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SHAKEDOWN IN MADAGASCAR: OCCURRENCE OF LAVAKAS (EROSIONAL GULLIES) ASSOCIATED WITH SEISMIC ACTIVITY

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ABSTRACT

Erosion via lavaka formation is widespread in Madagascar, but controls on why and where lavakas occur are not understood. GIS analysis reveals a spatial correlation between lavaka abundance and the frequency of seismic events: most lavakas occur in or near areas where earthquakes are most frequent. This correlation explains the unevenness of lavaka distribution in the Malagasy highlands, and highlights the importance of natural factors in lavaka formation. Seismic activity appears to pre-condition the landscape to lavaka formation, although the mechanism by which this happens is not yet known. Recognising the connection, however, allows us to pinpoint areas prone to future lavaka development in zones of active deforestation. Areas with greatest frequency of seismic events are most at risk for high-density lavaka development.

INTRODUCTION

Spectacular gullies dot the grassy highlands of Madagascar (Fig. 1). Known by the Malagasy name *lavaka* (literally "hole"), each represents thousands of m^3 of eroded material. Similar gullies occur elsewhere, but nowhere are they so plentiful as in Madagascar (Lageat and Gunnell, 2001; Wells et al., 1991). Erosion of Madagascar has been highlighted as a global concern (Boardman, 2006; Doucoure, 2006), with estimated removal of 20-100 t $acre^{-1}$ yr^{-1} (World Bank, 1996). Lavakas are regarded as emblematic of the problem (e.g. Rabarimanana et al., 2003), but why they form, and the relative roles of anthropogenic and natural triggers in their initiation, are not well understood (Wells and Andriamihaja, 1993). The analysis presented here is a step forward in understanding the prevalence of lavakas in Madagascar, perhaps bringing us nearer to effective prediction and control. From distribution of 61,000 lavakas we map Madagascar's lavaka-prone area and the hotspots within it (Fig. 2); we quantify a relationship between lavakas and seismic activity (Figs. 3, 4); and predict future hotspots in areas at risk for forest clearance (Fig. 2).

NOT YOUR AVERAGE GULLY

Lavakas differ from other gully types. They lack surface feeder channels and they can breach ridge crests by headward erosion. Most lavakas (>80%) initiate in mid-slope (Wells et al., 1991), detached from the valley drainage. They have steep to vertical walls and flat bottoms. Amphitheatrical headwalls narrow to tiny outlets as little as 1:1000 of lavaka width (Wells and Andriamihaja, 1993). They expand uphill by headwall collapse; and their outlets become progressively more incised, eventually connecting with the valley drainage. They often preserve pillars of undisturbed regolith isolated in their interiors (Wells and Andriamihaja, 1993; Wells et al., 1991). From field measurements of 450 lavakas (Cox and Rakotondrazafy, unpub. data; and Wells, unpub. data) the median lavaka is 30 m wide, 60 m long, and 15 m deep.

Lavaka formation requires a specific combination of bedrock geology, weathering profile, topography, and climate (Wells and Andriamihaja, 1993, 1997). Lavakas occur only in thick (10s of m) saprolites, such as develop on feldspathic crystalline basement in the Madagascar highlands (Riquier, 1954; Wells and Andriamihaja, 1997). The saprolitised topography is infiltration-dominated, forming steep convex hills. Near-isovolumetric weathering and lack of cement give mass losses of 40-54%, so saprolites have little inherent strength (Scholten, 1997; Scholten et al., 1997). When the protective lateritic duracrust is broken through, therefore, the friable saprolite is exposed to strong differential erosion (Wells and Andriamihaja, 1993, 1997). A monsoonal seasonality is essential for driving lavaka formation and growth. Baking and cracking of surface laterite during dry months provides conduits to the saprolite beneath (Tricart, 1953), and lavakas form and grow during the rainy months (≈October to March), when average precipitation can be 6-12 mm/day (Jury, 2003; Wells and Andriamihaja, 1993).

