

A REFINED CLASSIFICATION OF THE PRIMARY VEGETATION OF MADAGASCAR BASED ON THE UNDERLYING GEOLOGY: USING GIS TO MAP ITS DISTRIBUTION AND TO ASSESS ITS CONSERVATION STATUS.

David DU PUY & Justin MOAT

The Royal Botanic Gardens, Kew, Richmond, Surrey, TW9 3AB, UNITED KINGDOM

E-mail: D.Dupuy@rbgkew.org.uk & J.Moat@rbkew.org.uk

ABSTRACT - The map of vegetation domains drawn by HUMBERT (1955) and the more recent vegetation cover map of FARAMALALA (1988, 1995), produced from satellite images, are accepted as reflecting the broad vegetation zones of Madagascar. These maps have been superimposed on maps of the geology and protected areas, and analysed using Geographical Information Systems (GIS) techniques.

The species composition of the primary vegetation is very strongly influenced by the type of rock on which it occurs: the geology map (BESAIRIE, 1964) was therefore reclassified according to broad rock type categories which would markedly affect the composition of the vegetation which they support. A map of the current distribution of the 'Remaining Primary Vegetation' is compared with the 'Simplified Geology' map, and the resulting map of the 'Remaining Primary Vegetation classified by the Underlying Geology' is presented. Estimates are made of the extent remaining of each broad primary vegetation type. Comparison with a map of the protected areas has allowed the production of graphs and statistics showing which vegetation types are well represented in the current system of Parks and Reserves, and those which are inadequately covered. These maps and analyses provide information to assist the planning and management of effective biodiversity conservation in Madagascar.

KEY WORDS - Madagascar, Vegetation, GIS, Biodiversity, Conservation.

RESUME - La carte des domaines végétaux montée par Humbert (1955), et la carte plus récente de Faramalala (1988, 1995) de la répartition actuelle de la végétation, produite à base des images satellites, sont acceptées comme indicatives des zones végétales larges de Madagascar. Ces cartes ont été superposées sur les cartes de la géologie et des aires protégées, et analysées en utilisant des techniques Système Informatique Géographique (SIG). La composition spécifique de la végétation primaire est fortement influencée par le type de rocher sur laquelle elle se trouve : la carte géologique (Besairie, 1964) était donc réclassifiée selon des catégories larges du type de rocher qui pourraient exercer une influence nette sur la composition de la végétation qu'elles soutiennent. Une carte de la végétation primaire ('Remaining Primary Vegetation') est comparée avec la carte de la géologie simplifiée ('Simplified Geology'), et la carte résultante, de la distribution actuelle de la végétation primaire classifiée selon la géologie de base ('Remaining Primary Vegetation classified by the Underlying Geology'), est présentée. L'étendue qui reste de chaque large type de végétation primaire est estimée. Une comparaison avec la carte des aires protégées nous a donnée la possibilité de produire des graphiques et des statistiques qui montrent lesquels types de végétation sont bien représentés dans le système actuelle des aires protégées, et ceux qui ont une inclusion insuffisante. Ces cartes et analyses fournissent des données pour aider la planification et la gestion d'une conservation efficace de la biodiversité de Madagascar.

MOTS-CLES - Madagascar, Végétation, SIG, Biodiversité, Conservation.

Please referred this paper as:

Du Puy, D.J. and Moat, J. (1996). A refined classification of the primary vegetation of Madagascar based on the underlying geology: using GIS to map its distribution and to assess its conservation status. In W.R. Lourenço (editor), Proceedings of the International Symposium on the 'Biogeography de Madagascar', Paris, September 1995, pp. 205--218, + 3 maps. Editions de l'ORSTOM, Paris.

INTRODUCTION

One of the aims of our mapping studies, using Geographical Information Systems (GIS), is to analyse distribution patterns of vegetation types and plant biodiversity in Madagascar. It is not feasible to give an overview of the patterns of plant distribution based on individual species distributions, given that there are over 10,000 higher plant species in Madagascar, and that many of the species are poorly documented. The need for a way to summarise patterns of plant distribution, with a view to the inclusion of plant diversity in conservation planning, led us to look more closely at the vegetation types distinguishable in Madagascar, and at methods to map their current extent and distribution.

Field work has shown that the structure and species composition of the vegetation in a region often alters radically with changes in substrate. It is assumed, therefore, that the species composition of vegetation will alter radically with changes in the underlying rock type. A more informative vegetation map could thus be produced by subdividing the vegetation zones of HUMBERT (1955), or the categories of FARAMALALA (1988, 1995), according to the rock type on which they occur. We would like to present the base maps used in the analyses, and the resultant map combining current vegetation cover and geological substrate, and to highlight certain insights and implications resulting from these maps.

BASE MAPS

Two base maps were required to produce the combined map: 'Simplified Geology' and 'Remaining Primary Vegetation'. A map of 'Protected Areas' was also required for analyses of the cover given by the current system of parks and reserves. These three maps are introduced and discussed below.

SIMPLIFIED GEOLOGY MAP (Figure 1)

The 1:1,000,000 geology map of BESAIRIE (1964) was digitised, resulting in c. 2500 polygons with 81 different geological categories. Many of these categories, although geologically distinct, are likely to produce soils which have similar properties as far as plant growth is concerned, and will support similar vegetation. We therefore simplified this map into 10 categories which we considered to be distinct enough to have a major effect on the plant communities which they support. BRENON (1972) and BOAST and NAIRN (1982) give reviews of the geology, which have been useful in the interpretation of the geology map, and the sedimentary formations are discussed in detail by BESAIRIE and COLLINGTON (1972). The bulk of the centre and east of the island is composed of metamorphic and igneous rocks, with some restricted rock types recognised here as distinct (quartzites, marbles and ultrabasics). The sedimentary zone, mainly confined to the west, south and northern tip of Madagascar, can be broadly divided into recent drift deposits, continental facies and marine facies. Volcanic rocks are also widespread throughout the island (see BRENON, 1972 & STOREY et al., 1995).

