (0.2–1.5)
South	0.53	2.3 (1.3–4.0)	0.85–0.95	2.1 (1.1–3.8)	31 (27–35)	0.7 (0.3–1.3)
Lower slope	8.58	25.3 (17.2–35)		21.2 (13.7–31)		3.2 (1.5–5.6)
North	4.78	15.3 (9.6–22.5)	0.75–0.85	12.2 (7.2–19.1)	9 (6–11)	1.1 (0.4–2.1)
South	3.80	10 (7.6–12.5)	0.85–0.95	9.0 (6.5–11.9)	23 (17–29)	2.1 (1.1–3.5)
Total margin	22.05	158 (119–197)		114 (75–160)		48 (30–70)
Terrigenous mud lost beyond shelf and slope (see text)						11 (7–15)
Total						59 (37–85)

Sediment volume = area × thickness (variably averaged over the area, see text)

quartz sand, biogenic silica and pyrite contents were subtracted to yield a range in terrigenous mud content. Consistent compositional and thickness trends lend confidence to extrapolation of core data across the margin. The uncertainty of the estimated masses is reflected in the bracketed range in reported values (Table 1).

The Orange River delta sediment volume of 38 km^3 is based on seismic profiles (Hoyt *et al*., 1969). The Orange River delta is divided approximately in half at a water depth of 40 m between delta front muddy very fine sand (37–47% mud) and prodelta clayey silt (70–90% mud) (Rogers and Rau, 2006). The Orange River estuary has a sediment volume of 1.5 km^3 based on the depth to river channel bedrock (Murray *et al*., 1971) and surface estuarine samples (Compton, unpublished data, 2006) have a grain size similar to the delta front of muddy very fine sand. The high-energy, wave-dominated inner shelf (0–40 m water depth) outside the delta contains negligible mud.

Orange River mud transported south by the poleward undercurrent forms the mudbelt, a narrow wedge-shaped deposit in-filling the lowstand (125 m water depth) wave-cut knick point between the inner and middle shelf. The mudbelt has an area of 1.26×10^4 km^2 which varies in mean thickness from 9 m between the Holgat and Buffels rivers to 2 m between the Olifants and Berg rivers based on recovered cores and hydroacoustic sediment echosounder data (Meadows *et al*., 2002; Schneider *et al*., 2003). A total sediment volume of 48 (44–51) km^3 for the mudbelt was estimated by assuming a gradational thinning from north to south between echosounder profiles. The mean terrigenous mud content of the mud belt ranges from 70% to 80% and reflects the mean range in carbonate content (15–20%), organic matter (3–4%), biogenic silica (1–2%), pyrite (1–3%) and quartz sand (0–1%). The middle and outer shelf extend seaward to the shelf break at 300 to 500 m water depth and has a 0.4 (0.2–0.6) m thick Holocene sediment drape made up of approximately equal areas of muddy sand with 30% terrigenous mud, and sand with <10% terrigenous mud (Rogers and Rau, 2006). The slope is divided into north and south areas based on carbonate content, which tends to decrease in the southern area near the Cape Canyon (Figure 2; Table 1). The mean thickness of Holocene calcareous ooze on the upper slope (0.5 to 2 km water depth) is 0.35 (0.24–0.39) m in the northern area and 0.44 (0.25–0.75) m in the southern area. The mean thickness of Holocene calcareous ooze on the lower slope (2–3.5 km water depth) is 0.32 (0.20–0.47) m in the northern area and 0.27 (0.20–0.33) m in the southern area.

