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Investigation of the Possible Connection of Rock and Soil Geochemistry to the Occurrence of High Rates of Neurodegenerative Diseases on Guam and a Hypothesis for the Cause of the Diseases

By William R. Miller and Richard F. Sanzolone

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U.S. Department of the Interior
U.S. Geological Survey

[1]U.S. Geological Survey, Denver, CO 80225

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Introduction

High incidences of neurodegenerative diseases, mainly dementia, parkinsonism, and amyotrophic lateral sclerosis, occur on the island of Guam (Koerner, 1952; Kurland and Mulder, 1954). The occurrence and description of the diseases and a summary of the investigations can be found in Perl (1997). The diseases have been more prevalent along the southern coast, particularly the small villages of Umatac, Merizo, and Inarajan (Reed and Brody, 1975; Roman, 1996; and Perl, 1997) (fig. 1), and referred to as the southern villages in this report. Tertiary volcanic rocks underlie most of the southern part of the island, including these villages. The northern part of Guam, with lower incidences of the diseases, consists of carbonate rocks. Epidemiological studies beginning in the early 1950's failed to show the cause to be genetic etiology (Plato and others, 1986; Zhang and others, 1990). In recent studies, the search for pathogenic mechanisms has shifted to environmental factors. Excesses or deficiencies of various elements from dietary sources including drinking water can have an effect on human health. These deficiencies or excesses can usually be attributed to the geochemical composition of the rocks and derived soils that underlie the area. An example is the high concentration of Se in soil associated with the occurrence of selenosis in adults (Mills, 1996). Yase (1972) suggested that the neurodegenerative diseases on Guam may be related to accumulation of trace elements such as manganese and aluminum, both of which may cause neurodegeneration. It has been suggested that a deficiency in calcium and magnesium in the soil and water along with readily available aluminum could be connected to the occurrence of the diseases (Gajdusek, 1982; Yanagihara and others, 1984; Garruto and others, 1989). Some of the studies investigated metal exposure, particularly aluminum and manganese, and deficiencies in calcium and magnesium (Garruto and others, 1984). Aluminum has been shown to have neurotoxic effects (MacDonald and Martin, 1988), and aluminum has been implicated in the pathogenesis of Alzheimer's disease and similar dementia by Perl and others (1982). Studies of soils developed on volcanic rocks on Guam and other islands by McLachlan and others (1989) found that soils on Guam averaged 42-fold higher yield of elutable aluminum than soils developed on volcanic rocks on Jamaica or Palau. They did not detect unusually high dietary aluminum or low dietary calcium, but concluded that the soils and possibly the dusts of Guam might be a major source of aluminum entering the body of the inhabitants.

This study was conducted to investigate the geochemistry of the soils and rocks of the volcanic southern part of the island of Guam, particularly in the vicinity of the three southern villages (Umatac, Merizo, and Inarajan) with high incidences of the diseases. In addition to total chemical analyses of the soils and rocks, various extractions of soils were carried out. Both excesses and deficiencies of various elements were looked for. Because soluble aluminum in the soil was shown by McLachlan and others (1989) to be unusually high, water soluble extractions as well as sequential extractions of the soils were carried out. In addition, elements such as aluminum found in dust can traverse the nose-brain barrier in experimental animals (Sunderman, 2000) and respiratory epithelium is known to contain the highest concentration of aluminum in the human body (Tipton and others, 1957). The availability of elements, particularly aluminum from human inhalation of dust, derived from soil, was investigated. The available elements were determined by extractions of soils using a simulated lung-fluid extraction.

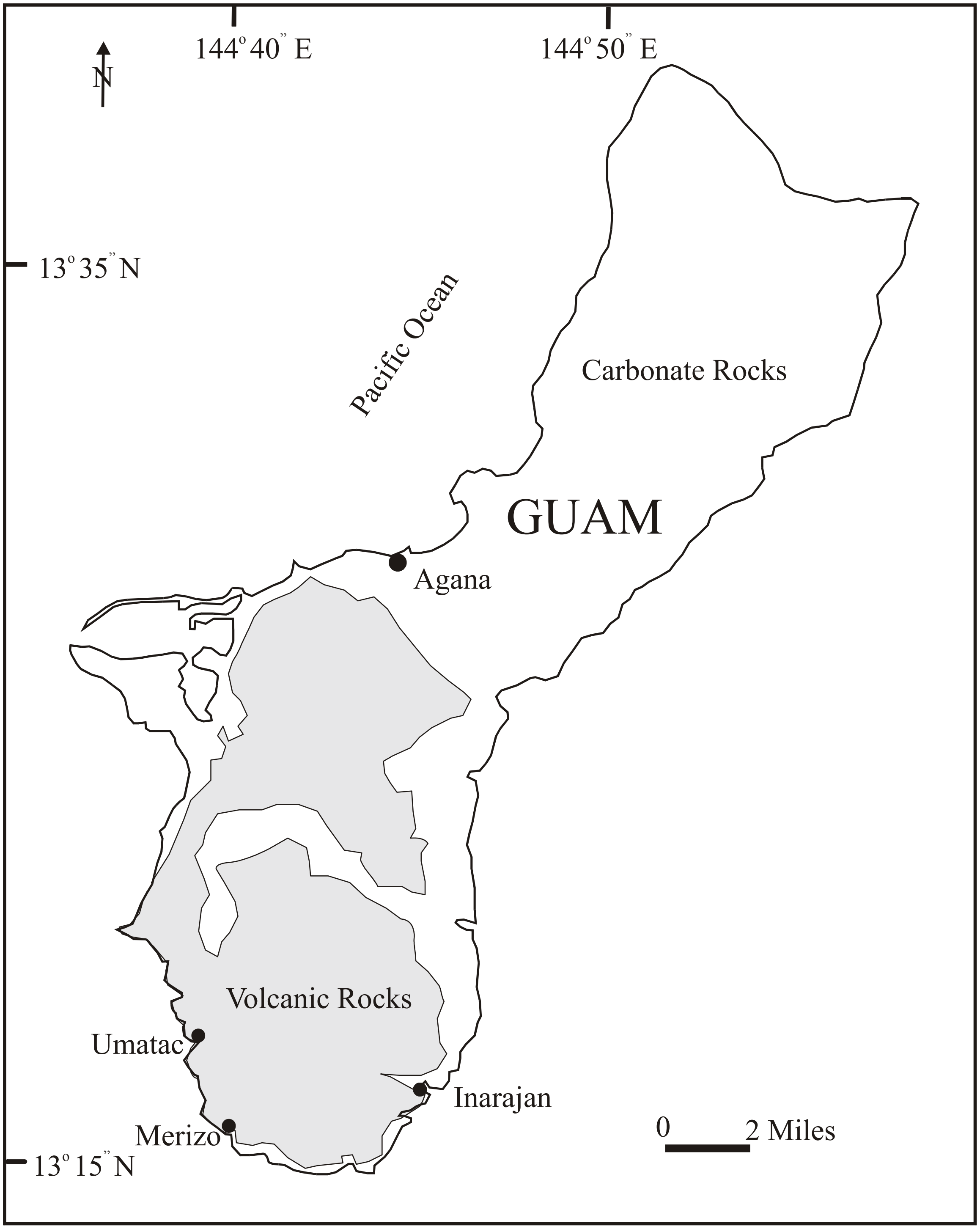

Figure 1. Location of the three southern villages in Guam with high incidences of neurodegenerative diseases.

In order to compare the results of the chemical data of rocks and soils from Guam to other rocks and soils elsewhere, samples of similar rocks and soils were collected in the western United States and similar analyses to those for the Guam samples carried out.

The complete chemical analyses of the soils, rocks, and streambed sediments as well as descriptions of the methods used can be found in Miller and others (2002).

Geology

The island of Guam is located at the southern end of the Mariana fore-arc (fig. 2). The volcanic rocks which occur on the southern portion of Guam consist of, from oldest to youngest, late-middle Eocene Facpi Formation consisting of submarine boninite pillow basalt flows and breccias, tuffaceous shale and sandstone, basaltic to andesitic dikes and minor limestone; the late Eocene to early Oligocene Alutom Formation consisting of tuffaceous shale and sandstone, volcanic breccia, conglomerate, and minor lava flows; and the Miocene Bolanos Formation of tuff breccia, tuffaceous sandstone, lenses of volcanic conglomerate, and minor basalt flows (Tracey and others, 1964; Reagan and Meijer, 1984; Siegrist and Randall, 1992). The Facpi Formation underlies the vicinity of the villages of Umatac and Merizo, and the Bolanas Formation underlies the vicinity of Inarajan (fig. 3). The northern portion of Guam consists of Tertiary to Quaternary carbonate rock (Tracey and others, 1964) (fig. 3).

The volcanic rocks are weathered to an average depth of 50 feet (Carroll and Hathaway, 1963). Soils developed on the volcanic rocks average 8 to 16 inches in depth with thicker soils on valley floors and narrow coastal plain areas (Young, 1988). The main difference in soil thickness is due to topography. The general process in the soil formation is that glass, zeolite, plagioclase, and pyroxene in rocks are weathered and transformed to smectite to kaolinite to gibbsite with increasing weathering intensity. The net effect is that silica is dissolved and removed and Fe_2O_3 and Al_2O_3 accumulate (Carroll and Hathaway, 1963).

Purpose

The purpose of this investigation is to determine if excesses and deficiencies of elements (compared to similar rocks and soils in other parts of the world) are present in Guam in the rocks, soils, or various soil extractions. The higher rates of neurodegenerative diseases in the southern villages occur in areas underlain by volcanic rocks compared to the northern portion of Guam, which is underlain by carbonate rocks. Unusual elemental concentrations or depletions of elements of the volcanic rocks would indicate permissive evidence of possible connections of the geochemistry of the soils and rocks and eventually to drinking water and foodstuff to the occurrences of the neurodegenerative diseases.

Methods

Sample Collection

Samples consisted of 25 soils and 15 rocks, which include four vein samples, collected in Guam in March 2001 (figs. 4-8). Sites were selected primarily to sample the areas in the vicinity of the southern villages and secondarily the soils and rocks elsewhere. Samples were collected along drainages, roads, or trails. The soils were

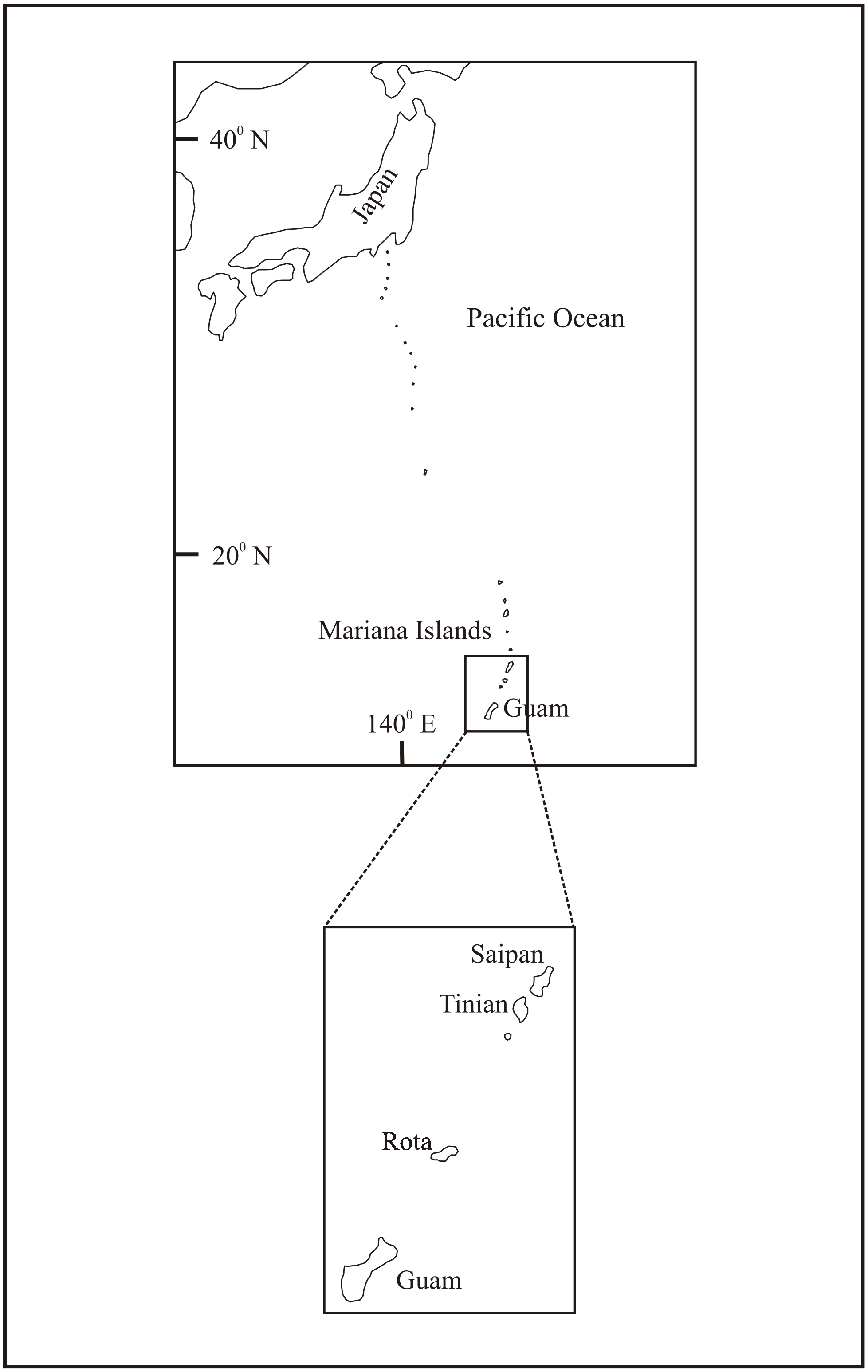

Figure 2. Index map showing location of Guam.