METAMORPHIC AND IGNEOUS ROCKS

Precambrian Basement Rocks (Metamorphic & Igneous). This is a broad category of ancient, mainly metamorphic rocks, including all crystalline rocks such as granites, migmatites and schists. They are dated from 3000 million to 550 million years old, and form the core of the island. Large areas of these rocks are covered by a thick blanket of lateritic clays. These rocks are mainly exposed on the steeper slopes of the eastern escarpment, and as cliffs and granitic inselbergs in the Central Plateaux, giving habitats for succulents and xerophytes. It may eventually be possible to subdivide this broad category of basement rocks into distinct types which support substantially different plant communities, as has been done already for the outcrops of quartzites and marble which are known to support endemic species and vegetation with markedly different species compositions.

Ultrabasics. There are very few areas of ultrabasic rocks large enough to be included in the geology map, the most significant being c. 15 km north-north-east of Moramanga (c. 10 km west of Mantadia National Park). This area is an outcrop of nickel-rich ultrabasics and merits botanical investigation. Dykes and sills of ultrabasic rocks occasionally occur scattered through the basement rock category, for example around Mananara on the Baie d'Antongil, and in the area between the Ivondro River and the Onibe River (which reach the coast near Toamasina (Tamatave) and Foulpointe respectively). These are mainly too small to digitise on the geology map, but may have a significant local effect on the vegetation they support.

Quartzites. The main outcrop of quartz is in central Madagascar, forming the mountains of the Itremo Massif (and Mont Ibity). The rocks are Precambrian (at least 630 Ma), and reach a thickness of c. 700 m. This range contains many locally endemic species, especially succulents and including a series of rare, locally endemic Aloe species. A second substantial area of quartzites occurs to the north of the Baie d'Antongil. There are also many outcrops of quartz in the basement rocks of eastern Madagascar which are too small to include in the geology map, but which can have a significant effect on the local vegetation.

Marble (Cipolin). The most substantial areas of marble again occur in central Madagascar, around the area of the Itremo Massif to the west of Ambositra, in association with the quartz system indicated above. They rarely now have substantial forest cover, but the little that exists is extremely different from the other areas of the Central Plateaux. Locally endemic succulent species are confined to these outcrops. A second, very poorly known area of marble occurs to the north of the Baie d'Antongil in eastern Madagascar, and this area certainly merits botanical exploration (see also under 'Quartzites' above).

Lavas (Volcanic and eruptive rocks including Basalts & Gabbros). The older group of lavas and basalts occurs along the eastern lowland belt from north of Taolañaro (Fort Dauphin) to near Toamasina (Tamatave), and from the eastern Masoala Peninsula to Voahangy, in the south in the Mandrare River basin, and also along the west and north-western lowlands. They are all formed from deep fissures exuding lava during the late upper Cretaceous period, 88 million years ago, probably coinciding with the break-up of Madagascar and India (STOREY et al., 1995). In eastern Madagascar they are reported to support vegetation with restricted endemic species (G. SCHATZ, pers. comm.). In contrast, more recent vulcanism is present in the Ankaratra Massif, the Tsaratanana Massif and the Montagne d'Ambre (BRENON, 1972). The Ankaratra Massif was formed by volcanic activity during the last 5 million years continuing until recently (Pliocene), giving the dark, fertile soils around Antsirabe. Although the Montagne d'Ambre has a long history of eruptions, dating back 50 million years, they ended in a (Quaternary) phase of eruptions less than 2 million years ago (BRENON, 1972). This relatively young age may account for the low numbers of locally endemic species, when higher levels would be expected given the rather isolated position of this mountain.

SEDIMENTARY ROCKS

Sandstones (mainly Continental Facies). These are mainly composed of sand eroded from the Precambrian Basement. The oldest layer is a glacial conglomerate dating from c. 280 Ma (base of the Permian), followed by coal deposits derived from fern forests. The surface is often covered in loose sand, such as in the Ankarafantsika and Zombitsy areas. In contrast, the soft sandstones of the Isalo Massif contain fractures which have become silicified, giving a reinforcement which withstands erosion. These sands are much more ancient than the unconsolidated sands towards the coast, and the vegetation they support seems distinctive in composition. There appear to have been frequent marine inundations finally giving rise to the Mesozoic Limestones discussed below. The Mozambique channel appears to have been formed during the middle Permian to the lower Triassic (c. 250-220 Ma), isolating Madagascar from Africa (BRENON, 1972). BRENON also notes that there is often silicified wood present (Araucarioxylon, Cedroxylon, Dadoxylon, characteristically unbranched), and it is interesting to note that all reptile fossils are bird and reptile ancestors (Sauropsides) rather than mammal ancestors (Therapsides). The Boina area sandstones (Mahajanga Basin, including Ankarafantsika) are more recent (Upper Cretaceous, c. 100-65 Ma).

Mesozoic Limestones + Marls (Marine Facies). The limestones have been categorised into two distinct age groups, separated by sandstone deposits and often also bands of basalts and lavas. The Mesozoic limestones are the oldest group. This series of limestones and marls were formed during the Mesozoic period (mainly the Jurassic and lower Cretaceous), between c. 195-100 Ma, at the same period as the earliest flowering plants were evolving, and are generally present as a limestone layer c. 400 m thick. These limestones include the areas of deeply eroded karst ('tsingy') of western and northern Madagascar, which occur in the Ankarana and Bemaraha Massifs and Namoroka, and also less spectacularly eroded areas such as the Ankara Plateau and Analamerana (all middle Jurassic, c. 172-162 Ma). The later limestones (upper Jurassic, lower Cretaceous) are more clayey and marly, often rich in fossil ammonites, and form a band along the western margin of the 'tsingy', except in the Ankarana where the adjacent soils are basaltic, derived from lava flows, and are quite different in character.

Tertiary Limestones + Marls & Chalks (Marine Facies). The Tertiary limestones (c. 65-7 Ma) are less deeply eroded, and occur mainly in southern and western Madagascar, generally nearer to the coast than the Mesozoic Limestones. They include the Mahafaly Plateau and the limestone outcrops near Mahajanga (Majunga), both formed during the Eocene (c. 54-38 Ma). Although these rocks are younger than the Mesozoic limestones discussed above, they are certainly old enough for the evolution of new taxa to have taken place, and the Mahafaly Plateau is an area of extreme botanical richness.

