RELATION BETWEEN BEDROCK GEOLOGY, TOPOGRAPHY AND LAVAKA DISTRIBUTION IN MADAGASCAR

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ABSTRACT

The characteristic gullies of central Madagascar–lavakas–vary greatly in abundance over short distances, but existing understanding does not explain why some hillsides should have high concentrations of lavakas when nearby slopes have fewer. We present a GIS analysis of lavaka abundance in relation to bedrock geology and topography, covering two areas in the central highlands: the region near Ambatondrazaka and that around Tsaratanana. Both regions have similar average lavaka density (6 lavakas/km^2 in Ambatondrazaka, and 5 lavakas/km^2 in Tsaratanana, but local lavaka concentrations vary widely. Individual one-km^2 squares can host up to 50 lavakas/km^2 in Tsaratanana and up to 150 lavakas/km^2 in Ambatondrazaka. We find no predictive relationship between bedrock type and lavaka abundance. There is, however, a relationship between lavakas and slope such that lavakas increase in abundance as slopes get steeper, up to an optimum steepness, beyond which they become less numerous. The optimum steepness for lavaka development is about 10 to 15° in Tsaratanana and 25 to 30° in Ambatondrazaka. Lavakas also seem to favour slopes where the gradient changes locally, with an optimum change in grade somewhere in the range 2 to 5°. Our results provide quantitative constraints on lavaka distribution that can be tested in other areas.

Introduction

The central highlands of Madagascar are speckled with gullies of a kind unusual in a global context but extremely common in Madagascar, to the extent that their international name is the Malagasy word for "hole": lavaka (Riquier, 1954). The archetypical lavaka has a "tadpole" or inverted-teardrop shape (Wells et al., 1991), with a broad headwall narrowing progressively to a slender outfall channel. In some cases adjacent lavakas merge, resulting in a composite gully with amalgamated scalloped headwalls (Figure 1).

Lavakas are unevenly distributed in Madagascar (Battistini and Petit, 1971; Besairie and Robequain, 1957; Cox et al., 2010). They are absent from both the forested eastern escarpment and the arid low-lying Phanerozoic basins of the west and southwest, but are very numerous in the central highlands (Figure 2), where thick saprolites overlie deeply-weathered crystalline basement rocks (Mulder and Idoe, 2004; Wells and Andriamihaja, 1997). But even within the central highlands, the extent of lavaka development varies considerably from place to place. Local densities can be tens of lavakas per km^2, while areas a few km distant can be almost lavaka-free (Cox et al., 2010; Wells and Andriamihaja, 1993).

Malagasy people are concerned about lavaka formation because the gullies have a number of undesirable effects. The growth of the hole itself consumes grazable hillslope area as well as creating a hazard to both people and livestock, and sediment issuing from the outfall during the rainy season inundates fields and destroys crops (e.g. DERAD, 2005; Mulder and Idoe, 2004). Numerous projects by local groups as well as international aid organizations have been undertaken to stabilize slopes and to prevent the growth of lavakas, with limited success (DERAD, 2005; Mulder and Idoe, 2004; Truong, 2000; Wells and Andriamihaja, 1997). A part of the problem in trying to

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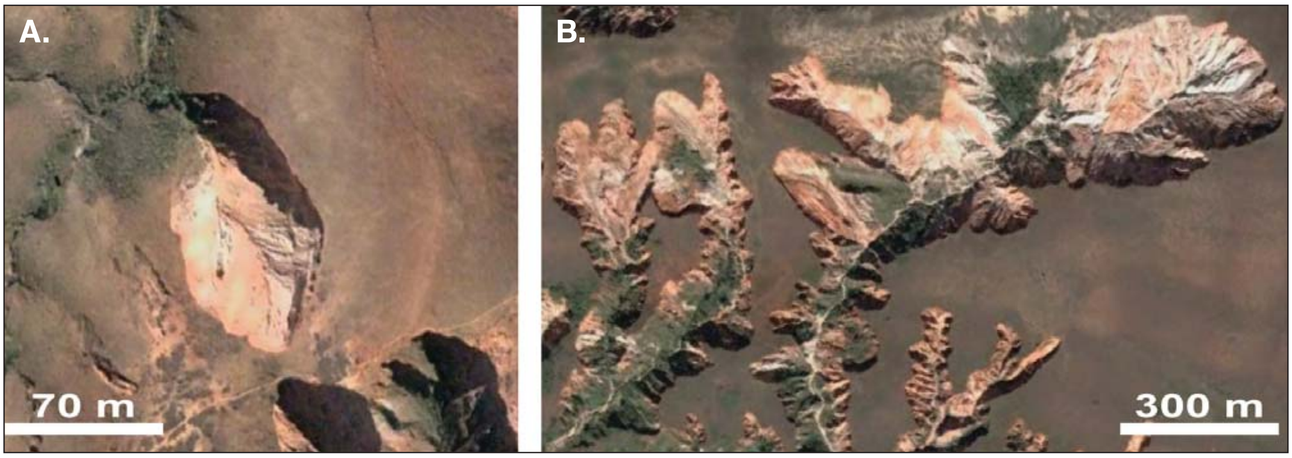


Figure 1. *Google Earth images showing the two main types of lavaka. Both examples are from the Ambatondrazaka study area. (**A**) simple lavaka (17.9401° S, 48.3830° E). (**B**) composite lavaka (17.8990° S, 48.4620° E).*

solve the lavaka problem is that the controls on their formation are very poorly understood.

Many early studies of lavakas concluded that they are caused mainly by human activity, the result of overgrazing, grassland burning, deforestation, and cart track formation (e.g. Hannah, 1997; Riquier, 1954; Tassin, 1995; Tricart, 1953). Several studies have demonstrated a relationship to that human activities, because in some places lavakas are clearly related to paths or roads, steep hillside farming, and ditch digging on slopes (e.g. Riquier, 1954; Hurault, 1971; Rabarimanana et al., 2003). Anthropogenic causes can be important: for example, W&A (1993) showed that 25% of lavakas are a direct result of human activities. But they also concluded that many lavakas seem independent of human causes. Aabout 25% appear to be natural in origin, with causes of the remaining 50% uncertain (W&A, 1993). Lavakas also pre-date human settlement in Madagascar: eroded remnants of ancient lavakas are revealed by recent deforestation (Wells and Andriamihaja, 1997), and ^{10}Be analysis suggests that lavakas were widespread in Madagascar at or before the arrival of humans less than 2000 years ago (Cox et al., 2009). Human activities cannot therefore be the fundamental cause of lavaka occurrence, and it is important to build understanding of the natural forcing factors that give rise to them.

Some of the fundamental drivers are known. Riquier (1954) categorised the main factors leading to lavaka formation as internal versus external. External factors promote surface erosion by permitting water accumulation at some points of the flank of the hill, while internal factors relate to the geologic characteristics of the area, reflected in the composition and structure of the saprolite. Lavakas are promoted by three factors: (1) hardening of exposed laterite surfaces, which favors incision relative to lateral erosion by protecting the underlying weak saprolite except in areas where the laterite has been cracked and breached, (2) the superimposition of concave run-off profiles onto convex hills and (3) local re-equilibration of watersheds after stream piracy and faulting (Wells and Andriamihaja, 1993). Their occurrence is correlated with high rainfall (Andriamampianina, 1985). Cox et al. (2010) showed that lavakas are concentrated in seismically active regions, and inferred that frequent ground shaking pre-conditions the regolith to lavaka formation. These investigations have improved our understanding but do not explain the short-range (100s of m to few km) differences in lavaka density that are evident on the ground.

To improve our understanding, therefore, we investigate two factors that might contribute to local variation in lavaka density: bedrock geology and topographic slope. Bedrock composition – which will be reflected in the overlying saprolites and laterites – is a first-order factor likely to affect lavaka formation (Barbier, 1980; Cox et al., 2010; Madison Razanatseheno et al., 2010; Riquier, 1954; Tricart, 1953). Heusch (1981) emphasized the tendency of lavaka concentrations to be aligned with regional lithologic trends, and considered lithologic heterogeneities to be a driver in lavaka formation. Riquier (1954) argued that feldspathic and micaceous rocks, such as gneisses, granites, and schists, would provide good lavaka substrate because their components are resistant to weathering. Mafic and ultramafic rocks, per his assertion, would not generate lavakas because greater degrees of weathering of ferromagnesian minerals would render the saprolitic carapace too weak to support the steep walls of lavakas, but he had no field data with which to support his thought experiment. Wells and Andriamihaja (1993) made field measurements of the relationships between lavaka orientation and bedrock strike, and concluded that the weathered rocks were too homogeneous to exert a strong influence on lavaka formation. Their study focused on lavaka orientation rather than on lavaka densities, and they did point out that geologically controlled valley-and-ridge systems could influence lavaka development; but it left open the question of

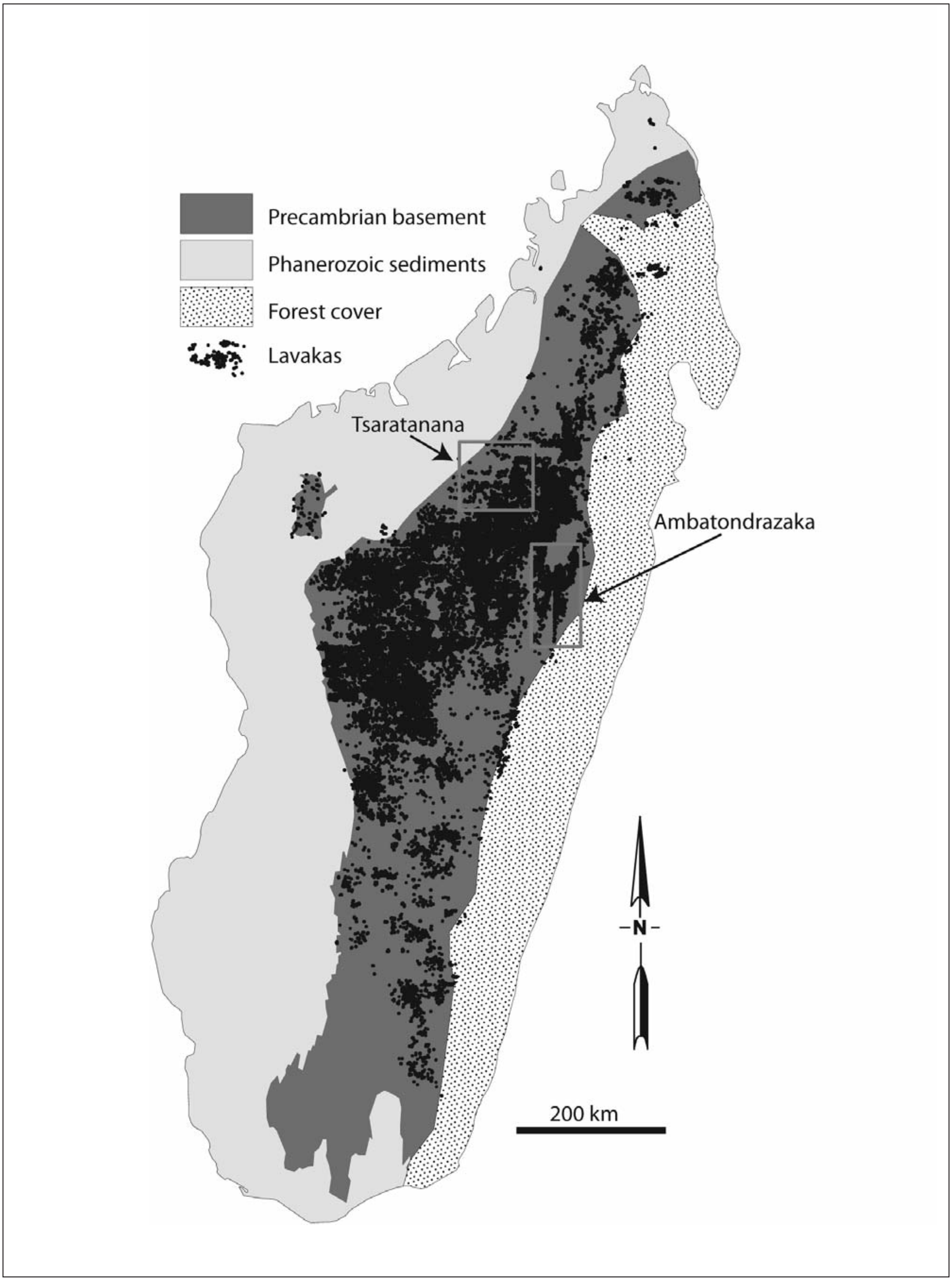


Figure 2. *Nationwide distribution of lavakas in Madagascar (data from Cox et al, 2010), showing the correspondence between Precambrian basement bedrock and lavaka concentrations. Location of Ambatondrazaka and Tsaratanana study areas given by inset boxes; detailed maps of each are shown in Figure 4.*

