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Weathering, bauxitisation and soil genesis from the Nakobalevu Basalt, South-East Viti Levu, Fiji

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Abstract

The augite-olivine flows (5.3 Ma) capping Mount Nakobalevu, a few kilometres north-west of Suva, Fiji, have been subjected to rapid and deep weathering. The Nakobalevu K1 and K2 weathering profiles (at approximately 454 m altitude) show features of strong bauxitisation, and the attributes of a "classical" lateritic profile. Aluminium and iron enrichment in the 2-3 m depth layers of the Nakobalevu weathering profiles is marked, with the presence of abundant gibbsite (as gravels and nodules, and in the silt and clay-sized fractions), goethite, kaolinite, haematite and magnetite (grains); the presence of fragmented (goethitic and gibbsitic) crustal materials in each of the studied horizons, and the distribution pattern of the Al_2O_3*,* Fe_2O_3 *and* SiO_2*, would infer the occurrence of several erosion and weathering cycles, some of which would have evolved under drier climatic regimes. Using Soil Taxonomy, the Nakobalevu Pedon (JBK-1) is a Typic Kandihumult, clayey, kaolinitic, isohyperthermic, which does not give any indication of the gibbsitic materials present.*
Keywords*: Basalt weathering, bauxitisation, Fiji*

1. Introduction

The humid tropical zone occupies about 30% of the Earth's land surface, and supplies about 90% of the dissolved silica and 38% of the ionic load delivered by rivers to the ocean, (Meybeck, 1979; Stallard, 1988; Milliman, 1990). Fiji's high temperatures, moist conditions, and luxuriant vegetation rapidly promote and accelerate the weathering of all exposed rock, creating, in some instances, deeply weathered profiles (Joyce, 1987), and excessive sediment and nutrient loss, with subsequent serious problems of soil and land use and management for agriculture (Liedke, 1989). Tertiary basaltic flows cover more than one third of the entire Fiji archipelago, and it has been estimated (Bonato, 1997) that 75% of their derived soils are utilised for intensive and subsistence farming.

There has been recent discussion in the literature concerning laterisation, laterites and lateritic profiles (e.g., Schellman, 1981; Ollier, 1988; Ollier, 1994). The incidence of 'lateritisation' has been frequently observed in parts of the Fiji Archipelago, particularly associated with pedological studies, and the bauxite and manganese mining operations of the 1940s and 1950s (Twyford and Wright, 1965; Colley, 1976; Morrison *et al*., 1987); however, comprehensive descriptions of these profiles have not been completed, especially in areas where bauxitisation has been suspected to occur. This study was undertaken to provide a comprehensive analysis of the parent material, the mineralogical transformations as a result of the chemical weathering of a Tertiary basalt flow located in the humid tropical environments in south-east Viti Levu, Fiji. The physical, chemical and mineralogical data on the soils that have developed over the weathered flows were collated and interpreted and the processes associated with laterisation and bauxitisation in the Nakobalevu (Colo-i-Suva) Basalt were investigated. An examination of the classification of the soil by Soil Taxonomy (Soil Survey Staff, 1999) was also completed.

2.0 Materials and Methods

2.1 Geomorphology of the Mount Nakobalevu and Colo-i-Suva Study Area

The Nakobalevu Basalts comprise a series of Tertiary flows in a locality known locally as Colo-i-Suva, approximately 8 km northwest of the national capital, Suva (Figure 1); the flows cap Mount Nakobalevu itself (454 m), three other lower adjacent peaks and a few small ridges; the probable extent of the total basalt outcrop area has been estimated (Bonato, 1997) to be in the vicinity of 0.5 km^2. The Nakobalevu basalts rest unconformably on the older volcanics of the Savura Volcanic Group, and dip slopes at Mount Nakobalevu itself (and nearby peaks) indicate the flows to be dipping gently towards the east (Bonato, 1997). The small line of peaks runs approximately NE-SW, parallel to a ridge of calcareous sediments, the Suva Marl, and separated from the marl by a moderately-sized valley enclosing the Savura Creek waterway, sloping into the valley steeply at about 80 degrees. At the northern end, the hills slope down to the adjacent Waimanu River at about 50 degrees, and the southern end of the peaks sharply meet the coastal alluvium at about 1-2 km from the seashore just to the west of Suva city (Figure 1).

