Erosion Rates and Sediment Sources in Madagascar Inferred from ^{10}Be Analysis of Lavaka, Slope, and River Sediment

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ABSTRACT

The central highlands of Madagascar are characterized by rolling hills thickly mantled with saprolite and cut in many areas by dramatic gullies known as lavakas. This landscape generates sediment to rivers via diffusive downslope movement of colluvium and event-driven advection of material from active lavakas; these two sediment sources have very different ^{10}Be signatures. Analyzed lavaka sediment has very little ^{10}Be (0.8–10 × 10^5 atoms ^{10}Be g^{-1}), consistent with deep excavation liberating previously shielded saprolite with little exposure to cosmic rays. Colluvium, in contrast, has greater ^{10}Be concentrations (6–21 × 10^5 atoms ^{10}Be g^{-1}), reflecting long residence times in the near-surface environment. Comparison of ^{10}Be abundance in hillslope, lavaka, and river sediment samples indicates that lavakas dominate the mass input to rivers (84% by volume) in spite of the fact that they occupy a small fraction of the land surface area. River terrace sediments that are at least a millennium old have ^{10}Be concentrations indistinguishable from those of modern lavaka-dominated river sands, from which we infer that lavakas were widespread on the landscape at or before the time that humans colonized the central highlands. Erosion rates derived from cosmogenic ^{10}Be in river sediment average approximately 12 m m.yr.$^{-1}$, or about 32 t km^{-2} yr^{-1}, which is three orders of magnitude lower than commonly reported erosion rates for Madagascar.

Introduction

With topographic relief comparable to that of New Zealand, tropical weathering in a monsoonal climate that has saprolitized cratonic basement to depths as great as 100 m, an unusual combination of steep slopes and deep weathering profiles, and fewer than 1.5 k.yr. of human habitation in the highlands, Madagascar is a dramatic and important place to study erosion. Along with the geomorphologic appeal, there are anthropologic and policy aspects to Madagascar's landscape evolution that lend interest to the analysis. International aid and development agencies have designated Madagascar's erosion rate the highest in the world (World Bank et al. 1986; USAID 1998); rates of 20,000–40,000 t km^{-2} yr^{-1} are most commonly cited (e.g., Randrianarijaona 1983; Lal 1988; Grieser 1994; Ralison et al. 2008). The large and deep gullies—lavakas—that are ubiquitous in the central highlands (Wells et al. 1991; Wells and Andriamihaja 1993, 1997; fig. 1) are commonly viewed both as anthropogenic in origin and as the main contributors to what are inferred to be extreme sediment loads in Malagasy rivers (e.g., Helfert and Wood 1986; Mottet 1988; Gade 1996; Aguiar 1998; Julien and Shah 2005). That lavakas are caused by human actions has become conventional wisdom, entrenched in atlases (e.g., Schlüter 2006), guidebooks (e.g., Fitzpatrick and Greenway 2001; Bradt 2007), and popular writing (e.g., Shoumatoff 1988; Mittermeier et al. 2005; Nilsson 2005). Deforestation, overgrazing, and grassland burning are the most commonly identified triggers (e.g., Helfert and Wood 1986; Tassin 1995; Gallegos 1997; Hannah 1997; Aguiar 1998; Julien and Shah 2005; Schlüter 2006). q1

But in spite of the status of lavakas as poster models for anthropogenic erosion and the international aid and policy issues raised by that des-

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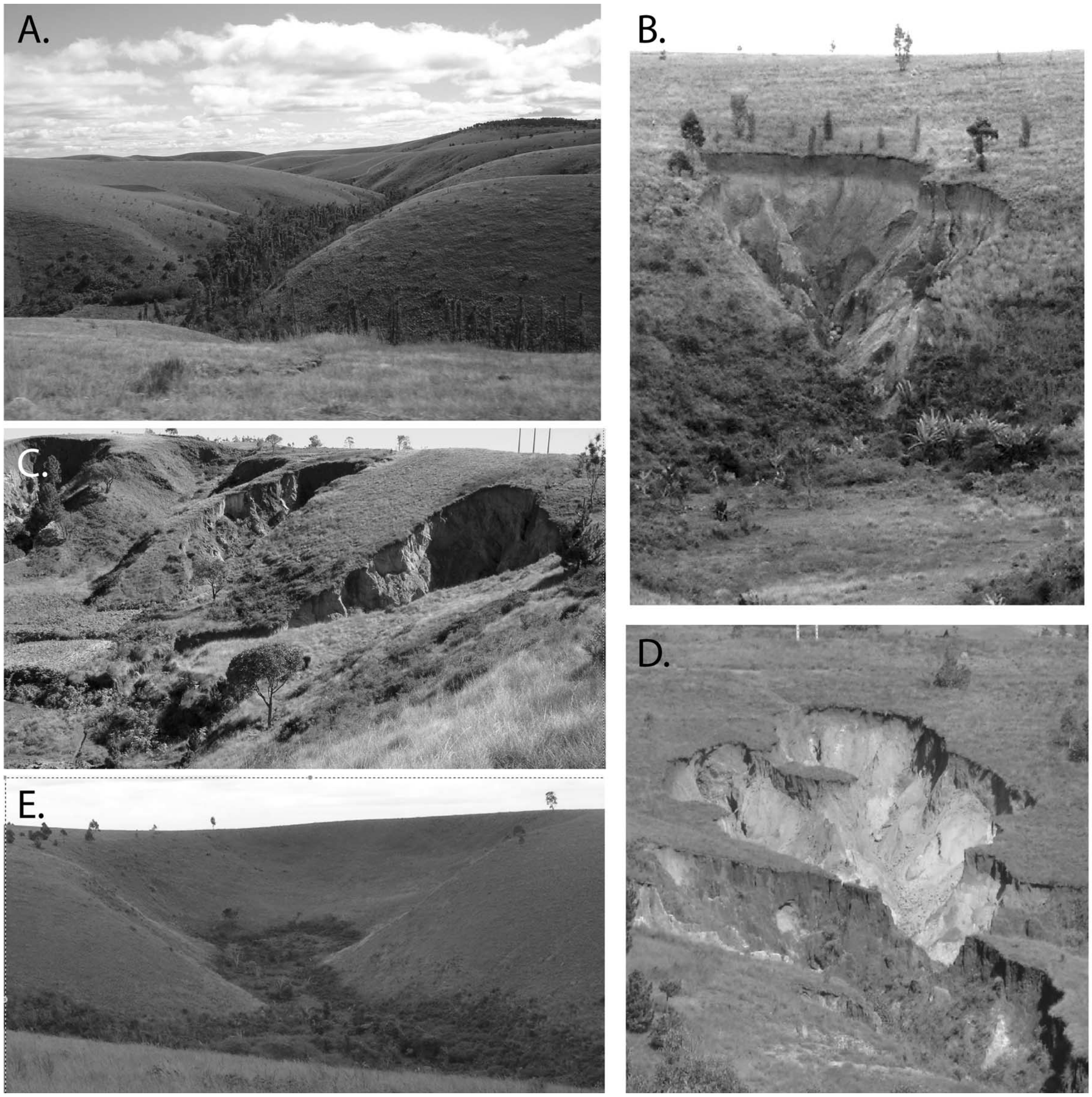

