2. LITERATURE REVIEW

Geology

The geology of the RNP region, and most of eastern Madagascar, consists of Precambrian metamorphic and igneous basement rocks (Figures 2.1 and 2.2). This Precambrian basement testifies to a complex geologic history that researchers have tentatively deciphered only within the last decade. The recent geologic advances have implications for pedology research in eastern Madagascar, because despite the availability of relatively high-quality geologic maps from the 1950s-1970s, no well-supported structural/tectonic scenario has previously existed for systematically correlating the igneous-metamorphic sequences from one region to another (Windley et al., 1994; Kroner et al., 2000). These geologic correlations provide a basis for more reliably defining the “soil systems” (Buol et al., 1989; Daniels et al., 1999) of the RNP region and possibly other areas of the eastern escarpment zone.

Until recently, even the origin of Madagascar's current geographic position was a source of lively scientific debate. Boast and Nairn (1982) summarized the three then-prevailing theories as to Madagascar's pre-Jurassic paleoposition: 1) adjacent to the Somalia-Kenya-Tanzania coast, 2) next to the Mozambique-Natal coast, or 3) essentially located where the island occurs today. A broad consensus has since emerged that Madagascar's paleoposition was adjacent to the present-day Somalia-Kenya-Tanzania coast, based upon a variety of data sources including magnetic anomalies, paleomagnetic data, geochronology, structural trends, lithologic correlations, stratigraphy, bathymetry, and biogeography (Martelat et al. et al., 1997, and sources therein; Paquette and Nédeléc, 1998; PALEOMAP Project, 1999).

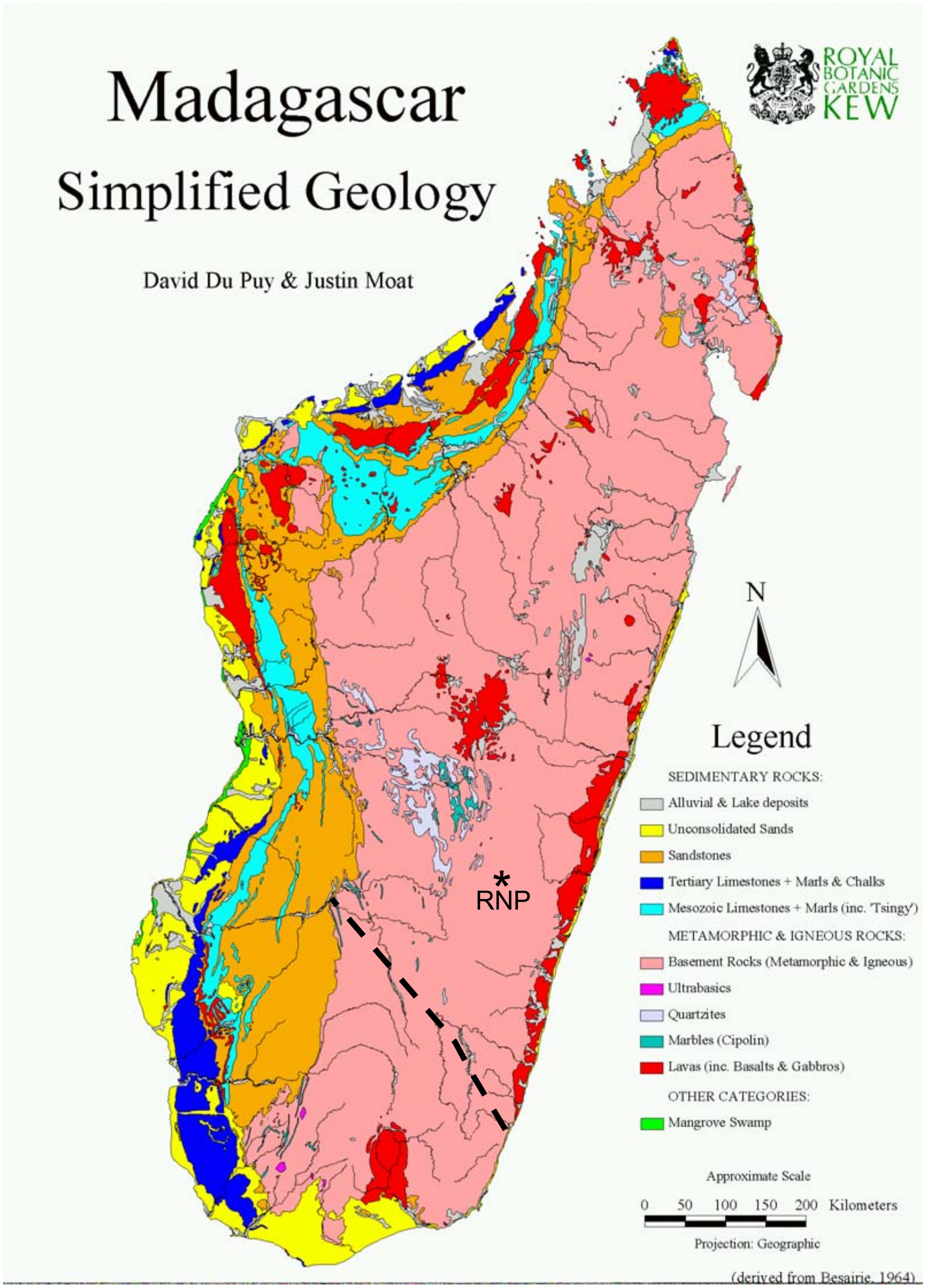

Figure 2.1. Simplified geology map by Du Puy and Moat (1996), after Besairie (1964). The general location of the RNP area is noted. Kroner et al. (2000) provide a detailed discussion of the lithotectonic subdivision of Madagascar's Precambrian basement. The dashed line represents the Ranotsara Shear Zone (added).

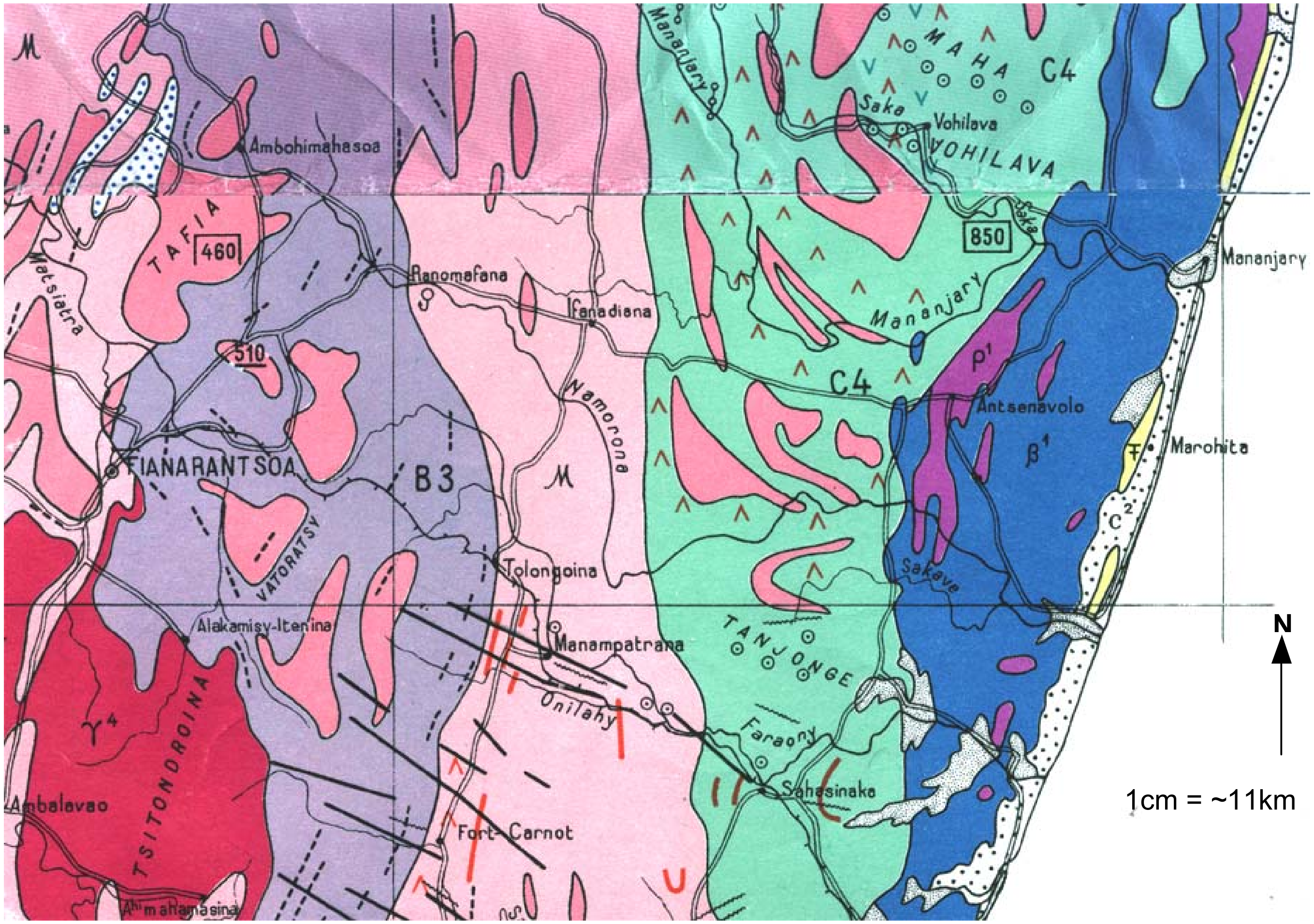

Figure 2.2. Geology map of the RNP region, taken from the “Madagascar Carte Géologique” by Henri Besairie (1964). The town of Ranomafana is in the upper left quadrant. A map legend is on the following page.

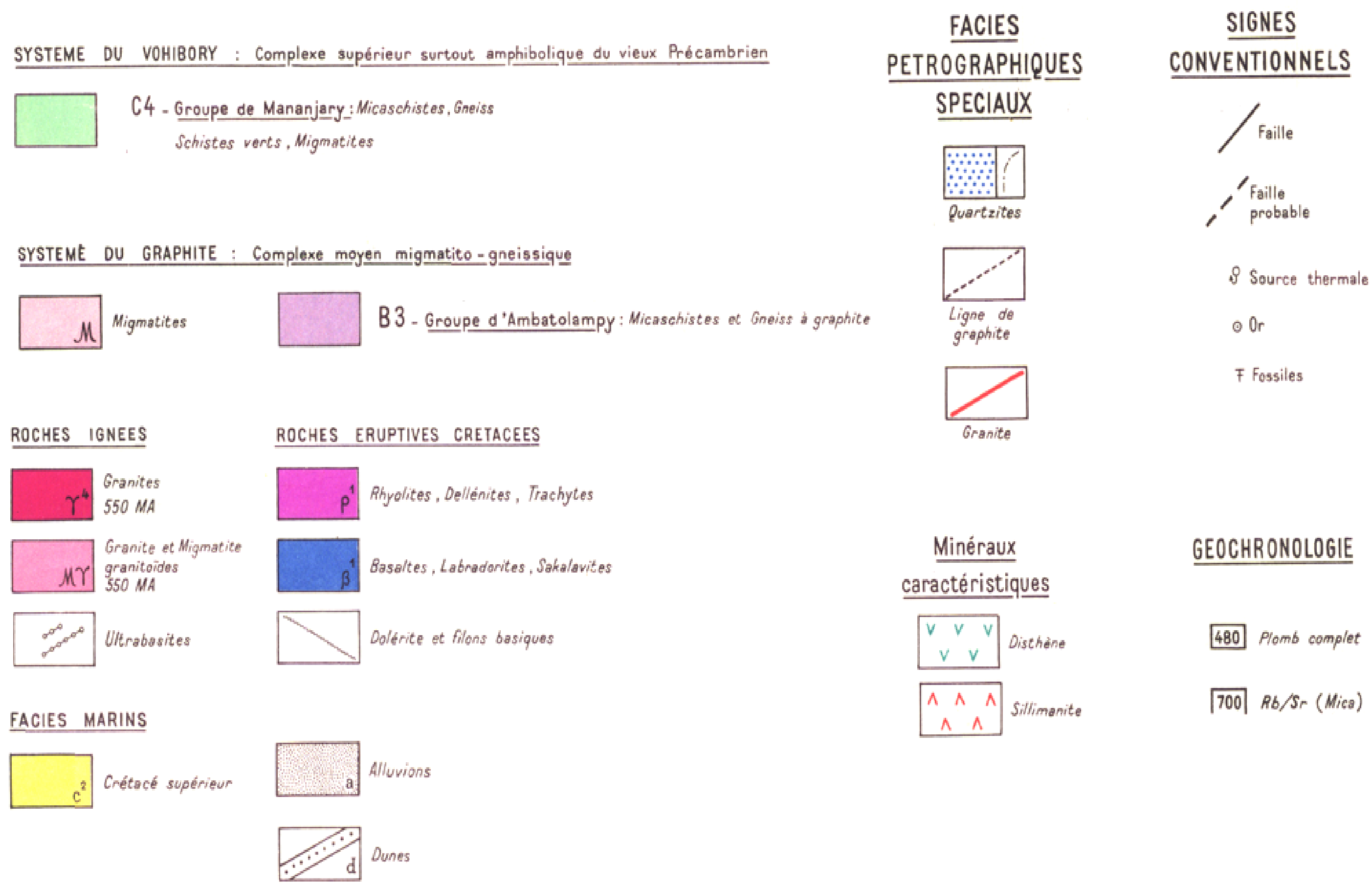

Figure 2.2 (continued). Legend for the geology map on the preceding page.

Madagascar's paleoposition placed it near the center of the southern supercontinent Gondwana, which formed in late Precambrian/early Cambrian time via the tectonic convergence of so-called western Gondwana (South American and West African cratons) with the cratons of east Gondwana (Arabia, eastern Africa, Madagascar, India, Sri Lanka, East Antarctica, and Australia). The convergence produced one of the largest orogenic belts ever on earth, the East African Orogen, with Madagascar at its center (Kroner et al., 2000). Although conventional interpretations describe a Himalayan-type collision between "pre-assembled" western and eastern supercontinents, geochronologic and structural data now indicate that eastern Gondwana underwent a polyphase assembly that was not fully completed until the amalgamation of greater Gondwana in early Cambrian time (Paquette and Nédélec, 1998; Meert, 2001). This massive assembly of continental crust provided the setting for intense metamorphism that generated the basement complex of the RNP region.

As stated by Windley et al. (1994), “The Precambrian of Madagascar represents the deep section of an exhumed thrust-thickened crust.” The basement rocks now exposed at the surface in the RNP region were formed at temperature and pressure conditions consistent with a depth of 15-18 km in the earth’s crust, or mid-crustal levels (Paquette and Nédélec, 1998; Martelat et al., 2000). This deep tectonic setting must be kept in mind when attempting to understand the geologic history of metamorphism, deformation, and igneous intrusions that produced the regional geology. The subsequent exhumation of this Precambrian terrain occurred as a function of the original tectonics and over 500 million years of weathering and erosion processes.

Geochronologic data, abrupt metamorphic changes, and tectonic structures (e.g., detachment faults, major shear zones) clearly indicate the presence of several major Precambrian crustal blocks or zones within Madagascar, each with a distinct geologic history (Windley et al., 1994; Collins et al., 2000; Meert, 2001). The geology references cited within this section generally provide information for wide regions throughout the island. For the purposes of this discussion, the geologic history is selectively reported here primarily as it affected the basement rocks of the RNP region. It should not be assumed that the geochronology, degree of metamorphism, and/or tectonic mechanisms that affected the study area necessarily apply to other Madagascar Precambrian sections.

The RNP region is geologically situated within a major tectonic unit designated as the “Antananarivo Block” (Collins et al., 2000; Kroner et al., 2000). This unit comprises much of the Precambrian basement in central Madagascar and extends into northern and southeastern areas of the country (Figure 2.3). The block is bounded on the south by the Ranotsara Shear Zone, which separates the Precambrian metamorphic belts of southern Madagascar and north-central Madagascar (Figures 2.1, 2.3). Kroner et al. (2000) interpreted the eastern margin of the Antananarivo Block to be a thrust over the Archean (3200-2500 Ma) Antongil Block and a possible major suture zone. However, they presented no structural evidence to support that interpretation and its reliability is therefore unknown. West of the RNP region, the Proterozoic metasediments and metabasites of the Itremo thrust sheet overlie the Antananarivo Block along a major extensional detachment, identified and named by Collins et al. (2000) as the Betsileo shear zone (Figure 2.3). Within the block itself, numerous major and minor shear zones record the compressional and extensional

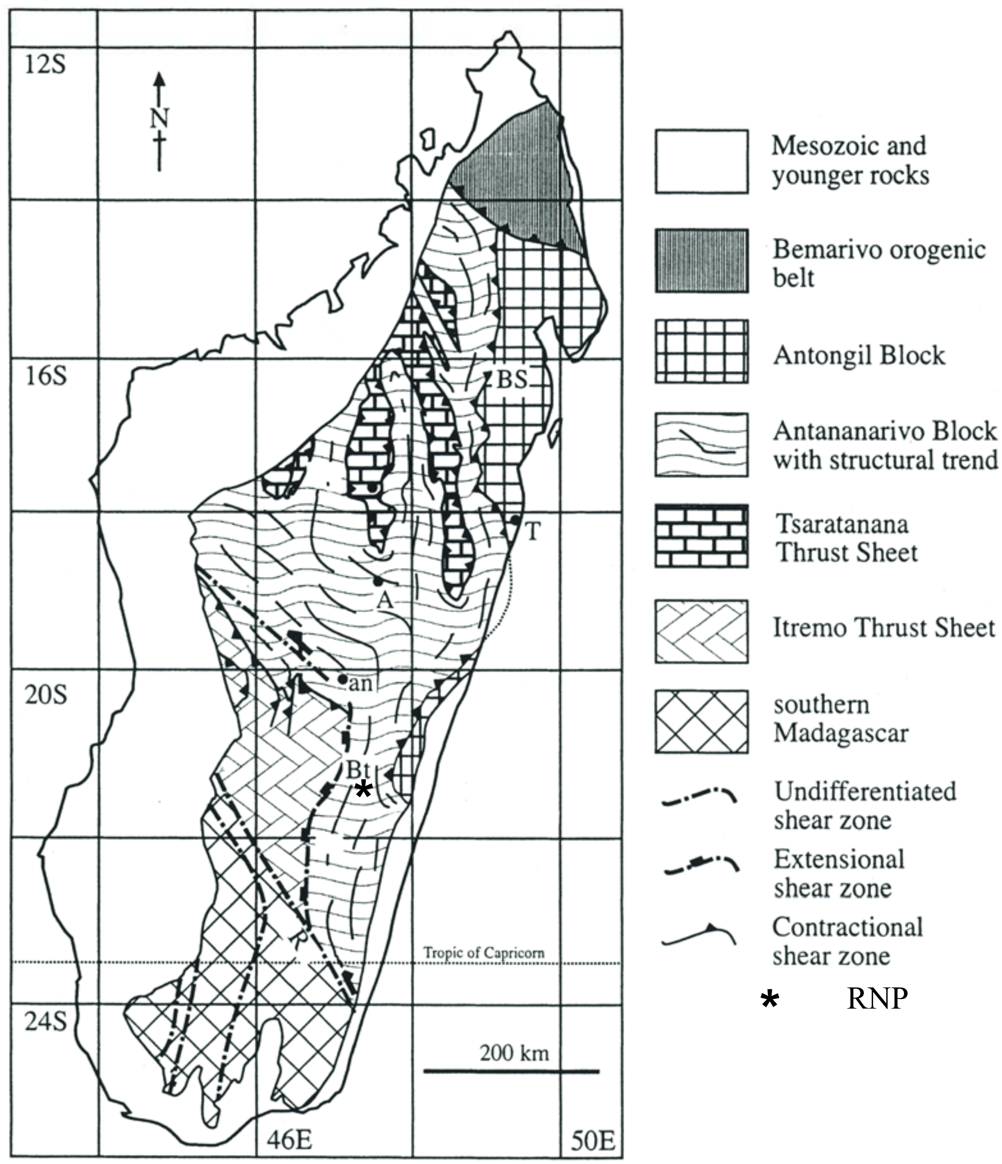

Figure 2.3. Schematic geologic map, showing the Antananarivo Block tectonic unit and its relationship to other major units (from Kroner et al., 2000). The RNP area (added) is located immediately below the "Bt" symbol. Bt = Betsileo shear zone, R = Ranotsara shear zone, A= Antananarivo, an = Antsirabe.

tectonics that accompanied metamorphism (Windley et al., 1994; Collins et al., 2000; Martelat et al., 2000).