The area has a mean annual precipitation of 3,500-4,000 mm with no significant dry season, and a mean annual temperature of 24-27^oC depending on

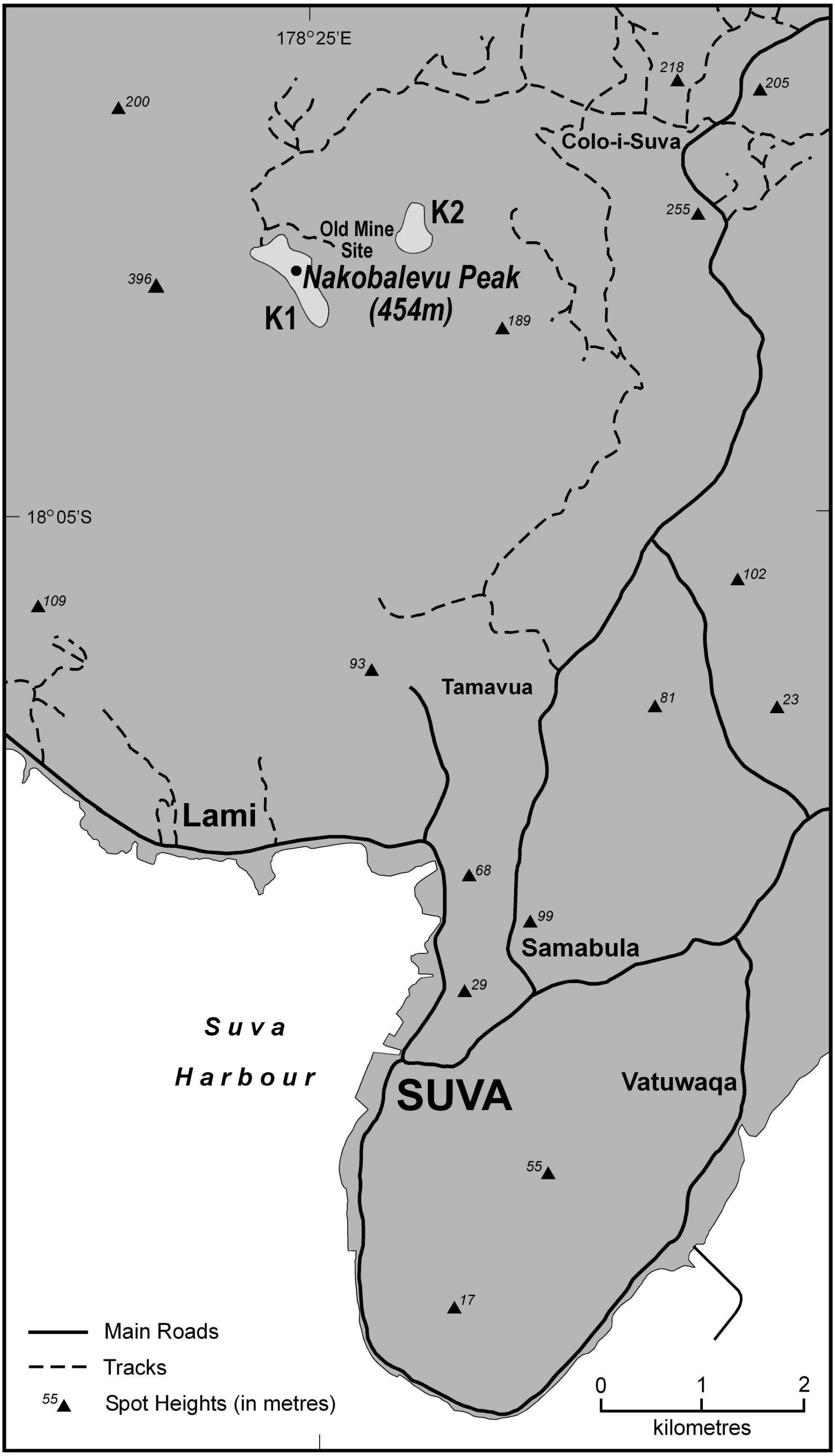

Figure 1. Location of the Nakobalevu study sites, S.E. Viti Levu, Fiji.