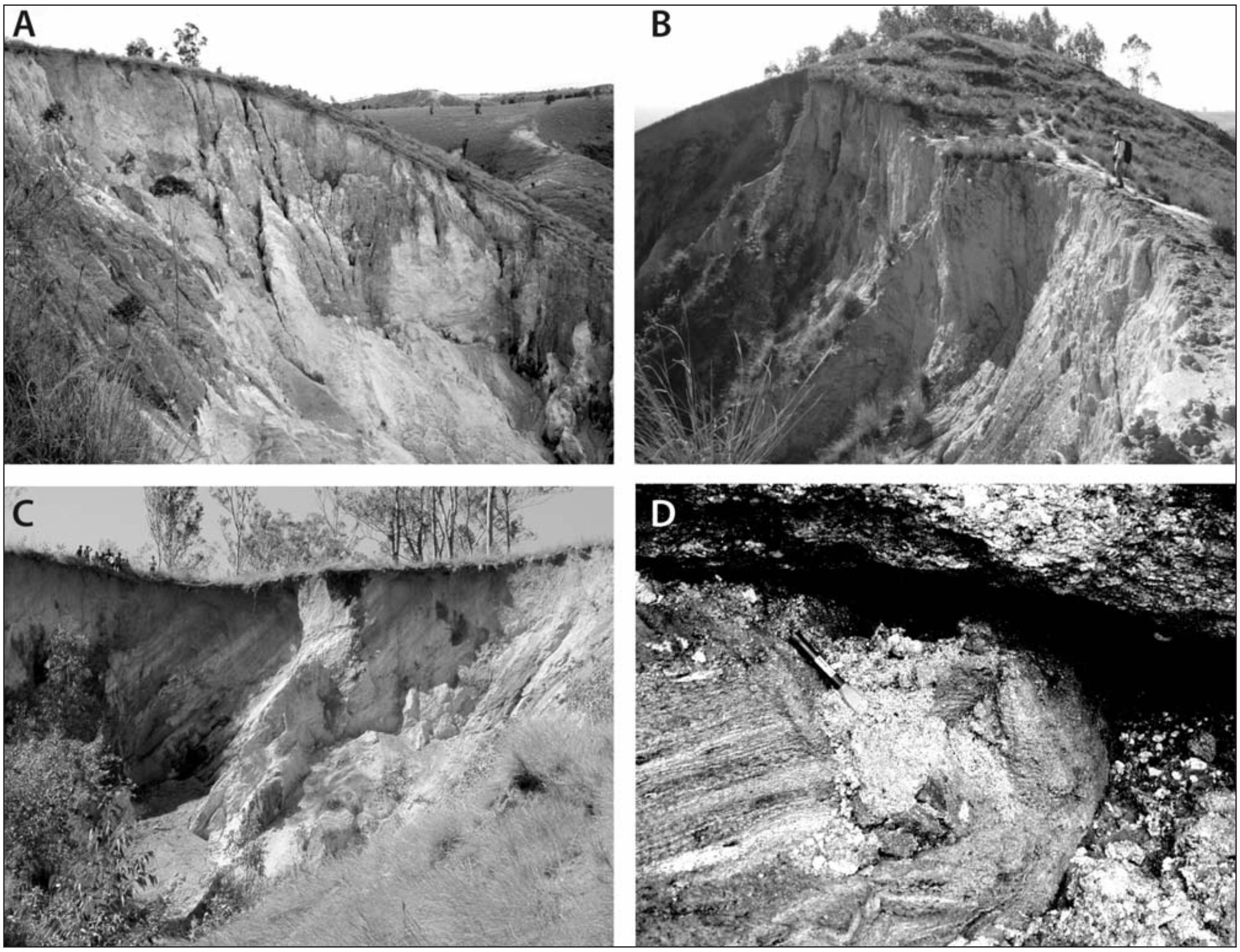


Figure 3. *Lavaka interiors, showing saprolite and slope characteristics. (**A**) Convex-up slope cut by lavaka. Thin rust-brown layer beneath grass is a 1.5 m-thick laterite; pink material beneath is the saprolite. This lavaka is 46 m deep (full depth not seen in photo), with no bedrock exposed. (**B**) Saprolite exposed in upper headwall of a 38 m deep lavaka. Convex-up hillslope profile visible on left of image. (**C**) Headwall of a 21 m deep lavaka, showing excellent preservation of geologic features in the saprolite. Almost no primary mineralogy remains, however, in these deeply weathered profiles, which –as shown in (**D**) – consist entirely of quartz, clay minerals and oxides.*

whether different rock types might host different concentrations of lavakas. This study therefore provides a quantitative analysis of the relationship between lavaka abundance and underlying geology.

Slope is also fundamental. Lavakas form on hillsides, so the local geomorphology must play a key role in gully nucleation. Wells and Andriamihaja (1993) noted that lavakas occur generally in convex-up "demi-orange" slopes, but they did not find a critical nor a maximal slope angle for lavaka formation. Rabarimanana et al. (2003) made a qualitative evaluation of slope effect, concluding only that lavakas favour steeper slopes. In this analysis we use DEM-derived slope maps to investigate in more detail the relationship between lavaka concentrations and slope steepness.

Finally, we examine two distinct areas to determine whether patterns and associations are consistent from one region to another. Although lavakas are developed throughout Madagascar's central highlands, much previous work focused almost exclusively on the area around Lac Alaotra (Heusch, 1981; Rabarimanana et al., 2003; e.g. Riquier, 1954; Riquier, 1956), which is not typical of the highlands. Broader-ranging work by Wells and co-workers (1993; 1991) examined a wide swath of central Madgascar using lengthy traverses along primary roads, and provided a different perspective on lavaka density and causal factors. In this study, by looking at two area – with differing geologic, topographic, and climatic characteristic – we hope to distinguish patterns that are universal from those that are purely regional, and we attempt to quantify similarities and differences.

This paper is a preliminary attempt to measure geologic and geomorphologic controls on lavaka formation, with the aim of building a broader understanding of lavakas, as must be at the heart of any program for erosion prediction or remediation in central Madagascar. Boardman (2006) has pointed out that geoscientific understanding of the fundamentals of soil erosion is very limited, and Poesen et al. (2003) focused specifically on the lack of information about gully erosion at large spatial scales. Our quantitative approach to lavaka occurrence is therefore significant in the larger context of erosion studies. It specifically addresses the issue of where erosion is occurring – identified by Boardman (2006) as a "big question" of erosion studies – in Madagascar, which he lists as a global erosion "hotspot".

What are lavakas?

Lavakas and lavaka-like features are found in places where hardened compact red soils overlie soft, thick weathered horizons. They have been reported from South Africa, Congo, and South Carolina (Riquier, 1954), from Cameroon (Hurault, 1970; Morin, 1994) and Gabon (Peyrot, 1998). Similar features also occur in Brazil (voçorocas of Chaves, 1994; Silva et al., 1993), the U.S. Great Plains (valley-head gullies of Brice, 1966), and Swaziland (Märker and Sidorchuk, 2003; Morgan and Mngomezulu, 2003).

Characteristically lavakas have the shape of a heart or inverted teardrop (Mulder and Idoe, 2004; Wells et al., 1991) broadening uphill and narrowing downhill (Figure 1). They do not have the features of standard drainages, in that they appear on convex slopes with no connection to overland flow patterns (Figure 1). They lack upslope feeder channels (Wells and Andriamihaja, 1993). Lavakas tend to form in mid-slope, initially unconnected to the valley drainage. They erode uphill by headwall collapse, breaching watershed hillcrests in some cases. These characteristics suggest that groundwater flow is important in their nucleation and development (Riquier, 1954; Wells and Andriamihaja, 1993), as has been interpreted for gullies with amphitheatrical headwalls in poorly-consolidated material elsewhere (Baker, 1990; Lamb et al., 2006; Schumm et al., 1995).

Riquier (1954) noted that new lavakas are always characterized by vertical walls, and that the initial U-shaped cross-section evolves to a V-shape as walls collapse over time. There is a marked contrast between the wide amphitheatrical headwall (commonly tens of m across) and the very narrow outflow channel, which can be as little as 1:1000th of the headwall width (Wells and Andriamihaja, 1993; 1997).

Wells et al. (1991) classified lavakas based on their position on the hillside: "midslope lavakas" which grow downhill as well as uphill (this type represents more than 80% of the total lavakas, (Wells and Andriamihaja, 1993); "toe-slope lavakas" which grow uphill from the base of the slope; and finally "valley-forming lavakas", the rarest kind, which are extreme instances of headward retreat into broad uplands (Wells and Andriamihaja, 1993). Riquier (1954) also classified lavakas based on two criteria: (1) shape (bulbous, dendritic, composite, oval and fan shaped; and (2) cross section (vertical wall with rounded shape and excavated wall with more curving. They can be very large – up to 300 m long, 75 m wide and 20 m deep (Wells and Andriamihaja, 1993) – but the median lavaka is about 60 m long, 30 m wide, and 15 m deep (Cox et al., 2010).

Geologic controls

Lavaka formation requires the combination of a hard compact surface layer (usually a lateritic soil horizon, 0.5 to 2 m thick) and an underlying layer, many m to 10s of m thick, of friable saprolite (Riquier, 1954; Wells and Andriamihaja, 1997). The saprolite has a higher modal abundance of coarse grains and lower proportions of fine clay minerals and oxides, and has an order of magnitude higher hydrologic conductivity than the laterite. (Udvardi et al., 2012). The weak saprolite is protected from erosion by the impermeable surface layer, but cracks in the laterite permit water infiltration, which can mobilize the fine grains in the saprolite beneath. When the laterite is breached and hydraulic gradients are steep, water infiltration drives erosion of the saprolite beneath, which can trigger lavaka genesis (Riquier, 1954; Wells and Andriamihaja, 1993). Petit and Bourgeat (1965) concluded that in deeply-weathered crystalline rocks in Madagascar, lavakas are natural agents of watershed development.

Geology is a major factor responsible for geographical distribution of Malagasy soils (Mulder and Idoe, 2004) and it also influences the growth of lavaka by influencing the texture and structure of the weathering horizon (Riquier, 1954). Lavakas form only in thick saprolites, which develop most readily in feldspathic, micaceous rocks (such as granite, granitic gneiss, and some migmatites). Mafic rocks rich in ferromagnesian minerals (gabbros and basalt, and their metamorphic equivalents) tend to have a thinner alteration zone (Riquier, 1954). The proportion of quartz in lavaka-bearing saprolite is higher than in the bedrock (Madison Razanatseheno et al., 2010).

But despite the relationships that appear to exist between geology and soil formation, the role of lithology in controlling lavaka formation is not clear. In some areas, such as Ambatondrazaka, lavakas appear to follow the geologic foliation (Heusch, 1981; Madison Razanatseheno et al., 2010), but in other places there is no indication that lavakas align with lithologic or structural trends. Geologic controls are therefore not simple. Wells and Andriamihaja (1993) argued that bedrock-related influence is underestimated because complexities such as veins, dikes, folds, fractures or porosity may influence sub-surface fluid flow. In this study we examine the first-order connections between lithology and lavaka abundance, noting that effects of small-scale lithologic features cannot be tested with our data.

Study area

We focus on two areas in north-central Madagascar that have abundant lavakas and both of which have been recently mapped at 1:100,000 (BGS-USGS-GLW, 2008)

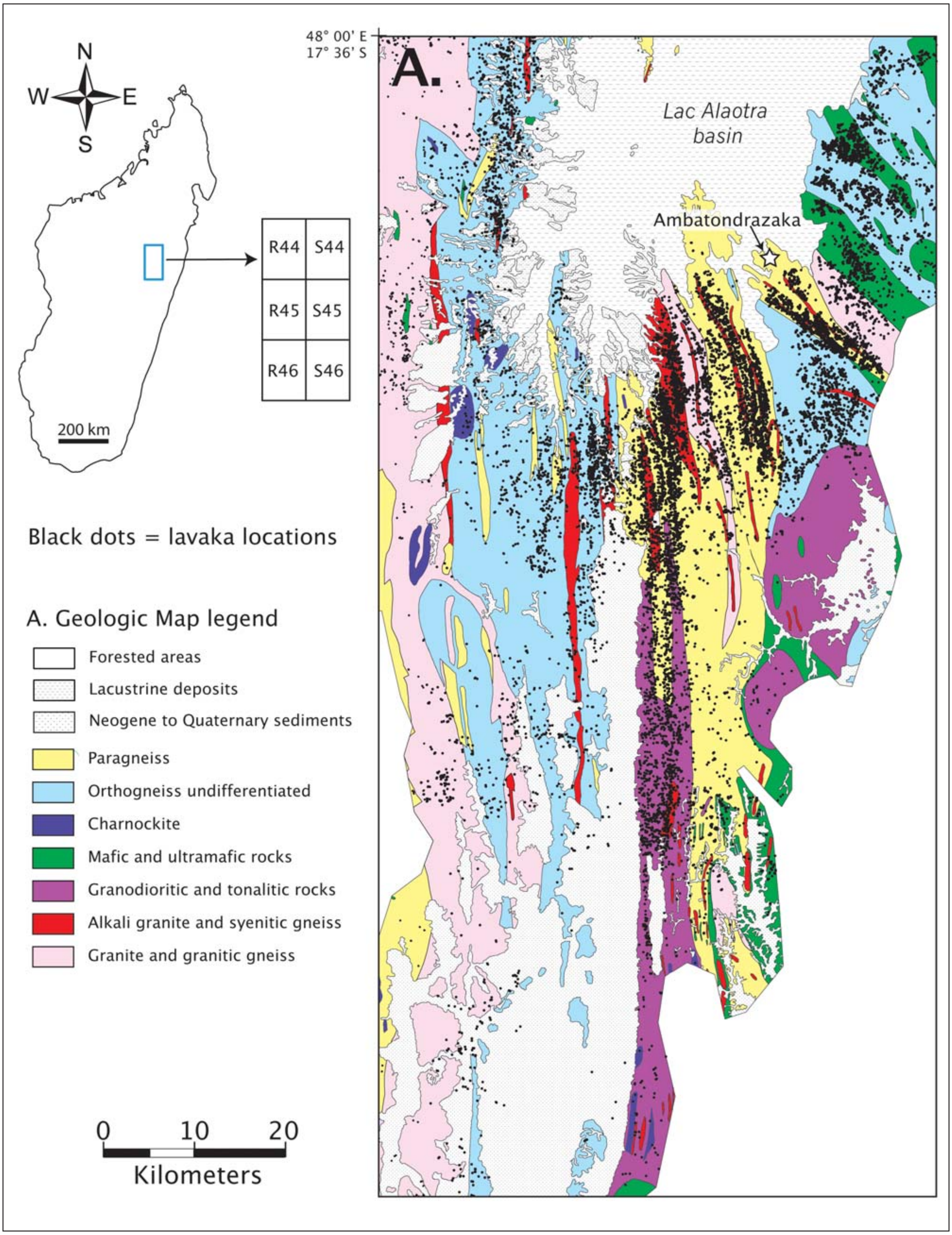
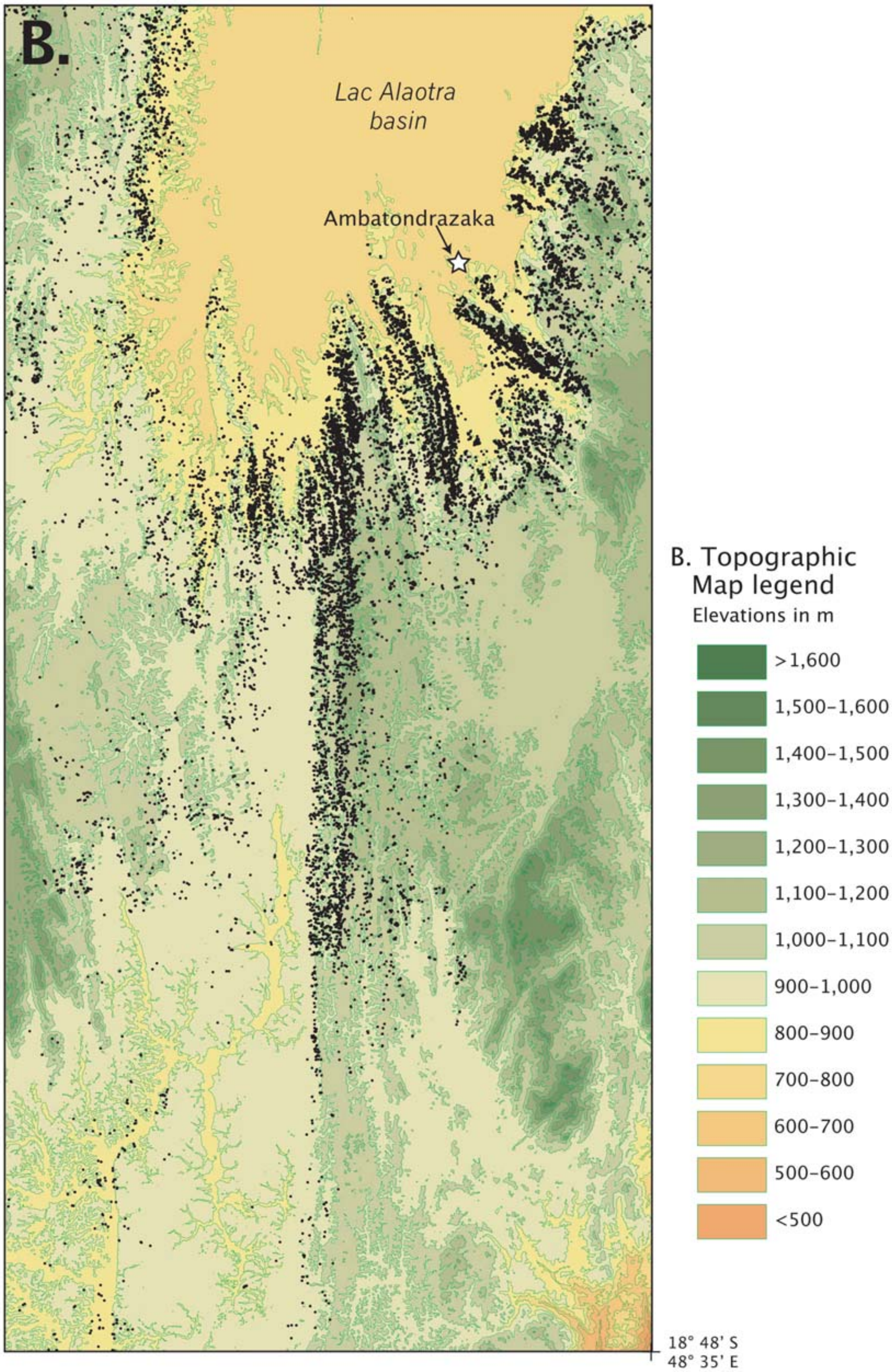