Lavakas are not produced by surface-flow downcutting, shown by the absence of feeder channels and the initial isolation from the valley drainage. And although slumping and landsliding do play a role in headward erosion of the established lavaka, the lack of rotational headscarps in newly-formed lavakas, and the common preservation of internal pillars, show that classic mass-wasting is not how they form (Wells and Andriamihaja, 1993). The main agents of lavaka growth are groundwater seepage and sapping. Lavakas initiate in thick laterite/saprolite on convex hills when triggered by local flow-focusing mechanisms, and their "inverted teardrop" shape (Fig. 1) is due to interaction of flow with a hard duracrust and soft subsurface saprolite (Wells and Andriamihaja, 1991, 1993).

Lavakas initiate abruptly. Local observations and newspaper reports indicate that new lavakas entrench in hours to days. The initial event appears dominated by vertical collapse: floors of new lavakas are carpeted by flat-lying still-vegetated slabs of the former slope surface that have pancaked downward. Within a short period (weeks to months) this roof material is disaggregated and flushed out of the new lavaka, and subsequent growth is by seepage, sapping, and rain attack, as described by Wells and Andriamihaja (1993, 1997).

Once the geologic, topographic, and climatic criteria are met, there are no systematic geomorphologic differences between slopes that contain lavakas and those that do not (Wells and Andriamihaja, 1993; Wells et al., 1991). In some areas, lavakas—both active and inactive—occur on virtually every slope (e.g. Fig. 7 of Cox et al., 2009); but geomorphologically identical areas elsewhere can be virtually lavaka-free (Fig. DR1). Reconciling these observations is a challenge for lavaka studies.

THE ROLE OF HUMANS IS GENERALLY OVEREMPHASISED

Lavakas are often asserted to be the result of human activities, with deforestation, overgrazing, and grassland burning the most commonly cited triggers (e.g. Aguiar, 1998; Gallegos, 1997; Helfert and Wood, 1986; Julien and Shah, 2005; Schlüter, 2006). Tracing these statements back through the literature, however, reveals that they are based on "errors, exaggerations and unquestioned assumptions" (Kull, 2000), and represent a received colonial and political narrative of environmental degradation rather than scientific interpretation (Klein, 2003; Kull, 2000, 2004).

If lavakas are primarily the result of human activities, then, all else being equal, the most heavily-used areas should be most affected; but comparison of areas with the same geology, topography, and climate shows differently. The most densely populated, heavily grazed, and de-vegetated regions (surrounding the cities of Antananarivo, Fianarantsoa, and Antsirabe) have only low to moderate lavaka densities (Fig. DR2). Contrariwise, some of the emptiest lands, almost devoid of cattle, grassland burning, or habitation—for example, areas west of Ambohitromby, west of Amborompotsy, and west and east of Andriamena—have among the highest lavaka concentrations.

Only 25% of lavakas studied can be directly linked to human activity (Wells and Andriamihaja, 1993), and much evidence indicates that lavakas pre-date the ≈2000-year human occupation of Madagascar. Carbon dating of sediment in lavakas (Bourgeat and Ratsimbazafy, 1975; Hoeblich and Hoeblich, 1983), air-photo interpretation of ancient lavaka topography revealed in newly-deforested terrain (Wells and Andriamihaja, 1993, 1997), and ^{10}Be signatures of modern and ancient sediment (Cox et al., 2009), all point to lavakas as part of the pre-human landscape.

This is not to say that there are not more lavakas now than there once were, nor is it to make light of Madagascar's erosional problems. Human activities do exacerbate lavaka formation (e.g. Riquier, 1954), and many lavakas have clear anthropogenic connections (Wells and Andriamihaja, 1993). But focus on human causation has led to a broad disregard for non-anthropogenic aspects of lavakas. Asserting, for example, that intense development of lavakas in areas bordering Lac Alaotra (Fig. 2) is due to deforestation (e.g. Bakoariniaina et al., 2006; Gade, 1996) overlooks the fact that many treeless areas have few or no lavakas (Fig. DR1). We contend that understanding natural triggers is fundamental to fully understanding lavakas, and to development of effective prediction and control strategies.

