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Weathering and Soil Genesis from the Nasinu Basalt, South-East Viti Levu, Fiji

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Abstract

Detailed studies of basalt weathering in the South Pacific Islands are relatively rare. In order to address this gap, this study investigated weathering changes and soil formation for the predominantly fine-grained feldspar-phyric basalt flows (6.4 Ma) in the Nasinu area, about 10 km north-north-east of Suva, Fiji. In the hot humid environment locally, these rocks have been subjected to rapid and deep weathering. Three weathering profiles (Nasinu S1, S2 and S3 at approximately 60 m elevation) show features of strong kaolinitisation. Aluminium and iron enrichment in the horizons of the Nasinu weathering profiles is marked, with the presence of kaolinite, gibbsite, goethite, haematite and magnetite (grains) confirming substantial mineralogical change. Suggested mechanisms for these changes are presented. Using Soil Taxonomy, the Nasinu soil pedon (JBS-1) developed on the weathered basalt is a Typic Palehumult, very fine, mixed, isohyperthermic. A comparison is made with the weathering pattern of the Nakobalevu basalt located only about 25 km from this location.
Keywords: *Basalt weathering; Soil genesis; Fiji*

1. Introduction

In humid tropical areas, rapid weathering of exposed rocks is promoted and accelerated by high temperature and rainfall conditions. This often leads to deeply weathered profiles and extensive sediment and nutrient loss (Joyce, 1987; Meybeck, 1979; Milliman, 1990; Palmer *et al.*, 2009; Rad *et al.*, 2006; Stallard, 1988). Weathering rates have been shown to be substantially influenced by the presence of water (Porder *et al.*, 2007) and by temperature (Rasmusson *et al.*, 2010). Accurate assessment of rates of weathering and soil formation is a key current research area in geomorphology (Brantley and Lebedeva, 2011; Dosetto *et al.*, 2012).

Tertiary basalt flows cover >35% of the Fiji group, and more than 75% of the derived soils are used for intensive and subsistence agriculture (Bonato, 1997). The weathering conditions support rapid change and such situations lead to problems of soil use and management for agriculture (Liedtke, 1989). Some research has been completed on the weathering of basalts in Fiji (Bonato and Morrison, 2012; Morrison *et al.*, 1986, 1987; Naidu *et al.*, 1987), but few studies have looked comprehensively at the parent material chemistry, mineral transformations during weathering, and the resulting soil chemistry. There has also been ongoing interest in 'laterisation' (Brandes and Nakayama, 2010; Ollier, 1994; Schellmann, 1981), as this has been observed frequently in parts of the Fiji Archipelago, particularly associated with pedological studies, and the bauxite and manganese mining operations of the 1940s and 1950s (Colley, 1976; Morrison *et al.*, 1987; Twyford and Wright, 1965). This study was initiated to examine the weathering products of the Nasinu Basalt, a relatively extensive area of basalt flows in south-east Viti Levu, the main island of the Fiji group to see if laterisation is occurring. The study also aimed to identify the type of soil formed from this parent material and evaluate its agricultural potential.

2. Materials and Methods

2.1. Geomorphology of the Nasinu Study Area

The major outcrop of the Nasinu Basalt occurs approximately 12 km north-east from the city of Suva, 1.5 km to the west of the shoreline of Laucala Bay, in a midsection of the Suva Peninsula; the urban area surrounding the basalt is the densely-populated satellite town of Nasinu. The flow under study has a probable outcrop area of 0.9 km^2, and has been subjected to severe and deep weathering (Bonato, 1997). The regolith now features a south-east convex slope of approximately 10 - 15 degrees, with a maximum height of 100 m. The sample sites at the Nasinu location, however, were within the immediate area of the Standard Concrete Industries Limited (SCIL) quarry site (the quarry ceased blasting operations in 2008), at an altitude of 60 m above mean sea level. Mean annual temperature of the Nasinu/Suva area is 26^{o}C, with an average annual precipitation of 3,500 mm and a weak dry season from July to October (Bonato, 1997).

The Laqere River, close to the study site, drains run-off from the slopes, and the basalt outcrops (boulders) are visible at the river's eastern end; there is no other surface drainage pattern. The sites and profiles are well-drained. Original rainforest is presumed to have existed up to the late 1800s; now the vegetation cover consists of thick grass, *Sporabolis sp.*, *Lantana camara*, *Psidium guajava* and *Artocarpus altilis* (breadfruit).

