

## Geophagy by the Bonnet Macaques (*Macaca radiata*) of Southern India: A Preliminary Analysis

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**ABSTRACT.** Bonnet macaques (*Macaca radiata*) in the Marakkanam Reserved Forest of southern India consume termitaria soils. Samples from the ingested termite mounds are compared with samples taken from the surrounding uneaten soils in an attempt to determine why the termitaria soils are eaten. Particle size, clay and primary mineral composition, geochemistry and scanning electron microscopic analyses are used to search for a possible explanation for geophagy among the bonnet macaques. Kaolin minerals abound throughout the Marakkanam soil sample suite. But the termitaria soils are distinguished by the presence of small amounts of smectite. An abundance of kaolin minerals in combination with small amounts of smectite strongly resembles the mineralogy of *eko*, a traditional African remedy for stomach ailments, and Kaopectate<sup>TM</sup>, a western anti-diarrhoeal preparation. The percentage of mature leaves and fruits of *Azadirachta indica* consumed by the bonnet macaques is relatively high. Plant feeding deterrents, such as, acid detergent fibre (ADF) and the inherent nature of the fruits of *Azadirachta indica*, when consumed in large quantities to act as a purgative, could cause gastrointestinal upsets and diarrhoea. At Marakkanam, bonnet macaques ingest termitaria earth that would act as a pharmaceutical agent to alleviate gastrointestinal upsets and control diarrhoea.

**Key Words:** Geophagy, Soil consumption, Primates, Bonnet macaques, *Macaca radiata*

### INTRODUCTION

Primates have an eclectic diet that is determined by temporal, spatial, anatomical and physiological parameters. These, combined with differences in habitat, produce a wide variety of diets (OATES, 1987). The great majority of primate species eat a combination of leaves, fruits, flowers and animal matter. They are also observed to eat mushrooms, roots, bark, seeds and gums; and a mixed diet seems to have been a dominant feature throughout primate evolution (MARTIN, 1990). Sometimes primates have been observed to deliberately eat "vague" items such as charcoal (STRUHSAKER et al., 1997), dead wood (STRUHSAKER, 1975) and soil. The deliberate ingestion of soil is termed geophagy.

Geophagic behaviour is prevalent in the animal world, particularly among generalist herbivores (JOHNS, 1990; KREULEN, 1985) and primates (KRISHNAMANI & MAHANEY, 2000). Of the 185 species of extant primates, only thirty-nine (21.1%) are reported to ingest soil and eleven (22.4%) of the 49 species of Cercopithecidae primates are observed to engage in geophagy. The number of primates known to indulge in geophagy is increasing, day by day, as more studies on primate ecology are published (KRISHNAMANI & MAHANEY, 2000). Soils eaten by nonhuman primates could be occasional and/or regular but constitute only a fraction of their diet.

Geophagy is a complex and variable behaviour, both in its stimuli and effects (MAHANEY et al., 1995b). The benefits and banes of soil ingestion by large herbivores have been reviewed by KREULEN (1985). Intake of parasites and/or harmful microbes and the possible ingestion of toxic inorganic soil components may be detrimental to the consuming animal. ROBBINS (1983) mentions that geophagy may be important nutritionally as a useful source of iron but sometimes can be a contributing factor for anemia in wild animals depending upon the chelating capacity of soil clay. For large mammals, the benefits derived from geophagy may include the improvement of food intake through modification of conditions in the digestive tract, such as pH, buffering capacity, osmotic pressure and the dilution rate of food. Other potential benefits relate to the protective effects of soil consumption against toxicity; the cation exchange capacity of the clay minerals is associated with adsorption of toxins (KREULEN, 1985). The function of geophagy varies from species to species and within one species may serve different functions at different times of the year (DAVIES & BAILLIE 1988). In primates, four principal functions that are nonexclusive have been attributed to geophagy: mineral supplementation, adsorption of toxins, antidiarrhoeal agent and pH adjustment of the gut (KRISHNAMANI & MAHANEY, 2000).

In this paper we report for the first time that bonnet macaques, *Macaca radiata*, of southern India, ingest termite mound soil. Here we present the results of analysis of earth samples eaten and not eaten by bonnet macaques in the Marakkanam Reserved Forest, Tamil Nadu, India, with the aim of comparing the mineralogy, geochemistry and microscopy of the ingested samples with soil sampled from nearby uningested soil.

## METHODS

### STUDY AREA

The Marakkanam Reserved Forest lies along the Coromandel Coast of peninsular India at 12°11' N and 79°57' E (Fig. 1). The forest is situated about 30 km north of Pondicherry in the South Arcot District of Tamil Nadu. The vegetation of the Marakkanam Reserved Forest is tropical dry evergreen forest.

The main distinguishing climatic feature of the Coromandel Coast is its peculiar rainfall regime. The regional climate may be classified as tropical dissymmetric, but unlike most tropical locations, the rainy season is concentrated in November rather than in the summer months (MEHER-HOMJI, 1974). Average annual rainfall is 1200-1600 mm. Maximum and minimum temperatures are 34°C and 24°C, and the mean average relative humidity is around 70% (data from the French Institute, Pondicherry).

The forest vegetation usually occurs on red ferruginous or ferrallitic sandy loam soils forming from sediments derived from sandstone of mid-Tertiary age. The ferrallitic soil is sometimes described as "fossil" laterite, because in the region of occurrence along the Coromandel Coast the present climate is not wet enough to result in laterites (MEHER-HOMJI, 1974). The lateritic soils are formed in fluvial sediments. The soil is predominantly formed in fluvial sediments of clay, sand and gravel in different proportions (BALASUBRAMANYAN, 1977). The gravel and smaller fractions are composed mostly of quartz. At several locations in the study area charnockite (high-grade metamorphic rock) outcrops are present and provide a source of colluvium giving a thin veneer of ferrallitic soil (BALASUBRAMANYAN, 1977).