LAVAKA DISTRIBUTION

Lavakas occur in areas with monsoonal climate and steep convex topography on Precambrian basement rocks that have weathered to deep saprolite capped by laterite (Wells and Andriamihaja, 1993). Outside the lavaka-prone area—where topography is too flat or too steep; climate is too wet or too dry; or where there is bedrock outcrop rather than the requisite thick saprolite—lavakas do not occur. But within the lavaka-prone area, the gullies are unequally distributed (Fig. 2). Some areas are peppered, whereas others—with essentially identical geology, topography, and climate—have few or none (Fig. DR1). Nominal lavaka densities range over an order of magnitude (Table DR1; Fig. DR2). Hotspots have concentrations up to 24 standard deviations from the mean (Fig. 2), and within these regions absolute densities are locally as great as 30 lavakas/km^2 (Wells and Andriamihaja, 1993).

Although local correlations are reported (Rabarimanana et al., 2003), neither saprolite depth nor slope predicts lavaka susceptibility in the wider region (Wells and Andriamihaja, 1993). And although the lavaka-prone area overlaps very strongly with the extent of Precambrian basement rocks (Lageat and Gunnell, 2001), lavaka densities do not correlate with land-use or geomorphologic variables; and this has been a barrier to understanding the drivers of lavaka formation (Wells and Andriamihaja, 1993). This contribution, however, reports spatial overlap between dense lavaka clusters and seismic zones (Figs. 2, 3) and shows a strong correlation between lavaka and seismic densities (Fig. 4, Table DR1).

SEISMIC MADAGASCAR

Madagasar is seismically active. About ≈1300 events are recorded yearly (Bertil and Regnoult, 1998; IOGA, 2008), and the 1897-1998 record of large events (Bertil and Regnoult, 1998) gives a 6-year recurrence interval for earthquakes of magnitude ≥ 5.0. The greatest densities of seismic events (Fig. DR3) are within the northeast-southwest trending Lac Alaotra rift basin (extending from Ambatondrazaka and Amparafaravola towards Antananarivo), and along a northwest-southeast trend from Ambohitromby through Antsirabe, encompassing the Itasy and Ankaratra volcanic fields (Bertil and

Regnoult, 1998; Rambolomanana et al., 1997). These trends show up in the spatial statistics as elongate zones with high G_i* values (Fig. 3).

LAVAKAS ARE MOST ABUNDANT IN SEISMICALLY ACTIVE REGIONS: WHY?

Of the mapped lavakas, 28,425 (46%) occur within seismic hotspots that occupy less than a quarter of the lavaka-prone area. Among the lavaka hotspots are 9 super-dense regions (G_i* >10: Fig. 2), of which 6 lie completely within seismic hotspot zones (Fig. 3). Of the 3 lavaka super-dense regions outside the seismic hotspots, 1 (just west of Andriamena) overlaps a seismic hotspot boundary; 1 (south of Andriamena) is only 10 km from a seismic hotspot; and 1 (west of Amborompotsy) is in an area that does not map as a hotspot, but which has above-average seismic event density (Fig. DR3).

The overlap is not total. Although a circle enclosing all super-dense lavaka hotspots would also enclose most of the seismic hotspots, the northwest-southeast and northeast-southwest trends visible in the seismic hotspot geometry (Fig. 2) are echoed but faintly in the lavaka data (Fig. 2). Some seismic hotspot areas have no lavaka hotspots: the seismically-active area west of Ambatondrazaka, for example (Fig 3), bears lavakas (Fig. DR2), but is not a hotspot (Fig. 2). Similarly, some areas with abundant lavakas are not adjacent to seismic hotspots. This is because other factors—bedrock geology most specifically—also determine lavaka susceptibility. But despite the multiplicity of factors that can influence lavaka occurrence (Wells and Andriamihaja, 1993), the correlation between lavaka density and seismic activity has R^2 = 0.85 (Fig. 4, Table DR1), and is significant at the 99% level.