2.2. Geology of Fiji and of the Nasinu Area

Rodda and Kroenke (1984) have summarised the plate-tectonic setting and geological history of the south-west Pacific. The geology and stratigraphy of Fiji have previously been well described (Colley and Flint, 1995; Hathway and Colley, 1994; Rodda, 1967, 1994). The basalts of Fiji range chronologically from the Late Eocene pillow lavas and flows of the Yavuna Group (approximately 38 Ma) to the most recent basalt flows and scorias of Taveuni (~700 years B.P.). Following the close of the Colo Orogeny (7 Ma B.P., Rodda and Lum, 1990), there was a period of widespread and voluminous volcanism reaching into 2.5 Ma. Rodda and Lum (1990) noted that it was subsequent to the Colo Orogeny that the first substantial landmass was established in Fiji.

The Nasinu Basalt comprises flows of predominantly fine-grained feldspar-phyric basalt containing olivine phenocrysts (and minor augite) with isolated beds and pockets of volcanic conglomerate or agglomerate; the Nasinu Basalt is now assigned to the Medrausucu Group of rocks at approximately 6.4 Ma. (Rodda, 1995, pers. comm.). The basalt is highly vesicular with amygdales of zeolite/calcite/chlorite and chalcedony, and has been clearly subjected to rapid weathering and alteration even deep within the flow. Gill (1970) provides the following modal analysis of the primary mineralogy: labradorite (80%), olivine (10%), clinopyroxene (approximately 5-8%), and opaques (approximately 1-2%) in interstices. The most extensive outcrop of basalt occurs at the location of the site of the Standard Concrete Industries Limited hard rock quarry, some 10 km north-north-east of the city of Suva (at 18°05'00"S, 178°29'55"E) Map 028/ 730 803 Grid Reference (Fiji Lands Department, 1990); smaller outcrops of the Nasinu Basalt have been described from the Colo-i-Suva area, but geological boundaries have not as yet been accurately defined.

The stratigraphic relationships between the Nasinu Basalt and adjacent rocks include: the basalt has a near contact with the andesitic breccias of the Vango Volcanics on the north and north-western boundaries - both andesite and basalt probably result from submarine fissure eruptions that occurred at different times, (andesitic lapilli and bombs are chilled within the Vango Volcanics, and regarded as part of it), (Rodda, 1995, pers. comm.). Near the quarry site itself, the Suva Marl overlies the basalt - these calcareous mudstones were most probably deposited in water at more than 500 m depth from 5.2 - 3.2 Ma (with sedimentation ceasing apparently due to a combination of tectonic uplift and the mid-Pliocene fall in sea level), (Nunn, 1994; Rodda, 1994). Drilling to the east of the quarry site penetrated 6 m of bedded sandstone at 46 m, between homogeneous and fragmental basalts (Standard Concrete Industries Ltd., pers. comm.). The Nasinu Basalt shows a general dip of about seven degrees towards the east-southeast.

The basaltic flows and basaltic agglomerates are irregularly layered. Within the working quarry the homogeneous black basalt units appear to make up about 35% of the rocks of the northern section, a dark-to-light grey homogeneous basalt constitutes about 20%, with the remainder comprising reddish-brown fragmental flow material showing clear evidence of chloritisation (Bonato, 1997).

2.3. Sample Collection

Approximately 1 kg bulk sample quantities of soil/saprolite/regolith/parent rock were removed from each of the three selected sites at Nasinu (S1, S2 and S3, all located within 500 m of each other at the Standard Concrete Industries Limited hard rock quarry). The S1, S2 and S3 sample sites were selected on the basis of being least-disturbed sites, and since the flow caps the study site, it was judged that sampling should be undertaken by the creation of a profile through excavation, and sample-batches of regolith and weathered material removed representatively at one metre intervals.

Samples from the weathering profile were secured by excavation and manual digging; two metre-wide pits exposing the deeply-weathered profiles were excavated until the parent rock-saprolite interface was reached. Representative sampling was carried out at one metre intervals longitudinally across the profile. At S1, an excavation of 7 m was required to reach hard base rock, while at S2 and S3, the fresh augite - olivine basalt rock was reached at 4 and 3 m depth respectively; in all profiles the parent rock-saprolite boundary was distinct. Four 1 kg samples of weathered material were removed each of the measured one metre-intervals of the profile. Specific sampling was also made of the horizon sections which featured pallid zoning, mottling, and crustal formation. On removal from the profile, samples of soil and regolith were doubly-wrapped in polythene bags and placed in cool storage to maintain field moisture levels. Prior to fine (< 2 µm) and very fine (<1 µm) particles extraction (clays), and larger (0.002-2 mm) particle size separation (sand and silt), the representative samples from each metre section were subsampled using coning and quartering, and were disaggregated manually under water and mixed thoroughly.