elevation (Fiji Department of Meteorology pers. comm.). Under these hot and wet conditions, maintained over a lengthy period, progressive deepening of the regolith, and decay and burial of the original flows have been paralleled by the development of an integrated drainage network and subsequent erosion. The area is extensively dissected with numerous small valleys and creek systems. Profile drainage would be classified as well-drained (Taylor and Pohlen, 1979). The Colo-i-Suva peaks, including Mount Nakobalevu itself, and the surrounding slope areas, indicate some evidence of cultivation early in the history of human settlement in Fiji; much of the higher ridges are now covered by grasses, guava and bamboo plants, while the mid-to-lower slopes are heavily-wooded with rainforest vegetation, and with occasional commercial logging operations (Bonato, 1997).

2.2 Geology of Fiji and of the Colo-i-Suva Area

The plate-tectonic setting and geological history of the south-west Pacific have been well summarised by Rodda and Kroenke (1984). The geology and stratigraphy of Fiji have previously been well described (e.g., Rodda 1967, 1994; Hathway and Colley, 1994; Colley and Flint, 1995). The oldest exposed Fiji rocks are the pillow lavas, gabbros and platform limestones of Late Eocene age in the south-western corner of Viti Levu (Hathway and Colley, 1994). In south-eastern Viti Levu (near Suva), the oldest exposed rocks are those of the Wainimala Group consisting of dacitic tuffs interbedded with Upper Eocene limestones and pillow basalts intruded by tonalites (trondjhemites).

In the Colo-i-Suva area north of Suva, the Savuru Volcanic group (Early Oligocene – Early Miocene, Ibbotson, 1960), comprise glassy fragmental andesitic breccias and rhyolites, and are separated by an angular unconformity from the older Wainimala strata, and this, in turn, is overlain by the Nakobalevu basalt. Radiometric dating of the Nakobalevu basalt suggests an age of 5.3 Ma (Whelan *et al*., 1985). The Nakobalevu basalt consists of phenocrysts of plagioclase (10-40%), olivine (10-15%) and augite (5-10%) in a holocrystalline equiangular matrix; the massive and relatively unaltered state of these basalts suggested possible use as road aggregate material (Band, 1968). A small area of copper-lead-zinc sulfide mineralisation 400 m to the east of the Nakobaleveu peak was, in 1959, surveyed for possible mine development for metallic sulfides (Colley and Flint, 1995), and worked for two years as a very small scale manual operation.

2.3 Sample Collection

Approximately 1.5 kg bulk sample quantities of soil/saprolite/regolith/parent rock were removed from each of the two selected sites at Nakobalevu (K1 and K2, see Figure 1). The two K1 and K2 sample sites were selected on the basis of being least-disturbed sites, and since the flow caps the main peak, 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 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 each of the two sites (K1 and K2), the fresh augite - olivine basalt rock was reached consistently at about 4.0-4.5 metres depth; 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 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 and very fine particle extraction (clays), and larger particle size separation (sand and silt), the four 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

Clay, silt, and sand fractions were separated employing the standard methods of sieving and sedimentation following dispersion using an ultrasound vibrator (Avery and Bascomb 1982). After organic matter destruction using hydrogen peroxide treatment, the separates were calcium-saturated, washed free of excess salt and air-dried. The iron and aluminium oxyhydroxides in each size fraction were extracted using the dithionite-citrate-bicarbonate (DCB) method of Mehra and Jackson (1960).

Hard rock specimens were slabbed and prepared for thin-sectioning, and about 750 g of hard unaltered basalt were powder-ground for two minutes in a Tema mill. The powders were required for X-ray fluorescence (XRF) disc fusions, for random powder rock mineral analysis by X-ray diffraction (XRD), and for clay extraction and identification. Saprolite and soil samples (approximately 500 g) were first oven-dried at $40^{o}C$, then pulverised for XRF disc fusions. Thin-sections (without coverslip) of parent rock samples from all the sites and profiles, in addition to thin sections of sand and silt fractions and of undisturbed unconsolidated material from each metre of the profiles, were prepared both for electron microprobe analysis (in the case of hardrock) and optical microscopy (for both the hardrock specimens and the sand and silt). The undisturbed subsamples were impregnated with Araldite-F resin and prepared in the normal manner; the grinding of the thin sections of unconsolidated material was carried out in a non-aqueous lubricated medium (Avery and Bascomb, 1982).