Mud transported beyond the offshore margin

The amount of terrigenous mud transported beyond the study area is estimated from the difference in the clay to mud ratio of Orange River suspended sediment (Bremner *et al*., 1990) and catchment soils (Compton and Maake, 2007), which ranges from 25% to 33%, and the clay to mud ratio of shelf (10–12%), upper slope (17%) and lower slope (27%) sediment (Mabote *et al*., 1997; Herbert, 2009). The clay to mud ratio of margin sediments is lower than that delivered by the Orange River and indicates that 11 (7–15) Gt of clay is transported beyond the study area. Dissipation of wave and tidal energy on the shelf and slope is a common feature of margins (eg, Nittrouer *et al*., 2007) including the western margin of southern Africa (Shannon and Nelson, 1996; Monteiro *et al*., 2005). These margin processes can result in frictional stresses in the bottom boundary layer which generate sediment resuspension 'loops' of erosion–transport–deposition (Thomsen, 2002) during which the finer, clay-size sediment is transported beyond the margin. Adding the amount of terrigenous clay lost from the margin gives a total Holocene terrigenous mud flux of 59 (37–85) Gt and a mean Holocene mud flux of 5.1 Mt/yr (Table 1). This mean value represents the long-term average mud flux with most mud delivered to the margin episodically on a 10–15 year flood cycle documented over the last 200 years (Benade, 1988; Bremner *et al*., 1990), as well as megaflood events documented by Orange River paleoflood deposits to occur on an approximate 1000 year cycle (Zawada, 2000; Herbert and Compton, 2007). Most (72%) of the Holocene terrigenous mud flux has accumulated on the shelf (43 Gt), 5 Gt (8%) has accumulated on the slope and 11 Gt (20%) has been transported beyond the margin (Table 1).

Escarpment retreat

What is the source of mud on the margin? Highest rainfall (650–1050 mm/yr) and relief in the Orange River catchment occur in the Drakensberg Mountains (Figures 1 and 3). But the Drakensberg basalt and the underlying Clarens Formation sandstone form a resistant cap rock (Figure 3) with basalt near the drainage divide

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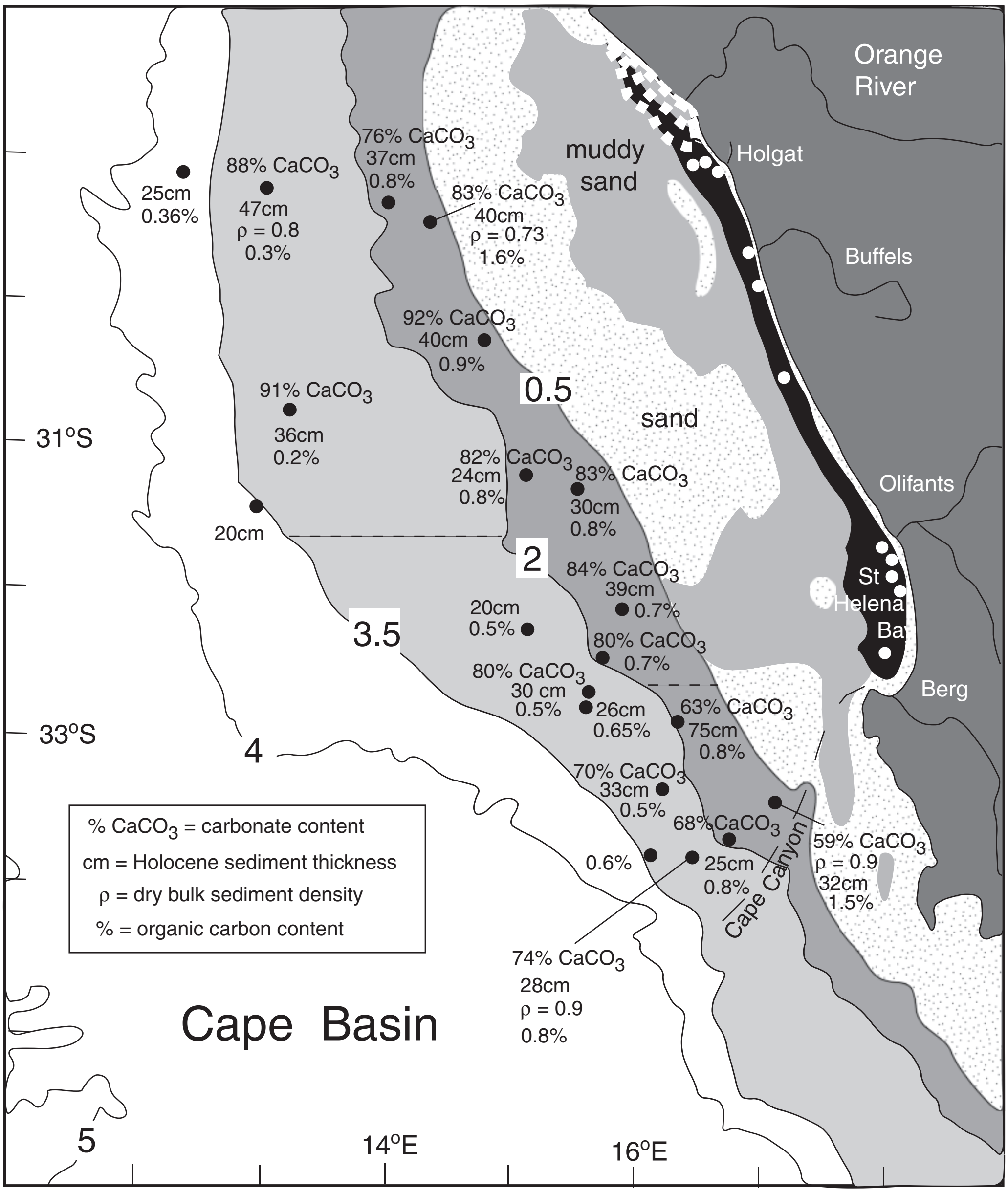