Figure 1. Topography and erosion in the central highlands of Madagascar. *A*, Convex-slope topography along Route Nationale 4, north of Antananarivo. The rolling grasslands commonly form convex hillslopes in the lateritized central highlands, at elevations ≈500–2000 m. In many places, remnant riparian forests remain in the declivitous valleys, as shown here; in other areas, the drainages are occupied by rice fields. *B*, Active stage II (sensu Wells et al. 1991) lavaka in the Amparafaravola region. The headwall is 33 m high, and the total width is 41 m. Sample 2005-2 (table 1) was collected from outfall sediments. *C*, Lavakas incising demi-orange topography in the Miarinarivo region. The nearest lavaka is the most active (stage II of Wells et al. [1991]), as shown by the steep and bare walls. It is 50 m long and 16 m deep. The lavakas in the background are less active (stage III of Wells et al. [1991]): their walls are not quite so steep, and the muted color is given by a clay veneer that coats noneroding walls. *D*, Stage II lavaka from the Miarinarivo region. This is the location of sample 2004-4 (table 1). The lavaka is 16 m deep, and the total width is 40 m. *E*, Ancient lavaka from the Amparafaravola region, similar to the sites of 2004-1, 2004-8, and 2005-5. Although the depression is fully vegetated, with no actively eroding walls, the characteristic lavaka shape is preserved: a deep amphitheater with concave internal slopes (in contrast to the convex slopes of the surrounding demi-orange landscape), a flat floor, and a narrow outlet. A color version of this figure appears in the online edition.

ignation (e.g. Grieser 1994; DERAD 2005; Julien and Shah 2005), there are no sediment generation rate data available for lavakas and no data quantifying the relationship between lavaka activity and human influence. In fact, measurements of sediment yields and inferences of erosion rates for Madagascar are local, few, and poorly constrained. Cited estimates, in the tens of thousands of tons per square kilometer per year, either represent small-scale plot studies in areas preidentified as zones of rapid erosion (e.g., Randrianarijaona 1983), which typically greatly overestimate regional erosion rates (Stocking 1996; Sanchez 2002), or are reported without supporting information on data collection methods (Grieser 1994; World Bank 1996; Rakotoarison 2003). Stream sediment gauging records for a few rivers, collected in the 1950s and 1960s, represent mostly rainy-season discharge (Bresson 1956; Anonymous 1972). They indicate far lower regional erosion rates—50–400 t km^{-2} yr^{-1}—than the numbers generally reported in the literature. Thus, the picture of erosion in Madagascar is fragmentary and confusing. Most relevant to our study is the notion that there is no way to determine from existing data the relative contribution to regional rivers from isolated lavakas versus widespread colluvial creep or sheet flow down hillslopes and into channels.

To quantify long-term regional rates of sediment generation and erosion and to evaluate the role of lavakas in supplying sediment to modern rivers, we report ^{10}Be concentrations measured in quartz sand from hillslope colluvium, lavaka interiors, rivers, and river terraces. We focus on two areas in the deeply lateritized Malagasy highlands (fig. 2), where Madagascar's rivers have their headwaters and where lavakas are abundant. By choosing field areas where lavakas are especially numerous, we hope to provide an upper limit on the contribution of lavakas to the sediment budget of modern rivers.

Because measurements of ^{10}Be in fluvially and colluvially transported quartz integrate sediment generation rates over millennia (Bierman and Nichols 2004), such measurements allow us to approach significant questions about Malagasy erosion. First, ^{10}Be analyses provide a means—impossible with suspended sediment or plot erosion studies—of fingerprinting the sources of sediment transported by rivers (Clapp et al. 2002), allowing us to apportion relative contributions from lavakas and hillslopes. Second, by providing background sediment generation rates integrated over millennia, ^{10}Be measurements provide a means by which to quantify anthropogenic effects on rates of landscape change.

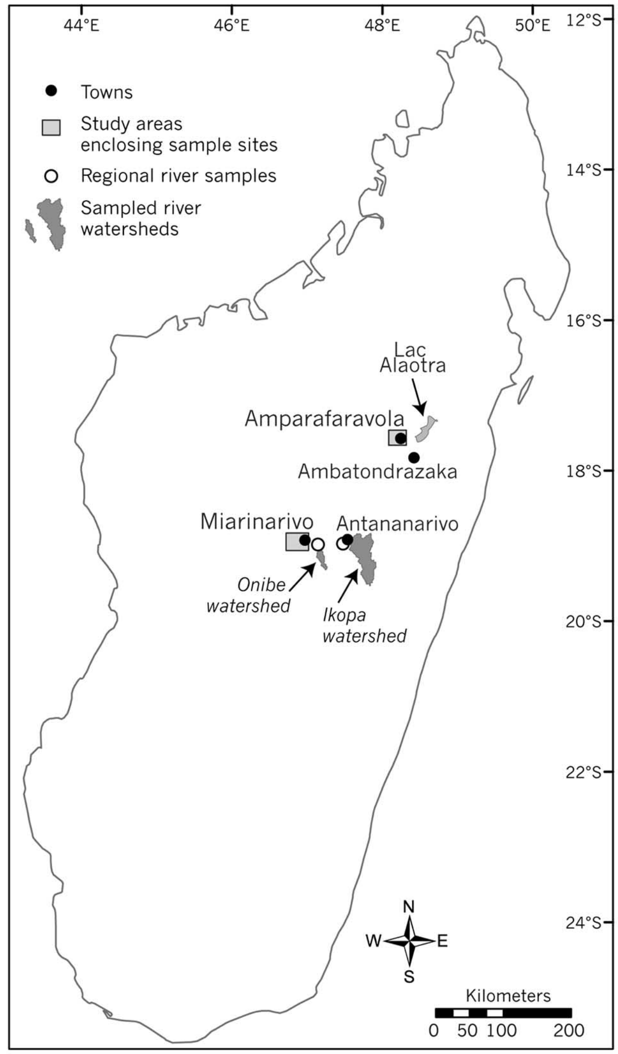

Figure 2. Map of Madagascar, showing the study area locations. Locations of major Malagasy towns are indicated by names and dots, as are places named in the text. The two boxes indicate the study areas, in the Amparafaravola and Miarinarivo regions, respectively. The circles inside the boxes show the locations of sample points; detailed location information is given in table 1. The two small circles outside the study area boxes are the regional river samples: the Ikopa (at Antananarivo) and the Onibe (between Antananarivo and Miarinarivo).

Finally, comparison of modern river sediment with older terrace sediment offers a glimpse into the interval between prehuman erosion rates and the full effect of human settlement. Our data thus provide the long-term and large-scale sediment generation rate context in which to consider the limited short-term, small-scale sediment yield data currently available for Madagascar.