There is a correlation, but what is the causation? The short answer is that we do not know. Earthquakes and land movements are often associated (Malamud et al., 2004), but we find no evidence in satellite imagery for new lavakas associated with locations of specific earthquakes; nor do interviews with residents suggest any connection between earthquakes and lavaka initiation. Lavaka abundance is not correlated with earthquake magnitude nor hypocentre depth. Consequently, we deduce that recurrent low-intensity shaking is the key. Understanding lavaka formation therefore lies in teasing apart the relative roles of groundshaking and groundwater. The lack of relationship between lavakas and the location or timing of specific temblors suggests that the seismicity-erosion connection is subtle and progressive. Seismicity may precondition the saprolite to lavaka formation by loosening grains and enhancing local permeability. But does seismic agitation loosen grain contacts, enhancing groundwater flow? Or do tremors disrupt the tenuous connections between grains in groundwater-washed saprolite from which the fines have already been elutriated? Low-intensity shaking might in fact compact the saprolite, reducing porosity and permeability, and forcing increased seepage out of hillsides during heavy rainfall. Any of these are possible, but the remote-sensing data presented here cannot address specific mechanisms: that will require detailed field work. But the strong spatial linkage between seismicity and lavaka abundance (Fig. 4) strongly suggests that recurrent groundshaking is a driver for lavaka formation.

CONCLUSIONS AND IMPLICATIONS

Steep slopes in Madagascar's central highlands are held up by thick mantles of unlithified saprolite. Formation of lavakas in this material is spatially linked to seismic activity. Because there is no connection between specific earthquakes and the initiation of specific lavakas, we infer that groundshaking preconditions the saprolite in some way—as yet unknown—that increasese the overall likelihood of lavaka formation in seismically active regions. It may be that shaking loosens grain-grain contacts (Haff, 2005) increasing permeability and groundwater flow efficiency. During the wet season, increased pore pressure from rapid water infiltration through surface cracks may reduce effective stress to the point where subsurface fluidisation occurs, causing collapse of the overlying laterite; and voilà, lavaka. The more frequent the low-magnitude shaking, the more susceptible the region to lavaka erosion.

The seismic connection explains the uneven distribution of lavakas in the central highlands, and underscores the natural causes of lavaka formation. It also permits a disconnect between the mechanism for initial lavaka formation and the mechanisms by which subsequent growth occurs, as suggested by the observations of Wells and co-workers (Wells and Andriamihaja, 1993; Wells et al., 1991). The anomalous profusion of lavaka-type gullying in Madagascar, and its relative rarity elsewhere (Lageat and Gunnell, 2001; Wells et al., 1991), is also thus explained: thick laterite-saprolite complexes on convex slopes in monsoonal regions are always capable of lavaka-type erosion, but only in the presence of significant seismic activity will lavakas be abundant.

Although recognising the role of seismicity does not provide a tool to stop lavakas developing in susceptible areas, it does provide us the ability to predict areas more likely to degrade rapidly via lavaka erosion in the near future. Lavakas form only in grasslands, which has led to the enshrining of deforestation as a major cause (Riquier, 1954); but the oft-overlooked lack of lavakas in many deforested areas (Fig. DF1) makes clear that some other factor is at play. Knowing seismic activity is a trigger allows us to predict where lavakas are more likely to form if forests are cleared. Deforestation continues to spread (Bakoariniaina et al., 2006), and Hurni (2000) has pointed out that lavakas pose a barrier to sustainable land management in Madagascar. Forest clearance in seismic areas may result in highly degraded, lavaka-filled terrain within a short period of time. Thus, such potential future hotspots (Fig. 2) should be high on the list of lands to be protected.

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FIGURE CAPTIONS

Fig. 1: Lavakas showing lack of overland feeder channels and steep to vertical headwalls. The large lavaka shows the flat floor and debris apron (partly vegetated) typical of an active lavaka, and its headwall has cut back through the ridge crest. It is 155 m wide and 38 m deep. The smaller lavaka to the right is 57 m wide and 19 m deep. Location ≈3 km northwest of Amparafaravola, at 17.564°S, 48.204°W.