Figure 4. *Geology, topography and lavaka distribution for Ambatondrazaka study area. Elevation ranges from 376 to 1543 m. The colour scale on the topographic map legend is the same as Figure 5: colour differences between the two maps reflect elevation differences between the two areas. Geologic units are simplified from BGS-USGS-GLW (2008); see Appendix 1. Lavakas were counted from high-resolution Google Earth images, and contours are derived from the Madagascar DEM (see Methods for details). A full-resolution digital version of this map is available on request from Rónadh Cox (rcox@williams.edu).*


B.
Lac Alaotra
basin
Ambatondrazaka
B. Topographic
Map legend
Elevations in m
>1,600
1,500–1,600
1,400–1,500
1,300–1,400
1,200–1,300
1,100–1,200
1,000–1,100
900–1,000
800–900
700–800
600–700
500–600
<500
18° 48' S
48° 35' E

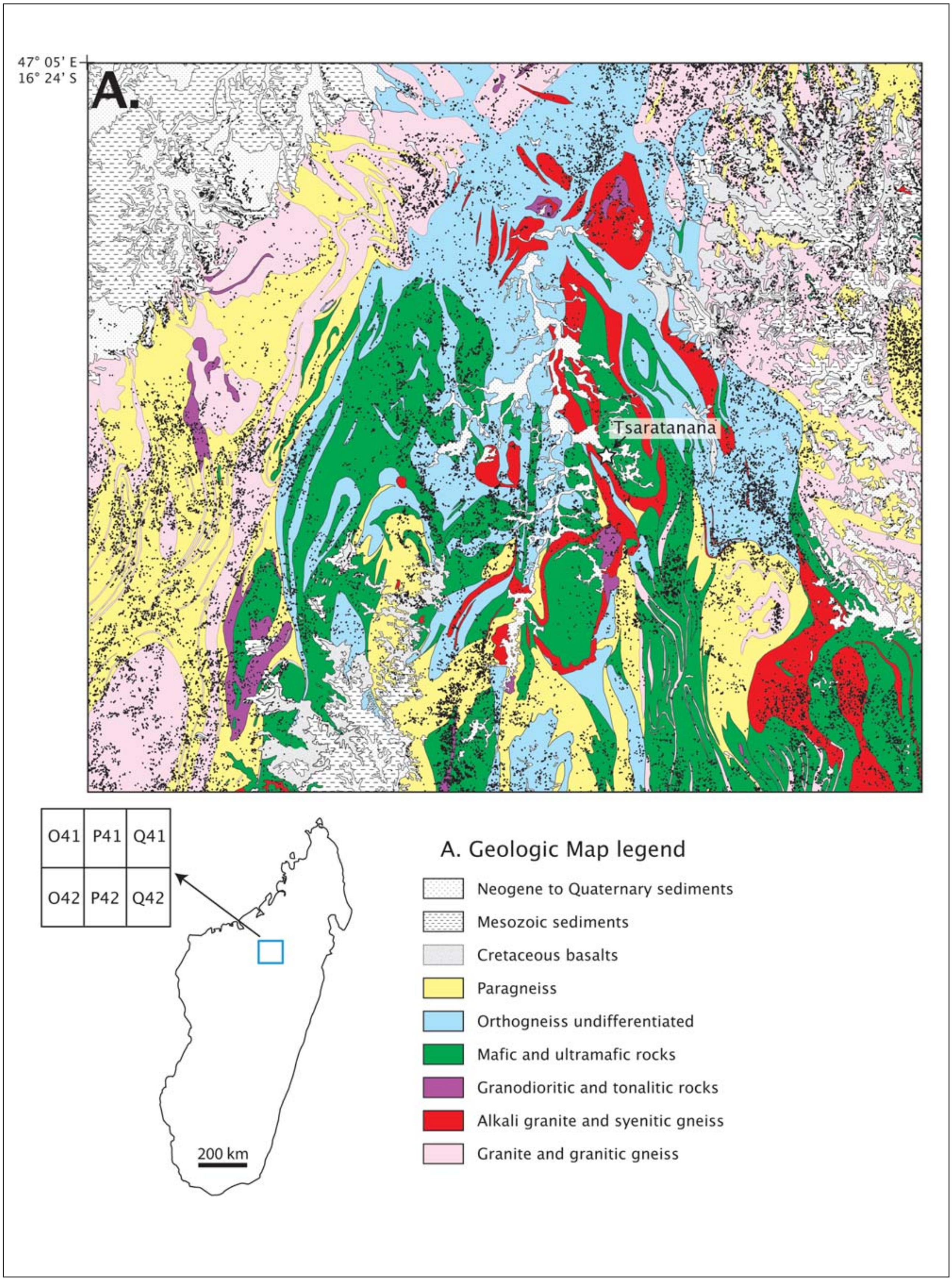
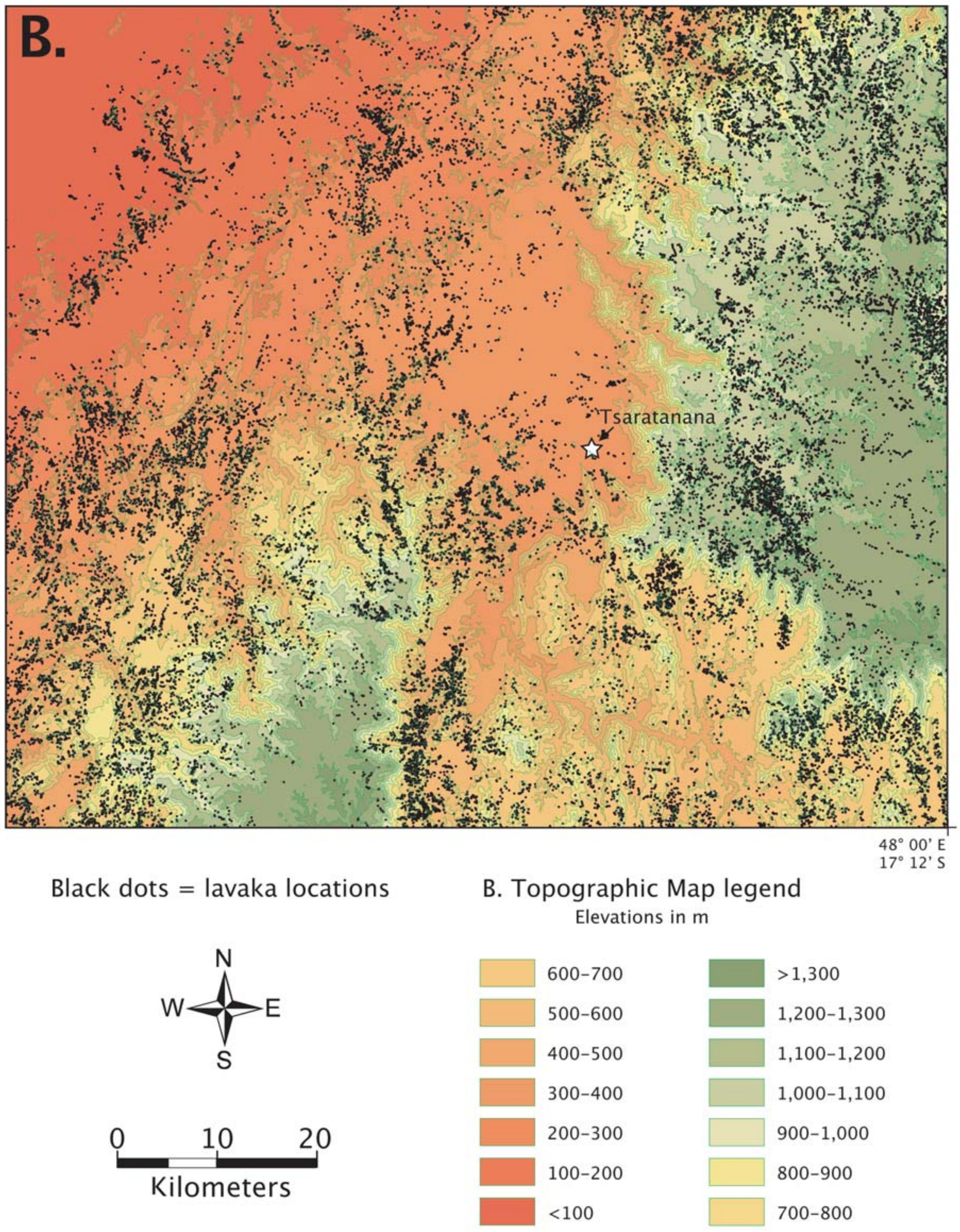


Figure 5. *Geology, topography and lavaka distribution for Tsaratanana study area. Elevation ranges from 23 to 1364 m. Mesozoic basalts are shown distinct from Precambrian mafic rocks in this map, but in the analysis all mafic rocks are combined (Table 2). See caption to Figure 4 for more information.*


B.
Tsaratanana
48° 00' E
17° 12' S
Black dots = lavaka locations
N
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Kilometers
B. Topographic Map legend
Elevations in m
600–700
500–600
400–500
300–400
200–300
100–200
<100
>1,300
1,200–1,300
1,100–1,200
1,000–1,100
900–1,000
800–900
700–800

Table 1. List of 1:100,000 geologic maps used for this project*. Quadrangle locations are shown on Figure 2.

Study area	Quadrangle reference	Sheet name
Ambatondrazaka	R44	Andilanatoby
Ambatondrazaka	R45	Andaingo
Ambatondrazaka	R46	Mandialaza
Ambatondrazaka	S44	Ambatondrazaka
Ambatondrazaka	S45	Didy
Ambatondrazaka	S46	Fierenana
Tsaratanana	O41	Maroadabo
Tsaratanana	P41	Tsaratanana
Tsaratanana	Q41	Tampoketsa de Beveromay
Tsaratanana	O42	Tsiandrarafa
Tsaratanana	P42	Betrandraka
Tsaratanana	Q42	Ambatobe

*BGS-USGS-GLW, 2008. The PGRM (Project de Gouvernance des Ressources Minerales) that produced these maps was funded by the International Development Agency and the French government, facilitated and implemented by the Malagasy government. The project produced comprehensive geologic and geophysical coverage of selected areas in northern, central, and southern Madagascar by an international consortium including Britain, France, Germany, Madagascar, South Africa, and the United States.

(Figure 2). The regions have broadly similar Precambrian basement lithologies, but differ in their structural styles (Figures 4 and 5) as well as their topographies and climatic regimes. They therefore present an opportunity to examine the roles of bedrock composition in different geomorphologic settings.

The Ambatondrazaka study area ranges in elevation from 755 to 1420 m. It includes Lac Alaotra, which at 40 km long is Madagascar's largest lake. The lake basin formed in response to late Tertiary extension (Kusky et al., 2010; Piqué, 1999), and the region is still seismically active (Bertil and Regnoult, 1998; Cox et al., 2010). Surrounding hills are deeply saprolitised with a laterite cap (Heusch, 1981; Kusky et al., 2010; Riquier, 1956), representing the mid-Cretacous to late Oligocene "African Erosion Surface" (Burke and Gunnell, 2008; Davies, 2009). The bedrock consists of high-grade metamorphic rocks, with a wide range of lithologies including paragneisses, granitic gneisses, mafic gneisses, and a variety of migmatitic rocks (Besairie, 1973; BGS-USGS-GLW, 2008). Cenozoic deposits of the Lac Alaotra system blanket the bedrock in the valleys and low-lying areas. Sediment accumulation in the basin has reduced the open-water area, and extensive swamps surround the remnant lake, which has average depth only 1 to 2.5 m (Mutschler, 2003). The fertile alluvial and lacustrine sediment in the valley is intensively farmed. The average population density is around 54 people/km^2, and the region produces about 320,000 tonnes of rice per year, with average productivity 3.64 tonnes/ha (Andriamainty Fils, 2009).

The Tsaratanana study area lies north and west of Ambatondrazaka (Figure 2). Most of the region lies in the central highlands, but the northwestern corner includes the edge of the Phanerozoic rift basins that open down to the west. There is considerable relief, with elevation ranging from 23 to 1362 m. The upland region is dominated by Precambrian crystalline rocks, with Phanerozoic sedimentary rocks occupying the lower-lying northwestern part of the study area. Flat-lying Cretaceous basalts and Cretaceous to Neogene sedimentary rocks also form a plateau on top of some of the Precambrian basement rocks (Besairie, 1973; BGS-USGS-GLW, 2008). The terrain is deeply weathered, and thick soils are developed on all lithologies (Zebrowski, 1968). Population is very sparse: the Betsiboka administrative area, of which Tsaratanana is a district, has an average population density of just 8 people/km^2, and total rice production in the administrative area is less than 50,000 tonnes/yr. The average productivity is only 0.02 tonnes/ha (Ralison and Goossens, 2006).