The Antananarivo Block is comprised predominantly of orthogneisses (gneisses derived from igneous source rocks), migmatites (partially re-melted metamorphic rocks), and granites. Minor metamorphic rocks include quartzites and garnet-sillimanite mica schists (Windley et al., 1994). Rock units within the “Système du Graphite”, a Precambrian subdivision that dominates the RNP area geology, commonly contain graphite as an accessory mineral. Although the metamorphic rocks of the Antananarivo block were directly derived from the reworking of preexisting metamorphic and igneous rocks, the presence of graphite and the relatively high aluminum content of the rocks indicate an original sedimentary source for the material (as opposed to magma).

The intrusive granitoid units of the Antananarivo Block generally occur as conformable lenses, sheets/sills (the so-called “stratoid” granites), and plutons within the metamorphic sequences, though some (e.g., the Carion granite) are late syn-orogenic to post-orogenic and undeformed. The conformable granitoids possess flow textures that parallel the gentle west-dipping foliations found in metamorphic rocks within the block. Compositions generally range from granite to granodiorite, with more monzonitic (lower quartz) compositions fairly common (Nédélec et al., 1995).

The Antananarivo Block was subjected to high-grade regional metamorphism corresponding to granulite and upper-amphibolite facies conditions (Windley et al., 1994; Kroner et al., 2000). The geographically wide extent of relic charnockites (granite-composition rocks containing orthopyroxene) suggests that granulite-facies conditions were prevalent throughout the block at the height of metamorphism. However, the predominance of biotite and hornblende gneisses/migmatites indicates a widespread metamorphic retrogression to upper-amphibolite facies after peak conditions (Collins et al., 2000). The upper amphibolite facies was specifically characterized by Windley et al. (1994) as corresponding to the sillimanite-almandine-orthoclase facies. Nédélec et al. (1994) reported a thermobarometric estimate for an area north of Antananarivo of T = 700-750°C and P = 4-5 kbar, which closely matches the estimate by Martelat et al. (2000) for the RNP area.

The combined advances in geochronology, structural geology, and igneous-metamorphic petrology help to clarify the sequence of tectonic events that shaped the geology of the Antananarivo Block and the RNP region. Paquette and Nédélec (1998) concluded that central Madagascar collided with eastern Africa (Kenya-Tanzania) between 700-650 Ma, and that the thickened crust subsequently underwent an extensional collapse around 630 Ma that produced the extension-related stratoid granites. The extensional collapse is petrologically evidenced by the stratoid granites and structurally evidenced by the Betsileo shear zone extensional detachment (Paquette and Nédélec, 1998; Collins et al., 2000). This represented the initial phase of Madagascar's tectonic incorporation into a partially assembled Gondwana (Meert, 2001). The orogenic crustal thickening and subsequent extensional collapse around 630 Ma fostered the granulite-facies metamorphism, syn-extensional deformation, and granitoid magmatism that reworked the predominantly Archean (~2500 Ma) crust through about 550 Ma (Paquette and Nédélec, 1998; Collins et al., 2000).

The Antananarivo Block contains numerous major and minor shear zones that record compressional tectonic events that occurred around 560-550 Ma (Paquette and Nédélec, 1998; Martelat et al., 2000). The timing of this event is well constrained by isotopic dating within the shear zones and plutonic cross-cutting relationships. One major shear zone occurs near the RNP and is known as the Ifanadiana Shear Zone (Martelat et al., 2000), which is continuous with the Angavo Shear Zone that extends north of Antananarivo (Paquette and Nédélec, 1998; Meert 2001, Figure 12). The shear zones represent tightly folded compressional zones with major strike-slip components, which accommodated the tectonic stresses associated with the final intracontinental reworking and suturing of Madagascar within Gondwana (Paquette and Nédélec, 1998).

By the early Ordovician Period (~490 Ma), Madagascar was fully incorporated within the center of the southern supercontinent Gondwana and its major orogenic tectonothermal events were concluded (Martelat et al., 2000; Meert, 2001). As noted by Boast and Nairn (1982), this point marked the beginning of a major gap in Madagascar's geologic record, since no other Paleozoic rocks are dated with certainty until the Late Carboniferous (~300 Ma) tillites of the Sakoa Group in southwest Madagascar– a hiatus of nearly 200 million years. The tillites were deposited at approximately the same time that Gondwana integrated into Pangea, the largest supercontinent ever documented within the geologic record.

While the eastern two-thirds of Madagascar is comprised primarily of Precambrian basement (Figure 2.1), the western third of the island contains thick sequences (>11,000 meters in places) of sedimentary rocks (Boast and Nairn, 1982). These west-dipping sedimentary rocks, and associated rift structures that deepened the basins, record the breakup of Gondwana/Pangea and the transition from predominantly continental to marine sedimentation. Coffin and Rabinowitz (1992) summarized evidence that extension and rifting between Madagascar and Africa began as early as Permo-Carboniferous time (~290 Ma), and that seafloor spreading was initiated by the mid-Jurassic (~165 Ma). Madagascar actually rifted and drifted from Africa still amalgamated to India, joined along Madagascar's present-day east coast and India's modern west coast. The landmass drifted via a combination of extensional and transform tectonics along the Davie fracture zone, with seafloor spreading between Africa and Madagascar ceasing at approximately 125 Ma (Coffin and Rabinowitz, 1992; Rogers et al., 2000).

The final major tectonic event that shaped the RNP regional geology was the rifting of the Indian subcontinent from Madagascar's present-day east coast. The rifting and associated Cretaceous magmatism relate to the track of the Marion hotspot relative to Madagascar's paleoposition (Storey et al., 1995; Torsvik et al., 1998). Approximately 65 km east of the RNP, flood basalts and rhyolites overlie Precambrian basement (Besairie, 1964). Storey et al. (1995) dated these extrusive igneous rocks near Mananjary at 84-86 Ma, which is essentially synchronous with the initiation of seafloor spreading between Madagascar and India. Mafic dykes in south India (Karnataka) reflect the same age and general composition as the Mananjary extrusives, supporting the idea that the Marion hotspot mantle plume may have caused the breakup of Madagascar and India (Kumar et al., 2001). This Late Cretaceous rifting event relates directly to the geomorphology and ecology of eastern Madagascar, because it ultimately resulted in the "great escarpment" (Ollier, 1985) that retains much of the island's remaining rainforest. Interestingly, the western margin of India possesses a great escarpment (the Western Ghats) that mirrors the great escarpment of Madagascar to a high degree (Ollier, 1985; Subrahmanya, 1998).

Madagascar's geologic history bears a direct relationship to its remarkably endemic biodiversity, and recent paleontological studies are shedding light on an old scientific problem. Krause et al. (1997, p.3) stated, “The biogeographic origins of the modern terrestrial and freshwater vertebrate fauna of Madagascar remain one of the greatest unsolved mysteries of natural history.” The main questions revolve around when Madagascar effectively became biogeographically isolated, whether the island’s current vertebrate fauna radiated from ancestral stocks since the Late Cretaceous or Paleogene, or whether the vertebrate taxa arrived via random (“sweepstakes”) dispersal across the Mozambique Channel from Africa since the Cretaceous. Rich vertebrate fossil assemblages found in the Maevarano Formation of northwestern Madagascar strongly suggest that the vast majority of modern vertebrate taxa arrived in post-Cretaceous time via random dispersal from Africa (Krause et al., 1999; Rogers et al., 2000). It should be noted here that a few researchers have published papers suggesting a land bridge may have existed along the Davie Ridge in Late Cretaceous or Tertiary time (e.g., McCall, 1997). The collective bathymetric, sedimentological, and geochronological data categorically refute those hypotheses (Rogers et al., 2000).

Little geologic literature exists that is specific to the RNP region, with the exception of the 1:100,000 scale geologic map coverage and an associated report. This is perhaps not surprising, given that prospects for economically significant minerals in the area are considered poor and the region is difficult to survey. The most definitive geologic research on the region was performed in 1967, which involved standard geologic mapping and prospecting by the Madagascar Service Géologique of an ~8000 km^2 area centered on the RNP (Chantraine, 1968). The report noted that the region was poorly known due to the difficulty in penetrating the forested escarpment zone, the deep weathering and lack of rock exposures, and the structural complexity of the geology. One other notable publication, Guiges and Laplaine (1949), provided detailed petrographic descriptions for a few rock units at the top of the Namorona River gorge.

The lithologies present within the RNP region have been described rather consistently by several researchers as predominantly gneisses and migmatites of upper amphibolite to granulite metamorphic facies. Chantraine (1968) describes two major zones surrounding the RNP, one encompassing the escarpment and highlands to the west (i.e. west of Ranomafana), and another at the foot of the escarpment that continues east of Ifanadiana (see Figure 3.1). The escarpment/highland zone is described as migmatitic with biotite predominant. The major rock types are described as migmatite, “granitoid migmatite” (highly quartzo-feldspathic), biotite gneiss, feldspathic gneiss, gneiss with amphibole and/or pyroxene, and granite. Minor rock types include garnet-sillimanite biotite schist and pegmatites. Due to the style of deformation, the outcrops of rock units are irregular and difficult to predict. Banks or veins of sillimanite, graphite, amphibolite, pyroxenite, and almandine are also noted. The overall composition of the major rock types ranges from granite to granodiorite to quartz diorite, with quartz, albite/oligoclase, orthoclase (often perthitic), microcline, biotite, hornblende, sillimanite, almandine, and graphite as common mineral species. Cordierite and epidote are not common but can be found. One tiny outcrop of ultrabasic rock, described as a serpentinite, was reported near Alakamisy.

The second zone described by Chantraine (1968), east of Ranomafana, was characterized as migmatitic with hornblende “predominant” and biotite “frequent”. The overall composition of the rocks is slightly more calco-magnesian than the escarpment zone. The metamorphic grade is slightly higher than that of the escarpment/highland zone, with associations of quartz, perthite, garnet, hornblende, diopside, and hypersthene that tend toward granulite facies. Quartzites with various iron minerals are present, in addition to the same mineral veins present as in the escarpment zone. The occurrence of cordierite is more common. An important “granodiorite facies” is present at the village of Kelilalina. Although upper-amphibolite and granulite metamorphic facies predominate, thermal/chemical heterogeneity and metamorphic retrogression at the outcrop scale can produce mineral assemblages from lower metamorphic facies. Good examples are muscovite and microcline, which typically are not present in these high-grade rocks, but which either form from retrogression reactions or are inherited from the protolith. Retrograde reactions usually occur extensively within high-grade terrains (Miyashiro, 1994).

The eastern zone described by Chantraine (1968) correlates in part with the Ifanadiana shear zone as mapped by Martelat et al. (2000). The Ifanadiana shear zone is visible in Figure 3.1, centered on the town of Ifanadiana, and is recognized by the regular outcrops of steeply dipping, tightly folded beds that trend north-south. This is perhaps the only portion of the study area where specific rock units/beds can be traced for a significant distance with any degree of confidence.

The study by Guiges and Laplaine (1949) involved petrographic descriptions for rock units just east of Vohiparara, where the Namorona River plunges over the escarpment. They reported mineralogy for several rock types: a granite, a feldspathic amphibole-rich schist, an amphibole-rich schist, and a garnet-bearing schist. It should be noted that the “schist” samples were apparently obtained from the ferromagnesian-rich zones of migmatite outcrops. The granite contained quartz, microcline (regular or perthitic), oligoclase, and biotite, with disseminated grains of zircon and apatite. The feldspathic amphibole-rich schist included quartz, plagioclase (reported as “probably” andesine), abundant green hornblende, augite, and apatite. The amphibole-rich schist contained large porphyroblasts of orthoclase embedded in thin layers of biotite, hornblende, quartz and feldspars. The garnet-bearing schist was similar to the amphibole-rich schist, with the addition of numerous coarse garnet crystals. These mineral assemblages generally reflect the range of compositions found within the gneiss-migmatite-granite terrain.

The thermal springs at Ranomafana occur due to the intersection of numerous brittle faults that provide an avenue for deep circulation of regional groundwater (Saint-Ours, 1958). The most prominent faults are generally oriented N60°W and extend from the highlands above the escarpment into the Ifanadiana shear zone, with minor faults controlled at least in part by the shear zone (J. Martelat et al., personal communication). The origin of the faults is not definitively addressed in the literature, but may well be related to the widespread Cretaceous igneous activity (Rechenmann, 1982; Storey et al., 1995). The Cretaceous igneous connection may be the most probable hypothesis for the major faults in the RNP region, based upon the similar N60°W orientation of Cretaceous dolerite dikes at the same latitude east and southeast of Morondava.

As stated by Windley et al. (1994), French and Malagasy geologists produced high-quality detailed geologic maps with the Service Géologique mapping program, under the leadership of Henri Besairie. These maps have provided an important baseline for all subsequent studies of Madagascar's geology. The 1:100,000 scale maps for this study included sheets O-52 (Ambohimahasoa), O-53 (Alakamisy), P-52 (Ambohimanga du Sud), and P-53 (Ifanadiana) (Service Géologique, 1970, 1977).

The older geologic literature for the Madagascar Precambrian basement (e.g., Chantraine, 1968) refers to lithostratigraphic groups and systems that were defined primarily on the basis of overall lithology, degree of metamorphism, and characteristic minerals (e.g., graphite). The more recent literature (e.g., Collins et al., 2000) tends to divide the Precambrian basement into tectono-metamorphic units based primarily upon lithologies, structural features (e.g., faults, shear zones) and geochronology data. Therefore, when interpreting older geologic map legends such as the legend for Figure 2.2, emphasis should be placed upon the lithologic descriptions for each unit (e.g., “micaschistes”) rather than the assigned unit name (e.g., “Groupe d’Ambatolampy”). For those who perform research using the older literature or maps, Caen-Vachette (1979) provides a useful schematic map that illustrates geographic locations for the various geologic units.

There are several key observations to make regarding the geology of the RNP region and its relationship to soil genesis and soil properties. One, the overall chemical composition of the geologic units ranges from granite to granodiorite or quartz diorite chemistry. High base-status parent materials (e.g., amphibolites and pyroxenites) are present, but occur only as small banks or veins. Two, although the regional geology is a fairly monotonous repetition of high-grade gneisses and migmatites with granite intrusions, the deformation style creates a geologic spatial variability that is difficult to predict on a landscape scale, and often even on an outcrop scale. Martelat et al. (2000) noted that beds with contrasting mineralogy vary on a scale from millimeters to tens of meters within the Ifanadiana shear zone. Finally, there is no doubt that the rugged terrain, deep weathering profiles, vegetative cover, and lack of roads often prevent a direct observation of underlying geology for documenting soil-parent material relationships.

One final note regarding the geology literature concerns magnetic declination. Some researchers working with the RNPP have indicated confusion regarding the direction of magnetic declination within the RNP region, which is important for accurate compass bearings in fieldwork. By convention, declination is assigned a negative sign when magnetic north occurs <u>west</u> of true north (i.e., west declination). Magnetic declination varies over time, so values must be checked periodically. Cattala (1955) reported that the magnetic declination between Fianarantsoa and Mananjary was 13° to 14° west declination (-13° to –14°) as of 1955. The author crudely measured the magnetic declination at Ranomafana with a Brunton compass as –14° in October 1991. Published declination values for Fianarantsoa indicate a –18° declination as of 1995 (Ranaivo-Nomenjanahary et al., 1998). Computer magnetic field models available at the US National Geophysical Data Center (NGDC, 2001) calculate magnetic declinations between –16° and –18° for the period 1991-2000, uncorrected for local factors. At this time, it appears that the most reliable number for magnetic declination is the 1995 measurement reported in Ranaivo-Nomenjanahary et al. (1998), which is –18° (west declination).

Geomorphology

The recent geology research on Madagascar yields an increasingly detailed picture of the island's geology and geologic history, yet the same unfortunately cannot be said for geomorphology research. Most of the limited Madagascar geomorphology literature dates from the 1950's to early 1970's, and while much of it represents excellent research, the science of geomorphology has advanced significantly since that time.

The Madagascar geomorphology research occurred at a time when a historical/descriptive approach to geomorphology predominated, thus the literature is characterized by general landform descriptions, models of cyclic erosion and planation surfaces (e.g., per William Morris Davis and Lester King), and the extrapolated dating of broad geomorphic surfaces based upon limited and/or incompletely documented evidence. The problem with these approaches alone, as opposed to process-oriented or integrated process-historical geomorphology studies, is that broadly generalized landscape interpretations are always open to debate and have little practical application in the geosciences (Ritter, 1988). In contrast, a more recent process-oriented study of Madagascar's stonelines (stone-layers) aids in understanding the genesis and distribution of these features, as well as providing a model for landscape evolution over long periods of time (Wells, et al., 1990).

Another unavoidable limitation of the older Madagascar geomorphology literature is that most published research occurred before the establishment of plate tectonics as a prevailing paradigm in geology, and certainly occurred before the widespread integration of tectonics, geophysics, geomorphology, thermochronology (e.g., apatite fission-track thermochronology), etc.. There are several key aspects of Madagascar's geomorphology that simply cannot be adequately explained without a modern tectonic and/or geophysical framework, perhaps most notably the formation of the eastern great escarpment (e.g., Ollier, 1985; Subrahmanya, 1998; Cockburn et al., 2000) and the anomalously high elevation of the central highlands Precambrian basement (Forte and Mitrovica, 2001).

Finally, the general lack of modern geomorphology research in Madagascar essentially created a vacuum that has compelled authors from various disciplines to cite outdated and occasionally inaccurate research. This general phenomenon was widely noted by RNPP researchers regarding several academic subject areas, not just geomorphology. In the absence of modern research, successive authors cite the same outdated geomorphology literature, and by sheer repetition the results of a few studies become entrenched in the general literature as “fact” without significant critical review and regardless of the original data quality. In reality, there appear to be no overall syntheses of regional geomorphology in Madagascar that are well supported with detailed geomorphology data, geochronologic and/or thermochronologic data, and a sound modern theoretical framework.

The general geomorphology of Madagascar is presented in Figures 2.4a and 2.4b. The digital elevation model (DEM) in Figure 2.4a highlights the three main zones or provinces typically described in narratives of Madagascar’s physical geography: the “sedimentary zone” to the west, the central highlands, and the “eastern slope” or east coast domain (Battistini, 1972; Chaperon et al., 1993). The limits of each of these geomorphic regions can be seen on the island cross-section (Figure 2.4b). In general, Madagascar displays a pronounced topographic asymmetry in an east-west direction, a function of the bedrock geology and variable surface processes acting over millions of years. The higher elevation regions and the “continental” drainage divide occur close to the eastern escarpment, as demonstrated in Figure 2.5. The topographic asymmetry is also evident in Figure 2.5 when comparing the relative length of rivers and drainage basin sizes east and west of the divide. Average elevations decrease gradually toward the west, while the topography abruptly lowers to the east across the escarpment.

Figure 2.4a. Shaded DEM image of Madagascar. The topographic cross-section A-A' extends 500 km between the Mangoky River delta and the mouth of the Mananjary River (see Figure 2.4b). The RNP is indicated by the red polygon. The eastern escarpment is visible south of Antananarivo as the dark line sub-parallel to the east coast (and corresponds to the remaining rainforest on Figure 1.1). Shaded DEM courtesy of the Center for Conservation Biology, Stanford University, produced from Digital Chart of the World (DCW) 30 arc-second data.