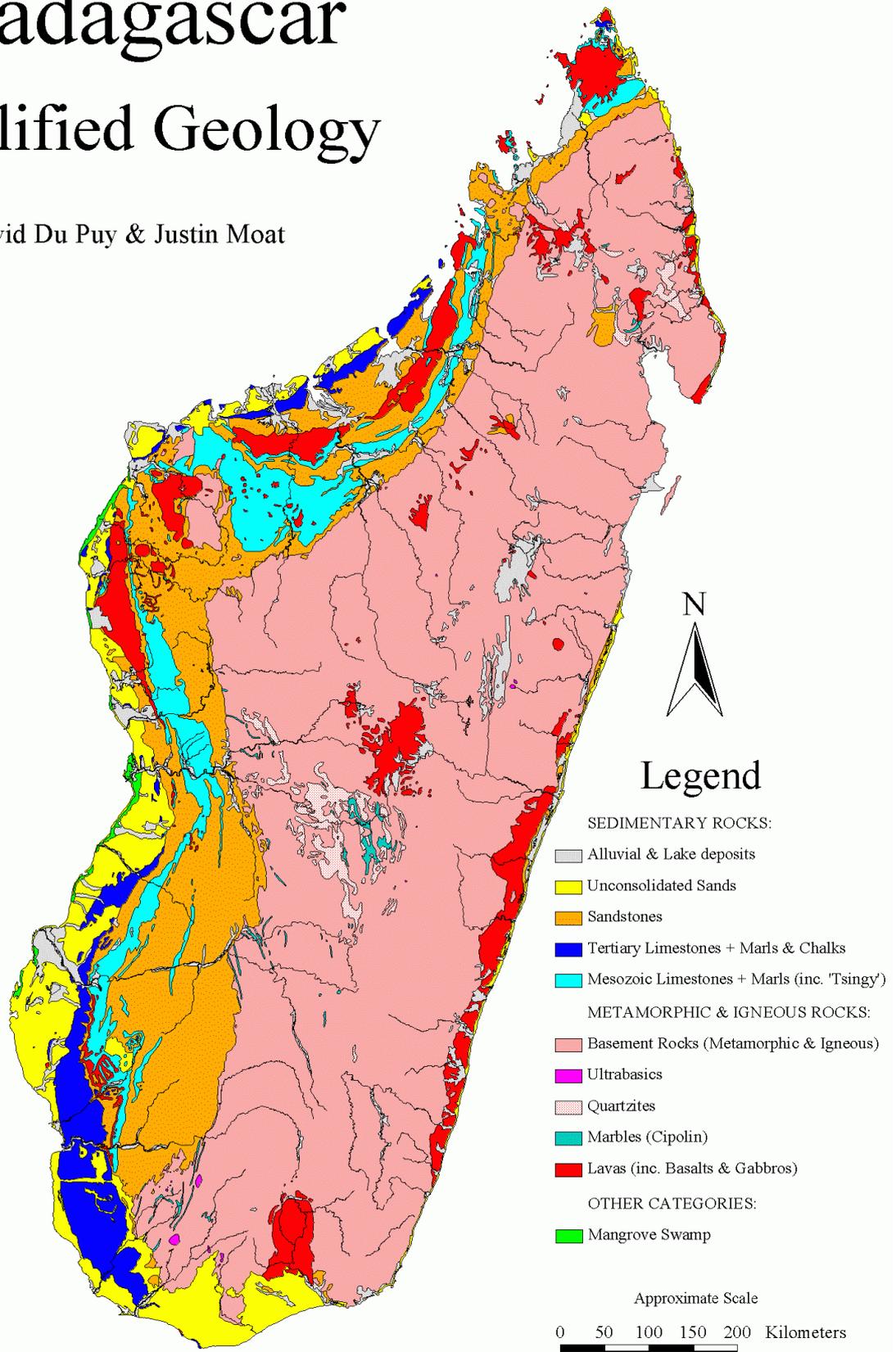
Unconsolidated Sands (Recent and Drift Deposits). These form a plain around the west and south of Madagascar, and a narrow band forming the eastern coastal plain. The forests on sand or alluviums along the east coast are almost all destroyed, but what little remains is very distinctive, containing numerous endemic species and even endemic genera, particularly in south-eastern Madagascar around the zone of contact between the evergreen eastern and the southern deciduous vegetation. The forest on sand around south-western and southern Madagascar (e.g. Forêt de Mikea, the Tulear coastal plain, Itampolo) has a vegetation and species composition which is very distinct from the adjacent vegetation on the limestone of the Mahafaly Plateau.

Alluvial and Lake Deposits (Recent and Drift Deposits). These are finer-grained than the unconsolidated sands. The alluviums, which are generally richer in nutrients, are particularly frequent in western and southern Madagascar. The availability of water and nutrients may give rise to taller forest, such as in southern Madagascar where the riverine forest is dominated by Tamarindus ('Kily') trees. The lake deposits are mainly confined to the Central Plateaux, and are often used for rice cultivation such as around Lac Alaotra. **MANGROVE SWAMP**. This category is often linked to alluvial deposits, such as at large river estuaries, or to unconsolidated coastal sands. They are confined to the north, west and some small strips of the southern coasts.

Madagascar

Simplified Geology

David Du Puy & Justin Moat



(derived from Besairie, 1964)

REMAINING PRIMARY VEGETATION MAP (Figure 2)

This map was derived from the vegetation map of FARAMALALA (produced in 1988, based on LANDSAT satellite imagery acquired between 1972 and 1979, and digitised by Conservation International, 1995), the first stage being to remove all secondary vegetation types, leaving only the areas of remaining primary vegetation. Only 16 vegetation types were selected. These were then simplified into 11 categories, these divided into two groups, evergreen or deciduous (with mangroves and marshes falling outside of this classification), as indicated in Table I.