The Ambatondrazaka area, with its more easterly location and higher mean elevation, has correspondingly greater rainfall and lower average temperatures than the Tsaratanana region (Cornet, 1974). Lying on the inland side of the steep eastern escarpment (Battistini and Petit, 1971) with its pronounced orographic effect, the Ambatondrazaka region is both tropical and humid. Monthly average temperatures range from 18°C (in the winter months of July and August) to 24°C in the summer months. Total annual rainfall is more than 1000 mm, ranging from 4 to 9 mm/month in the dry season (May-September) to 110 to 300 mm/month in the rainy season (November to March) (Ratsimbazafy, 1968).

Tsaratanana is warmer on average than Ambatondrazaka, with a winter month average temperature of 27°C and summer average of 30°C (Jury, 2003): i.e. winter temperatures for the Tsaratanana area are similar to summer temperatures in Ambatondrazaka. Ambatondrazaka's annual rainfall, however, is higher than that for Tsaratanana. The two regions have similar January precipitation (10 to 12 mm/day), but whereas Tsaratanana gets only trace amounts of dry-season precipitation (<1 mm/day in July) Ambatondrazaka receives some rain year round, averaging >4 mm/day in the dry season (Jury, 2003).

Both areas are underlain mostly by Precambrian basement rocks, but they differ in structural style. The Ambatondrazaka region has a strong north-south tectonic grain (Figure 4), whereas rocks in the Tsaratanana area have more variable strike (Figure 5). The Ambatondrazaka area is structurally overprinted by Tertiary to Recent extensional tectonics that produced the Lac Alaotra basin (Piqué et al., 1999). The Tsaratanana area on its northwestern edge has been subject to Mesozoic faulting and Mesozoic rift-basin sedimentation.

The Ambatondrazaka region is characterised by elongate north-south trending hills and valleys that flank the Lac Alaotra graben. In Tsaratanana the topography is dominated by river-incised plateaux. But in spite of their relief and mountainous aspect, there is little outcrop geology in either region, as both areas have thick

Table 2. Lavaka densities measured in different lithologic units. Areas represent lavaka-prone terrain only. Flat lake beds and forested ground are not included. All rocks are Precambrian in age except where indicated.

Lithology	Areal extent (km^2)		Lavakas counted		Densities (Lavakas/km^2)	
	Ambato.	Tsarat.	Ambato.	Tsarat.	Ambato.	Tsarat.
Granite and granitic gneiss	928	1369	1695	8487	1.8	6.2
Alkali granite and syenitic gneiss	192	493	2704	2069	14.1	4.2
Granodioritic and tonalitic rocks	471	106	1538	616	3.3	5.8
Mafic and ultramafic rocks	265	1558	2294	8495	8.7	5.5
Charnockite	45	—	32	—	0.7	—
Orthogneiss undifferentiated	1332	1414	5746	7415	4.3	5.2
Paragneiss	879	1670	6876	10272	7.8	6.2
Mesozoic basaltic rocks	—	391	—	2779	—	7.1
Mesozoic deposits	—	807	—	2316	—	2.9
Neogene to Quaternary deposits	508	687	681	1966	1.3	2.9

saprolites (tens of m in places) that formed on crystalline Precambrian basement rock. A lateritic carapace, usually 0.5 to 1 m thick (Besairie and Robequain, 1957), is developed on top of the saprolite.

Methods

Our geologic basemap was created from twelve 1:100,000 quadrangle maps (Table 1) produced as part of the Project de Gouvernance des Resources Minerales (PRGM) (BGS-USGS-GLW, 2008). Each study area (Figure 2) is covered by six quadrangle maps totaling 8550 km^2 (Figures 4 and 5). We imported the geologic maps into ArcGIS v.10 as raster images, which we georeferenced and georectified to an existing Madagascar basemap (from Cox et al., 2010). We digitised all lithologic boundaries to create polygons outlining the geologic units. We used the Oblique Mercator Laborde projection (Roggero, 2009), which was also that used for the PRGM mapping (BGS-USGS-GLW, 2008).

We standardized and simplified lithologic groupings from the PRGM map legends (Appendix 1). This was necessary both because of inconsistencies in lithologic unit names from one PRGM map to another (units that extended across quadrangle boundaries in some cases had different lithologic designations on the neighbouring maps), and because the maps were very detailed in their lithologic subdivisions: there were 60 distinct units described on the 12 quadrangles we used. To examine responses to weathering and erosion among different rock types, we therefore created broad compositional groupings by eliminating some of the finer distinctions among rock types, and by combining magmatic rocks and their metamorphic equivalents based on overall chemical composition. Thus, we grouped granites with granitic gneisses, we combined alkali granite and syenitic gneiss as one compositional group, and merged mafic gneisses with their mafic and ultramafic igneous counterparts[1]. We kept paragneiss as a separate category because mineralogic composition, porosity and induration state are so different from the sedimentary rock equivalent that their weathering responses are likely to be also different. By the same logic, we subdivided unmetamorphosed sedimentary rocks into Mesozoic (which in these regions are generally cemented

Table 3. Surface area at different slope angles, and distribution of lavakas within slope categories. Slopes are derived from the USGS DEM with resolution 90 m/pixel, derived by elevation difference between neighbouring pixels. Areas represent lavaka-prone terrain only. Flat lake beds and forested ground are not included.

*Slope °	Areal extent (km^2)		Lavakas counted		Densities (Lavakas/km^2)	
	Ambato.	Tsarat.	Ambato.	Tsarat.	Ambato.	Tsarat.
5	1056	3676	3105	12462	2.9	3.4
10	1906	2532	7775	16789	4.1	6.6
15	1133	1286	6469	9706	5.7	7.5
20	423	628	3246	3882	7.7	6.2
25	76	254	649	1252	8.5	4.9
30	14	87	123	245	9.1	2.8
35	1.9	25	11	74	5.7	3.0
40	2.2	7.5	0	5	0.0	0.7

*Value represents the upper limit of the slope category. So 5° bin includes slopes ≤5°, 10° bin is 5.1 to 10°, etc.

[1]This is the sole case where we integrate Precambrian and Mesozoic rocks. The Cretaceous basalts, which underlie 391 km^2 of the Tsaratanana area (Figure 5) have very similar average lavaka density to the Precambrian mafic rocks (7 lavakas/km^2 vs. 6 lavakas/km^2).

but friable) and Cenozoic (commonly less well-indurated cover sediments).

Some kinds of terrain – especially locations of net sediment accumulation and forested areas – are immune to lavaka formation, so we identified the areas where lavakas were excluded by geographic factors, and clipped them from the geologic base maps. For Ambatondrazaka this caused a substantial reduction in analysis area (to 4620 km^2 of lavaka-prone terrain). Tsaratanana, on the other hand, had a final analysis area of 8496 km^2.

We counted lavakas from high-resolution imagery in Google Earth version 6.0 (resolutions ranging from 1 ± 0.2 m to 7 ± 1 m per pixel) using a mapping scale of 1:8,500, which permitted us to recognize lavakas as small as 20 ± 2 m in length. Only currently active lavakas (exposing bare saprolite in their interiors) were counted. Simple lavakas were represented by a single point, but within multi-lobed composite lavakas (e.g. Figure 1b) – which record several discrete lavaka-forming events – we placed a location point within each erosional amphitheatre. Digitized lavaka locations were imported to ArcGIS by converting the data from .kmz format to ArcGIS shapefiles, which were reprojected in Laborde coordinates and added to the project database. We measured the number of lavakas within each lithology polygon using ArcMap’s spatial join tool, then summed the data from all polygons to arrive at total numbers of lavakas associated with each lithology (Table 2).

Topographic data (Figures 4 and 5) are from the 90 m/pixel Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) of Madagascar, distributed by the United States Geological Survey. Slope data were derived from the DEM using tools in ArcMap that allowed us to assign a slope value to each 90 m^2 pixel in the DEM, permitting us to calculate topographic roughess measures. Although the DEM resolution is coarse, recent work has demonstrated that broad patterns of roughess are conserved across a wide range of DEM spatial resolutions (10 to 100 m) and measurement-window sizes (Grohmann et al., 2011). Furthermore, the 90 m/pixel SRTM data have more accurate elevations and fewer inaccuracies (Bolch et al., 2005; Hirt et al., 2010), provide more precise watershed boundaries (Pryde et al., 2007) and can better predict landscape characterisation (Clennon et al., 2010) than do finer-scale ASTER data. We are therefore confident in our ability to examine lavaka-slope relationships at this scale.

We binned the pixels in 5° slope increments and calculated the total area represented by each slope interval. We used ArcMap’s spatial join tool to measure the number of lavakas in each slope-interval area, from which we could calculate the lavaka density associated with slopes of different steepness (Table 3). We also looked at the hillslope characteristics for the individual lavakas by creating a 100-m radius buffer around each lavaka datapoint, and using ArcMap's zonal statistics to calculate the slope range and average about each lavaka.

Geologic comparisons

The areas have broad lithologic similarity, both dominated by crystalline basement rocks (Figure 4, Figure 5). About 40% of each area is underlain by gneisses (Ambatondrazaka is 16% paragneiss and 24% orthogneiss, and Tsaratanana 20% paragneiss and 17% orthogneiss). Granite and granitic gneiss occupy a further 16% of both areas, with an additional few percent (3% and 6%, respectively) of alkalic rocks (Table 2).

There are a number of lithologic differences between the two areas. Mafic rock distribution differs significantly: only 6% of Ambatondrazaka is underlain by Precambrian mafic igneous rocks and mafic gneisses, but almost a quarter of the Tsaratanana area has mafic outcrop or subcrop. The Tsaratanana mafic rocks are mostly Precambrian (18.5% of total area), but with a small proportion (4.5% total area) of Late Cretaceous basaltic rocks that are absent from Ambatondrazaka. Intermediate (granodioritic and tonalitic) rocks are likewise unequally distributed, comprising 8% of Ambatondrazaka but only 1% of the Tsaratanana area. A final significant difference is in the distribution of Phanerozoic sedimentary deposits. Ambatondrazaka has no Mesozoic rocks, but 9% of the Tsaratanana area exposes Mesozoic strata. Neogene to Quaternary deposits – largely lake beds of the Lac Alaotra basin – cover 27% of the Ambatondrazaka area, whereas Tsaratanana has just 8% Quaternary sediment, flooring alluvial valleys. In Ambatondrazaka the youngest sediments occupy the lowlands (Figure 4), but in Tsaratanana they also cap the crystalline basement at high elevations, creating mesa-like plateaus (Figure 5).

Overall distribution of lavakas

Of the approximately 17,000 km^2 covered by the PRGM maps, 3794 km^2 is either forested or occupied by flat-lying recent sediment, environments in which lavakas do not develop. The remaining 13,206 km^2 is potentially lavaka-prone: 4620 km^2 in Ambatondrazaka and 8496 km^2 in Tsaratanana.

We counted 21,566 lavakas in Ambatondrazaka and 44,415 in Tsaratanana. The smaller number of Ambatondrazaka lavakas reflects the fact that 46% of that terrain consists of lake-bed and forested environments, where no lavakas occur. The aggregate densities for the two regions, calculated over the sum of all lavaka-eligible territory, are in fact very similar: 4.7 lavakas/km^2 for Ambatondrazaka and 5.2 lavakas/km^2 for Tsaratanana. There are large spatial differences in lavaka abundance, however (Figures 4 and 5). In the areas of highest lavaka concentration, we performed sub-counts in one-km^2 tracts, and found that maximum local densities are 50 lavakas/km^2 in the Tsaratanana area, and as high as 150 lavakas/km^2 in Ambatondrazaka. So although the overall densities are more or less

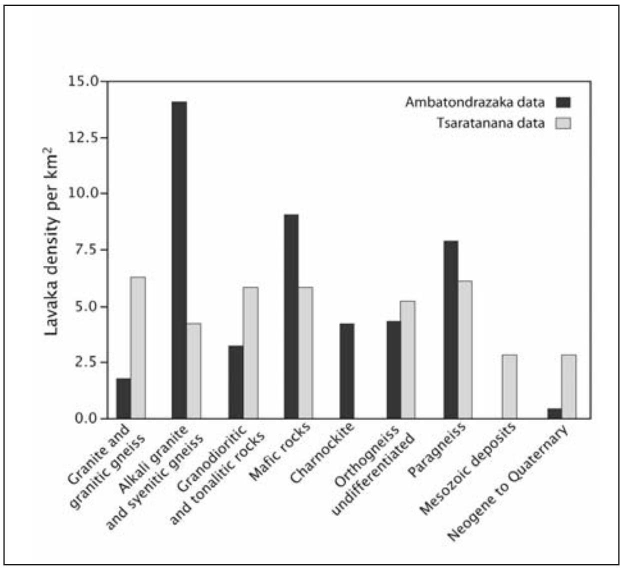


Figure 6. *Lavaka densities associated with lithologic groupings in the Ambatondrazaka and Tsaratanana study areas. There is no predictive association between rock type and lavaka abundance.*

the same (≈5 lavakas/km^2), we infer that regional geologic or geomorphologic differences produce local erosional differences that are significantly greater in Ambatondrazaka than in Tsaratanana.

Lithology and lavakas

We find no predictive first-order links between lithology and lavaka density (Table 2, Figure 6). Average lavaka densities in the Tsaratanana area range from 3 to 6 lavakas/km^2 among the different lithologies, without much variation from one rock type to another. In Ambatondrazaka the range is greater – 1 to 14 lavakas/km^2 – with a far greater tendency for lavaka formation in alkalic rocks than in any other rock type. The tendency is not inherent to alkalic rocks in general, however, because in Tsaratanana such lithologies have on average only 4 lavakas/km^2.

In contrast to the hypotheses of Riquier (1954), we do not find a marked difference between the lavaka vulnerability of mafic and felsic rocks. In Ambatondrazaka, for example, mafic rocks have on average higher lavaka densities than intermediate or granitic rocks (Figure 6). Wells and Andriamihaja (1993) argued that saprolitised bedrock in the crystalline uplands is inherently too homogeneous and too deeply altered to exert a strong control on erosional propensity; they made the point that were lithology a strong driver for lavaka formation we would expect a strong relationship between bedrock strike and lavaka orientations. They tested and found no such relationship in their data, and their inferences are borne out by our finding that in general lavaka densities do not map strongly to lithologies. We conclude that, at this scale of study, bedrock geology does not appear to be the primary driver for lavaka formation.

Seismicity, faulting and lavakas

We find no spatial correlation between lavaka clustering and fault traces on the geologic maps. Although we do not show fault traces in Figure 4 and Figure 5 for scale reasons, we examined the relationship between lavaka occurrence and the location of faults. Our findings were the same as those of Rabarimanana et al. (2003, their figure 10): although lavakas are abundant in the faulted areas, there is no increase in their density around individual faults, and groups of lavakas commonly align at an angle to fault traces.