### STUDY POPULATION

Bonnet macaques, *Macaca radiata*, are endemic to peninsular India. This study was conducted in Kurumbaram, part of Marakkanam Reserved Forest. Two troops of bonnet macaques

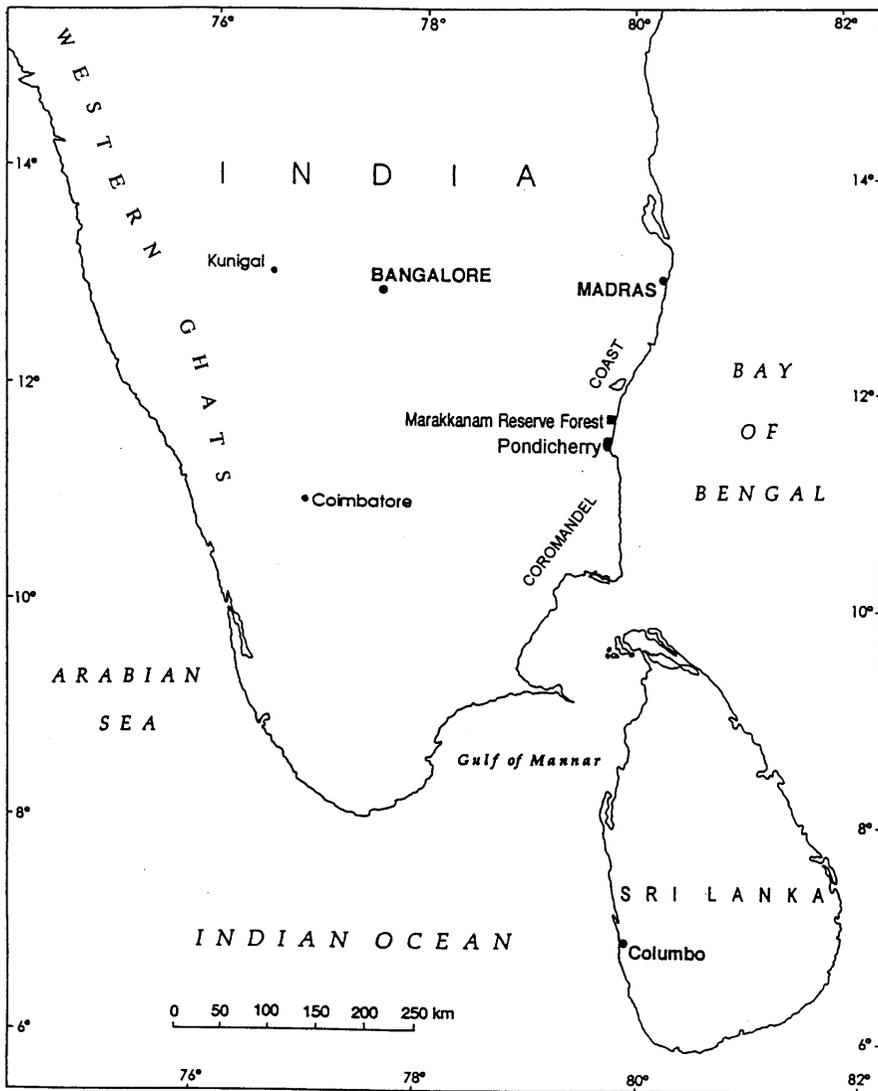


Fig. 1. Location of the Marakkanam Forest Reserve, southern India.

were found in this part. The study (between July 1, and August 17, 1991) concentrated on the troop that occupied the eastern part of the forest. A narrow road, from Marakkanam to Tindivanam, divided the forest into two. On one side of the road, was a patch of *Eucalyptus* plantation and on the other a relatively pristine patch of tropical dry evergreen forest. The study troop had 23 individuals and members of both sexes from immatures to adults were observed to ingest soil.

STUDY SITE SAMPLES

From the Marakkanam Reserved Forest, six soil samples are examined in this study. They include samples of three termite mounds from which bonnet macaques were observed

ingesting soil and three three (uneaten) control soil samples taken randomly from the ground at various distances surrounding the termite mounds. The mounds from which the Marakkanam bonnet macaques consumed earth were built by the *Odontotermes obesus* species. Descriptions of *Odontotermes obesus* can be found elsewhere (ROONWAL, 1962).

## SOIL ANALYSIS

Soil colours follow the *Standard Soil Color Charts* of OYAMA and TAKEHARA (1970). Air dried samples were sieved to remove mineral matter >2 mm. Samples were treated with 30% H<sub>2</sub>O<sub>2</sub> to remove organic matter, chemically dispersed with sodium pyrophosphate, and mechanically disaggregated by sonification to achieve deflocculation. Particle size separations were made by first wet sieving, and then dry sieving the sands (2 mm - 63 µm) following procedures outlined by Day (1965); fine fractions (silt & clay, <63 µm) were calculated by sedimentation (BOUYOCOS, 1962).

Following procedures established by WHITTIG (1965), clay samples (<2 µm) were centrifuged onto ceramic tiles and X-rayed using an ADG-301H Toshiba X-ray Diffractometer with Ni-filtered CuK alpha radiation. X-ray diffraction patterns were interpreted using procedures outlined by BRINDLEY and BROWN (1980), and MOORE and REYNOLDS (1989) to determine clay and primary mineralogy. Geochemical analysis of the samples was performed by instrumental neutron activation analysis (INNA) and was carried out in the SLOWPOKE Reactor Facility of the University of Toronto (HANCOCK, 1984).

Sand grains from the medium to fine fractions (500-63 µm) were randomly selected for scanning electron microscope analysis and energy dispersive spectrometry (SEM-EDS). At least 300 grains were scanned in each sample, with 25-30 grains studied in considerable detail (VORTISCH et al., 1987). Gravimetric methods were used to make a microconcentrate of heavy mineral grains from the fine sand fraction (250-63 µm) (THEOBALD, 1957). These sands were analyzed by SEM-EDS for grain mineralogy and for coatings that might reveal the chemistry of weathering products.

## RESULTS

### SOIL COLOURS AND PARTICLE SIZE ANALYSIS

Marakkanam termite mound samples 1 and 2 are reddish-brown (5YR 4/8), whereas termite mound 3 is bright reddish-brown (5YR 5/8). The three Marakkanam control samples are similar in colour to the termite mounds. Control samples 1 and 2 are bright reddish-brown (5YR 5/6 and 5YR 5/8, respectively). Sample 3 is reddish-brown (2.5YR 4/8).