Figure 2 Western continental margin of South Africa showing the location of cores used in this study and regions defined in this study (Table 1). Thickness of Holocene sediment, percent CaCO$_3$, percent organic carbon (%) and dry bulk density (ρ) are shown where available. Holocene mudbelt is shown in black, muddy sand in grey and sand in stippling on the shelf. Black dashed lines separate north and south upper slope (at 32.7°) and lower slope (at 31.7°), and white dashed lines separate Orange River delta front and prodelta. Bathymetric contours are shown in kilometers

having a denudation rate of only 6 m/Myr based on cosmogenic isotopes (Fleming *et al*., 1999). Stream waters draining basalt and sandstone rocks of the Drakensberg Mountains are clear and become charged with suspended sediment only once they incise the relatively easily eroded mudstone of the underlying Elliot Formation on the lower slopes of the Drakensberg escarpment (Rooseboom, 1975; Rooseboom and Harmse, 1979; Compton and Maake, 2007). Incision below the Elliot Formation is limited by underlying resistant Molteno Formation sandstone layers. Therefore, the Elliot represents the cutting edge of the Drakensberg escarpment, constituting only 1.1% of the catchment area but providing a significant amount of the Holocene Orange River mud flux.

The retreat velocity of the western Drakensberg escarpment is unknown, but the flow of most mountain runoff to the west of the drainage divide (Figure 3) suggests that it is greater than the 100 (45–200) m/Myr retreat velocity estimated for the eastern escarpment from cosmogenic ^{36}Cl analyses (Fleming *et al*., 1999; Brown *et al*., 2002). Holocene erosion is focused on the interior, Drakensberg escarpment with denudation rates decreasing rapidly to the west of the escarpment because of less rainfall and topographic relief (Le Roux, 1990). Cosmogenic nuclide measurements indicate denudation rates of 1–3 m/Myr for the interior plateau of South Africa (Kounov *et al*., 2007) and a retreat velocity of 10 m/Myr for the coastal plain escarpment in Namibia (Cockburn *et al*., 2000). Therefore, prior to human impacts, most of the Orange River mud flux was derived from erosion of Elliot Formation mudstone at the base of the western Drakensberg escarpment.

Soil erosion

The recent ten-fold increase in the Orange River mud flux compared with the mean rate for the Holocene is attributed to soil erosion (Garland *et al*., 1999) and not to unusual flood events (Benade,