It is clear, however, that lavakas tend to be more intensely clustered in Ambatondrazaka than in Tsaratanana (Figure 4): the difference between the background lavaka density (≈5 lavakas/km^2) and the maximum local density is a factor of 10 in Tsaratanana and a factor of 30 in Ambatondrazaka. The highest concentrations of Ambatondrazaka lavakas surround the seismically active Lac Alaotra basin (Figure 4). We attribute the difference to a greater frequency of seismic events in Ambatondrazaka. The Tsaratanana region has 50 recorded seismic events in the interval 1979 to 1994, whereas there are 289 in the Ambatondrazaka area (based on analysis of Cox et al., 2010, data from Bertil and Regnoult, 1998; Institut et Observatoire de Géophysique d'Antananarivo, 2008). Comparison of the generalised seismic and lavaka distributions nationwide in Madagascar (Figure 7) shows that the Tsaratanana area has a lower overall seismic density than does Ambatondrazaka, and that its apparent (i.e. Landsat-image-resolvable, as reported in Cox et al. 2010) lavaka density is likewise less. We interpret this to reflect a seismic control on overall lavaka abundance, and this we infer to drive the strong differences in local concentration (maximum 50 lavakas/km^2 in Tsaratanana versus 150 lavakas/km^2 in Ambatondrazaka). This does not, however, explain all of the short-range differences in lavaka concentration. Within both study areas there are zones with high lavaka concentrations, and zones where concentrations are low.

Lavakas and slope

Slope characteristics appear to predict lavaka location better than underlying geology. We find that in both study areas lavaka density increases as terrain steepens up to some maximum, beyond which density decreases (Table 3). In Ambatondrazaka, lavaka densities climb with increasing slope up to average slope angles of 30°, beyond which lavaka densities decline. In the Tsaratanana area, the lavaka-density maximum comes at lower slope: density increases with slope angle up to 15°, and drops off as slopes steepen beyond that (Table 3). In both Tsaratanana and Ambatondrazaka the steepest slopes have very low lavaka density (although we note that there is only 4 km^2 surface area and 11 lavakas counted at these high slope angles, so the very low density values could be a small-sample artifact). The overall indication is that slope matters, and that it there is some optimum steepness for lavaka

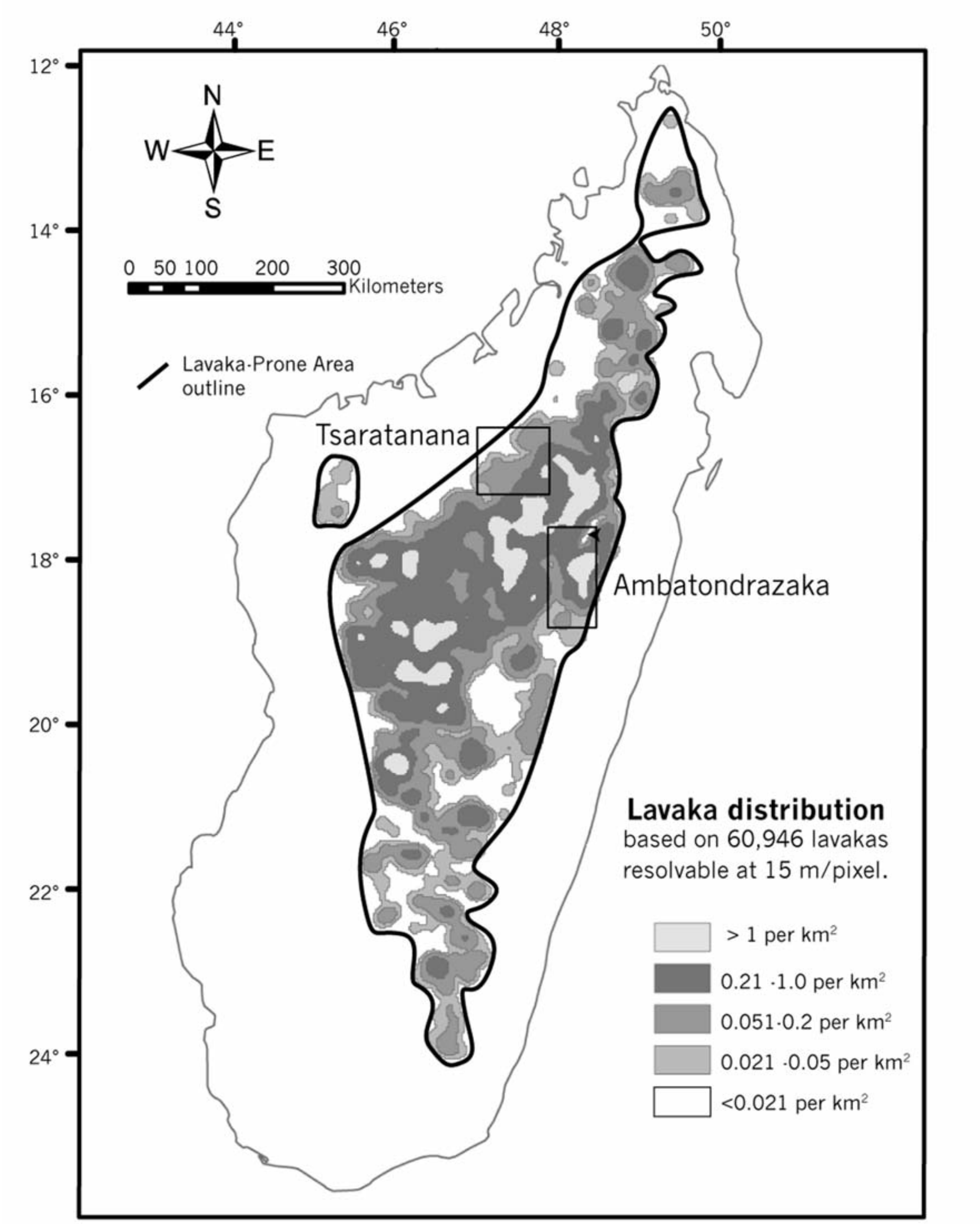
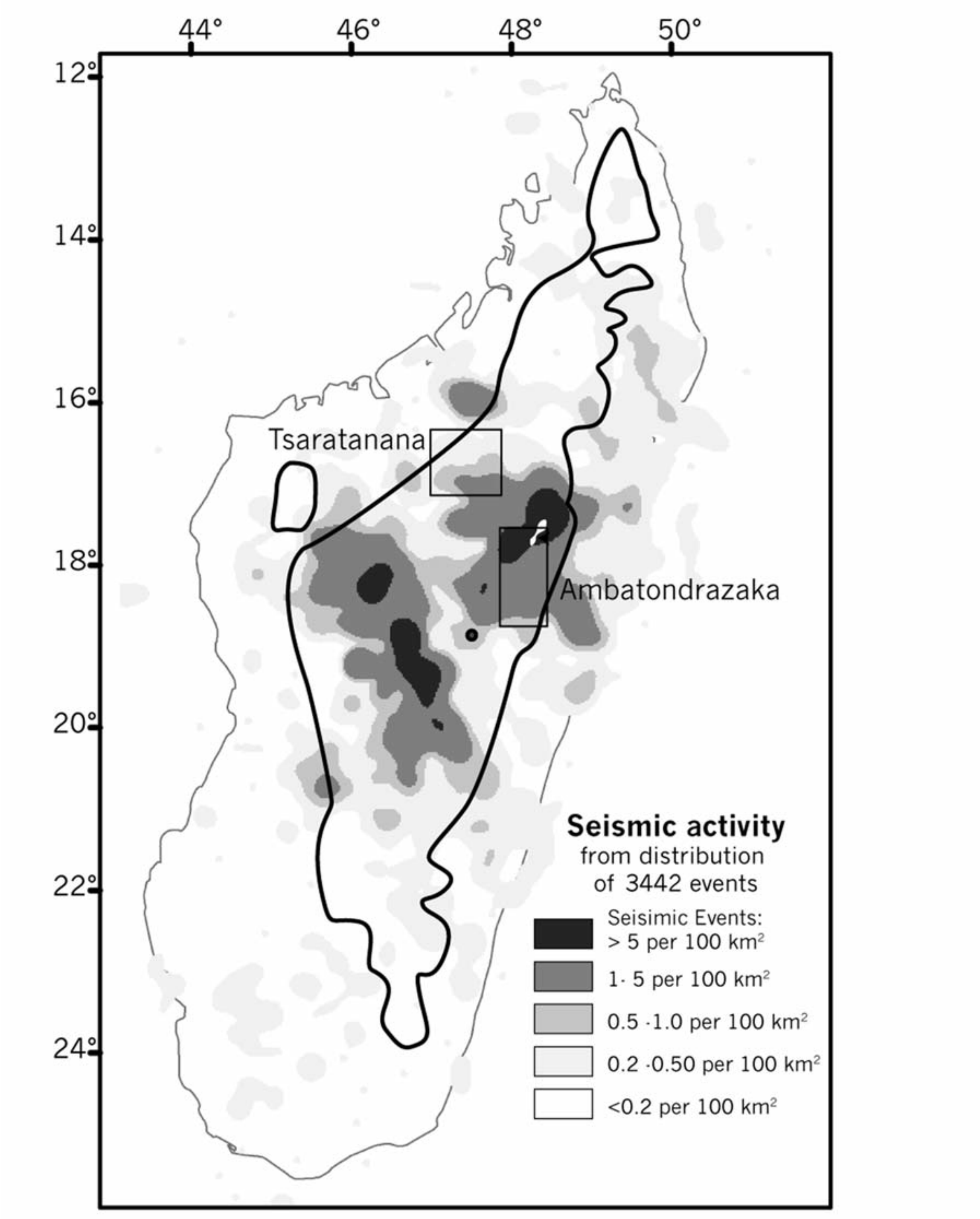


Figure 7. *Contour plots of the distribution of lavakas and seismic events in Madagascar (after Cox et al., 2010). Boxes show location of the two study areas. The lavaka densities are based on Landsat images at 15 m/pixel: they represent apparent densities only, and therefore are much lower than the high-resolution data recorded in for the two study areas in this paper. The seismic data are from Bertil and Regnoult (1998) and Institut et Observatoire de Géophysique d'Antananarivo (2008). The maps show that the Tsaratanana rectangle has a lower seismic-event density than does the Ambatondrazaka area, and that the lavaka density is likewise smaller.*


44°
46°
48°
50°
12°
14°
16°
18°
20°
22°
24°
Tsaratanana
Ambatondrazaka
Seismic activity
from distribution
of 3442 events
Seisimic Events:
> 5 per 100 km²
1- 5 per 100 km²
0.5 -1.0 per 100 km²
0.2 -0.50 per 100 km²
<0.2 per 100 km²

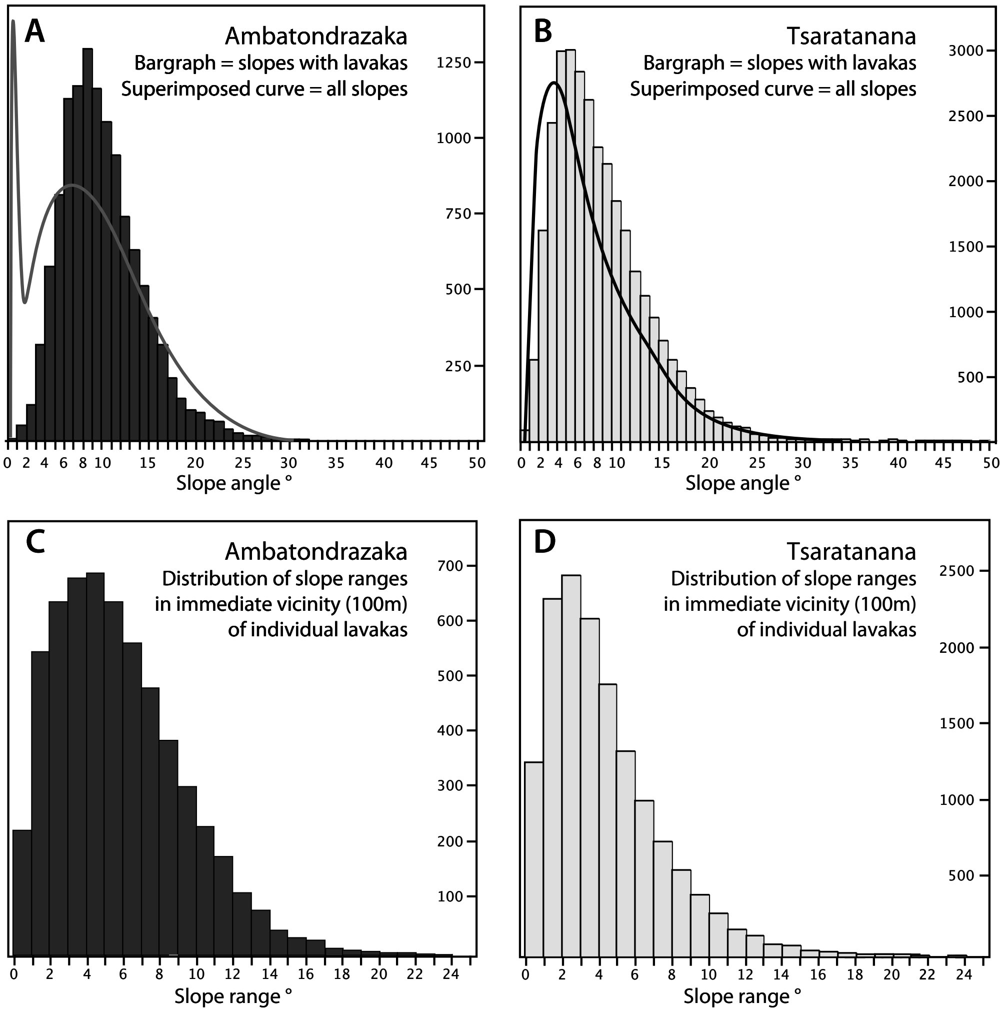


Figure 8. *Two ways of looking at the relationships between lavakas and slope. Bar graphs in A and B show frequency distribution of slope angles associated with individual lavakas (note logarithmic sale on the x axes of (**A**) and (**B**). The curve superimposed on each bar graph shows the shape of the frequency distribution of all slopes in that study area (the bimodal distribution in the Ambatondrazaka slope curve reflects the strong topographic influence of the Lac Alaotra lake basin). The overlay curve is not at the same scale as the lavaka slope histogram: the overlay is to show that lavakas are not distributed equally among available slope angles, and that lavakas tend to prefer steeper slopes. (**C**) and (**D**) show the slope variability (Ruszkiczay-Rudiger et al., 2009), which is the distribution of slope ranges associated with individual lavakas: i.e. for each lavaka in the database, the difference between the maximum and minimum slope angles measured within 100 m of the lavaka centre. The graphs in C and D show that lavakas form most frequently on slopes that have a 4 to 5° change in steepness over a 100-m interval.*

formation. That optimum steepness is not a constant, however. In Tsaratanana it appears from the binned data to be around 10 to 15°, whereas in Ambatondrazaka densities are greatest in areas where the regional slope is 25 to 30°.