Particle size distributions show that the termitaria soils are finer in texture than the control soils (Table 1 and Fig. 2). Percent sand in the mound soils varies from 54% to 59%, whereas in the control soils sand makes up 74% to 84% of the samples. Correspondingly, silt increases in the termite mound soils ranging from 12% to 17%. In the control soils silt percentages are significantly lower from 6% to 8%. The percent clay in the mound soils ranges from 26% to 31%, whereas in the control group it drops to between 8% and 19%.

### MINERALOGY

Analysis of the <2 µm fractions from the Marakkanam termitaria and uneaten control samples show similarities in the abundance of 1:1 (Si:Al = 1:1) clay minerals (Table 2). Halloysite occurs almost equally in all six samples, while metahalloysite is abundant in termite mound 1 and control soil 3. Kaolinite is missing from mound 1 and control 3, but is found in moderate to abundant quantities in the remaining four samples. In the samples where kaolinite amounts are significant, metahalloysite is present in smaller amounts.



**Table 2.** Clay and primary mineralogy of the soils collected from the termite mounds and control soils.

Site	K	MH	H	I	Ch	S	V	IS	P	Q	O	Ca	Mi
Termite Mound 1	-	xxx	xx	x	tr?	x	tr?	tr	tr	x	tr	tr	x
Termite Mound 2	xxx	x	tr	tr	tr	x	-	tr	tr?	x	x	tr	x
Termite Mound 3	xx	xx	x	tr	-	tr	-	tr	tr?	x	tr	-	x
Control Soils 1	xx	x	tr	x	x	-	tr	tr	-	x	tr	-	x
Control Soils 2	xxx	x	x	x	-	-	x	tr	tr	x	x	-	x
Control Soils 3	-	xxx	x	x	x	-	-	x	tr	xx	x	tr	x

Minerals: K: kaolinite, MH: metahalloysite, H: halloysite, I: illite, Ch: chlorite, S: smectite, V: vermiculite, IS: illite-smectite, P: plagioclase, Q: quartz, O: orthoclase, Ca: calcite, Mi: mica. Quantities: tr: trace, x: small amount, xx: moderate amount, xxx: abundant.

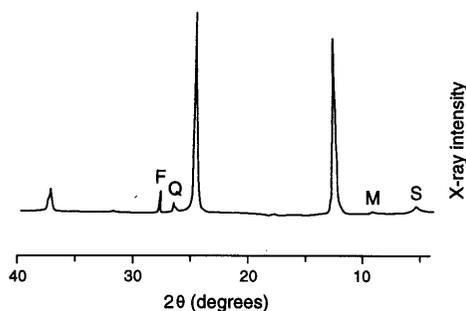
Among the 2:1 and 2:1:1 clay minerals observed in the samples, illite, vermiculite, and chlorite are found in greater quantities in the control soils. Illite-smectite, a randomly interstratified, mixed-layer clay, occurs in minor amounts throughout all the samples. Smectite, however, is found in small amounts in the termite soils and is missing from the control soils (Table 2). The primary minerals quartz and mica occur throughout the samples in small amounts; small to trace quantities of the feldspars, orthoclase and plagioclase, are also present (Table 2).

The X-ray diffraction pattern for the termite soils (exemplified by mound 2 in Fig. 4), showing the relative abundances of clay and primary minerals, resembles that of the commercial anti-diarrhoeal preparation, Kaopectate<sup>TM</sup> (Pharmacia & Upjohn, Peapack, New Jersey, U.S.A.) (Fig. 3). Both show similar patterns of kaolin, smectite, mica, quartz and feldspar occurrences.

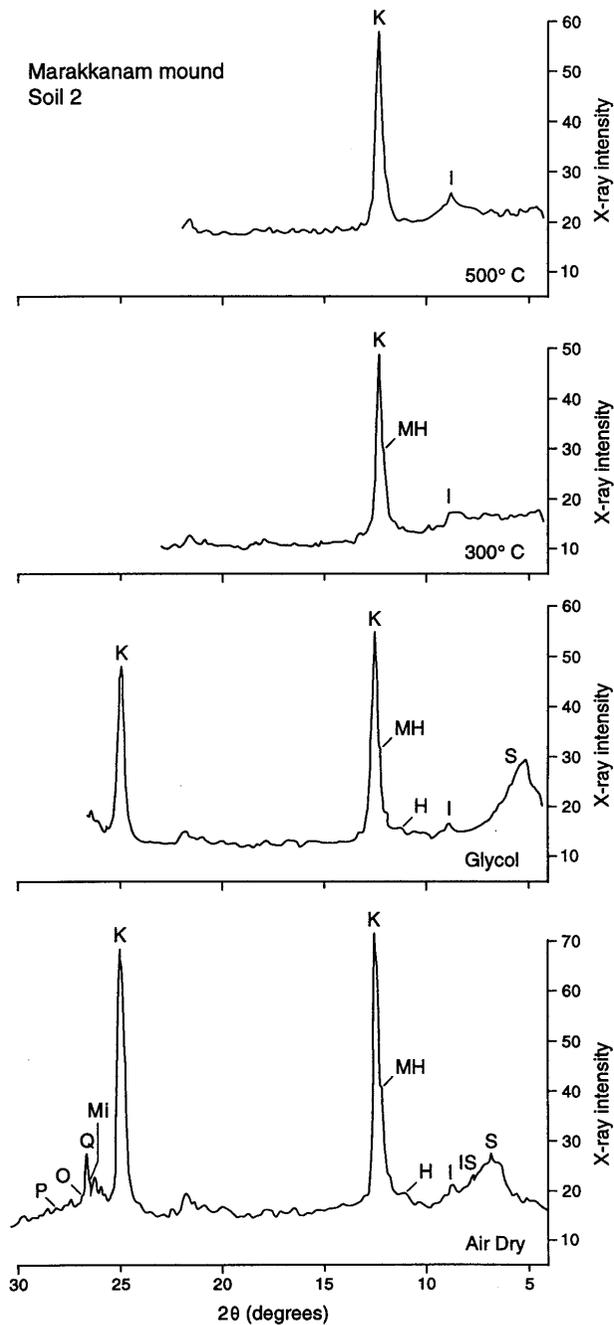
Although insufficient sample was available to measure soil pH, we estimate from the clay mineralogy and ferrallitic soils in the field area that pHs probably range from slightly acidic to slightly alkaline, or from 6.0 to 7.5. Most likely the pH undergoes seasonal variation ranging from alkaline (dry) to acidic (wet).