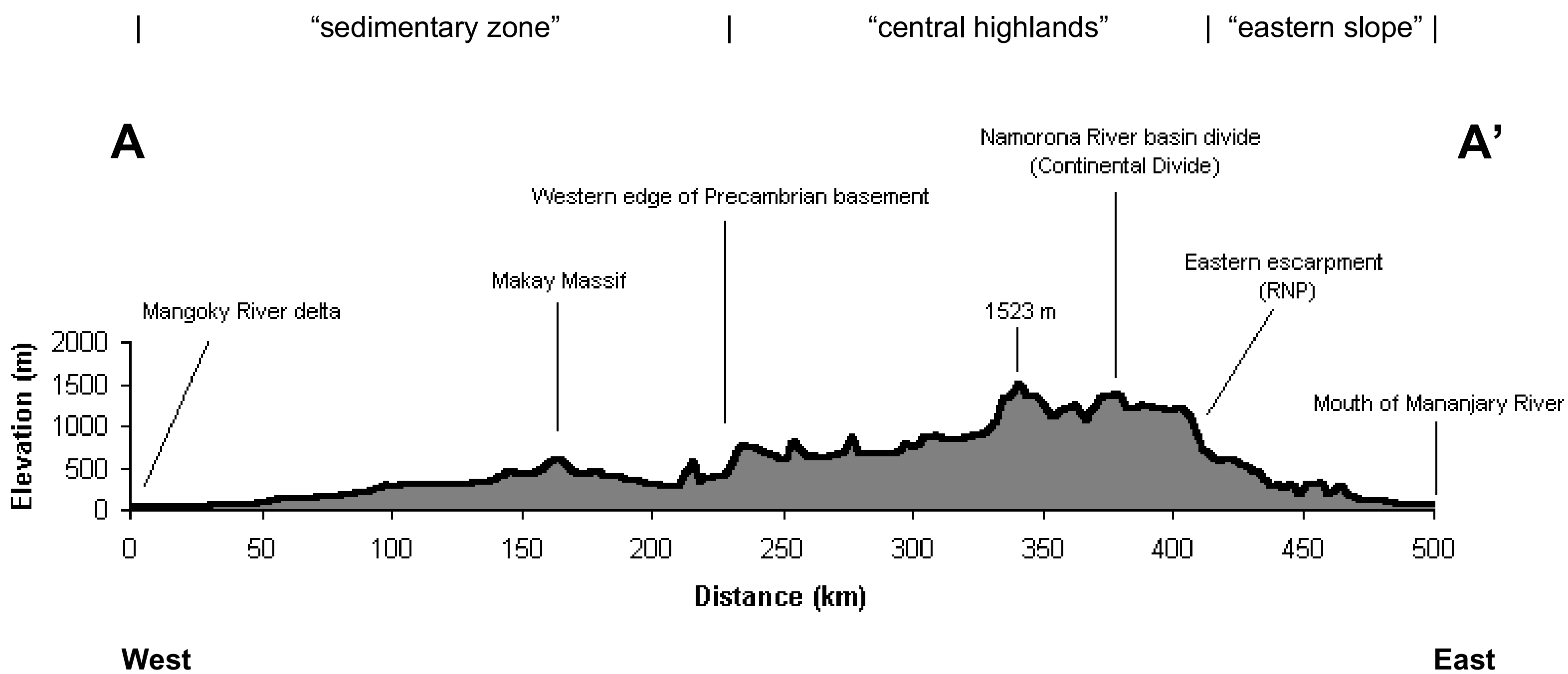

Figure 2.4b. Topographic cross-section A-A', as indicated on Figure 2.4a. Major landmarks and geomorphic breaks are noted. The highest point on the cross-section (1523 m) is found 30-40 km northwest of Fianarantsoa, on Precambrian quartzite/granite. It is important to note that the 30 arc-second DEM elevation data have a grid spacing of approximately 1 km and limited resolution. Therefore, both the DEM and derived cross-section must be considered as topographic approximations. Comparisons with published topographic maps indicate that the data are generally accurate.

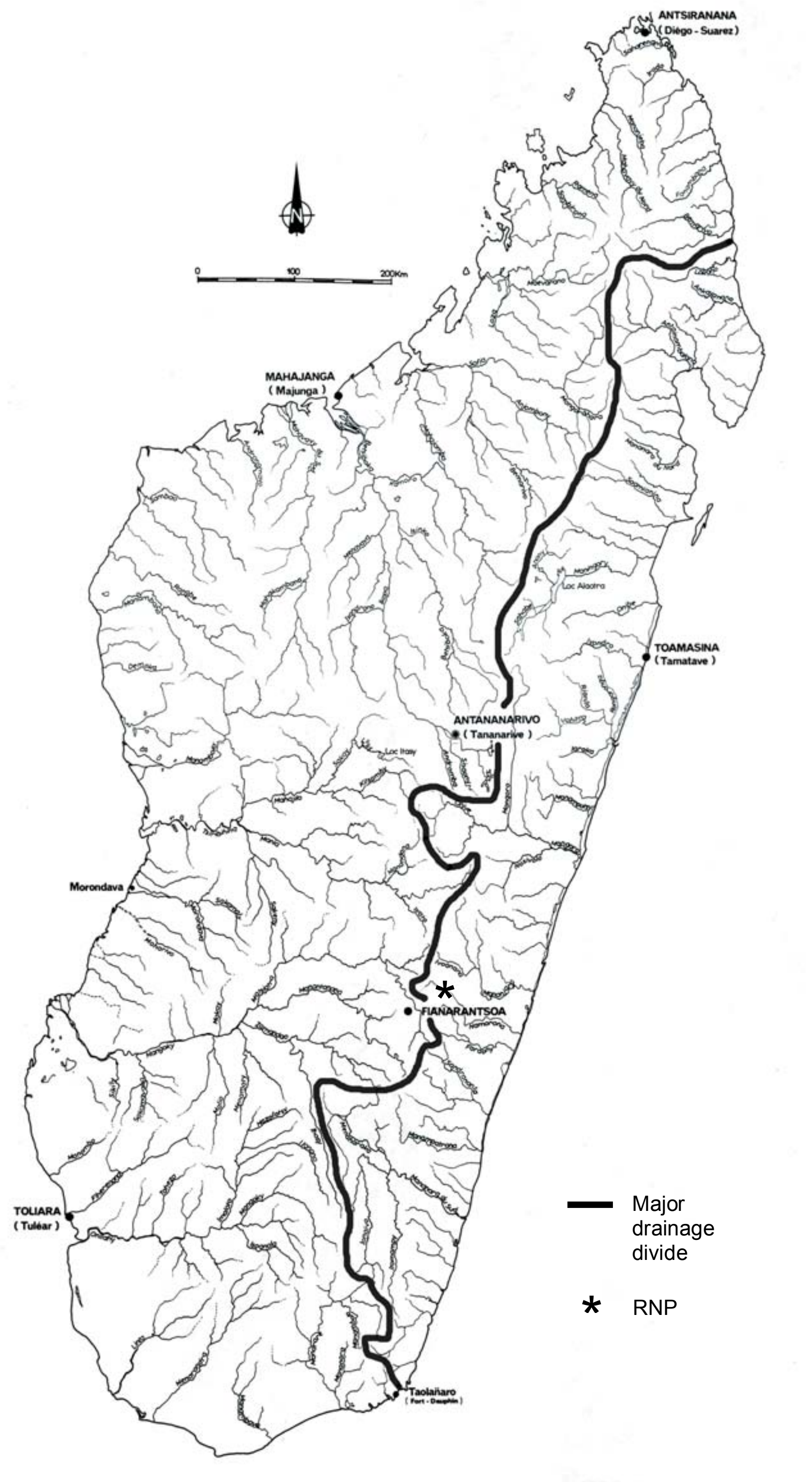

Figure 2.5. Major drainage patterns in Madagascar, from Chaperon et al. (1993). The major drainage divide (added) is approximate. The Namorona River bisects the RNP.

The “central highlands” are generally defined in the literature as including the broad area of Precambrian basement between the sedimentary zone and the eastern escarpment (Battistini, 1972; Chaperon et al., 1993). The boundary with the sedimentary zone can readily be seen on the DEM (Figure 2.4a) and the simplified geology map (Figure 2.1), while the eastern escarpment is plainly visible on the DEM north and south of the RNP. Both older and recent literature sometimes refer to the central highlands as the “hauts plateaux” (“high plateaus”), which is a misnomer considering that most of the land in this zone is neither flat, nor are extensive flat regions elevated above the surrounding terrain. The term “central highlands” (“hautes terres centrales”) is therefore preferred (e.g., Bourgeat, 1972; Chaperon et al., 1993; Segalen, 1995). This central region includes the highest elevations in Madagascar. Two of the highest points occur within the geologically “young” Plio-Quaternary volcanic regions of Tsaratanana (2876 meters) and Ankaratra (2642 meters). Another high point (2658 meters) occurs on Precambrian syenites of the Andringitra area, south-southwest of Fianarantsoa.

Madagascar’s main drainage divide occurs within the central highlands, just west of the eastern escarpment (Figure 2.5). The divide maintains a generally regular distance from the east coast for most of its length, with two obvious exceptions. Southwest of Fianarantsoa, the divide is deflected westward by the topographic break across the Ranotsara Shear Zone (Figure 2.1). The other major anomaly, south of Antananarivo, resulted from the blockage of an originally westward-draining river by the emplacement of the Plio-Quaternary Ankaratra volcanics. The topography in that area slopes generally to the west, yet the present-day Onive River flows to the east, since the volcanic blockage forced the river system to reverse its original drainage direction (Bourgeat, 1972).

To the west of the central highlands, the sedimentary zone maintains a relatively subdued topography (Figure 2.4a). The sedimentary strata dip westward, and local topographic highs are generally due to the presence of east-facing cuestas. The cuestas result from differential erosion and the persistence of erosion-resistant formations, which include sedimentary rocks as well as igneous extrusives. The sedimentary zone meets the Precambrian basement via a combination of faults and unconformities (Besairie, 1964; Boast and Nairn, 1982). The presence of datable fossiliferous beds, occasionally interstratified with Cretaceous lavas, and the documented sedimentary stratigraphy provide the best opportunities in Madagascar for both relative and absolute dating of older erosion surfaces.

The central highlands south of Antananarivo are bounded directly on the east by the great escarpment, which can be traced nearly the length of Madagascar (Figure 2.4a). The escarpment is typically referred to in the French literature as “la grande falaise oriental” (e.g., Besairie, 1970). East of Antananarivo, the escarpment trend is complicated by the presence of the Alaotra-Mangoro grabens that formed in Pliocene time (Bertil and Ragnoult, 1998), and the escarpment is known in that region as the “Falaise de l’Angavo” (Bourgeat, 1972). At the RNP, the escarpment relief averages approximately 500 meters, and is expressed as abrupt cliffs or a series of steeply incised surfaces across various drainage basins. The escarpment marks the abrupt transition from the central highlands to what is often referred to (even in geomorphology articles) as the “coastal plain” (e.g., Dixey, 1960).

Examination of topographic maps and/or aerial photographs reveals that the 50-100 km wide “coastal plain” between the escarpment and the east coast actually contains relatively little flat land, except for areas immediately bordering the coast. An accepted definition of “coastal plain” is as follows:

> A low, broad plain that has its margin on an oceanic shore and its strata either horizontal or very gently sloping toward the water, and that generally represents a strip of recently prograded or emerged sea floor (Bates and Jackson, 1984, p. 95).

The only portion of the definition that is met by this region is its adjacency to the Indian Ocean. In fact, most of this area maintains local relief of 100 meters or more, measured from hilltops to local base levels, and the landscape becomes progressively more dissected and steep inland from the coast. This is true even of the basalt/rhyolite terrain west and southwest of Mananjary (FTM/IGN, 1962). Most of the surface geology is dominated by Precambrian basement and Cretaceous extrusives, with only limited occurrences of Cretaceous sedimentary strata 0-20 kilometers from the coast (Besairie, 1964). Therefore, the application of the term “coastal plain” to this region is erroneous. The term suggested here is “eastern lowlands”, which conforms to the convention for the “central highlands” region. Alternatively, the term “eastern slope” (“versant oriental”) has been utilized in the French literature (e.g., Bourgeat, 1972; Chaperon et al., 1993) and is generic enough to be accurate. In any case, the regional geomorphology designations should be followed by accurate descriptions of topography, supported where possible by morphometric data such as average relief, predominant slope classes and their proportional extent, river gradients, etc.

A single geomorphology article by Dixey (1960) remains the primary English-language source on the regional geomorphology of Madagascar. The primary French-language literature is not much more recent or extensive (e.g., Dresch, 1962; Battistini and Petit, 1969; Bourgeat and Petit, 1969; Besairie, 1970; Bourgeat, 1972). All of the regional geomorphology literature essentially details a succession of “planation surfaces” (“surfaces d’aplanissement”), their local correlation with datable strata where possible, and the extrapolation of the correlated surfaces across large distances. All rely heavily on the African landscape evolution models as proposed by Lester King (e.g., King, 1953). Dresch (1962) and Bourgeat (1972) correctly noted these geomorphic studies represented several tentative “attempts” to decipher the landscape, as the definition and dating of widespread erosion surfaces were based upon limited and often inconclusive evidence. They also indicated that these defined surfaces were essentially altimetric in nature, which rested upon application of a Davisian landscape paradigm, an assumed lack of structural controls on erosion, and an assumed lack of differential tectonic adjustments since Jurassic time, among other considerations (Bourgeat, 1972).

Based upon these assumptions, and widespread field observations, Dixey (1960) defined four major planation surfaces in Madagascar (Figure 2.6). The basic scheme was largely retained by Besairie (1970) and bolstered with more discussion of geomorphic data and relative dating. The major difference between their interpretations rested with Besairie’s view that the majority of Madagascar’s Precambrian basement terrain essentially represented polycyclic landscapes (where uplift establishes a new base level prior to completion of a planation “cycle”), while Dixey bracketed specific ages for each set of major surfaces. Dixey did recognize the polycyclic nature of certain regions, but apparently emphasized dating the major cycles and surfaces over the vagueness of simply labeling broad areas as “polycyclic”. The dating of surfaces was based mainly upon the local relationship of the intermediate-elevation erosion

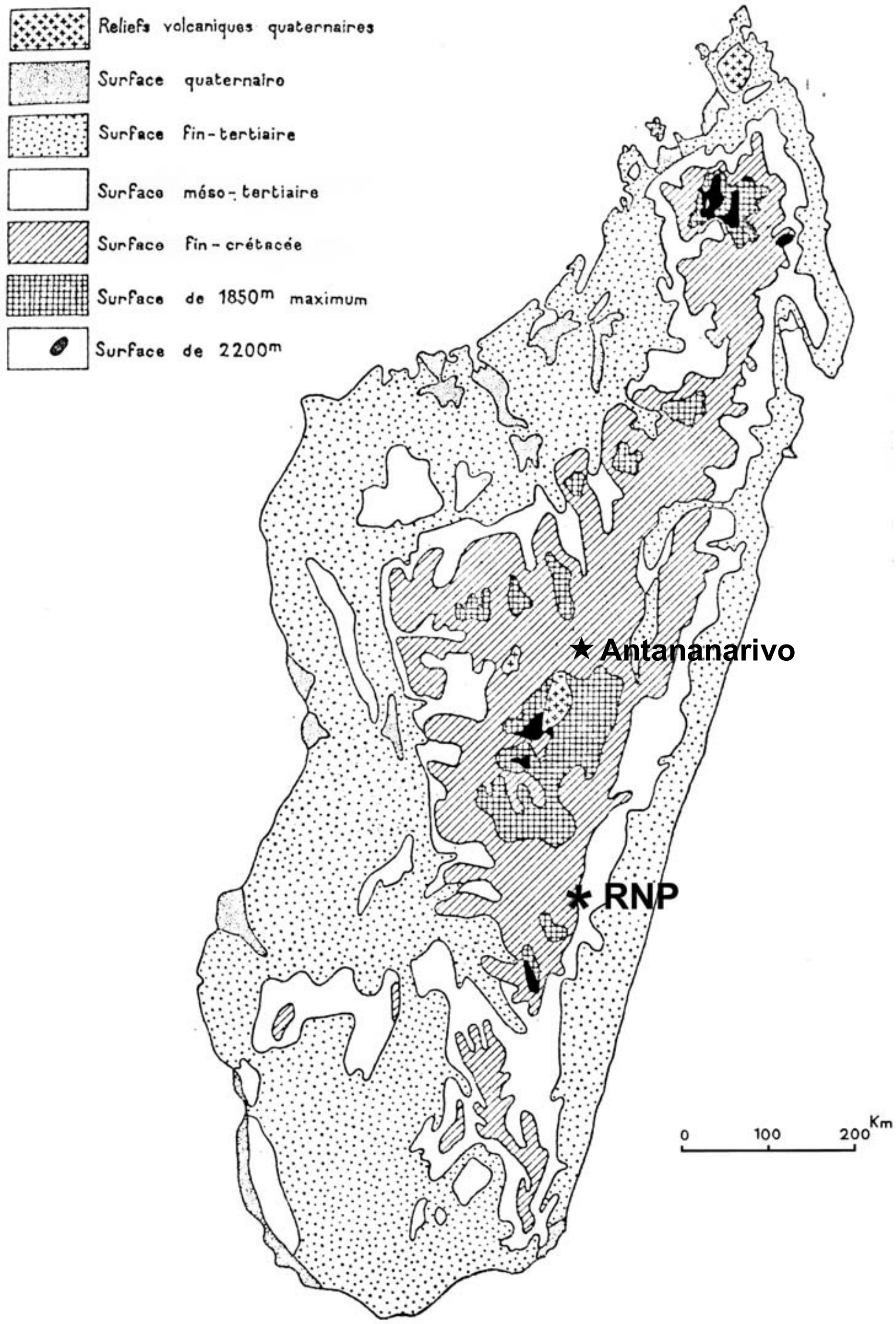

Figure 2.6. Schematic map of major geomorphic surfaces from Dixey (1960). The two highest surfaces shown (excluding Plio-Quaternary volcanic regions) were attributed to a Jurassic age. Quaternary surfaces and volcanic relief are also depicted. (The approximate location of the RNP and Antananarivo were added to the original.)

Table 2.1. Summary of major erosion surfaces after Dixey (1960) and Besairie (1970).

Attributed Age	Descriptions from Dixey (1960) and Besairie (1970)
"Jurassic"	Two major surfaces, the higher reaching maximum elevations of 2200 meters (e.g., Andringitra, Ibity), and the lower 1850 meters (e.g., Fenoarivo and Ankazobe, northwest of Antananarivo). These occur on relatively flat elevated highlands (*tampoketsa*). The geologic age of these surfaces "are attributed to the Jurassic but without established dating." (Besairie, 1970, p. 129) The Jurassic age was assigned because these surfaces occur substantially higher in the landscape than the intermediate surfaces established as Late Cretaceous in age (see below). [Note that the high elevation areas of the Tsaratanana and Ankaratra volcanic centers cannot be Jurassic in age, since the volcanic deposits are only of Tertiary and Quaternary origin.]
"Cretaceous"	According to Dixey, this is represented by *tampoketsa* and other surfaces within the central highlands, occurring at ~1300-1600 meters elevation. Besairie depicted a much more limited extent of Cretaceous surfaces, and assigned much of Dixey's scheme to a polycyclic set of surfaces. Maximum date (Late Cretaceous) is well constrained in central Madagascar (e.g., Kamoro, Beveromay, Analatsimo, all north of Antananarivo) by planation of ~88Ma weathered basalts and sedimentary strata. In the southwest, surfaces at comparable elevations cut across slightly younger basalts. The tops of some granite inselbergs presumably correlate with this surface. The eastern escarpment essentially demarcates the eastern border of this surface.
"Mid-Tertiary"	Dixey (1960) depicted these surfaces between 1000-1100 meters elevation, essentially surrounding the edge of the central highlands. Besairie (1970) designated a more limited extent of these surfaces between 1000-1200 meters elevation, and placed much of Dixey's mid-Tertiary surface into a polycyclic category. Both authors showed the surfaces comprising extensive areas in the southwest and west of Madagascar. The Horombe plateau represents the best example of this surface. The age of the Horombe surface was constrained by its truncation of Eocene sediments, and the deposition Miocene limestones above it. In the east, Besairie depicted polycyclic landscapes above and below the escarpment. Dixey interpreted the escarpment as a transition from Cretaceous to mid-Tertiary surfaces.
"End-Tertiary"	Both authors described these surfaces between elevations of "near sea level" to 400-500 meters, occupying most of the sedimentary zone and the eastern lowlands. Elements of this surface were described up to 900 meters elevation in major river valleys and "intermont plains". The end-Tertiary date was assigned based upon the relationship of the surfaces to Pliocene deposits on the west coast. Based upon each author's schematic map, the end-Tertiary surfaces are the most extensive of the major erosion surfaces.

surfaces to fossiliferous sediments and igneous extrusives in western and southern Madagascar (see also Bourgeat, 1972), and the surfaces were defined by the authors as summarized in Table 2.1. Both authors noted that in addition to the major erosion surfaces, the Quaternary surfaces are represented by the youngest coastal plains, alluvial deposits, and rejuvenated (incised) erosion surfaces within the older landscapes.