Fig. 2. Spatial statistical analysis of lavaka distribution (see Supporting Online Material for methods). The lavaka-prone area is ≈40% of the total area of Madagascar. Lavaka densities vary by an order of magnitude (Fig. DR2). Clustering is quantified by the Getis-Ord statistics shown here. Hotspots (Getis and Ord, 1996) have G_i* values >1.96 (i.e. clustered at > 95% confidence). G_i* values range up to 24 (i.e. 24 standard deviations from the mean). Areas at risk to become lavaka hotspots are places where the current boundary of the lavaka-prone area corresponds to the extent of forest, and where nominal seismic densities (Fig. DR3) exceed 0.5 events/100 km^2.

Fig. 3: Spatial statistical analysis of seismicity (see Supporting Online Material for methods and description of data). Most (80%) of the events occur within the lavaka-prone area.

Fig 4: Correlation between lavaka densities and seismic activity (data from Table DR1). Each point corresponds to a seismic-density bracket, and represents the sum of the areas (km^2) characterised by a specific density of seismic events, as determined by kernel density function analysis. We counted the number of lavakas within each seismic-density bracket, and thence computed the lavaka density (lavakas/km^2) for that seismic-density bracket. See Supporting Online Material for methods.

Figure 1
Click here to download Figure: Fig_01_LavakaPhoto.pdf

Cox et al. Figure 1

Figure 2

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Cox et al. Fig. 2
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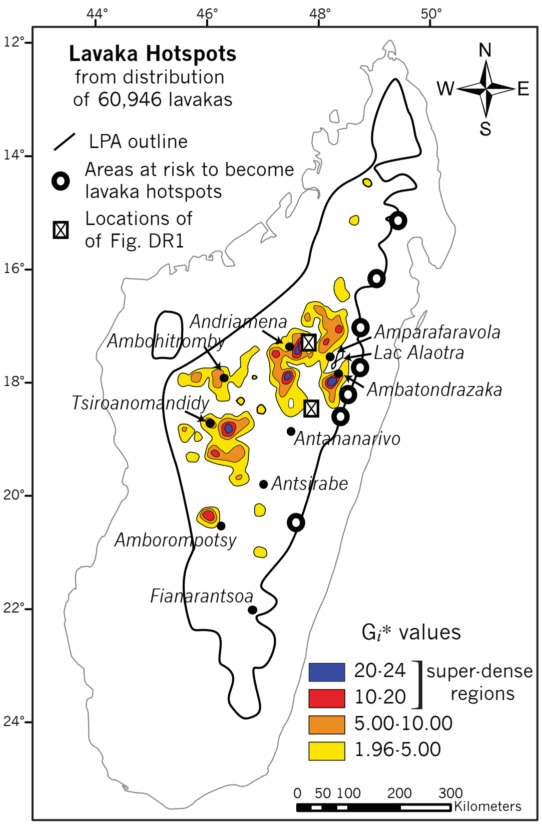

Figure 3

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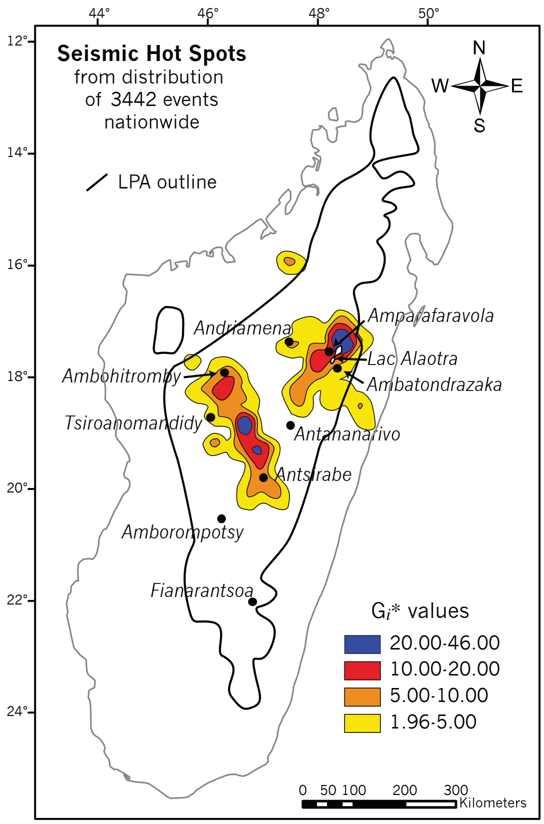