## GEOCHEMISTRY

Concentrations of major, minor and trace elements show minor nutrient differences between the termite mounds and uneaten control soils (Table 3). Scandium and cobalt concentrations are generally higher in the termite soils than in their respective controls, while



**Fig. 3.** X-ray diffraction pattern of Kaopectate clay (oriented sample). Major peaks are produced by kaolinite. Minor peaks are feldspars (F), quartz (Q), mica (M), and smectite (S). (VERMEER & FERRELL, 1985 p.635).



**Fig. 4.** Marakkanam termite mound 2. X-ray diffraction patterns of air-dried sample, glycol sample, 300°C, 500°C. K: kaolinite, I: illite, MH: metahalloysite, H: halloysite, S: smectite, IS: illite-smectite, Mi: Mica, O: orthoclase, P: plagioclase, Q: quartz .

hafnium and thorium are the only two elements to show the reverse behaviour, possibly implying sandier controls. Hafnium may be primarily associated with zircon and silica in the samples, and hence may corroborate the particle size data. Thorium may be primarily associated with monazite.

Bromine is at least five times more abundant in the termite soils; but in absolute terms, bromine values remain low. Aluminium is higher, site by site, throughout the termite mounds relative to the uneaten soils (Table 3), which follows from the higher clay content. Though not a nutrient element, aluminium may interact with tannins and aid in their detoxification (JOHNS & DUQUETTE, 1991).

Among the other major elements sodium, potassium, calcium and magnesium, which are known to have dietary significance for some primates (WATERMAN et al., 1983), calcium is found in slightly higher concentrations in the termite soils, although amounts remain very low. Potassium and sodium are similarly low throughout the eaten and uneaten soils, while magnesium is below the limit of detection for all samples.

Iron concentrations are reasonably high (3-5%) throughout the sample suite, except for control soil 2 where the value is slightly lower. Chlorine falls below detection limits, effectively ruling out salt (sodium chloride) as a possible nutritional supplement. The highest amount of manganese is found in one of the control soils, although the manganese data are rather scattered.

**Table 3.** Geochemistry of the soils from termite mounds and control soils (quantities in ppm unless otherwise noted).

Element	Termite Mound			Control Soils		
	1	2	3	1	2	3
Al %	5.6	5.1	6.7	2.5	3.3	5.1
Ca %	0.22	0.21	0.21	< 0.06	0.08	< 0.06
Fe %	3.22	3.06	5.00	3.11	2.29	3.72
K %	0.84	0.72	1.07	0.63	0.85	1.04
Mg %	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Na %	0.10	0.07	0.12	0.10	0.06	0.07
Ti %	0.32	0.27	0.27	0.36	0.31	0.40
As	4.5	4.7	6.9	4.9	3.6	5.7
Ba	440	370	1160	380	360	360
Br	5.0	5.3	7.4	< 0.02	< 0.01	1.4
Ce	89.9	61.9	72.7	61.3	73.4	85.6
Cl	< 45	< 53	< 46	< 55	< 30	< 48
Co	13.9	12.3	13.3	9.9	10.0	13.0
Cr	81	72	113	88	78	91
Cs	1.20	1.00	1.20	0.43	0.55	0.89
Dy	2.3	< 1.6	< 1.2	< 1.6	< 0.9	< 1.6
Eu	0.99	0.89	0.75	0.44	0.54	0.58
Hf	10.4	7.8	12.3	13.5	13.0	17.7
I	13	< 6	< 6	< 6	< 4	< 6
La	24.3	22.1	21.4	13.6	17.6	20.8
Lu	0.22	0.18	0.19	0.13	0.17	0.18
Mn	427	397	436	515	262	434
Nd	18	17	12	8	13	14
Sc	6.26	5.33	7.10	3.02	3.66	4.92
Sm	2.87	2.52	2.27	1.49	2.03	2.34
Tb	0.43	0.37	0.40	0.24	0.34	0.38
Th	6.3	5.8	8.4	7.2	10.7	10.6
U	1.5	1.3	1.5	1.2	1.3	1.7
Yb	2.0	1.6	1.8	1.3	1.7	1.8

Statistical analysis of chemical elements considered important in nutrition and/or zoopharmacognosy shows that means for the eaten group have relatively higher concentrations of aluminium, iron and bromine (Table 4). Aluminium may play an antacid role but most probably relates only to increases in concentrations of clay minerals, aluminium being the chief cation in the octahedral coordination. Bromine is a known sedative (CROUNSE et al., 1983), although it is not known whether this might be a stimulus for geophagy among the bonnet macaques. Iron, an essential trace element, could be an incentive for geophagy in this instance. However, it is also important to consider the reduced statistical power with sample rather than population means and standard deviations. The standard deviations for iron show considerable variation about the mean, which might change with a greater run of samples in a more detailed study.

Chondrite-normalized rare earth element (REE) graphs (Fig. 5) of the mound and control samples follow roughly the same path, although the control soils show lower overall REE concentrations possibly as a result of lower clay content. The physiological significance of any REE differences is unknown.

#### MICROSCOPY

Microscopy investigation of soils is chiefly important for identifying minerals and mineral-coatings as well as estimating the degree of weathering. Exchangeable cations released into the soil solution by mineral-coatings and the weathering of minerals represent possible sources of nutritional supplementation.