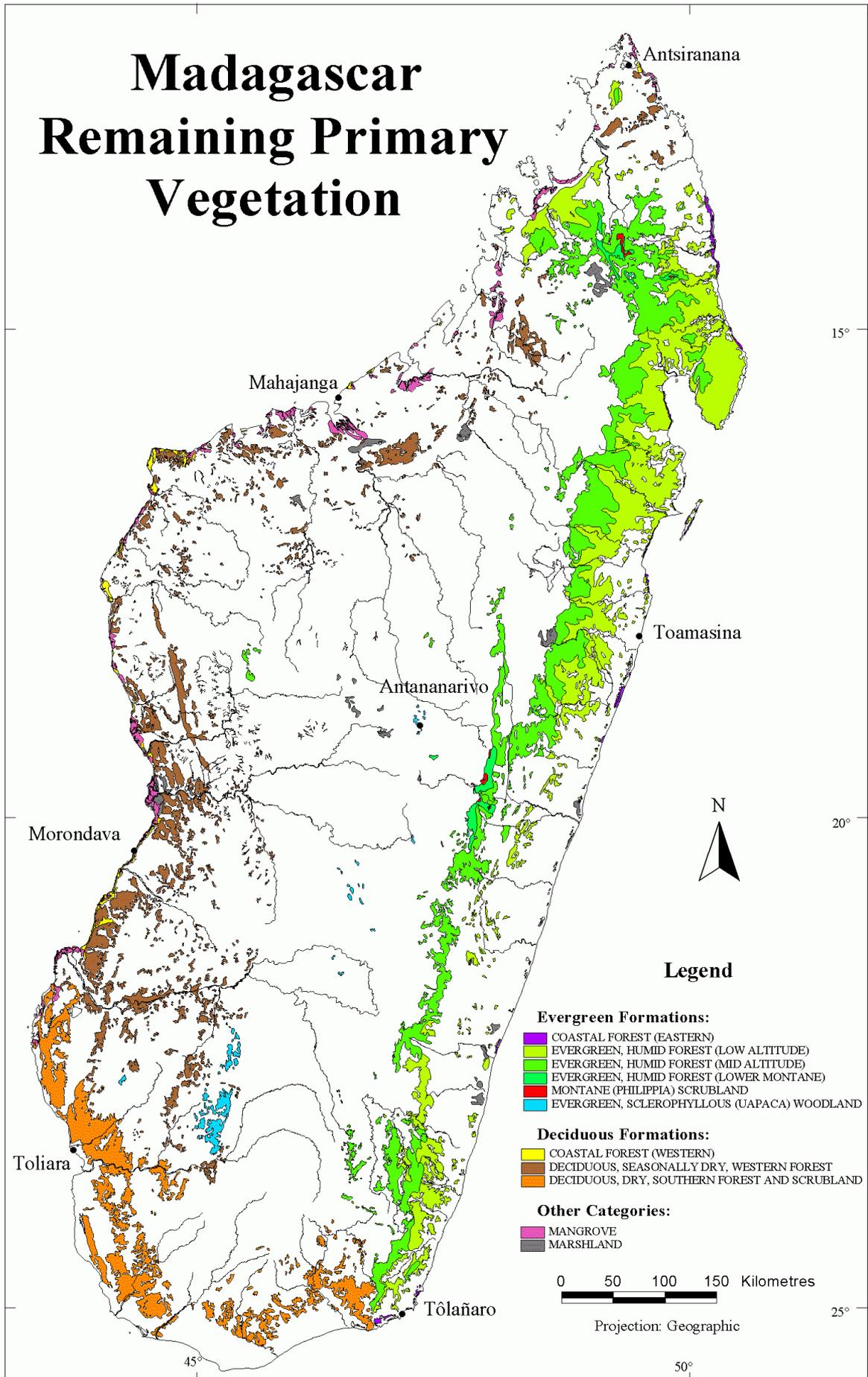
The vegetation maps of FARAMALALA and of HUMBERT already reflect environmental factors such as climate, seasonality and altitude. The broad zonation of the map of FARAMALALA differs little from that of HUMBERT, except for the evergreen forest of west-central Madagascar (NW of Tsiroanomandidy) being included with the eastern, evergreen, humid forests, the recognition of a separate group of 'Forêt sclérophylle basse' (Low, sclerophyllous forest) in central Madagascar, and the extension of the southern domain further inland along the Onilahy River valley. These changes are accepted here. The division of the eastern forests according to altitude is also maintained, although this division from low-altitude to mid-altitude forest at 800 m is regarded as artificial. Alterations to the classification used in FARAMALALA's map involved simplification by uniting several of the categories, as follows:

The Sambirano was not recognised as distinct from the system of evergreen, humid eastern forests: it was regarded simply as a centre of endemism.

The Karst and riverine vegetation of the west were not recognised as distinct from the broader classification as deciduous forest, as they were based on changes of substrate only (which become evident on comparison with the geology map).

The subdivision of the south of Madagascar into two vegetation types was not upheld as the two types were not readily distinguishable through satellite image analysis (but become clear on comparison with the geology map).

Madagascar Remaining Primary Vegetation



HUMBERT'S DOMAINS (1954)	FARAMALALA (1995): PRIMARY VEGETATION CATEGORIES	PRIMARY VEGETATION CATEGORIES (USED IN THIS STUDY)
REGION ORIENTALE		
Domaine de l'est (0-800 m)	EST 0-800 m:	EVERGREEN FORMATIONS (EAST AND CENTRE):
	Forêt littorale	Coastal forest (eastern)
	Forêt dense humide sempervirente	Evergreen, humid forest: low altitude (0-800 m)
Domaine du Sambirano (0-800 m)	SAMBIRANO 0-800 m:	
	Forêt dense ombrophile	(<-included in the above category)
Domaine du centre (800-2000 m)	EST 800-1800 m:	
	Forêt dense humide sempervirente saisonnière	Evergreen, humid forest: mid altitude (800-1800 m)
Domaine des hautes montagnes (2000 m)	MONTAGNES 1800-2000 m:	
	Forêt dense humide basse montagnarde	Evergreen, humid forest: lower montane (1800-2000 m)
	Fourré à <i>Philippia</i>	Montane (<i>Philippia</i>) scrubland (> 1800 m)
	HAUTES MONTAGNES 2000 m:	
	Fourré dense	(<-included in the above category)
Domaine du centre, pentes occident. (800-2000 m)	OUEST 800-1800 m:	
	Forêt sclérophylle basse très dégradée*	Evergreen, sclerophyllous (<i>Uapaca</i>) woodland (800-1800 m)
REGION OCCIDENTALE		
Domaine de l'ouest (0-800 m)	OUEST 0-800 m:	DECIDUOUS FORMATIONS (WEST AND SOUTH):
	Dune et sable salé	Coastal forest (western)
	Forêt dense sèche	Deciduous, seasonally dry, western forest (0-800 m)
	Faciès karstique	(<- included in the above category)
	Faciès ripicole	(<- included in the above category)
Domaine du sud	BASSE MERIDIONALE 0-300 m:	Deciduous, dry, southern forest and scrubland (0-300 m)
	Forêt dense sèche à <i>Didierea</i> et <i>Euphorbes</i>	(<- included in the above category)
	Fourré dense sec	
AUTRES:		
	Zone à mangrove	Mangrove
	Marécage	Marshland

Table I: A comparison of the vegetation zones of HUMBERT (1954), the primary vegetation categories recognised by FARAMALALA (1995), and how the latter have been simplified for this study.

