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Neotectonics and pastoralism: how they impact flood regimes in Madagascar's Highlands

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26 sequestration through integrated watershed management rather than on hard-defence
27 engineering against overflowing rivers on the plains, which has been the costly but ineffectual
28 approach since the 17th century.

29
30 Key words: neotectonics; chronostratigraphy; flooding; urban sprawl; integrated watershed
31 policy; rangeland management

32

33 **1. Introduction**

34 Strategies and institutions of governance and development interact with the conditions and
35 process regimes set by geology, hydrology, ecology, geomorphology and climate. In addition
36 to being products of the contingent biophysical processes that shape the Earth, landscapes are
37 thus also the product of power relations and other disparities. As a discipline, geography has
38 long embraced the unity of social science and physical landscape change in the service of
39 social and environmental transformation, but the recently branded concept of ‘critical physical
40 geography’ (Lave et al., 2014) also reminds us that there is an underlying political economy
41 of processes such as soil erosion, land-cover change, natural hazards, and disaster mitigation
42 strategies. Studies of the total environment thus gain from perspectives which combine expert
43 knowledge of biophysical science and technology with critical attention to political ecology,
44 i.e. to relations of social power in which some voices get silenced while others get amplified.
45 These many variables are often difficult to untwine, but for environmental policymaking
46 purposes it is essential that they be unpacked and diffracted in ways that help to convey a just
47 and lucid portrayal of the total environment.

48 The creation of sustainable, safe, and socially just operating spaces for socio-ecological
49 systems is commonly a goal intended to achieve wellbeing for all while simultaneously
50 ensuring that the underpinning biophysical processes and environmental services are
51 exploited within scientifically informed boundaries of sustainability (Dearing et al., 2014;

52 Hossain et al., 2017). The concept of ecologically safe and socially just spaces has been
53 addressed at global level in generic terms through the ‘planetary boundaries’ concept (e.g.
54 Rockström et al., 2009), but less so at regional levels such as watersheds, wetlands, and other
55 coherent natural units where the dissemination of policymaking based on an integrated
56 understanding of complex interactions really matters to communities.

57 Floodplains, for example, which may contain permanent wetlands and temporary lakes, are
58 valued for their biological productivity, and for the ecosystem services and other natural
59 resources they provide, but they are also coveted for agriculture. In the midst of a
60 mountainous island-continent and one of the poorest countries in the world, the upland
61 intermontane basins of Madagascar’s Highlands have historically been developed and
62 managed for the purpose either of rice monoculture or more diversified cropping systems
63 (Abé, 1984). The Highlands, or Hautes Terres, which in Madagascar refer to the elevated
64 backbone of weathered Precambrian basement, concentrate 45% of the nation’s population of
65 ~25 M (in 2016). This core zone of the island’s interior (~130,000 km², i.e. 22% of the island;
66 elevation range: 800–2800 m; mean annual rainfall: 1200–1500 mm) features population
67 density clusters of > 250/km² in and around the intermontane basins. Such has been the case
68 consistently for at least ~100 years (de Martonne, 1911; Gourou, 1967). Following a sharp
69 rise since the late 1990s, the population of the capital city’s metropolitan area, Antananarivo,
70 reached 3 M in 2015 and is now recording an annual growth rate of 4.6% (Attoumani et al.,
71 2019; Defrise, 2020). The Highlands are physically and culturally separate from the wide
72 band of sedimentary scarplands forming the west of the island (Fig. 1), which corresponds to
73 an area of dry forest, scrub and pseudo-steppe dominated by extensive pastoralism. It is, by
74 comparison, very thinly populated (< 25/km², and often < 4/km²).

75 The interior basins of the Highlands are primarily natural wetlands (typically fens: Mietton
76 et al., 2018), and as such have been attractive for their level topography and their potential for

77 paddy cultivation. Wetlands, however, are transient features at geological time scales and
78 their life span can be substantially shortened by human action in the catchment — either by
79 changing the hydrological balance (e.g. excessive water abstraction by an irrigation scheme,
80 or excessive outlet release) or by sediment overfilling the basin’s accommodation space (e.g.
81 as a result of excessive soil erosion in the surrounding catchments). At shorter time scales of
82 years to centuries, the persistence of sufficient accommodation space to avoid lake or wetland
83 extinction depends on a fine balance depending on how processes governing the lithosphere,
84 biosphere, atmosphere and hydrosphere intersect with the anthroposphere (Lisenby et al.,
85 2019). Wetland persistence is typically a function of geometrical constraints (initial relief,
86 length of the river, hypsometry of the catchment), lithological parameters (rock erodibility),
87 climate (precipitation and evaporation rates), and — often neglected or harder to quantify —
88 the relatively slow (and thus imperceptible over years and centuries) rate of tectonic
89 subsidence and crustal deformation (i.e. uplift rate, duration, and its spatial distribution; see
90 Graphical abstract). Modelling of tectonics-controlled inland lakes shows that once uplift
91 declines and/or lake or wetland capture is achieved by headward drainage recession, the
92 upland wetlands risk getting reintegrated into the drainage network and drying up (Garcia-
93 Castellanos, 2006).

94 Lisenby et al. (2019) have emphasized that existing wetland characterisation tools tend to
95 neglect geomorphology, so that managers or development agencies who rely on them may
96 build up an incomplete set of expectations regarding the characteristic processes, forms and
97 timescales of wetland and floodplains dynamics. This may be particularly problematic where
98 this dynamism occurs on management-relevant timescales of years to decades because
99 incorporation of geomorphological perspectives into management planning and practice can
100 improve understanding of the relative importance of natural and anthropogenic drivers of
101 wetland change, and thus help to decide when, and when not, to intervene.

102 Among the rice-growing areas of Madagascar, the central Highlands are the region where
103 the rainfall conditions are seasonally best adapted to rice growth despite constraints relating to
104 low winter temperatures (Le Bourdieu, 1974). Annual rainfall totals range between 1000 and
105 1500 mm and occur during the warmer season (November to April). This is also, however, the
106 most mountainous and topographically fragmented part of the island, so that the optimal areas
107 for high-yield paddy cultivation are restricted to the flat-floored intermontane basins — often of
108 limited size (Bied-Charreton et al., 1981). Importantly, most of these upland plains result
109 from impeded drainage controlled by some form of bedrock constriction at the exit point,
110 either because of tectonic faulting, of a lava dam, or a combination of both — which to
111 varying degrees has promoted water ponding and sediment aggradation. The
112 geomorphological behaviour of these outlets is what promotes the alluvial aggradation and
113 poor drainage potentially advantageous to human settlement and paddy cultivation, but only
114 on condition that the intensity of these processes can be maintained within a certain critical
115 bandwidth of variability. The wetland base levels and hydrological regimes are thus subtly
116 controlled by tectonic faults, by basement rocks with differing sensitivities to differential
117 erosion, and by the varying intensities of topographic incision by rivers (Raunet, 1980).

118 Although the tectonic and fluvial regimes in Madagascar are difficult to measure or
119 monitor directly, a chronostratigraphy of the sediment retained in the wetland basin should
120 provide a proxy of how long this regime has been sustained, and at what rate. The
121 waterlogged wetlands contain clay-rich sediment and weakly decomposed (and thus
122 radiocarbon-datable) organic matter such as peat. Insights obtained from sediment coring and
123 trenching can thus provide long-term baseline information for underpinning an integrated,
124 basin-scale management strategy of the total environment that avoids short-sighted, sectorial
125 measures such as unplanned urbanisation (Dabat et al., 2004; Aubry et al., 2012; Defrise,
126 2020), short-sighted hydraulic engineering, and detrimental land-use policies.

127 By comparing different Highland basins with somewhat different characteristics, in this
128 study mainly focused on the Antananarivo Plain we show how tectonic, hydrological,
129 sedimentological and palaeoenvironmental variables have played out over the last several
130 thousand years prior to human settlement, and how engineering and human agency in the last
131 ~100 years have been interfering — and could interfere critically in the future — with the
132 baseline trends. We thus gauge and analyse the boundaries to sustainability of these key rice-
133 growing basins (Fig. 1) which, as the new evidence suggests, hinge on a finely balanced long-
134 term equilibrium between tectonic regime, sedimentation rate, and cumulatively evolved
135 socio-ecological practices which control soil erosion in the wider tributary catchments and
136 their nested sub-catchments.

137 This kind of multidisciplinary and integrated approach to watershed management, articulating
138 the biophysical and the social sciences while including a long-term historical dimension,
139 reframes the technocratic approach to river flood-hazard modelling which, by focusing
140 unilaterally on simplified channel hydraulics and on the short-term prospect of constructing
141 hard defences at locations where the flooding occurs (often calibrated on limited hydrological
142 time series datasets), inflates the playbook that large engineering corporations have been
143 writing for the last ~200 years while missing two key points: these sectorial risk-reduction
144 planning approaches (i) expediently ignore the important dimension of political ecology, and
145 (ii) historically have often failed to meet the targets of their own forecasts (both aspects
146 comprehensively critiqued in McCully, 2001).

147 As an alternative perspective, the holistic approach explored in this study paves the way
148 towards a form of systemic thinking among environmental managers that also allows room
149 for participatory methods rather than the conventional, top-down technocratic solutions.
150 Holistic thinking along these lines has gained some traction through the relatively recent
151 ‘ecosystem services’ paradigm, with perhaps the most famous operationally successful

152 example being the conservation of urban water quality in the Catskills/Delaware watershed
153 for the benefit of the city of New York based on a ‘payment for ecosystem services’ (PES)
154 scheme. The scheme grew out of public consultation and was guided by the motto “we all live
155 downstream”, including stakeholders who actually reside and operate in the catchment
156 headwaters (see “How to put a watershed to work”, in Daily and Ellison, 2002).
157 Such ‘success stories’, however, still today remain rare almost anywhere, and in an
158 economically poor country like Madagascar these approaches are in their infancy at least
159 partly because agencies involved in environment and land issues tend to promote sectorial
160 rather than integrated solutions. This study thus puts Madagascar and its state capital on the
161 global map of research into integrated watershed management — in the present case showing
162 how curiosity-driven research on tectonics and past environments ties in with policy-driven
163 research. Furthermore, whereas conventional flood-mitigation policies in most biomes
164 typically advocate planting trees as a natural means of promoting water infiltration over
165 runoff (this can range from state-controlled, single-species protection forest, to more
166 participatory forms of agroforestry: e.g. Aryal et al., 2019), we emphasise instead the
167 importance of bespoke, place-based solutions through a holistic consideration of
168 geomorphological, hydrological, ecological, but also cultural components of Madagascar’s
169 environment. In the case of Madagascar’s central Highlands, where the natural vegetation is
170 overwhelmingly not forest but grassland savanna or pseudo-steppe (see Graphical abstract),
171 afforestation is actually neither a natural solution nor a culturally accepted one. Instead, we
172 consider the importance of pastoralism, forage, and fire in these landscapes where the
173 economic, cultural, and environmental footprint of pastoralists and their livestock is
174 substantial, but where these socially marginal stakeholders are recurrently ignored by rural
175 development programmes, which focus on farming and forestry.

176 The rationale and successive steps of the methodology are summarised by a flow diagram
177 presented in Figure 2.

178

179 **2. The Antananarivo Plain: its key features**

180 **2.1. Hydrology**

181 The Antananarivo plain (~162 km², 1247–1255 m a.s.l.) lies in the upper Ikopa River basin
182 (catchment area above the Farahantsana channel knickpoint: 4466 km²; Fig. 3). The
183 intermontane basin operates as the local base level for a number of left- (Sisaony,
184 Andromba/Katsoaka) and right-bank tributaries (Mamba, Maniandro), all of which converge
185 on the plain. Stream convergence is frustrated by the fact that the Ikopa River has been
186 continuously or partially constricted by artificial levees over a distance of 45 km, as far as
187 Bevomanga. The Sisaony River in the early 20th century used to join the Ikopa at Anosizato
188 (Fig. 2; Isnard, 1955). The Ikopa channel gradient is very gentle (~0.00025), and decreases to
189 0.00013 just before the junction with the Andromba River. From the Bevomanga ‘narrows’ to
190 the Farahantsana knickpoint (Fig. 4), the Ikopa flows in a bedrock channel. The river then
191 plunges 50 m down a gorge displaying a succession of rapids and waterfalls, and eventually
192 joins the Betsiboka and the Mozambique Channel.

193 Only part of the interior wetland has been converted to farmland. Reclamation of what was
194 initially a periodically flooded mosaic of scrub and marshland began in the 17th century under
195 the authority of the Merina monarchs (at first under King Ralombo, 1575–1610; but mostly
196 under King Andrianampoinimerina’s reign: 1785–1810; see Abé, 1984), ostensibly at a time
197 of enhanced rainfall (1500–1850 CE) compared to the preceding 500 years — but nonetheless
198 containing a nested sequence of multi-decadal rainfall fluctuations documented within that
199 time span (Scroxtton et al., 2017). These early efforts, aided by copious availability of slave
200 labour (Raison, 1986; Larson, 2000; Campbell, 2005), focused on the right bank of the

201 Ikopa River, where the Ankadimbahoaka levee, or ‘embankment of the people’, was
202 constructed. The plain, progressively criss-crossed by 200 km of canals (often multipurpose:
203 for drainage, irrigation and navigation), was given the name Betsimitatatra, meaning ‘that
204 which no longer needs reclamation’ (for a detailed historical geography, see Isnard, 1955;
205 Raison, 1972; Douessin, 1974). The Farahantsana bedrock sill partially closes off the basin
206 and causes in-channel bedload deposition upstream. As a result, the channel bed has risen
207 between its levees to elevations greater than the surrounding plain, thus causing frequent
208 levee breaching, crop inundation, and flooding of the capital city’s low-lying sprawl. Raising
209 the levees incrementally has simply perpetuated the flood hazard issue in a self-reinforcing
210 feedback loop.