2.4. Sample Preparation for Instrumental Analysis

Details of the procedures used are given in Bonato (1997) and Bonato and Morrison (2012). In summary, clay, silt, and sand fractions were separated by sieving (2, 0.05, 0.02 mm) and sedimentation, and treated with hydrogen peroxide and dithionite-citrate-bicarbonate (DCB) to isolate the aluminosilicate clays. Thin-sections (without coverslip) of parent rock samples from all the sites and profiles were prepared for optical examination and microprobe analysis. Total element analyses were assessed using X-ray fluorescence (XRF). Clay minerals were first identified using X-ray diffraction (XRD) and confirmations were obtained by infrared spectrophotometry. Halloysite confirmation was attempted via XRD using a paste (not allowed to dry out after collection in the field), followed by drying at 105°C for 5 min which caused collapse of the c-spacing from 10.4 to 7.4 Å, but no halloysite was found. Scanning electron microscopy (SEM) analyses confirmed visually some of the clay and gibbsite morphologies.

2.5. Mineralogy

Mineralogical analyses were completed using optical microscopy methods for the study of thin sections of the sand and silt fractions (or ion-electron microprobe analysis), with XRD, IR spectroscopy and SEM used for the clay fractions. In the Nasinu S1, S2 and S3 profiles, the sand and silt fractions, as seen in thin section, were consistently formed of augite, magnetite, some minor plagioclase, minor olivine in the lower horizons of the profile. These mineralogies were confirmed by the XRD of the sand-size crustal material, and of powdered whole-samples.

2.6. Soil Classification

For the soil profile description (see Appendix) and analyses, a 2 m × 2 m × 2 m pit was dug at site S1, and the soil profile described according to Taylor and Pohlen (1979), except that the term nut structure was replaced with sub-angular blocky. The horizon designations are according to the FAO-UNESCO legend (1974). Samples were collected and analysed at the University of the South Pacific Institute of Applied Sciences according to the methods of Blakemore *et al.* (1987) and the Soil Conservation Service of the United States Department of Agriculture (SCS-USDA, 1984). The JBS-1 pedon was classified according to Soil Taxonomy (Soil Survey Staff, 1975, 1999, 2014).

3. Results and Discussion

3.1. Total Elemental Analysis and Elemental Mobilities

Data on the total elemental analyses of fresh samples of Nasinu Basalts, of some of the weathered crust, and of materials along the length of the weathering profile at approximately one-metre depth intervals, are presented in Tables 1-4. Elemental analysis data of the extracted clay-sized fraction to assist in confirming the mineralogical interpretations are given in Table 5.

The total elemental analysis data indicate the elemental percentage changes from fresh unaltered basalt to the corresponding weathered profiles. The Nasinu Basalt data (Table 1) lie within the accepted norm (Middlemore, 1985) for the chemical definition of basaltic rocks: silica 45-50%, alumina about 18%, iron oxyhydroxides at approximately 10-11%, and titanium approximately 1%; the alkali oxides are indicative of the olivine and augitic mineralogies.

Tables 2, 3 and 4 place the elemental analyses of the basalt rock samples in the context of the weathering profiles, and indicate the elemental mobilities of the major elements in the Nasinu profiles. The weathering profiles overlying the hardrock base indicate that the Na_2O and K_2O are depleted most rapidly; sodium is $\geq$ 90% depleted within 1 m of the base rock (and at all levels above that), and potassium occurs at about 10-20% of the original value in the upper horizons. CaO is very quickly depleted and MgO is also removed relatively quickly to about <20% of the original content. Phosphorus is quickly depleted to about 15-30% of the original values, but for MnO there is minimal evidence of depletion - values show variations indicating some accumulation during the weathering process, especially in the middle of each profile. This may be related to the frequent observation that this element is often incorporated into secondary minerals in the weathering profile (Ollier, 1959).

Titanium shows an initial increase in S2 and S3, but otherwise some variability is indicated throughout the profiles; Ti^{4+} is known to migrate within the weathering profile producing some local areas of enrichment and others of depletion; titanium is often lost from titano-magnetite and ilmenite low in the profile, and redeposited as anatase in the saprolite (Sherman, 1952). Iron shows enrichment towards the top of the profiles, e.g., ranging from approximately 10.5% Fe_2O_3 to about 18% at the S1 site. Al_2O_3 values are also enriched with decreasing depth, but the degree of enrichment in all 3 Nasinu profiles is significantly less than in the laterite development in the Nakobalevu basalt about 25 km away (Bonato and Morrison, 2012). Silica (SiO_2)

decreases markedly (~30% loss), similar to other tropical basalt weathering sequences (Herbillon and Nahon, 1988; Ollier, 1984). One possible explanation of this difference is the increased kaolinitisation at Nasinu, compared with laterisation at Nakobalevu.

Table 1. Total elemental analysis data (%) for fresh Nasinu basalt samples.