Dresch (1962) observed that if indeed the planation surfaces “dominate” Madagascar’s geomorphology, then they are complex, highly dissected, and complicated by structural factors. The reality is that most of Madagascar’s topography is not dominated by planation surfaces; the major erosion surfaces are merely the presumed benchmarks for relative dating of landscapes. Furthermore, the concept of landscape “age” poses serious problems for geomorphologists, as highlighted by Thomas (1994). Landscapes represent multiple geologic ages, and there is a major conceptual difference between the *initiation* age of a general landscape form (e.g., a major planation surface) and the age of the present topography. By landscape “age”, geomorphologists typically refer to the initiation of landscape form, as represented by the highest/oldest preserved surfaces, even while acknowledging that downwearing lowers the entire “landscape form” over long periods (10^6-10^8 years) of time (e.g., the southeast US piedmont). Conceptually, Dixey’s map of major geomorphic surfaces (Figure 2.6) delineates regions with similar maximum landscape ages, even though extensive younger geomorphic surfaces exist within each of these landscapes.

The scant geomorphology literature makes it difficult to evaluate the validity of conclusions regarding the definition and dating of these major erosion surfaces. The publications are predominantly narrative, and do not provide enough detailed field data to support the regional correlation of surfaces, nor constraints on their ages. It is possible that some remnants of a Jurassic landscape exist, such as they are, given Madagascar's geologic history within Pangea. Ollier (1991) cites several examples of Mesozoic planation surfaces from around the world, including Africa and Australia, where geomorphic field relationships and geochronologic data are apparently well documented. However, Lester King eventually concluded that only a very small extent of Jurassic to mid-Cretaceous surfaces in Africa survives today, and that widespread surfaces there are mainly Late Cretaceous to Mid-Miocene in age (cited in Thomas, 1994). Madagascar may well represent a similar set of maximum landscape ages.

Admittedly, the widespread lack of Mesozoic and/or Cenozoic geologic materials within the highlands of eastern Madagascar frustrates any attempt to tightly control regional correlations of major geomorphic surfaces in those areas. Therefore, surface ages must be correlated over long distances from western and southern Madagascar field evidence, across the island's major drainage divide, which introduces greater potential for error. The absolute ages of landscapes within the RNP study area are therefore essentially the subject of only educated guesses, largely tied to concepts regarding the formation of the eastern escarpment.

The eastern escarpment of Madagascar poses an interesting geomorphology problem, one that has been debated at least since the 1930's (Lenoble, 1935). The geomorphic history of the escarpment has great potential significance for pedology studies. The fundamental issue centers on whether the escarpment formed primarily via faulting "in place" with little subsequent migration (i.e., the escarpment coincides closely with a fault zone), or whether it formed due to the extensive inland erosion of a rifted passive margin. If the escarpment formed directly along a major fault zone, the interaction of faulting age(s), rates of movement, paleoclimates, erosion, and deposition could have produced a variety of landforms and soil parent materials below the escarpment (e.g., alluvial fans, fault-scarp pediments, etc.). In contrast, an escarpment that evolved primarily via erosion and degradation of a continental passive margin would produce a dissected landscape with relatively few constructional landforms. The genesis of the escarpment also has a direct bearing upon the relative ages of geomorphic surfaces above and below the escarpment.

Lenoble (1935) reported that “certain authors” (unnamed) directly attributed the eastern escarpment to a large fault, but that the hypothesis was unproven. He speculated that the escarpment was probably formed by erosion. Dixey (1960) concurred that the escarpment was essentially erosional, and added that it was a product of several uplifts and erosional cycles. Besairie provided a mixed review, stating in a 1970 article that the feature was erosional, while also clearly stating in a 1971 publication that an inland “great fault” was responsible for the escarpment (Besairie, 1970, 1971). It is notable that whatever claims have been made for a direct fault-related escarpment genesis, no geophysical, stratigraphic, or structural data have supported the existence of a major fault near the present-day escarpment. Extensive gravimetric data led Rechenmann (1982) to conclude that, despite literature and maps indicating the possible presence of a coincident major fault, no such fault was confirmed and the escarpment was therefore probably erosional.

Notably, the same debate for the Western Ghats of India (on the conjugate margin of the Cretaceous Madagascar-India rift) failed to produce evidence of faulting for the direct origin of that escarpment (Ollier and Powar, 1985). The erosional nature of the Western Ghats is also evident by the fact that the escarpment predates the

Deccan Traps flood basalt emplacement, yet runs continuously across the boundary between the Deccan Traps and Precambrian rocks to the south (Subrahmanya, 1998).

In a seminal work entitled The Morphotectonics of Passive Continental Margins, Ollier (1985) noted that "Great Escarpments" were strangely neglected in geomorphology research, given their striking nature and widespread extent. Great escarpments are often thousands of kilometers in length and hundreds of meters in height. The escarpments separate elevated continental interiors, where older geomorphic surfaces, lower relief, and slower erosion rates predominate, from coastal lowlands with moderate relief and higher erosion rates. Prime examples of these major geomorphic features include the great escarpments of southern Africa and Australia, the Western Ghats of India, the Transantarctic Mountains, and the Serro do Mar of Brazil. These landforms have formed in variety of geologic and climatic settings, and the only common feature is their association with passive continental margins. This association may be best exemplified in southern Africa, where the great escarpment runs roughly parallel to the horseshoe-shaped coast from Namibia to Mozambique.

Ollier (1985, p. 6) specifically recognized that Madagascar's eastern escarpment might well represent a so-called great escarpment, the formation of which he characterized by two basic processes:

> 1. An original continental slab is isolated from an original supercontinent (e.g., Gondwanaland) by chasmic faults and new sea floor.
>
> 2. Erosion and scarp retreat from the new continental margins creates the coastal lowlands backed by a major escarpment.

The first process indeed occurred along Madagascar's east coast, where separation from India produced the remarkably straight east-coast fault and an abrupt transition from continental crust to new sea floor (Rechenmann, 1982). While the second point is currently the subject of intense debate in terms of process (e.g., Partridge and Maud, 1987; Beaumont et al., 2000; Cockburn et al., 2000), the geomorphic description perfectly describes eastern Madagascar.

Some researchers have questioned whether great escarpments meet the strict definition of an escarpment. Lester King (cited in Ollier and Marker, 1985, p. 38) noted that, "Though not invariably an escarpment in the strict sense of the term, it always constitutes a sharp rise from the marginal parts of the country to the high interior plateau." A current definition of the term "escarpment" is as follows:

> a long, more or less continuous cliff or relatively steep slope facing in one general direction, separating two levels or gently sloping surfaces, and produced by erosion or faulting (Bates and Jackson, 1984, p. 170).

The general morphology of great escarpments clearly meet the main points of the definition, especially when the phrase "one general direction" can be equated to "facing a continental margin" (as in the case of southern Africa). At continental scales, these features generally maintain a sub-parallel orientation to the rifted margin. The local irregularities in the great escarpment trends are generally due to the relatively rapid headward erosion of major river systems at the escarpment edge.

The eastern Madagascar escarpment and the Western Ghats share several major characteristics that emphasize their common ancestry (Subrahmanya, 1998). The escarpments extend for approximately 1200-1500 kilometers and are sub-parallel to passive margin coastlines. On the high-grade Precambrian rocks of southwest India (between Belgaum and the Palghat Gap), the continental drainage divide occurs a short distance inland from the present-day escarpment, as it does in eastern Madagascar (Ollier and Powar, 1985; Subrahmanya, 1998). River capture (stream piracy) is common along both escarpments, as high-gradient rivers draining below the escarpments incise into low-gradient drainage basins above the escarpments (Lenoble, 1935; Ollier and Powar, 1985). The pronounced east-west asymmetry in Madagascar's topography and drainage patterns, shown in Figures 2.4 and 2.5, is mirrored in southwest India. Both escarpments display a relatively regular trend at continental scales, but possess numerous irregularities at watershed scales due to headward erosion by rivers.

Ollier (1985) and many other geomorphologists invoked parallel escarpment retreat as the main mechanism for producing great escarpments. This model appeared logical given the sub-parallel orientation of the escarpments to coastal areas, their distance inland from the rifted margins, the high relief within the escarpment zones, the amount of time since rifting (10^7 – 10^8 years) and the apparent parallel retreat of the escarpments today. This conventional model of escarpment retreat implied an average retreat rate of approximately 1km Ma^{-1} for southern Africa, Madagascar, and elsewhere, based upon the positioning of an initial escarpment at the rifted margin, retreating to its present position over the time span since rifting.

Recent field investigations, however, have indicated that present rates of escarpment retreat may be 1-2 orders of magnitude lower than predicted by a simple parallel retreat model. Cockburn et al. (2000) utilized a combination of apatite fission track thermochronology (AFTT) and cosmogenic nuclide (^{10}Be, ^{26}Al) data to estimate average denudation rates oceanward of Namibia's great escarpment at less than 20m Ma^{-1}, and escarpment retreat at only ~10m Ma^{-1} since the end of the Eocene. The AFTT data showed an initial phase of rapid denudation at the original rifted margin shortly after rifting occurred, followed by decreasing denudation rates as base levels adjusted over time. Fleming, et al. (1999) employed cosmogenic ^{36}Cl to estimate average summit denudation rates in the more humid Drakensberg escarpment of southeastern Africa at 6m Ma^{-1}, and escarpment retreat rates at 50-95m Ma^{-1} over the past 10^4-10^6 years. The results of these two studies, and results from other continents, indicate that simple parallel escarpment retreat cannot be the primary mechanism for great escarpment evolution.

Recent computer simulations using coupled tectonic-surface process models have produced results that closely approximate the overall morphology and scale of Madagascar's escarpment, the Western Ghats, and other great escarpments (Figure 2.7; Beaumont et al., 2000). The studies mentioned in the previous paragraph were designed in part to provide empirical data for constraining these numerical models, and thus far the models (e.g., Kooi and Beaumont, 1994; Beaumont et al., 2000) and the field data have been in reasonably close agreement. The computer models suggest that the primary control on the evolution of passive margin escarpments is the distance between the main antecedent drainage divide and the initial escarpment that forms at a newly rifted margin.

Where the antecedent drainage divide occurs far inland from the initial rifted-margin escarpment, the large catchment areas of rivers draining to the rifted margin result in high river discharges across this initial escarpment edge, where the lowered base level within the rift zone provides high gravitational energy for erosion. In this scenario, the rivers become deeply incised, river heads migrate rapidly toward the drainage divide, and the initial escarpment at the rifted margin quickly degrades. The region between the rifted margin and the drainage divide evolves as long interfluves develop, and subsequent dissection/downwearing of the interfluves lowers the landscape. As the steep river heads eventually erode toward close proximity to the

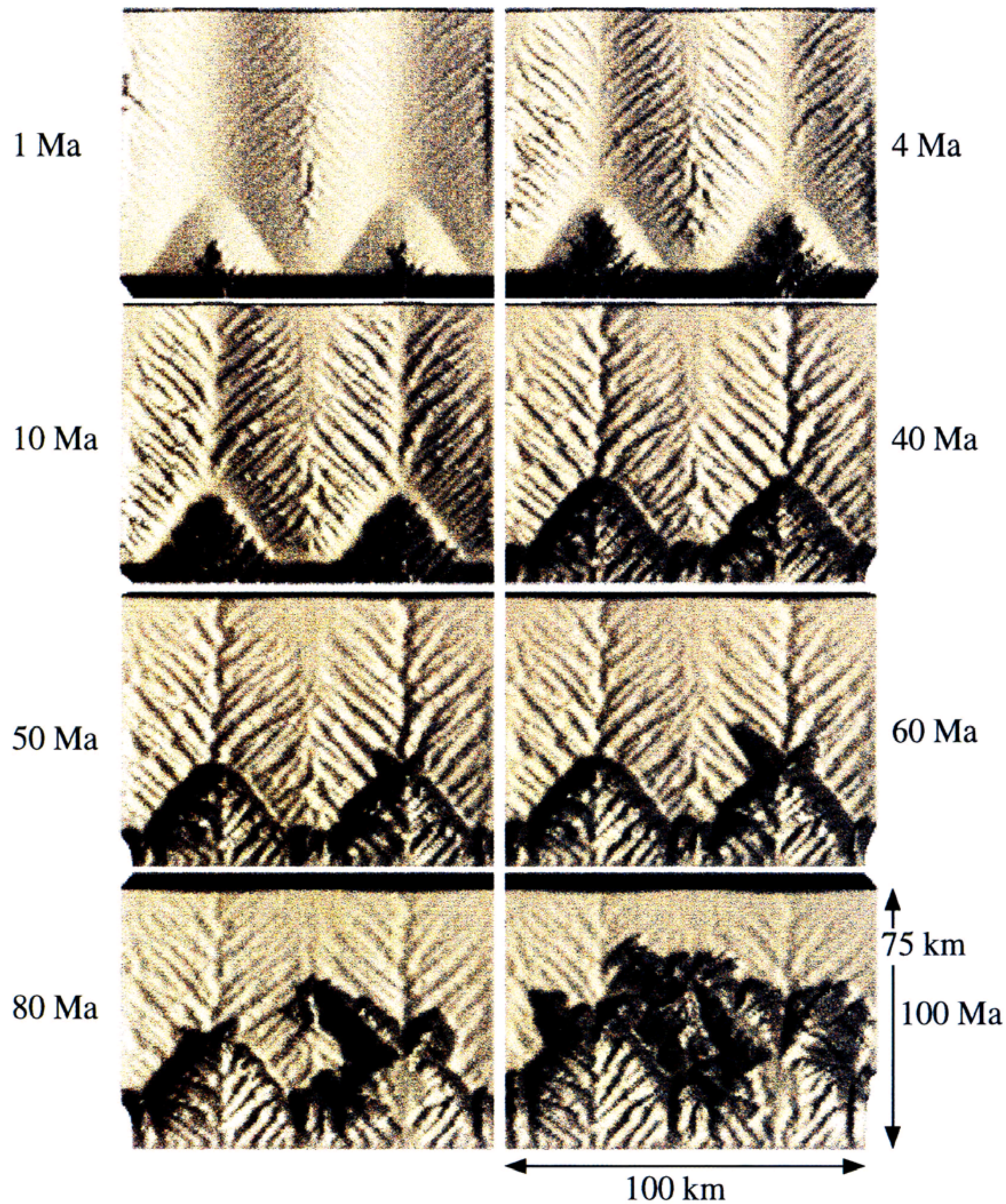

Figure 2.7. Diagram from Beaumont et al. (2000), illustrating escarpment evolution as predicted by a coupled tectonic-surface process model. This model, as applied to rifted margins, produced results for escarpment morphology at 80-100 Ma that closely approximate Madagascar's eastern escarpment of similar inception age. Model results are also consistent with apatite fission track thermochronology (AFTT) data from several continents. The bottom edge of each panel represents the location of the original rifted margin.

drainage divide, catchment areas above the escarpment edge are greatly diminished, river discharges decrease, headward erosion stabilizes, and a “new” escarpment is established near the drainage divide.

Model results from Kooi and Beaumont (1994) suggest that as the new escarpment becomes positioned (“pinned”) at the drainage divide, parallel retreat then dominates to maintain the steep escarpment morphology. As stated by Beaumont et al. (2000, p. 42), “The key to preservation of escarpment slopes and, therefore parallel retreat, is the competition between diffusive slope decline and fluvial slope steepening that occurs in the vicinity of the escarpment top when it is a drainage divide.” Irregularities in the escarpment trend, river knickpoints and convex reaches, and successively incised erosion surfaces along river valleys suggest that headward erosion by rivers may operate along the lines of a dynamic equilibrium model (Hack, 1976) as local base levels adjust over time.

Published AFTT data from several continents agree well with this general model of rapid incision, degradation of the original rifted margin escarpment, dissection and denudation of the region oceanward of the drainage divide, establishment of a “new” escarpment far inland, and subsequent slow parallel retreat of the “new” great escarpment. The AFTT data have consistently displayed initially rapid increases in apparent fission-track age with distance inland from the rifted margin, then slow increases in apparent age toward the great escarpment, with maximum ages occurring beyond the drainage divide (O’Sullivan et al., 1998; Cockburn et al., 2000). These data appear to validate the model scenario of initial rapid fluvial incision and denudation, followed by a shift to a slow parallel retreat mode near the drainage divide. This also explains how modern rates of escarpment retreat can be so low when compared to the position of the great escarpments so far inland from their respective rifted margins, over the time period since rifting occurred (Fleming et al., 1999; Cockburn et al., 2000).

An AFTT study in eastern Madagascar reported results that fit the numerical models and data from other great escarpments (Seward et al., 1998). The regional pattern of apparent AFTT ages showed an increase away from the rifted margin toward the inland drainage divide, with the highest derived denudation values occurring close to the east coast. Additional sampling since 1998 now clearly indicates that the central highlands have been a relative topographic high at least since the Paleozoic (D. Seward, personal communication). Interpretation of the AFTT data in eastern Madagascar is complicated by the Late Cretaceous passage of the island over the Marion hotspot and the associated heat flow, but the general data trends support the numerical models described above and other great escarpment AFTT data sets.

The conjugate margins of Madagascar and India share the same Late Cretaceous age. If the numerical models for great escarpment formation are valid, as suggested by their ability to explain their characteristics, then the age of the initial escarpment at the rifted margin is approximately synchronous with the initiation of normal faulting along the margin. This appears to be the case along the East African rift and at the Lake Baikal rift (Beaumont et al., 2000). Since rifting events represent several interactive tectonic processes of doming, faulting, extension, etc. over time, it remains unclear exactly when in this sequence the initial escarpment formation began. The 86-87 Ma lavas of Madagascar’s east coast near Mananjary flowed directly on the low-lying coastal Precambrian basement, an observation that led Dixey (1960) to suggest that the escarpment had already retreated significantly inland from a presumably coastal origin (or degraded) by the time the lavas were erupted. This would imply that escarpment initiation at the rift occurred well before the hotspot-related volcanism and sea-floor spreading, perhaps as a consequence of earlier doming and downfaulting. Thus, the 86-87 Ma age should be considered the minimum age for escarpment initiation, and the actual age of escarpment initiation at the coast may actually be millions or tens of millions of years older.

Based upon the tectonics of rifted margins, geochronology data from the east coast igneous rocks, and an erosional model for great escarpment evolution, the central highlands landscape “age” directly west of the RNP eastern escarpment may well correspond to a Late Cretaceous age. Dixey (1960) proposed that his Late Cretaceous surface (Figure 2.6; Table 2.1) might actually represent two or more erosion cycles. In this interpretation (exemplified by southwest Madagascar in Dixey’s paper), a coastal pre-volcanic Cretaceous erosion surface was subsequently covered by Late Cretaceous lavas and/or marine sediments, which were in turn eroded to produce a post- 86-87 Ma surface. By combining Dixey’s observations with the eastern escarpment model, it appears probable that the residual landscape directly west of the RNP escarpment (i.e., the upper Namorona River basin) has an overall approximate Late Cretaceous age. This is in accordance with the observation that at 86-87 Ma, the escarpment’s early retreat/dissection would have produced an eroded narrow coastal strip where volcanics were being deposited (a pre- 86-87 Ma surface), with an even older Late Cretaceous surface above and to the west of the escarpment.

This scenario is supported by AFTT data from southeast Australia, where consistent decreases in apparent AFTT ages occurred from the Great Divide toward the southeast coast (O’Sullivan et al., 1998). The researchers concluded that the data clearly demonstrated that erosional landforms near the coast were younger than landforms inland of the escarpment.

Alternatively, Bourgeat (1972) ascribed an end-Cretaceous age to the highest major surfaces (“Tampoketsa”) in the Central Highlands, based upon unconfirmed dating of truncated sedimentary layers. He reported that the general end-Tertiary age of the eastern lowlands was well constrained. Therefore, in the absence of direct datable evidence he interpolated a broad “mid-Tertiary” age to the Central Highlands directly west of the RNP, significantly younger than the age proposed by Dixey (1960). Regardless of the true age of the landscape formation, both authors agree that direct geologic evidence for dating is sorely lacking for the boundary between the central highlands and the eastern escarpment, and that geomorphic ages are poorly constrained.

Thomas (1994, p.362) emphasized that the geomorphology of ancient escarpments is much more complex than is commonly acknowledged, and that studies of erosion surfaces depend crucially upon the timing of faulting/uplift leading to escarpment formation. He quoted Partridge and Maud (1987, p.189) from their study of southern African geomorphology:

> …of fundamental importance to an understanding of all subsequent landscape evolution within the subcontinent is an appreciation of the fact that, throughout this and later cycles, erosion proceeded simultaneously at different levels above and below the great escarpment.