Clay minerals were first identified using XRD analysis. Clay fractions (<0.0015 mm) were separated by sedimentation and centrifugation processes after ammonium hydroxide treatment and ultrasonic wave dispersion (Kirkman and Pullar, 1978); deferration was also carried out (Mehra and Jackson, 1960). Dispersed clay aliquots were pipetted onto glass slides and examined after heating to 500^{o}C for kaolinite and chlorite. For mineralogical confirmation, deferrated powdered whole samples were also analysed as random powders.

2.5 Instrumentation

The total elemental analyses of hardrock, saprolite, and clay separates were obtained by XRF spectrometry (Haukka and Thomas, 1977) using an Applied Research Laboratories 8420 double goniometer, fully-automated multi-analysis system (sequential) enabling quantitative data on the ten major oxides and 23 other elements. The XRD patterns were obtained using a Siemens powder diffractometer, 40 kV counter tube goniometer, with monochromatised Cu K-α radiation. The oriented specimens were scanned through a range of 3-30^o at a scanning rate of 2^o/2θ per minute. Individual minerals were identified following Brindley and Brown (1980).

Infra-red spectrophotometry was employed for further confirmation of clay minerals (Lyon, 1964; Joe, 1972; Balasubramaniam and Gopinath, 1979). The potassium bromide disc method and methods for the semi-quantitative measurement of each clay mineral, gibbsite and goethite, described by Farmer and Russell (1967), and Zussman (1977) were used. Specimens were scanned over the 4000-200 cm^{-1} region using a Perkin Elmer 781 double-beam spectrophotometer, after the overnight drying of the KBr disc at 105^{o}C to remove free water. A JXA-5A Electron Probe Microanalyser (featuring EDX multichannel analyser), operating at a 30 mA beam current (15 kV), was used to confirm the mineralogies of the specimens prepared by thin-sectioning; the microprobe analysis of the hardrock sample of Nakobalevu basalt in thin section was useful in more accurately defining the pyroxene mineralogy of this basalt. Probe standards employed were: sapphire (Al-ox), pure Fe, Ni and Mn, wollastonite, rutile (Ti-ox), periclase (Mg-ox), and kaersutite.

2.6 Soil Classification

For the soil profile description (see Appendix A) and analyses, a 2 m x 2 m x 2 m pit was dug at site K1, 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 JBK-1 pedon was classified according to Soil Taxonomy (Soil Survey Staff, 1999).

3. Results and Discussion

3.1 Total Elemental Analysis and Elemental Mobilities

Data on the total elemental analyses of fresh samples of Nakobalevu Basalts, of some of the weathered crust and gibbsitic/ferruginous nodular fragments, and of materials along the length of the weathering profile at approximately one-metre depth intervals, are presented in Tables 1-3. Elemental analysis data of the extracted clay-sized fraction to assist in confirming the mineralogical interpretations are given in Table 4.

The total elemental analysis data indicate the elemental percentage changes from fresh unaltered basalt to the corresponding weathered profiles. The Nakobalevu augitic 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 oxides at approximately 10 - 11%, and titanium approximately 1%; the alkali oxides are indicative of the olivine and augitic mineralogies.

Tables 2 and 3 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 Nakobalevu profiles. A sample of crustal material removed from about 2 m depth in the K1 profile indicates clearly the ferrallitic nature of the gravel - high aluminium and iron oxyhydroxide formation accompanied by a substantial hydration factor (high LOI value); this interpretation is supported by the mineralogical data given below which indicates abundant gibbsite, iron oxyhydroxide minerals and minor kaolinite in this coarse material. The weathering profiles overlying the hardrock base indicate that the Na_2O and K_2O are depleted most rapidly; sodium is about 90% depleted within 1 m of the base rock (and at all levels above that), and potassium occurs at about 1% of the original value in the upper layers. MgO and CaO are depleted almost as quickly, although values in the middle of the K1 profile show a slight reversal of trend – a likely indication of the existence of several weathering cycles and mineralogical translocation. Phosphorus and manganese are quickly depleted (in both K1 and K2) to about 60% of their original values - these elements are often incorporated into secondary minerals in the weathering profile (Ollier, 1959).