Table 1. Sample Information and ^{10}Be Data from the Central Highlands of Madagascar

Sample	Latitude (°S)	Longitude (°E)	Altitude (m)	Production rate multiplier[a]	Region	Sample type	^{10}Be concentration[b] (atoms g^{-1} ^{10}Be) $\times 10^5$	Erosion rate[c] (m m.yr.$^{-1}$)	Slope[d] (°)	Watershed area (km^2)	Lavakas in watershed[e]	Lavakas km^{-2}[e]
2004-1	18.9279	46.7996	1404	1.92	Miarinarivo	Ancient lavaka (stage V)	4.1 ± .15	...	30			
2004-8	18.9163	46.9002	1420	1.73	Miarinarivo	Ancient lavaka (stage V)	15.5 ± .48	...	25			
2005-5	17.5861	48.1832	833	1.23	Amparafaravola	Ancient lavaka (stage V)	21.1 ± .71	...	7			
2004-5	18.9944	46.9642	1421	1.94	Miarinarivo	Colluvium, 10 cm depth	10.2 ± .31	5.8 ± .8	...			
MG1-A[f]	17.5491	48.2099	850	1.25	Amparafaravola	Colluvium, 10–20 cm depth	9.9 ± .63	3.2 ± .2	33			
MG2-A[f]	17.5491	48.2099	850	1.25	Amparafaravola	Colluvium, 60–70 cm depth	6.2 ± 1.05	3.3 ± .6	33			
2004-6A	19.0045	47.1251	1303	2.15	Onibe watershed	River sand (few lavakas in basin)	5.9 ± .18	11.4 ± 1.5	9	209	22	.11
2004-9A	18.9500	47.5259	1254	1.92	Ikopa watershed	River sand (few lavakas in basin)	10.0 ± .23	5.8 ± .8	9	1541	183	.12
2004-2A	18.9452	46.8227	1188	1.8	Miarinarivo	River sand (many lavakas in basin)	3.7 ± .14	15.1 ± 2.0	9	134	152	1.13
2005-3B	17.5496	48.2078	824	1.23	Amparafaravola	River sand (many lavakas in basin)	4.1 ± .13	9.2 ± 1.2	8	.3	1	3.85

2005-3C	17.5504	48.2077	812	1.25	Amparafaravola	River sand (many lavakas in basin)	3.4 ± .11	11.4 ± 1.5	7	5	28	5.96
2005-6	17.5648	48.2640	775	1.21	Amparafaravola	River sand (many lavakas in basin)	4.3 ± .12	8.6 ± 1.1	8	2	8	4.00
2005-7	17.6280	48.2041	778	1.29	Amparafaravola	River sand (many lavakas in basin)	2.1 ± .06	19.7 ± 2.5	9	56	302	5.39
2004-2B	18.9452	46.8227	1188	1.80	Miarinarivo	River terrace	5.0 ± .16	11.1 ± 1.4	9	134	…	…
2004-6B	19.0045	47.1251	1303	2.15	Onibe watershed	River terrace	5.4 ± .17	12.4 ± 1.6	9	209	…	…
2004-3	18.9268	46.8946	1368	1.87	Miarinarivo	Active lavaka (stage II)	1.2 ± .04	…	35			
2004-4	18.9570	46.9264	1360	1.86	Miarinarivo	Active lavaka (stage II)	2.5 ± .08	…	12			
2004-7A, 7B	18.9379	46.8958	1260	1.73	Miarinarivo	Active lavaka (stage III)	.8 ± .03	…	29			
2005-1	17.5493	48.1854	863	1.26	Amparafaravola	Active lavaka (stage III)	4.1 ± .16	…	24			
2005-2	17.5182	48.1815	856	1.26	Amparafaravola	Active lavaka (stage III)	9.8 ± .26	…	25			
2005-3A	17.5478	48.2107	821	1.22	Amparafaravola	Active lavaka (stage III)	2.2 ± .06	…	31			
2005-4	17.5943	48.1853	811	1.21	Amparafaravola	Reactivated lavaka (reactivated stage V)	7.4 ± .23	…	20			

[a] Calculated from Lal (1988) for neutrons only.

[b] Uncertainties on individual samples represent 1σ analytical uncertainty. For amalgamated samples (MG1 and MG2), uncertainty is given as the standard error of the means for samples from each of four transects.

[c] Erosion rates are calculated using density of 2.7 g cm^{-3}, attenuation coefficient of 165 g cm^{-2}, and sea level, high-latitude production rate of 5.3 atoms g^{-1} yr^{-1}. For shallow samples, shielding of 22 g cm^{-2} is used, assuming soil density of 1.45 g cm^{-2}. For deeper samples (>20 cm), assumed shielding is 94 g cm^{-2}. Erosion rates are expressed in rock equivalent (r = 2.7 g cm^{-2}).

[d] For river samples, slope is the watershed average measured from the 50-m digital elevation model. For lavakas and colluvium, it is the local average, measured at the sample location.

[e] This is the number of lavakas resolvable at 15 m $pixel^{-1}$; therefore, it does not include lavakas smaller than ≈900 m^2.

[f] Average of the means of four sets of six samples each, with each set representing a single contour elevation on a hillside (Jungers 2008).

Setting

Madagascar has a young landscape superimposed on old geology. The island consists mostly of crystalline Precambrian basement—metamorphosed in latest Proterozoic and earliest Phanerozoic time—that rifted from Africa at ≈160 Ma and from India at ≈70 Ma (de Wit 2003). Neogene-Quaternary thermal events (≈15–0 Ma) produced volcanic centers with associated faulting and uplift throughout the island (Piqué et al. 1999; de Wit 2003), so that in spite of its cratonic underpinnings, the island has dramatic relief: the highest point, at 2876 m, is only 120 km from the coast. The highlands are dominated by rolling convex hills (fig. 1*A*), with 50–500 m of local elevation change (Wells and Andriamihaja 1993). The convex hillslopes are flattest on top and steepen toward their bases. Toe slopes are commonly greater than 30° and may exceed 45° (Wells and Andriamihaja 1993; DERAD 2005). Bedrock underlying this high and steep terrain is generally deeply weathered and altered, with 1–2 m of laterite overlying tens of meters of saprolite in most places. Madagascar is also seismically active, with an average of ≈100 events per year that are magnitude 3 or greater (Bertil and Regnoult 1998).