This leads to a complex reality in eastern Madagascar. The oldest landscapes near the RNP region are certainly above the escarpment, given the escarpment’s erosional nature. The next oldest landscapes most likely occur near the coast where river incision and scarp retreat first created a coastal lowland, and progressively younger landscapes are thus generally found moving inland toward the modern escarpment, retracing the path of its complex erosional evolution. Of course, significant downwearing since the Cretaceous creates difficulty in reconstructing any generalized picture of landscape evolution in such highly dissected terrain. Post-Cretaceous through Quaternary erosion surfaces exist above and below the escarpment.

The eastern Madagascar escarpment is also notable as the demarcation between landscapes that possess widespread stonelines (central highlands) and those that generally do not (the escarpment itself and eastern lowlands). Stonelines (hereafter referred to as "stone-layers" to reflect their three-dimensional geometry) can be defined as a concentration of coarse fragments that occurs as a layer within a finer-grained matrix of regolith. The genesis and geomorphic significance of stone-layers are somewhat controversial, and numerous hypotheses have been proposed to explain the great variation in stone-layer properties that are exhibited worldwide. A general critique of stone-layer literature is beyond this review, but an excellent stone-layer reference can be found in a special volume of the journal Geo-Eco-Trop (Geo-Eco-Trop, Volume 11, No. 1-4, 1987). Works regarding stone-layers in Madagascar include Dresch (1962), Bourgeat and Petit (1966), Vogt (1966), Riquier (1969), Bourgeat (1972), and Wells et al. (1990).

Wells et al. (1990) presented a thorough study of stone-layers within the central highlands south and west of Antananarivo. They observed that most convex-upward stone-layers typically mantled modern hillslopes, and interpreted the stone-layers as colluvially buried hillslope surface lags. Saprolite fabric was usually observed immediately below the stone-layer. Concave-upward stone-layers were typically thicker, with more rounded clasts, and were interpreted to represent fluvial accumulations in hollows and valley floors. While many of the stone-layers paralleled the modern topography, some stone-layers outlined former surfaces directly opposed to the modern surface slope (e.g., a concave-upward stone-layer deeply underlying a convex-upward interfluve), indicating the shifting of hills and valleys over time even to the point of topographic inversion. The authors concluded that evidence of shifting topography probably precluded a great geologic age for the landforms, leaving the landscape at a "sub-mature" stage of development.

Several researchers noted the near-total predominance of quartz in the composition of stone-layers within Madagascar's central highlands (Vogt, 1966; Bourgeat, 1972; Wells et al., 1990). At the eastern edge of the central highlands, however, the quartz composition yields to an intriguing predominance of "*pseudo-concretions*" [French terminology], or lithic fragments that possess a concretionary iron-oxide coating (Bourgeat and Petit, 1966; Vogt, 1966; Segalen, 1995). Another observation made by several researchers is the widespread extent of stone-layers within the central highlands, yet there are no published reports of extensive stone-layers east of the great escarpment. Alluding to one genetic theory that stone-layers may reflect a paleoclimatic shift from arid/semi-arid conditions to a more humid climate, Dresch (1962) proposed that the eastern escarpment and coastal regions may have simply remained humid throughout the duration of their respective landscape development, while the central highlands were more susceptible to arid climate shifts in the geologic past and therefore prone to form surface lags that were subsequently buried. He also suggested that the steeper slopes of eastern Madagascar might have precluded either the formation or preservation of stone-layers. These collective observations regarding stone-layers provide provocative clues for potentially deciphering landscape evolution within the RNP study area.

Bourgeat (1972) indicated that stone-layers within the central highlands were essentially post-Pliocene, based upon local stratigraphic relationships with dated basalt flows and the similarity of associated soil properties across major erosion surfaces. He concluded that the stone-layers confirmed the existence of Quaternary climate variations. Wells et al. (1990) indicated that at least some of the stone-layers were Pleistocene age. Although local dating of stone-layers in Madagascar has occurred, a systematic study of stone-layer dating appears to be lacking. One key research challenge involves the integration of stone-layer dating with overall models for landscape evolution in central and eastern Madagascar. At this point in time, the stratigraphic and geochronologic data are so limited or non-existent that the ages of stone-layers potentially span a very wide range. Recent advances in the geomorphology applications of cosmogenic nuclide dating techniques (e.g., ^{10}Be, ^{26}Al, ^{36}Cl) could address the absolute ages of stone-layers and landforms across large areas of Madagascar's Precambrian landscape (see Gosse and Phillips, 2001 for a review).

A final point on Madagascar's geomorphology relates to the increasing integration of tectonics, geophysics, and surface processes research. The doming and rifting episodes of Madagascar's eastern margin were activated by passage over the Marion hotspot mantle plume (Torsvik et al., 1998), a scenario believed to be a primary mechanism for producing great escarpments on "marginal swells" or rift-related elevated margins. However, Madagascar's Precambrian central highlands maintain an anomalously high average elevation relative to Precambrian cratons from around the globe, as do southern and eastern Africa. Most cratons possess an average elevation of 400-500 meters, while the southern Africa, eastern Africa, and Madagascar Precambrian regions exhibit average elevations approximately one kilometer higher or more (the so-called “African superswell”). Lithosphere isostatic mechanisms have proved insufficient to explain these anomalously high elevations. Furthermore, Madagascar has experienced east-west extension and volcanism since the late Tertiary that has been attributed to a thermal bulge under the center of the island, but until very recently no geophysical model accounted for this thermal occurrence (Bertil and Regnoult, 1998; Pique et al., 1999).

A recent, major geologic research advance involves direct linkages between long-term geomorphology and flow patterns within the earth’s mantle. It now appears that a broad zone of actively upwelling mantle beneath southern Africa, eastern Africa, and Madagascar is responsible for dynamically supporting these excessively elevated Precambrian areas (Lithgow-Bertelloni and Silver, 1998; Forte and Mitrovica, 2001). This so-called “dynamic topography”, or surface deformation related to mantle-depth vertical stresses, is a major addition to plate tectonic theory. According to this theory, not only does mantle convection drive the horizontal movement of plates across the earth’s surface, but the convection also results in positive and negative *vertical* stresses that interact with isostatic continental-scale uplift and subsidence.

This mantle “superplume”, detected and mapped via seismic tomography, provides direct geophysical evidence for tectonic geomorphology features such as the Great Escarpment of southern Africa, the east African rift valley, and the anomalously elevated Precambrian areas. Model predictions based upon geophysical data indicate that the superplume has likely existed for approximately 100 Ma (A. Forte, personal communication), in which case the African plate (including Madagascar) would have drifted northward over it during the Cenozoic. A branch of the superplume occurs directly under Madagascar, and provides a unifying explanation for the island's anomalously high Precambrian central highlands, Plio-Quaternary volcanism in central and northern Madagascar, and Plio-Quaternary east-west extension that includes the Alaotra-Mangoro grabens and present-day normal faulting. Any valid modern synthesis of Madagascar's long-term geomorphology must consider these geophysical and tectonic factors.

To conclude, while major gaps remain in our understanding of Madagascar's geomorphology, progress in geological research on Madagascar provides increasing opportunities for geomorphology advances. Perhaps the greatest need is a modern re-examination and tightly controlled verification of datable major erosion surfaces, and their correlation using a high-resolution DEM, thermochronology, cosmogenic nuclide dating, and other similar technologies combined with standard geomorphic fieldwork. This would provide a benchmark for subsequent geomorphology research and augment a sparse record of tentative studies that are now more than 30 years old.

Despite the lack of detailed geomorphology information for the RNP study area, the geology and geomorphology literature clearly establish a critical fact: that the RNP straddles an escarpment that is erosional in nature. Recent models for great escarpment evolution (Beaumont et al., 2000; Cockburn et al., 2000) provide the best explanation for observations of Madagascar's east-west topographic asymmetry, AFTT data sets in eastern Madagascar (Seward et al., 1998), past and present inferred rates of denudation and escarpment migration, the coincidence of the modern escarpment with the drainage divide, and the current morphology of the escarpment itself. The remarkable similarities between Madagascar's escarpment and the Western Ghats of

India (Subrahmanya, 1998) provide additional support for these proposed mechanisms. Several ongoing independent research efforts in southern Africa, Australia, and elsewhere are currently applying thermochronology, sediment balance calculations, tectonic and surface process modeling, and other techniques to further refine the detailed mechanisms and significance of great escarpment evolution.

This partial geomorphology synthesis underscores that the cumulative evidence favors a common landscape evolution and geomorphic history for large portions of eastern Madagascar (at least south of the Alaotra-Mangoro grabens) that resulted in the formation of a great escarpment sub-parallel to the present-day east coast. This knowledge, along with geologic mapping and climatic data, significantly increases our ability to provide a sound basis for defining regional “soil systems” (Buol et al., 1989; Daniels et al., 1999) in greater detail than previous soil survey work in Madagascar. However, the near-total lack of detailed geomorphologic mapping, systematic stone-layer studies above and below the escarpment, and absolute dating of surfaces provides major geomorphology research needs and opportunities in eastern Madagascar.

Climate

The climate patterns for Madagascar are generally well characterized, owing to the existence of a network of long-term weather stations that were established predominantly in the 1930s and which continuously recorded data into the 1960s. Periodic climate data since the 1960s also exist in the records of Madagascar’s Service Météorologique, particularly for smaller towns and villages (e.g., Ranomafana), but datasets typically span only a few (<10) years. Several books and articles describe

Madagascar's overall climatic geography, but two particular publications provide a high level of detail and data for analytical purposes. Oldeman (1990) compiled a detailed climate database for the agroclimatic characterization of Madagascar, to define major rice growing environments as an aid to agronomic research and extension. Chaperon et al. (1993) produced a massive hydrological monograph that included climatic data and numerous statistical analyses, in order to characterize the surface water resources for river basins in Madagascar.

Oldeman (1990) indicated that out of 178 stations reported in his study, 131 maintained records for 25 years or more, 16 stations maintained records for 20-24 years, and 31 sites had records for 10-15 year periods. These climate station data sets, augmented by additional data from Chaperon et al. (1993), provide a sufficiently dense climatological network to assess climate variables throughout much of eastern Madagascar. Along with the geology and geomorphology information described previously, the climate data provide an increased ability to define soil systems for portions of the eastern escarpment zone.

Long-term precipitation means reported by Oldeman (1990) and Chaperon et al. (1993) differ slightly for the same recording stations between Mananjary and Fianarantsoa, but the differences are two percent or less of the means and are not considered significant for climate characterization. The differences are most likely due to slight differences in the time periods used to calculate the long-term means. Therefore, readers may note slight differences in the mean annual precipitation totals between Figures 2.8 and 2.9 and Tables 2.3 - 2.5 for a given location.

The major determinants of eastern Madagascar's climate are 1) the prevalence of the southeast trade winds blowing from the southern Indian Ocean, 2) the island's geographic position relative to the Intertropical Convergence Zone (ITCZ), and 3) the topographic variability between the east coast and central highlands.

The relative strength of the southeast trade winds exerts a major control on eastern Madagascar's climate, with seasonal variations controlled by the general atmospheric pressure patterns over the Mozambique Channel and southern Africa (Oldeman, 1990). During the austral summer (December-March), low-pressure areas develop over southern Africa while sea surface temperatures are relatively high, promoting strong southeast trade winds, warmer temperatures, humid conditions, and seasonally high rainfall throughout eastern Madagascar. These same conditions promote the arrival of tropical storms and cyclones that can be highly destructive, and which sometimes unfortunately occur prior to major rice harvests. Eastern Madagascar as a whole experienced numerous major cyclones and tropical storms in the last decade, for example, though the storm centers encountered the island at varying latitudes.

The austral summer also coincides with the southward migration of the ITCZ, which "frequently" extends to 15-20° south latitude but not as far south as the RNP area (Oldeman, 1990). The principal effect of this shift is the appearance of heavy monsoon rains in northwest Madagascar, but the southern limit of ITCZ migration also corresponds to higher mean annual rainfall within the central highlands northward of 20° south latitude (i.e., the approximate latitude of Antsirabe). The principal effect of the ITCZ position for the RNP area relates to the tracking of tropical storms and cyclones as they approach Madagascar.

Topographic factors affect eastern Madagascar's climate in two critical ways. South of Antananarivo, the east-west elevation change from sea level (at the coast) to over 1500 meters (at or near the eastern edge of the central highlands) occurs within a horizontal distance of less than 100 kilometers, with half of the elevation rise occurring abruptly at the eastern escarpment. The simple effect of increased elevation causes adiabatic cooling that generally produces lower temperatures, establishing a temperature gradient that has significant implications for natural ecosystems, agriculture, and forestry. The dramatic change in elevation at the eastern escarpment also produces a strong orographic uplift effect as the humid southeastern trade winds rise across it, producing some of the highest annual rainfall totals in Madagascar, frequent fog/mist at higher elevations, and simultaneously producing a strong relative rainshadow just west of the escarpment edge.

The combined effects of latitude (i.e., the ITCZ), southeast trade winds, and topographic effects on annual precipitation can be clearly discerned in the isohyet pattern on Figure 2.8, taken from Chaperon et al. (1993). The overall effect of the eastern escarpment presents itself as closely spaced isohyets south of Antananarivo, and to a lesser extent northward toward the Masoala Peninsula. The strongest rainfall gradient clearly occurs between 19° S and 22° S latitude, which is enlarged for clarity in Figure 2.9. The annual rainfall trend between Mananjary and Fianarantsoa illustrates the predominant pattern in the portion of eastern Madagascar surrounding the RNP. Annual rainfall at the coast (Mananjary, 2739 mm y^{-1}) reflects precipitation from onshore southeast tradewinds, and this initial coastal elevation rise promotes high rainfall that also appears to result in slightly less annual rainfall further inland (e.g., Ifanadiana, 2509 mm y^{-1}).

Ifanadiana, at 450 meters elevation, represents the eastern limit of the study area. The data from Chaperon et al. (1993) show a slight increase in annual rainfall for

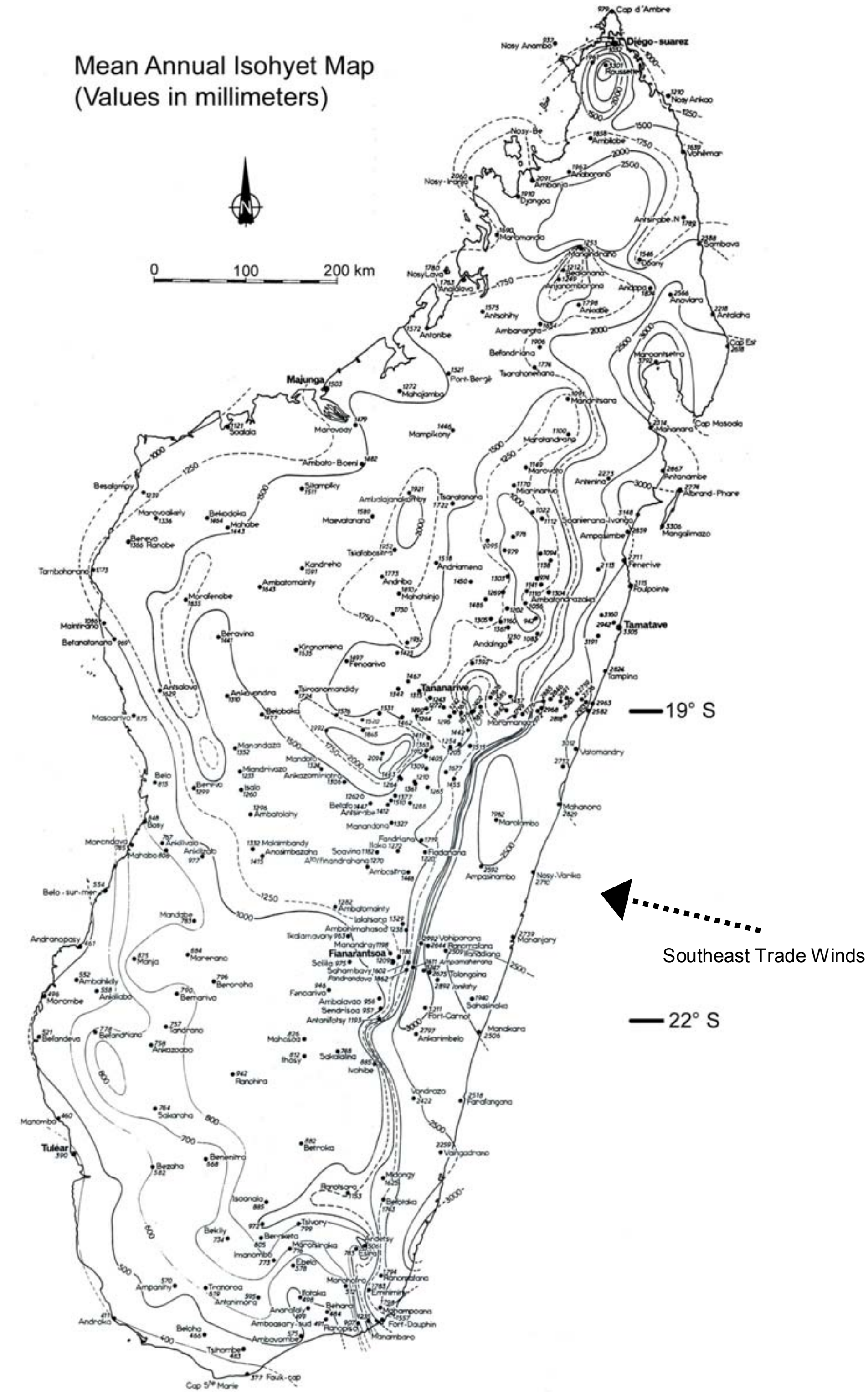

Figure 2.8. Mean annual rainfall map from Chaperon et al. (1993). Note the steep annual rainfall gradient at the escarpment between 19°S and 22°S latitude.

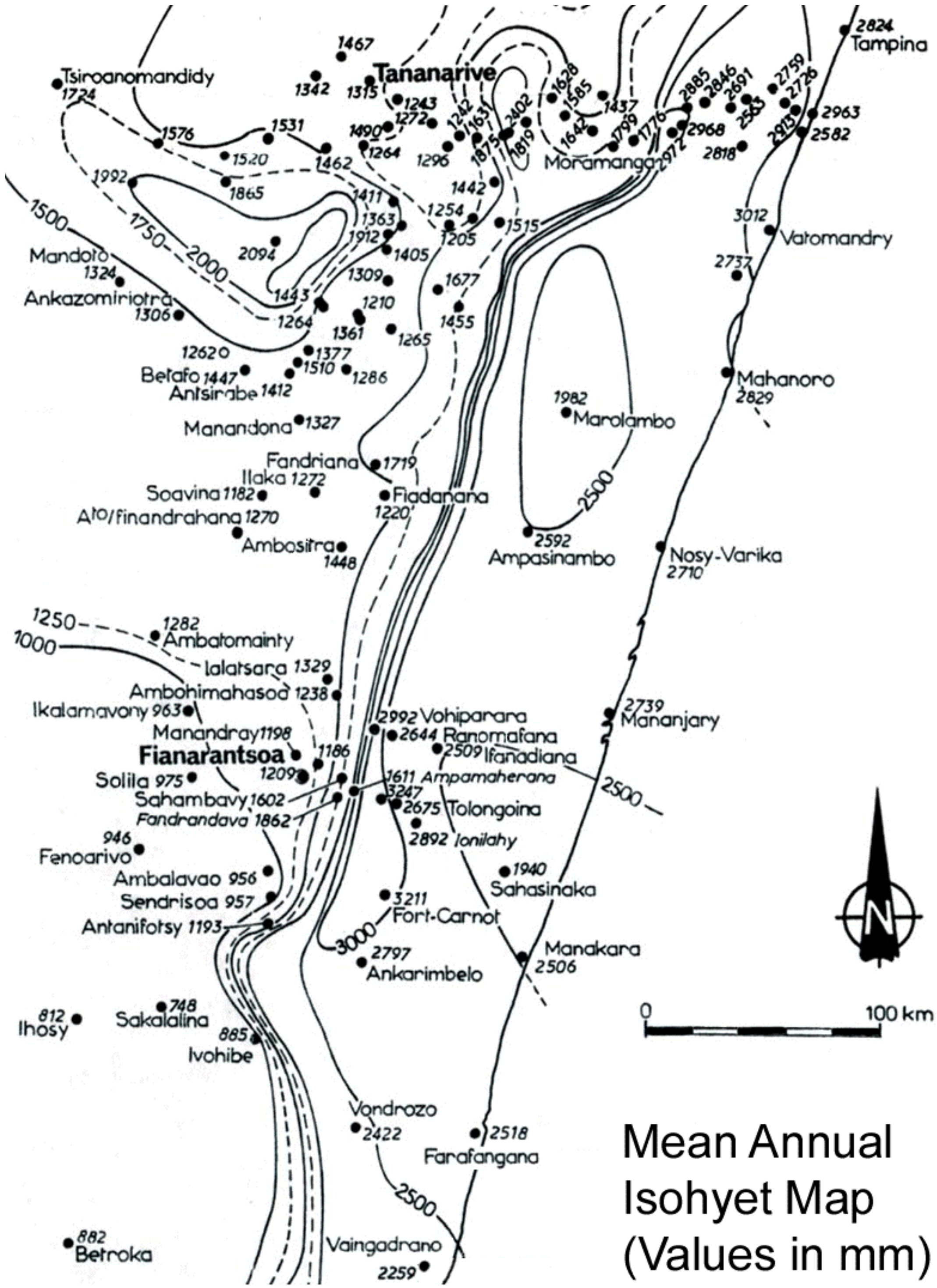

Figure 2.9. Enlarged view of the RNP region of Figure 2.8. Ifanadiana, Ranomafana, and Vohiparara are located in the center of the diagram.