* Although this category is defined as very degraded, it remains a distinctive native vegetation remnant which contains an important range of species which do not occur elsewhere. This category is included due to the almost complete absence of undisturbed native forest in central Madagascar

PROTECTED AREAS MAP

The digitised version of the Protected Areas map of Madagascar (COEFOR & CI, 1993) was divided into two classes of protected area. The lower class included areas with little protection (Réserve Forestière and Forêt Classée) which are designed more for forestry and exploitation than conservation of the native vegetation, while the upper class included those areas with a good degree of protection (Parc National, Réserve Spéciale and Réserve Naturelle Intégrale). The degree of protection is somewhat misleading, as even those areas with good theoretical protection are often not well protected due to lack of surveillance and resources, but the statistics concerning the current network of protected areas are nevertheless informative.

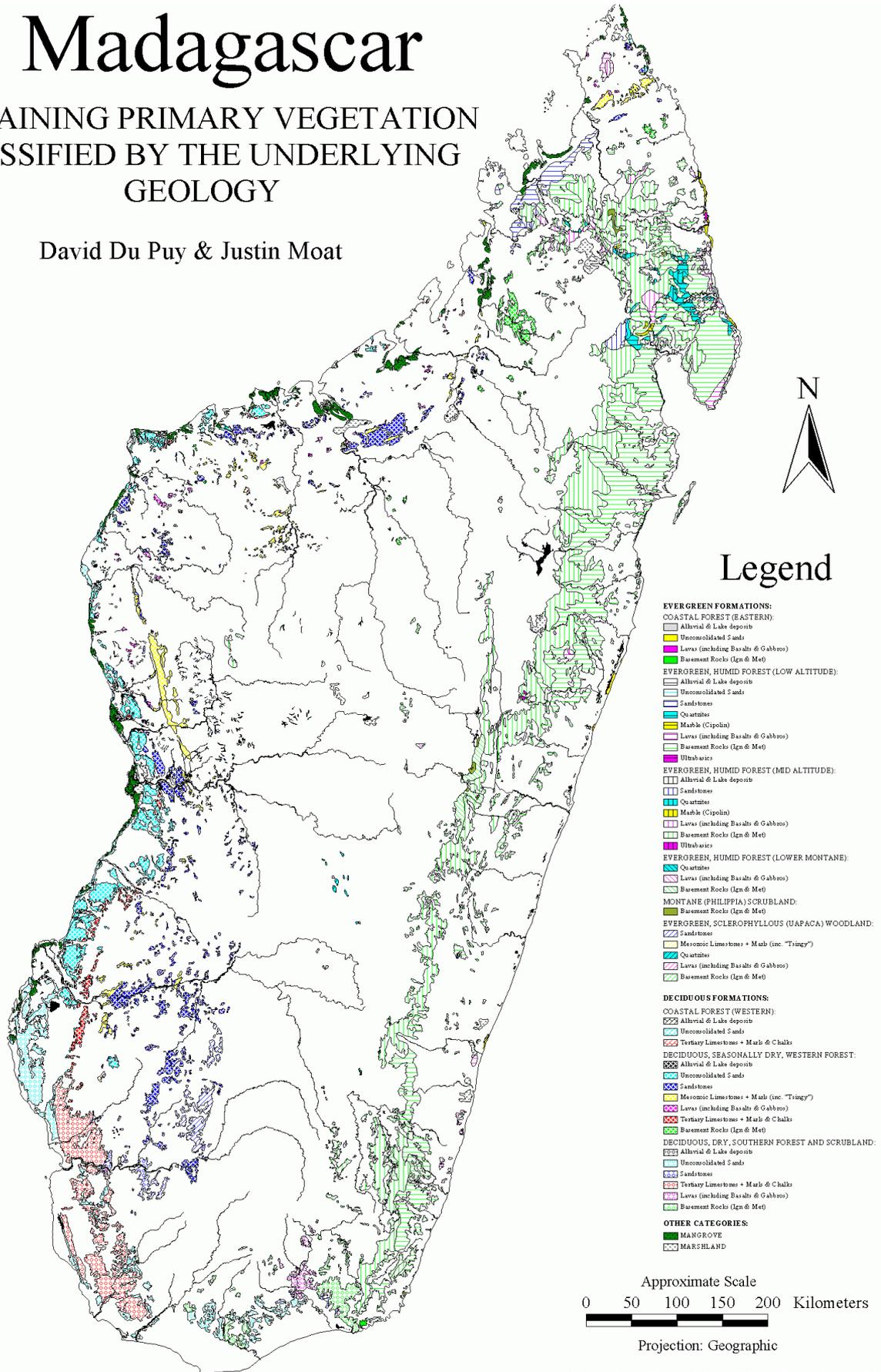
MAP OF THE REMAINING PRIMARY VEGETATION CLASSIFIED BY THE UNDERLYING GEOLOGY

Using ARC/INFO and ARC/VIEW (donated to the project by ESRI), the map of 'Remaining Primary Vegetation' types was then overlaid on the 'Simplified Geology' map, producing a map of the remaining areas of primary vegetation types, subdivided according to the substrate on which they occur. The resulting vegetation map provided new insights into the distributions of the various types of vegetation, mirroring the different types recognised from field work, especially in western and southern Madagascar where the geology varies substantially. [Note: The categories used on a scale covering all of Madagascar are necessarily broad. Refinements lead to too many categories, but would be applicable in localised study areas.]