Titanium shows an initial increase, but otherwise some variability is indicated throughout the profile; Ti^{4+} is known to migrate within the weathering

Table 1. Total Elemental Analysis Data (%) for fresh Nakobalevu Basalt samples.

Component	**K1A**	**K1B**	**K2A**	**K2B**	**K2C**
$Si0_2$	49.43	45.67	48.25	49.23	48.98
$Ti0_2$	0.70	0.69	0.65	0.67	0.72
Al_20_3	18.55	18.07	16.67	18.42	18.32
Fe_20_3	9.41	11.55	11.08	9.73	9.34
Mn0	0.16	0.19	0.18	0.16	0.19
Mg0	6.48	7.75	7.16	6.49	7.62
Ca0	11.07	10.91	10.63	10.92	10.91
Na_20	2.45	2.01	1.82	2.31	2.36
K_20	0.86	1.09	1.04	0.90	1.02
P_20_5	0.20	0.20	0.19	0.19	0.21
LOI	0.23	1.86	1.85	0.25	0.28
TOTAL	99.70	100.14	99.72	99.79	100.32

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 laterite (Sherman, 1952). Iron shows enrichment towards the top of the profiles, e.g., ranging from approximately 9.5% to about 28% at the K1 site; the lower and more consistent iron values from the K2 weathering profile are probably a further expression of the reworking that has occurred from cyclic periods of erosion and weathering. Aluminium oxide values are typical of lateritic profiles (Schellman, 1981); relative enrichment more than any other major oxide has occurred (e.g., 18 - 46% in the K1 profile), with essential consistency in values, but with some depletion in the upper parts of the profile; these results are consistent with the data of Schellman (1981) on the chemical composition of a wide variety of lateritic profiles. Silica (SiO_2), decreases markedly in both the K1 and K2 profiles and then increases slightly and irregularly nearer to the profile surface when kaolinite and gibbsite form (see below); the Si content of the original rock, in excess of that necessary to combine with Al_2O_3 in kaolinite, is assumed to have been leached out (Herbillon and Nahon, 1988).

As weathering begins, leaching 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 (e.g., the alumina enrichments in the weathering profiles at the Nakobalevu sites). The presence of abundant precipitated gibbsitic material and ferruginous crust in the Nakobalevu area, distributed throughout a large part of the two profiles studied, would indicate the occurrence of drier climatic conditions during some of the earlier cycles (Ollier, 1959).

The trace component data (Tables 2 and 3) show that for S, Cr and V there is a marked increase in concentration on going from the hard rock to the weathered materials, although the increases are not uniform on moving up the profile. For Cu and Zn, the patterns are less obvious, with minimal evidence of enrichment on moving up the profile. The clay samples analyses (Table 4) show a dominance of SiO_2, Al_2O_3 and Fe_2O_3, with an almost complete removal of Na, K and Ca. SiO_2 and MgO concentrations decrease from the hard rock clay fraction to the weathered material clays, while Fe_2O_3, TiO_2, P_2O_5 concentrations show general increases. The Al_2O_3 concentrations show differing patterns in the two profiles with the K2 samples showing an increase on going from the rock to the weathered materials, and the K1 samples showing increases and decreases within the core. These results are generally in line with basalt weathering patterns found elsewhere in high rainfall environments (e.g., Schellman, 1981).

Tables 2 and 3 also contain composition data for the gibbsitic gravels found within the 2 m layer. These data show a dominance (>50%) by Al_2O_3, with significant concentrations (10-15%) of Fe_2O_3, with the K2 samples also containing appreciable concentrations (4.5%) of SiO_2. There is no obvious explanation for the differences in the SiO_2 contents. Schellman (1981), based on a study of approximately 800 laterite profiles resting on a variety of parent rocks, concluded that lateritic gravels consisted mostly of SiO_2, Al_2O_3, Fe_2O_3 and H_2O. Additionally a few percent of TiO_2 and (for basic/ultra-basic rocks)

Table 2. Total Elemental Analysis Data (%) of Materials Extracted from Nakobalveu Site K1.