Ranomafana (2644 mm y^{-1}) at the base of the escarpment (610 meters elevation) compared to Ifanadiana. The period of record for the Ranomafana data is much shorter than that for Ifanadiana (~7 years versus 30 years), so the true trend is somewhat uncertain. Oldeman (1990) did not report climate data for Ranomafana. However, the dramatic increase in annual precipitation between Ifanadiana and the upper escarpment edge, typified by Vohiparara (2992 mm y^{-1}) at 1125 meters elevation, appears to be a consistent trend for the entire escarpment between the latitudes of Manakara and Antananarivo (Figure 2.9). This pattern is repeated south of the RNP between Tolongoina (2675 mm y^{-1}) and Andrambovato (3247 mm y^{-1}), and also east of Moramanga at the approximate latitude of Antananarivo. The available climate data indicate that for the region between Vohiparara and Ifanadiana, even the driest months (September and October) on average receive more than 50 mm of rainfall (Coulaud, 1973; Oldeman, 1990; Overdorff and Wright, in review).

Another consistent trend along the escarpment is the dramatic drop in annual precipitation west of the upper escarpment edge. A decrease in annual precipitation of 1000-1500 millimeters or more occurs within a lateral distance of approximately 10-20 kilometers, documented by numerous climate stations east of Fianarantsoa and Antananarivo as shown in Figure 2.9. A close examination of Figure 2.9 shows that the east-west trends in mean annual precipitation totals are nearly identical east of Fianarantsoa and Antananarivo between the coast and the central highlands, and also from Nosy-Varika to Ampasinambo to Ambositra. The high degree of similarity in east-west precipitation trends between 19°S and 22°S latitude is not surprising, given the similarities in trade wind patterns and topography that are the primary controls on spatial and temporal rainfall distribution.

Notably, while the region east of Vohiparara experiences on average more than 50 mm of precipitation even in the driest months, long-term climate stations west of the study area receive less than 50 mm of rainfall for at least half of the year. Fianarantsoa, located approximately 40 km southwest of Vohiparara, on average receives less than 50 mm of rainfall seven months of the year, with four of those months (June-September) recording less than 25 mm (Oldeman, 1990). Alakamisy-Ambohimaha, located halfway between Fianarantsoa and Vohiparara, experiences six months per year on average with less 50 mm rainfall, with one month (September) less than 25 mm (Service Météorologique, 1991).

In terms of extreme rainfall events in the RNP region, the Ifanadiana station (period of record 1930-1965) recorded a maximum of 258 millimeters (10.2 inches) of rain within a 24-hour period. For perspective, 39 of the lower 48 United States have recorded maximum 24-hour rainfalls that exceed this total (NCDC, 1998), illustrating that this “tropical rainforest” precipitation does not necessarily imply unusually high rainfall intensity when compared to temperate regions. The maximum 24-hour rainfall for Fianarantsoa over the same observation period was 167 millimeters (6.6 inches) (Chaperon et al., 1993). Coulaud (1973) reported a maximum 24-hour rainfall for Vohiparara at 378 millimeters (14.9 inches), associated with Cyclone Dany in February 1969. The rains from Cyclone Dany, incidentally, were sufficient to severely flood the town of Ranomafana, and cut off a major meander of the Namorona River just outside the town. According to Overdorff and Wright (in review), two to three major storm events are reported annually between February and April. Long-term maximum 24-hour rainfall data from Chaperon et al. (1993) indicate that six of the top twelve 24-hour events at Ifanadiana occurred in January, so the tropical storm/cyclone season for the region may be characterized as January-early April.

Though these storm events are not statistically more severe than many other areas of the world, eastern Madagascar does experience tropical storms and/or cyclones that can cause widespread flooding, serious agricultural losses, and tree damage, which complicates long-term agricultural and forestry development. Cyclone damage to infrastructure such as roads and railroads can affect the transport of agricultural and forestry products to market, exemplified by the heavy damage in March 2000 to the Fianarantsoa-Manakara railroad line that serves the southern RNP region. Unfortunately, the period of greatest storm probability coincides with the main rice growing and harvest season in the RNP region. The annual rice yields, staple of both the local diet and economy, depend greatly upon the timing of cyclones relative to the timing of harvests.

Long-term temperature data are available for many of the stations listed by Oldeman (1990) and Chaperon et al. (1993), though many stations that recorded precipitation near the RNP region did not also record temperature. Therefore, spatial trends for temperature throughout the region are not as detailed as the precipitation (e.g., Figure 2.9). However, Oldeman (1990) performed regressions to estimate maximum and minimum annual air temperatures as a function of elevation for eastern Madagascar, using long-term data from stations above and below the escarpment. Given the range in elevations across the study area (400m – 1400m), these estimates are useful for agricultural and forestry purposes, and serve as a check on estimates of soil temperature regimes (see “Soils” section, Chapter 2). Table 2.2 provides mean

Table 2.2. Calculated mean annual air temperature (MAAT) as a function of elevation, derived from Oldeman (1990).

Elevation (meters)	Calculated Mean Annual Air Temperature (MAAT) in °C
400	22.0
500	21.5
600	21.0
700	20.5
800	20.0
900	19.5
1000	19.0
1100	18.5
1200	18.0
1300	17.5
1400	17.0

annual air temperature (MAAT) as a function of elevation, derived from the regression equations in Oldeman (1990).

The calculated MAAT values below the escarpment for Ifanadiana and Marolambo underestimate the actual 30-year MAAT by 0.6 and 0.4 degree centigrade, respectively. In the central highlands surrounding the RNP region, calculated MAAT values for Fianarantsoa and Amobositra overestimate the actual 30-year MAAT by 0.1 degree centigrade at both locations. Given the variability in topography and rainfall in the RNP region, and the lack of long-term temperature data between Ifanadiana and Fianarantsoa, the estimates provided by Oldeman’s equations (Table 2.2) provide the best available information regarding mean annual air temperatures for the region as a whole.

In terms of absolute maximum and minimum temperatures within the study area, few published data are readily available. Temperature data collected at Ifanadiana from 1940-1950 show an absolute maximum of 35.1°C (December) during that period, and an absolute minimum temperature of 2.9°C (June) (Service Météorologique, 1956). Comparable data were not obtained for the central highlands near the RNP, but researchers and villagers report that killing frosts occasionally occur there during the austral winter (June-September). The minimum temperatures reflect the combined effects of latitude, altitude, and diminishing strength of the trade winds in southeastern Madagascar during those months (Oldeman, 1990).

Long-term data (1931-1960) for the Ifanadiana and Fianarantsoa climate stations are summarized in Tables 2.3 and 2.4, respectively. The long-term monthly precipitation means for these stations reveal several climate trends. The annual rainfall distribution pattern in the region is unimodal, on average peaking in February for Ifanadiana and January for Fianarantsoa. Both stations tend to receive more than half of their mean annual rainfall in January, February, and March. On average, Fianarantsoa receives approximately half of the total annual rainfall received at Ifanadiana, which highlights again the strong east-west rainfall gradient between the eastern lowlands and the central highlands. The MAATs for Ifanadiana and Fianarantsoa are 21.2 and 18.6 degrees centigrade, respectively.

Oldeman (1990) also reported long-term (1936-1960) monthly precipitation means for Ambohimahasoa, located approximately 25 km northwest of Vohiparara and 15 kilometers from a soil characterization location for this study (Ambalakindresy). Ambohimahasoa, like Fianarantsoa and Alakamisy-Ambohimaha (see below), occurs west of the Namorona River watershed that defines the “continental divide” west of the

Table 2.3. Long-term monthly precipitation and temperature means, Ifanadiana climate station (450 meters elevation).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Precipitation	422	445	424	167	102	112	97	82	77	55	168	324	2475
Max. Temp.	29.4	29.0	28.2	27.4	25.2	23.5	22.8	23.4	24.8	27.4	28.6	29.6	26.6
Min. Temp.	19.2	19.0	18.8	17.5	14.6	12.6	11.9	12.4	13.4	15.4	17.6	18.5	15.9
Mean Temp.	24.3	24.0	23.5	22.4	19.9	18.0	17.3	17.9	19.1	21.4	23.1	24.0	21.2

Source: Oldeman (1990) for observation period 1931-1960.

Precipitation: Mean monthly precipitation in mm
Max. Temp.: Maximum temperature (average of the month) in °C
Min. Temp.: Minimum temperature (average of the month) in °C
Mean. Temp.: Mean temperature (average of the month) in °C

Table 2.4. Long-term monthly precipitation and temperature means, Fianarantsoa climate station (1106 meters elevation).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Precipitation	291	206	174	44	27	20	19	17	24	34	131	237	1224
Max. Temp.	26.0	25.7	25.3	24.6	22.3	20.1	19.4	20.7	22.4	25.6	26.9	26.4	23.8
Min. Temp.	16.8	16.3	16.2	14.7	12.0	10.3	9.5	9.5	10.5	12.7	14.5	16.0	13.3
Mean Temp.	21.4	21.0	20.8	19.7	17.2	15.2	14.5	15.1	16.5	19.2	20.8	21.2	18.6

Source: Oldeman (1990) for observation period 1931-1960.

Precipitation: Mean monthly precipitation in mm
Max. Temp.: Maximum temperature (average of the month) in °C
Min. Temp.: Minimum temperature (average of the month) in °C
Mean. Temp.: Mean temperature (average of the month) in °C

Table 2.5. Long-term monthly precipitation means, Ambohimahasoa climate station (1200 meters elevation), in millimeters.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Precipitation (mm)	263	189	211	51	32	30	33	27	27	33	124	223	1243

Source: Oldeman (1990) for observation period 1936-1960.

Table 2.6. Long-term monthly precipitation means, Alakamisy-Ambohimaha climate station (1100 meters elevation), in millimeters.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Precipitation (mm)	277	238	163	46	36	33	39	32	16	56	124	241	1301

Source: Service Météorologique for the observation period 1972-1984 and 1987-1990 (15 years total).

RNP, and therefore is on the leeward side with regard to the southeast trade winds. Table 2.5 shows that the long-term mean annual precipitation for Ambohimahasoa is 1243 mm y^{-1}, well below half of the 2992 mm y^{-1} reported by Chaperon et al. (1993) for Vohiparara and nearly the same as the mean annual precipitation recorded at Fianarantsoa (Figure 2.9).

Rainfall data were obtained from the Service Météorologique for Alakamisy-Ambohimaha, which lies just west of the study area and provides climate data within the gap (~40-50 km) between Vohiparara and Fianarantsoa (Table 2.6). The data were recorded for a total of 15 complete years, from 1972-1984 and 1987-1990 (Service Météorologique, 1991). The precipitation means in Table 2.6 cannot be strictly compared with the long-term means from Ifanadiana and Fianarantsoa, since the data were collected during a completely different time period and for only half as long. However, the mean annual precipitation for Alakamisy-Ambohimaha (1301 mm y^{-1}) is consistent with interpolation between data points and isohyets on Figure 2.9, and provides a useful rainfall approximation for soil profiles described west of Vohiparara (e.g., Sahavondronina, Vatomitantana). The precipitation means for Alakamisy-Ambohimaha track closely to the Fianarantsoa and Ambohimahasoa means, indicating a rather uniform long-term annual rainfall pattern within the central highlands west of Vohiparara, and west of the initially steep decline in total annual rainfall adjacent to the escarpment edge.

Any complete account of climate patterns in the RNP region must address the effects of fog/mist on “true” precipitation, temperature, potential evapotranspiration, agroecological environments, and forest structure. Although not well documented in the literature, numerous researchers (e.g., Turk, 1997) have noted the prevalence of

Figure 2.10. Clouds/fog within the Namorona River valley at approximately 1000 meters elevation, Ranomafana National Park (RNP). This photo was taken by the author in October, one of the drier months of the year, illustrating the ecological significance of “horizontal precipitation” during the dry season. Note also the arrows that identify a break between major geomorphic surfaces in this area, with the higher surface grading to a former river level much higher than the present-day riverbed.

clouds, mist, fog, and/or drizzle within the RNP, especially higher on the escarpment (Figure 2.10). As stated by Williams (2001), “Curiously enough the ‘dry’ season (June through September, austral winter) actually seems wetter than the ‘wet’ season (December through March)-- in July there is a continual cold, grey drizzle, while January gets late-afternoon/evening cloud bursts.” Ecologists and forestry researchers at the RNP, as elsewhere on the eastern escarpment, have long noted decreased forest stature at higher elevations within the escarpment zone where the mists typically occur. The two main hypotheses proposed to explain decreased forest stature were 1) microclimate conditions (temperature, moisture, insolation, etc.) at the higher elevations, and/or 2) changes in soil properties coincident or nearly coincident with the boundary between the escarpment edge and the central highlands.

A bibliographic review by Stadtmüller (1987) highlighted that fogs and mists can add a significant amount of moisture to montane forest ecosystems, and that many researchers consider the combination of additional water and lower temperatures to be an important ecological factor. Stadtmüller (1987) cited data that this “horizontal precipitation” may make a relative contribution of 7-18% of total annual rainfall in “extremely rainy” climates presumably similar to the RNP. More importantly, perhaps, is the observation that fog or mist may contribute more water to montane forest ecosystems than actual rainfall during the “dry” season. This precipitation may be “effective” in the sense that evapotranspiration is lower due to reduced insolation and lower temperatures, leaving more water in the soil profile for eventual use by plants and/or for mineral weathering and leaching.

Given the experience of researchers within the RNP, it may well be that the “dry” season rainfall measurements (June-September) fail to capture an ecologically significant amount of water arriving via mist/fog/drizzle that is intercepted by the rainforest vegetation. Estimates of potential evapotranspiration (PET) based upon long-term climate data would also likely underestimate PET for the upper escarpment zone, and therefore calculated annual soil-water budgets would indicate drier conditions than actually exist within the forest. Moisture and temperature effects of higher-elevation fog/mist may also influence soil organic matter content, nutrient cycling dynamics, and soil classification relating to "humic" taxa.

Raw long-term climate data were not obtained that would allow a statistical characterization of inter-annual climate variability. These data are currently being requested and may hopefully be incorporated in a subsequent publication derived from this soil study. However, data collected during the 1990s at the RNP Talatakely research station provide an indication of inter-annual rainfall variability within the RNP itself (Overdorff and Wright, in review). The mean annual precipitation for a nine-year period (1991-2000, excluding 1995) was approximately 2800 mm, which falls between mean annual precipitation values for Ranomafana and Vohiparara. During this nine-year period, total annual precipitation varied from 1589 mm to 3646 mm, with five of the nine years varying from the mean by 500 mm or more. Most of the annual variation was due to the variability of wet-season rainfall and the presence, absence, and severity of tropical storms/cyclones. Dry season precipitation did not vary substantially between years. Overdorff and Wright (in review) also reported that annual temperature patterns over four years did not correlate with rainfall, and temperature patterns were more stable between years than rainfall patterns.

The long-term climate conditions detailed in this section provide useful information for pedology studies and general agriculture and forestry planning. Buol et al. (1989) noted that many soil properties correlate well with precipitation and temperature trends, though local factors and parent materials may modify these relationships. In an agronomic application, Oldeman (1990) utilized the climate data to define areas where low temperatures and shorter rainfall periods (e.g., Amobohimahasoa) suggest that short-duration rice cultivars might yield better than other varieties. However, Sanchez (1976, p. 14) noted that no matter how useful long-term rainfall averages might be for general predictions and general agrotechnology transfer, they "are practically worthless in predicting moisture adequacy for a specific crop."

Sanchez (1976) presented two key observations regarding long-term rainfall averages. First, long-term rainfall data may seem to imply that little to no crop moisture stress occurs during the "rainy" season, but this is certainly not the case. Droughts lasting several weeks are not uncommon in the humid tropics during the rainy season, and droughts do occur in the RNP region even during the main growing season. Depending upon the crop water requirements, the timing of drought periods relative to plant growth, and the farming system involved (e.g., rainfed hill rice or paddy rice), the impact of these "mini-droughts" may be more or less severe.

Secondly, "the best predictive tool for the tropical agronomist is an estimate of weekly rainfall probabilities," which are derived from long-term daily rainfall data (Sanchez, 1976, p. 14). These estimates provide a statistical picture of rainfall variability that allows for a relative assessment of risk, by quantifying the upper and lower confidence limits on rainfall for any given week of the year. Hargreaves and Samani (1986) compiled monthly probabilities for 11 stations in Madagascar, but none are close enough to the RNP region to provide reliable information. Long-term daily rainfall data were not available for this review, but the Service Météorologique in Antananarivo should possess the necessary raw data to compute weekly rainfall probabilities for Fianarantsoa, Ambohimahasoa, and Ifanadiana at the least, and possibly for stations such as Alakamisy-Ambohimaha and Vohiparara with ~15 years of data.

Long-term climate data also provide the means to estimate the soil moisture regime (SMR) and soil temperature regime (STR) of soils, which are necessary for soil classification at various categorical levels of Soil Taxonomy (Soil Survey Staff, 1999). The estimation of SMR and STR for the RNP region is discussed in the next section.

Soils

Madagascar possesses a surprisingly long history of published geology and soils research, dating at least to the year 1901. A bibliography title by Pernet (1951) implies that soils literature may extend back as far as 1884. However, researchers performing earth-science literature reviews on Madagascar frequently encounter difficulties in discovering, locating, and obtaining primary source material (at least for researchers outside of Madagascar and/or France). The current availability of extensive electronic library databases and Internet search capabilities can circumvent some of these problems, but cross-checking between various electronic databases often reveals widely differing results for the same searches. These differences appear to result from several sources: differences as to which publications are indexed for each database, variations in database query structures, conventions and language differences for of keywords and subject headings, etc. Many times there are no apparent reasons for the differences.

Much earth-science literature on Madagascar typically remains undiscovered by researchers because it was published only in Madagascar and not widely indexed. Therefore, a thorough literature search on Madagascar's soils (and geology, climate, etc.) requires creativity, investigative zeal, persistence, and patience. Recent efforts to create a comprehensive database of environmental research in Madagascar (Hoeblich and Rasolofoharinoro, 1996) provide a new opportunity for information dissemination that may aid future research, particularly if it is made available on the Internet or at numerous libraries internationally.

The majority of literature identified for this study was found through searching electronic databases such as GeoRef, AGRICOLA, Cambridge Scientific Abstracts, Science Citation Index, WorldCat, etc. However, these databases do not index many important materials that were published in Madagascar or France. One major source of soils publications on Madagascar, and their associated bibliographies, can be found at the Institut de Recherche pour le Développement (IRD) in Paris. Many articles on Madagascar's soils, including those from the serial "Cahiers O.R.S.T.O.M. – Série Pédologie," can be accessed from the Internet (http://www.bondy.ird.fr/pleins_textes/) by using the website's internal search engine. The Cahiers O.R.S.T.O.M. – Série Pédologie journal is also widely available at US university libraries. These articles were extremely useful for understanding the history of pedology and soil survey research in Madagascar, and for identifying future potential research needs.

Several potentially interesting sources on Madagascar's soils could not be obtained for the current review. These sources include a 1901 publication, perhaps the first formalized soils science research in Madagascar, entitled "Une évaluation agronomique des terres des Madagascar" ("An agronomic evaluation of the soils of

Madagascar") (Müntz and Rousseaux, 1901). The researchers performed chemical analyses on approximately 500 soil samples collected throughout Madagascar, and reported results for nitrogen, phosphorus, potassium, and calcium carbonate (the first author was trained primarily as a chemist and today would be considered a soil fertility or soil chemistry expert). As such, it apparently represented the first attempt to systematically evaluate the agricultural potential of various soils in Madagascar, and a map is included with the publication.