211 With new technology — particularly explosives in addition to manpower — the colonial
212 authorities introduced two additional measures.

213 (i) In order to reduce the perennial risk of flooding, the Ikopa underwent channel deepening
214 aimed at hastening floodwater evacuation, limiting water pressure against the levees, and
215 with benefits also expected for the vulnerable residential areas of Antananarivo. The first
216 blasts along this 5-km-long reach were carried out around Farahantsana in 1914, then in
217 1938 and 1940 — deepening the channel by 1.6 to 3 m over a width of 80 m, thereby also
218 steepening the channel gradient (Ciolina, 1946; Isnard, 1955). An estimated 430,000 m³ of
219 rock were removed, among which 170,000 m³ of bedrock. A wave of headward erosion
220 soon ensued, clearing the channel of its sediment, exposing the bedrock in new reaches,
221 and thus effectively extending the knickzone upstream to Bevomanga. An accompanying
222 measure was to build a needle dam further upstream (Tanjombato Dam) as a means of
223 raising the hydraulic head by ~1.4 m to irrigate some of the higher land traditionally
224 devoted to second-season cropping.

225 (ii) The second major undertaking was the construction of the Mantasoa (1938) and
226 Tsiacompaniry (1956) dams (125 and 260 M m³ design capacities, respectively), designed
227 for hydroelectricity and both flooding a network of valleys in the remote headwaters of
228 the Ikopa catchment near the island's continental drainage divide (Fig. 3). The expectation
229 was that these reservoirs would also retain excess water during the rainy season and
230 reduce the flood hazard, as well as ensure low-flow augmentation (by 5–12 m³/s) for
231 securing dry-season irrigation.

232 The frequent flooding today in Antananarivo strongly suggests that the engineering works
233 of the past century were of limited avail. Catastrophic flood damages reported for Jan.–Feb.
234 1917 (Chaperon et al., 1993) recurred in Feb. 1932 (peak flow measured at Bevomanga
235 gauging station: 600 m³/s), March 1941, Jan. 1954, and March 1959. Benchmark records from
236 1948–49 to 1976–77 at Bevomanga document annual peak discharges consistently in excess
237 of 250 m³/s on the Ikopa River, with a record maximum of 642 m³/s measured on March 31st,
238 1959, and an estimated 1750 m³/s at Farahantsana (Anonymous, 1965). As with most
239 regulated rivers, artificial levees are merely a relative solution to flood-hazard mitigation
240 because they force in-channel sediment load deposition, thus raising the channel bed and
241 waterline. This promotes levee breaching and channel overspill. Accidental overspills present
242 the advantage of reducing instantaneous maximum discharge at locations situated
243 downstream, and this is confirmed for the Ikopa River: it records greater peak discharge
244 maxima where it enters the plain at Antelomita (upstream of Antananarivo: e.g. 710 m³/s on
245 March 31st 1959) than near its exit at Bevomanga. Neither of the two headwater reservoirs
246 have thus proved effective at curbing flood peaks on the Ikopa.

247 The hydrological hazard is exacerbated by cyclones making landfall on central
248 Madagascar, particularly when these occur towards the end of the rainy season on swollen
249 water tables and saturated lowland soils. As a result of the flooding, rice yields in the

250 Antananarivo plain can fluctuate by up to 50% from one year to the next (Dabat et al., 2004),
251 thus increasing dependency on imports. Flood hazards are also exacerbated by Antananarivo's
252 urban sprawl across the surrounding flood-susceptible paddy fields (Aubry et al., 2012;
253 Ciampalini et al., 2019). During the colonial period, 22 ha of marshland were reclaimed and
254 landfilled to develop the new district of Analakely and open the (now renamed) Avenue de
255 l'Indépendance, inaugurated in 1935. Both now lie at the heart of the city (Fig. 5). During that
256 same period, and despite being 'protected' by river levees, expanding slums on the west side
257 (mostly established on shoddily and illegally reclaimed wet-rice cropland) soon became
258 insalubrious and exposed to flooding because of a backwater effect caused by excessive in-
259 channel sediment aggradation around Bevomanga. The entailing rise in water levels upstream
260 of Bevomanga also exacerbates lateral pressure on the Ikopa levees (similar effects occur
261 simultaneously on the Sisaony and Andromba rivers), and thus the frequency of breaching
262 and floodplain spills occur even before the peak flood wave on the Ikopa enters the plain.
263 Today, floodwater evacuation is impeded by the unfettered increase in paved surfaces and
264 chronic obstruction of the low-gradient stormwater drainage systems by urban detritus and by
265 the insufficient hydraulic head between the urban drainage and the Ikopa River base level.

266

267 **2.2. Geological setting**

268 *2.2.1. Lithology*

269 The Antananarivo Basin lies at a structural node in the Precambrian fabric of the
270 basement known as the Antananarivo virgation zone (Nédélec et al., 1994), a twist in the
271 Panafrican orogen where the strike of the stratoid granites changes from N–S to E–W.

272 Most of the Ikopa catchment area consists of migmatites and gneiss, with a few
273 outcrops of plutonic granite (Carion Massif, Behenjy Massif), stratoid granite (Nédélec et al.,
274 2000), and minor charnockite (Fig. 6). The highest summits of Antananarivo's urban

275 topography coincide with ridges reinforced by quartzite beds, outcrops of which also strike
276 across the Farahantsana bedrock sill. The basement south of the Antananarivo Basin is
277 covered by the volcanic rocks of the large Ankaratra volcano and various satellite intrusions.
278 Ankaratrite flows (nepheline basanite) 20 km to the SW of Antananarivo (e.g. Delubac et al.,
279 1963) were generated by the small Vontovorona volcano (Fig. 6). The sediment fill of the
280 basin itself remained relatively undocumented until recent excavations in the context of urban
281 construction projects. The material is largely of an alluvial nature and described in this study.

282

283 *2.2.2. Evidence of neotectonics*

284 Despite the great antiquity of the basement rocks and the deceptive assumption of stability
285 often associated with Precambrian shield regions, the topography of central Madagascar is
286 extremely youthful. The main cause of base-level change was late Cenozoic (Neogene) crustal
287 uplift, mostly as a result of sub-lithospheric mantle convection beneath Madagascar causing
288 crustal buoyancy, regional-scale updoming, and intraplate volcanism. Supporting evidence for
289 this has been provided by several lines of research. In addition to the well-established
290 succession of erosion surfaces in the Highlands (Bourgeat and Petit, 1969), which suggests
291 base levels falling in successive steps in response to regional uplift, fission-track data likewise
292 suggest that rapid regional uplift and denudation commenced within the last 20 Ma
293 (Stephenson, 2019). Delaunay (2018) and Roberts et al. (2012) used the distribution of
294 erosion surfaces and inverse modelling of river longitudinal profiles, respectively, to also
295 conclude that Madagascar had undergone wholesale regional uplift during the last 15 Ma. A
296 remarkable feature of most rivers in Madagascar is indeed that none display typical concave-
297 up equilibrium profiles. Instead, they exhibit distinct convex profiles interrupted by a large
298 number of knickzones and waterfalls typical of disequilibrium conditions driven by tectonic
299 activity (Fig. 4).

300 Additionally, the present-day elevation of the crust is anomalously high despite its lower-
301 than-normal thickness evidenced by gravity and seismic data (Rechenmann, 1981; Fournou,
302 1990; Rakotondraompiana, 1992). Independent tomographic and petrological evidence
303 confirms that the epeirogenic uplift of Madagascar can be accounted for by the existence of a
304 layer of anomalously hot asthenospheric mantle directly beneath a thin lithospheric plate
305 (Rindraharisaona et al., 2013; Andriampenomanana et al., 2017; Stephenson et al., 2019). The
306 upwelling asthenosphere provides the dynamic support needed for maintaining the elevated
307 topography.

308 Consistent with these broad-scale geological findings, seismicity is also an important
309 feature of central Madagascar, where 97% of the island's thousands of earthquakes occur
310 annually. No fewer than 3346 earthquakes with a magnitude greater than 3.0 were recorded
311 between 1975 and 2007, mostly associated with extensional faulting (Rindraharisaona and
312 Rambolamanana, 2008). The most active area lies beneath the late Neogene to modern
313 Ankaratra and Itasy volcanic edifices (Hariniony, 2018), barely 50 km SSW of Antananarivo
314 (Figs. 1, 3), where 658 events were recorded just between 2003 and 2016 and registered peak
315 magnitudes of M_L 6.1 (typically at shallow crustal depths of 15–30 km). Although some of
316 these could be related to subsurface magmatic activity, a much larger, nonvolcanic seismic
317 sub-region immediately to the north (so-called 'Famoizankova seismic region'), effectively
318 adjacent to, and west of, the Antananarivo study area, recorded 104 seismic events during that
319 same period, with an even higher peak event registering at M_L 6.4 (Hariniony, 2018). On
320 nonvolcanic rocks of the Highlands, surface expression of the recent and ongoing crustal
321 deformation has been inferred from gully erosion ('lavaka', from a word meaning 'hole':
322 spectacular gullies on hillsides, see Graphical abstract), showing that high-density lavaka
323 'hotspots' coincided spatially with foci of more intense seismicity (Helisoa, 1983; Cox et al.,

324 2010). The intensity of hillslope dynamics could thus be a response to, and thus used as a
325 proxy for, the magnitude of tectonic deformation.

326 Unlike the Alaotra Basin (Fig. 1), which geologically is an active tectonic graben (Mietton
327 et al., 2018), the Ikopa catchment and the Antananarivo Basin do not correspond to one of
328 these lavaka hotspots. The digitations of the Antananarivo Basin (Figs. 3, 6) primarily suggest
329 its origin as an etch basin, i.e. a lowland originally generated by differential weathering in
330 petrographically heterogeneous or diversely fractured basement outcrops (e.g. Lageat and
331 Gunnell, 2001) rather than by tectonics. The low hills and interfluves rising from the plain
332 correspond to the late Neogene erosion surface 'S3'. As elsewhere in the Highlands, (i) its
333 elevation (here ~1300 m) is controlled by a local, non-marine base level set by the bedrock
334 sill on the trunk river; and (ii) it has developed across lithologies highly susceptible to decay
335 under intense tropical weathering conditions, such as schist, gneiss and migmatite (Bourgeat
336 and Petit, 1969; Hoeblich and Hoeblich, 1983). Accordingly, the interfluves are blanketed by
337 ~30-m-deep Ferralsols.

338 Despite not displaying the first-order morphological features of a faulted graben, the
339 Antananarivo Basin nonetheless displays features suggesting neotectonic overprints. In
340 addition to a major E–W Precambrian shear zone cutting across the basin (e.g. Nédélec et al.,
341 2016), these include:

- 342 (i) a NE–SW fault which cross-cuts the Anjafy–Angavo anticline from north of the
343 Ankay to south of Antananarivo. This fault probably continues beneath the Ankaratra
344 volcanic cover and eventually intersects the Vavavato and Ibity faults farther west
345 (Fig. 1);
- 346 (ii) a NW–SE lineament guiding the drainage net, one of several in the wider region and
347 parallel to the major, elongated seismicity hotspot identified by Cox et al. (2010)
348 farther to the west, consistent with NE–SW fault-solution mechanisms inferred for the

349 Itasy, Ankaratra, and Famoizankova seismic subregions (Barimalala and
350 Rambolamanana, 2008);

351 (iii) a series of N20° to N30°E structures north of the Antananarivo Basin (around the
352 small town of Mahitsy), reported on the basis of microtectonic observations in a
353 quarry (Arthaud et al., 1990; Dussarrat, 1994) and also reported as locally offsetting
354 weathering profiles. This strike direction also has an important influence on the local
355 drainage network, and may bear some connection with a long E–W lineament mapped
356 by Rakotondraompiana (2001) and passing along the north edge of the Antananarivo
357 Basin.

358 (iv) Brenon (1952) speculated that the Ikopa plain had formed because of a tectonic block
359 rising across its path, and Bourgeat (1968) interpreted it as a downthrown block east
360 of the tentatively named N–S ‘Imerintsiatosika–Antambola line’ (Fig. 3) — perhaps a
361 tectonic lineament, despite the fact that the geology of this region west of the capital
362 city has never been mapped. Fournon (1990) likewise accredits the hypothesis of a
363 tectonic origin for the Antananarivo Basin.