The upland hillslopes are incised by steep-sided gullies termed "lavakas" (named for the Malagasy word meaning "hole"; Tricart 1953). These gullies (fig. 1*B*–1*D*) average 30 m wide, 60 m long, and 15 m deep (based on 450 measurements; R. Cox and
q2 A. F. M. Rakotondrazafy, unpub. data; N. A. Wells, unpub. data) but can be up to several hundred meters long and wide and up to 70 m deep. Some parts of the highlands have few or no lavakas, but in other areas regional lavaka densities can be up to 30 km^{-2} (Wells and Andriamihaja 1993). Lavakas are not fed by channeled overland drainage and may have no upslope catchment at all: field observations indicate that they are formed by groundwater sapping and vertical collapse in addition to the action of rain and subsequent runoff on the exposed and vulnerable regolith in the lavaka itself (Riquier 1954; Wells et al. 1991). They expand laterally and uphill by episodic headwall failure, usually triggered by heavy rainfall in the wet season. Sediment movement within the lavakas is sporadic and dominated by sediment gravity flow processes. Flow of water and sediment through the lavakas during these events can cause further downcutting and erosion of the saprolite. But, over time, lavaka expansion wanes, the interiors fill with trees and shrubs (and are often farmed), and the vertical walls relax to angle-of-repose slopes, acquiring a grassy mantle (fig. 1*E*). Thus, active bare-saprolite lavakas evolve to inactive sediment- and vegetation-filled depressions (Wells et al. 1991; Wells and Andriamihaja 1993).

Our study sites represent different areas of the Malagasy highlands (fig. 2). The main study sites are near Amparafaravola (an area of about 250 km^2 west of Lac Alaotra) and the district around Miarinarivo area, west of Antananarivo (about 1700 km^2). The Miarinarivo and Amparafaravola regions were chosen because they both have densities of active lavakas and therefore provide upper limits on erosion due to lavakas and on the proportion of lavaka-derived sediment in rivers. Two additional samples come from the Onibe and Ikopa rivers (fig. 2). The Onibe River was selected to represent a watershed with few lavakas. The Ikopa River in Antananarivo (fig. 2), with a watershed of ≈1500 km^2, provides regional context, integrating over many smaller catchments both with and without lavakas.

Methods

Our samples, collected to characterize the ^{10}Be content of a range of surficial materials in central Madagascar (table 1), include sediment from seven modern rivers and two fluvial terraces associated with the sampled rivers; sand from ephemeral channels draining six active modern lavakas and one reactivated ancient lavaka; colluvium from the floors of three inactive, revegetated, and infilled ancient lavakas; and amalgamated colluvium samples from two convex hillslopes unaffected by lavakas.

River samples were collected in midstream from submerged channel sands. Active lavakas (corresponding either to stages II and III of Wells et al. [1991] or to reactivated stage V) are represented by sand from unvegetated and unreworked outflow channels at the lavaka bases, in which we dug through ≈20 cm of graded and flat-laminated layers (each representing a dilute sediment gravity flow or sheet flow) to collect a sample that integrated across several sedimentation events. We suspect that such sampling will integrate material derived from different levels of the lavaka walls. In ancient infilled lavakas (soil-filled, fully vegetated, bowl-shaped depressions that can be identified by their characteristic shapes; stage V of Wells et al. [1991]), we sampled by digging ≈20-cm-deep trenches in lavaka centers. Hillslope colluvium was collected from convex hillsides. One sample represents a single 20-cm-deep soil pit; the other two come from a study in which six sample pits were dug along each of four transects, spaced 10 m apart downslope (for a matrix of 24 pits, covering 100 m along contour and 30 vertical meters; Jungers 2008). From each pit, Jungers (2008) collected both shallow (10–20-cm depth) and deeper (60–70 cm) samples. For this study, we report a composite shallow and a composite deep ^{10}Be concentration from the transect data (table 1). Further details are reported by Jungers (2008).

From two older river terraces, we collected well-sorted, traction-structured fluvial sand to investigate the ^{10}Be concentration in sediment predating human settlement in the study area. Both terrace samples were overlain by at least one soil horizon greater than 1 m thick, indicating at minimum several centuries of residence time. Charcoal (twigs and small woody chunks) from one of the terrace locations (2004-2B) provided a radiocarbon sample stratigraphically overlying the corresponding cosmogenic sample 2004-2B (fig. 3). Beta Analytic carried out the analysis (lab nos. Beta-201540, 201542), and the data were calibrated according to McCormac et al. (2004), using the program CALIB (Stuiver et al. 2006).

For the ^{10}Be analysis, isolation of sand-sized quartz followed the method of Kohl and Nishiizumi (1992). We extracted Be at the University of Vermont per Bierman and Caffee (2002). Samples were measured at Lawrence Livermore National Laboratory and normalized using standards developed by Nishiizumi et al. (2007), assuming a ^{10}Be half-life of 1.5 m.yr. (KNSTD 3110, $^{10/9}$Be ratio for standard of 3.15×10^{12}). We reduced the data by using accepted interpretive models (Brown et al. 1995; Bierman and Steig 1996; Granger et al. 1996), incorporating latitude and elevation (Lal 1991) and a normalized (high-latitude, sea level) production rate of 5.2 atoms ^{10}Be g^{-1} yr^{-1}. For drainage basin samples, we calculated effective production rates by using basin hypsometry, the neutron-only correction of Lal (1991), and a 100-m bin interval.

We used GIS analysis to calculate watershed area and hypsometry and to count the lavakas in each watershed (table 1). Watersheds were delineated
q3 from the 50-m digital elevation model using the spatial analyst watershed tool within ArcMap 9.2. To count lavakas, we used Landsat ETM+ data, to which panchromatic band sharpening (15 m pixel^{-1}) was applied.

Results and Interpretation

Substantial accumulations of ^{10}Be in our samples (up to 21×10^5 atoms ^{10}Be g^{-1}; $n = 22$; table 1) indicate long near-surface residence times for sediment in the Malagasy highlands and thus correspondingly low denudation rates over geologic

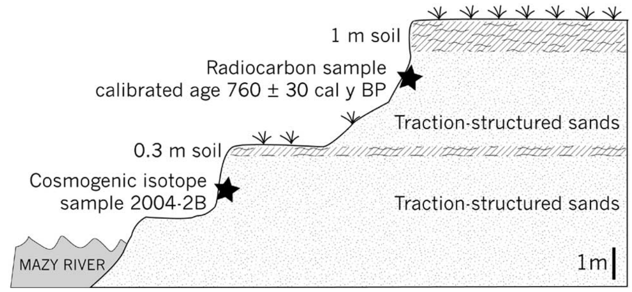

Figure 3. Stratigraphic relationship between river terrace ^{10}Be sample 2004-2B and the younger, age-constraint-providing radiocarbon sample.

timescales. There is a wide range of ^{10}Be concentrations among the different sample types. Hillslope colluvium ($6–10 \times 10^5$ atoms ^{10}Be g^{-1}) and ancient lavakas ($4–21 \times 10^5$ atoms ^{10}Be g^{-1}) document slow weathering on stable slopes. In contrast, active lavaka sediment ($0.8–10 \times 10^5$ atoms ^{10}Be g^{-1}) records rapid incision of gullies into less dosed material at depth. Fluvial and terrace sediments ($2–10 \times 10^5$ atoms ^{10}Be g^{-1}, with an average $\sim 5 \times 10^5$ atoms ^{10}Be g^{-1}) have ^{10}Be concentrations substantially lower than those measured from hillslope colluvium, closer to those of lavaka sediment.