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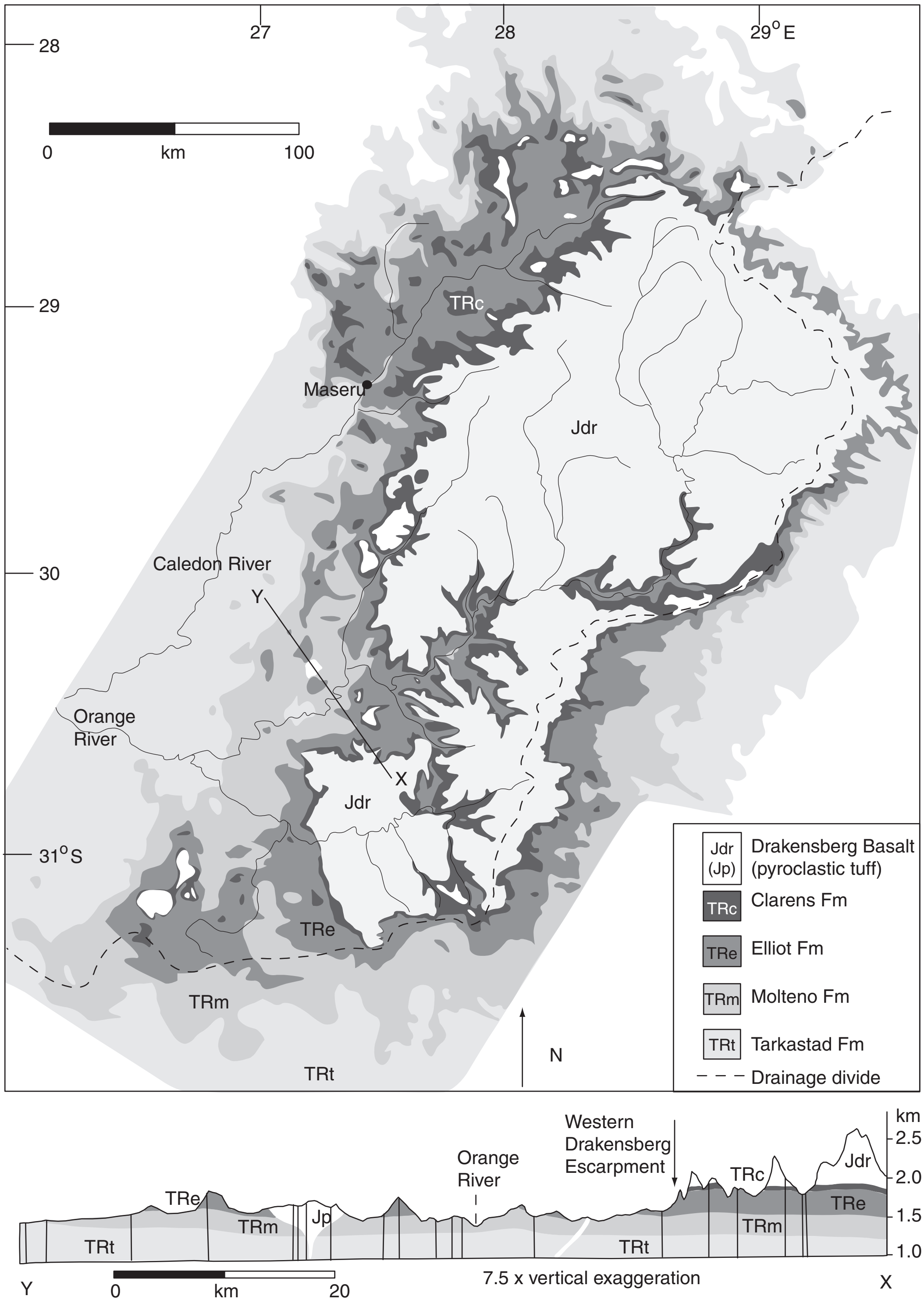

Figure 3 Geological map of the Drakensberg Mountain area showing the distribution of the Elliot Formation (adapted from the Council for Geoscience 1:1 000 000 scale map). Geological cross section (X–Y) for the western Drakensberg escarpment showing the position of the Elliot Formation (TRe) at the base of the principal and subsidiary escarpments (adapted from the Council for Geoscience 1:250 000 scale Aliwal North map)

1988; Zawada, 2000). Can the additional mud flux of 45 Mt/yr be reconciled with estimates of soil erosion within the Orange River catchment? Although difficult to quantify on regional scales (Garland *et al*., 1999; Le Roux *et al*., 2007), soil erosion is estimated here for magisterial districts of South Africa by scaling the qualitative degree of soil degradation indicated by sheet, rill and gully erosion (Hoffman *et al*., 1999) to measured rates of soil loss as summarized by Garland *et al*. (1999) (Table 2) and multiplied by percent land use type (cultivated crops and livestock grazing) (supplementary Table 3, available online). The erosion rate equivalence to the qualitative degree of soil degradation presented in Table 2 is an initial best estimate based on available erosion data from areas generally much smaller than magisterial districts. The scaling up of these erosion rates may be problematic in deriving absolute rates of soil erosion. However, the relative differences in soil erosion rates are useful to indicate where soil erosion is most intense. In the eastern catchment there are 15 magisterial districts with erosion rates >400 (410–1440) t/km^2 per yr and 13 with rates of

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Table 2 Conversion of degree of soil degradation to soil erosion rate

Degree of soil degradation		Erosion rate[a]	
		Crops	Grazing
0	none	200	50
1	light	500	100
2	moderate	1000	200
3	strong	3000	300
4	extreme	7000	>300

[a](t/km^2 per yr); no magisterial district in the catchment has a degree of soil degradation greater than 3.