364 Dussarrat (1994) tentatively estimated that the E–W faults were younger than the N–S set
365 because microtectonic striations generated by the N–S extension were cross-cut by striations
366 generated by the E–W extension. The E–W fault movements were most likely late Pleistocene
367 (i) because small vertical offsets were reported from the 25–10 ka alluvial deposits (Bourgeat,
368 1968; Bourgeat and Ratsimbazafy, 1975), and (ii) because those faults did not offset peat
369 layers of early Holocene age (9–2.6 ka) — the latter only estimated, however, by intuitive
370 correlation of the peat with an independently established period of climatic stability (e.g.
371 Burney, 1987) rather than by direct dating.

372 In summary, tectonic deformation in the Highlands of Madagascar is geologically recent,
373 and seismicity is low- to medium-intensity and ongoing. Crucially, the link between

374 sedimentation, hydrological regulation, land use, and tectonics becomes critical upstream of
375 where the Ikopa River exits the basin.

376

377 **3. Methods**

378 The sedimentary fill sequence of the Antananarivo Basin lacks natural sections, and
379 quarries in weathered profiles do not reach the bedrock. As a result, the stratigraphy beneath
380 the alluvial plain had until now never been investigated. The need to survey the subsurface
381 has nonetheless grown from increasing demand for high-rise urban construction and as part of
382 hydrogeological exploration for supplying the city with water. In clay-rich sequences,
383 electrical surveys are less efficient than electromagnetic surveys for detecting depths to the
384 bedrock floor because of backscatter effects. Mechanical trenches and boreholes remain the
385 best source of information. Recent drilling operations have cored mostly through clay and
386 sand-rich layers (rarely loam), but significantly also through a number of peat levels.

387 Here we collected, compiled and correlated unpublished data from recent civil engineering
388 studies, and from reports by geologists: 3 construction-drill auger cores < 10 m deep (BRL
389 Ingéniérie, 2018), 1 test pit reported by Bourgeat and Ratsimbazafy (1975), and 14 boreholes
390 up to 30 m deep (sources: Colas; Laboratoire National des Travaux Publics et du Bâtiment;
391 Laplaine, 1957; Rakoto et al., 2017). The goals were to estimate the thickness of the sediment
392 fill in the Antananarivo Basin, characterise its stratigraphy, constrain its depositional age, and
393 infer time-averaged sedimentation rates upstream of the Farahantsana bedrock sill. The
394 accuracy of results and interpretations hinged on precise altitudinal correlation of marker
395 levels between the different boreholes, but the engineering reports and borehole logs each
396 provided a highly accurate datum allowing precise spatial interpolation between the data
397 points. Interpolation accuracy was further controlled and calibrated from 1:50,000
398 topographic maps, Google Earth spot heights, and handheld GPS measurements in the field,

399 all in good agreement to within 5%. Inspection of sample textures from different core depths
400 also allowed possible confusion between alluvium and in situ weathered rock, and between
401 topsoil and surface landfill, to be lifted or to benefit from altitude corrections.

402 Peat levels were radiocarbon-dated at two sites, F5 and F6, where excavations during the
403 course of this study could be directly monitored. Radiocarbon age results by Bourgeat and
404 Ratsimbazafy (1975) were also included. The four dated peat samples of excavation site F5
405 (at depths of -1.80 m, -3 m, -11.60 m, -13.50 m) were also subjected to pollen analysis in
406 order to characterise the vegetation prevalent at the time of peat deposition, infer the
407 palaeoenvironmental conditions, and compare the data with published evidence from other
408 wetlands in Madagascar's Highlands. Pollen samples of 4 g each were collected, prepared
409 following standard chemical treatment (Moore et al., 1991), and each involved a minimum of
410 300 grain counts. Using a Zeiss microscope at $\times 400$ magnification, pollen taxa were identified
411 from photographic atlases for Madagascar and tropical Africa (Straka, 1991; Schüler and
412 Hemp, 2016; Rasoloarijao et al., 2019).

413 Mineral characterisation in samples was used to determine sediment provenance, and
414 thus potentially tephra and glass shards from volcanic sources. Mineral extraction was
415 obtained by standard magnetic and density separation methods (Blockley et al., 2005).

416 In order to test the hypothesis of recent or ongoing basin subsidence, and of possible uplift
417 occurring in the vicinity of the basin's bedrock outlet in the west, a continuous series of
418 seismicity records was acquired from the Institut et Observatoire de Géophysique Appliquée
419 (IOGA) at Antananarivo University. Several thousand seismic events were recorded between
420 July 1988 and October 2017 with their date, time, epicentre latitude and longitude, Richter
421 magnitude, and focal depth. The data series was processed to filter out tremors caused by
422 blasting in the multiple quarries situated within a radius of 10 km around Antananarivo.

423 Events exceeding M_L 4 were retained as being the most likely to bear upon the long-term
424 morphotectonic behaviour of the Antananarivo Basin.

425 Lastly, for comparative purposes on a wider scale across the Hautes Terres, we evaluated
426 lavaka density distributions throughout the Ikopa catchment based on aerial photography
427 (Helisoa, 1983; BDPA et al., 1994) and Google Earth updates in order to (i) compare them
428 with documented lavaka densities in catchments around the Alaotra Basin (Mietton et al.,
429 2006), and (ii) assess differences in sediment load entering the two respective tectonic basins.
430 We also cored and radiocarbon-dated sediment fill on the floor of the Ambohibary Basin (Fig.
431 1; also sometimes referred to as the Sambaina Basin), another semi-enclosed basin of the
432 Highlands (Fig. 2), and compiled previous radiocarbon ages similarly obtained from the
433 Alaotra Basin (Mietton et al., 2018). The preliminary regional dataset thus obtained was
434 conducive to (i) a calculation of long-term sedimentation rates; (ii) the inference of long-term
435 tectonic subsidence rates; and (iii) the possibility to estimate on that basis the opportunities
436 for lake formation in the past and the relative vulnerability of each basin to frequent flooding
437 in the present.

438

439 **4. Results**

440 ***4.1. Basin-scale stratigraphy of the Antananarivo plains***

441 Whereas the three auger cores (noted S1, S2, S3, Figs. 6, 7) documented the ubiquity of a
442 shallow peat level at constant depth but provided limited information about deeper levels, the
443 14 borehole and trench data provided good constraints on the stratigraphy of the sedimentary
444 sequence. The list is as follows: Ivaty-Agrival (F1), Novotel-Ankorondrano (F2), Ibis-
445 Ankorondrano (F3), Tour Orange (F4) Andrahara (F5), Antanimena (F6), Behoririka (F7),
446 Madarail-Soarano (F8), Mahamasina: F9; Anosizato: F10; Tsimbazaza: F11; Bi-Pass (F12),
447 Filatex (F13) and Andoharanofotsy (F14), offset further to the south (Fig. 6). Data obtained

448 by Noizet (1968 a, b) on depths to the bedrock and bedrock lithology along the Ikopa River
449 (e.g. evidence of quartzite outcrops on mid-channel bars) were also mapped, correlated, and
450 triangulated against a series of geodetic markers (Fig. 8).

451 The altitudinal correlations between cores are remarkably consistent for all levels,
452 including the peat layers (Fig. 7). Overall, the sediment fill is fine-textured and its maximum
453 known thickness does not exceed ~20 m. Peat was found to occur everywhere at one, and at
454 some sites at two, stratigraphic levels (Fig. 7): the shallower level is uniformly widespread
455 across the plain and close to the surface at an altitude of 1248–1250 m; the other typically lies
456 at depths of 10 to 15 m, and thus at altitudes of 1233 m (F3, F4) and 1241 m (F13). This
457 lower peat level was struck by 5 boreholes on the inner plain and along the inner Ikopa
458 floodplain.

459 Age data for the upper peat layer are summarised in Table 1. The radiocarbon ages were
460 obtained from a single level at Antanimena (F6), and from four different depths at Andrahara
461 (F5), where an organic black clay layer occurs between –11 and –13 m. The near-surface peat
462 deposits are consistently early Holocene (11,270–9100 yr BP), whereas the deeper black clays
463 are late Pleistocene (37,000 yr BP). The absence of deep-seated peat in cores other than F3,
464 F4, F5, F12 and F13 is explained either by the boreholes being insufficiently deep, or because
465 of having struck structural highs of bedrock on the highly irregular, deep weathering mantle
466 of the basin floor (F1, F6, F7, F10).

467

468 ***4.2. Tectonic constraints on the Antananarivo Basin***

469 The cross-section through the Antananarivo Basin (Fig. 9) shows that the sediment fill
470 sequence lies entirely or partly at an elevation below the altitude of the Farahantsana (1248
471 m) and Bevomanga (1250–1251 m) bedrock sills. The fact that the peat beds have been buried
472 by alluvium (the ‘backfill’ mentioned in Figure 7 is typically alluvium disturbed by heavy

473 machinery) also testifies to tectonic subsidence. Post-peat sedimentation rates were 0.2–0.3
474 mm/yr for the near-surface horizon, and 0.3–0.4 mm/yr for the deep peat level at Andrahara,
475 suggesting by inference that subsidence rates have been relatively steady since the late
476 Pleistocene (Table 1). Such geological background rates are plausible for an intraplate setting
477 and, based on recent seismic records, tectonic deformation is ongoing. On an axis from the
478 Ankaratra northward via the Farahantsana–Bevomanga upper knickzone area (Fig. 10), and
479 within a band of just 20 km to the west of Antananarivo, 27 earthquakes ($M_L > 4$) were
480 recorded in the last 20 years (1999–2019), with a M_L 5.08 event on Oct. 20, 2015 (Lat.
481 $18^\circ44.28$ S, Long. $47^\circ31.98$ E). Widening the band to 70 km towards the west reveals that the
482 region between Antananarivo and Lake Itasy recorded 206 $M_L \geq 4$ earthquakes between 1988
483 and 2019. Among these, five exceeded M_L 5.0 (maximum of M_L 5.32 on Aug. 23, 1995;
484 $18^\circ.43$ S, $46^\circ.24$ E; focal depth: 27 km). Although fault-slip and crustal deformation rates are
485 undocumented, a critical seismic alignment striking N–S out of the Ankaratra volcanic edifice
486 thus appears to be a region of active seismicity.

487 The fracture net and subsidence conspire to control the drainage pattern (Figs. 3, 6). The
488 rivers strike N–S but undergo 90° bends in response to westward tectonic tilting towards the
489 Antananarivo Basin (areas marked 3 and 4 in Fig. 6). At locations numbered 1 to 5 in Fig. 6,
490 the loci of these changes in direction support the notion that E–W faults also control drainage
491 and basin morphology, particularly where they cut across the N–S, quartzite-reinforced
492 basement ridges around Farahantsana and Bevomanga. The fracture pattern also has an
493 influence on right-bank Ikopa tributaries (Mamba, Mambakely, Andranoroasosona; Fig. 6).

494

495 ***4.3. Palaeoenvironmental constraints in the Antananarivo Basin***

496 None among the four Andrahara samples contained tephra, but the sand to silt fraction was
497 rich in all of the primary minerals typical of the gneiss and migmatite bedrock, namely quartz,

498 feldspar and biotite. Numerous smooth oxeas (needle-shaped sponge spicules, with sharp
499 tips at both ends) and belonging to the siliceous skeleton of freshwater sponges (order:
500 Spongillida) were also recovered. Given the additional morphotraits required for identifying
501 encrusting freshwater sponge fauna to genus and species level, these fossil remains are
502 insufficient to be used with confidence as palaeoecological indicators (Pronzato et al.,
503 2017). Nonetheless, specimens of living freshwater sponge species, only recently
504 discovered for the first time in Madagascar (Manconi et al., 2015, 2019), were collected
505 from “silty shallow water along the seasonally flooded riverside” of large rivers similar to
506 the Ikopa, thus providing a plausible clue to late Quaternary floodplain environments in the
507 Antananarivo Basin.

508 The four samples from the Andrahara (F5) peat deposits were also analysed for their pollen
509 inventories. Pollen preservation and content were generally lower in the two deeper peat
510 samples, but overall pollen analyses revealed substantial differences in terms of pollen
511 assemblages in the four studied peat samples. The pollen spectra at –13.50 m contained
512 Ericaceae (i.e. heather family; 62%), Asteraceae (i.e. daisy family of flowering plants, 14%),
513 and Poaceae (i.e., grasses; 12%). Among the other identified taxa, only Cyperaceae (i.e.,
514 sedges), *Podocarpus*, *Artemisia* and *Protea* exceeded proportions of 1%. In the sample at –
515 11.60 m, Ericaceae were still dominant (> 75%). Excepting Poaceae (18%), all the other taxa
516 recorded less than 5%. In the sample at –3 m, Ericaceae (53%) continued to prevail but
517 proportions shifted in favour of Cyperaceae (23%) and Poaceae (19%). Only *Podocarpus* and
518 Asteraceae exceeded 1%. In the shallowest sample at –1.80 m, the pollen spectra were
519 dominated by Cyperaceae (51%) and Poaceae (22%), with a clear eclipse of Ericaceae (down
520 to 10%). In this near-surface peat layer, several taxa such as *Podocarpus*, *Macaranga*,
521 Asteraceae, Urticaceae, Rubiaceae, etc., exceeded proportions of 1%.