Colluvium. The upper part of the weathering profile is generally similar throughout the grassy highlands of Madagascar (Wells and Andriamihaja 1990; Wells et al. 1990). A baked duracrust 10 cm q4
thick overlies sandy feralitic soil—generally referred to as laterite sensu lato (Wells and Andriamihaja 1990; Wells et al. 1990)—which has a total depth of about 1.5 m and grades to saprolite. There is little or no horizontal zonation within the laterite: the only inhomogeneity is given by occasional quartz clasts and rare remnant bedrock clasts. The grass cover sends thin roots to the depth of a few centimeters, and any soil mixing is inferred to be shallow and due to small insects and creep processes (Wells et al. 1990). Slope vegetation consists of grass clumps interspersed with biocrusted bare earth, and the biological soil crusts in our sample area had level-of-development index (Belnap et al. 2008) values of 5–6, suggesting a stable soil surface.

When sampled on convex slopes, this lateritic colluvium has high concentrations of ^{10}Be. Shallow soil (10–20 cm) has more ^{10}Be than soil collected at 60-cm depth (table 1), consistent with in situ dosing and minimal soil stirring. The ^{10}Be concentrations of the three colluvium samples can also be interpreted as erosion rates (3–6 m m.yr.$^{-1}$) by assuming steady surface erosion of the laterite and minimal mixing, an assumption supported by significantly lower ^{10}Be concentration at depth than at surface (table 1) and by the stable nature of the duracrust.

In sediment collected from the base of colluvial hollows, concavities representing what we and others (Wells et al. 1991) interpret to be ancient inactive lavakas, we measured not only the most variable ^{10}Be concentrations ($4–21 \times 10^5$ atoms g^{-1} ^{10}Be) but also some of the highest concentrations (16 and 22×10^5 atoms g^{-1} ^{10}Be; figs. 1*E*, 4; table 1). Because the geomorphic setting and history of ancient lavakas are not consistent with the assumption of erosional steady state, we do not calculate rates of erosion from these ^{10}Be concentrations; however, these substantial ^{10}Be concentrations are consistent with both long histories of ancient lavaka complexes, as indicated by an age of 11,580 ± 400 ^{41}C yr B.P. recorded from sediment in one such feature (Bourgeat and Ratsimbazafy 1975), and the reworking of highly dosed near-surface lateritic material. In summary, the steep, lateritized hills of the Malagasy highlands, which include ancient (inactive) lavakas and convex hillslopes with no lavakas, contain some of the most highly dosed ($4–21 \times 10^5$ atoms ^{10}Be g^{-1}) material in our study, suggesting, on average, long near-surface residence time and thus relatively slow rates of erosion.

Lavaka Erosion. Lavakas excavate deep into the landscape: those from which we sampled ranged from 3 to 30 m deep (average 17 m), which is representative of lavakas overall (R. Cox and A. F. M. Rakotondrazafy, unpub. data; N. A. Wells, unpub. data). Material exhumed by lavakas therefore includes both near-surface colluvium that has been exposed to substantial cosmic radiation and subterranean saprolite from depths where cosmic-ray penetration—and thus ^{10}Be buildup—is minimal. The haphazard nature of erosion within a lavaka—contributions from the near-surface laterites and exhumation of deep saprolite are both spatially and temporally variable, as well as unpredictable—means that ^{10}Be concentrations within lavaka sediments will vary from rainfall event to rainfall event, from year to year, and from place to place. Our sampling methodology attempted to control for this by sampling across several sedimentation units within each active lavaka.

The order-of-magnitude variation in ^{10}Be concentrations in the lavaka samples (table 1; fig. 4) attests to the inherent inhomogeneity of material issuing from active lavakas. Highly dosed lavaka samples must represent event deposits sourced primarily by

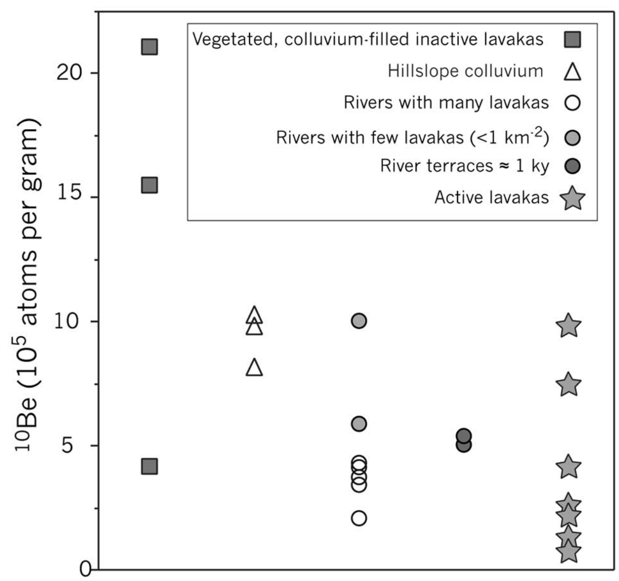

Figure 4. Measured cosmogenic ^{10}Be abundances for central Madagascar samples. Samples are separated by type along the horizontal axis, grouped (left to right) in the same order in which they are arranged in table 1.

falls from high in the headwalls; those with very low ^{10}Be concentrations are sourced from the deeper saprolites. No one sample is likely to represent an integrated average for the lavaka from which it came, but, en masse, the sample set illustrates the range of inter- and intralavaka variation, and we interpret the average value as a reasonable first approximation of the ^{10}Be signature of lavaka sediment. Because each lavaka sample is an idiosyncratic mix of material excavated from different depths, the steady state assumption integral to the ^{10}Be interpretive models used for other sample types (such as hillslopes and river sediments) is not valid. Thus, the concentration of ^{10}Be in active lavaka sediment cannot be interpreted directly as an erosion rate.

The least dosed sediment—^{10}Be concentrations as low as 0.8×10^5 atoms g^{-1}—is found in active lavakas, but not all lavaka sediment is lightly dosed. Some lavaka sediment has high ^{10}Be concentrations (up to 9.8×10^5 atoms g^{-1}; table 1; fig. 4), reflecting the fact that wall collapse—which preferentially contributes detritus from high in the weathering profile—is a major lavaka growth mechanism (Wells et al. 1991). Moreover, lavakas gradually fill in as they age, recovering the deep saprolite with slumped material from more heavily dosed upper walls. The ^{10}Be concentration of a given lavaka outwash sample is thus expected to vary, both stochastically (as individual collapse and erosion events tap different parts of the weathering profile) and as some function of the age of the lavaka (the probability of deep-saprolite sources decreasing with time). Our data suggest that this is not a simple progression: there is considerable overlap between the ^{10}Be signatures of samples from stage II (very recent) and stage III (more developed) lavakas. However, a single stage V (very old) lavaka, now reactivated, contains material with high ^{10}Be concentration (7.4×10^5 atoms g^{-1}; table 1; fig. 4), consistent with the model of stabilizing lavakas filling with material from the upper headwall.