In addition to looking at the density of lavakas developed on slopes of different steepness, we can look at specific slope angles associated with individual lavakas. If lavakas had no slope preference, the frequency distribution of all slope values would have the same shape as the frequency distribution of slopes with lavakas on them. But in fact we find that the lavaka distribution is shifted toward steeper slope values, indicating that lavakas form less readily on shallow slopes (Figure 8, A and B). The distribution rolls over and drops off quite steeply, however, suggesting that very steep slopes are likewise not favourable to lavaka development. Thus the data from individual lavakas also appear to suggest that there is an optimum slope most favourable to lavaka formation.

As with the binned lavaka-density-slope data (Table 3), however, we find that although the two study areas have broadly similar patterns, the peaks in the distributions are at different absolute slope values (Figure 8): The most common slope angle for Ambatondrazaka lavakas is 8 to 9°, whereas those in the Tsaratanana area more frequently have shallower slopes of 4 to 6°. So slope angle alone is not the dominant control: some other factor must also be at play.

Another way of thinking about slope is to consider the shape of the hillside close to the lavaka. To that end we look at the slope variability (defined as the difference between the maximum and minimum slope angle: Ruszkiczay-Rudiger et al., 2009) within a 100 m radius of the lavaka centre. A small value means that the slope, whether steep or shallow, does not vary much over a 200 m horizontal distance, whereas a large variability number means that the hill steepens measurably in the vicinity of the lavaka. We find that very few lavakas occur on hillsides with zero slope variability, and that very few occur on slopes with a large slope range (Figure 8, C and D). This means that – independent of the actual slope angle – lavakas tend not to form on slopes of very uniform steepness; and likewise that they do not tend to form on slopes over which the steepness value changes rapidly. The peak in the curve represents an optimum slope profile, with moderate change in slope that clearly favours lavaka development.

We can refine the slope-lavaka relationship by considering surface roughness, defined as the standard deviation of slope values within a specified area (Grohmann et al., 2011). In our dataset, the slope roughness associated with lavakas (measured in the 200-m diameter buffers) has a median value of 1.4° for Ambatondrazaka and 1.2° for the Tsaratanana area. The ranges in surface roughness (associated with lavakas) are 0 to 10° for Ambatondrazaka and 0 to 40° for Tsaratanana. Thus lavakas clearly favour slopes that have low but not negligible topographic roughness.

The two study areas show very similar lavaka-associated slope patterns: in Ambatondrazaka the optimum slope variability is 3 to 5°, and in Tsaratanana it's 2 to 3°. The slopes with lavakas in the two areas have almost identical median roughness values (1.4° and 1.2° respectively). These values are statistcally indistinguishable from one another, and so we interpret this to mean that the optimum configuration for lavaka development is a condition of low surface roughness, with slope variation of about 2 to 5° across the hillside.

The optimum slope profile may occur at different slope steepness in different areas, which would explain why the greatest concentrations of lavakas are on steeper slopes in Ambatondrazaka than in Tsaratanana. Furthermore, the GIS data show a correlation between slope range and actual slope value, such that steeper slopes are significantly more likely (at the >99% level) to have a greater short-range slope increase. Thus, the lack of availability of appropriate slope shapes at steeper angles may be one of the reasons why lavakas occur less frequently on steeper slopes.

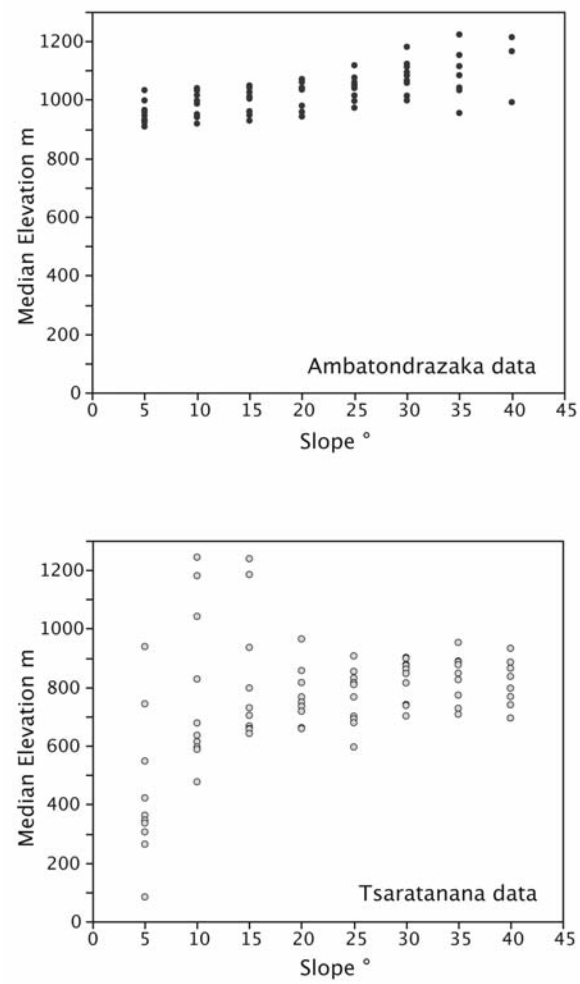


Figure 9. Distribution of elevations as a function of slope, showing the greater range in elevations in Tsaratanana and consequent differences in slope-elevation distribution. Data (from Appendix 2) are binned by slope and lithology: each point represents the median elevation for a lithologic unit at that slope interval. (To label the lithologies in this graph would make it so as to emphasise the geomorphologic slope-elevation relationships (and also because the slope-elevation characteristics are for the most part independent of lithology). The low-slope, high-elevation excursions in the Tsaratanana data are due to plateau-capping Mesozoic and Cenozoic basalts and sedimentary rocks.

Topographic relief in Tsaratanana is greater than that in Ambatondrazaka, so slopes are distributed across a greater range of elevations (Figure 9) The slope-elevation data for Ambatondrazaka trend continually upward (perhaps flattening out at slopes above 35°, but there are insufficient data at high slope and high

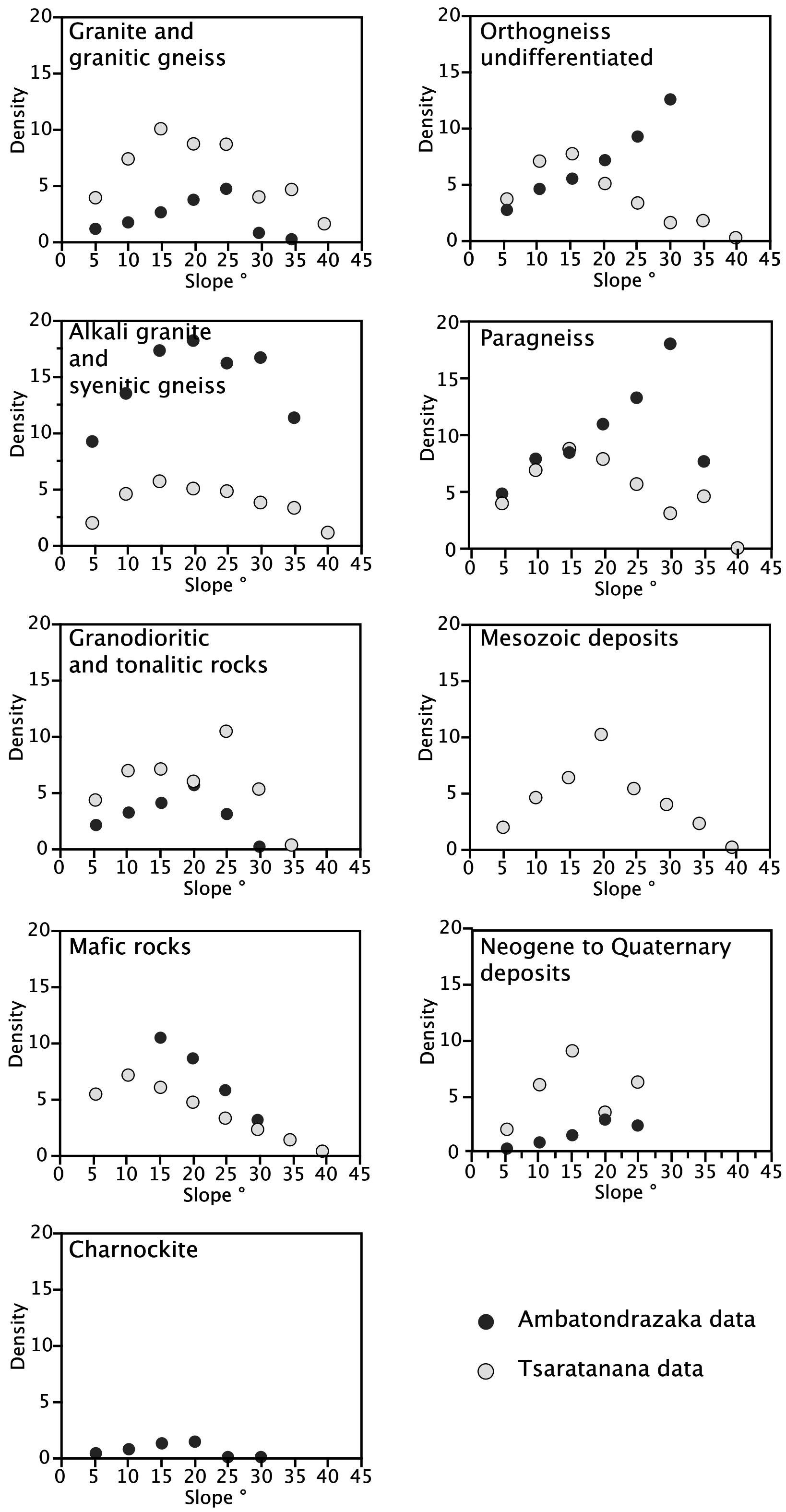


Figure 10. *Lavaka density (lavakas/km²) as a function of slope, broken down by lithologic unit. All graphs are at the same scale. X-axis values represent binned slope data: thus 5° represents all slopes (in lavaka-prone terrain) <5°. A value of 10° represents slopes in the range 5.1 to 10°; and so on. Lavaka density is computed by drawing polygons enclosing the regions with slope values in a given range, calculating their total area, and counting the number of lavakas enclosed by the polygons.*

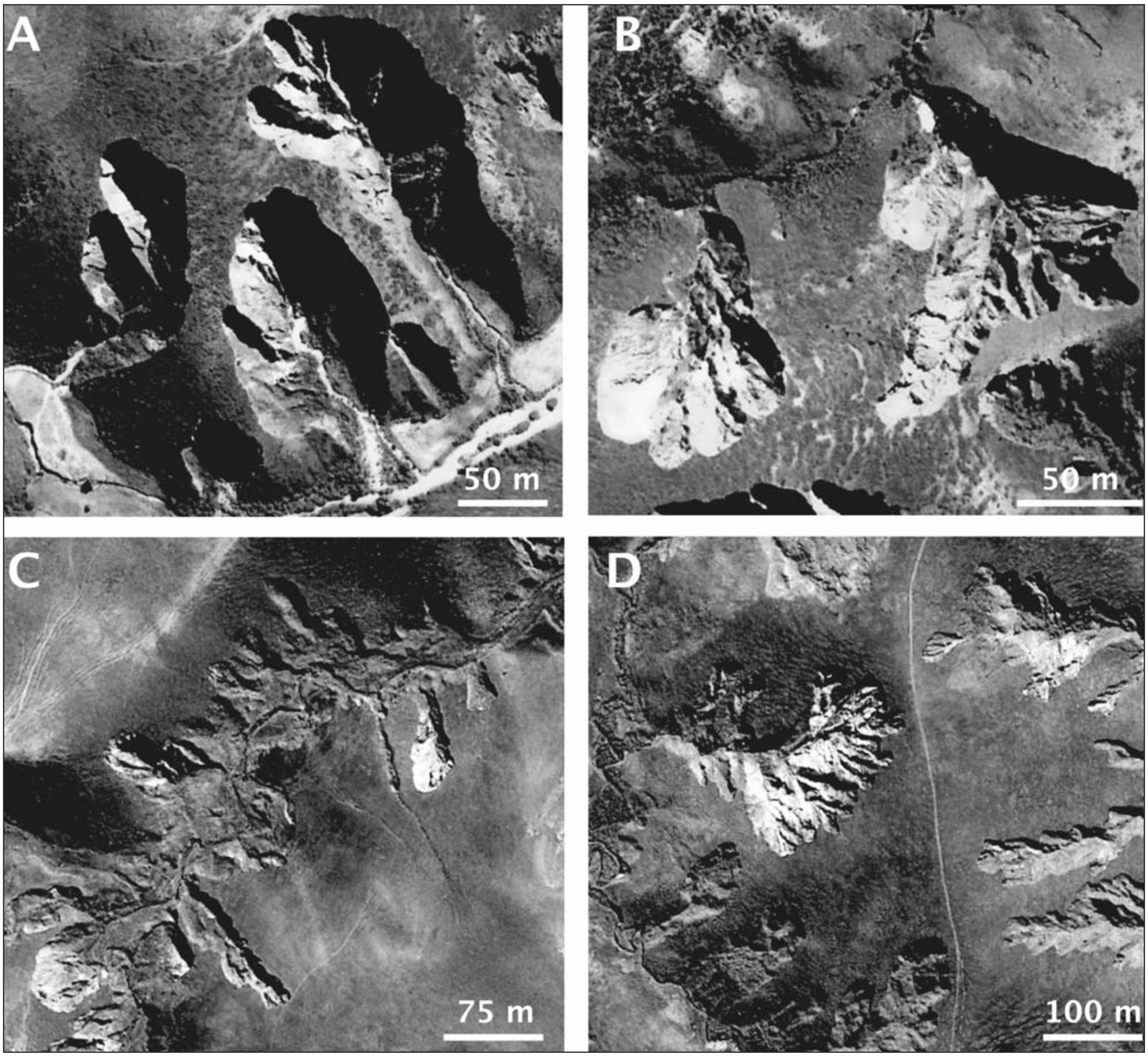


Figure 11. *Google Earth images showing broad morphologic differences between lavakas in the two study areas. (**A**) and (**B**) are from the Ambatonrazaka area (17.9102° S, 48.3736° E and 17.9513° S, 48.3420° E). (**C**) and (**D**) are from Tsaratanana (16.8220° S, 47.8041° E and 16.9463° S, 47.8004° E) North is up in all images. Lavakas in the Ambatondrazaka area tend to have a more rounded headwall and fewer internal drainage ways. Tsaratanana lavakas have more scalloped headwalls and are more dendritic in form. Lavakas in the Ambatondrazaka area appear deeper in general than those in the Tsaratanana region – which may suggest regional differences in saprolite thickness – but this has not been measured in the field.*

elevation to constrain that). The data for Tsaratanana show a different tendency. If we ignore the low-slope, high-elevation datapoints (slopes 5 to 15° above 900 m, which represent the plateau-forming Mesozoic and Cenozoic cover rocks; see Appendix 2), the data trend steeply upward at shallow slopes, and then flatten out at slopes greater than 20°.