											Trace Indications (mg/kg)						
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	Cr	V	Cu	Zn	LOI	**TOTAL**
Hard rock	49.43	0.70	18.55	9.41	0.16	6.48	11.07	2.45	0.86	0.2	60	63	280	147	103	0.23	99.70
4 metres	11.77	1.46	38.92	24.42	0.13	0.23	0.02	0.12	0.01	0.14	1623	2855	826	94	51	22.21	100.03
3 metres	20.32	1.48	32.42	28.22	0.07	0.32	0.04	0.14	0.01	0.08	1490	1725	747	130	35	17.34	100.90
2 metres	9.50	1.15	46.59	17.42	0.02	0.18	0.01	0.09	0.00	0.07	1089	2205	587	81	7	25.33	100.79
1 metre	14.42	1.75	34.54	27.89	0.09	0.20	0.03	0.13	0.01	0.13	1438	3591	815	150	53	20.48	100.31
Fully weatherd basalt boulder	6.89	1.43	43.06	23.21	0.08	1.01	0.08	0.13	0.02	0.17	1700	104	750	194	81	24.31	100.72
Gibbsitic gravel material from 2 metres	0.75	0.98	52.17	15.36	0.01	0.9	0.04	0.07	0.00	0.09	865	1789	512	28	1	30.18	99.99

Table 3. Total Elemental Analysis Data (%) of Materials Extracted from Nakobalveu Site K2.

											Trace Indications						
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	Cr	V	Cu	Zn	LOI	**TOTAL**
Hard Rock	45.67	0.69	18.07	11.55	0.19	7.75	10.91	2.01	1.09	0.20	37	52	322	163	64	1.86	100.14
4 metres	18.90	1.38	39.88	14.68	0.14	0.24	0.02	0.10	0.06	0.12	926	480	483	106	76	24.45	99.95
3 metres	29.69	1.36	35.23	14.23	0.06	0.56	0.04	0.12	0.14	0.07	854	290	599	163	64	19.28	101.02
2 metres	38.25	1.24	32.57	13.11	0.05	0.71	0.03	0.10	0.14	0.07	457	149	489	209	78	14.17	100.62
1 metre	35.70	1.25	33.94	13.87	0.05	0.67	0.02	0.08	0.28	0.05	418	290	571	226	54	14.82	100.90
Fully weathered basalt boulder	6.72	1.51	43.20	24.45	0.06	1.09	0.06	0.10	0.02	0.16	1680	94	686	201	51	22.58	99.95
Gibbsitic gravel material from 2 metres	4.46	0.49	54.46	10.45	0.15	0.10	0.01	0.02	0.00	0.06	405	1191	318	73	10	29.56	99.99

Table 4. Elemental Analysis Data for Extracted Clay Fraction Materials form the Nakobalevu Sites.

K1 SITE	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	55.34	0.41	26.89	2.59	0.03	2.98	0.02	0.05	0.04	0.02	10.71	99.20
Depth 4 metres	14.15	1.81	30.47	32.63	0.16	1.18	0.02	0.11	0.01	0.19	18.81	100.12
3 metres	21.90	1.63	24.94	30.73	0.05	0.59	0.02	0.07	0.01	0.11	15.49	96.11
2 metres	19.87	1.64	24.89	36.56	0.05	1.00	0.03	0.13	0.01	0.15	15.52	100.44
1 metre	20.87	1.29	24.94	35.75	0.05	0.88	0.02	0.12	0.01	0.14	15.61	100.24
K2 SITE												
Clay from Hard Rock	55.41	0.43	27.34	2.48	0.02	2.82	0.02	0.05	0.04	0.02	10.81	99.72
Depth 3-4 metres	36.81	0.76	33.34	11.69	0.02	1.36	0.02	0.08	0.12	0.06	15.54	99.99
2 metres	38.42	0.75	32.86	10.52	0.01	1.13	0.01	0.03	0.14	0.06	15.17	99.30
1 metre	39.40	0.65	33.54	8.74	0.01	1.56	0.02	0.07	0.22	0.05	15.15	99.67

Cr_2O_3 are present, but for the Nakobalevu samples, these elements were less than 1%.