Component	S1	S2A	S2B	S3A	S3B	S3C
SiO_2	48.58	49.26	46.08	49.39	47.80	49.17
TiO_2	1.08	1.06	0.99	1.05	1.05	1.21
Al_2O_3	18.58	18.46	17.72	18.77	18.46	21.14
Fe_2O_3	10.54	10.50	10.83	10.67	11.01	9.99
MnO	0.18	0.17	0.23	0.18	0.20	0.09
MgO	4.67	5.28	6.68	5.26	5.39	2.69
CaO	10.33	10.51	6.96	10.37	8.04	9.65
Na_2O	2.95	2.78	3.90	2.89	2.33	3.10
K_2O	0.94	0.89	1.05	0.92	1.79	1.14
P_2O_5	0.28	0.27	0.27	0.28	0.27	0.34
LOI	0.72	0.88	5.65	0.23	3.54	1.06
Total	99.02	100.21	100.50	100.17	100.04	100.13

S1 = Site 1, S2 = Site 2 (3 profiles A, B, C), S3 = Site 3

Table 2. Total elemental analysis data (%) of materials extracted from Nasinu site S1.

Component	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Olivine basalt	48.58	1.08	18.58	10.54	0.18	4.67	10.33	2.95	0.94	0.28	0.72	99.02
7 metres	39.20	0.95	28.16	15.75	0.68	0.99	0.03	0.14	0.09	0.03	14.88	101.15
6 metres	35.72	1.21	28.82	19.84	0.15	0.82	0.01	0.13	0.06	0.07	13.38	100.5
5 metres	37.93	1.05	28.84	17.64	0.20	0.98	0.03	0.13	0.11	0.06	13.73	100.95
4 metres	36.73	0.99	30.04	16.71	1.07	1.07	0.05	0.14	0.11	0.09	13.98	101.23
3 metres	35.32	1.03	28.88	17.74	1.10	0.90	0.03	0.13	0.10	0.04	13.75	99.29
2 metres	34.35	1.19	29.80	19.05	0.41	0.67	0.01	0.09	0.06	0.06	15.19	100.14
1.0 metres	32.65	1.12	31.59	18.81	0.21	0.71	0.03	0.10	0.09	0.04	15.16	100.74
weathered saprolite from Nasini Profile 1	40.51	1.07	27.27	17.57	0.22	1.28	0.04	0.13	0.12	0.06	12.43	100.9

As weathering begins, processes cause only the removal of certain elements from the rock and their replacement by water - the primary rock configuration is most often preserved (Ollier, 1984). The least soluble elements are re-incorporated in certain minerals higher in the profile (nearer to the surface) and this increases their weight percentages, in some instances far beyond their initial values (the Al_2O_3 and Fe_2O_3 enrichments in the S1, S2 and S3 weathering profiles are shown in Tables 2, 3 and 4 respectively).

The clay samples analyses (Table 5) show a dominance of SiO_2, Al_2O_3 and Fe_2O_3, with an almost complete removal of Na, K and Ca; this is particularly evident for profiles S1 and S3; S2 shows that in the lowest horizon, some change has already occurred with lower SiO_2 and higher Al_2O_3 and Fe_2O_3. MgO, CaO, K_2O and Na_2O, concentrations decrease from the hard rock clay fraction to the weathered material clays. These results are generally in line with basalt weathering patterns found elsewhere in high rainfall environments; for example, Schellmann (1981) found similar decreases in the basic oxide components in laterite development in a number of tropical countries.

The particle size distribution data (Table 6) show another difference between the 3 profiles. The S2 and S3 samples show a general increase in clay and decrease in sand content on moving upwards, while the S1 samples show no major patterns. There is no obvious explanation for these differences. These results support the premise that the Nasinu weathering profiles have undergone several cycles of erosion and weathering; elements have been released from mineral fabrics to be redistributed and reprecipitated as new minerals within each cycle, resulting in a more constant elemental composition pattern, most probably under differing climatic conditions (Ollier, 1959).

Table 3. Total elemental analysis data (%) of materials extracted from Nasinu site S2.

Component	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Olivine basalt	49.17	1.21	21.14	9.99	0.09	2.69	9.65	3.10	1.14	0.34	1.06	100.13
4 metres	40.96	1.75	30.71	11.99	0.37	0.98	0.31	0.31	0.25	0.19	12.46	100.51
3 metres	37.50	1.72	30.89	14.05	1.36	0.96	0.16	0.22	0.04	0.23	13.66	101.13
2 metres	35.98	1.15	30.97	17.09	0.08	0.58	0.07	0.11	0.02	0.07	14.14	100.52
1 metre	30.72	1.82	31.22	20.32	0.18	0.54	0.26	0.14	0.02	0.10	15.31	100.83

Table 4. Total elemental analysis data (%) of materials extracted from Nasinu site S3.