522 The pollen assemblages indicate different paleoenvironmental conditions. With high
523 proportions of Ericaceae (60–80%) associated with high values for Asteraceae, the
524 environmental signature for the deeper organic levels is one of shrubby heathland. By
525 reference to the distribution of modern pollen spectra in central Madagascar (Burney, 1988),
526 such proportions of Ericaceae only appeared during the Last Glacial Maximum at elevations
527 800–1000 m lower than at present (Straka, 1996). The recorded colder period in the
528 Antananarivo Basin (36–37 ka BP, i.e. one of the cooler stades of Marine Isotope Stage 3, or
529 MIS 3) was thus also drier than today, as likewise confirmed by pollen spectra from the crater
530 lake at Tritrivakely (e.g. Gasse and van Campo, 2001). The shallower samples (–3 m and –
531 1.80 m) document a relative diversification of taxa involving a replacement of heather by
532 sedges and grasses. Whereas sedge supports the notion of a marsh or fen, a proportion of the
533 grasses and other flowering taxa signal seasonally wet meadows in a mosaic also involving
534 woody taxa. The Holocene signature thus illustrates warmer and wetter conditions. Such data
535 are likewise consistent with results from Lake Tritrivakely. The paleoenvironmental
536 conditions of the two generations of peat is strengthened by the fact that both intervals match
537 the early Holocene occurrences dated between 12,000 and 9000 yr BP in the Antsirabe
538 (Burney, 1987, 1996; Burney et al., 2004; Gasse and van Campo, 2001; Razafimahefa et al.,
539 2012) and Alaotra basins (Mietton et al., 2018), and the MIS 3 interval (36,000–32,000 yr BP)
540 in the Ankaratra Massif (Rakotondrazafy, 1992; Straka, 1996; Razafimahefa et al., 2012).

541 ***4.4. Basin subsidence rates in Madagascar's Highlands: a comparative analysis***

542 The population of agriculturally important but flood-exposed semi-enclosed basins in the
543 Highlands of Madagascar is much larger ($n \approx 25$, e.g. Bied-Charreton et al., 1981) than the
544 examples of the Antananarivo and previously studied Alaotra (Mietton et al., 2018) basins can
545 currently document, but apart from the Antsirabe Basin (Fig. 1; Razafimahefa et al., 2012),
546 few have benefited from coring and stratigraphic analysis. The basins also vary quite

547 substantially in size, although none attain the dimensions of the Alaotra. A few, like the
548 Alaotra and Antananarivo, are entirely in basement, but a large proportion of them were
549 formed by lava dams, particularly around the edges of the Ankaratra and Tsaratanana
550 stratovolcanoes. Neotectonics has often also interfered with the drainage pattern. For example
551 the Mangamila Basin, 70 km NE of Antananarivo (Fig. 1), displays discontinuous vestiges of
552 thick alluvial deposits now perched 40 m above the basin exit point, where the Mananara
553 valley (Figs. 1, 4) continues to down to Anjozorobe (18°31'44.68''S, 47°52'15.70''E). The
554 tectonics-driven drainage capture event detected in that basin could be recent given that a peat
555 sample contained in an alluvial deposit 500 m upstream of the waterfall at the exit point has
556 produced an age of 12.6 ka BP (Table 1). Future research in this and other basins would
557 broaden the scope of these preliminary findings.

558 The Ambohibary Basin (Figs. 1, 11), which belongs to the class of partly volcanic upland
559 basins, was nonetheless investigated here in order to test the extent to which it could enrich
560 the comparative regional analysis of basin subsidence rates and sharpen the diagnostic criteria
561 required for understanding their vulnerability to flooding. Based on the hypothesis that the
562 outlets of the different basins in the Highlands of Madagascar display a range of sensitivities
563 to environmental change, which should thus impart contrasting environmental behaviours and
564 signatures to each individual case, the following three examples were compared:
565 Ambohibary, Alaotra, and Antananarivo.

566

567 *4.4.1. The Ambohibary Basin*

568 The Ambohibary Basin, which is nationally important for its fruit and vegetable crops
569 but also for rice (Ambohibary means 'rice village'), is drained by the upper Ilempona River
570 (Fig. 1, 4), which slices through the tectonically active Betampona Fault scarp (Fig. 11). Soil
571 erosion and floods in this mostly volcanic catchment are less pronounced than in the

572 Antananarivo and Alaotra: no lavaka, limited in-channel sedimentation, few overbank
573 sedimentary deposits on the plain. The exit point is cut in weathered gneiss (Fig. 11), and
574 thereby more vulnerable to river incision than the Farahantsana–Betampona quartzites. Thus
575 facilitated, incision is more likely to keep up with the intermittent shuttering by fault
576 movements at the exit point.

577 In the absence of sediment cores, tectonic displacement on the fault was estimated from three
578 test pits, in which radiocarbon dating of organic-rich clays could reveal relative basin
579 subsidence. Samples Amb 1 and Amb 3 are from the plain, whereas Amb 2 lies on the edge
580 but 5 m above the modern basin floor (Table 1; Fig. 11). Amb 1 is young (~4 ka BP), whereas
581 Amb 2 and Amb 3 date back to the Last Glacial Maximum, i.e. MIS 2 (~26 ka and ~22 ka BP,
582 respectively). Age–depth ratios for Amb 1 and Amb 3 provide mean sedimentation rates of
583 0.1 mm/yr in each case, i.e. three times less than at Antananarivo over a similar time span,
584 and one order of magnitude less than the Alaotra Basin. The relative topographic positions of
585 the two samples of similar age, Amb 2 and Amb 3, but with Amb 2 raised by 8 m, suggest a
586 tectonic offset between the two land units (Fig. 11). This interpretation is corroborated by an
587 absence of other vestigial organic layers above the basin floor, thereby ruling out the
588 hypothesis of a palaeolake berm at site Amb 2; and likewise by the regional prominence of
589 the Betampona Fault (Fig. 1). This N–S fault continues south to the Antsirabe Basin, where its
590 recent activity is well documented (Razafimahefa et al., 2012). North of the basin, some > 40
591 ka lignite beds (Table 1) are also topographically raised (Fig. 11), there also suggesting that
592 postdepositional uplift of organic deposits began in the more distant past.

593 From a palaeoenvironmental perspective, parts of the basin were intermittently
594 transformed into a wetland during the Lateglacial and Holocene (Lageat and Peyrot, 1974;
595 Samonds et al., 2019), with peat levels, and abundant subfossil remains of aquatic mammals
596 and reptiles. The flagship hippopotamus remains (site Amb 0, Fig. 11), retrieved from a depth

597 of 80 cm and with an age of 14.6 ka BP (17.56 cal BCE; Samonds et al., 2019), also testify to
598 low sedimentation rates (0.05 mm/yr) and, by inference, low subsidence rates. These low
599 rates could accredit at least intermittent conditions suitable for generating a palaeolake, but
600 the floor of the deepest excavation at the centre of the basin (−8 m, Amb 3) did not reveal any
601 lacustrine sediments comparable to those described in detail by Lenoble (1949) in the
602 Antanifotsy Basin, farther to the east (Fig. 11).

603

604 4.4.2. *The Alaotra Basin*

605 The Alaotra Basin (Fig. 1) is shut off by a raised bedrock sill above a river knickzone
606 (Fig. 4) which, on a 10–10⁵-year time scale at least, seems immune to knickpoint retreat
607 (Mietton et al., 2018). Given this boundary condition (Garcia-Castellanos, 2006), the fairly
608 stable long-term surface-area of the lake is ensured by a precarious relative balance between
609 sediment-influx-controlled accommodation space (Mietton et al., 2018) and the tectonic
610 subsidence regime. Sediment delivery is substantial, sedimentation rates are high (0.5–2
611 mm/yr; Table 1), but these are offset by equally rapid tectonic subsidence rates. Taking
612 advantage of this geodynamic balance, despite some vulnerability to flooding the Alaotra
613 plain has grown to become the most productive rice-growing area of Madagascar. The mean
614 monthly level of the lake varies normally by 2 m between a maximum in March and a
615 minimum in November (Ferry et al., 2009). Levels rise further during tropical cyclones, and
616 rice fields that have been expanded lakeward by farmers to the detriment of natural wetland
617 habitats get flooded. The natural vegetation, some of it woody (amid the ‘zetra’ papyrus
618 swamps), benefits uniquely from these episodically more extreme floods and is host to a rare
619 endemic species of lemur (*Hapalemur alaotrensis*). An under-reported consequence of rapid
620 subsidence in the Alaotra Basin is a chronic destabilisation of the irrigation infrastructure,
621 which has been precisely engineered and monitored by topometric methods. A subsidence of

622 1 mm/yr has been seen to offset drainage ditches requiring centimeter-level-precision
623 operational gradients in just 10 years (Mietton et al., 2018). Where subsidence is particularly
624 intense, such as in the parallel Sasomangana and Ilakana valleys (Figs. 1, 12) where the rivers
625 undergo frequent and major avulsions (e.g. documented between 1963 and 1983 by
626 Bourgeon, 1984), new water-filled depressions develop and prove impossible to drain off.
627 Such adverse hydraulic gradients make canal construction and ditching uneconomical in those
628 areas.

629

630 *4.4.3. The Antananarivo Basin*

631 The Antananarivo Basin is shut off by the hardest rocks in the regional rock strength scale
632 (quartzite), with a presumption of either uptilting (i.e. relatively slower subsidence: 0.2–0.3
633 mm/yr) (Table 1) of this western edge of the basin floor along an E–W-striking pivot fault, or
634 by dint of an uptilted or upthrown block along the N–S Imerintsiatosika–Antambola seismic
635 line close to the basin outlet (Fig. 10). Sediment aggradation in the last ~40,000 years in the
636 Antananarivo Basin was also a function of river sediment loads. This variable can be
637 estimated from a limited data base summarised in Table 2. Turbidity measurements
638 obtained from the Mahitsy road bridge (near Farahantsana) at shallow water depths suggest
639 that suspended load in the Ikopa River is moderate: 20 mg/L (for a discharge of 30 m³/s) to 60
640 mg/L (128 m³/s) (EDF, 1950). According to Hervieu (1968), average turbidity varies between
641 100 mg/L (579 m³/s) and 930 mg/L (735 m³/s), but these values were obtained from the
642 Antsatrana gauging station (Fig. 1), i.e. at quite some distance downstream of the
643 Antananarivo Basin. At Antsatrana, average textural composition of the Ikopa suspended load
644 was 48% clay, 32% silt, 19% fine sand, 1% coarse sand. Based on the mean annual discharge
645 of the Ikopa and a tentative discharge / turbidity rating curve, Roche and Aldegheri (1964)
646 calculated that the mean specific catchment erosion rate was 360 t/km²/yr.

647 Despite the sand mining in the active channels of the Ikopa and Sisaony (BDPA et al.,
648 1994), raising of channel beds caused by in-channel sedimentation has clearly been an
649 enduring trend for as long as observations have been available (Douessin, 1974;
650 Ramboarison, 1990). This, however, is the effect of the very low channel gradients on the
651 plain rather than of exacerbated soil erosion in the catchments. Soil loss in the headwaters of
652 the Ikopa is more limited than in other areas of the Highlands because lavaka — which are the
653 only processes capable of delivering coarse bedload to river channels because they expose the
654 lithomarge — are relatively scarce (average catchment-wide density of 0.08 lavaka/km²,
655 compared for example to the SE area of Lake Alaotra with densities of up to 8/km², i.e. 100
656 times greater) (Mietton et al., 2006). Among the incoming tributaries, the highest lavaka
657 densities are observed in the Sisaony and Andromba subcatchments (locally up to 0.63
658 lavaka/km²; see Table 3 and Fig. 10).

659 Such a relatively low sediment influx combined with the hydrological bottleneck at the
660 basin outlet could in theory promote the existence of at least a shallow lake in the
661 Antananarivo Basin. The absence of a lake is probably explained by the low magnitude of
662 basin subsidence, thus producing a relatively overfilled basin despite the moderate
663 sedimentation rates. Lakes will form typically in underfilled basins (Garcia-Castellanos,
664 2006), i.e. under conditions closer to what has been evidenced in the Alaotra Basin (Mietton
665 et al., 2018). In Table 2, modelling of basin accommodation space (for sediment, for water)
666 shows that in the Alaotra graben, values of sediment aggradation and tectonic subsidence are
667 relatively balanced (calculated and measured specific denudation rates, respectively abridged
668 as SDR_c and SDR_m in Table 2, share the same order of magnitude), thus having allowed a
669 very shallow lake (and fen) to persist for ~30,000 years (see also Mietton et al., 2018).
670 Specific denudation in the Sasomangana (2000 t/km²/yr) and Sahamaloto (2400 t/km²/yr)
671 catchments (Fig. 1), respectively to the SE and west of Lake Alaotra (Ferry, 1985; Mietton et

672 al., 2006), are thus compensated by the comparatively high subsidence rates that appear
673 endemic to this rift zone of NE Madagascar. The dynamic equilibrium between tectonics and
674 sedimentation at Lake Alaotra is still threatened by mismanagement of the wetland (Mietton
675 et al., 2018), but the more intense tectonic regime than in the Antananarivo setting is what has
676 so far preserved the lake from extinction. In the Alaotra graben, the abundant volumes of
677 sediment delivered are thus absorbed by the accommodation space.