300–400 t/km^2 per yr (Figure 4). In southern districts soil erosion rates of 150–300 t/km^2 per yr are common whereas the western and northern districts generally have rates <150 t/km^2 per yr.

Soil loss from all South African districts within the Orange River catchment is estimated to be 110 Mt/yr. Soil erosion for Lesotho is estimated to be 5.4 Mt/yr based on 12% arable land (3600 km^2) and 18 000 km^2 grazing land having average erosion rates similar to bordering districts in South Africa of 750 and 150 t/km^2 per yr, respectively. Similarly, areas of southern Botswana and Namibia within the Orange River catchment have a range in soil erosion of 12 to 30 Mt/yr based on soil loss rates of 50 to 125 t/km^2 per yr in the bordering districts of South Africa. Total soil erosion from the Orange River catchment is estimated to be 127–145 Mt/yr or 48–55 Mt/yr mud assuming soils contain an average of 38% mud (Compton and Maake, 2007). The estimated soil erosion mud flux of 48–55 Mt/yr is in reasonable agreement (10–20%) with the estimated additional anthropogenic mud flux discharged by the Orange River of 45 Mt/yr (the difference between the pre-dam (1930–1969) flux of 50 Mt/yr and the mean Holocene flux of 5.1 Mt/yr).

On the timescale of the Holocene, the flux of mud to the coast is assumed to be more or less in steady state with catchment erosion, although long-term changes in sediment storage may result from infilling or erosion of river channel alluvium in response to variations in rainfall (Scott and Lee-Thorp, 2004). On shorter, decadal to century timescales, the total amount of erosion from the land surface can be considerably greater (90% or more) than the amount transported out of the catchment because of temporary storage of eroded sediment in the catchment (Trimble, 1981; Boardman and Foster, 2008). For example, overgrazed and partially cultivated badlands in the Karoo have erosion rates on the order of 5500 t/km^2 per yr, but the amount transported to dam reservoirs is 270–500 t/km^2 per yr and indicates that most eroded sediment is stored in the catchments at least on the timescale of 50 years (Boardman and Foster, 2008). The net transport of 270–500 t/km^2 per yr falls within the range of erosion rate for moderate to extreme degrees of soil degradation for grazing lands in Table 2, consistent with the generally large extent of soil degradation in the badlands of the Karoo. The general reconciliation of soil erosion rate to the net exported sediment flux, suggests that the values of soil erosion used in this study (Table 2) are representative of the net sediment export from the Orange River catchment and exclude sediment storage within the catchment. Inclusion of stored sediment may increase the total amount of soil erosion considerably. If only 10% of eroded soil has been transported to the coast, then a tenfold increase in the mud flux implies a hundredfold maximum potential increase in total soil erosion. However, the preferential transport of mud in the suspended load and the lesser extent of the Orange River floodplains and estuary relative to most river systems would limit the amount of mud storage.

Erosion during the Holocene is focused in areas of high relief and rainfall along the Drakensberg escarpment but has shifted recently to intensely cultivated, low-relief agricultural areas having moderate to high rainfall (Figure 4). One-third of the total