Sediment Sources. The two primary sources of sediment to rivers in the central highlands of Madagascar are hillslopes and lavakas. Hillslope colluvium has a higher average ^{10}Be concentration ($\mu = 8.8 \times 10^5$ atoms ^{10}Be g^{-1}) than does material sourced from lavakas ($\mu = 4.0 \times 10^5$ atoms ^{10}Be g^{-1}; fig. 4). The overlap in the ranges of colluvium and lavaka sediment is driven primarily by the fact that lavakas include sedimentation events sourced from the upper colluvial (and therefore highly dosed) part of the lavaka profile. But colluvium, because it never taps the deep saprolite, does not include lightly dosed material. Using a two-component mixing model (per Clapp et al. 2002) and the average ^{10}Be concentration of river, lavaka, and colluvial sediment (fig. 5), we calculate that, on average, ≈16% of river sediment originates by erosion of convex slopes and ≈84% comes from lavakas. We note that this is a gross approximation, but the disproportion between lavaka and colluvial sediment ^{10}Be concentration is so large that despite the imprecision of the estimate, our data clearly illustrate that lavaka-supplied sediment dominates the sediment supply to present-day Malagasy rivers.

Although lavakas contribute the majority of sediment in fluvial transport in the Malagasy highlands, they occupy a relatively small proportion of the land surface. The average map area of a lavaka is ≈1400 m^2 (R. Cox, unpub. data; N. A. Wells, unpub. data), and the maximum number of lavakas per square kilometer is ≈30 (Wells and Andriamihaja 1993). This yields a crude maximum of ≈4% of the land surface occupied by lavakas in the relatively restricted areas of high lavaka density (which represent only 1% of the area of Madagas-
q5 car; Cox et al., unpub. data). In the rest of the highlands, the areal lavaka density is far less. In the Lac Itasy watershed, for example (which includes the Miarinarivo region of this study and is considered to be a lavaka-dense area), 400 active lavakas were mapped in a 7480-km^2 area—i.e., 19 lavakas km^{-2}—and the total lavaka extent was determined to be 1230 Ha, or 0.2% of the total basin surface area (DERAD 2005). The approximate active-lavaka coverage for individual watersheds analyzed in this study ranges from 0.02% to 1.3% (from lavaka densities in table 1, using the average lavaka area and assuming that the Landsat counts underestimate lavaka abundance by a factor of ≈0.3; Cox et al., unpub. data). The preponderance of lavaka sediment in the highland fluvial system suggested by our data is therefore remarkable, given their small areal extent, and speaks to the large volumes of sediment excavated from these gullies. It also means that any small increase in lavaka area has the potential to greatly increase sediment yield and decrease ^{10}Be concentration in river sediment.

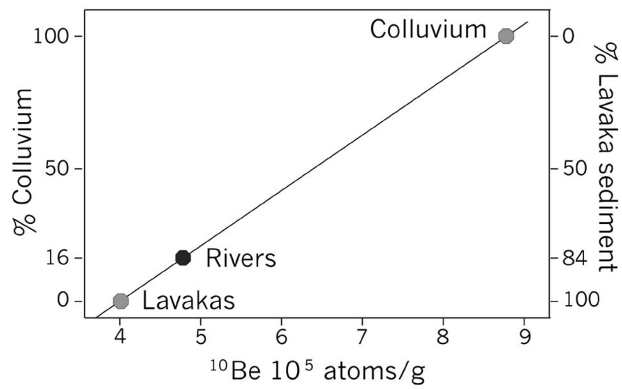

Figure 5. Mixing line showing proportional average ^{10}Be concentrations among samples from lavakas, modern rivers, and colluvium. River sediment can be modeled as a mixture of ≈80% lavaka and ≈20% colluvial detritus.

Rivers and Their Watersheds. River and terrace samples, interpreted using an accepted model (Brown et al. 1995; Bierman and Steig 1996; Granger et al. 1996), have model erosion rates between 6 and 20 m m.yr.$^{-1}$, equivalent to sediment generation rates of 16–54 t km^{-2} yr^{-1} (for sediment density, 2.7 g cm^{-3}). Our data suggest that much of the variability in the river sediment ^{10}Be concentrations can be explained by lavaka density in the watershed (fig. 6). Rivers with few lavakas (≈0.1 lavaka km^{-2}) in the hinterland transport sediment with high ^{10}Be concentrations ($\mu = 7.9 \times 10^5$ atoms ^{10}Be g^{-1}; $n = 2$) whereas rivers associated with larger numbers of active lavakas yield samples with lower ^{10}Be concentrations ($\mu = 3.5 \times 10^5$ atoms ^{10}Be g^{-1}; $n = 5$). The seven fluvial sediment samples we analyzed yield average long-term watershed erosion rates of 8.6 m m.yr.$^{-1}$ for lavaka-poor watersheds versus 12.8 m m.yr.$^{-1}$ for lavaka-rich drainages, equivalent to 23 and 35 t km^{-2} yr^{-1}, respectively.

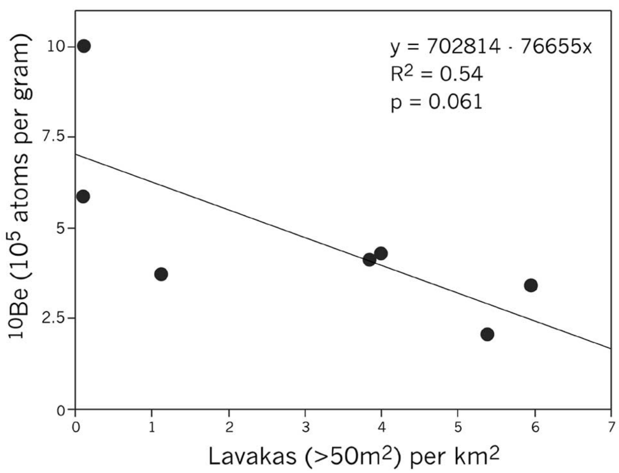

Figure 6. Relationship between the ^{10}Be abundances in modern river samples and the density of sizable (greater than ≈900 m^2) lavakas in their watersheds. The lavaka size limit was imposed by the 15 m pixel^{-1} resolution of the Landsat panchromatic band, and the lavakas included represent approximately the largest two-thirds of the whole population. The correlation between the two is statistically significant, suggesting that lavakas influence the ^{10}Be-determined basin-scale erosion rate in central Madagascar. Compare the ^{10}Be abundance values with those for active lavakas and hillslope colluvium in figure 4.