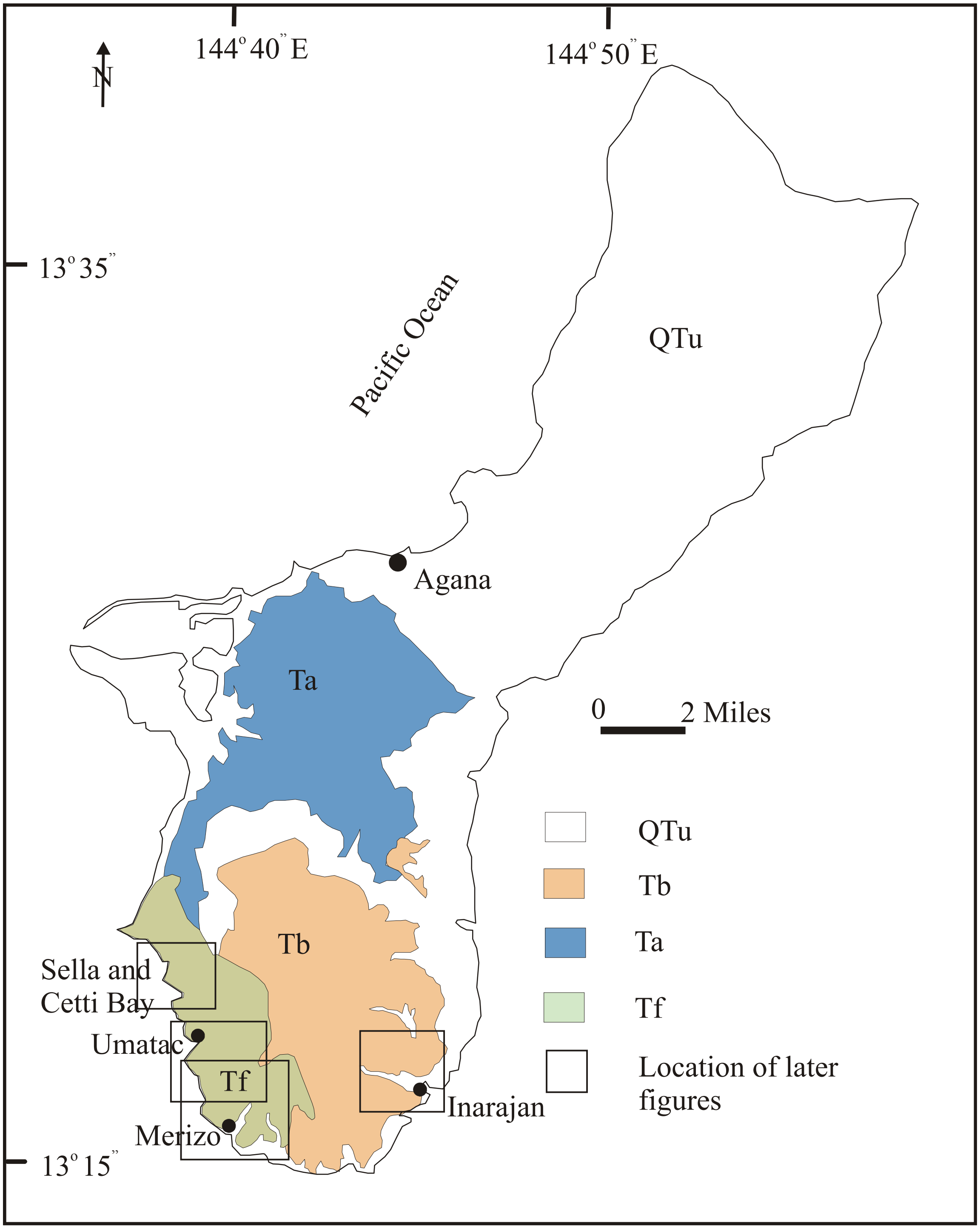

Figure 3. Generalized geologic map of Guam (modified from Tracey and others, 1964, and Siegrist and Randall, 1992). See next page for map explanation.

Generalized Geologic Map of Guam
Explanation

Age	Map symbol	Formation or rock type	Description
Tertiary to Quaternary	Qtu	Carbonate rocks	Carbonate rocks
Miocene	Tb	Bolanos Formation	Tuffaceous shale and shale, limestone, tuff breccia, basalt and volcanic conglomerate.
Eocene and Oligocene	Ta	Alutom Formation	Tuffaceous shale and sandstone, volcanic breccia, conglomerate and minor interbedded lava flows.
Eocene	Tf	Facpi Volcanics	Submarine boninite pillow basalt flows and breccias, tuffaceous sediments, tholeiitic basalt dikes, minor pelagic carbonate sediment.

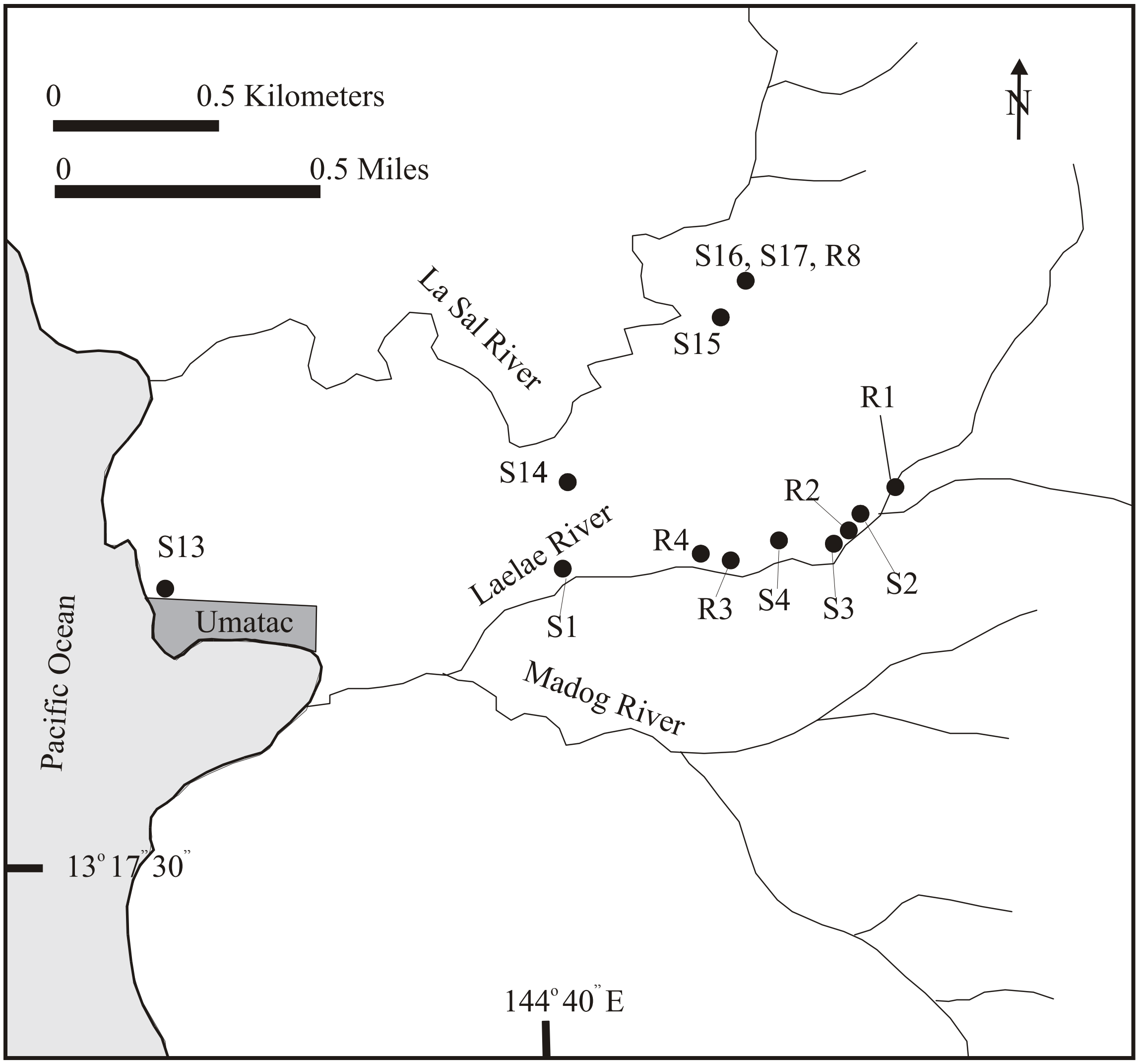

Figure 4. Map showing locations of sample sites within the Facpi Formation in the vicinity of Umatac. Sites prefixed with "S" are soils and "R" are rocks.

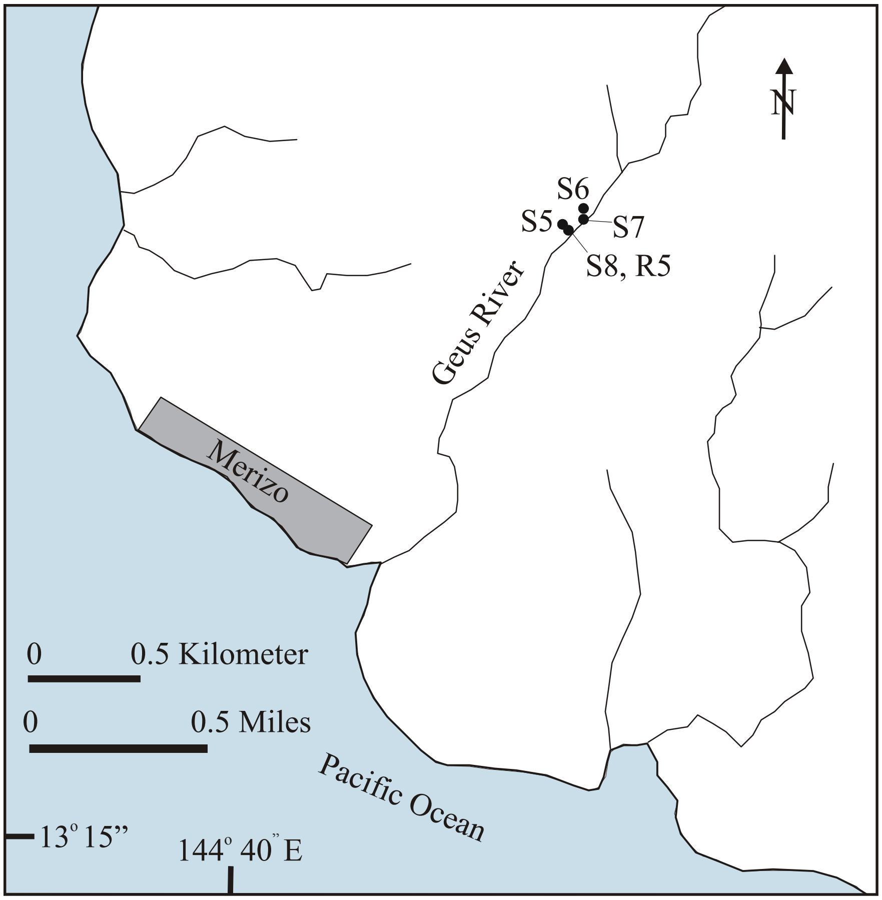

Figure 5. Map showing locations of sample sites within the Facpi Formation in the vicinity of Merizo. Sites prefixed with "S" are soils and "R" are rocks.