Madagascar

REMAINING PRIMARY VEGETATION CLASSIFIED BY THE UNDERLYING GEOLOGY

David Du Puy & Justin Moat



EVERGREEN FORMATIONS (EAST AND CENTRE)

Coastal Forest (Eastern). A narrow band of sand and alluviums along the east coast supports coastal forest. Much of this forest has been removed: the little which remains is under threat, and is inadequately protected. The main remaining areas of this vegetation type occur around Taolañaro (Fort Dauphin: Ampetrika (Petriky), Mandena and Cap Sainte Luce), at Ambila Lemaitso and from the Masoala Peninsula north to Vohemar, with some vestiges on Isle Sainte Marie. The forests around Taolañaro are threatened due to impending mining for titanium-rich sands. These forests are of major interest particularly because they occur in the zone of contact between the deciduous, dry, southern vegetation and the evergreen, humid, eastern vegetation, and are known to contain rare and locally endemic genera and species.

Evergreen, Humid Forest: Low Altitude (0-800 m) and Evergreen, Humid Forest: Mid Altitude (800-1800 m). These two categories contain the largest areas of remaining forest. The division of these categories at the 800 m contour is artificial in that there is a continual gradation from one to the other. Moreover, the contour line may be more appropriately placed at around 600 m (G. SCHATZ, pers. comm.), and it is unlikely that the division will occur at the same altitude along the length of the island, with some reduction in the altitude probable towards the south of the island. This would substantially reduce the area of forest classified as 'low altitude'. The eastern evergreen forests mainly occur on the metamorphic and igneous basement rocks, and are rather uniform in our categorisation using the underlying rock type. Although the full geology map indicates various categories of granites and migmatites, it seems improbable that these different rock categories will greatly affect the forest cover they support. More detailed studies of particular areas may find further subdivisions of the geology map appropriate and informative.

The area distinguished by both HUMBERT and FARAMALALA as the 'Sambirano' is recognised here as a centre of localised endemism. This region is included with the rest of the evergreen forests (following discussion with G. SCHATZ). The endemism may be accounted for by the sandstone substrate in this area, the endemic species probably also spreading up the alluviums of the Sambirano River. Another zone of interest in the eastern forests is the area to the north and west of Maroansetra, where the rock type is extremely varied, including quartzites, sandstones, basalts and even marbles which will give rise to calcareous soils. This unique area is poorly known, and should be a focus for further collection and inventory.

There are considerable areas of evergreen, humid forest on old basaltic lavas (Late Cretaceous, c. 88 Ma), such as at low altitudes north of Taolañaro (Fort Dauphin), and from the eastern coastal zone of the Masoala Peninsula towards Vohemar. G. SCHATZ (pers. comm.) indicates that there is evidence of endemic species in these areas. In contrast, the area of Montagne d'Ambre is an area of recent volcanic eruption (Quaternary, less than 2 Ma), and this is reflected in the low local endemism of the area.

There are few outcrops of ultrabasic rocks large enough to include on the geology map, although they should contain very distinctive vegetation. The only one still supporting primary vegetation cover is situated slightly west of Andasibe / Perinet. There are several areas (Mananara, Toamasina-Foulpointe) where narrow dykes of ultrabasic rocks occur, and these areas merit botanical survey.

The geology of the centre of the island is similar to that of the east, usually covered by deep beds of laterite. Inselbergs and exposed rocky slopes provide habitats for succulent species. They are 'islands' of succulent vegetation, the species often having evolved into variants distinct to each isolated outcrop. It has not been possible to include the inselbergs on the map as their succulent vegetation is not apparent as primary vegetation on satellite images. Another notable example of exposed rocks is the region of the Itremo Massif and the Mont Ibity range which stands out as being based on quartzites and marbles. This area is recognised as containing many endemic species with highly restricted distributions.

Evergreen, Humid Forest: Lower Montane (1800-2000 m). This category mostly occurs on the metamorphic and igneous basement rocks, with the main areas occurring on the Tsaratanana and Marojejy Massifs and on the edge of the Central Plateaux south-east of Antananarivo, with a small amount remaining in the Ankaratra Massif. It is inadequately protected at present.

Montane (Philippia) Scrubland (> 1800 m). This restricted vegetation occurs in the same areas as the above category (although it is absent from Ankaratra). It is at present minimally protected.

Evergreen, Sclerophyllous (Uapaca) Woodland (800-1800 m). The Uapaca and Sarcolaena dominated sclerophyllous woodlands are valuable examples of a very restricted vegetation type which has mostly been replaced by artificial, fire-induced grassland. The main remnants, in the Isalo and Itremo Massifs, occur on sandstone and quartzite respectively, and have different species compositions.

DECIDUOUS FORMATIONS (WEST AND SOUTH)

Coastal Forest (Western). This category is probably similar in character to the western forests on unconsolidated sands (see below), except for specialised dune vegetation where restricted species are recorded, and areas with saline soils.

Deciduous, Seasonally Dry, Western Forest (0-800 m). The deciduous western forests occur on various distinctive rock types, including principally those on Mesozoic limestones, those on unconsolidated sand, those on sandstones and those on the metamorphic basement.

The most distinctive, and currently the most fully protected, are those on the Mesozoic limestones, including the reserves of Ankarana and Analamerana, Namoroka and Bemaraha. These areas contain the highly eroded and spectacular limestone karst and pinnacles known as 'tsingy', which makes access extremely limited and is an effective natural protection against over-exploitation, burning and cattle grazing. The Tertiary limestones in western Madagascar, in contrast, have very little forest cover remaining.

The western forests on unconsolidated sands extend in a broad zone towards the coast from the northern tip of Madagascar south to the Mangoky River. They are amongst the most poorly known formations in Madagascar, and merit further field study. The main areas exist to the west of the Bemaraha Massif and between Morondava and the Mangoky River.

The forests on sandstones include Ankarafantsika and the Zombitsy forest (near Sakaraha). The underlying rocks are often highly eroded resulting in a thick bed of loose sand on the surface. It is not known whether the species composition differs radically from that on the younger, unconsolidated sands. This requires verification through field work and comparisons with distribution data of individual species.

Towards the north of the island, south of the Tsaratanana Massif, there is a restricted and poorly prospected area of deciduous forest on metamorphic basement rocks. This area merits further field research to determine the levels of local endemism.