The eminent French mineralogist Alfred Lacroix produced a massive, comprehensive three-volume monograph on the mineralogy of Madagascar (Lacroix, 1922; 1923), which not only included hundreds of total elemental analyses for specific rock types, but also included many similar analyses for alteration products such as clay minerals and "lateritic" soil materials. Lacroix described the prevalence of gibbsite ("hydrargillite"), kaolinite, and "colloidal clay" (perhaps halloysite or poorly-crystalline clays) as products of feldspar weathering in acid rocks of eastern and central Madagascar (e.g., feldspathic gneiss, granite, etc.), including the complete pseudomorphic replacement of macroscopic feldspar grains by these clay minerals. Lacroix reported microscopic examinations that revealed "silhouettes of micas transformed into gibbsite [hydrargillite]," which does not appear likely given current understandings of mica weathering. However, the study occurred before the days of X-ray diffraction, etc., and Lacroix may have described grains of hydroxy-interlayered minerals and/or kaolinite (e.g., Rebertus et al., 1986). He noted that weathered granites and gneisses between Ambohimahasoa and Amobositra were dominated by kaolinite in the clay fraction. Materials high in iron and aluminum sesquioxides (e.g., ironstone, bauxite) from throughout Madagascar were also described and analyzed.

Lacroix (1923) noted that the depth of weathering within the igneous-metamorphic terrain of Madagascar often reached several tens of meters, an observation repeatedly verified since then by other geology and pedology researchers (e.g., Erhart, 1926; Bourgeat, 1972; Segalen, 1995).

Although 19th century geographers commented on Madagascar's red tropical soils, general geomorphology, etc., the first true pedology literature appears to be a 122-page study by geologist Henri Erhart (1926) with the translated title, "The influence of geologic origin and external factors on the formation and agricultural value of the lateritic soils of eastern Madagascar." Unfortunately, this publication was also unavailable for review, but given its potential relevance and historical value to this study, it will hopefully be reviewed for any subsequent publications. Eastern Madagascar in particular lacks the coverage of soil mapping found in other areas of the country (as described below), so any soil data for the region are potentially useful for pedology research, especially given the possibility of correlating some useful data with updated geologic mapping.

Few pedology publications were apparently produced in Madagascar during the 1930s and 1940s. Henri Besairie published two 20-30 page works in 1937 on the general pedogenesis and distribution of major soil types in Madagascar (Besairie, 1937a; 1937b). Another contribution was a 1:2,500,000 scale soils map of Madagascar (Besairie, 1946), which may have been the first authoritative attempt to map soil associations countywide (the bibliographic notes for Erhart's 1926 publication are not clear if Erhart had previously produced such a map). Besairie's 1946 soils map was followed a few years later with a brief explanatory note (Besairie, 1949), although some bibliographic references are contradictory as to the publication date (some references imply it was published simultaneously with the map).

Until the late 1940s, Madagascar's soils apparently had been studied exclusively by geologists (Lacroix, Erhart, Besairie) and soil chemists (Müntz, Rousseaux). After 1946, ORSTOM pedologists, assisted by French and Malagasy agronomic researchers, geologists, etc., performed a large number of reconnaissance soil surveys and pedology investigations throughout Madagascar (Hervieu, 1964; 1967). These efforts, conducted primarily during the 1950s and 1960s, represent the vast majority of published pedology information on Madagascar and form the primary basis for all subsequent generalized soil maps of the country (Riquier, 1968; FAO, 1974; World Soil Resources, 1996a, Soil Survey Staff, 1999).

The pedology research and mapping in Madagascar explicitly focused on providing usable soil information for agricultural and forestry development, engineering purposes, regional planning, etc., and as paraphrased from Hervieu (1964; p.153) "the soil mapping was not an end in itself." The classification and mapping of soils in Madagascar were subsequently utilized to identify specialized research needs for studies on pedogenesis, soil fertility trials, use and management of soils, etc. The French and Malagasy scientists who designed and implemented the soil survey program deserve much credit for emphasizing the practical value of soil survey and pedology research for national development. Even if funding, logistics, and political issues did not allow the entire country to be mapped and a soil survey program to be continuously supported, this initial mapping provided a basis for agricultural extension and future soil mapping programs.

The soil survey program from 1949-1977 produced 15 reconnaissance soil surveys at 1:200,000 scale (Figure 2.11), mainly in the northwest, south, and west of Madagascar (ORSTOM, 1985). Only one of these surveys (Moramanga-Brickaville) occurred in eastern Madagascar, and the index map (Figure 2.11) indicates that the survey did not extend to the great escarpment (“Falaise d’Angavo”) in that area. Four other soil surveys at 1:100,000 scale were published for the Tulear region and Antsirabe, and 11 more reconnaissance surveys at 1:50,000 scale were conducted almost exclusively north of Antananarivo. The available information indicates that no soil surveys at scales smaller than 1:20,000 exist for anywhere in Fianarantsoa province, where the RNP is located. Apparently, no soil surveys at any scale were published that cover the eastern great escarpment zone that contains much of Madagascar’s remaining rainforest.

The prioritization of areas for soil surveys, while not explicitly confirmed by available literature, was most likely decided according to the intensities of soil use and the needs for soil management information. This would be especially true for plantation crops, rice, and other export or staple crops. The prioritization pattern is similar to soil survey progression in the southeastern United States, where the forested Appalachian Mountains were among the last locations designated for modern soils investigations and surveys. In Madagascar, the demands for soil information in these forested and formerly forested steepland areas are now critical for sustainable agriculture and forestry if the remaining rainforest is ever to be preserved and/or expanded.

Five large scale (1:10,000 or 1:5,000) soil surveys were published within Fianarantsoa province, but of these only one was located within 50 kilometers of the RNP, and the others were not located in areas with parent materials or climate

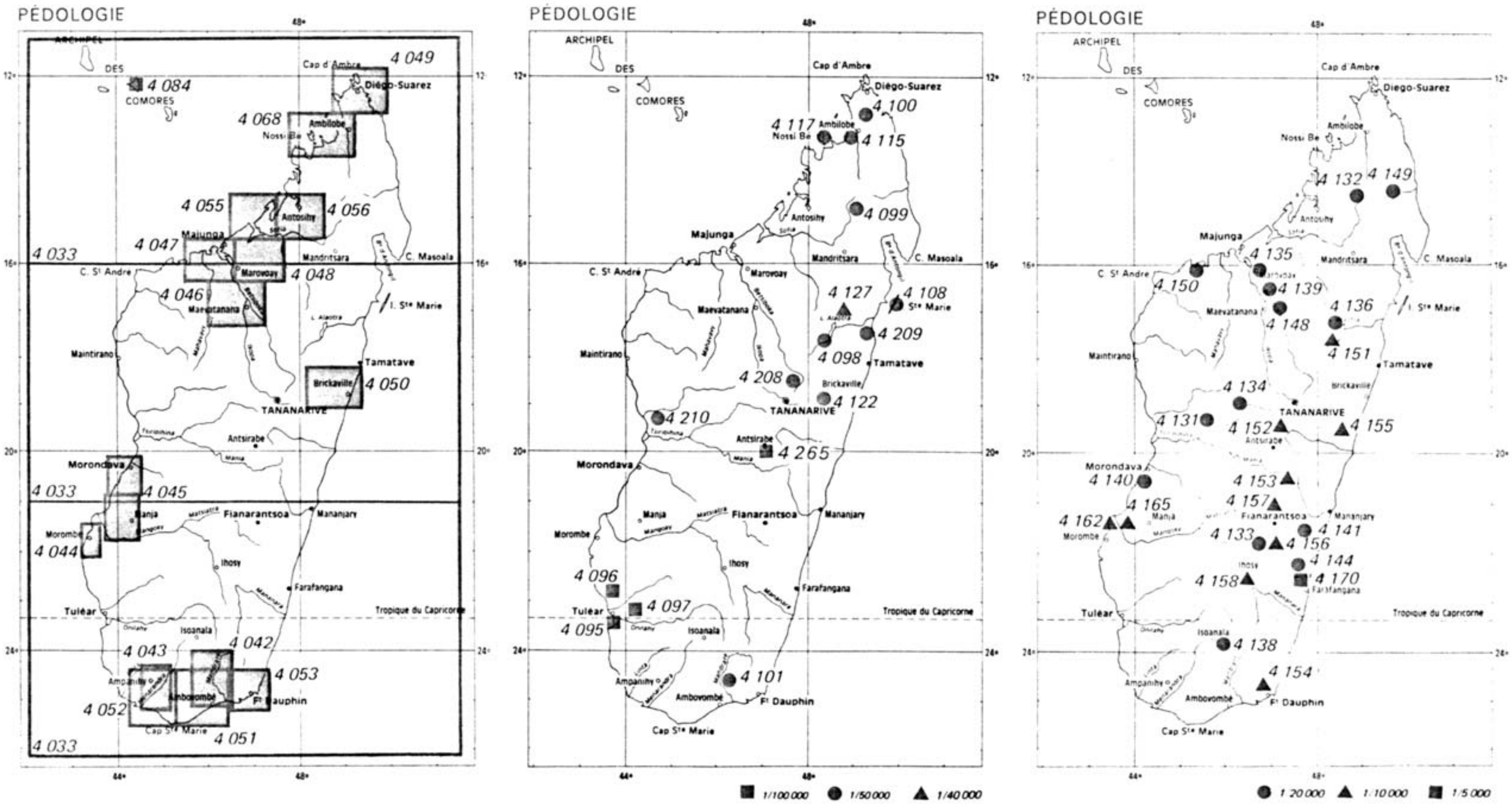

Figure 2.11. Index of published ORSTOM soil maps in Madagascar, 1949-1977 (ORSTOM, 1985). These index maps illustrate the general lack of published soil maps for the RNP region and the eastern escarpment zone. The map on left shows locations of 1:200,000 scale maps. Numbers refer to the ORSTOM map catalog code. The RNP is located approximately one-third of the distance from Fianarantsoa to Mananjary.

conditions similar to the RNP region. The one survey near the RNP, “Sols de la vallée de l’Ankona” (published in 1959, 1:10,000 scale) was situated somewhere near Ambohimahasoa, west of the Namorona River watershed divide. This soil survey might have some applicability to the present study but could not be obtained.

In total, Hervieu (1964) reported that more than 15 million hectares of soil were surveyed in Madagascar, or slightly more than one-quarter of the country’s land area. The soil surveys also resulted in the definition and inventory of provisional soil types throughout Madagascar, published in a separate document by Hervieu (1961).

Only two other pedology studies within a 50-kilometer radius of the RNP were discovered for this literature review; these were not part of the main soil survey program. The first (Bouchard, 1963) reported abbreviated profile descriptions (without Munsell color notations), particle-size analyses, and basic soil chemistry data for an area immediately northwest of Ambalakindresy. The second study (Bouchard, 1966) provided similar data (but with Munsell notations) for the Alakamisy-Ambohimaha area. Portions of both studies were obtained, but insufficient information on laboratory methodologies (e.g., pH, exchangeable bases, base saturation, phosphorus) does not allow direct comparisons with other soil data sets. In general, however, the author commented that the upland soils at both locations were “very” acid, very low in bases, and very low to extremely low in phosphorus. “Hydromorphic” soils were reported to have similar attributes, except for one profile near Alakamisy-Ambohimaha that displayed a marked increase in calcium and magnesium in what may have been a buried “O” or “A” horizon, resulting in an unusually high base saturation.

Differential thermal analysis (DTA) curves were provided for one profile near Alakamisy-Ambohimaha, a yellowish (7.5YR) upland profile occurring on a >20% slope that was then classified as a “sol ferrallitique typique jaune”. The DTA curves indicated the presence of kaolinite along with gibbsite and/or goethite. Although the endothermic peak for kaolinite diminished with depth over three soil horizons, the endothermic peak for gibbsite and/or goethite remained relatively unchanged, suggesting a significant presence of gibbsite throughout the profile.

The French soil classification system for tropical soils evolved mainly in the early 1950s, and the classification presented by Aubert and Duchaufour (1956) largely formed the basis for the system that was formally adopted in 1967 (Commission de Pédologie et de Cartographie des Sols, 1967; Soil Survey Staff, 1975). The 1967 French taxonomy defined hierarchical categories of class, subclass, group, and subgroup (in descending order), which correspond roughly to the higher categories of Soil Taxonomy (Soil Survey Staff, 1975). The soil classification schemes utilized in the Madagascar soil surveys therefore remained reasonably consistent over time, due to the coincidence of the French soil classification system’s evolution and the Madagascar soil survey program timeframe, and the fact that the small-scale surveys classified soils at relatively high categorical levels that changed little since their inception in the 1950s.

A thorough synthesis of pedology research and soil survey in Madagascar was published by Jean Hervieu in 1967, which summarized the general soil-forming factors in Madagascar, an overview of the soil classification system employed there, and the distribution of major soil types within the various broad climatic regions (Hervieu, 1967). This publication is also notable because it contains an extensive bibliography of pedology research in Madagascar, and cited many in-country soil reports that are not typically indexed in electronic databases or catalogs.

Based upon two decades of soil survey activities as described above, Riquier (1968) compiled a reconnaissance soil map of Madagascar at a scale of 1:1,000,000 (3 sheets, in color), utilizing the 1967 French soil classification system. Several published soil maps are derived from this compiled reconnaissance soil map. Roederer and Bourgeat (1969) subsequently produced a simplified and revised version of the map at 1:4,000,000 scale that was published in the Atlas de Madagascar. This simplified map was used in the preparation of the 1:5,000,000 scale Soil Map of the World (FAO, 1974). Soil maps of Madagascar displayed in the Soil Taxonomy system were produced by reclassifying the dominant soil components from polygons depicted on the FAO map to the order categorical level, augmented by climate data (Figure 2.12) (World Soil resources, 1996a; Soil Survey Staff, 1999).

At a broad level of generalization, Figure 2.12 indicates that eastern Madagascar was correlated as Oxisols and Inceptisols. The same areas were generally mapped on the FAO Soil Map of the World (FAO, 1974) as Orthic Ferralsols and Ferralic Cambisols, with Rhodic Ferralsols depicted on the coastal Cretaceous basalts. The Oxisols/Ferralsols correlate closely with the igneous-metamorphic Precambrian basement of Madagascar, as well as the Cretaceous and Plio-Quaternary volcanics (see Figure 2.1). Segalen (1995) generally groups the soils of the escarpment edge and the eastern lowlands (formed on gneiss and granite) as “sols ferrallitiques jaune/rouge,” noting that the color change from the yellow upper profile to red lower profile did not correspond to textural changes or any features impeding internal soil drainage. He also reported kaolinite as the dominant clay mineral in these yellow-over-red soils, with gibbsite and goethite also present. As was noted by Dresch (1962), Bourgeat (1972), Segalen (1995) and others, stonelayers found in ferrallitic

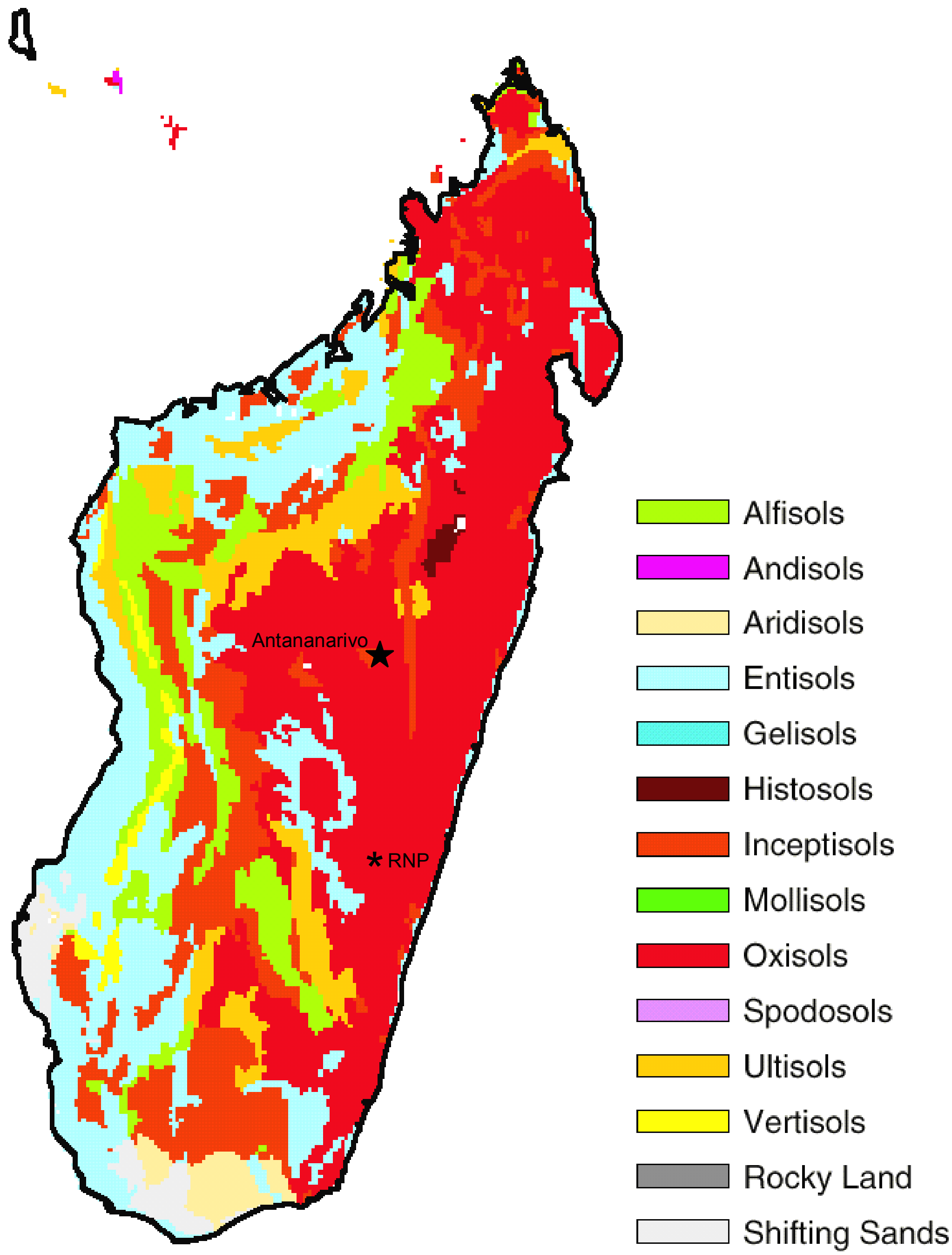

Figure 2.12. Generalized soil map of Madagascar, showing distribution of soil orders per Soil Taxonomy (Soil Survey Staff, 1999). The map was produced by reclassifying the FAO/UNESCO Soil Map of the World polygons (FAO, 1974) into the Soil Taxonomy system (World Soil Resources, 1996). At this level of generalization, Oxisols correlate closely with Madagascar's Precambrian basement and younger volcanics (see Figure 2.1). The scale of the map shown above is approximately 1cm ≈ 100 km.

jaune/rouge soils of the highlands/escarpment transition zone consist of both quartz and ferruginous “pseudo-concretions,” although Segalen provided an additional detail that the iron-oxide concretionary material was relatively aluminum-rich.

Hervieu (1967) reported that “sols ferrallitiques lessivés” (in the intended sense, low-activity clay Ultisols, or Inceptisols with translocated clays) were infrequently found in eastern Madagascar. Segalen (1995) confirmed that ferrallitic soils possessing an argillic horizon or ped coatings (cutans) were rarely described in Madagascar, but were not completely absent. In general, Bourgeat and Aubert (1972) concluded that the Malagasy ferrallitic soils exhibited lower base status than ferrallitic soils on mainland Africa.