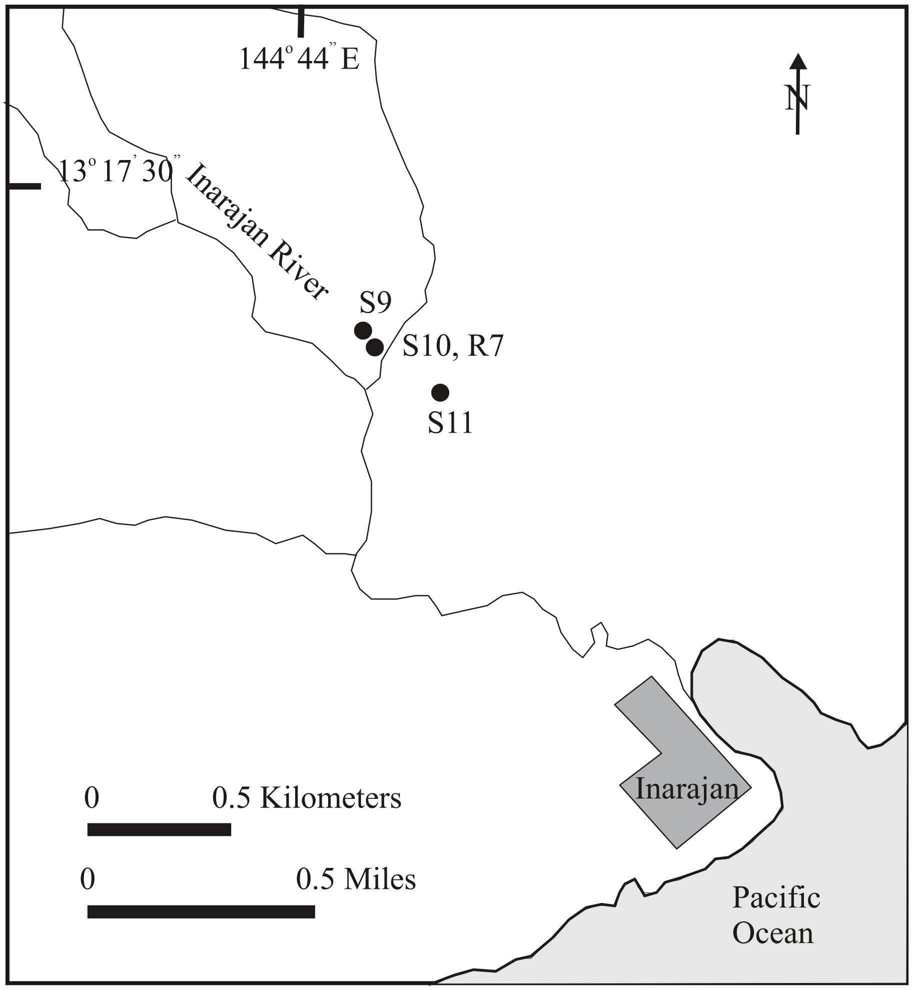

Figure 6. Map showing locations of sample sites within the Bolanos Formation in the vicinity of Inarajan. Sites prefixed with "S" are soils and "R" are rocks.

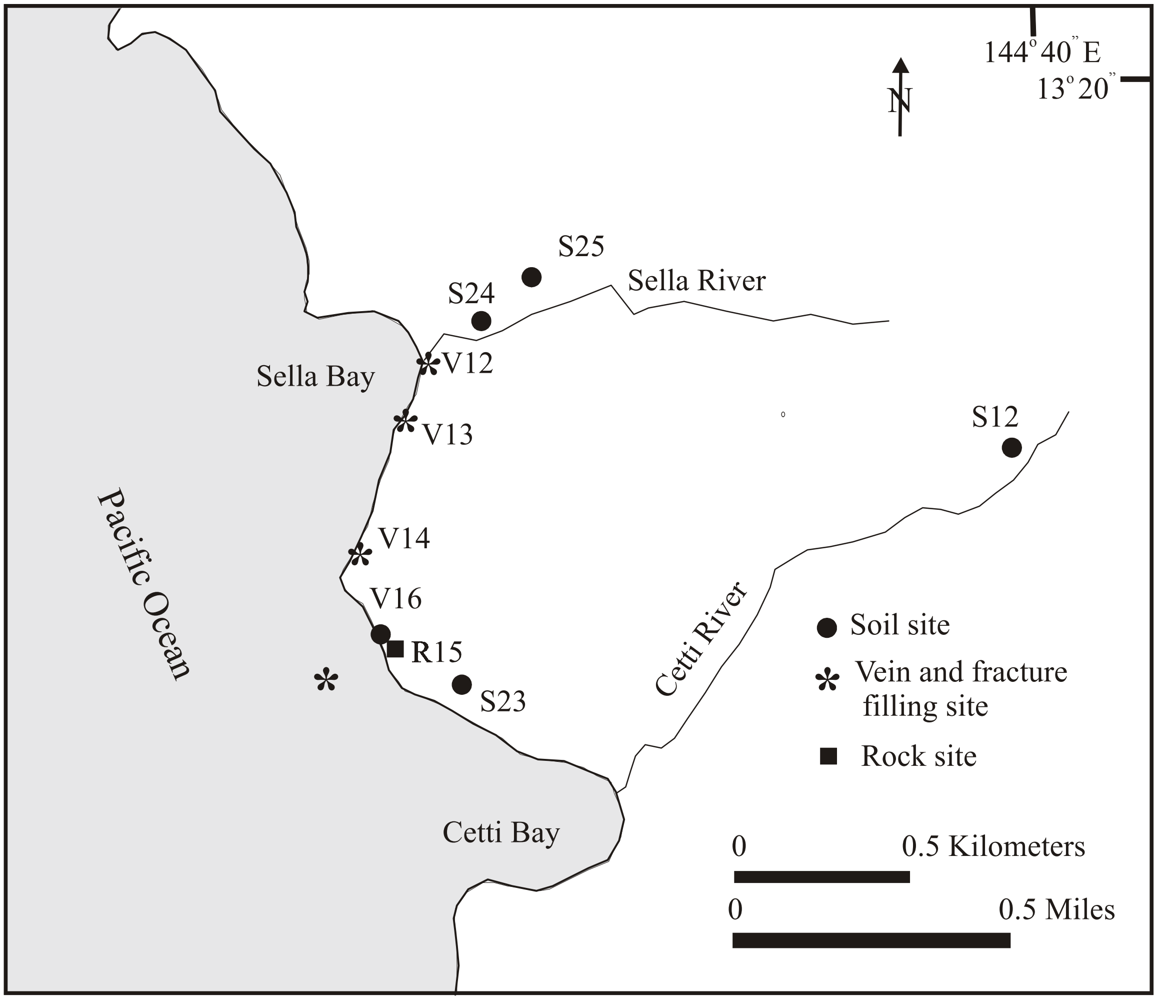

Figure 7. Map showing locations of sample sites within the Facpi Formation in the vicinity of Sella Bay and Cetti Bay. Sites prefixed with "S" are soils, "V" are vein and fracture filling, and "R"is rock.

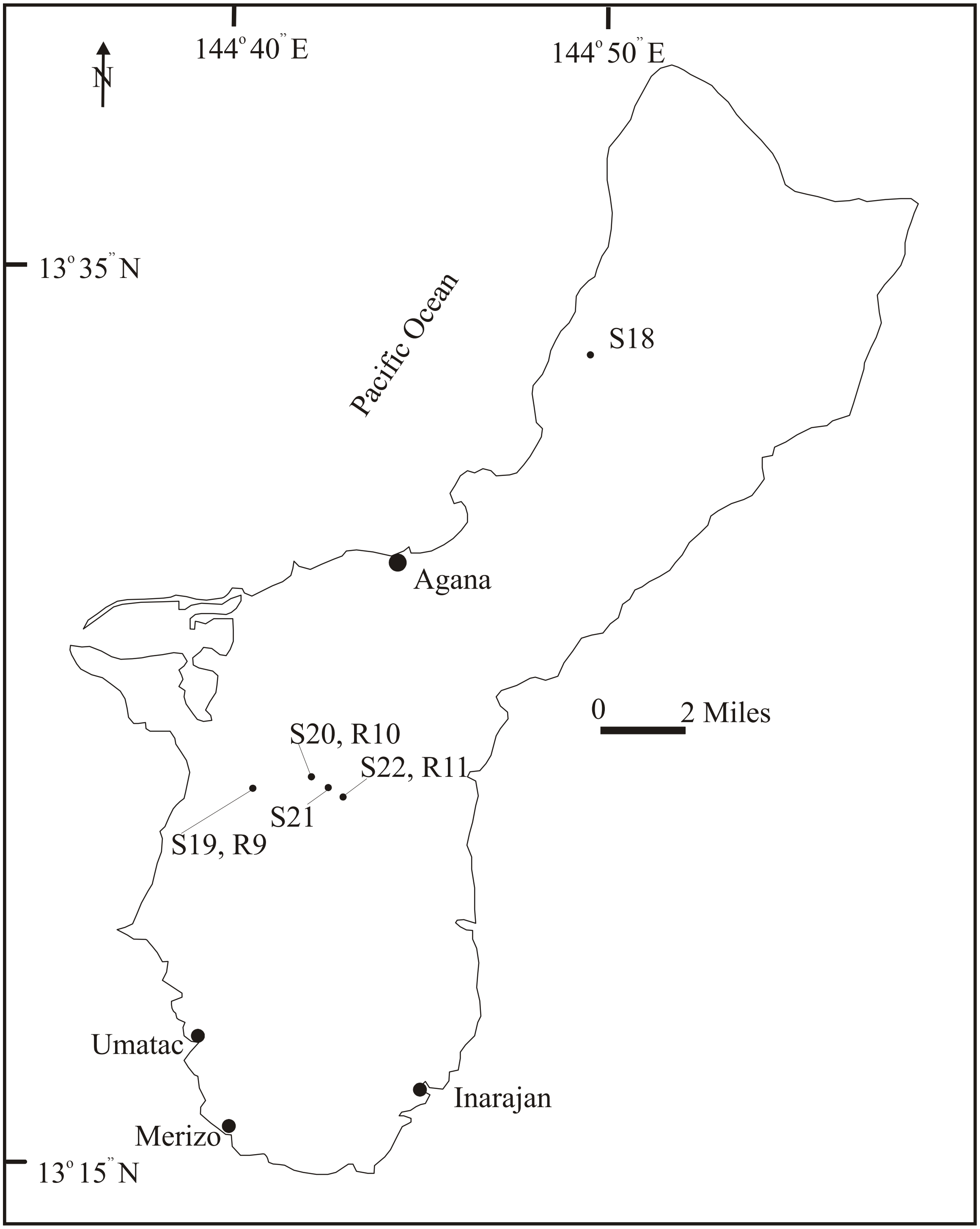

Figure 8. Map showing locations of sample sites within the Alutom Formation (except site S18 which is within the carbonate rocks) in the central part of Guam. Sites prefixed with "S" are soils and "R" are rocks.

collected from the surface to a depth of about four inches. Rocks were collected by compositing chips of rock from surface outcrops. The rocks were all weathered to some degree and may not represent original unweathered rock. Results of chemical analyses of unweathered rocks from Guam can be found in Reagan and Meijer (1984).

To allow comparisons of the chemical data from Guam to similar rocks and soils elsewhere, samples of 36 soils and 10 rocks were collected in Colorado and New Mexico, referred to in the text as western United States. The reason that soils and rocks were collected from the western U.S. is that these sites with similar rocks were the closest and most convenient to sample from our location. Chemical analyses of rocks and soils for similar rock types are available in the literature, but soils were need for the extraction procedures so the results could be compared to the Guam samples. The soils from the western U.S. were not well developed and contained significant weathered rock material. The samples were sieved through a < 2 mm stainless steel sieve during collection. Samples of rocks were collected by compositing chips from surface outcrops.

Sample Preparation

In the laboratory, the soil samples were dried in a convection oven at ambient temperature and split using a Jones splitter. A split was then sieved, using a stainless-steel sieve to < 63 microns, which makes up the majority of the soil sample material. The material passing through the sieve was used for all chemical analysis. Rock samples were put through a jaw crusher and then ground to < 150 micron using a ceramic plate grinder prior to analysis.