Component	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Olivine basalt	49.39	1.05	18.77	10.67	0.18	5.26	10.37	2.89	0.92	0.28	0.23	100.17
3 metres	41.40	1.52	26.95	16.42	0.30	1.59	0.30	0.19	0.13	0.19	11.21	101.09
2 metres	41.11	1.59	27.47	16.72	0.23	2.10	0.46	0.11	0.11	0.08	10.48	100.65
1 metre (from top of profile)	37.05	1.72	29.34	18.96	0.15	0.89	0.04	0.12	0.04	0.04	12.37	100.92
0.5metres (from surface)	32.65	1.12	31.59	18.81	0.21	0.72	0.04	0.13	0.12	0.05	12.72	101.30

3.2. Mineralogy

Clay fractions separated from the crushed fresh hardrock showed the presence of chlorite, kaolinite, goethite, haematite and gibbsite in the Nasinu Basalt. The mineralogy of the clay fractions from the S1, S2 and S3 sites consistently showed abundant kaolinite, with moderately strong peaks indicating goethite and some haematite; gibbsite intensities were low; in the Nakobalevu profiles, gibbsite was also low in the clay size fraction, but it was highly concentrated in coarser materials, especially lateritic gravels (Bonato and

Morrison, 2012). Such gravels are not found in the Nasinu sites, showing a distinct difference between the weathering outcomes at the two sites. The mineralogy of the weathering profile shows a qualitative consistency: kaolinite as the predominant fine clay, with strong goethite peaks and some haematite and gibbsite. Peak intensities indicate limited changes in mineral abundances throughout the profile. The almost complete absence of primary minerals in much of the profile (minor plagioclase and magnetite were present) resulted in a sharp mineralogical boundary between the fresh Nasinu Basalt base and the overlying saprolite. Similar patterns have been observed in China (Lu *et al.*, 2008) and in Hawaii (Ziegler *et al.,* 2005).

Table 5. Elemental analysis data (%) for extracted clay fraction materials from the Nasinu Sites.

S1	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total
Clay from hard rock	49.80	0.17	23.07	2.43	0.13	9.41	2.43	0.69	1.13	0.24	10.32	99.96
Depth 7 metres	40.26	0.65	28.59	12.85	0.36	3.00	0.03	0.12	0.12	0.03	13.95	100.19
6 metres	35.16	0.85	28.28	17.18	0.10	2.90	0.03	0.08	0.06	0.05	14.26	99.16
5 metres	37.86	1.12	28.15	15.86	0.19	2.26	0.02	0.08	0.14	0.05	14.30	100.22
4 metres	37.03	1.02	27.90	15.25	0.13	2.32	0.01	0.07	0.12	0.07	14.33	99.45
3 metres	35.56	0.63	29.16	15.37	0.20	3.47	0.02	0.04	0.07	0.06	14.86	99.62
2 metres	35.62	0.74	28.24	15.74	0.20	2.94	0.02	0.02	0.07	0.05	14.53	99.43
1 metre	36.38	1.21	28.80	15.91	0.05	1.45	0.03	0.09	0.10	0.07	14.62	99.10
S2												
Depth 3-4 metres	36.53	1.71	30.58	12.19	1.28	2.19	0.10	0.31	0.05	0.31	14.70	100.28
2 metres	33.46	1.61	29.86	14.84	0.19	1.96	0.13	0.28	0.11	0.19	14.86	98.49
1 metre	30.76	1.32	30.24	18.71	0.16	1.83	0.09	0.11	0.03	0.13	16.40	100.00
S3												
Clay from hard rock	48.26	0.18	24.67	2.51	0.13	9.46	2.43	0.74	1.15	0.28	11.69	99.21
Depth 3-4 metres	42.34	0.62	27.89	11.61	0.18	2.49	0.12	0.22	0.08	0.33	13.16	99.97
2 metres	40.62	1.40	28.02	13.44	0.18	2.82	0.15	0.10	0.11	0.19	12.41	99.68
1 metre	33.62	1.93	27.86	19.70	0.22	2.37	0.02	0.08	0.06	0.08	13.63	99.77

Table 6. Particle size distribution data (fine-earth, mm%) for the Nasinu weathering profiles.