678 In contrast, despite much lower volumes of sediment delivery, the low tectonic subsidence
679 rate in the Antananarivo Basin is not sufficient to accommodate the sediment influx. This
680 imbalance is expressed in Table 2 by the values of SDR_m being much higher than SDR_c,
681 indicating that the Antananarivo Basin is vulnerable to overfilling and that there is no
682 potential for a lake. As a result, among the currently documented intermontane basins of
683 Madagascar's Highlands, the wetland plain around the capital city is the most vulnerable to
684 frequent flooding, a situation exacerbated by the previously mentioned risk (see Section 2.1)
685 of levee breaching along the trunk river and its tributaries.

686

687 **5. Future-proofing the Antananarivo Basin: a discussion on policy perspectives**

688 *5.1 A metastable wetland environment since the late Quaternary*

689 The lack of potential for a lake today in the Antananarivo Basin, as inferred from the
690 modelling presented in Table 2, is consistent with the evidence provided by the results that
691 there is also no palaeoenvironmental record of a former lake in the Antananarivo Basin. The
692 lake hypothesis was mooted only by Noizet (1968b) on the basis of right-bank terrace
693 deposits between Bevomanga and Soavinimerina (Fig. 8) — in this case imagined to have
694 formed in the context of a raised lacustrine base level and therefore older than the sediment
695 fill displayed in Figure 7. The occurrence of freshwater sponge remains is likewise
696 inconclusive given that sponges are reported from lotic as well as lentic environments and

697 thus cannot be used as unequivocal evidence for lacustrine conditions. The absence of
698 lacustrine deposits other than perhaps locally and intermittently is a common feature shared
699 by the Antananarivo, Alaotra (Mietton et al., 2018) and Antsirabe intermontane basins
700 (Razafimahefa et al. 2012). As likewise in the Ambohibary Basin (Fig. 1; Lenoble, 1949),
701 alluvial clay and sand in the Antananarivo Basin are the dominant materials. In the Antsirabe
702 Basin, the only distinctive difference is that the fluvio-palustrine sequence is covered by a
703 thick layer of tephra.

704 In the Antananarivo plains, the sediment has thus buried an irregular topography etched into
705 the weathered crystalline basement, with hills still rising out of the sedimentary sequence and
706 concentrating the rural settlements (as a result, the rice fields are quite a good proxy for
707 mapping the sediment cover by default, at least where urbanisation has not yet encroached;
708 see Fig. 5a for the situation in 2017, and Graphical abstract for 2020). Evidence that the
709 Antananarivo Basin underwent neotectonic activation, perhaps for the first time in the
710 region's geological history, during the Quaternary is indirectly provided by the older peat
711 deposits resting directly on weathered rock profiles such as at sites F3 and F4 (Fig. 7), with
712 fluvio-palustrine sediment aggradation through widespread overbank deposition over the
713 irregular topography of the Antananarivo etch basin beginning around 37,000–36,000 yr BP
714 and continuing uninterrupted until today. Irrespective of its earlier geomorphological history,
715 which currently evades documentation, from at least ~40 ka onwards the Antananarivo Basin
716 thus became a tectonic basin where sediment fill is controlled by a delicate balance between
717 tectonic subsidence rate and hydrological outflow at the outlet. The nature of sedimentation
718 dynamics was apparently a direct function of the rate of tectonic forcing, with peat deposition
719 apparently coinciding with accelerations in tectonic subsidence (Table 1).

720

721 ***5.2. Flood-mitigating options for Antananarivo's upland plain***

722 The flood hazard in the Antananarivo and Alaotra basins poses major problems for
723 agriculture and human settlement, but it is clearly around the capital city, where a population
724 of 700,000 already lives in the flood zone, that environmental issues are most acute.
725 Catastrophic flooding events, often unreported in the global media but occurring with
726 increasing frequency (March 1982, Feb. 1994, Jan. 2007, Feb. 2015, Feb. 2019, Jan. 2020),
727 are the result of low-grade housing, mostly populated by the more recently arrived among the
728 urban poor, sprawling across the lowest-lying areas of the city (Fig. 5b). Under the pressures
729 of urbanisation, by 2004 agricultural land use had fallen to 43% of the plain area. By 2010,
730 irrigated crops had fallen to 2530 ha (6800 tenancies), the remainder lost to urban conversions
731 (M.S. Andrianjafimahatratra, President of the Water Users' Federation, pers. comm. 2019).
732 Raising the agricultural plain for urban construction through landfill operations was
733 previously widespread north of the Ikopa, but it has now expanded to the left-bank areas,
734 mainly upstream of Tanjombato (Fig. 5a). The consequences of urbanisation on wetlands are
735 well known, and involve (i) sanitation hazards relating to stagnant water, to its pollution, and
736 to unsuitable or inexistent sewage infrastructure — in both cases exacerbated in Madagascar
737 by the coincidence between the rainiest and warmest seasons; and (ii) safety hazards
738 (structural failure of buildings, electrocution, impeded traffic). Given these threats and
739 constraints, any land-use and urban planning project for the capital city is narrowly linked to
740 hydrological management of the Ikopa's channel and floodplain, particularly downstream of
741 the city centre. The floods of Feb.–March 2015, exacerbated by cyclone Chezda, entailed the
742 displacement of 30,000 residents for several months, caused several dozen fatalities (Defrise,
743 2020), and came as a shock to political authorities clearly oblivious to the 1959 and earlier
744 catastrophic events.

745

746 *5.2.1. The playbook of hydraulic engineering solutions*

747 The behaviour of each tectonic basin's hydrological outlet is key to the delicate balance
748 under which the intermontane wetland can avoid extinction, and under which it can sustain its
749 function as provider of (i) supporting ecosystem services to agriculture in a mountainous
750 nation, and of (ii) provisioning ecosystem services to its sprawling capital city in the form of
751 flood-hazard mitigation.

752 Intuitive awareness of the importance of this boundary condition has motivated hydraulic
753 and agricultural land management authorities to seek engineering solutions such as bedrock
754 channel deepening at Farahantsana during the first half of the 20th century, described in
755 Section 2.1. Similar designs were likewise planned at the outlet of the Ambohibary Basin on
756 the upper Ilempona River during the 1940s; and at Lake Alaotra, where, in a classic situation
757 of destocking post-wartime surpluses of explosives, Longuefosse (1923) advocated an
758 expensive project involving 200,000 m³ of bedrock blasting of the Alaotra lake outlet
759 (Maningory knickpoint, Fig. 4). The objective was to drain away the lake water, reclaim vast
760 expanses of wetland as a result, and regulate outflow with a 14-m-high, 17,000 m³ concrete
761 dam equipped with a hydroelectric power station. By pumping water to convey it along new
762 canals to parts of the Alaotra Basin until then impossible to develop just by gravitational
763 irrigation (Ciolina, 1946), rice cultivation would thus expand and prosper.

764 All of these engineering initiatives were soon abandoned because of their prohibitive costs,
765 and because of their ensuing negative ecological and engineering impacts: headward erosion
766 of the exit gorge into the basin in the first two cases; lowering of groundwater tables as a
767 result of channel incision, causing a drop in water levels in wells on the floodplain and
768 impacting the parameters of rice cultivation; and permanent flooding of arable lands on the
769 lakeshore because of a widespread backwater effect at Lake Alaotra. The Alaotra fenland,
770 home to some endemic wildlife species, is now protected by the Ramsar Convention (since
771 2003).

772 Blueprints for a number of new projects aimed at regulating the Ikopa River and managing
773 land use on the floodplain have been drafted by environmental engineering consultancies
774 (Someah, 2010; Someah–Artelia Madagascar, 2012; BRL Ingénierie, 2017a, b). One
775 masterplan advocates the construction of a left-bank canal parallel to the Ikopa; a variant
776 envisages that this artificial overflow structure should be activated as a derivation canal with a
777 succession of spillways in operation only during floods. This would maintain the current
778 functions of the river’s natural channel, including during the low flow season. Reinforced
779 weir structures designed to arrest headward channel erosion have been planned for the Ikopa
780 and the Mamba rivers. However, like their colonial ancestors, because of the expropriations,
781 land acquisitions and the magnitude of earth-moving operations involved, all of these projects
782 are exceedingly expensive. Additionally, flood hazard simulations have been restricted to
783 return periods (and peak flood discharges) of 5 (210 m³/s) to 10 years (420 m³/s). This
784 amounts to lowering the Ikopa water line by 2 m and 1.3 m (for the 5- and 10-year return
785 periods), respectively. Given the strong likelihood of much higher discharges in the future
786 (e.g. 100-year flood), these hard-defence solutions would imply rapidly increasing costs for
787 every additional increment of engineered waterline lowering (e.g. for accommodating the 20-,
788 50-year floods and above). Accordingly, and given that the lower-frequency, higher-
789 magnitude floods are the most damaging, the cheaper, yet still expensive, options are already
790 almost pointless. Undoubtedly, a magnitude of flood waterline lowering by just 2 m on the
791 Ikopa would be beneficial as it would enhance gravity-driven drainage gradients for both
792 agricultural and urban (sewage etc.) infrastructure. Nonetheless, the impact from larger floods
793 (likely and perhaps increasingly frequent in the future given the accelerating trend since 2015)
794 is currently undocumented. Its consequences for water table levels across the plain, for
795 example, is unknown because the interaction between the river and the floodplain aquifers is
796 still poorly understood (note that the new 28 MW hydroelectric power station at Farahantsana,

797 soon to be completed at the time of writing, is a penstock-fed, run-of-the-river facility without
798 a dam across the Ikopa channel, and should thus have no influence, such as backwater effects,
799 on matters addressed in this study).

800 Continuing unregulated urban growth of Antananarivo's metropolitan area strongly
801 suggests that ribbon development along future road arteries will also alter rainfall-runoff
802 response times, worsen stormwater containment and first-foul flushes, and lengthen
803 floodwater recession times back to the river and water table. Available funds should thus
804 prioritise the protection of the agricultural plain north and east of the Ikopa channel and
805 preserve water-spreading buffer zones already present in those areas. Enforcement of this
806 policy should be uncompromising in the face of pressure from property developers.

807

808 *5.2.2. Integrated watershed management options*

809 Solutions to urban flooding and crop destruction in the upland plains of Madagascar may
810 require proximal engineering fixes, but also depend on an understanding of the total
811 environment at the entire catchment scale. This includes land-use patterns and agricultural
812 practices, which impact on water and sediment delivery further downstream. Here we
813 examine land cover solutions as a means of curbing peak discharges and in-channel alluvial
814 aggradation, which both threaten the levees, the plains, and thus the sustainability of the
815 nation's agriculture and the safety of city dwellers. These issues are most serious in the two
816 upland ricebowls of Madagascar: Antananarivo and the Alaotra, because in other agricultural
817 basins such as Ambohibary and Antsirabe, hillslopes in the young and moderately weathered
818 volcanic rock are not gullied by lavaka and release more limited masses of debris.
819 Furthermore, those basins are situated at higher altitudes, and focus on crops more resistant to
820 winter temperatures (commonly falling to below 4 °C) than rice. Resource optimisation is

821 thus less narrowly dependent on the subtle strategies required in paddy cultivation for
822 controlling water budgets at nested time scales, including at short notice.

823 Natural soil erosion is endemic in the Ferralsols of the Alaotra catchment area, and
824 erosion-control and slope restoration measures such as gabions and brushwood check dams
825 have been deployed in vain for many years. In the Ikopa catchment, which is endowed with
826 far fewer lavaka and where conditions are thus more favourable to ecological engineering, the
827 smaller number of active lavaka (most in the Andromba and Sisaony subcatchments, Fig. 10)
828 has been fairly successfully curbed by afforestation of the erosional scars with *Eucalyptus*
829 *robusta*, *Grevillea banksia*, *Cassia spectabilis*, and seeding of herbaceous plants such as
830 *Crotalaria*, particularly *Crotalaria juncea* (sunn hemp): a fast-growing, nitrogen-fixing,
831 nematode- and drought-resistant legume forming dense cover as well as a source of green
832 manure, fodder, and perhaps biofuel in the near future. Whereas the Alaotra plain is thus
833 potentially more vulnerable to sediment aggradation than its Antananarivo counterpart
834 because lavaka densities are up to 100 times greater, the Antananarivo plain nonetheless lacks
835 the Alaotra's vast foreshore area, and thus the capacity to contain floodwater and sediment
836 upstream of Antananarivo's urban and irrigation infrastructure. This contrast between the two
837 settings highlights a situation where the potential for disconnectivities in the sediment cascade
838 (Fryirs, 2013) is much greater in the Alaotra than in the Antananarivo basins (Fig. 12). The
839 capital city is thus uniquely exposed (Fig. 5).

840 Land use characteristics in the Ikopa and Alaotra catchments are relatively similar, but
841 disconnectivities in the sediment cascade matter at all scales within the catchment area, and in
842 the case of the Antananarivo Basin, upscaling this concern for sedimentary disconnectivities
843 to the entire catchment is where the key to future policy action lies. Population densities are
844 low and intensive agriculture is restricted to valley bottoms (rice), which are wide in the
845 Alaotra area and narrower in the Ikopa catchment, and to terraced interfluvial footslopes on

846 Ferralsols and colluvium. The networks of flat-floored valleys (dambos) constitute the first
847 sediment trap, or disconnectivity node, in the catchment-scale sediment cascade. As loci of
848 sediment aggradation in quantities that remain manageable on an annual basis, unmechanized
849 farming communities have evolved a number of strategies for retaining the sediment and
850 coopting it to agricultural benefit. The antler-shaped networks of valley floors (examples
851 visible in Figure 5a), however, only represent ~10% of the land area. The remaining 90% of
852 the Ikopa catchment (and no less than ~50% nationwide; Randrianjafy, 2006) consist of low-
853 gradient interfluves with convex hillslopes underlain by 10–30-m-thick weathering profiles
854 and named ‘tanety’. The ‘tanety’ are potentially far more vulnerable to runoff-related erosion
855 and gullyng, and deserve greater attention.