Analytical Methodology

A complete description of the analytical techniques is shown in Miller and others (2002). The following is a summary of the techniques used.

Total Elemental Composition: The total element composition for rock and soil samples was determined for 56 elements by inductively coupled plasma – mass spectrometry (ICP-MS) after a multi-acid (hydrochloric, hydrofluoric, nitric, and perchloric) decomposition method modified from Briggs and Meier (1999).

Soil pH Determination: The pH was determined for soil samples by mixing 10 g of soil material with 20 mL of distilled and deionized water, letting the sample rest for 15 minutes and remixing

Water Soluble Extraction: Soils were mixed with water to determine the water soluble component of the samples. A 0.5 g sample of soil was placed into a 12 mL centrifuge tube and 5 mL of distilled and deionized water were added. The sample was shaken for one minute followed by centrifugation for 10 minutes at 15,000 rpm using a refrigerated centrifuge set at 22 ^{o}C. The procedure was selected to approximate previous work on Guam, Palau, and Jamaica to evaluate aluminum and calcium availability in soils (McLachlan and others, 1989).

Sequential Extraction: A six-step sequential partial dissolution scheme was applied to selected soil samples to partition elements into operationally defined modes of occurrence or associations. The assessment of such techniques has been summarized by Tessier and others (1979), and Chao (1984). The scheme was applied to Guam soil samples to examine possible relative differences in the mode of occurrence of elements. The procedure used 0.5 grams of soil which was extracted sequentially with 25 mL of reagent to partition elements into the following associations: fraction A- water soluble, sorbed and exchangeable; fraction B-carbonates; fraction C-manganese oxide; fraction D-amorphous iron oxides; fraction E-crystalline iron and aluminum oxides and acid volatile sulfides; fraction F- residual. Extracts were centrifuged for 10 minutes at 15,000 rpm in a refrigerated centrifuge prior to analyses.

The sequential partial extraction scheme releases constituents in decreasing order of availability to the environment. Elements solubilized in extraction A are considered to be highly available to the environment; those released in B are considered to be available; those in C, D, and E are considered to be conditionally available (having the potential to become available through changes in Eh, pH or by microbial mobilization); and those in F are considered unavailable.

Simulated Lung Fluid Extraction: The simulated lung fluid was adapted from that presented in Matson (1994) and Eastes and Hadley (1995). This solution was selected because it provided an environment that is relevant to the extracellular fluid in the lung. One-gram soil samples were weighed into 20 mL scintillation vials equipped with a polyethylene mesh insert. Twenty mL of simulated lung fluid were added to the vials to make a 1:20 mass/volume incubation ratio. Vials were placed into a Vitron Dynamic Organ Culture Incubator for 24 h at 37°C. The incubator was implemented in order to keep samples in a constant rolling motion while holding the temperature constant. Following incubation, the vials were centrifuged for 5 min at 15,000 rpm and the simulated lung extract was then syringe-filtered through a 0.45-micron nitrocellulose filter. The filtered extract solution was analyzed by ICP-MS. High lung fluid reagent blanks limited the number of elements reported to 25.

Results

Rock Geochemistry

Samples of rock were collected from 15 sites on Guam; seven sites from areas underlain by Facpi Formation (figs. 4, 5, and 7), four veins and fracture fillings within the Facpi Formation (fig. 7), one sample from the Bolanos Formation (fig. 6), and three samples from the Alutom Formation (fig. 8). The complete chemical analyses of samples are shown in Miller and others, (2002). The chemistry of selected elements and means for each rock type are shown in Table 1. Rocks of mostly the Facpi Formation underlie the vicinity of Umatac and Merizo. Rocks of the Bolanos Formation underlie the vicinity of Inarajan.

The rock samples from the Facpi Formation consist of one dike, two basalts, and four tuffaceous sediments. Tuffaceous sediments generally occur inland and tend to form areas of low relief. Basalt occurs particularly along the coast, and inland forms prominent cliffs. Vein fillings occur within the pillow basalts, particularly along the coast between Sella and Cetti Bays. The pillow basalts are usually vesicular with vesicle

Table 1 . Chemical analyses and means of various rock types from Guam

Field No.	Al %	Ca %	Fe %	Mg %	Ag ppm	As ppm	Cd ppm	Co ppm	Cr ppm	Cu ppm	Mn ppm	Mo ppm
					Facpi Formation, tuff							
R01	4.5	21	3.2	1.4	0.39	2	<0.1	16	97	54	790	0.3
R02	1.2	34	0.95	0.43	0.23	<0.5	0.2	4.3	24	20	1000	< 0.1
R03	1.4	28	1.4	0.62	0.16	<0.5	<0.1	6.8	48	60	1400	< 0.1
R04	1.6	35	0.90	0.55	0.12	<0.5	0.2	3.8	54	9	830	0.1
R05	3.1	29	2.0	1.3	0.1	<0.5	0.2	8.2	30	20	530	< 0.1
Mean	2.1	29	1.50	0.77	0.18	<0.5	0.13	6.8	45	26	866	0.17
					Facpi Formation, basalt							
R08	7.2	5.8	6.1	5.1	0.08	<0.5	0.2	49	830	63	1100	0.2
R15	7	17	5.4	4.4	0.07	<0.5	0.4	33	270	81	940	0.5
Mean	7.1	9.9	5.7	4.7	0.08	<0.5	0.28	40	473	71	1017	0.32
					Facpi Formation, veins							
R12	1.4	6.2	0.58	0.43	0.06	<0.5	0.1	2.5	29	260	290	0.1
R13	3	33	2.6	3.4	0.04	<0.5	0.8	20	160	44	560	0.2
R14	4.6	27	4.3	3.8	0.05	0.6	<0.1	26	260	110	1200	0.2
R16	1.2	42	2.4	1.5	0.03	<0.5	0.6	10	52	94	520	< 0.1
Mean	2.2	22	1.99	1.7	0.04	<0.5	0.43	10.7	89	104	564	0.16
					Bolanos Formation							
R07	7.8	3.4	5.6	3.1	0.11	<0.5	<0.1	25	80	110	420	< 0.1
					Alutom Formation							
R09	4.6	17	3.2	2.6	0.06	<0.5	0.1	18	100	39	720	0.1
R10	>20	0.2	7.7	2.0	0.07	<0.5	<0.1	120	120	430	1700	< 0.1
R11	9.8	0.07	8.4	2.1	0.08	<0.5	0.2	52	400	140	1300	0.1
Mean	10.4	0.62	5.9	2.2	0.07	<0.5	0.11	48	169	133	1167	0.1

Table 1 . Chemical analyses and means of various rock types from Guam

Field No.	Ni ppm	Pb ppm	Sb ppm	U ppm	Zn ppm
	Facpi Formation, tuff				
R01	56	2.1	0.2	0.40	46
R02	16	0.8	<0.1	0.10	20
R03	40	1.9	<0.1	0.20	20
R04	12	0.5	0.1	1.2	10
R05	14	1.3	<0.1	0.30	20
Mean	23	1.2	0.1	0.31	21
	Facpi Formation, basalt				
R08	230	0.9	0.2	0.07	64
R15	130	1.6	<0.1	0.40	50
Mean	173	1.2	0.12	0.17	57
	Facpi Formation, veins				
R12	11	0.2	1.8	0.07	31
R13	130	0.4	<0.1	0.20	32
R14	140	0.8	<0.1	0.20	41
R16	57	0.3	<0.1	0.20	10
Mean	58	0.37	0.15	0.15	25
	Bolanos Formation				
R07	26	1.9	<0.1	0.40	64
	Alutom Formation				
R09	58	0.8	<0.1	0.30	33
R10	77	3.2	0.1	0.82	160
R11	220	1.6	<0.1	0.30	130
Mean	99	1.6	<0.1	0.42	88

content up to 40 %. Vesicles contain the zeolites analcime and natrolite, and also clay minerals and calcite (Reagan and Meijer, 1984). The pillows generally contain glass rinds. The zeolite minerals and glass are usually the first minerals to weather and both can serve as a source of mobile Al to the environment.

Because of the prominence of basalt in the vicinity of the southern villages, mean worldwide basalt is used for comparisons. The Facpi Formation basalt and tuff and the Bolanos Formation pyroclastic rocks are low in Al compared to mean worldwide basalt or even crustal abundance (Table 2). The Facpi Formation tuff, which underlies areas inland from the coast is significantly low in Al compared to mean basalt. The mean Ca content of the Facpi Formation basalt is high compared to mean basalt and crustal abundance, but low for Facpi Formation tuff and Bolanos Formation pyroclastic rocks. The Alutom tuff, which occurs mainly in the central part of the island, is unusually low in Ca compared to mean basalt. Mean Fe and Mn contents of rocks of the Facpi, Bolanos, and Alutom Formations are less than mean basalt. Mean Mg content of rocks compared to mean basalt is similar for the Facpi Formation basalt, much less for the Facpi Formation tuff, and less for rocks of the Bolanos and Alutom Formations.

The metal contents of Cu, Zn, Co, Cr, and Ni were investigated because excess amounts in the environment may pose health risks. Mean Cu content for rocks of the Facpi Formation, except for vein and fracture fillings which are slightly higher, is less than mean basalt, but Cu is greater for rocks of the Bolanos and Alutom Formation compared to mean basalt (Table 2). The mean Zn content for all volcanic rock types in Guam is less than mean basalt. The mean Co content of rocks of the Facpi Formation basalt and Alutom Formation is slightly higher than mean basalt, but lower for rocks of the Facpi Formation tuff, Bolanos Formation, and Alutom Formation. Mean Cr and Ni contents are high for rocks of the Facpi Formation basalt and low for the remaining rock types compared to mean basalt. The most anomalous metal content in rocks is Cr in the Facpi Formation basalt, which is more than double that of the mean basalt content. Mean Cd values are low for all rock types, but rocks of the Facpi Formation basalt and vein and fracture fillings are higher than mean basalt. Means of other trace elements such as Ag, As, Mo, Pb, Sb, and U are all low in rocks; either below or near values for mean basalt. The remaining trace element contents in rocks are also low or only slightly elevated compared to mean basalt (Miller and others, 2002).

The Facpi and Bolanos Formations underlie the vicinity of the villages of Umatac, Merizo, and Inajahan with high occurrences of the neurodegenerative diseases. These rocks are low in Al and high in Ca compared to mean basalt. With the exception of high Cr in the Facpi Formation basalt, the remaining trace elements in rocks are low or only slightly elevated in concentration compared to mean basalt. The chemical composition of the rocks does not support the hypothesis of abundant Al and low Ca, or the presence of anomalous trace elements, except for Cr, in the vicinity of the southern villages. There is no direct association of the chemical composition of the rocks with the high occurrence of neurodegenerative diseases.

Soil Geochemistry

Soil samples were collected from 25 sites on Guam - 17 sites in areas underlain by the Facpi Formation (figs. 4, 5, and 7), three sites in the Bolanos Formation (fig. 6),

Table 2. Mean chemical composition of rocks from Guam compared to mean crustal average and mean worldwide basalt. All values in ppm

Element	Mean worldwide basalt[1]	Mean crust[2]	Facpi Fm tuff n=5	Facpi Fm basalt n=2	Facpi Fm vein fillings n=4	Bolonas Fm pyroclastic n=1	Alutom Fm tuff n=3
Al	87600	82000	20600	71000	21900	78000	104000
Ca	49000	41000	28900	99300	22000	34000	6200
Fe	94000	41000	15000	57400	19900	56000	59200
Mg	45000	23000	7700	47400	17000	31000	22000
Ag	0.1	0.07	0.18	0.08	0.04	0.11	0.07
As	1.5	1.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cd	0.13	0.11	0.13	0.28	0.43	<0.1	0.11
Co	35	20	6.8	40	10.7	25	48
Cr	200	100	45	473	89	80	169
Cu	90	50	26	71	104	110	133
Mn	1500	950	866	1017	564	420	1167
Mo	1	1.5	0.17	0.32	0.16	<0.1	0.1
Ni	150	80	23	173	58	26	99
Pb	3	14	1.2	1.2	0.37	1.9	1.6
Sb	0.2	0.2	0.10	0.12	0.15	<0.1	<0.1
U	0.43	2.4	0.31	0.17	0.15	0.4	0.42
Zn	100	75	21	57	25	64	88

[1] Taylor (1964)
[2] Bowen (1979)

four sites in the Alutom Formation (fig. 8), and one site from the carbonate rocks (fig. 8). Soil samples were collected from the upper four inches of the soil profile; this upper zone being the more likely to contain readily mobile elements. The samples were collected from mostly undisturbed sites, but a few sites were collected from abandoned gardens. The chemistry of selected elements and means for each soil type is shown in Table 3.