Horiz.	Depth (m).	Sand (2-0.05)	Silt (0.05-0.002)	Clay <0.002	Sand Fractions 2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	2-0.1	Int. c. sa 2-0.2	Int f. sa. 0.2-0.02	Int. Silt 0.02-0.002	Clay <0.002	Fine clay <0.0002	Fine / Total clay
S1-1*	1.0	21	31	48	0	3	4	4	6	15	13	2	27	48	43	0.90
S1-2	2.0	16	57	27	0	3	4	4	5	11	8	2	63	27	25	0.92
S1-3	3.0	13	46	41	0	3	3	3	4	9	7	19	33	41	37	0.90
S1-4	4.0	14	36	50	0	2	7	1	4	10	10	23	17	50	47	0.94
S1-5	5.0	21	32	47	1	6	7	4	3	18	16	14	23	47	43	0.91
S1-6	6.0	16	50	34	0	3	7	4	2	14	11	18	37	34	29	0.85
S1-7	7.0	17	44	39	0	4	10	2	1	16	15	12	34	39	35	0.90
S2-1	1.0	34	16	50	5	11	7	8	3	31	27	11	12	50	45	0.90
S2-2	2.0	44	21	35	5	11	14	8	6	38	32	18	15	35	33	0.94
S2-3	3.0	66	12	22	62	18	14	13	9	57	41	21	16	22	17	0.77
S3-1	1.0	9	45	46	0	2	3	2	2	7	5	18	31	46	43	0.93
S3-2	3.0	35	39	26	0	2	8	15	10	25	15	32	27	26	20	0.77
S3-3	6.0	57	28	15	8	18	13	10	8	49	45	21	19	15	11	0.73

*S1-1 = Site 1, 1 metre depth

Unlike the Nakobalevu site, some 25 km west of Nasinu, there is no particular evidence of laterisation at Nasinu. While XRD indicates some presence of gibbsite in the Nasinu profiles, the concentrations were minimal. Thin section study revealed minimal parent rock primary minerals in much of the three profiles. Haematite peaks were expressed moderately strongly in some horizons, but less so in others. The predominant mineral at Nasinu was clearly kaolinite, not only in the clay fraction, but there is also some evidence that some of the sand and silt fractions are hardened kaolinite aggregates not adequately dispersed by the techniques used. This has also been observed in other kaolinite dominated soils in Fiji (Morrison, 1998; Willatt *et al.*, 1995), and in Guam (Young, 1988). Although thin section study did indicate the presence of opaques, and some olivine in the lowest horizons of the S1 and S2 sites, the amounts were minimal and they did not appear in the XRD outputs of the whole fraction samples. The Nasinu profiles were in general of a uniform mineralogical composition, and the elemental data has indicated several cycles of weathering and soil formation; the colours of the profiles are more consistently uniform than found at Nakobalevu (Bonato and Morrison, 2012), and the distinction between pallid and mottled zonation is not clearly evident. The Nasinu profiles therefore belong to the *kaolinitised lateritic profile* or to the *weak laterisation* as described by Schellman (1981) and Herbillion and Nahon (1988) in their discussion of the limits of kaolinitisation and laterisation fields for the case of basaltic weathering. In such processes, the whole Al_2O_3 content of the original unweathered rock (or most of it) is retained and transformed into kaolinite.

Table 7. Mineralogy of powdered whole samples of Nasinu weathered materials.

	Depth (m)	Kaol	Gibb	Goeth	Mgt	Haem	Chlor	Other*
S1	7	X	XX	XX	X	XXX	X	X
	6	XX	X	XX		XXX		X
	5	XXX	X	XX		X		X
	4	XXX	X	XX		X		X
	3	XXX	X	XX		X		X
	2	XXX	X	XX		XXX		X
	1	XXX	X	XX		X		X
S2								
	3	XXX	X	X		XX		X
	2	XXX	X	XX		XXX		X
	1	XX	X	XX		XX		X
S3								
	3	XX	X	XX	X	XX		X
	2	XX	X	XX	X	XX		X
	1	XX	X	XX	X	XX		X

NB: Fresh Rock Mineralogy: augite (5-10%), plagioclase (labradorite)(50-70%), olivine (5-15%), magnetite (~5%), goethite (trace), kaolinite (trace)
* In each of the metre horizons: minor plagioclase (and magnetite grains)
Abundance Ranges: XXX (20-30%); XX (5-20%), X (trace)
Kaol = Kaolinite; Gibb = Gibbsite; Goeth = Goethite; Mgt = Magnetite; Haem =Haematite; Chlor = Chlorite

While the Nasinu and Nakobalevu sites show similarities in evidence of rapid weathering of basalts, probably involving several cycles of weathering and erosion, the profiles produced show distinct differences. The major differentiating feature is the accumulation at Nakobalevu of gibbsitic gravels and more extensive evidence of laterisation. As the basalts are of relatively similar composition and age, and they occur in relatively similar climatic zones, no specific explanation is forthcoming for the differences in weathering outcomes other than elevation. This may have led to earlier exposure of the Nakobalevu materials and thus a longer period of subaerial weathering. It is possible that, over time, greater laterisation may occur at Nasinu, but the current quarrying is likely to restrict any long-term further studies. The slope position may also have provided an opportunity for greater removal of SiO_2 at Nakobalevu, allowing Al_2O_3 to accumulate at the expense of kaolinite (or some kaolinite may have been desilicified).