856 The elevation band of steep lower hillslope convexities is where village settlements occur.
857 It is usually well tended to by terracing and various forms of polyculture, and well managed
858 by indigenous soil conservation methods involving terracing and grassy strips on arable field
859 boundaries (Roose, 1982). The land use higher up on hillsides and hilltops today is commonly
860 plantation forestry (eucalyptus, pine) in replacement of grassland savanna, mainly for urban
861 charcoal manufacturing and timber consumption. This woodland cover increases
862 evapotranspiration and infiltration but, whether under state-controlled or corporate land use, it
863 is also resented by cattle herders, who for centuries have been traditionally co-opting hilltops
864 for grazing under complex customary rules also involving fire management practices. The
865 cross-country transhumance routes are well known (Raison, 1969), and herds of many tens of
866 thousands of zebu gravitate annually to the Antananarivo area, where some of the country’s
867 largest cattle markets and industrial abattoirs are located. The competition between state or
868 private forestry and traditional pastoralism is enhanced, in areas closer to the cities, by recent
869 land grabs by urban elites or foreign investors with alternative land development objectives.
870 Whether under a ‘kijàna’ regime (cattle pasture and rest area managed locally for the village

871 herds), or the ‘tanin’aômby’ regime, where large herds of transhumant zebu cattle are left to
872 roam freely (Rasamoelina, 2017), the grassland surfaces under customary common-property
873 management are shrinking, thus increasing risk of overstocking and overgrazing. The
874 potential for enhancing surface runoff and soil erosion on the ‘tanety’ as a result of inadequate
875 rangeland management is therefore substantial (Fig. 12).

876 A watershed and irrigated-zone management policy was formulated for Madagascar at
877 the turn of the 21st century. As in many developing countries, in a political context where
878 environmental policies are based on close relationships between governments, global
879 environmental NGOs, and development banks, the governance of natural resources in
880 Madagascar draws farmers and other land managers into partnerships with global public–
881 private networks (Duffy, 2006). As a result, land management solutions deployed in
882 Madagascar are imbued with often quite specific corporate doctrines, most of them crafted by
883 overseas development agencies and consultancies. This affects the politics of environmental
884 aid to Madagascar, and likewise the rhetoric in which it is embedded (Corson, 2016).

885 Most funding bodies in Madagascar’s agricultural sector, which usually broaden their
886 scope to rural development and watershed management (Agence Française de Développement,
887 Japan International Cooperation Agency, World Bank, Kreditanstalt, USAid, Food and
888 Agricultural Organization of the UN etc.), have thus become major partners of the new
889 PNBV/PI (Programme National Bassins Versants Périmètres Irrigués) launched by the central
890 government in 2006. This policy is based in theory on a catchment-wide approach to land-use
891 and land-cover management, with consideration for up- as well as downstream environments,
892 and on a diverse range of action plans and self-governing organisations partly modeled on the
893 chambers of agriculture prevalent in some European countries. These are aimed at
894 strengthening farmers’ governance structures (federations, social networks, training
895 workshops...) and placing agricultural producers centre-stage. The main three strategies of

896 'agro-ecological' engineering in that context each apply to different facets of the landscape
897 system. They are usually sponsored by foreign NGOs and funding agencies (Serpantié et al.,
898 2013) and comprise of: (i) payment for watershed-based environmental services (e.g. Porras
899 et al., 2008) — more often, however, in steep forest areas than in wetlands or agricultural
900 watersheds (Wendland et al., 2010; Villa et al., 2015; Onofri et al., 2017; Van Soesbergen and
901 Mulligan, 2018); (ii) rainfed 'conservation agriculture' on the hilltops, using a package of
902 techniques usually imported from Brazil (Knowler and Bradshaw, 2007; Serpantié, 2009);
903 and (iii) a system of rice intensification (SRI) aimed at dambos and intermontane basins,
904 developed by an NGO from Madagascar with attempts to export it to the rest of world (e.g.
905 Serpantié, 2017).

906 A difficulty with applied research in agronomy is that sources of information about its
907 results are rarely independent from the various organisations and agencies self-promoting
908 their own experiments and innovations (Serpantié et al., 2013). Here we merely emphasize
909 that despite the rich forms of development-motivated advocacy underpinning the PNBV/PI,
910 and despite the fact that the grassland-covered 'tanety' constitute up to 90% of the land
911 surface in any given part of the fluvial catchments (Fig. 12), pastoralists, who are socially
912 marginalised in Malagasy society, are often invisible to the development agencies and
913 virtually never integrated into those policies. The aid policies target sedentary village
914 communities and focus on elaborating legislative frameworks aimed at enshrining land-tenure
915 security for producers and farmers. The pastoralists nonetheless impact on the territory
916 through their cyclical combination of hilltop grazing and forage burning. The grassland
917 communities are dominated by *Aristida*, *Loudetia*, *Ctenium*, *Andropogon*, *Panicum*, *Imperata*,
918 all of which have Malagasy vernacular names (Sarremejean, 1961; Bourgeat et al., 1995), and
919 are unpalatable to zebu unless burned periodically to promote new flushes (Granier et al.,

920 1976). They are, however, too tussocky and shallow-rooted to avoid soil erosion under
921 conditions of overstocking (Fig. 12).

922 Two categories of pastoralists are concerned by the prospect of sustainable grassland
923 management: (i) the village communities themselves, who practice mixed farming and thus
924 usually have a small village herd of mainly male zebu (used as draught cattle), which is kept
925 on the interfluves away from dambo crops during the rice-growing season; and (ii)
926 transhumant pastoralists, who travel long distances, e.g. from the highlands west of Lake
927 Alaotra across to the east coast (Toamasina), and from the savannas and pseudo-steppes of the
928 western scarplands (Fig. 1) eastward to the Ikopa catchment and Antananarivo's abattoirs.
929 The nomadic pastoralists are not present all year but drive very large herds of bovine cattle
930 over the rangelands towards the end of the dry season (also the cooler season), keeping to
931 these upland droveways as a means of avoiding arable fields in the dambos and conflict with
932 farmers. The timing of this mass movement occurs for economic reasons, i.e. (i) the need to
933 sell the cattle at a time when other forms of revenue (e.g. crops) are scarce, (ii) the low
934 dividends from continuing to graze cattle on dry pasture, and (iii) the opportunity of selling or
935 slaughtering the cattle before seasonal decline in weight loss. Crucially, however, these late
936 dry-season livestock loads on thin, tussocky pasture also imply that the first rains have a
937 disproportionately large impact on the soils and hydrology of the savanna-covered interfluves,
938 and therefore also have consequences for surface runoff and sediment load among the rivers
939 converging on the Antananarivo Basin. These impacts are exacerbated by fire practices.
940 Burning enhances the beneficial 'green bite' appreciated by the cattle, but is also tacitly
941 appreciated by farmers because (i) the runoff on the 'tanety' routinely conveys fertile ash to
942 the arable dambo soils, and (ii) the rice farmers are also the owners of part of the livestock
943 using the interfluves under the kijàna regime. Most rural stakeholders thus have a vested

944 interest in fire and pastoralism, but collectively conspiring, overall, to far-field hydrological
945 hazards downstream.

946 At catchment scale, a recommended agro-ecological strategy to save intermontane
947 basin wetlands such as the Alaotra and Antananarivo from excessive sediment aggradation
948 and/or to buffer the catchments against catastrophic flooding would thus be to expand the
949 introduction of new pasture and forage plants — whether grasses or legumes — to the
950 naturally treeless interfluvial hillslopes and hilltops. The nitrogen-fixing *Stylosanthes*
951 (pencilflower; Fabaceae), native to the Americas and the world's most widely used pasture
952 legume (Granier et al., 1972; particularly *Stylosanthes guianensis*: Cook et al., 2005; Husson
953 et al., 2008); and most of all *Brachiaria* (Poeaceae), native to central Africa, have been
954 recommended (Granier et al., 1966; Bosser, 1969; Seguy, 2006). *Brachiaria brizantha* (bread
955 grass, a tufted perennial which stays green even during dry seasons of 3 to 6 months) has deep
956 roots (up to 2 m) and thus stabilises the soil. It is recommended over *Brachiaria ruziziensis*
957 (Congo grass, which has also been introduced to Madagascar) because of its better natural
958 seed dispersal capacity, wider ecological niche (rainfall, temperature, pH, etc.), and tolerance
959 to low-fertility soils even though it improves with manuring. It can also be used as cut-and-
960 carry hay and silage for village cattle (Cook et al., 2005). Used in combination, these multi-
961 purpose grasses and creeping legumes can withstand high stocking rates in areas currently
962 identified as vulnerable to soil erosion (e.g. Fig. 12); are adapted to the nutrient-poor, low pH
963 soils; and combine the benefits of palatability to bovine cattle, of fire and drought resistance
964 (large soil seed bank of the pencilflower, and thus rapid recovery), with good runoff-arrest
965 and soil-retention abilities (Ferry et al., 2009, 2013). They are also advocated as a substitute
966 to the endemic use of fire (Randrianjafy, 2006), with obvious value for curbing carbon
967 emissions.

968 Although introduced to Madagascar in the 1950s, however, *Brachiaria* has never been at
969 the forefront of development policies. Additionally, fire practices in Madagascar are
970 widespread but culturally and politically complex (Kull and Laris, 2009). As a result, any
971 prospects of pastoralism without fire would probably need to adjust rangeland management
972 practices to the introduction of new forage plants on multiple institutional and behavioural
973 levels. One of the social bottlenecks could be resistance from dambo farmers to see any
974 change to fire practices on the ‘tanety’ because they also benefit indirectly from the ash-laden
975 runoff. Nevertheless, forging an alliance with pastoralists in ways that enhance their
976 livelihoods and preserve their rangeland resources is recommended here as a way forward,
977 thus establishing a counter-intuitive feedback loop between tectonic regime and rangeland
978 management for the purpose of preserving the sustainability of rice farming — especially in
979 the Alaotra Basin — and mitigating flood hazards in and around the nation’s capital city: a
980 potential win–win for town and country, upland and lowland.

981

982 *5.2.3. Overarching policy perspectives and wider methodological implications*

983 While attempting to assess the assets and vulnerabilities of the Ganga–Brahmaputra delta
984 in Bangladesh as a safe operating space, Hossain et al. (2017) showed that operating the life-
985 supporting system of the floodplain to increase long-term resilience, and to help to revise
986 environmental policies which were having negative impacts on a regional scale, required
987 managing feedback on several levels, including the slow biophysical variables. In central
988 Madagascar, we have shown that a key slow variable was the tectonic regime; another,
989 equally subtle key was the vulnerability of the Ferralsols to topsoil erosion, exacerbated
990 runoff, and possible lavaka initiation (Fig. 12). That window of vulnerability is opened every
991 year as a consequence of overstocking on interfluves and lighting bush fires at the end of the
992 dry season. This regional study focusing on the rice-growing tectonic basins of Madagascar

993 thus demonstrates how the concepts of slow and fast variables, shocks (e.g. Walker et al.,
994 2012), tipping points, limits to adaptation, and boundaries for sustainable development may
995 be defined in real-world socio-ecological systems.

996 Like everywhere else in the world, deforestation, land degradation and urbanisation in
997 watersheds increase the speed at which water runs off the land and into rivers, and climate
998 change may be increasing the variability, intensity and frequency of cyclones and other severe
999 rainstorms. The construction of hard defences such as artificial levees and embankments,
1000 however, creates a false sense of security and encourages urban developers and speculators to
1001 open-up the floodplain for settlement. This makes future floods more damaging than if the
1002 plain had been left undeveloped. Furthermore, expensive structural controls such as dams and
1003 levees can worsen the severity of extreme floods because the river level becomes raised above
1004 the height of the surrounding plain, with potential for disastrous flash floods when the levees
1005 break. A recurring tendency among human societies is to underprepare for disasters because
1006 of environmental myopia, historical amnesia, administrative inertia, technological optimism,
1007 herding bias (a tendency to base choices only on the observed actions of others), and/or — as
1008 emphasised in this study — simplification bias: i.e. a tendency to selectively attend to only a
1009 subset of the relevant factors requiring to be considered when making choices involving risk
1010 (Meyer and Kunreuther, 2017). Awareness of these biases, and cultivating the memory of
1011 such historically documented past disasters along the Ikopa River, is essential for planning the
1012 future of the Madagascar's upland economy. The promotion of watershed-based
1013 environmental services in Madagascar would gain from not just focusing, for example, on the
1014 prevention of siltation of hydroelectric dam infrastructures in the forest belt of the Highlands
1015 (Villa et al., 2015), but also from extending as much as possible the sustainability of the
1016 intermontane grainbaskets of the country, which are located in a savanna / pseudo-steppe
1017 environment. This involves not just intensifying the agriculture through agronomic and

1018 hydraulic engineering on the plains themselves, which has long been the major focus of
1019 research and funding efforts, but also an integrated consideration for subsistence agriculture
1020 and pastoralism in the upper watersheds, concern for river knickpoint dynamics driven by
1021 active tectonics, and a strict and uncompromising control of land use and urban planning
1022 around the sprawling capital city. All are intimately linked through sediment budgets in the
1023 catchment-wide sediment cascade.