Compared to soils developed on basalts from the western U.S., the mean element contents of soils developed on the Facpi Formation basalt are: lower in Al, Fe, Cd, Cr, Cu, Sb, and U; higher in Ca, Mg and Mo; and similar or near the mean for Pb, Mn, Ag, As, Co, Ni, and Zn (Table 4). Compared to soils developed on basalts from the western U.S., the soils developed on the Facpi Formation tuff are: lower in Al, Fe, Mg, Cd, Co, Cr, Cu, and Ni; higher in Ag, As, Mo, U, and Zn; and near the mean for Mn and Ag. Compared to soils developed on basalts from the western U.S., the mean element contents of soils developed on the Bolanos Formation rocks are lower in Al, Mg, Mn, Cd, Co, Cr, Cu, and Ni; and higher in Ca, Fe, Ag, As, Mo, Pb, Sb, U, and Zn. These soils occur in the vicinity of the southern villages in the southern part of Guam. Although some of the elements are higher compared to soils developed on basalts from the western U.S., none of the elements other than Ca can be considered extremely high or anomalous in concentrations.

The mean element contents of soils from the Alutom Formation are higher in Al, Fe, Mn, Co, Cr, Cu, and Ni and lower in Ca, Ag, As, Cd, Mo, Pb, Sb, and U; and the same mean concentrations for Mg and Zn, compared to soils developed on basalts from western U.S (Table 4). These soils occur in the mid-central part of Guam and are not near the southern villages. The most anomalous concentration of elements occurs in the soil sample developed on the carbonate rock. The sample was anomalous in Ag, Al, As, Cd, Co, Cr, Fe, Mn, Mo, Ni, Pb, Sb, and U and low in Mg (Table 4). This is only one sample and not representative for all soils developed on the carbonate rocks, but suggests that anomalous metals are present in soils developed on the carbonate rock. This is not unusual in this climate because the high rainfall dissolves and removes the carbonate mineral, which is the bulk of the rock, leaving a soil residue with these elevated elements.

The mean element contents of soils developed on the Facpi and Bolanos Formations, which occur in the vicinity of the southern villages, are generally low or only slightly above the mean of soils developed on basalts from the western U.S. except for Ca which is significantly elevated. Although some of the elements are higher compared to soils developed on basalts from the western U.S., none of the elements other than Ca can be considered extremely high or anomalous in concentrations. There is no evidence of elevated element contents, except for Ca, in soils in the vicinity of the southern villages, and therefore no direct association with the high occurrence of neurodegenerative diseases.

Water Soluble Extraction Geochemistry

Because a previous study (McLachlan and others, 1989) determined high amounts of elutable Al from Guam soils, water soluble extractions of soils developed on the rock types of Guam were carried out. These results were than compared to extractions determined for soils developed on basalts from the western U.S. A summary of selected results of the water soluble extraction is shown in Table 5. The complete set of analyses

Table 3. Chemical analyses and means of soils from Guam

Field No.	Al %	Ca %	Fe %	Mg %	Ag ppm	As ppm	Cd ppm	Co ppm	Cr ppm	Cu ppm
				Facpi Formation, tuff						
S01	8.4	2.0	3.5	0.82	0.18	4	0.3	11	24	20
S02	7.8	2.8	3.7	0.80	0.13	3	0.2	13	39	20
S03	8.9	5.4	6.6	2.3	0.11	2	0.3	34	95	61
S04	8.0	2.6	3.6	0.88	0.09	3	0.2	12	35	20
S05	8.0	2.2	3.5	1.0	0.12	2	0.2	12	27	20
S06	8.2	3.0	5.0	1.1	0.12	3	0.3	24	79	52
S07	8.6	2.7	4.0	1.3	0.12	2	0.2	17	64	31
S08	6.6	9.0	4.7	1.7	0.09	6.9	0.2	20	67	37
Mean	8.0	3.3	4.2	1.16	0.12	3.0	0.23	17	48	30
				Facpi Formation, basalt						
S15	7.6	1.7	4.0	0.90	0.10	5	0.3	22	68	35
S16	7.1	1.1	3.3	0.67	0.10	5.1	0.3	15	44	31
S17	7.8	1.5	3.7	0.84	0.10	6.1	0.3	16	46	30
S12	8.0	3.5	7.3	1.3	0.10	2	0.2	23	64	32
S13	6.3	8.2	3.6	1.1	0.12	4	0.3	15	30	30
S14	8.8	4.9	6.3	2.0	0.15	<0.5	0.1	24	14	34
S23	8.2	3.1	7.4	4.7	0.02	<0.5	0.2	52	570	96
S24	7.3	2.3	7.7	3.7	0.02	1	0.4	60	560	95
S25	7.4	3.1	7.5	6.7	0.02	<0.5	0.1	58	620	74
Mean	7.6	2.7	5.3	1.77	0.06	1.5	0.22	27	97	45
				Bolanos Fromation						
S09	7.3	5.7	5.2	1.1	0.09	8	0.2	16	36	20
S10	7.8	5.8	6.5	1.3	0.08	4	0.2	20	52	30
S11	8.2	4.6	6.2	1.6	0.1	3	0.2	26	72	75
Mean	7.8	5.3	5.9	1.3	0.09	4.6	0.2	20	51	36
				Alutom Formation						
S19	7.4	12	5.3	2.9	0.06	<0.5	0.4	33	150	78
S20	15	0.20	12	0.44	0.05	0.9	<0.1	31	310	380
S21	11	0.59	8.5	3.6	0.03	<0.5	0.4	50	280	110
S22	14	0.2	13	1.1	0.04	2	0.1	97	530	160
Mean	11.4	0.73	9.2	1.50	0.04	0.81	0.18	47	288	151
				Limestone						
S18	26	1.2	14	0.10	0.18	57	7.1	47	730	46

Table 3. Chemical analyses and means of soils from Guam

Field No.	Mn ppm	Mo ppm	Ni ppm	Pb ppm	Sb ppm	U ppm	Zn ppm
			Facpi Formation, tuff				
S01	1300	1.3	12	26	0.6	2.5	110
S02	1000	1.2	16	22	0.6	2.6	110
S03	1400	0.6	44	18	0.3	1.2	110
S04	820	1.1	14	21	0.5	2.1	81
S05	890	1.6	13	24	0.6	3.8	94
S06	1800	0.7	42	22	0.5	1.7	100
S07	1200	0.9	28	20	0.5	2.2	97
S08	890	0.8	39	13	0.7	1.6	86
Mean	1124	0.98	23	20	0.52	2.1	98
			Facpi Formation, basalt				
S15	1100	0.9	44	20	0.7	2.3	87
S16	940	1	23	20	0.8	2.5	88
S17	860	1	26	22	0.8	2.3	93
S12	1200	1.3	28	19	0.6	2.3	140
S13	780	0.8	21	16	0.7	1.8	79
S14	1000	0.9	19	11	<0.1	0.88	120
S23	1300	0.3	270	6.1	<0.1	0.2	70
S24	1400	0.7	240	3.6	0.3	0.4	92
S25	1300	0.1	310	<0.8	<0.1	0.06	72
Mean	1078	0.64	57	9.0	0.30	0.85	91
			Bolanos Fromation				
S09	900	1.1	19	15	0.7	3.4	110
S10	1000	1.3	22	16	0.9	2.1	130
S11	1400	1.2	49	22	0.7	2.7	120
Mean	1080	1.2	27	17	0.76	2.7	120
			Alutom Formation				
S19	1400	0.2	100	3.6	0.4	0.5	77
S20	940	0.7	140	5.6	0.3	1.3	81
S21	1800	0.2	150	2	0.2	0.4	100
S22	2300	0.6	380	2	0.3	0.4	97
Mean	1528	0.36	168	3.0	0.29	0.57	88
			Limestone				
S18	5600	4.3	320	77	14	17	57

Table 4 . Mean chemical composition of soils from various rock types of Guam compared to mean soil developed on basalt from the western U.S. All values in ppm.

Element	Mean soil Western U.S. basalt[1] n=8	Mean soil Facpi Fm. tuff n=8	Mean soil Facpi Fm. basalt n=9	Mean soil Bolanos Fm. n=3	Mean soil Alutom Fm. n=4	Guam limestone rock n=1
Al	84000	80300	75800	77600	114000	260000
Ca	12000	32600	27400	53400	7300	12000
Fe	58000	42200	53300	59400	91600	140000
Mg	15000	11600	17700	13200	15000	1000
Ag	0.07	0.12	0.06	0.09	0.04	0.18
As	1.7	2.96	1.48	4.58	0.81	57
Cd	0.28	0.23	0.22	0.20	0.18	7.1
Co	31	17	27	20	47	47
Cr	112	48	97	51	288	730
Cu	62	30	45	36	151	46
Mn	1150	1124	1078	1080	1528	5600
Mo	0.48	0.98	0.64	1.2	0.36	4.3
Ni	56	23	57	27	168	320
Pb	9	20	9	17	3	77
Sb	0.46	0.52	0.30	0.76	0.29	14
U	0.98	2.1	0.85	2.68	0.57	17
Zn	88	98	91	120	88	57

[1] Miller and others (2002)

Table 5. Mean chemical composition of water soluble extractions of soils from Guam and the western U.S. Values in ppm

Element or specie	Soil Facpi Fm. tuff n=8	Soil Facpi Fm. basalt n=9	Soil Bolanos Fm. n=3	Soil Alutom Fm. n=4	Soil limestone rock n=1	Soil Western U.S. basalt n=8
pH	6.33	7.16	6.04	6.38	7.58	8.02
Al	3.74	5.83	2.37	2.54	4.03	2.25
Ca	113	44	5.6	22	106	42.9
Fe	4	4.6	1.7	0.85	0.35	1.2
Mg	17	20	11	10	1.7	7
Ag	<3	<3	<3	<3	<3	<3
As	<10	<10	<10	<10	<10	12.4
Be	0.45	<0.5	0.52	<0.5	0.6	0.5
Cd	2.7	0.77	0.62	0.2	0.72	0.57
Co	10.5	10.6	11.9	7.5	8.1	3
Cr	16.5	28	<10	<10	146	3.8
Cu	240	164	140	75	20	70
Li	5.8	9.8	2.3	1.5	<1	3.6
Mn	0.65	0.31	0.42	0.3	0.68	0.17
Mo	4.2	3	4.3	2	<2	2.9
Ni	58	94	22	14	48	17
Pb	19	11	2.9	2.2	6.9	6.3
Sb	3.1	1.7	1.2	1.1	<1	1.1
Se	15	<10	<10	13	10	8
Si	40	39	34	18	<0.2	21
SO_4^{2-}	49	35	18	25	21	17
U	0.29	0.28	0.44	0.4	0.99	0.86
Zn	160	65	93	11	16	19

is shown in Miller and others (2002). Comparing the results from the different soil types of Guam to the chemistry of the soils from the western U.S., the soils from the Facpi Formation tuff are high in Cd, Cr, Cu, Fe, Ni, Pb, Sb, and Zn; the soils from the Facpi Formation basalt are high in Al, Cr, Cu, Fe, Li, Ni, Pb, and Sb; the soils from the Bolanos Formation are high in Cu, Co, Mo, and Zn; and the soil from the carbonate rock is high in Al, Ca, and Cr. The range of water soluble extractions of Al is 2.25 to 5.83 ppm, about a 2 fold range for the different soil types. Although the extraction methods are not identical, our results are unlike McLachlan and others (1989), which found much greater amounts and a much greater range of elutable Al among different soil types.

The most anomalous concentrations of elements of the water soluble extractions of soils from Guam are Cr from soils developed on carbonate rock, followed by Cu, Pb, and Zn from the Facpi Formation tuff. Concentrations of Fe, Cd, Cu, Li, Ni, Pb, Sb, and Zn are high in water soluble extractions of soils developed on the Facpi Formation, which occurs in the vicinity of the southern villages. High concentrations of these elements, if available to humans, could constitute a problem for human health. However, the absolute amounts are small and there is probably no effective mechanism to make them available to humans.