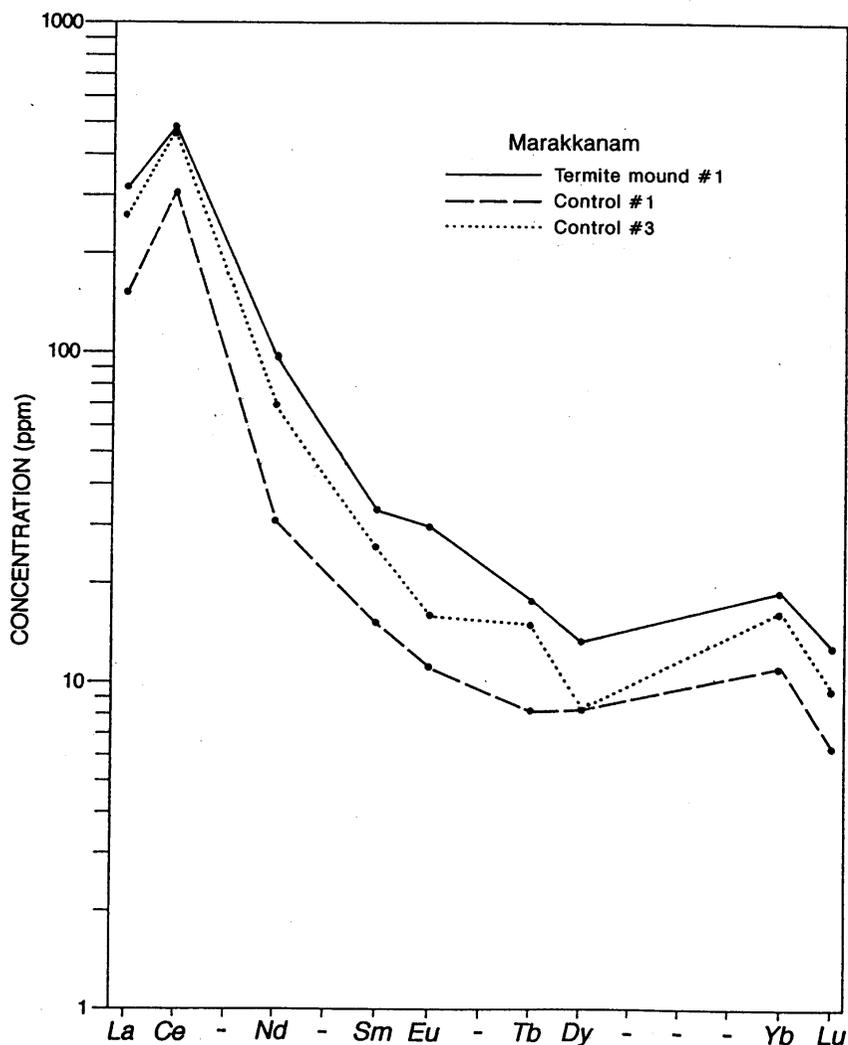
From a random selection of fine-sand grains (63-250 $\mu$ m), quartz was the most frequently observed mineral in each of the Indian samples. Of the approximately 25 grains studied in detail by SEM-EDS, well over half were quartz. Throughout the sample suite, most quartz grains show V-shaped percussion cracks typical of fluvial sands. Grains tend to have rounded edges, an indication of fluvial transport, and to a lesser extent, bulbous edges, which probably denote wind transport. Iron coatings, which may provide chemical elements important in primate physiology, are present on a significant number of quartz grains in both the termite and control samples. A mix of fresh and weathered quartz is in evidence throughout; no differences in weathering trends were observed between the eaten and uneaten samples.

Preliminary SEM-EDS analyses of eight, weathered, heavy (high density) mineral grains from termite mound 2, show the effects of tropical weathering on the high grade metamorphic charnockite rocks of the region. Minerals formed under high temperature tend to be

**Table 4.** Chemical elements important to nutrition and/or zoopharmacognosy: mean and standard deviations for the elements present in the ingested soils and control soils.

Elements	<u>Ingested Soils (Termite mounds)</u>		<i>Control Soils</i>	
	Mean	S D*	Mean	S D*
Al (%)	5.8	0.7	3.6	1.1
Ca (%)	0.21	0.00	d.l.	xx
Fe (%)	3.80	0.90	3.00	0.60
K (%)	0.90	0.20	0.80	0.20
Mg (%)	d.l.	xx	d.l.	xx
Na (%)	0.10	0.00	0.08	0.00
As (ppm)	5.4	1.1	4.7	0.9
Br (ppm)	5.9	1.1	d.l.	xx
Co (ppm)	13.2	0.7	11	1.4
Cr (ppm)	89	18	86	6
Mn (ppm)	420	17	404	105

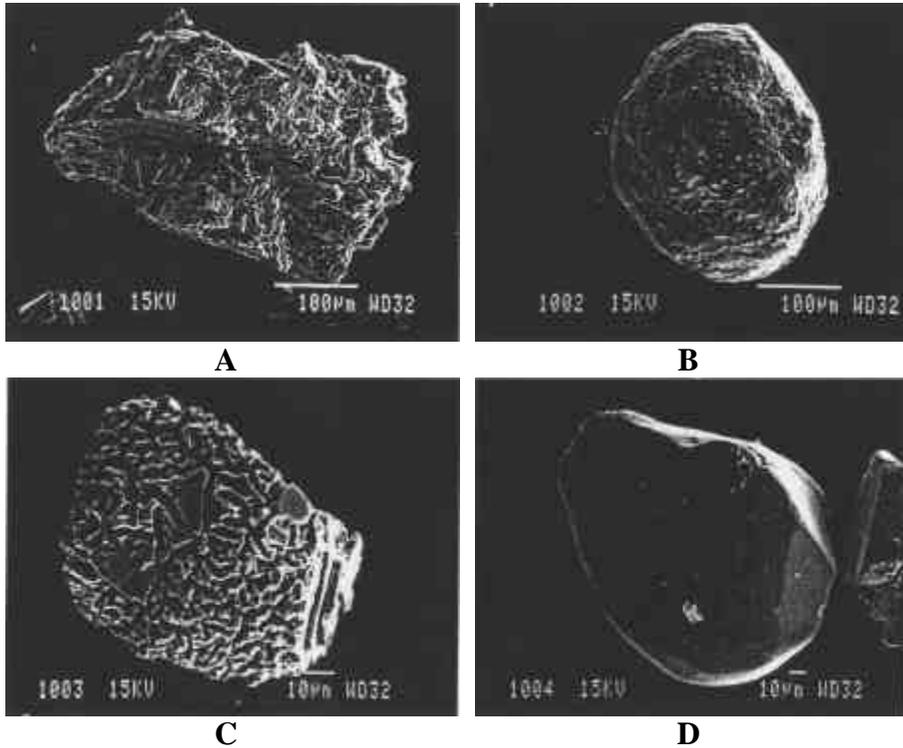
\* Sample standard deviations; d.l.: below detection limits; ppm: parts per million.