The relationship between slope and lavaka density is largely independent of lithology (Figure 10), suggesting that the slope-lavaka relationship is a fundamental landscape property. Densities increase with increasing slope up to some maximum, and decrease thereafter, and the slope optimum is steeper in Ambatondrazaka than in Tsaratanana. In Tsaratanana, maximum lavaka densities occur at slope values around 15° for most lithologies. Exceptions are Mesozoic deposits (peak is at 20°), mafic rocks (10°), and granodiorites/ tonalites (peak at 25°). Ambatondrazaka data show greatest lavaka density at steeper slopes: maxima are between 20° and 30°, with mafic rocks the sole exception. The mafic rocks, in both study areas, peak at small slope values (10 to 15°), and decline monotonically at increasing slope angle. These data suggest that the slope-lavaka relationships are intrinsic to each region, and that slope exerts a stronger control than lithology on lavaka development. The slope patterns seen in our data are similar to those for other types of gullies studied elsewhere (Conforti et al., 2010)

The north-south aligned lavaka concentrations that are so evident in the Ambatondrazaka map (Figure 4) correspond to north-south ridges that are geologically controlled; but our data show that the lavaka concentrations, rather than being controlled primarily by lithology, in fact reflect slope characteristics along those ridges. The concentrations change when the slopes change, even if the bedrock lithology remains the same (Figure 10).

Discussion

Simplistic interpretation of lavakas as *a priori* responses to anthropogenic activities generates a tendency to ignore the numerous environmental forcing factors that contribute to this kind of gullying. Although climate (rainfall and temperature) are clearly important variables in any geomorphologic process, the lack of systematic record-keeping in Madagascar precludes such analysis for lavakas. Maps, however, provide a hard dataset that can be analysed for specific patterns. Once identified, those relationships can be used to form hypotheses to further test controls on lavaka formation. The purpose of this study was therefore to isolate two key variables – lithology and slope – and examine the extent to which they are correlated with lavaka abundance.

Our analysis overturns previous interpretations (Rabarimanana et al., 2003; Riquier, 1954) that lavakas are more likely to form in felsic than in mafic rocks. Such interpretations may have arisen because most lavaka studies (e.g. Heusch, 1981; Rabarimanana et al., 2003; Riquier, 1954; Tricart, 1953) have focused on the agriculturally important Lac Alaotra-Ambatondrazaka area, in which granitoid rocks are indeed more lavaka-prone than mafic rocks (Figure 6). Casting the net over a broader geographic area, however, tends to show that the lavaka-lithology connection is not so simple. Wells and co-workers (1993; 1991), who used the primary road system to make a series of long traverses that ranged over wide regions of the highlands, did not find any greater tendency for lavaka formation in granitoid substrates, and our comparative analysis of two topographically and geologically distinct areas backs up their interpretations.

We don't know why there is such a lack of correlation between lithology and lavaka abundance, but we suspect that it may have something to do with the great thickness of the saprolite. Unfortunately there are no detailed soil thickness maps for Madagascar, but recent hydrologic mapping indicates saprolite thicknesses 20 to 50 m over Precambrian basement in the areas where lavakas occur (Davies, 2009) . Studies (in places other than Madagascar) that have described relationships between bedrock lithology and susceptibility to gully formation generally do not report a thick weathering mantle (e.g. Felfoul et al., 2003; Marden et al., 2005; Rustomji, 2006), suggesting that bedrock in these study areas may be close to the surface. Depth to bedrock and the degree of disintegration of the parent material are known to be important criteria affecting groundwater flow and hillslope stability (Davies, 2009), and we would like to see those aspects factored in to future analysis of gullying. A thick weathered carapace seems likely to increase overall susceptibility to erosion and to mute any inherent differences in resistance among rock types.

Support for this hypothesis comes from work done in Swaziland, which – like Madagascar – has convex hills underlain by deep saprolite (>60m thick: Märker and Sidorchuk, 2003) in which lavaka-like gullies are commonly developed (Märker and Sidorchuk, 2003; Morgan and Mngomezulu, 2003). Saprolites from different parent lithologies show only slight differences in abundance of quartz, clays, and pedogenic oxides (Scholten, 1997; Scholten et al., 1997), and – although no studies have specifically tested for the effects of lithology – the results of investigations in which bedrock lithology was recorded suggest that sub-saprolite geology plays little role in controlling susceptibility to gully formation (Märker and Sidorchuk, 2003; Morgan and Mngomezulu, 2003; Scholten, 1997).

Bedrock geology may not have an a priori influence on lavaka formation, but geology clearly influences landscape (in ways that vary from region to region depending on local variations in structural/tectonic history and climate). As pointed out by Wells and Andriamihaja (1993), small-scale features such as fractures and veins (not resolvable at the regional map scale) may influence groundwater flow and saprolite stability, and hence lavaka formation. Field mapping of the orientations of faults, joints, and veins, and their relationship to lavaka locations and orientations, would therefore be an important next step.

The complexity of the relationships between lavaka formation and regional geomorphology is illustrated by systematic differences in lavaka morphology between the two regions studied here (Figure 11). In Tsaratanana, the characteristic lavaka is an elongated dendritic gully that seems to represent headward erosion of an established drainage network. In Ambatondrazaka, in contrast, lavakas are usually lobate in shape and are less closely linked to valley drainage. The Ambatondrazaka lavakas have a more classic mid-slope lavaka form given by groundwater sapping of the headscarp (Wells and Andriamihaja, 1993). We did not measure lavaka size for this project, but a qualitative assessment indicates that average size and apparent lavaka depth are greater in Ambatondrazaka area than in the Tsaratanana region. This may relate to climate and/or saprolite thickness differences; but more work is needed to evaluate this.

Saprolite characteristics are likely to be an important part of the story: present and past climatic differences between the two areas (discussed earlier) may be reflected in weathered-mantle thickness, which would be likely to produce the different slope-related erosional responses identified in this study. The grain size of the saprolite (and overlying laterite) is likely also to be important, as Poesen et al. (2003) show that the proportion of sand and silt can dramatically affect the type and volume of gully erosion. The bedrock in both areas is generally deeply buried (up to 50 m), but only generalised saprolite thicknesses are known (Davies, 2009). Regional mapping of saprolite characteristics would be informative. Field data would also permit examination of the effects of small-scale lithologic differences that are below the scale of resolution of our maps. Joints and fractures in the saprolite, for example, or quartz vein systems could have significant local hydrologic and geomorphologic effects.

Our comparative analysis shows that there is no simplistic "one-size-fits-all" interpretation of why lavakas form where they do. In order to fully understand lavakas, which is a necessary first step toward ultimately controlling or preventing their formation and growth, we need to know more about what drives their formation. It is difficult to tease apart cause and effect in lavaka distribution because the key variables – slope, lithology, and elevation – are interlinked. The geology makes the topography, and that relationship is also a function of climate, with precipitation and temperature being key variables. The lack of systematic climate records in Madagascar makes it impossible to conduct a detailed regional analysis of rainfall patterns and storm frequencies that might be tied in to lavaka development; and even were such data available they would cover only a few decades so that the long-term relationships between geomorphology and climate would remain speculative.

We infer that interplay among saprolite thickness, regional relief, and hydrology ultimately govern the form and distribution of lavakas; but much additional work is required to tease apart the inter-relationships among these factors. We expect that GIS and quantitative analysis will continue to play an important role in answering these questions, but local field studies and detailed site measurements will also be necessary.

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Appendix 1. Mapping units described in PRGM maps (BGS-USGS-GLW, 2008; Table 1) and the corresponding simplified lithologic groupings that we used for this study. Original descriptions on the PRGM maps are given in French, and have been translated here into English.

Simplified lithologic groupings used in this study	Corresponding geologic unit descriptions from PRGM map legends (translated from the original French)	Study area	Quadrangles
Granite and granitic gneiss	Nebulitic granite with biotite ± hornblende with schlieren of older gneiss	Ambatondrazaka	S44, R44, S45
Granite and granitic gneiss	Granitic to granodioritic gneiss and charnockite with coarse grain	Ambatondrazaka	R44, R45, R46
Granite and granitic gneiss	Xenolitic granite with medium grain (dioritic xenoliths)	Ambatondrazaka	R44, R45
Granite and granitic gneiss	Augen granitic gneiss (porphyroclastic, locally sheared)	Tsaratanana	O41, O42
Granite and granitic gneiss	Biotite bearing granite	Tsaratanana	O41,
Granite and granitic gneiss	Migmatitic granitoid and undifferentiated granite	Tsaratanana	O41, P41, O42
Granite and granitic gneiss	Sills of gneissic leucogranite, sometimes migmatitic	Tsaratanana	P42, Q42
Granite and granitic gneiss	Biotite bearing metagranite ± amphibole	Tsaratanana	O41, P41, O42, Q41, Q42
Granite and granitic gneiss	Biotite bearing metagranite ± amphibole, unit of magnetite-bearing quartzite	Tsaratanana	O41, P41, O42, Q41
Alkali granite and syenitic gneiss	Alkali granites and syenitic gneiss, stratified, multiphase, coarse to medium grain, undifferentiated (mainly syenogranite with biotite, alkali leucogranite and quartz-syenite)	Ambatondrazaka	S44, R44, S45, R45, S46, R46
Alkali granite and syenitic gneiss	Alkali granite and syenite with biotite ± amphibole	Tsaratanana	O42
Alkali granite and syenitic gneiss	Foliated alkali microgranite		Tsaratanana P41, P42, Q41, Q42
Alkali granite and syenitic gneiss	Charnockitic syenite, massive and foliated	Tsaratanana	P41, P42, Q41, Q42
Granodioritic to tonalitic rocks	Granodiorite	Tsaratanana	O41, O42
Granodioritic to tonalitic rocks	Granodiorite to quartz diorite, locally xenolitic	Tsaratanana	O42, P42, Q42
Granodioritic to tonalitic rocks	Foliated granodiorite with biotite - hornblende, locally migmatitic with enclaves of biotite bearing gneiss ± amphibole and amphibolite	Tsaratanana	P41
Granodioritic to tonalitic rocks	Metatonalite with amphibole and biotite	Tsaratanana	O41
Granodioritic to tonalitic rocks	Tonalitic gneiss with hornblende ± clinopyroxene with boudins of amphibolite ± garnet and pyroxene bearing metadiorite, charnockitisation	Ambatondrazaka	R45, S46, R46
Mafic and ultramafic rocks	Gabbro	Ambatondrazaka	S45, S46, R46
Mafic and ultramafic rocks	Ultramafic and metaultramafic rocks	Ambatondrazaka	S44, S45, S46, R46
Mafic and ultramafic rocks	Metagabbro/Orthoamphibolite	Ambatondrazaka	S44, R44, S45, R46
Mafic and ultramafic rocks	Quartz tholeitic basalt flows (sakalavites), volcanic breccia	Tsaratanana	P41, P42, Q42
Mafic and ultramafic rocks	Metagabbro/gabbronorite, norite and orthoamphibolite; with locally lenses of ultrabasic rocks	Tsaratanana	P41, O42, P42, Q41, Q42
Mafic and ultramafic rocks	Foliated norite	Tsaratanana	O41, O42
Mafic and ultramafic rocks	Foliated and banded gneiss, mafic and biotitic, locally sheared, with quartzite, pyroxene bearing amphibolite, metagabbro and metaultramafic rocks	Ambatondrazaka	S44
Mafic and ultramafic rocks	Mafic gneiss with biotite ± hornblende with lenses of quartzites, graphitic rocks and ultramafic/ultrabasic rocks	Ambatondrazaka	S45, S46
Mafic and ultramafic rocks	Mafic gneiss with hornblende ± biotite, pyroxene, amphibolite, iron quartzite, lenses of serpentinites and pyroxenite and magnetite bearing quartzite	Tsaratanana	O41, P41, P42
Mafic and ultramafic rocks	Amphibolite gneiss with abundant layers of leucogranitic gneiss, non-differentiated	Tsaratanana	Q42
Mafic and ultramafic rocks	Amphibolitic and migmatitic gneiss ± biotite, clinopyroxene and amphibolite with layers of leucogranitic gneiss and lenses of quartzite and magnetite bearing quartzite	Tsaratanana	P42, Q41, Q42
Mafic and ultramafic rocks	Gneiss and mafic granoblastic granofels with amphibole ± pyroxene with metabasaltic/metagabbroic composition (granulitic metabasite) with acti-tremolitites and micaschistes	Tsaratanana	P41, O42, P42, Q42
Charnockite	Charnockite	Ambatondrazaka	R44, R45, S46, R46
Orthogneiss undifferentiated	Migmatitic gneiss with feldspar and biotite ± horneblende ± clinopyroxene, granitoide orthogneiss	Ambatondrazaka	S44, R44, R45, S46
Orthogneiss undifferentiated	Migmatitic orthogneiss with garnet-hornblende ± biotite	Ambatondrazaka	S45
Orthogneiss undifferentiated	Charnockitic orthogneiss, leucocrate to intermediate (tonalite to diorite), locally banded and foliated with enclaves of granoblastic metagabbro, pyroxene bearing amphibolite and magnetite bearing quartzite	Tsaratanana	O42, P42, Q42
Orthogneiss undifferentiated	Tonalitic orthogneiss with biotite, hornblende, locally charnockitic (tonalite to diorite), leucocrate; with lenses of amphibolites and pyroxenite, and BIF	Tsaratanana	O41, P41, P42, Q41, Q42
Paragneiss	Epibolitic gneiss with biotite (± sillimanite ± graphite) with lens of quartzite and amphibolite	Ambatondrazaka	S44, S45
Paragneiss	Paragneiss with biotite ± hornblende and quartz-feldspar bearing paragneiss with lenses of quartzites, graphitic rocks ± sillimanite ± garnet, sometimes calc-silicate rocks and marble	Ambatondrazaka	S44, R44, S45, R45, S46
Paragneiss	Migmatitic paragneiss and metasediments, undifferentiated.	Ambatondrazaka	R45, R46
Paragneiss	Gneiss with biotite and/or amphibole and amphibolite, locally migmatitic, unit magnetite bearing quartzite	Tsaratanana	P41, Q41, Q42
Paragneiss	Calcic gneiss with diopside-actinolite-epidote ± hornblende, garnet and gneiss with biotite-epidote ± amphibole	Tsaratanana	O41, P41, O42, Q41
Paragneiss	Metapelite and stromatic paragneiss with two micas, with thin unit of quartzite (± sillimanite)	Tsaratanana	O41
Paragneiss	Metapelites, stromatic paragneiss and with thin unit of quartzite (± sillimanite), with abundant layers of alkali granite and biotite-sillimanite-grenat bearing gneiss	Tsaratanana	O42
Paragneiss	Feldspar paragneiss with biotite	Tsaratanana	Q41
Paragneiss	Migmatitic paragneiss with biotite ± hornblende, clinopyroxene and schistose paragneiss with biotite ± sillimanite, garnet, cordierite, graphite	Tsaratanana	O41, P41, O42, P42, Q42
Paragneiss	Quartz-feldspar paragneiss (leptynite)	Tsaratanana	P41, O42
Paragneiss	Quartz-feldspar paragneiss with biotite (leptynitic gneiss)	Tsaratanana	O41,