We have fitted a linear model to the data (fig. 6), but we note that they are also well fitted by a logarithmic equation, $\log(y) = 13.4188 - 0.1529x$. This latter model, which has $R^2 = 0.6$ and $P = 0.04$, suggests that relatively few lavakas in the drainage may swamp the colluvial isotopic signal, such that at lavaka concentrations greater than a few per kilometer, the curve flattens out at a ^{10}Be concentration of 3–4 × 10^5 atoms g^{-1}, close to the average ^{10}Be concentration of material issuing from lavakas. We suspect that this may be the case and that river basins may be separable into low lavaka and lavaka dominated, but because our number of samples is small and the logarithmic model is anchored by a single high ^{10}Be value (fig. 6), this remains a hypothesis to be tested. We are, however, confident that lavaka densities in the watershed do exert a strong first-order control on river ^{10}Be concentrations.

Looking at the Premodern: A View from the Terrace. River terraces offer a glimpse into the recent past and provide a first-order basis for interpreting whether there have been large-scale recent changes in sediment input to the system. Sediment sampled from two river terraces contains about 5 × 10^5 atoms ^{10}Be g^{-1}—identical within error to the modern river sand concentrations ($\mu = 4.8 \times 10^5$ atoms ^{10}Be g^{-1}; $n = 7$). The terrace ^{10}Be concentrations can be modeled as background erosion rates of 11.1 and 12.4 m m.yr.$^{-1}$, respectively (table 1), assuming no substantial dosing since deposition. These numbers are comparable to the erosion rates based on modern river sediment and are especially close to the average for lavaka-rich drainages. The data are valuable because they indicate the ^{10}Be concentration of Malagasy river sediment and thus the erosion rate before significant human impact on the landscape.

We can constrain the depositional age of this terrace sediment by radiocarbon ages from charcoal twigs and wood chunks (at sample site 2004-2B; fig. 3), which yielded a calibrated weighted mean radiocarbon age of 760 ± 30 yr B.P. (1220–1160 AD). A soil horizon (0.3 m thick) occurs above the cosmogenic sample but stratigraphically beneath the radiocarbon sample (fig. 3); thus, the ^{10}Be sample is substantially older than 760 yr. On the basis of the characteristics of the intervening soil, which has marked leaching patterns and well-developed vertical differentiation, we estimate a minimum formation time of 200–300 yr. For the second terrace sample (2004-6B), we do not have quantitative age constraints, but it lies 2 m below a 50-cm-thick soil and is therefore likely to be similar in age to sample 2004-2B. We accordingly estimate the terrace cosmogenic data to represent sediment in fluvial transport no less (and possibly considerably more) than 1000 yr in the past.

When the terrace sediment was deposited—at least a millennium ago—there were few if any people in the region. Spikes in the charcoal abundance record, interpreted as the onset of anthropogenic influence, appear south of the study area at 670–900 AD and northwest of it at 1050–1430 AD (Burney et al. 2004), as a slow wave of human land use progressed from south to north (Burney 1999). Village settlement in the highlands was not extensive until about 1200 AD (Wright and Rakotoarisoa 2003). The 760 ± 30-yr B.P. age of our radiocarbon sample (1190 ± 30 AD) is close to the probable settlement time for the study area, but the considerably older cosmogenic sample (fig. 3) must represent material in fluvial transit at least 1000 yr ago, thus predating substantial human influence in the study area.

The terrace data therefore indicate that current predominance of lavaka-sourced sediment in the fluvial system is not simply a modern phenomenon: lavaka-generated detritus not only has contributed to but also has dominated the Malagasy fluvial system for at least a millennium. The observation that presettlement sediments have the same lavaka-dominated ^{10}Be signature as do modern river sands indicates that the hillslopes of central Madagascar were studded with lavakas before human modification of the landscape. This conclusion is in line with evidence from air photographs of recently deforested areas, which show the outlines of ancient lavakas on newly exposed prerainforest landscape (Wells and Andriamihaja 1993, 1997), and is also in accord with observations of the Malagasy countryside that show recent lavaka activity superimposed on a background of extinct q6 ancient lavakas (fig. 8). Thus, lavakas, although their numbers and activity may have been enhanced by human activities, are a natural feature of the Malagasy landscape.

Discussion

The cosmogenic isotope data suggest that the Malagasy landscape has been surprisingly stable on timescales of millennia to hundreds of millennia, especially considering how steep, warm, and wet the environment can be. The long-term basin-scale erosion rate determined from ^{10}Be in river sediment is low—only 12 ± 5 m m.yr.$^{-1}$—despite central Madagascar's high-relief, warm, monsoonal climate, deeply weathered bedrock, and abundant seismicity. This rate is similar to that measured in Sri Lanka (Hewawassam et al. 2002, 2003) and in the southern Appalachian Mountains (Bierman et al. 2007), suggesting that—climate and topography notwithstanding—old orogens are quite resistant to erosion.

Our data support the view that lavakas are major contributors to river sediment. Hillslope colluvium and lavaka sediment have sufficiently different average ^{10}Be isotopic concentrations that they can be viewed as end-member compositions in a spectrum of river-sediment source material: colluvium contains highly dosed sediment recording low surface-lowering rates on convex hillslopes, whereas lavaka sediment has low average ^{10}Be concentrations from incision deep into the weathering profile and liberation of both highly dosed near-surface sediment and minimally dosed saprolite from many meters below. Fluvial sediment, delivered to the channel both by creep and sheet flow down hillslopes and by event sedimentation from lavakas, has an average ^{10}Be concentration very similar to that of sediment currently leaving lavakas. This observation suggests that despite the tiny fraction of land area they occupy (e.g., DERAD 2005), these deep and striking gullies (fig. 1) supply the bulk of the sediment carried by Malagasy rivers (fig. 5).

But—in contrast to conventional wisdom—the ^{10}Be data further suggest that lavakas were major sediment contributors before humans significantly altered the Malagasy landscape. The ^{10}Be concentration and average erosion rate (11.8 m m.yr.$^{-1}$; $n = 2$) deduced from millennium-aged terrace sediments match closely the average erosion rate cal- q7 culated from modern river sediments (11.6 m m.yr.$^{-1}$; $n = 7$). If lavakas were a new feature denuding an otherwise stable landscape of convex hillslopes, older river terrace sediment would reflect a lower proportion of lavakas and a greater relative contribution from well-dosed colluvium. Terraces from a hypothetical lavaka-free or low-lavaka prehuman landscape would contain far more than the $\sim 5 \times 10^5$ atoms ^{10}Be g^{-1} we measured and be a closer match to the hillslope end member (8.8×10^5 atoms ^{10}Be g^{-1}). The cosmogenic data thus refute the widely held view (e.g., Grieser 1994; Gallegos 1997; Julien and Shah 2005; Mittermeier et al. 2005; Bakoariniaina et al. 2006) that land management practices pushed the Malagasy highlands across an erosional threshold that triggered lavaka initiation. River sediment, both today and from a millennium ago, is equally dominated by material sourced from lavakas. The conclusion from cosmogenic isotope data that lavakas have long been the dominant source of sediment to Malagasy rivers is in accord both with the observation that ancient (prerainforest) lavakas are revealed by forest clearance (Wells and Andriamihaja 1993, 1997) and with the fact that much of the central highlands landscape has a greater density of infilled ancient lavakas than of active ones (fig. 7). The implication is clear: sediment moving through Malagasy streams before the highlands were settled was already dominated by material sourced from lavakas.