**Fig. 5.** Chondrite-normalized plots of light (La-Eu) and heavy (Eu-Lu) rare earth elements. La: lanthanum, Ce: cerium, Nd: neodymium, Sm: samarium, Eu: europium, Tb: terbium, Dy: dysprosium, Yb: ytterbium, Lu: lutetium.

unstable in the weathering environment. Newly exposed minerals could behave as slow-release fertilizers in the immediate area of the termite mound (BRENER & SCHOTT, 1982), releasing chemical elements of importance as nutritional dietary supplements or medical agents.

Strong surface corrosion is apparent on many grains. On two orthoclase grains, the development of etched surfaces increases the surface area of the mineral and accelerates the supply of potassium cations to the soil solution (Fig. 6A and Fig. 7C). Similarly, strongly etched spinel may be a source of iron and chromium cations (Fig. 6C). The angular silicate mineral (Fig. 7B) containing iron, calcium and magnesium (either diopside-hedenbergite or tremolite-ferroactinolite) shows shallow, surface etching. The fact that magnesium

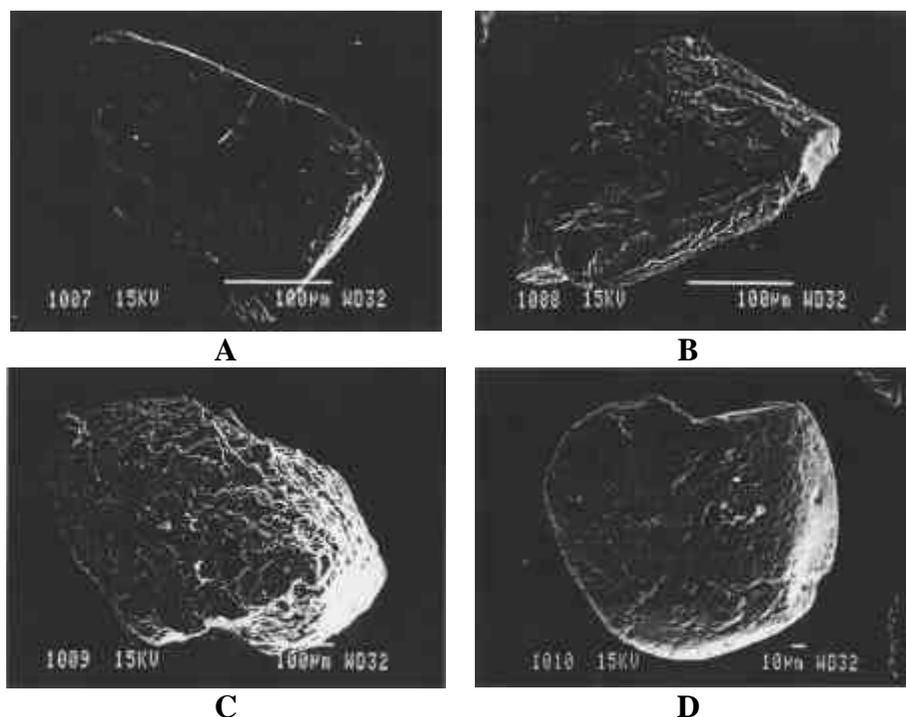


**Fig. 6.** Micrographs (Set 1): heavy mineral sand grains from Marakkanam termite mound 2. (A) orthoclase, strongly etched along cleavage; (B) iron-manganese nodule; (C) etched Cr-Fe spinel (or chromite), originating in ultramafic rocks in the charnockitic suite of rocks; (D) clay mineral coating.

concentrations fall below the detection limit (Table 3) suggests that this mineral is uncommon. A surplus of iron from the charnockitic suite of rocks is apparent in nodules of iron, and manganese-iron nodules in the soil (Figure 6B); these promote the storage of cations that could function as nutrients. A uniformly thick clay mineral coating (Figure 6D) represents a chemically reactive surface and site of the release of cations into the soil solution.

The relatively inert, light rare earth element (LREE)-rich mineral, monazite, is present in the termite soil as a round, alluvially transported grain dominated by cerium and thorium. (Fig. 7D). The same mineral species also is present in the termite soil as an angular, detrital monazite dominated by lanthanum (Fig. 7A). These LREE signatures in monazite demonstrate some mixing of the local bedrock component with the regional alluvial mineralogy. The angular monazite of local provenance, characterized by higher lanthanum values, represents the source of higher lanthanum amounts in the geochemical analysis of the eaten samples (Table 3 and Fig. 5). The cerium anomaly shown by chondrite-normalized REE analysis (Fig. 5) is undoubtedly owing to the presence of alluvial monazite in both termitaria and controls.

Exposure of all six soil samples to a magnet suggests that the magnetic minerals ilmenite, magnetite, and chromite make up an equally small percentage of both termite and control soils. From a weathering standpoint of the iron oxides, there appears to be little benefit to the consuming organism of ingesting termite mound soils over control soils. However, the slow release of nutrients from heavy minerals may play a beneficial role in geophagy.



**Fig. 7.** Micrographs (Set 2): heavy mineral sand grains from Marakkanam termite mound 2. (A) Angular monazite grain dominated by La; (B) Angular mineral (diopside-hedenbergite or tremolite-ferroactinolite) showing shallow, surface etching; (C) Orthoclase, strong chemical solution at the surface; (D) Alluvial monazite grain dominated by Ce.