3.3. Soil Genesis

South Pacific island soils derived from basalt have been widely investigated in several countries including Samoa (Asghar *et al.*, 1988; Morrison, 1991; Schroth, 1970; Wright, 1963), the Cook Islands (Lee *et al.*, 1979; Widdowson and Blakemore, 1977), Vanuatu (Quantin, 1978) and Fiji (Latham, 1979; Naidu *et al.*, 1987). Soils vary from older, strongly weathered low pH and low base saturation Ultisols to relatively young soils having high base saturation and intermediate pH (i.e., 5.7-6.5). The prevailing hot, very wet local environment leads to rapid weathering and leaching of parent rock materials; 'rejuvenation' of such soils where recent volcanic ash is an addition, becomes an important soil-forming factor (Morrison, 1991; Naidu *et al.,* 1987).

Full site and profile descriptions for the Nasinu Pedon JBS-1 are given in the Appendix. Laboratory data are presented in Table 8. The Pedon JBS-1, formed over the fine-grained olivine basalt at Nasinu showed features (argillic horizon) typical of the Ultisol Order in Soil Taxonomy (Soil Survey Staff, 1975, 1999). In the 1975 Soil Taxonomy, the Nasinu pedon, JBS-1, has an ochric epipedon (lacks dark colours and is relatively low in bases) overlying an argillic horizon of low base status; therefore it is classed as an *Ultisol.* The upper part of the profile indicates high organic carbon content, and thus the soil is classified in the *Humults* suborder. The clay content at depth remains high; confirmed by water retention against 1500 kPa suction (Gangaiya *et al.*, 1982) indicating palaeo-features, and the absence of weatherable minerals in the upper section of the profile is a further confirming factor. The subgroup classification is *Typic Palehumult,* and the family classes are *very fine, mixed, isohyperthermic* (Soil Survey Staff, 1975). In the 1999 Soil Taxonomy (Soil Survey Staff, 1999), there is a similar classification (assuming the clay content at depth as determined from the 1500 kPa water retention data).

The most recent update of Soil Taxonomy (Soil Survey Staff, 2014) gives a similar classification assuming that at depth the clay content is indicated by the minimal change in 1500 kPa water retention. This *Typic Palehumult, very fine, mixed, isohyperthermic* classification gives a clear indication of the properties of the JBS-1 soil, indicating no unusual features and the likely response of the soil to management. The soil has good moisture retention features for crop growth, is likely to respond to liming especially if limed below 15 cm; a good response to fertiliser use is expected with the relatively high P retention values (Asghar *et al.*, 1988). The soil structure indicates that maintaining the A horizon would be important, as loss of this layer would expose the weakly structured B horizon that would be prone to erosion.

Table 8. Laboratory data for soil profile JBS-1.

Pedon	No.	JBS-1		Soil	Series	Unnamed		
Location:	Nasinu,	SE Viti Levu, Fiji						
Lab Nos:	INR	8701/	01-05	Classification	Typic mixed,	Palehumult isohyperthermic	fine,	

Depth (cm)	Horizon	Perticle Size Information and Diameter (mm)				
		Sand%	Silt	Clay	Coarse	Fragments
		(2-0.05)		(<0.002)		(> 2 mm)
0-14 cm	A	17	19	64		0
14-46	Bt	0	23	77		2
46-78	Bt	8	25	68		2
78-144	BC	7	19	74		1
144-210	C	17	25	58		3

Depth (cm)	pH (H_2O)	pH(KCl)	Organic C%	P retention (%)
0-14 cm	5.60	4.10	4.42	79
14-46	4.90	3.50	1.78	84
46-78	4.70	3.40	0.40	88
78-144	4.40	3.40	0.30	89
144-210	4.20	3.50	0.18	91

Depth (cm)	Ion Exchange							
		Exchang. Bases (cmol/kg)						
	Ca	Mg	K	Na	TEB	CEC (pH7)	KCl H	Extr. Al
0-14 cm	5.40	2.96	0.29	0.31	9.96	24.28	0/11	0
14-46	1.73	1.05	0.11	0.41	3.30	26.10	0.13	6.23
46-78	0.47	0.69	0.11	0.31	1.58	26.02	0.21	10.80
78-144	0.31	0.82	0.17	0.28	1.58	24.12	0.15	10.36
144-210	0.32	0.85	0.18	0.29	1.64	26.49	0.11	12.25

Depth (cm)	BS%	BS%	CEC	Exch. Acidity	Acid Oxalate	
	Sum	NH_4OAc	pH 8.2	pH 8.2	Al	%Fe
0-14 cm	22	37	41.96	32.00	0.47	0.69
14-46	9	13	35.21	31.91	0.52	0.36
46-78	5	6	33.11	31.53	0.48	0.12
78-144	4	7	36.01	34.43	0.50	0.27
144-210	3	6	34,52	35.68	0.49	0.19