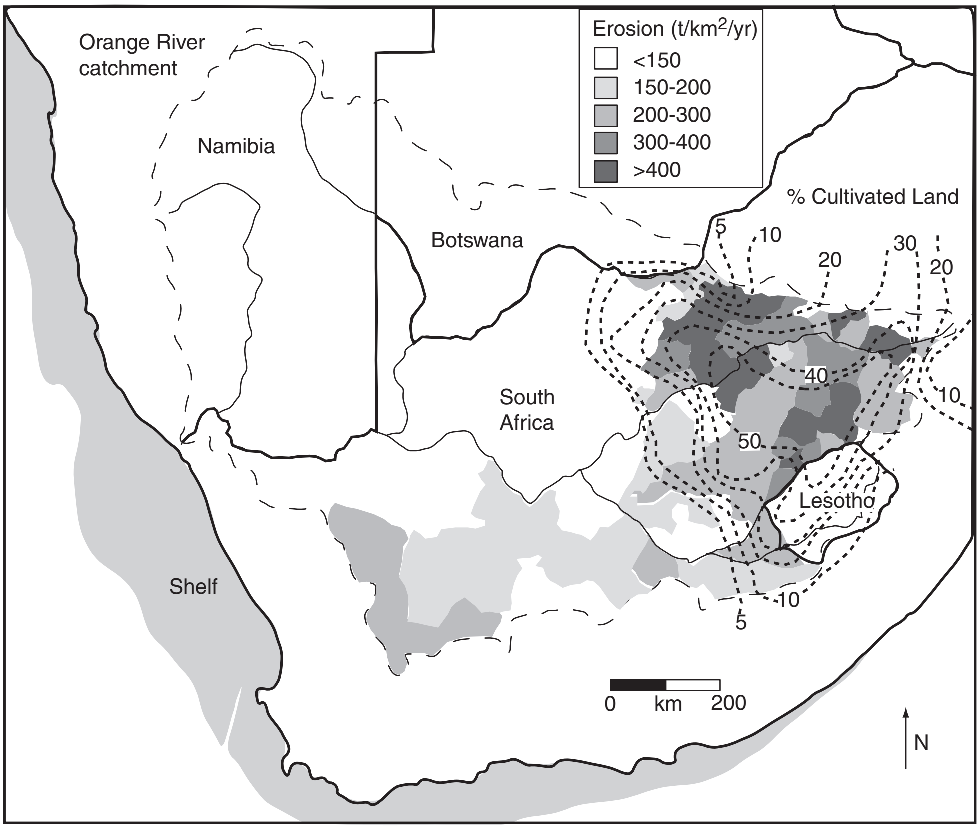

Figure 4 Soil erosion rates for magisterial districts of South Africa. Soil erosion is most intense in areas of high rainfall (Figure 1) and heavily cultivated land (Le Roux, 1990)

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eroded soil is derived from only 8% of the catchment having >30% cultivated land and 60% of eroded soil is derived from one-third of the catchment having >10% cultivated land. Areas of high soil erosion from this study generally overlap with areas of high denudation rate as indicated by the sediment infilling of dams (Le Roux, 1990). Therefore, heavily cultivated land where rain falls primarily as intense summer storms appears to have the greatest soil erosion (Le Roux, 1990; Garland *et al*., 1999). Outside of the Caledon River valley, most of these cultivated lands do not coincide with areas of high long-term Holocene erosion rates associated with exposures of the Elliot Formation on the lower Drakensberg escarpment. Although soil erosion is limited by low rainfall and thin soils in grazing lands of the western catchment, land degradation can be more severe and less reversible than in cropland areas (Garland *et al*., 1999; Hoffman *et al*., 1999).

Conclusions

The mean Holocene mud flux of the Orange River is estimated here to be 5.1 (3.2–7.4) Mt/yr based on an inventory of sediment on the western margin of South Africa. Most (72%) of the terrigenous mud (43 Gt) is retained on the shelf in the Orange River delta and in the mudbelt, a clayey silt extending in a narrow band 500 km south of the Orange River. Only 8% (5 Gt) of the terrigenous mud is deposited on the slope and 20% (11 Gt) is transported as clay beyond the margin. During the Holocene, much of the mud was sourced from erosion of Elliot Formation mudstone which forms the cutting edge at the base of the western Drakensberg escarpment. The recent tenfold increase in the Orange River mud flux compared with the mean Holocene flux reflects increased soil erosion primarily from heavily (>30%) cultivated areas in the eastern catchment and from grazing lands in the southern catchment. A tenfold increase in the river mud flux from land degradation implies a maximum potential hundredfold increase in soil erosion if only 10% of eroded sediment has exited the catchment. The amount of eroded sediment stored over periods of decades to centuries can be large in small subcatchments but the extent of mud storage prior to the building of large dams is unknown. The capacity for mud storage in the Orange River is probably less than in most other river systems because of the limited extent of the Orange River floodplain and estuary.

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