## DISCUSSION

Important to the discussion of the function of geophagy among bonnet macaques is an examination of some of the potential problems associated with their diet. Mature leaves (17%) form the second most important food item after fruits (41%) for bonnet macaques (KRISHNAMANI, 1994). In soils where sand predominates, such as in the Marakkanam Reserved Forest (Table 1), the leaves are rich in chemical plant defenses (e.g. tannins and other phenolics: JANZEN 1974; MCKEY 1978; GARTLAN et al. 1980; OATES et al. 1990). Ingestion of secondary plant compounds associated with mature leaves might cause gastrointestinal upsets in the macaques.

RUDRAN (1978) found that the two troops of blue monkeys, *Cercopithecus mitis stuhlmanni*, he studied consumed 7.34% and 2.89% of mature leaves respectively, whereas the bonnet macaques consumed 17.2% of mature leaves. This is unusually high considering that bonnet macaques are frugivores/omnivores and the percentage of leaves eaten by bonnet macaques inhabiting a dry deciduous forest is only 3.8% (ALI, 1986). The percentage of mature leaves eaten by certain other cercopithecine primates is less than 5% (Table 5). Bonnet macaques are monogastric and hence are certainly ill-adapted to a high proportion of mature leaves in their diet.

Among secondary compounds present in mature leaves, acid detergent fibre (ADF) is a major deterrent of food selection (WATERMAN, 1983; 1984). Phytochemical analysis

conducted in a deciduous forest (Rajaji National Park, Uttar Pradesh, India: KAR-GUPTA &

**Table 5.** Proportion of fruits and mature leaves eaten by Cercopithecine primates.

Primate species	Mature leaves (%)	Fruits (%)	Source
Bonnet macaque, <i>Macaca radiata</i>	17.2	41.0	KRISHNAMANI, 1994
Bonnet macaque, <i>Macaca radiata</i>	3.2	53.4	ALI, 1986
Crab eating macaque, <i>M. fascicularis</i>	1.6	87.0	WHEATLY, 1980
Rhesus macaque, <i>M. mulatta</i>	NA	65-70.0	LINDBURG, 1977
Pig-tailed macaque, <i>M. nemestrina</i>	2.7	73.8	CALDECOTT, 1986
Lion-tailed macaque, <i>M. silenus</i>	< 1.0	60.0	KUMAR, 1987
Sulawesi crested black macaque, <i>M. nigra</i>	< 2.4	60-70.7	O'BRIEN & KINNAIRD, 1997
Blue monkey, <i>Cercopithecus mitis stuhlmanni</i>	5.1*	60.5	RUDRAN, 1978
Red-tail monkey, <i>C. ascanius schmidtii</i>	3.3	43.6	STRUHSAKER, 1978
Gray-cheeked mangabey, <i>Lophocebus albigena</i> (= <i>Cercocebus albigena</i> )	< 1.0	62.2	WASER, 1977

\* Average for two troops.

KUMAR, 1994) and in a tropical wet evergreen forest of India (Kalakkad-Mundanthurai Tiger Reserve, Tamil Nadu, India: OATES et al. 1980) suggest that ADF was 22.6% (n = 8) and 42.2% (n = 15) respectively. The deciduous forest species have less ADF than those in wet evergreen forests. A comparison of the evergreen and deciduous tree species of climax forest in Costa Rica revealed that long-lived leaves were more fibrous than short-lived leaves (JANZEN & WATERMAN, 1984).

The tropical dry evergreen forests of the study area are in a transition phase between tropical wet evergreen and dry deciduous forests (MEHER-HOMJI, 1974). There are more evergreen species present at Marakkanam than in the dry deciduous forest, hence the bonnet macaques may face the same selection pressure as that operating in wet evergreen forests. Primates are sometimes forced to feed on unfamiliar trees or to ingest more leaves from a particular tree than they normally would because of seasonality, overpopulation and/or habitat destruction (GLANDER, 1977). In the Marakkanam Reserved Forest, where these bonnet macaques live, all three factors are evident.

Fruits make up the largest proportion (41%) of the macaques' diet (KRISHNAMANI, 1994). The fruits of *Azadirachta indica* act as a tonic, anti-periodic, *purgative*, emollient and as an anthelmintic (NADKARNI, 1982; CSIR, 1985). The fruits of plants listed to serve as purgatives are considered to possess a laxative property (SHAANKAR et al., 1997). Generally fruit laxatives enhance the gut passage rate of ingested seeds and increase the frequency of defecation (MURRAY et al., 1994). PUTZ (1993, page 177) says that, "eating large quantities of fruit can have grave gastro-intestinal consequences for animals". Increased consumption coupled with the inherent property of the fruits of *Azadirachta indica* to act as a purgative might lead to dehydration and diarrhoea.

Feeding on the fruits of *Azadirachta indica*, by bonnet macaques, is a seasonal phenomenon. Mountain gorillas, *Gorilla gorilla beringei*, also suffer from diarrhoea by consuming >90% bamboo shoots (*Arundinaria alpina*) seasonally and get relief by consuming the weathered regolith (all unconsolidated material overlying bedrock; MAHANEY et al., 1995a). Thus a combination of eating mature leaves (relatively more than other cercopithecine primates) and ingesting more fruits of *Azadirachta indica* could lead to gastrointestinal upsets and diarrhoea in the bonnet macaques.

Mineralogical analysis suggests that the macaques would gain some control over these malaises by consuming termitaria earth. Ingestion of clay minerals is associated with the relief of diarrhoea and gastrointestinal distress caused by secondary phytochemicals and other organic compounds (VERMEER & FERRELL, 1985; AUFREITER, et al. 1997; ABRAHAMS & PARSONS 1996). DAVIES & BAILLIE (1988) note that clays with 2:1 lattice structures (e.g.,

smectite) are likely to be effective in the adsorption of tannins and other organic molecules while 1:1 clays (kaolin minerals) tend to be effective against gastric disorders.

Chimpanzees in the Mahale Mountains National Park, Tanzania, may consume earth from termite mounds to gain temporary relief from gastrointestinal ailments (MAHANEY et al., 1996). The combination of metahalloysite (a kaolin mineral) and smectite in the Tanzanian termitaria soil resembles the mineralogy of Kaopectate™. Rwandan mountain gorillas may eat earth containing halloysitic clay minerals to alleviate gastrointestinal problems associated with seasonal dietary changes (MAHANEY et al., 1995a). Rhesus macaques of Cayo Santiago, Puerto Rico, apparently consume soils rich in smectite to treat gastrointestinal upsets or diarrhoea (MAHANEY et al., 1995b).