Appendix 1. continued

Simplified lithologic groupings used in this study	Corresponding geologic unit descriptions from PRGM map legends (translated from the original French)	Study area	Quadrangles
Paragneiss	Quartz-feldspar and aluminous paragneiss with biotite ± garnet, sillimanite, cordierite with unit of quartzite and graphite, amphibolites and amphibolo-pyroxenites	Tsaratanana	P42
Neogene to Quaternary deposits	Alluvial and lacustrine deposits, undifferentiated	Ambatondrazaka	S44, R44, S45, R45, S46, R46
Neogene to Quaternary deposits	Undifferentiated alluvium	Tsaratanana	O41, O42, P41, P42, Q41, Q42
Neogene to Quaternary deposits	Sand carapace	Tsaratanana	O41
Neogene to Quaternary deposits	Lateritic hardpan and caliche	Tsaratanana	O42, P42, Q41, Q42
Neogene to Quaternary deposits	Aluvial deposits of high terraces	Tsaratanana	O41, P41
Mesozoic deposits	Argillite, marl and carbonate	Tsaratanana	O41
Mesozoic deposits	Arkosic sandstone, volcanoclastic sandstone, with locally conglomerate and sandy clay	Tsaratanana	P41, O42, P42, Q41, Q42
Mesozoic deposits	Continental sandstone	Tsaratanana	O41, P41
Mesozoic deposits	Continental sandstone and conglomerates	Tsaratanana	O41, P41
Mesozoic deposits	Mixed continental sandstones, silts and carbonates	Tsaratanana	O41

Appendix 2. Data from GIS analysis relating lithologies to surface area, elevation and slope characterisitcs, and lavaka densities

Study area	Lithology	Slope °	area (km^2)	Number of lavakas	Density avakas/km^2)	Elevation minimum (m)	Elevation maximum (m)	Elevation range (m)	Elevation median (m)
Ambatondrazaka	Granite and granitic gneiss	5	243	229	0.9	766	1368	602	959
Ambatondrazaka	Granite and granitic gneiss	10	361	551	1.5	771	1374	603	987
Ambatondrazaka	Granite and granitic gneiss	15	217	528	2.4	774	1391	617	1004
Ambatondrazaka	Granite and granitic gneiss	20	79	281	3.6	787	1392	605	1038
Ambatondrazaka	Granite and granitic gneiss	25	23	104	4.6	793	1391	598	1075
Ambatondrazaka	Granite and granitic gneiss	30	5.2	3	0.6	838	1385	547	1113
Ambatondrazaka	Granite and granitic gneiss	35	0.8	0	0.0	884	1349	465	1153
Ambatondrazaka	Granite and granitic gneiss	40	0.1	0	0.0	1119	1257	138	1166
Ambatondrazaka	Alkali granite and syenitic gneiss	5	41	376	9.2	756	1290	534	923
Ambatondrazaka	Alkali granite and syenitic gneiss	10	72	958	13.4	759	1292	533	949
Ambatondrazaka	Alkali granite and syenitic gneiss	15	54	925	17.2	763	1291	528	961
Ambatondrazaka	Alkali granite and syenitic gneiss	20	19	347	18.0	790	1273	483	980
Ambatondrazaka	Alkali granite and syenitic gneiss	25	4.5	73	16.0	806	1292	486	1015
Ambatondrazaka	Alkali granite and syenitic gneiss	30	1.3	22	16.5	861	1216	355	998
Ambatondrazaka	Alkali granite and syenitic gneiss	35	0.3	3	11.2	896	1189	293	955
Ambatondrazaka	Granodioritic and tonalitic rocks	5	109	212	1.9	896	1281	385	1033
Ambatondrazaka	Granodioritic and tonalitic rocks	10	183	560	3.1	899	1331	432	1040
Ambatondrazaka	Granodioritic and tonalitic rocks	15	128	502	3.9	904	1343	439	1044
Ambatondrazaka	Granodioritic and tonalitic rocks	20	45	247	5.5	911	1323	412	1061
Ambatondrazaka	Granodioritic and tonalitic rocks	25	5.8	17	2.9	922	1318	396	1118
Ambatondrazaka	Granodioritic and tonalitic rocks	30	0.3	0	0.0	996	1295	299	1181
Ambatondrazaka	Granodioritic and tonalitic rocks	35	0.02	0	0.0	1223	1241	18	1223
Ambatondrazaka	Mafic and ultramafic rocks	5	63	362	5.7	759	1286	527	966
Ambatondrazaka	Mafic and ultramafic rocks	10	40	537	13.3	776	1312	536	1016
Ambatondrazaka	Mafic and ultramafic rocks	15	67	690	10.4	777	1289	512	1027
Ambatondrazaka	Mafic and ultramafic rocks	20	80	679	8.5	767	1273	506	1037
Ambatondrazaka	Mafic and ultramafic rocks	25	4.3	24	5.6	799	1314	515	1050
Ambatondrazaka	Mafic and ultramafic rocks	30	0.7	2	2.9	946	1237	291	1095
Ambatondrazaka	Charnockite	5	15	5	0.3	783	1109	326	947
Ambatondrazaka	Charnockite	10	18	13	0.7	781	1178	397	941
Ambatondrazaka	Charnockite	15	9	11	1.2	788	1153	365	948
Ambatondrazaka	Charnockite	20	2	3	1.4	810	1161	351	959
Ambatondrazaka	Charnockite	25	0.5	0	0.0	820	1147	327	996
Ambatondrazaka	Charnockite	30	0.1	0	0.0	1007	1132	125	1083
Ambatondrazaka	Charnockite	35	0.01	0	0.0	1084	1142	58	1084
Ambatondrazaka	Orthogneiss undifferentiated	5	385	970	2.5	755	1332	577	925
Ambatondrazaka	Orthogneiss undifferentiated	10	544	2407	4.4	756	1420	664	951
Ambatondrazaka	Orthogneiss undifferentiated	15	300	1604	5.4	758	1399	641	959
Ambatondrazaka	Orthogneiss undifferentiated	20	85	595	7.0	769	1397	628	979
Ambatondrazaka	Orthogneiss undifferentiated	25	16	147	9.2	785	1359	574	1042
Ambatondrazaka	Orthogneiss undifferentiated	30	1.7	21	12.5	807	1343	536	1058
Ambatondrazaka	Orthogneiss undifferentiated	35	0.1	2	20.1	947	1208	261	1033
Ambatondrazaka	Orthogneiss undifferentiated	40	0.01	0	0.0	992	992	0	992
Ambatondrazaka	Paragneiss	5	199	951	4.8	757	1327	570	929
Ambatondrazaka	Paragneiss	10	315	2472	7.9	756	1379	623	997
Ambatondrazaka	Paragneiss	15	244	2048	8.4	758	1396	638	1049
Ambatondrazaka	Paragneiss	20	96	1043	10.9	770	1406	636	1071
Ambatondrazaka	Paragneiss	25	21	281	13.2	779	1404	625	1076
Ambatondrazaka	Paragneiss	30	4.2	75	18.0	833	1383	550	1066
Ambatondrazaka	Paragneiss	35	0.8	6	7.6	929	1273	344	1115
Ambatondrazaka	Paragneiss	40	0.1	0	0.0	1005	1264	259	1214
Ambatondrazaka	Neogene to Quaternary deposits	5	1039	189	0.2	758	1124	366	909
Ambatondrazaka	Neogene to Quaternary deposits	10	372	277	0.7	757	1133	376	919
Ambatondrazaka	Neogene to Quaternary deposits	15	115	161	1.4	772	1134	362	929
Ambatondrazaka	Neogene to Quaternary deposits	20	18	51	2.8	782	1141	359	943
Ambatondrazaka	Neogene to Quaternary deposits	25	1.3	3	2.3	803	1077	274	973
Ambatondrazaka	Neogene to Quaternary deposits	30	0.1	0	0.0	984	1046	62	1014
Tsaratanana	Granite and granitic gneiss	5	596	2244	3.8	52	1318	1266	264
Tsaratanana	Granite and granitic gneiss	10	430	3129	7.3	59	1315	1256	596
Tsaratanana	Granite and granitic gneiss	15	190	1906	10.0	107	1299	1192	657
Tsaratanana	Granite and granitic gneiss	20	92	797	8.6	135	1278	1143	661
Tsaratanana	Granite and granitic gneiss	25	38	330	8.6	149	1227	1078	679
Tsaratanana	Granite and granitic gneiss	30	15	57	3.8	159	1175	1016	702
Tsaratanana	Granite and granitic gneiss	35	4.9	22	4.5	259	1135	876	708
Tsaratanana	Granite and granitic gneiss	40	1.5	2	1.4	458	1112	654	695

Appendix 2. continued

Study area	Lithology	Slope °	area (km^2)	Number of lavakas	Density avakas/km^2)	Elevation minimum (m)	Elevation maximum (m)	Elevation range (m)	Elevation median (m)
Tsaratanana	Alkali granite and syenitic gneiss	5	122	241	2.0	193	1311	1118	363
Tsaratanana	Alkali granite and syenitic gneiss	10	121	551	4.5	215	1307	1092	678
Tsaratanana	Alkali granite and syenitic gneiss	15	106	600	5.7	279	1307	1028	730
Tsaratanana	Alkali granite and syenitic gneiss	20	80	403	5.0	286	1305	1019	735
Tsaratanana	Alkali granite and syenitic gneiss	25	41	195	4.8	328	1295	967	767
Tsaratanana	Alkali granite and syenitic gneiss	30	16	60	3.8	404	1249	845	815
Tsaratanana	Alkali granite and syenitic gneiss	35	5.0	17	3.3	488	1203	715	848
Tsaratanana	Alkali granite and syenitic gneiss	40	2.0	2	1.1	468	1154	686	837
Tsaratanana	Granodioritic and tonalitic rocks	5	39	159	4.1	113	990	877	422
Tsaratanana	Granodioritic and tonalitic rocks	10	35	238	6.7	125	987	862	636
Tsaratanana	Granodioritic and tonalitic rocks	15	19	130	6.9	186	997	811	668
Tsaratanana	Granodioritic and tonalitic rocks	20	9	53	5.8	220	983	763	662
Tsaratanana	Granodioritic and tonalitic rocks	25	3	32	10.3	241	952	711	692
Tsaratanana	Granodioritic and tonalitic rocks	30	1	3	5.1	470	903	433	738
Tsaratanana	Granodioritic and tonalitic rocks	35	0.3	0	0.0	502	808	306	728
Tsaratanana	Granodioritic and tonalitic rocks	40	0.02	1	40.3	740	748	8	740
Tsaratanana	Mafic and ultramafic rocks	5	648	3386	5.2	188	1359	1171	744
Tsaratanana	Mafic and ultramafic rocks	10	689	4801	7.0	198	1356	1158	828
Tsaratanana	Mafic and ultramafic rocks	15	361	2110	5.8	203	1349	1146	798
Tsaratanana	Mafic and ultramafic rocks	20	169	757	4.5	228	1339	1111	767
Tsaratanana	Mafic and ultramafic rocks	25	60	181	3.0	257	1292	1035	832
Tsaratanana	Mafic and ultramafic rocks	30	17	34	2.0	302	1284	982	875
Tsaratanana	Mafic and ultramafic rocks	35	4.8	5	1.0	532	1225	693	890
Tsaratanana	Mafic and ultramafic rocks	40	1.0	0	0.0	699	1206	507	865
Tsaratanana	Orthogneiss undifferentiated	5	588	2063	3.5	64	1293	1229	336
Tsaratanana	Orthogneiss undifferentiated	10	414	2870	6.9	87	1293	1206	477
Tsaratanana	Orthogneiss undifferentiated	15	231	1756	7.6	108	1286	1178	642
Tsaratanana	Orthogneiss undifferentiated	20	111	546	4.9	122	1246	1124	659
Tsaratanana	Orthogneiss undifferentiated	25	47	149	3.2	229	1234	1005	701
Tsaratanana	Orthogneiss undifferentiated	30	17	24	1.4	256	1188	932	741
Tsaratanana	Orthogneiss undifferentiated	35	4.5	7	1.6	413	1017	604	773
Tsaratanana	Orthogneiss undifferentiated	40	1.8	0	0.0	502	1012	510	768
Tsaratanana	Paragneiss	5	597	2340	3.9	63	1361	1298	346
Tsaratanana	Paragneiss	10	527	3612	6.9	69	1358	1289	588
Tsaratanana	Paragneiss	15	308	2684	8.7	112	1352	1240	704
Tsaratanana	Paragneiss	20	154	1215	7.8	145	1317	1172	749
Tsaratanana	Paragneiss	25	60	338	5.6	179	1294	1115	816
Tsaratanana	Paragneiss	30	20	61	3.1	246	1285	1039	878
Tsaratanana	Paragneiss	35	4.8	22	4.6	428	1237	809	887
Tsaratanana	Paragneiss	40	0.9	0	0.0	596	1217	621	836
Tsaratanana	Mesozoic deposits	5	540	976	1.8	28	1359	1331	84
Tsaratanana	Mesozoic deposits	10	203	915	4.5	41	1357	1316	1181
Tsaratanana	Mesozoic deposits	15	47	295	6.3	68	1354	1286	1185
Tsaratanana	Mesozoic deposits	20	10	101	10.2	708	1306	598	965
Tsaratanana	Mesozoic deposits	25	4.0	22	5.3	699	1274	575	907
Tsaratanana	Mesozoic deposits	30	1.5	6	3.9	708	1252	544	899
Tsaratanana	Mesozoic deposits	35	0.5	1	2.2	758	1176	418	877
Tsaratanana	Mesozoic deposits	40	0.3	0	0.0	769	1053	284	886
Tsaratanana	Cenozoic deposits	5	546	1053	1.9	23	1363	1340	306
Tsaratanana	Cenozoic deposits	10	112	673	6.0	33	1362	1329	1244
Tsaratanana	Cenozoic deposits	15	25	225	9.0	120	1364	1244	1239
Tsaratanana	Cenozoic deposits	20	2.8	10	3.5	133	1292	1159	857
Tsaratanana	Cenozoic deposits	25	0.8	5	6.2	383	1277	894	596
Tsaratanana	Cenozoic deposits	30	0.1	0	0.0	579	1218	639	862