1024

1025 **6. Conclusion**

1026 The water and sediment budgets of the intermontane basins in Madagascar's Highlands are
1027 strongly dependent on the metastable equilibrium of the land-use mosaics in the catchments.
1028 With the added basin-outlet control by tectonics, basin-floor subsidence rates, river channel
1029 dynamics at the basin exit points, and the urban sprawl of the capital city across its floodplain,
1030 the Antananarivo Basin is increasingly exposed to damaging flood risks as a result of ill-
1031 conceived engineering fixes and unregulated urbanisation. Having been functioning as a
1032 dynamic natural wetland since at least the late Pleistocene, this environment is unlikely to
1033 yield easily to continuing reclamation efforts beyond certain limits. The fact that rural and
1034 urban development schemes in Madagascar both persistently ignore the socially most
1035 vulnerable, i.e. respectively pastoralists and the urban poor, confirms that there is a strong
1036 political component to the environmental issues at stake. As also shown here in the Highlands
1037 of Madagascar, embracing the total environment not only means understanding how the
1038 different 'spheres' (atmo-, hydro-, litho-, bio-, anthropo-) intersect and interact through
1039 cumulative causation, offsets, feedbacks or nonlinearities, but also how systems scale up or
1040 down according to nested or cascading architectures. It also benefits from integrating social
1041 and biophysical records at regional scales through time by taking a long view of the past
1042 through historical records (e.g. Dearing et al., 2015; Shanmugasundaram et al., 2018) and by

1043 dating sedimentary archives, thereby providing policy recommendations that are calibrated
1044 not just on treating the symptoms and — often ineffectually — controlling the fast variables
1045 (e.g. lavaka scarring, episodic levee breaching), but also calibrated on an understanding of the
1046 underpinning slow variables — i.e. those that no one can control (tectonic regime, cyclones,
1047 intrinsically low soil fertility and vulnerability to runoff erosion), but where an awareness of
1048 their existence adjusts the bandwidth of what is possible or relevant, and sets the dial of policy
1049 framing efforts to a position where long-term sustainable solutions are realistic, ecological,
1050 cost-effective, and socially just.

1051

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1061

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1431

1432 **Figure legends**

1433

1434 Fig. 1. Oblique view of central Madagascar's relief. The intermontane basins documented in
1435 this study (white lettering), and rivers, lakes, and localities mentioned in the text, are named.

1436 Large white box locates Figure 3, small white box locates Figure 11 (Ambohibary Basin).

1437 Digital topography based on Shuttle Radar Topography Mission (SRTM) v.3. Reference

1438 coordinate system: WGS 1984.

1439

1440 Fig. 2. Flow diagram summarising the research methodology.

1441

1442 Fig. 3. Ikopa drainage basin upstream of the Farahantsana bedrock knickzone. The Ankaratra

1443 massif, in the SW corner, is a large, late Cenozoic to Quaternary volcanic edifice resting on

1444 the Precambrian basement, and one of the highest summits in Madagascar. Blue, red, and

1445 yellow boxes show outlines of Figures 5a, 6, and 8, respectively. Digital topography based on

1446 Shuttle Radar Topography Mission (SRTM) v.3. Reference coordinate system: WGS 1984.

1447

1448 Fig. 4. Knickpoints and longitudinal channel profiles of five major rivers of Madagascar's

1449 Highlands (see locations in Fig. 1).

1450

1451 Fig. 5. Antananarivo, Madagascar's capital city in its environmental setting.

1452 A. Antananarivo city limits and surrounding land use in 2017. Land classification based on

1453 Pléiades, Sentinel-2 and Landsat-8 imagery after Dupuy et al. (2020). In the wider Ikopa

1454 catchment north, east and south of the city, note the large footprint of the savanna biome

1455 (green on 'tanety', i.e. interfluvial summits) compared to the dambo network (yellow). Even in

1456 this urbanized and highly agricultural map area in the immediate surroundings of the capital

1457 city, the savanna covers 39% of the land surface. The Different hues of green take account of

1458 proportions of tree presence, but overall tree cover is minimal in the natural grassland

1459 savannas of the Highlands despite a push for afforestation by development agencies (see Fig.

1460 12). In the remaining 75% of the Ikopa drainage basin, grassland covers closer to 90% of the

1461 land surface. Abbreviations: AI-Avenue de l'Indépendance; A-Andrahara; Amb-
1462 Ambohitrimanjaka; T-Tanjombato.

1463 **B.** Oblique view of a suburb of Antananarivo (location in panel A), where housing between
1464 2003 and 2017 has rapidly been crowding out rice fields and natural wetlands. CNES/Airbus
1465 and Landsat/Copernicus imagery, oblique views generated in Google Earth.

1466

1467 Fig. 6. Geology of the Antananarivo Basin (after Delubac et al., 1963), and location of
1468 trenches and boreholes used for documenting the basin's late Quaternary chronostratigraphy.

1469

1470 Fig. 7. Stratigraphy of the Antananarivo Basin sediment fill based on available civil
1471 engineering excavations and the main pollen assemblages (%) analysed from the four dated
1472 samples in section F5. See text for data sources.

1473

1474 Fig. 8. Geological setting of the Bevomanga bedrock channel reach (after Noizet, 1968a, b,
1475 modified and adapted).

1476

1477 Fig. 9. Cross-section through the Antananarivo Basin sediment fill along the right bank of the
1478 Ikopa River. Profiles based on the data provided in Figures 7 and 8.

1479

1480 Fig. 10. Distribution of $M_L > 4$ earthquakes recorded between 1999 and 2019, and of the
1481 highest densities of lavaka in the Ikopa catchment. Mean lavaka densities mapped and
1482 computed from raw data from BDPA et al. (1994). Quadrat 1: 0.63 lavaka/km²; Q2: 0.42
1483 lavaka/km²; Q3: 0.38 lavaka/km²; Q4: 0.32 lavaka/km². Anywhere else in the Ikopa
1484 catchment, lavaka densities are much lower by Madagascar standards (see Table 3).

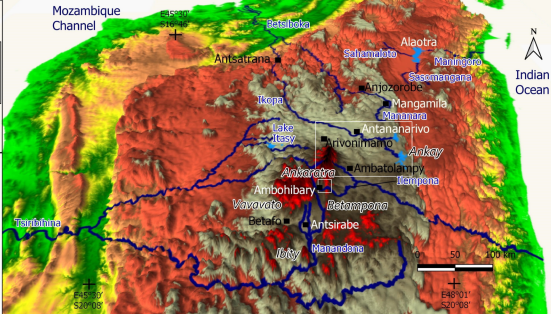
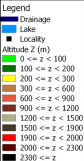
1485

1486 Fig. 11. The Ambohibary Basin and its outlet down the Ilempona River gorge. See location in
1487 Figure 1. CNES/Airbus imagery, oblique generated produced in Google Earth. Vertical
1488 exaggeration of relief x3, aimed at accentuating the key topographic features.

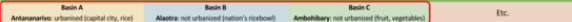
1489

1490 Fig. 12. The rice-growing Sasomangana valley, a rapidly subsiding tectonic sub-basin of the
1491 Alaotra graben, and the open savanna grasslands typical of Madagascar's highland
1492 landscapes. See location in Fig. 1. This landscape view summarises the diversity of
1493 disconnectivities in water and sediment discharge (sensu Fryirs, 2013) at several nested scales
1494 in the landscape, from local gullies to the floodplains typical of the semi-enclosed basins of
1495 Madagascar's Highlands and their catchment areas. 'Lohafasika' means 'source of sand'. DF:
1496 terminal debris fan generated by a locally active 'lavaka' situated outside the picture frame. In
1497 this example its feeder channel does not join the main river but is a threat to one of the major
1498 irrigation channels (here the 'Canal Principal de Rive Gauche', CPRG). P: small lake formed
1499 by ponding behind a 'lavaka' deposit. The 'lavaka' scar on the slope is already revegetated. In
1500 the foreground, note the predominantly convex hillslope profiles of the interfluves, here
1501 belonging to erosion surface 'S3', and in the background the basin's footwall uplands with
1502 range fronts scarred by large and active lavaka (L). In both cases this vast grassland savanna
1503 biome (*Aristida* sp.) is entirely devoid of agriculture and dedicated to pastoralism, either
1504 involving long-distance zebu cattle herds (S: overstocking scars along a hilltop droveway), or
1505 local village mixed herds (T: terracettes, typical of livestock trampling on hillslopes). Note
1506 how bare, overgrazed patches of soil on the hilltops can operate as contributing areas to gully-
1507 generating runoff, and how this feeds into the sediment cascade. The soils are particularly
1508 vulnerable after fires at the end of the dry season. Credits: M. Mietton.

1509



Sampling strategy — **Focus:** semi-enclosed agricultural wetland basins of Madagascar's Highlands



Sub-sample of 3 upland topographic basins

Secondary data compilation — **Focus:** setting preliminary constraints on state variables and boundary conditions



Primary data acquisition — **Focus:** documenting past and modern environments to assess future system behaviours



Results and interpretation — **Focus:** age and long-term behaviour of Madagascar's wetlands



Discussion — **Focus:** policy measures for mitigating flood hazards (integrated watershed & rangeland management vs. hard engineering)

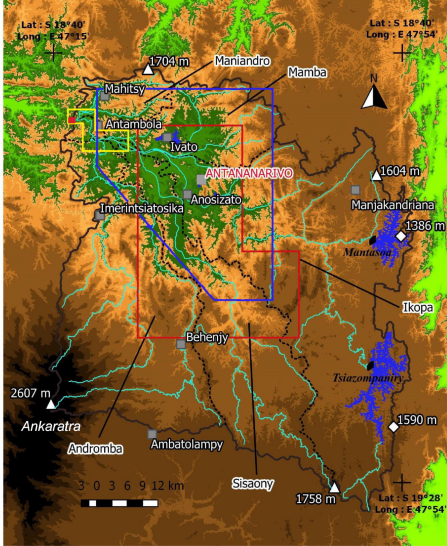
Conclusions and recommendations

Legend

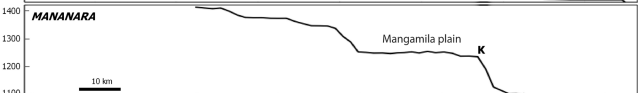
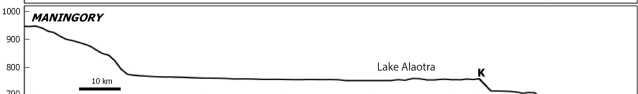
- Ikopa catchment boundary
- Sub-catchment boundaries
- Drainage
- Summit
- "Pass"
- Farahantsana knickpoint
- Dam
- Reservoir
- Locality

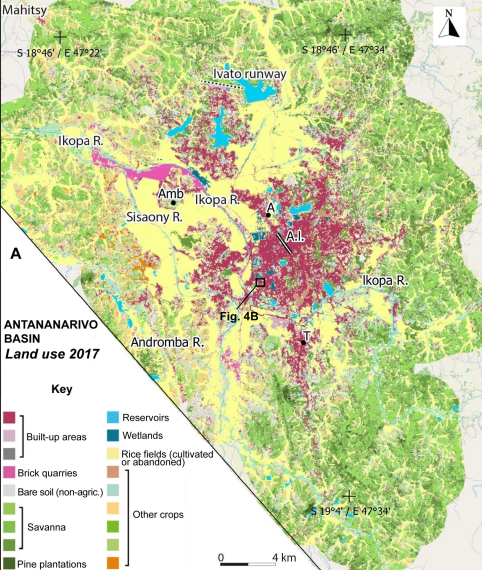
Altitudes z (m)

- $z < 1000$
- $1000 \leq z < 1100$
- $1100 \leq z < 1200$
- $1200 \leq z < 1225$
- $1225 \leq z < 1250$
- $1250 \leq z < 1275$
- $1275 \leq z < 1300$
- $1300 \leq z < 1350$
- $1350 \leq z < 1400$
- $1400 \leq z < 1550$
- $1550 \leq z < 1700$
- $1700 \leq z < 1850$
- $1850 \leq z < 2000$
- $2000 \leq z$