Deciduous, Dry, Southern Forest And Scrubland (0-300 m). When divided according to underlying rock type, the divisions within the vegetation of southern Madagascar correspond closely with those indicated by Faramalala on her vegetation map. The major divisions, such as that dividing the vegetation on the Tertiary limestones of the Mahafaly Plateau ('Forêt dense sèche') from that on the unconsolidated sands ('Fourré dense sec') become immediately obvious, and the extent of each type of vegetation is more accurately mapped. Cap Sainte Marie is a restricted outcrop of this limestone with a remarkable flora with many restricted endemic species.

Not only does the geology effectively divide the vegetation of the south into two major categories, that on sand and that on limestone, it also gives further information on other possible divisions, such as the basaltic region of the Mandrare River basin, the sandstones of the upper Onilahy River valley (including the Beza Mahafaly area), and the metamorphic rocks of the Andohahela Reserve (Parcelle 2). The Mandrare River basin contains ancient lavas and basalts, and this area merits further investigation for localised endemism.

OTHER CATEGORIES

Mangrove. Mangroves occur along the northern, western and southern coasts, with the largest areas occurring in the west, in the alluviums of the deltas of large rivers such as the Betsiboka. There are no significant areas of mangrove within the present system of protected areas.

Marshland. Marshland is included here, as the habitat may be important for certain species. Much marshland has been lost to rice cultivation.

AREAS FOR INVENTORY

This study has highlighted several areas for further inventory work, including the remaining eastern coastal forests, the eastern evergreen forest (low altitude) on basalts and lavas, the evergreen, humid forest area to the north of Maroansetra on sandstones, quartzites and marbles, the deciduous, seasonally dry, western forest on unconsolidated sands along the west coast between Morombe and Cap Saint André and on metamorphic rocks to the south of the Tsaratanana Massif, and the southern deciduous vegetation on the lavas of the Mandrare River basin. This list is not comprehensive, and further inventory and collection is required in many other areas.

VERIFICATION OF THE COMBINED VEGETATION AND GEOLOGY MAP

Comparisons of individual species distributions with this combined map will be used to verify that the resulting categories reflect the ecological variation found. We have hypothesised that many species will be confined to vegetation on one, or a subset of related rock types. We will be able to test these vegetation categories using databases of species distributions: a demonstrable concordance of species distributions with distinct vegetation categories will not only be evidence to confirm these categories, but will also allow their characterisation using chorological data. It is also probable that distribution patterns in fauna species will also be reflected in the vegetation categories, since changes in the substrate and consequently the vegetation composition will also affect the fauna which the vegetation can support.

THE EXTENT OF THE REMAINING PRIMARY VEGETATION, AND ITS CURRENT PROTECTION: CONSERVATION IMPLICATIONS

The map of 'Protected Areas' (COEFOR & CI, 1993) was overlaid on the map of 'Remaining Primary Vegetation'. Histograms of the area remaining of each vegetation type could then be produced, showing the amount of each type which falls within the current system of protected areas (Figure 4). It is immediately obvious which vegetation types are poorly represented in the current system of protected areas, and those which are not currently protected. Maps showing the current distribution of individual vegetation types can then be examined to show where large, intact areas suitable for conservation still exist. This type of analysis gives data which is extremely useful in planning biodiversity conservation.

IMPLICATIONS FOR CONSERVATION

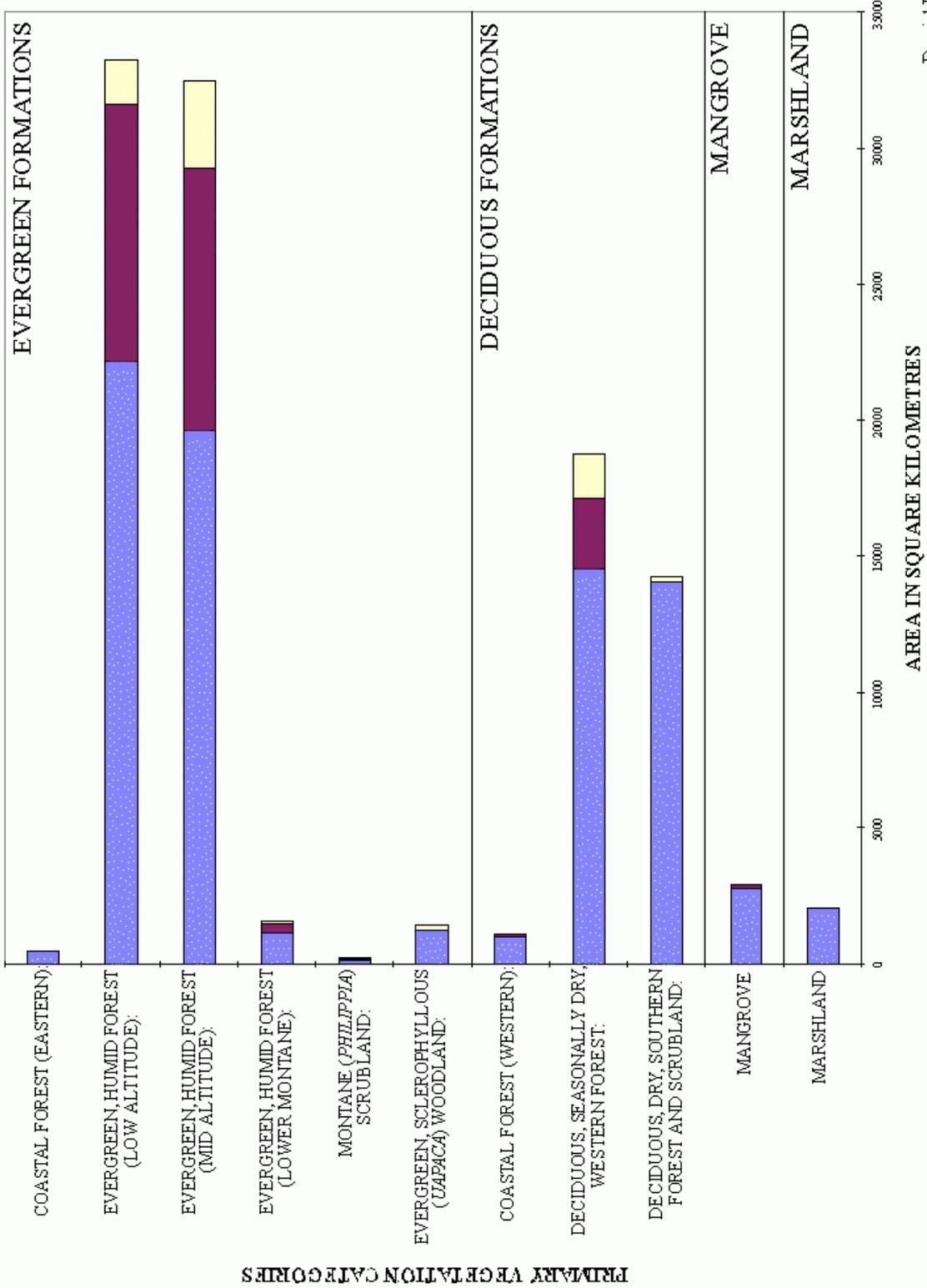
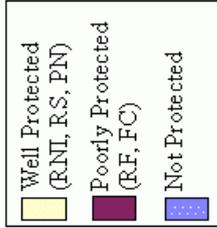
Priority areas for inclusion in new reserves should include examples of both extensive and restricted vegetation categories which are not adequately protected within the current system of protected areas. The 'Evergreen, Humid Forests' in eastern Madagascar have the largest areas protected, both at low and medium altitudes, but confirmation is required that areas on basalts and lavas are included. If the altitude limit of 800 m currently used to divide these two categories is lowered to 600 m, the amount of 'low altitude' forest protected will be substantially reduced. The highly restricted 'Coastal Forest (Eastern)' is an outstanding example of a vegetation type under imminent threat and without adequate protection. Portions of both restricted montane vegetation categories ('Evergreen, Humid Forest: Lower Montane' and 'Montane (Philippia) Scrubland') are included in protected areas. The 'Evergreen, Sclerophyllous (Uapaca) Woodland' on sandstone is protected in the Isalo National Park, but this vegetation on the quartzite and marble areas of the Itremo Massif should also be protected, particularly given the importance of the endemic succulent flora in this region. From the histograms, the 'Deciduous, Seasonally dry, Western Forest' appears to have a good degree of protection, but many of the reserves are in areas of Mesozoic limestone ('tsingy'), and the protection of vegetation on other rock types should be carefully examined (in particular, the forests on unconsolidated sand, sandstone and metamorphic & igneous rocks). At least one substantial area of 'Mangrove' should also be protected. The most outstanding need is for additional reserves in the 'Deciduous, Dry, Southern Forest and Scrubland', which contains vegetation on several distinctive rock types, and is an area of outstanding diversity on a global scale, but which currently has only a very small area within protected areas.