Sequential Extraction Geochemistry

In order to determine the association of elements and inferred relative availability, sequential extractions of soils from Guam and the western U.S. were carried out (Table 6). The two fractions of interest are A and B, because these represent the most readily exchanged, soluble, or elements associated with the carbonate minerals that are usually partially water soluble. For fraction A, the expected phase dissolution is the water soluble, sorbed, and exchangeable elements. For fraction B, the expected phase dissolution is the carbonate fraction. Al from fraction A is below the detection limit of 8 ppm for all soils and for fraction B is generally low, the highest is 563 ppm from carbonate rock. Fraction B of soils from the Facpi and the Bolanos Formations ranged from 63 to 101 ppm Al compared to 106 ppm for a basalt from the western U.S.. Most of the Al is in the mineral phases E and F, which is tightly bound in mineral structures. The conclusion is that very little Al in soils from Guam, particularly from the Facpi and Bolanos Formations, are readily available in the surfical environment. Fe and Mn exhibit similar behavior. Concentrations of other elements, including some that may have a detrimental effect on human health, were determined. Concentrations of Cr, Co, Ni, Cu, Zn, As, Mo, Cd, Pb, and U are all less than analytical detection or only slightly above levels of detection in the A and B fractions. The soils of Guam have very little of the above-mentioned elements readily available to the surfical environment. The results for Ca show that significant amounts are available in the B fraction, particularly for soils from the Facpi and Bolanos Formations.

Prior studies (Gajdusek, 1982; Yanagihara and others, 1984; Garruto and others, 1989) have suggested that high Al and low Ca may play a role in the occurrences of neurodegenerative diseases in Guam. The results of the sequential extractions of soils from Guam show that very little Al as well as most other elements are readily available. The exception is Ca, in which significant amounts are readily available in the B fraction. The results do not support the hypothesis of the connection of the neurodegenerative

Table 6. Sequential extractions of soils from Guam and the western U.S. All values in ppm

Site	Soil from formation or rock type	Fraction A	B	C	D	E	F
		Al					
		Guam					
S01	Facpi Fm. tuff	< 8	86.3	17.9	1490	8110	50400
S04	Facpi Fm. tuff	< 8	63.2	9.87	1720	7000	56700
S08	Facpi Fm. tuff	< 8	76.0	12.7	1580	9210	47000
S13	Facpi Fm. basalt	< 8	69.0	13.2	1630	8920	44100
S18	Carbonate rock	< 8	234	121	5990	178000	21200
S22	Alutom Fm. tuff	< 8	563	74.7	2470	29200	82400
S24	Facpi Fm. basalt	< 8	101	< 8	6280	28800	31700
		Western U.S.					
CS06	mineralized tuff	< 8	39.3	10.9	1480	6240	39900
CS10	marine shale	< 8	40.1	11.3	1020	5650	40300
CS12	basalt	< 8	106	13.8	1780	12100	45000
CS15	evaporite	< 8	15.6	< 8	227	7500	16400
		Ca					
		Guam					
S01	Facpi Fm. tuff	2730	999	386	586	190	10800
S04	Facpi Fm. tuff	4950	1400	96.8	700	289	14900
S08	Facpi Fm. tuff	8320	53900	1330	634	780	15300
S13	Facpi Fm. basalt	6410	52900	1620	1660	205	8980
S18	Carbonate rock	1570	1490	262	181	4350	1120
S22	Alutom Fm. tuff	2070	< 20	< 20	< 20	< 20	< 20
S24	Facpi Fm. basalt	6400	1040	66.3	282	786	9690
		Western U.S.					
CS06	mineralized tuff	1530	22.7	29.8	241	< 20	682
CS10	marine shale	5640	14600	3250	16700	387	345
CS12	basalt	941	< 20	30.2	193	296	7140
CS15	evaporite	59500	34600	9400	17400	338	287
		Fe					
		Guam					
S01	Facpi Fm. tuff	< 50	< 50	< 50	716	18200	18200
S04	Facpi Fm. tuff	< 50	< 50	< 50	925	16100	22300
S08	Facpi Fm. tuff	< 50	< 50	< 50	1840	28000	18700
S13	Facpi Fm. basalt	< 50	< 50	< 50	448	17800	18800
S18	Carbonate rock	< 50	< 50	110	1890	111000	33900
S22	Alutom Fm. tuff	< 50	< 50	202	1060	116000	33700
S24	Facpi Fm. basalt	< 50	< 50	70	8600	56200	18300
		Western U.S.					
CS06	mineralized tuff	< 50	< 50	< 50	2340	17900	9760
CS10	marine shale	< 50	< 50	< 50	638	18200	7700
CS12	basalt	< 50	< 50	< 50	4050	26400	13300
CS15	evaporite	< 50	< 50	338	907	9780	1120
		Mg					
		Guam					
S01	Facpi Fm. tuff	209	109	22.0	422	2590	3260

Table 6. Sequential extractions of soils from Guam and the western U.S. All values in ppm

Site	Soil from formation or rock type	Fraction A	B	C	D	E	F
S04	Facpi Fm. tuff	333	104	15.6	353	2370	4210
S08	Facpi Fm. tuff	251	390	34.8	1270	8990	5130
S13	Facpi Fm. basalt	218	424	39.3	571	3350	4460
S18	Carbonate rock	18.9	59.7	38.3	60.2	379	201
S22	Alutom Fm. tuff	1140	74.4	6.88	42.2	2170	4730
S24	Facpi Fm. basalt	2700	292	20.3	2910	18700	9000
			Western U.S.				
CS06	mineralized tuff	112	10.9	3.44	88.9	1920	2000
CS10	marine shale	306	2120	1720	11000	2420	2510
CS12	basalt	262	21.8	4.21	606	4750	4100
CS15	evaporite	734	3600	6530	11700	15800	919

			As				
			Guam				
S01	Facpi Fm. tuff	< 2	< 2	< 2	< 2	< 2	< 2
S04	Facpi Fm. tuff	< 2	< 2	< 2	< 2	< 2	< 2
S08	Facpi Fm. tuff	< 2	< 2	< 2	< 2	4.1	< 2
S13	Facpi Fm. basalt	< 2	< 2	< 2	< 2	2	< 2
S18	Carbonate rock	< 2	< 2	< 2	< 2	26.4	24.6
S22	Alutom Fm. tuff	< 2	< 2	< 2	< 2	2	< 2
S24	Facpi Fm. basalt	< 2	< 2	< 2	< 2	< 2	< 2
			Western U.S.				
CS06	mineralized tuff	< 2	< 2	< 2	6.2	25.8	< 2
CS10	marine shale	< 2	< 2	< 2	< 2	6.8	< 2
CS12	basalt	< 2	< 2	< 2	< 2	3.5	< 2
CS15	evaporite	< 2	< 2	< 2	< 2	2	< 2

			Cd				
			Guam				
S01	Facpi Fm. tuff	< 0.02	0.09	0.05	0.04	0.04	0.04
S04	Facpi Fm. tuff	< 0.02	0.09	< 0.02	0.04	0.03	0.03
S08	Facpi Fm. tuff	< 0.02	0.09	< 0.02	0.03	0.04	0.04
S13	Facpi Fm. basalt	< 0.02	0.14	< 0.02	0.03	0.03	0.03
S18	Carbonate rock	< 0.02	0.63	1.08	0.86	2.54	2.54
S22	Alutom Fm. tuff	< 0.02	0.02	0.03	< 0.02	0.05	0.05
S24	Facpi Fm. basalt	0.02	0.12	0.02	0.07	0.07	0.07
			Western U.S.				
CS06	mineralized tuff	< 0.02	0.06	0.06	0.09	0.05	0.05
CS10	marine shale	< 0.02	0.11	< 0.02	0.05	0.08	0.08
CS12	basalt	< 0.02	0.05	< 0.02	0.05	0.05	0.05
CS15	evaporite	< 0.02	0.05	< 0.02	< 0.02	< 0.02	< 0.02

			Co				
			Guam				
S01	Facpi Fm. tuff	< 0.1	< 0.1	2.24	1.04	2.94	2.75
S04	Facpi Fm. tuff	< 0.1	0.16	0.55	1.38	3.84	4.51
S08	Facpi Fm. tuff	< 0.1	0.24	1.60	2.58	8.25	4.08
S13	Facpi Fm. basalt	< 0.1	0.19	1.21	1.79	4.51	4.42

Table 6. Sequential extractions of soils from Guam and the western U.S. All values in ppm

Site	Soil from formation or rock type	Fraction A	B	C	D	E	F
S18	Carbonate rock	< 0.1	< 0.1	26.8	3.46	3.74	2.11
S22	Alutom Fm. tuff	0.17	2.71	40.9	19.1	9.05	7.52
S24	Facpi Fm. basalt	< 0.1	2.08	3.52	14.0	25.2	5.62
			Western U.S.				
CS06	mineralized tuff	< 0.1	< 0.1	0.66	1.52	3.08	1.55
CS10	marine shale	< 0.1	0.44	0.30	0.61	3.78	1.46
CS12	basalt	< 0.1	0.23	1.04	1.97	7.53	4.36
CS15	evaporite	< 0.1	0.50	0.50	0.28	2.97	0.43

			Cr				
			Guam				
S01	Facpi Fm. tuff	< 0.2	0.9	< 0.2	< 0.2	11.4	39.4
S04	Facpi Fm. tuff	< 0.2	0.7	< 0.2	< 0.2	13.7	49.7
S08	Facpi Fm. tuff	< 0.2	1.0	< 0.2	< 0.2	16.9	69.7
S13	Facpi Fm. basalt	0.5	1.6	< 0.2	< 0.2	12.8	49.8
S18	Carbonate rock	1.4	3.2	< 0.2	4.5	534	177
S22	Alutom Fm. tuff	1.1	2.6	< 0.2	0.4	360	174
S24	Facpi Fm. basalt	0.8	4.1	< 0.2	8.0	155	321
			Western U.S.				
CS06	mineralized tuff	1.2	2.4	< 0.2	< 0.2	8.0	45.0
CS10	marine shale	1.4	3.2	< 0.2	0.4	13.9	66.7
CS12	basalt	1.4	3.4	< 0.2	1.4	24.2	90.2
CS15	evaporite	1.6	3.2	< 0.2	< 0.2	29.7	26.5

			Cu				
			Guam				
S01	Facpi Fm. tuff	0.69	4.7	1.1	17.2	9.5	8.5
S04	Facpi Fm. tuff	1.8	1.4	< 0.5	12.9	11.4	12.3
S08	Facpi Fm. tuff	1.9	6.0	0.85	22.8	16.9	17.8
S13	Facpi Fm. basalt	1.7	2.2	< 0.5	10.2	11.5	19.2
S18	Carbonate rock	1.1	8.3	1.6	19.4	24.3	26.7
S22	Alutom Fm. tuff	1.4	17.7	1.9	18.7	67.7	66.0
S24	Facpi Fm. basalt	1.8	2.4	< 0.5	25.2	55.5	21.4
			Western U.S.				
CS06	mineralized tuff	0.92	3.0	0.62	12.0	10.3	15.6
CS10	marine shale	3.1	7.7	< 0.5	21.3	14.6	7.4
CS12	basalt	0.70	5.8	0.50	6.9	11.5	21.6
CS15	evaporite	1.0	5.5	< 0.5	4.1	7.1	6.4

			Mn				
			Guam				
S01	Facpi Fm. tuff	0.5	37.6	674	168	167	218
S04	Facpi Fm. tuff	4.2	66.1	234	106	98.6	224
S08	Facpi Fm. tuff	< 0.2	38.6	228	81.2	273	214
S13	Facpi Fm. basalt	< 0.2	45.8	276	71.4	99.9	203
S18	Carbonate rock	< 0.2	104	4650	456	510	95.4
S22	Alutom Fm. tuff	51.8	68.9	973	723	575	73.4
S24	Facpi Fm. basalt	32.9	111	364	392	430	123

Table 6. Sequential extractions of soils from Guam and the western U.S. All values in ppm