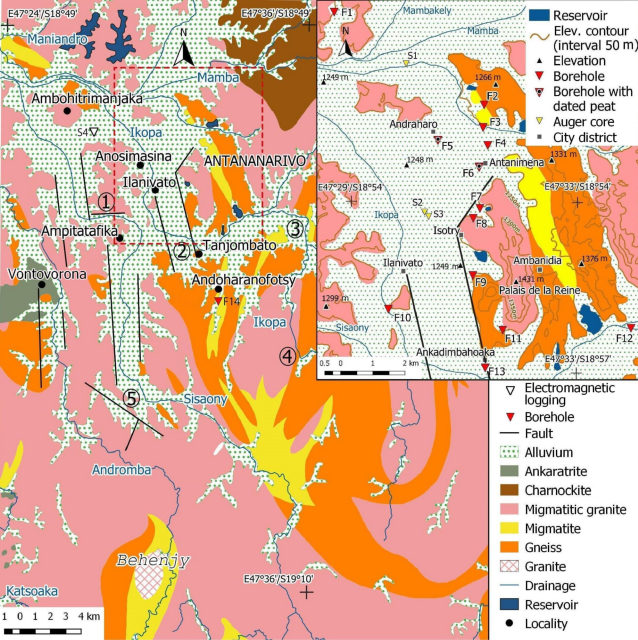


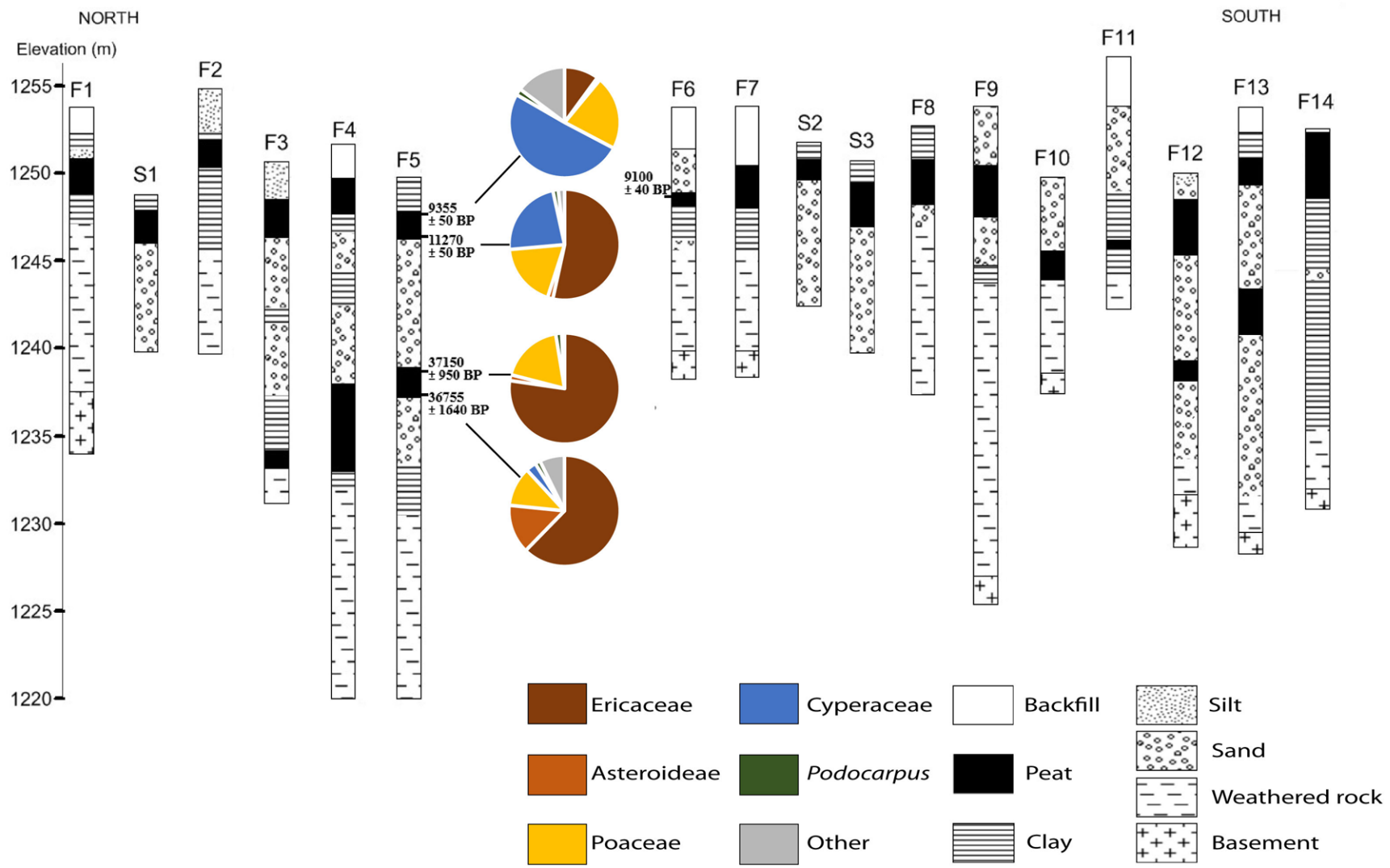
K : Knickpoint

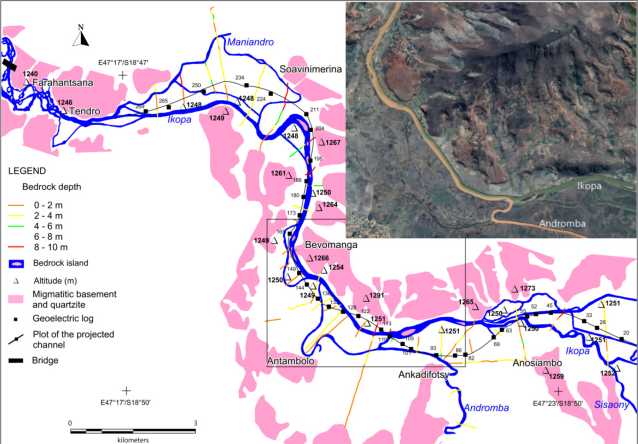












NW

SE

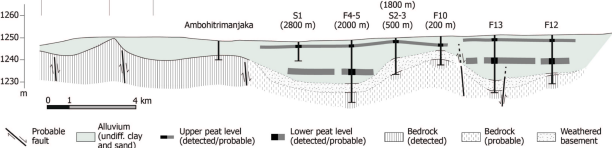
W

E

Confluence
Ikopa-
Sisaony (RD)Bevomanga
sill






Farahantsana

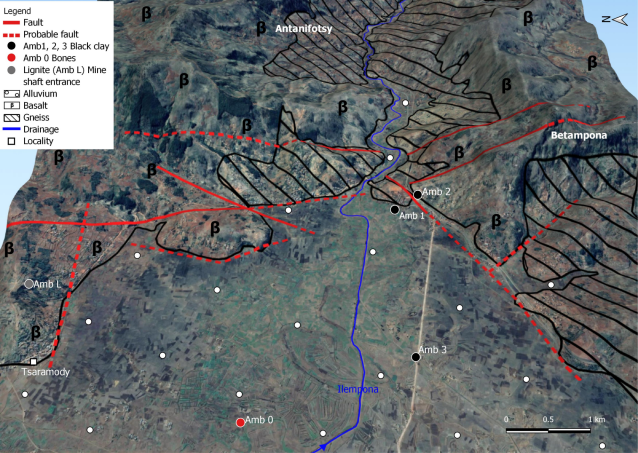
ANTANANARIVO





Legend

-  Highest densities of lavaka
-  Epicenter (magnitude : 5.1 - 20/10/2015)
-  Epicenter ($4 < \text{magnitude} < 5$)
-  Drainage pattern
-  Locality





Sasomangana

Sasomangana

Lohafasika

CPRG

DF

S

ST

L

P

S

L

L

L

Table 1. Radiocarbon age constraints on sedimentation rates in Madagascar's upland basins

Sample name	Location			Depth below surface (m)	¹⁴ C age (yr BP ± 1σ)	Calibrated age interval (1σ) ⁴ (cal BCE)	Inferred sedimentation rate (mm/yr)
	Latitude (South)	Longitude (East)	Altitude (m)				
Antananarivo							
<i>Antanimena</i>							
Ly-17145	18°53'24"	47°31'16"	1254	3	9100 ± 40	8321–8269	0.33
<i>Andrahara</i>							
SacA 53838	18°52'57"	47°30'32"	1250	2	9355 ± 50	8656–8561	0.21
SacA 53839	18°52'57"	47°30'32"	1250	3	11,270 ± 50	11,216–11,125	0.27
SacA 53840	18°52'57"	47°30'32"	1250	11.6	37,150 ± 950	40,396–38,834	0.31
Ly-17616	18°52'57"	47°30'32"	1250	13.5	36,755 ± 1640	40,571–36,659	0.37
<i>Edge of Mamba valley</i> ¹							
Gif-1479	Approx 18°48'	Approx 47°33'	1453	8-8.5	24,000 ± 100	26,200–25,921	0.34
Alaotra							
<i>Mahakary</i> ²							
Ly-15506	17°41'18"	48°21'43"	775	1.4	2700 ± 35	853–812	0.52
Ly-15507	17°41'18"	48°21'43"	775	2–2.45	4140 ± 35	2864–2634	0.55
Ly-15508	17°41'18"	48°21'43"	775	6–6.50	9405 ± 40	8733–8635	0.65
<i>Ambohitromby</i> ²							
Ly-10265 (GrA)	17°48'00"	48°11'30"	775	0	28,970 ± 140	31,466–31,033	n.a.
<i>Marianina</i> ²							
Ly-6770 (GrA)	17°51'15"	48°23'30"	770	23	12,130 ± 50	12,156–11,978	1.9
Ly-6769 (GrA)	17°51'15"	48°23'30"	770	28.5–30	15,270 ± 60	16,678–16,513	1.9
Ly-6768 (GrA)	17°51'15"	48°23'30"	770	30–30.5	14,770 ± 60	16,110–15,929	2
<i>Lake diatoms</i> ³							
	17°25'00"	48°11'30"	752	0.6–0.7	5190 ± 110	4078–3934	
	17°25'00"	48°11'30"	752	0.9–1.0	6830 ± 110	5814–5632	
Ambohibary							
Amb 1. PozA 118363	19°36'40"	47°11'13"	1655	0.3	4460 ± 40	3327–3029	0.07
Amb 2. PozA 118364	19°36'46"	47°11'16"	1663	3	26,090 ± 240	28,760–28,111	
Amb 3. PozA 118361	19°36'43"	47°10'18"	1652	3.1	22,150 ± 150	24,586–24,198	0.14
Amb L. Ly-12572	19°34'55"	47°10'38"	1710	Mine shaft	> 38,000	> 40,000	
Mangamila							
Ly-16508	18°34'42"	47°51'40"	1345	1	12,625 ± 45	13,988–12,961	0.08

Notes: 1: after Bourgeat et al., 1975; 2: after Mietton et al., 2018; 3: after Burney et al., 2004; 4: calibrated using Reimer et al. 2013 and Calib 7.10; Sample codes: Ly: Lyon CDRC; GrA: Groningen accelerator; SacA: Saclay accelerator; PozA: Poznan accelerator; Gif: Gif sur Yvette.

Table 2. Subsidence and specific denudation rates in the Alaotra and Ikopa drainage catchments

Variable of interest	Alaotra catchment (and Alaotra Basin depocentre)	Ikopa catchment (and Antananarivo Basin depocentre)
Accommodation space ¹ (m ³ /yr)	3525·10 ³	48·10 ³
Equivalent mass ² (t/yr)		
<i>Bulk density 1.2 t/m³</i>	4230·10 ³	57.6·10 ³
<i>Bulk density 1.8 t/m³</i>	6345·10 ³	86.4·10 ³
Equivalent specific denudation rate (SDRc), calculated ³ (t/km ² /yr)	940 to 1380	1.3 to 2
Specific denudation rate (SDRm), measured ³ (t/km ² /yr)	2000 to 2400	360
SDRm/SDRc ratio ⁴	~2	~150

Notes: 1. Accommodation space is measured as: depocentre area (km²) x mean sedimentation rate (mm/yr), and thus is expressed here as the volume of sediment that the basin accommodates annually without overflowing, i.e., without overtopping the bedrock sill at the basin's exit point. By equivalence, it is the annual accommodation space made minimally available by the tectonic subsidence rate. The Alaotra depocentre is 2350 km², the Antananarivo is 160 km². The sedimentation rates, 1.5 and 0.3 mm/yr, respectively, are the arithmetic means of the data (treated as grouped data) presented in Table 1.

2. Equivalent sediment mass deposited is calculated here on the basis of two optional values for sediment bulk density.

3. Specific denudation rates were measured for two montane watersheds SW and W of the Alaotra by Mietton et al. (2006), and were estimated for the Ikopa River by Roche and Aldegheri (1964). The two contributing montane catchment areas (i.e., depocentres excluded) are of similar sizes; Alaotra: 4600 km²; Ikopa: 4300 km². Range of reported denudation values depends on bulk density input.

4. Note that the ratios yield a value close to 1 for the Alaotra, but a high value for Antananarivo, suggesting in the latter case a strong imbalance between sedimentation rate and subsidence rate.

Table 3. Lavaka distribution in the Ikopa catchment upstream of Farahantsana knickpoint

Sub-catchment name	Sub-catchment area (km ²)	No. of lavaka	Mean density (lavaka/km ²)
Sisaony	838.4	124	0.15
Andromba	1239	103	0.09
Ikopa	1855	93	0.05
Mamba	376	17	0.04
Maniandro	158.2	6	0.03
<i>Total</i>	4466.6	343	0.08

Data source: from Helisoa (1983), maps consulted in BDPA et al. (1994), and spot checks and updates using Google Earth.