The areas indicated above are preliminary indications, and more detailed analyses using the underlying geology to subdivide the broad vegetation types will undoubtedly indicate further priority areas.

MADAGASCAR: AREAS OF REMAINING PRIMARY VEGETATION & THEIR DEGREES OF PROTECTION



KEY:



David Du Puy & Justin Moat

CONCLUSION

The base maps 'Remaining Primary Vegetation' and 'Simplified Geology' are documented, and the combined map 'Remaining Primary Vegetation classified by the Underlying Geology' is presented. Comparison of the 'Remaining Primary Vegetation' map with the 'Protected Areas' map has allowed histograms showing the total areas of remaining primary vegetation to be produced, with the amount of each which currently occurs within protected areas indicated.

Some of the possible applications have been presented briefly, including conservation planning and management, identification of priority areas for inventory and interpretation of species distribution patterns. One application to which we hope this work may contribute is in the planning of priorities for the conservation of biodiversity in Madagascar, such as in the establishment of new reserves in habitats not currently covered by the existing series of protected areas, in order to include as much of the island's biodiversity as possible.

ACKNOWLEDGMENTS

We would like to thank the Weston Foundation for supporting this research. We would also like to thank ESRI for the donation of computer software, Conservation International, ANGAP, the Ministère des Eaux et Forêts (Madagascar) and FTM for allowing the use of their maps, and the Royal Society and the National Geographic Society for funding research in Paris and field work in Madagascar. We would also like to thank the Parc de Tsimbazaza and the University of Antananarivo for collaboration and assistance particularly with field work. We are also grateful to the many individuals who have contributed to our understanding of the vegetation in Madagascar.

REFERENCES

- BESAIRIE, H., 1964. Carte Géologique de Madagascar, au 1:1,000,000e, trois feuilles en couleur. Service Géologique, Antananarivo.
- BESAIRIE, H. and M. COLLIGNON, 1972. Géologie de Madagascar; I, Les terrains sédimentaires. *Annales Géologiques de Madagascar*, 35: 1-463.
- BOAST, J. and A.E.M. NAIRN, 1982. An Outline of the Geology of Madagascar. In: A.E.M. Nairn and F.G. Stehli (eds.), *The Ocean Basins and Margins, Vol. 6, The Indian Ocean*. pp. 649-696. Plenum Press, New York & London.
- BRENON, P., 1972. The Geology of Madagascar. In: R. Battistini and G. Richard-Vindard (eds.), *Biogeography and Ecology in Madagascar*. pp. 27-86. Dr. W. Junk B.V. Publ., The Hague, Netherlands.
- COEFOR/CI, 1993. Répertoire et Carte de Distribution : Domaine Forestier de Madagascar. Direction des Eaux et Forêts, Service des Ressources Forestières, Projet COEFOR (Contribution à l'étude des Forêts Classées), et Conservation International, 20 p. + 1 map.
- FARAMALALA, M.H., 1988. Etude de la Végétation de Madagascar à l'aide des Données spatiales. Doctoral Thesis, Univ. Paul Sabatier de Toulouse, 167 p. + map at 1:1,000,000.
- FARAMALALA, M.H., 1995. Formations Végétales et Domaine Forestier National de Madagascar. Conservation International (et al.), 1 map.
- HUMBERT, H., 1955. Les Territoires Phytogéographiques de Madagascar. Leur Cartographie. Colloque sur les Régions Ecologiques du Globe, Paris 1954. *Ann. Biol.* 31: 195-204, + map.
- STOREY, M., J.J. MAHONEY, A.D. SAUNDERS, R.A. DUNCAN, S.P. KELLEY, M.F. COFFIN. Timing of Hot Spot Related Volcanism and the Breakup of Madagascar and India. *Science* 267: 852-855 (1995).