In the Marakkanam samples, mineralogical variations between ingested and uneaten soils rest chiefly on differences in concentrations of smectite. Kaolin minerals occur abundantly in both consumed and control samples, but small amounts of smectite are found only in the termite soils. Abundant amounts of kaolin in combination with small amounts of smectite make up a mixture that resembles *eko* clay, a traditional West African remedy for stomach ailments, and the commercial anti-diarrhoeal preparation, Kaopectate™ (VERMEER & FERRELL, 1985; MAHANEY et al., 1996). Results of X-ray diffraction analysis confirm the similar mineralogical compositions of the termite soils and Kaopectate™. Hence it is likely that the bonnet macaques' consumption of termitarium soils, which contain smectite and metahalloysite, would act to quell gastrointestinal upsets and/or diarrhoea.

Soil textural data are consistent with the results of previous studies that show primates (human and nonhuman) consuming finer grained soils with high percentages of clay size particles (AUFREITER et al., 1997; MAHANEY et al., 1996; 1997; GEISLER et al., 1997). Generally, termites tend to sort and differentially concentrate finer-grained particles (mainly silt and clay) for mound construction. As a result, mounds tend to have a higher content of clay than the soil from which they are constructed (LEE & WOOD, 1971; WOOD & SANDS, 1978). The finer texture of termite mounds may contribute to the alleviation of gastrointestinal distress since fine material, having greater surface area, is believed to aid in the adsorption and eventual excretion of dietary toxins (OATES, 1978; MAHANEY et al., 1990; MAHANEY, 1993).

The question of whether geophagy soils might be nutritionally beneficial to the macaques is addressed through geochemical and SEM analyses. Among the macro and trace elements measured (see geochemistry section) iron, occurring in excess of 3%, emerges as a possible nutrient supplement. Iron frequently appears to be a stimulus for human geophagists (ABRAHAMS & PARSONS, 1996); and its content in soils has been cited as important to geophagic mountain gorillas (MAHANEY et al., 1990).

The presence of significant amounts of iron is also evident from soil colour analysis. The red soils of the study area are an indication of the region's intense weathering environment and the resulting accumulation of iron oxides and hydroxides. Many primates ingest soil of a red or reddish colour (MAHANEY et al., 1996; 1997; AUFREITER et al., 1997). BOLTON et al., (1998) observed that hybrid macaques of the Kowloon Peninsula (Hong Kong) rejected lighter coloured soils while accepting darker red soils. For the Marakkanam macaques, however, the termitaria and uneaten soils are similar in colour. Thus there appears to be little relationship between soil colour alone and the bonnet macaques' soil consumption habits. Nevertheless, a red soil colour and its related high iron content may well play a role in the physical consequences of geophagy, provided the iron is available in a readily absorbed form.

Preliminary SEM-EDS analysis of heavy minerals suggests that the strong weathering regime of the area would accelerate the release of nutrient elements to the surrounding soil solution. Etching and corrosion are evident on many of the examined mineral grains in the eaten soil. Geochemical concentrations of lanthanum suggest that the termitaria soils contain a greater percentage of charnockitic bedrock than the control group. This high-grade metamorphic rock tends to be unstable in a tropical weathering environment, which points to the likelihood of a slow release of potentially useful chemical elements in the immediate

area of the termite mounds. Nodules made up of iron and iron-manganese, and expected to be more prevalent in termite soils (because of greater amounts of chernockite), also could be a source of potential dietary supplements.

Findings are preliminary, however. Relative abundances and degree of weathering of heavy minerals were not investigated for the uneaten samples to determine whether differences exist between eaten and uneaten soils. Studies at other well documented primate geophagy sites such as Karisoke in the Volcans National Park, Rwanda (MAHANEY et al., 1990), Kibale National Park in Uganda (MAHANEY et al., 1997) and Mahale Mountains National Park in Tanzania (MAHANEY et al., 1996), have demonstrated that differences in the degree of weathering exist between consumed and uneaten soils.

Geophagy as a possible strategy for adjusting gut pH was not investigated for the macaques. Kaolin is used as an antacid in veterinary practice (DAYKIN, 1960), and appears to be effective in eliminating excessive acid production in the forestomachs of colobines (DAVIES & BAILLIE, 1988; POIRIER, 1970; OATES, 1978). For monogastric species, however, pH of the ingested soils themselves (not available for this study) is of more interest. Acidic soils are associated with the enhancement of secondary plant compound adsorption and excretion. Such soils also may act to prevent the proliferation of harmful bacteria species in the gut, and consequently lower the risk of intestinal microbial infection (JOHNS, 1991).

In summary, bonnet macaques in the Marakkanam Reserved Forest ingest relatively high amounts of *Azadirachta indica* fruits and mature leaves. The potential for gastric upset and diarrhoea, caused by secondary plant compounds such as ADF and the purgative effects of *A. indica* fruit, would be alleviated by the macaques' consumption of termitaria soils. Evidence of a nutritional benefit for geophagy is inconclusive; significant amounts of iron may or may not be beneficial to the ingesting macaques depending on whether it is available in a bioavailable form.

**Acknowledgements.** We acknowledge financial support from the Minor Research Fund of Atkinson College to WCM. The soil analysis was completed at the Geomorphology and Pedology Laboratory in Atkinson College with the assistance of CAITLIN MAHANEY. Figures were produced by CAROLYN D. KING, York University. Neutron activation analysis was undertaken at the SLOWPOKE Reactor Facility at the University of Toronto and was partially funded by an NSERC infrastructure grant to the facility. T. G. MYLES, Forestry - Earth Science Centre, University of Toronto, provided helpful discussion and reference material regarding termites of India. This article was written when RK was studying the Lion-tailed macaques with financial assistance from the Chicago Zoological Society, International Primatological Society, Primate Conservation Inc., Wildlife Conservation Society and the National Geographic Society.

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— Received: September 24, 2001; Accepted: October 21, 2001

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