A portion of the Riquier (1968) map for the RNP region is presented in Figure 2.13, at approximately the original map scale (1:1,000,000; or 1cm = 10km). Since apparently little actual soil characterization occurred in the RNP region, it is important to consider that the reconnaissance mapping largely reflected the extrapolation of soil studies from other regions (e.g., Moramanga-Brickaville), data from the few soil profiles that were observed in the region, perhaps supplemented by geology maps and general knowledge of the area. The map displays a predominance of “Sols Ferrallitiques” (Oxisols) between Fianarantsoa and Mananjary. The two main soil types are formed on acid rocks (granites, gneisses, migmatites), and were distinguished mainly by color (“rouge” versus “jaune sur rouge”). Higher estimated soil organic carbon contents were treated as a phase criterion (“phase humifère locale”). Segalen (1995) generally attributed higher organic carbon content in ferrallitic soils to a combination of higher rainfall and higher elevations (cooler temperatures). If the mapping were translated into Soil Taxonomy classes (Soil Survey Staff, 1999), these soils would correspond to

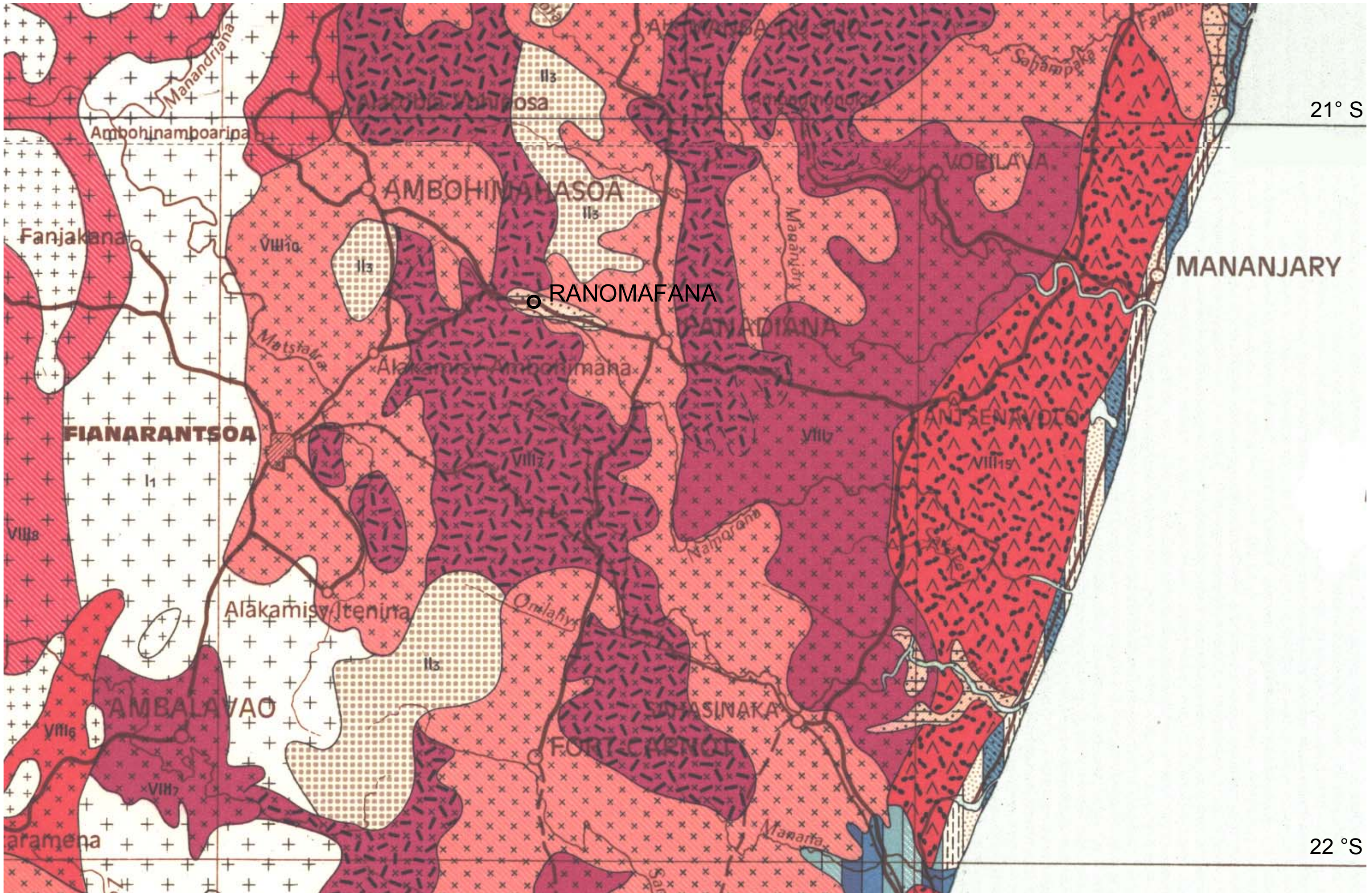

Figure 2.13. Soils map of the RNP region, taken from Riquier (1968) at the original map scale (1cm = 10km). The town of Ranomafana is located above and left of center. See map legend on the following page.

Figure 2.13 (continued). Legend for soils map on previous page.

Hapludox soils, possibly "humic" subgroups for the "phase humifère locale" and possibly "xanthic" subgroups for the "jaune sur rouge" soils if the yellower portions of the profile met color and thickness criteria.

The "Sols Peu Évolués, sols humifères des forêts ombrophyles" mapped north and west of Ranomafana similarly would correspond most closely to humic subgroups of Dystrudepts in Soil Taxonomy, with or without lithic properties. The map unit delineation at the town of Ranomafana within the Namorona River valley ("sols ferrallitiques, sols lessivés, en colloides, jaunes") is a bit more ambiguous to covert into another system, but it appears by the mention of "ancient alluvium" that the concept may have been similar to yellowish Udults on higher river terraces.

The foregoing discussion places all of the soils into "udic" suborders of Soil Taxonomy, not solely based upon the high rainfall and short "dry season" of the RNP region. Soil moisture regimes reported by Van Wambeke (1982) for Madagascar, estimated via the Franklin Newhall method (Soil Survey Staff, 1975), indicated that virtually all of Madagascar east of the great escarpment meets criteria for the udic soil moisture regime (small areas of soils with perudic soil moisture regimes may exist at the Masoala Peninsula and portions of the eastern escarpment as suggested by the highest rainfall zones in Figure 2.8). For stations in the central highlands, soils located at Antsirabe and Ambositra were estimated to have "Typic Udic" conditions, while soils at Fianarantsoa were estimated to have "Dry Tropudic" conditions (Van Wambeke, 1982). The dry tropudic designation reflected model estimates that the soils at Fianarantsoa met udic soil moisture regime criteria, but that the days of consecutive and cumulative moist conditions in the model profile were markedly fewer than in the other udic areas (i.e., a more pronounced dry season exists). Model output data and a detailed map of global soil moisture regimes produced using the Newhall method (World Soil Resources, 1996b), indicate that the transition from udic to ustic conditions in south central Madagascar is approximately 75-100 kilometers west of Fianarantsoa.

In terms of soil temperature regimes, nearly all of Madagascar's soils were classified within the isohyperthermic and isothermic soil temperature regime classes, except for some regions mostly south of the Tropic of Capricorn that possessed aridic and ustic hyperthermic soils (World Soil Resources, 1996b and undated computerized printouts). However, with the 1998 change in criteria for the "iso-" soil temperature regimes to a 6 °C difference between mean summer and mean winter soil temperatures (Soil Survey Staff, 1998), it appears that all of Madagascar's soils now would classify into "iso-" soil temperature regimes. These Newhall method calculations assumed a difference of +2.50 °C between mean annual soil temperature (MAST) and mean annual air temperature (MAAT) throughout all of Madagascar (i.e., MAST – MAAT = +2.50) (World Soil Resources, undated computer printouts). The isothermic soil temperature regime is generally associated with the central highlands, while the isohyperthermic region in eastern Madagascar is generally indicated east of the great escarpment below 500 meters elevation.

The transition between isothermic and isohyperthermic soil regions in eastern Madagascar was apparently delineated either by interpolation between climate stations or a computation, because no long-term published climate data within the escarpment zone have been available for direct calculations of soil temperature regimes. If we assume that the relationship between elevation and temperature in eastern Madagascar is generally correct (Table 2.2 and discussion on page 65), and that the true difference of MAST-MAAT=+2.50, then an elevation of 900 meters would correspond to the 22 °C MAST limit between isothermic and isohyperthermic classes (900 m elevation has an estimated MAAT of 19.5 °C, plus 2.50 °C = 22 °C MAST).

This rough calculation is intriguing, particularly since a distinctive forest type dominated by Araliaceae has been recognized along the upper edge of the escarpment (1100-1200 m) from Fianarantsoa to north of Antananarivo, which is substantially different from forest composition in the RNP area between 600-950 m elevation (Lowry et al., 1997). Thus, a major forest composition change in the RNP area seems to occur between 950 – 1200 meters elevation. More vegetation data are required, along with replicated soil temperature measurements, but it would be a fortunate coincidence if the change in soil temperature regime were closely correlated with a measurable change in forest composition, and vice-versa, with elevation serving as a convenient and easily mapped proxy for both.

Whatever the conceptual framework for soil survey in eastern Madagascar, it is clear that no extensive mapping activities occurred within Fianarantsoa province, nor did any occur within the eastern escarpment zone. Small-scale reconnaissance maps of Madagascar (e.g., Riquier, 1968) designated map units within and around the escarpment zone, primarily based upon soils mapped in the central highlands and the Moramanga-Brickaville region and supplemented by sparsely documented observations from other studies (e.g., Dresch, 1962; Bourgeat, 1972). Tentative classification of these eastern Madagascar soils in the <u>Soil Taxonomy</u> system has occurred, but only as an approximate conversion of soil map units from the French classification system. The present study attempts to address this void by characterizing and classifying representative pedons in and around the RNP eastern escarpment region via Soil Taxonomy criteria, and providing information on soil-landscape relationships for future soil survey work within the general region.

Vegetation

In eastern Madagascar, the influences of soil properties upon vegetative productivity (edaphology) and geographic distribution (chorology) are poorly understood. Likewise, the potential influences of differing vegetation types on soil genesis and soil properties remain equally unknown. To some extent, this ignorance exists simply because detailed plant-soil relationships have not been extensively studied in Madagascar, and because only generalized geology, soil, and vegetation maps are available for most of the country. The lack of knowledge also reflects the limited evolution of vegetation classification and mapping in Madagascar, which traditionally has emphasized broad bioclimatic or “phytogeographic” zones rather than a more detailed characterization of the geographic distribution of distinct plant taxa and/or communities (chorological approach). A refined understanding of plant community distributions throughout eastern Madagascar, and the environmental variables associated with those communities, would facilitate applied research for conservation, reforestation, sustainable forest uses, agroforestry, biological prospecting, soil mapping, etc., to name a few potential uses.

As with much of the other published information on the natural resources of Madagascar, much of the literature regarding vegetation classification and mapping can usually be traced to a few primary publications that do not necessarily provide detailed information that is directly applicable to research activities. Lowry et al. (1997) provide a thorough and insightful review of the history of vegetation classification and mapping in Madagascar. The authors noted that the classical vegetation maps and "phytogeographic" domains of Henri Perrier de la Bâthie (1921) and Henri Humbert (e.g., Humbert and Cours Darne, 1965), traditionally the most widely cited vegetation publications on Madagascar, were principally based upon a somewhat subjective combination of vegetative community structure (e.g., forest, grassland, etc.) and climatic variables, and most vegetation maps of Madagascar were essentially derivations of the concepts developed by Perrier de la Bâthie (1921). The vegetation map by Humbert and Cours Darne (1965) also deserves mention because geology and soil types were used in part for the definition and mapping of vegetation units, and because it employed aerial photography to distinguish between "natural" forest and secondary growth after *tavy*.

In contrast, Lowry et al. (1997) emphasized that White (1983) employed a chorological approach to produce a vegetation map of Africa and Madagascar, based upon vegetation community structure and the geographic distribution of thousands of vascular plant taxa. Interestingly, this approach quantitatively delimited vegetation map units that possessed very similar bioclimatic attributes, though climate was not considered in developing the system. White's approach produced a useful biological research tool for continental Africa, but the lack of extensive data and experience in Madagascar produced a map that by default followed Humbert's earlier work. Lowry et al. (1997) asserted that application of a chorological mapping approach in Madagascar could convincingly address the debate regarding the distribution of natural vegetation prior to human arrival. A chorological mapping approach could also provide the most promising data set for understanding of interrelationships between vegetation communities and soil types, which could aid in their mutual field recognition.

The existing vegetation maps for eastern Madagascar, therefore, delineate map units that are only broadly defined and very extensive. For example, the 1965 map for the RNP region defines a “low elevation rainforest” at less than 800 meters elevation, and a “mid-elevation rainforest” at elevations ranging from 800-1800 meters (Humbert and Cours Darne, 1965; Lowry et al., 1997). Although characteristic plant families and indicator species are described for these vegetation classes, the definitions are broad, essentially lumping the eastern rainforest vegetation into a few classes distinguished by elevation. The map delineations corresponding to these classes are thus very large, extending in bands for essentially the length of Madagascar. This information may have use for global forest geography, or even national level forestry planning, but it provides little useful information for the purpose of soil characterization and survey, edaphology, biological prospecting, etc. As shown previously in Figure 1.1, the majority of eastern Madagascar’s vegetative cover in 1999 consisted of various stages of secondary growth (*savoka*) following one or more cycles of slash-and-burn agriculture.

Even the broad classes in the 1965 vegetation map should not be construed as different “types” of rainforest vegetation, nor should the 800-meter elevation break inject a bias into pedology or other scientific research. The limit (800 m) between “low” and “mid” elevation rainforest, as noted in the previous section, does not appear to be an appropriate break between floristically distinct rainforest communities in the RNP area. One-hectare permanent vegetation survey plots have been established within the RNP along an altitudinal gradient, and will hopefully yield more information about vegetation transitions within the escarpment zone (Lowry et al., 1997). Turk (1997) noted an absence of many tree species within the RNP that typically occur outside the park below 600 m elevation, perhaps indicative of another significant climatic limit for forest composition.

Outside of the rainforest, Gillard (1954) published an inventory of pasture vegetation in Fianarantsoa province, and acknowledged that soil-related vegetation patterns could not be assessed due to a lack of soils information. The study, conducted to assess the carrying capacity for cattle, listed predominant forage species from the genera *Hyparrhenia, Aristida, Trichopteryx, Imperata, Heteropogon, Panicum*, and many other accessory plants. In general, Gillard reported that pastures were of low forage quality, dominated by fire-tolerant grass species, and cattle should therefore be incorporated into mixed farming systems to promote higher animal productivity. Peters (1996) reported that Tanala villages near primary forest allow cattle to freely range through the forest for six months per year.

Changes in vegetation structure and composition after *tavy* follow a general progression from primary forest to degraded secondary forest (*savoka*), subsequent *tavy* conversion of secondary forest to grasslands containing species such as *Imperata cylindrical* and *Hyparrhenia spp.*, and with continued frequent burning, ultimate conversion to grasslands dominated by *Aristida spp*. (Gillard, 1955; Turk, 1997) Secondary forests comprise a substantial proportion of the land area around the RNP, but the secondary forest structure and species composition differ substantially from primary forest. Native pioneer species (e.g., *Harungana madagascarensis*) and invasive exotic species such as strawberry guava (*Psidium cattleianum*), lantana (*Lantana camara*), and Koster’s curse (*Clidemia hirta*) commonly occur in these degraded secondary forests. Native tree species lacking prolific seed dispersal mechanisms typically do not colonize these areas, eventually eliminating those species from the seed pool and reducing chances for long-term "original" forest regeneration (Turk, 1997).

Turk (1997) performed an extensive forestry study to evaluate the potential of indigenous tree species for reforestation and agroforestry uses east of the RNP. The first component of the research documented an indigenous tree flora of approximately 60 families, 158 genera, and 305 species within and around the RNP. Turk described a new tree species (*Astrotrichilia pterophylla* Turk ined.; Meliaceae) and new shrub species (*Eugenia jomae* Turk ined.; Myrtaceae) within the RNP. Virtually all of the RNP has been selectively logged, particularly for Madagascar rosewood or "polysander" (*Dalbergia baroni*). Turk noted that many forest species were altitudinally limited, with some found only above or below the escarpment, while other species occurred throughout the RNP area (e.g., *Harungana madagascariensis*, *Weinmannia rutenbergii*). In his inventory, he also described unusual plant communities on "quartzite sand" east of Ranomafana, corresponding with soils on older/higher alluvial terraces of deep, quartz-dominated sands.

Styger et al. (1999) performed an ethnobotanical study in eastern Madagascar (which included the RNP area) to determine the potential for cultivating indigenous fruit trees as part of an overall agroforestry system. They identified 17 priority fruit tree species and recommended further research to specify ecological requirements (including soil properties), propagation methods, economic potential, etc. The authors also noted that the lack of botanical reference specimens hindered the identification of fruit trees beyond the genus level.

As these types of detailed vegetation inventories are carefully documented for the RNP region and other areas of eastern Madagascar, the potential grows for linking pedology and forest conservation research. The metamorphic geology of the RNP area can exhibit significant local variability in terms of rock chemistry (e.g., ≈100 m^2 occurrences of weathered amphibolite lenses within a feldspathic gneiss area), where soil properties (soil texture, pH, base saturation, phosphorus content, etc.) may also vary to the degree where local floristic composition becomes determined by the soil. The author of the present study assisted in ecological classification research in the Chattooga River basin of western North Carolina, in metamorphic terrain geochemically similar to the RNP. There, the localized occurrence of paw-paw (*Asimina triloba*) almost invariably indicated the presence of hornblende gneiss or amphibolite geology within an otherwise calcium-poor environment. Hopefully, the day is not far off when botanists and pedologists in Madagascar may recognize specific changes in soil properties by noting changes in natural vegetation patterns, and where the propagation of plant species valuable to both nature and man may be facilitated by knowledge of soil distribution.

Land Use and Socioeconomic Factors

Land use within the RNP area (Figure 3.1) is dynamic and has not been reliably quantified to date in terms of acreage. However, aside from the conservation uses of the RNP itself, the landscape around the park is a mosaic of *tavy*, rice paddies, fallow secondary regrowth, villages, remnant and/or sacred (burial ground) forest, and miscellaneous land uses. The Malagasy inhabitants of the area generally identify with the Betsileo and Tanala ethnic/social groups, though these distinctions often become vague, as group identity depends as much on patterns of living as lineage (Ferraro, 1994; Peters, 1996). The Betsileo are associated mainly with paddy rice cultivation, while the Tanala are involved primarily with *tavy* and forest-extraction activities, although these practices are not exclusive to either group (the Tanala, for example, also cultivate paddy rice). The Betsileo do practice *tavy* when conditions necessitate, as when availability of paddy land and/or terraces is limited, or when yields of paddy rice decline.

Subsistence agriculture and extraction of forest products comprise the major economic activities of the area (Ferraro, 1994; Peters, 1996). Rice cultivation is the single most important activity, as the Malagasy people are one of the highest per-capita rice consumers in the world, eating rice every meal of every day if possible. Supplies of rice for most farming families around the RNP frequently become exhausted for several months each year. Rice is cultivated on hillsides as the first crop following slash-and burn of primary forest, on hillside paddy terraces (generally in the central highlands), and in lowland rice paddies. Rice paddies are tilled by hand, or with animal-drawn plows, and puddling is accomplished by either animal traction or communal human labor.

Other staple crops grown and consumed when rice is not available include green bananas, cassava, sweet potato, and taro. Coffee, cultivated at lower elevations east of the RNP, is an important cash crop. Bananas and beans serve as both foods and cash crops, provided transportation routes are nearby (Ferraro, 1994). Pineapples constitute a common crop, especially on *tavy* fields that have been cultivated for several cropping cycles and are declining in fertility status. A variety of beans, corn, leafy vegetables, and minor crops are cultivated, while tree crops such as avocadoes and litchi fruit are harvested as available.

Anecdotal reports of historic deforestation extent around the RNP, as well as scientific analyses (e.g., Green and Sussman, 1990), confirm that the acreage of primary forest has decreased substantially within the last few decades. The RNP was established explicitly to prevent deforestation and serve as a protected area for biodiversity. Unfortunately, particularly for the Tanala, this exclusion places local people in direct competition with the RNP for resources and alters the basic human ecology of the region. Peters (1996, p. 33) eloquently stated, “as *tavy* represents a way of life, governs a set of cultural beliefs, and dictates local social organization, the ban on *tavy* will have an impact beyond the disruption of the local economy.” The implications of this sociological observation for future conservation and development efforts cannot be overstated.

Many ecological, social, economic, and cultural factors affect the use of *tavy* and therefore the rates of deforestation. Forest conservation and *tavy* are mutually exclusive land uses, at least in the context of the RNP regional landscape and its associated population densities. Regardless of the strategies attempted to achieve some sustainable balance between human development and biodiversity conservation in the RNP region, soils information provides one major component of a technical basis for resource management. This soils information becomes even more critical in an environment where naturally low-fertility soils and an impoverished population require an optimal use of limited natural and human resources. As many researchers have observed, neither time nor resources can be wasted in eastern Madagascar if rainforest conservation and sustainable development represent the ultimate common goal.