	Bulk	1500	KPa	1500 kPa	CDB Extr.	(%)
	Density Mg/m^3	Water moist %	Retention air-dry %	water/clay ratio	Al	Fe
0-14 cm	0.78	36.0	28.4	0.44	1.22	6.38
14-46	0.89	45.3	32.6	0.42	1.24	6.57
46-78	0.89	47.0	31.9	0.48	1.00	6.07
78-144	0.94	47.4	30.4	0.41	0.91	6.28
144-210	0.96	47.3	30.6	0.53	1.04	6.46

4. Conclusion

Within the geological setting of Viti Levu (Fiji), stratigraphy, and tectonic history, the site geology and geomorphology of a weathering profile above Tertiary basaltic rocks close to the Suva Peninsula, has been described. The Nasinu Basalt boundaries are still undefined, and more work is required to define its precise contact with the younger Suva Marl and agglomerates. Elemental and mineralogical data for three weathering profile sites Nasinu, establish major differences between the weathering at this site relative to that at Nakobalevu about 25 km to the west. At Nasinu, the patterns indicate kaolinitisation with only modest laterisation, at the three sites. There is evidence at Nasinu of a multi-cycle pattern of erosion and weathering. The Nasinu Pedon (JBS-1) is a clay-rich Ultisol, with abundant iron oxyhydroxides, with moderate soil-fertility status.

Further studies are required to more accurately define the extent of the outcrop boundaries of the Nasinu Basalts, with subsequent updating of Suva area geological maps. Minimal accurate data exists on weathering solutions, and the chemistry of percolating water remains little known in spite of its important role in the generation of weathering products.

Solution equilibria studies would highlight the importance of drainage conditions, weathering solution composition, pH value, and pO_2 value, in the control of weathering and the sequence of secondary minerals in the weathering profile. Future pedological studies on soils that have developed from basalt in other localities in Fiji (for example, Vanua Levu, Taveuni) would provide a better understanding of the impact of specific factors on mineralogical changes, and associated soil fertility status.

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Appendix 1: Site and Profile descriptions for JBS-1

Classification:	Typic Palehumult, fine, mixed, isohyperthermic.
Location:	Within quarry area of Standard Concrete Industries, Nasinu 8 miles; SE Viti Levu, Fiji. Turn left into Tovata Road; just past SCI quarry and then into the quarry area 500 m from Kings Road/Tovata Road junction.
Physiography:	Lower third SE facing 10-15^{o} convex slope; smooth, slightly convex slope; altitude ~60 m above a.m.s.l.
Topography:	Site on 7^{o} SE facing slope.
Drainage:	Site and profile well drained.
Vegetation:	Original rainforest existed in area approximately 50 years ago; now *Psidium guava*, *Artocarpus altilis* (breadfruit), *Sporabolis* sp. (grass), *Lantana camara*, *Clidemia hirta*; thick ground cover.
Parent Material:	Basalt rock classified as Nasinu basalt, an early Miocene flow.
Climate:	Average annual temperature 26^{o}C; rainfall approx. 3500 mm annually with weak dry season July-October.

Appendix 2: Profile description

Ap 0-14 cm:	slightly moist; dark reddish brown (5 YR 3/4) slightly gritty clay; strongly developed medium to fine subangular blocky and granular structure; friable; slightly sticky; slightly plastic; abundant fine and very fine roots; a few coarse roots; distinct smooth boundary.
Bt 14-78:	moist; dark red to red (2.5 YR 3/6 to 4/6) clay; weakly developed coarse subangular blocky structure breaking to moderately to strongly developed medium and fine subangular blocky and granular; firm to friable; slightly sticky; slightly plastic; common fine roots; a few macropores associated with old tree roots; thin, discontinuous clay coatings on vertical ped faces; diffuse smooth boundary.

BC 78-144: moist; 85% dark reddish brown (2.5 YR 3/4) 10% yellowish brown (10 YR 5/6) 5% dark greyish brown (10 YR 4/2) slightly gritty clay; weakly developed coarse blocky structure breaking to weakly developed fine subangular blocky and granular; firm to friable; very slightly sticky; slightly plastic; very thin discontinuous clay skins on some vertical ped faces; pieces of strongly weathered basalt, maximum diameter about 3 cm, occupy 10% of horizon; indistinct wavy boundary.

C 144-210: moist; horizon is made up of yellow, red, greyish-black weathered basaltic flow material *in situ*, with streaks of dark reddish-brown (2.5 YR 3/4), and yellowish-brown (10 YR 5/6) in the fissures of the original rock; gritty clay loam; firm; not sticky; not plastic; very few rocks.

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