Furthermore, the existence of lavakas in different stages of degradation (figs. 1, 7) suggests a dynamic interplay in the landscape: lavakas are always present, but the locus of gullying (and source of low-concentration ^{10}Be input) changes as individual lavakas switch on and off. For example, the south-flowing drainage in figure 7 (*white line*) receives sediment pulses from two large lavakas in its downstream reaches, but there are no active lavakas in the northern part of the watershed. A cluster of ancient lavakas surrounds the northern headwaters, however, indicating voluminous lavaka input to the upper reaches of the stream in the past.

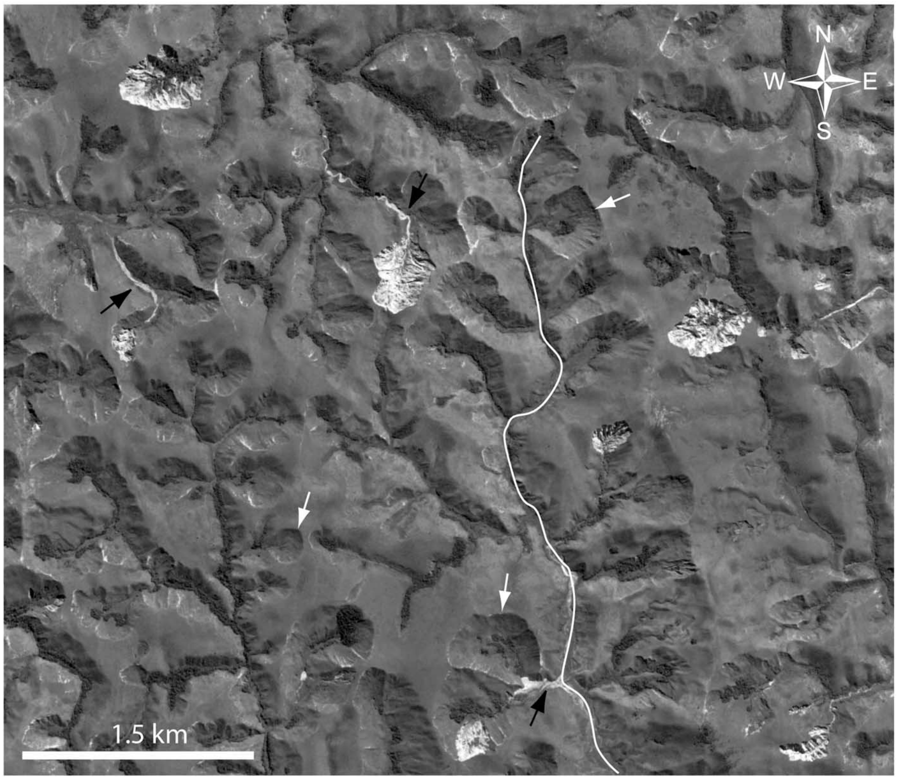

Figure 7. Aerial view of terrain in the central highlands of Madagascar, showing active lavakas superimposed on a network of ancient, inactive, and fully vegetated lavakas. The image center is at 18.09°S, 48.36°E, located about 55 km SSE of Amparafaravola and 180 km NE of Miarinarivo. Black arrows indicate recent sediment flows from active lavakas into the drainage network. Seven large, active lavakas are evident from the pale-colored saprolite they expose, but far more numerous are the inactive vegetated ancient lavakas, a few examples of which are indicated by white arrows. The drainage indicated by the white line is discussed in the text. (Image copyright 2008 Europa Technologies, Digital Globe, and Google Earth; reproduced by fair-use permission; http://www.google.com/permissions/geoguidelines.html.) A color version of this figure appears in the online edition.

Extrapolation to larger basin scales explains the relative homogeneity of river sediment ^{10}Be concentrations over time despite what must be great differences in ^{10}Be concentration of sediment delivered to any one place in the channel over time and space. But we do not know the timescale of lavaka evolution and healing or whether it represents dynamic equilibrium or simple geomorphic secular variation.

The relationship between lavakas and the Malagasy landscape is clearly a long-standing and complex one. With this reconnaissance set of cosmogenic data, we can confirm previous inferences from independent lines of evidence that lavakas have a long history (Bourgeat and Ratsimbazafy 1975; Wells and Andriamihaja 1993, 1997) and that they are not a recent result of anthropogenic activity. The low background erosion rate indicated by ^{10}Be measured in river sediment does not, however, preclude recent changes in lavaka activity or sediment yield due to population increases and land use practices: the average ^{10}Be concentrations of lavaka-derived sediment and sediment in transport through Malagasy rivers are so similar that the mixing model (fig. 5) is largely insensitive to an increased flux of sediment from lavakas.

There is a disconnect between the sediment generation rates inferred from ^{10}Be in river sediment (6–20 m m.yr.$^{-1}$; table 1), which correspond to 16–54 t km^{-2} yr^{-1}, and the short-term erosion and sediment yield values reported in the literature, which are three orders of magnitude higher (e.g., Randrianarijaona 1983; Lal 1988; Grieser 1994; Ralison et al. 2008). In part this disparity reflects the difference between small-scale local sampling and the watershed-scale averaging represented by the river samples in this study. Comparing the ^{10}Be-based rates with the limited available stream sediment gauging data (Bresson 1956; Anonymous 1972), we find that the cosmogenic-isotope-based rates are far closer to—although still lower than—the 50–400 t km^{-2} yr^{-1} we calculate from the mid-twentieth-century river sediment records. The higher erosion rates derived from the sediment gauging could reflect a recent upswing in erosion rates that is not yet manifest in the ^{10}Be data, which average over longer timescales (Bierman and Nichols 2004). But the gauging data (Bresson 1956; Anonymous 1972) are short term (1–2 yr) and not continuous: with the exception of a single year-long record, they represent spot sampling at intervals of days or weeks and during the rainy season only.

Conclusion

The data presented in this article advance our understanding of background erosion in the central highlands of Madagascar and demonstrate the importance of lavakas, both as long-term geomorphic elements and as major contributors of sediment to Malagasy rivers. The data clarify that lavakas were a dominant source of sediment at the time that humans were first beginning to infiltrate the highlands and confirm that they are not an anthropogenic addition to the landscape. Our data do not address whether there has been recent (decadal- or centennial-scale) increase in lavaka density or sediment yield. The answer to that question requires that multiyear stream sediment gauging records be collected for Malagasy rivers, which can then be compared with the background rates recorded in the cosmogenic isotope data.

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1 In the legend for figure 1, do any changes need to be made to the print version, which will appear with the black and white figure (demi-orange)?

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