Figure 4
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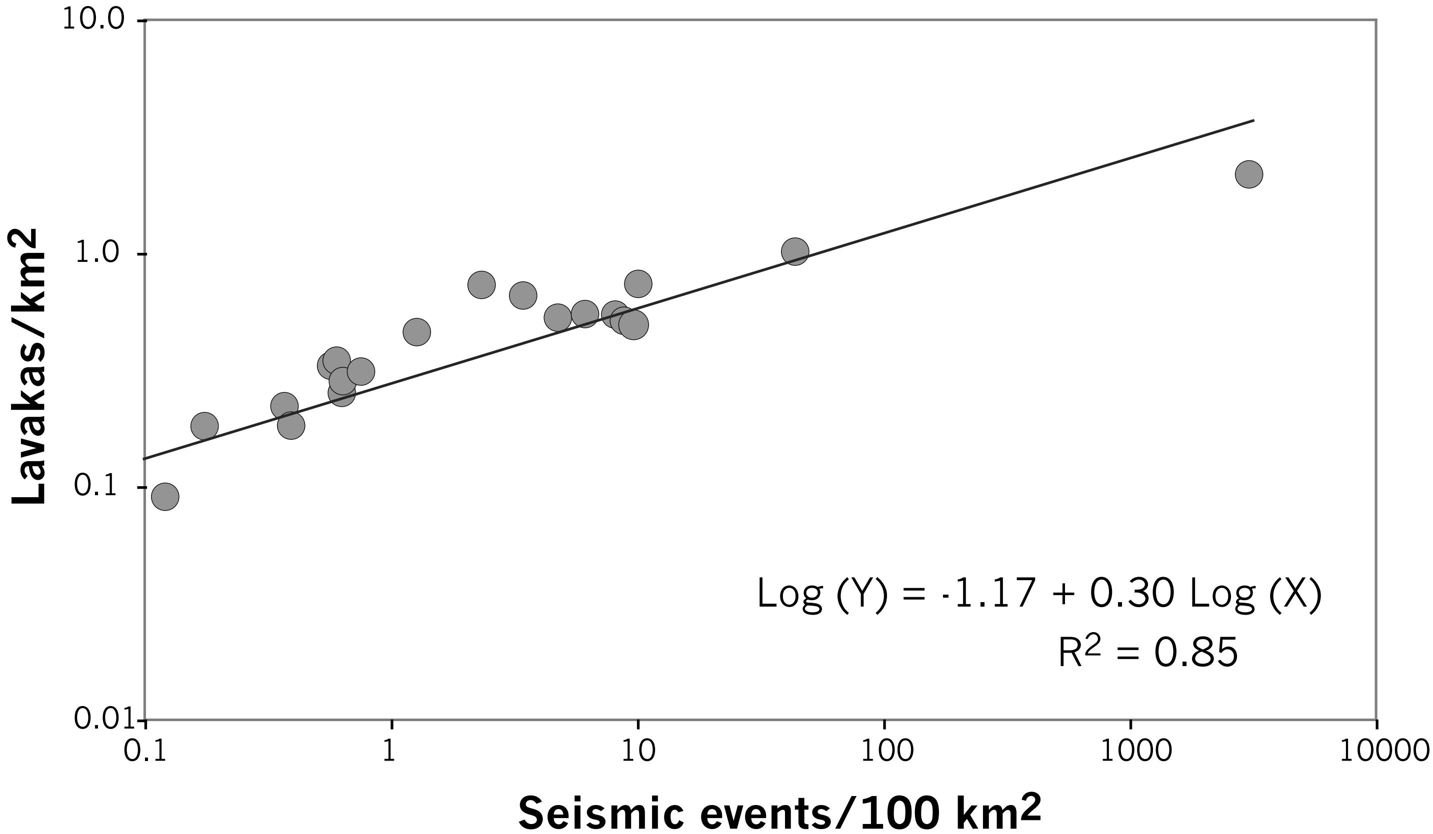

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