Site	Soil from formation or rock type	Fraction A	B	C	D	E	F
		Western U.S.					
CS06	mineralized tuff	1.2	10.6	352	589	343	92.2
CS10	marine shale	0.2	40.9	22.7	24.5	56.6	28.9
CS12	basalt	4.9	11.1	53.1	114	311	140
CS15	evaporite	0.4	48.4	32.7	51.7	39.3	10.5
		Mo					
		Guam					
S01	Facpi Fm. tuff	< 0.2	< 0.2	< 0.2	< 0.2	0.89	0.72
S04	Facpi Fm. tuff	< 0.2	< 0.2	< 0.2	< 0.2	0.63	0.80
S08	Facpi Fm. tuff	< 0.2	< 0.2	< 0.2	< 0.2	0.65	0.53
S13	Facpi Fm. basalt	< 0.2	< 0.2	< 0.2	< 0.2	0.62	1.14
S18	Carbonate rock	< 0.2	< 0.2	< 0.2	< 0.2	1.46	1.80
S22	Alutom Fm. tuff	< 0.2	< 0.2	< 0.2	< 0.2	0.73	0.32
S24	Facpi Fm. basalt	< 0.2	< 0.2	< 0.2	< 0.2	0.58	0.61
		Western U.S.					
CS06	mineralized tuff	< 0.2	< 0.2	< 0.2	0.31	6.63	1.27
CS10	marine shale	< 0.2	< 0.2	< 0.2	< 0.2	1.36	0.68
CS12	basalt	< 0.2	< 0.2	< 0.2	< 0.2	0.86	0.64
CS15	evaporite	< 0.2	0.25	< 0.2	0.40	4.74	0.66
		Ni					
		Guam					
S01	Facpi Fm. tuff	< 1	1.2	< 1	2.6	7.3	4.1
S04	Facpi Fm. tuff	< 1	< 1	< 1	2.6	8.2	5.9
S08	Facpi Fm. tuff	< 1	2.1	< 1	5.8	23.3	7.3
S13	Facpi Fm. basalt	< 1	1.6	< 1	3.0	10.8	7.8
S18	Carbonate rock	< 1	4.1	69.0	21.2	130	39.7
S22	Alutom Fm. tuff	< 1	1.8	< 1	3.9	64.7	272
S24	Facpi Fm. basalt	< 1	8.2	< 1	30.6	116	61.2
		Western U.S.					
CS06	mineralized tuff	< 1	< 1	< 1	1.0	6.4	5.8
CS10	marine shale	< 1	1.1	< 1	2.9	16.1	9.1
CS12	basalt	< 1	< 1	< 1	2.3	28.6	20.0
CS15	evaporite	< 1	1.0	< 1	< 1	16.5	6.0
		Pb					
		Guam					
S01	Facpi Fm. tuff	< 0.2	< 0.2	< 0.2	13.7	4.0	10.0
S04	Facpi Fm. tuff	< 0.2	< 0.2	< 0.2	9.4	3.3	8.3
S08	Facpi Fm. tuff	< 0.2	< 0.2	< 0.2	5.3	3.9	6.0
S13	Facpi Fm. basalt	< 0.2	< 0.2	< 0.2	6.2	3.8	9.1
S18	Carbonate rock	< 0.2	< 0.2	< 0.2	6.9	46.6	19.4
S22	Alutom Fm. tuff	< 0.2	< 0.2	< 0.2	1.5	2.0	1.1
S24	Facpi Fm. basalt	< 0.2	< 0.2	< 0.2	3.6	1.8	1.9
		Western U.S.					
CS06	mineralized tuff	< 0.2	< 0.2	< 0.2	29.8	17.4	8.0
CS10	marine shale	< 0.2	< 0.2	< 0.2	6.3	8.9	4.1

Table 6. Sequential extractions of soils from Guam and the western U.S. All values in ppm

Site	Soil from formation or rock type	Fraction A	B	C	D	E	F
CS12	basalt	< 0.2	< 0.2	< 0.2	8.8	7.4	6.9
CS15	evaporite	< 0.2	< 0.2	< 0.2	0.79	1.1	5.3
			U				
			Guam				
S01	Facpi Fm. tuff	< 0.02	0.05	< 0.02	0.10	0.27	1.30
S04	Facpi Fm. tuff	< 0.02	0.07	< 0.02	0.08	0.23	1.09
S08	Facpi Fm. tuff	< 0.02	0.04	< 0.02	0.04	0.20	0.93
S13	Facpi Fm. basalt	< 0.02	0.04	< 0.02	0.03	0.17	0.95
S18	Carbonate rock	< 0.02	0.84	< 0.02	0.81	4.83	3.94
S22	Alutom Fm. tuff	< 0.02	0.04	< 0.02	0.02	0.12	0.08
S24	Facpi Fm. basalt	< 0.02	0.08	< 0.02	0.06	0.09	0.07
			Western U.S.				
CS06	mineralized tuff	0.04	0.97	< 0.02	1.34	2.85	3.76
CS10	marine shale	< 0.02	0.07	< 0.02	0.20	0.53	1.74
CS12	basalt	< 0.02	0.07	< 0.02	0.15	0.27	1.11
CS15	evaporite	0.11	1.12	< 0.02	0.40	0.32	1.05
			Zn				
			Guam				
S01	Facpi Fm. tuff	< 5	< 5	< 5	9.0	44.1	44.5
S04	Facpi Fm. tuff	< 5	< 5	< 5	8.1	29.6	40.3
S08	Facpi Fm. tuff	< 5	< 5	< 5	8.5	42.3	35.9
S13	Facpi Fm. basalt	< 5	< 5	< 5	7.2	34.4	35.3
S18	Carbonate rock	< 5	< 5	< 5	< 5	27.5	28.3
S22	Alutom Fm. tuff	< 5	< 5	< 5	< 5	54.8	34.3
S24	Facpi Fm. basalt	< 5	< 5	< 5	19.9	50.0	14.9
			Western U.S.				
CS06	mineralized tuff	< 5	< 5	< 5	9.8	67.9	44.9
CS10	marine shale	< 5	< 5	< 5	6.9	56.6	25.2
CS12	basalt	< 5	< 5	< 5	< 5	44.2	40.3
CS15	evaporite	< 5	< 5	< 5	< 5	12.2	< 5

diseases to the high concentrations of available Al and the lack of available Ca in soils in the vicinity of the southern villages.

Simulated Lung Fluid Extraction

McLachlan and others (1989) have suggested the possibility of ingestion of dust into the respiratory system as a pathway of elements to the human body. In order to determine if breathing dust derived from soils was a possible pathway of elements to the body, simulated lung fluid extractions of soils from Guam and western U.S. were made. Dust in Guam would contain a large component of local soil, particularly the fine fraction. The upper four inches and the < 63 microns fraction of soils was used for analyses to represent local dust of Guam. Note that the detection for some elements was not obtainable because high concentrations of these elements were present in the blanks of the reagents. The results of the lung fluid extraction show that the range of Al is < 0.02 to 2 ppm (Table 7). The highest values for Al occur in soils from Facpi Formation tuff and basalt and carbonate rock. Soils from the western U.S. had up to 1 ppm Al. The extraction of the soil from the Bolanos Formation was < 0.02 ppm Al. Although Al in lung fluid extractions varied by soils from different rock types, none of the soils are highly anomalous in Al. Ca in lung fluid extractions of soils ranged from 480 to 3230 ppm. Significant Ca is mobilized by the lung fluid extraction. The highest Ca concentrations are soils from Facpi Formation tuff and basalt, which are 2-fold more than soils from western U.S. Mn has a range of < 0.01 to 38.9 ppm; elevated Mn occurs in two soils, one from the Facpi Formation basalt near Sella Bay north of Umatac and one from the Alutom Formation tuff in the mid-part of the island. Most of the extractions from the Guam soils are much higher in Mn than soils from western U.S. Co ranged from < 4 to 255 ppb. Co in lung fluid extractions is much higher in soils from Guam compared to western U.S., the highest being a soil from Facpi Formation basalt near Sella Bay. The detection limit for Cr in the lung fluid extractions is high, but two samples are detectable; one soil (1510 ppb) from carbonate rock and one soil (280 ppb) from Facpi Formation basalt from near Sella Bay. Ni ranged from < 20 to 1070 ppb; the highest from Facpi Formation basalt near Sella Bay. All the lung fluid extractions for Ni of soils from Guam are significantly higher than soils from western U.S. Pb is below the detection limit of < 10 ppb of lung extractions for all soil samples. Significant U is present in lung fluid extractions of all soil samples, but one soil from western U.S. was the most anomalous.

The results of the lung fluid extractions of soils show that several elements such as Mn, Co, Cr, and Ni are elevated in the simulated lung extractions. A soil developed on Facpi Formation basalt near Sella Bay was particularly high in Mn, Co, Cr, and Ni. The ingestion of dust by humans could be a pathway for Mn, Co, Cu, and Ni to the body. Al, which has been suggested as being implicated in the occurrence of neurodegenerative diseases in Guam, is not anomalous in the simulated lung dissolutions of soils of Guam. Other elements such as Fe are below detection limit of 10 ppm for all samples.

Table 7. Chemical composition of simulated lung fluid extraction of soils from Guam and the western U.S.

Field No	Soil from formation or rock type	Al ppm	Ca ppm	Mg ppm	K ppm	Mn ppm	Fe ppm	Si ppm	Ba ppb
Guam									
S04	Facpi Fm. tuff	2	2230	262	468	8.77	<10	262	7440
S08	Facpi Fm. tuff	<0.02	2280	215	374	2.96	<10	31	11100
S13	Facpi Fm, basalt	2	2480	176	215	3.43	<10	312	17600
G24	Facpi Fm, basalt	2	3230	1600	458	38.9	<10	245	700
S10	Bolanos Fm, tuff	<0.02	1770	175	616	2.04	<10	290	7810
S22	Alutom Fm. tuff	<0.02	620	758	146	18.5	<10	<40	2800
S18	limestone	2	480	12	6	<0.01	<10	<40	<20
Western U.S.									
CS06	mineralize tuff breccia	1	1090	85	93	0.97	<10	<40	2210
CS12	basalt	<0.02	790	205	129	0.62	<10	<40	14600
CS18	basalt	1	1096	203	227	2.14	<10	86	8500

Table 7. Chemical composition of simulated lung fluid extraction of soils from Guam and the western U.S.

Field No	Soil from formation or rock type	Co ppb	Cr ppb	Li ppb	Ni ppb	Pb ppb	U ppb	V ppb
Guam								
S04	Facpi Fm. tuff	53.7	<200	152	124	13	115	450
S08	Facpi Fm. tuff	34.3	<200	23	45	<10	29.0	784
S13	Facpi Fm, basalt	36.2	<200	<20	<20	<10	26.0	558
G24	Facpi Fm, basalt	255	280	<20	1070	<10	59.7	92
S10	Bolanos Fm, tuff	21.7	<200	<20	<20	<10	52.0	964
S22	Alutom Fm. tuff	170	<200	<20	151	<10	12.5	<20
S18	limestone	16.5	1510	<20	133	<10	325	112
Western U.S.								
CS06	mineralize tuff breccia	<4	<200	<20	<20	<10	1590	36
CS12	basalt	6.4	<200	<20	<20	<10	71.8	161
CS18	basalt	7.1	<200	<20	<20	<10	227	427

Conclusion

The conclusions of the geochemical study of rocks, soils, and various soil extractions are:

1) Rocks of the Facpi and Bolanos Formations underlie the vicinity of the villages of Umatac, Merizo, and Inajajan, which have high occurrences of the neurodegenerative diseases. These rocks are low in Al, near the mean for Fe, and high in Ca compared to mean basalt. With the exception of high Cr in the Facpi Formation basalt, the remaining trace elements are low or only slightly elevated in concentrations compared to mean worldwide basalt. The rock chemistry does not support the hypothesis of high concentrations of Al and low concentrations of Ca in the surficial environment or unusually high concentrations of trace elements in the vicinity of the southern villages;

2) Compared to the means of soils developed on basalts from the western U.S., soils developed on the Facpi and Bolanos Formations, which occur in the vicinity of the southern villages, are generally low or near the mean in elements including Al and Fe, but elevated in Ca, while soils developed on the carbonate rocks and to a lesser extent the Alutom Formation in the mid part of the island are anomalous in many elements. Therefore there is no evidence that elevated element content in soils in the vicinity of the southern villages is associated with the high occurrence of neurodegenerative diseases;

3) Results of the water soluble extractions of soils show that the most anomalous element is Cr in carbonate rock, followed by Cu, Pb, and Zn in Facpi Formation tuff. Fe, Cd, Cu, Li, Ni, Pb, Sb, and Zn are high in water soluble extractions of soils developed on the Facpi Formation, compared to the remaining samples. These elements are more available in the surfical environment and if available to the humans, could constitute a problem for human health; but the absolute amounts being small and a lack of an effective mechanism to make available to humans probably negate the effect of the moderately elevated elements on human health;

4) The results of the sequential extractions of soils from Guam showed that very little Al and most other elements are readily available. The exception is Ca, which is readily available in the B fraction and does not support the possibility of lack of available Ca in soils in the vicinity of the southern villages;

5) The results of the simulated lung fluid extractions of soils show that several elements such as Mn, Co, Cr, and Ni are elevated in the lung fluid extractions. A soil from Facpi Formation basalt near Sella Bay was particularly high in Mn, Co, Cr, and Ni. The ingestion of dust by humans could be a pathway for Mn, Co, Cu, and Ni to the body. Al, which has been suggested as being implicated in the occurrence of neurodegenerative diseases in Guam, is not unusually high in the lung fluid extractions of soils from Guam.

The most significant results of the geochemical study of rocks and soils are: 1) there is no evidence for large amounts of readily available Al as well as Fe in the surficial environment; 2) Mn is generally not readily available in the surficial environment with the exception of one soil developed on Facpi Formation basalt near Sella Bay; lung fluid extraction of this soil was high in Mn. The inhalation of soil dust in this vicinity would allow a pathway for Mn to the body; 3) Cr, Co, and Ni are elevated mainly because of the basaltic rock type; 4) generally the remaining elements in the rock, soil, and various soil extractions are low; and 5) The results show that high concentrations of Ca as well as readily available Ca is present in rocks and soils of the Facpi and Bolanos Formations, which occurs in the vicinity of the southern villages. The suggestion that low concentrations of Ca is present in the vicinity of the southern villages and a contributing factor in the occurrence of the diseases is not supported.

The results of the study suggest little evidence that the chemistry of the rocks and derived soils, which underlie the southern part of Guam, play a role in the occurrence of the neurodegenerative diseases.

Hypothesis for the Occurrence of Neurodegenerative Diseases on Guam

Background information on the description and occurrence of the neurodegenerative diseases on Guam and the history of the research carried out can be found in Perl (1997) and Sacks (1997). Many theories have been proposed to account for the high rates of neurodegenerative disease on Guam, but none have been successfully proven. The theory must be able to account for the greater occurrence of the diseases in the southern volcanic portion of the island compared to the northern limestone portion of Guam. The high occurrence of the diseases is not present elsewhere in the Marianas islands, except Rota. Nearby islands such as Saipan, which contain the same indigenous Chamorro population, do not have the high occurrence of the diseases. The geology of many of the other Marianas islands as well as the Caroline islands to the south, and many areas worldwide have geology and rock compositions similar to Guam without the high occurrence of the diseases. This is permissive evidence that volcanic rock composition of Guam is not directly related to the high rates of these diseases.

During fieldwork, we observed that streams and rivers occur only in the volcanic portion of Guam and are absent from the limestone portion of the island (fig. 9). We also observed that along the Umatac River near Umatac, the Geus River near Merizo, and the Inarajan River near Inarajan, villages were usually located near the mouth of rivers, obviously to have access to the sea and to fresh water for human consumption. Along these rivers, particularly in the lower stretch of the Umatac River near its mouth, abundant filamentous material occurred covering large portions of the river surface in some areas, as well as abundant dead filamentous material along the banks at previous high water levels. This filamentous material is either algae or cyanobacteria (formally blue-green algae). At this time of year (March), the rivers were low and slow flowing. An algal bloom had probably occurred earlier during this dry period when temperatures of the water would have been elevated.

Algae can be defined as chlorophyll-containing organisms, which have no true roots, stems, or leaves. The taxonomy of algae consists of the kingdom: Monera that includes cyanobacteria (~1600 species) and the kingdom: Protista that includes dinoflagellates, diatoms, green algae, red algae, brown algae, and euglenoids. In this report we use the term algae to include both phyla. A small number algal species produce hepatoxins or neurotoxins. Neurotoxins affect the nervous and respiratory systems and can cause muscle tremors, stupor, staggering, rapid paralysis, and respiratory failure (Falconer, 1993; Edwards and others, 1992; Schwimmer and Schwimmer, 1968). Toxins of human health significance occur mostly in dinoflagellates, diatoms, and cyanobacteria. An example of a dinoflagellate, which releases toxins and caused human health problems, is *Phfiesteria piscicida* (Burkholder and others, 2001). Cyanobacteria do not actively secrete toxins, but release them in the aquatic environment as the result of

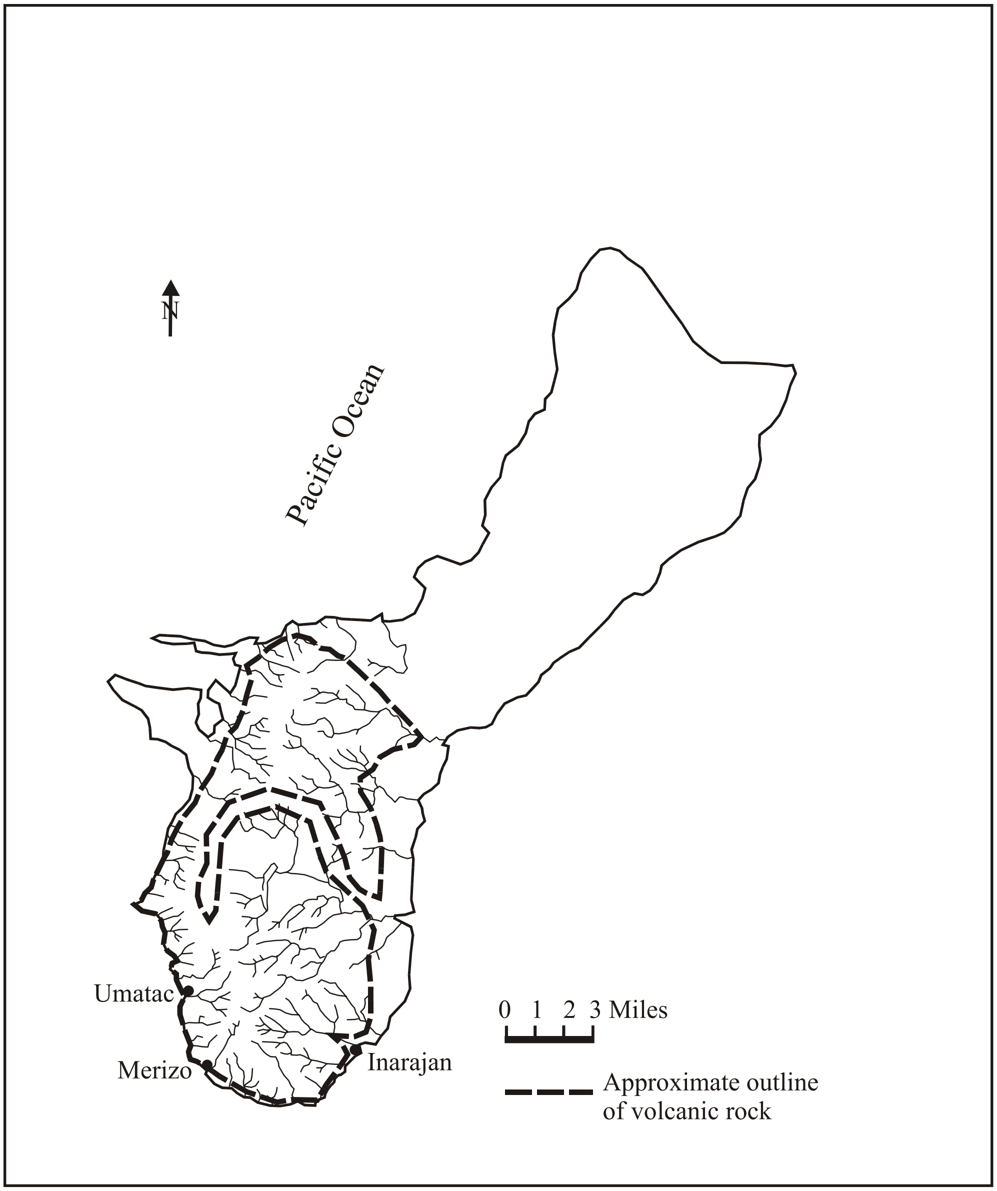

Figure 9. Map of Guam showing drainage pattern.

death. As noted, abundant dead filamentous material were observed along the high water mark of the Umatac River near its mouth. The decay processes associated with dying blooms also depletes oxygen (Falconer, 1988), which can lead to the production of ammonia, sulphides, and other compounds. The neurotoxins released by cyanobacteria include anatoxin-a, anatoxin-a(s), saxitoxin, and neosaxitoxin (Carmichael, 1994). Cyanobacteria is known to occur in the marine environment of Tuman Bay to the north (Thacker and others, 2000). In addition to the release of toxins, some cyanobacteria are capable of hosting bacteria and virus. Cholera outbreaks in Bangladesh are thought to be caused by bacteria contained in marine cyanobacteria that washed in during the moonsons and contaminated local water supplies (Ezzell, 1999).

Our hypothesis is that cyanobacteria, and/or algae such as dinoflagellates found in the rivers and streams, release toxins at certain times of the year, probably after blooms and die-off during dry periods, into the fresh water. Humans in the southern part of Guam use streams for drinking water. In the past, this water would not have been treated, and the toxins, if present, would be available to humans. It would be the ingestion of the toxins (and/or bacteria or virus associated with cyanobacteria), particularly over a long period of time, which would be responsible for the diseases. Repavich and others (1990) show evidence of long-term chronic human health hazards caused by toxins of cyanobacteria through drinking water. Garruto and others (1985) reported over the last 20 years, a decrease in the diseases and suggested that the reason was change in diet to more imported foodstuffs and the adoption of a more westernized diet. Our interpretation would be that in recent times, the water is treated, particularly filtering through activated carbon, which would remove the toxins and would account for the decrease in incidence of diseases today.

If this hypothesis is correct and the diseases are related to the release of toxins (or bacteria or virus associated with algae) into the water used for drinking or bathing, the reason that the disease rate is higher in the southern part of the island, underlain by volcanic rock, is the presence of rivers and streams and indirectly rock type. Guam can be divided broadly into two land surfaces: the southern portion of hilly to mountainous terrain of dissected volcanic uplands with rivers and streams and a northern portion of uplifted limestone with cliffs tilted gently to the southwest. The southern portion contains a dendritic pattern of streams, while the northern portion contains sinkholes with no permanent streams (fig. 9).   The geochemical composition of rocks and the derived soils is not directly related to the occurrence of the diseases, but the rock composition influences weathering and formation of drainage patterns of streams and rivers.

As to the question of why the high rates of the diseases do not occur on other islands such as Saipan, the answer may be that the rivers are not slow enough or big enough to support algae or cyanobacteria; or that local water sources were mainly groundwater from sinkholes or from springs mostly out of contact of direct sunlight. Another possibility is that the specie or species responsible for the toxin (and/or bacteria or virus) require certain environmental conditions such as size of stream, dry periods, flow rate, or intensity of sunlight.

Two additional areas with a high occurrence of neurodegenerative diseases occur on the Kii Peninsula, Japan (Kimura and others, 1961 and Shirake and Yase, 1975) and the southern lowlands of Irian Jaya, New Guinea (Gajdusek, 1963 and Gajdusek, 1982). The cause of the diseases may be similar to that in Guam. The geology of these two areas and Guam is dissimilar. Southern Guam is underlain by Tertiary volcanic rocks, the area in Japan by Cretaceous marine accretionary rocks (Hirokawa, 1978), and the area in Irian Jaya by Quaternary alluvium, thinly overlying Tertiary and Quaternary sedimentary rocks (Dow and others, 1986). In Japan, villages are located near the mouths of rivers. In New Guinea, villages occur along slow moving rivers. The occurrence of algae or cyanobacteria with associated toxins (and/or bacteria or virus) may be present, similar to Guam. If so, species of algae or cyanobacteria responsible for the disease may exist in this part of the Pacific. Guam is located approximately 2200 miles from each of the two areas. The three areas contain indigenous people that have existed there for long periods of time. These indigenous people in the past (and perhaps presently) would have obtained untreated water from local streams.

Future Considerations for Testing the Hypothesis

- Search for algae or cyanobacteria species with associated toxins
- Search for possible related bacteria and virus
- Examination of possible pathways of toxins from water or biota consumed by humans
- Examination of historic water supplies
- Examination of breathing aerosols containing toxins from cyanobacteria or algae

Most importantly, even before these studies are carried out, an educational program should be carried out to make the local inhabitants aware of the possible hazards of untreated water from streams and rivers, particularly the southern villages of Umatac, Merizo, Inarajan, and other villages in the southern portion of Guam (as well as the two areas in Japan and Irian Jaya). In addition, inhabitants should avoid direct contact of stream water with skin and the consumption of stream biota particularly during and after algal blooms.

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