The particle size distribution data (Table 5) show another difference between the 2 profiles. The K1 samples show a general increase in clay and decrease in sand content on moving upwards, while the K2 samples show the reverse. The silt contents also show a decreasing trend on moving upwards for K2, while the K1 samples show minimal change. There is no obvious explanation for these differences.

3.2 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 Nakobalevu K1 and K2 profiles, the sand and silt fractions, as seen in thin section, were consistently formed of the following minerals: augite, magnetite, some very minor plagioclase, minor olivine in the lower layers of the profile, and large distribution of gibbsitic material of both sand and silt size. These mineralogies were confirmed by the XRD of the sand-size crustal material, and of powdered whole-samples.

Clay fractions separated from the crushed fresh hardrock showed the presence of chlorite, kaolinite, goethite, and haematite, in the Nakobalevu Basalt. The mineralogy of the clay fractions from the K1 and K2 sites consistently showed abundant kaolinite, with moderately strong peaks indicating goethite and some haematite; gibbsite intensities were low; this is explained by the fact that most of the gibbsitic material in the Nakobalevu profiles exists in nodular and gravel forms as coarse and fine sand particles and as silt-sized material. The XRD data for the powdered whole samples (Table 6) indicate moderately-strong intensities for gibbsite in the lower sections of the profile - further evidence for a multi-cycle erosion and weathering process on this basalt flow (Ollier, 1984; Ollier, pers. communication).

The mineralogy of the weathering profiles shows a qualitative consistency: gibbsite (mainly in the form of nodules and gravels of varying size fractions), kaolinite as the predominant fine clay, with strong goethite peaks and some haematite. Peak intensities indicate changes in mineral abundances throughout the profile with the gibbsite abundant in the lower layers, and reducing in amounts towards the surface. The almost complete absence of primary minerals in much of the profile (minor augite, and magnetite were present, with magnetite being the most consistently abundant throughout) resulted in a sharp mineralogical boundary between the fresh Nakobalevu Basalt base and the overlying saprolite.

These results are in line with the results of other studies on laterisation. In a study of lateritic profiles in India, Balasubramaniam and Gopinath (1979) report eleven to thirteen minerals present in various sections of the profile, with gibbsite being the dominant hydrated mineral, and in high-grade bauxites it may constitute up to 85%. Gilkes and Suddhiprakaran (1981) reported that the mineralogy of laterite developed over granites in south-western Australia contained halloysite, kaolinite, magnetite altered to haematite at surfaces, and halloysite, kaolinite, gibbsite, goethite, haematite in pallid zones, with the major alteration product in the mottled zones being gibbsite. Schellman (1981) reported that the mineralogical composition of the many lateritic profiles showed a markedly uniform distribution: minerals of the kaolin group, gibbsite, haematite, goethite, quartz (in silica-containing rocks), and anatase form the major mineral types; in some laterites, boehmite, maghemite, rutile and chromite are also present. In summary, primary silicates are kaolinised in the early weathering stages with most of the alkalis and alkaline earths removed. Under very favourable drainage conditions primary silicates can also be transformed directly into aluminium oxyhydroxides. In the latter situation, the more intensive weathering stages are characterised primarily by the two processes: (a) the incongruent dissolution of kaolinite with the formation of gibbsite (and hence concentration of Al_2O_3 and Fe_2O_3) - predominant in the lateritisation of basic rocks, and markedly evidenced at the Nakobalevu sites; (b) the congruent dissolution of kaolinite through which the alumina and silica are simultaneously removed, and only the iron oxyhydroxides accumulate (a feature pronounced in acidic rocks).

3.3 Lateritisation Development on Mt. Nakobalevu in Colo-i-Suva

Ollier (1994) described laterite as the hard iron-rich material at, or near, the top of a laterite profile; there is some confusion over earlier definitions and terminology employed to describe developed features; laterite profiles are now proposed in terms of the iron crust, a mottled zone and a pallid zone overlying the parent material (Ollier, 1994; Schellman, 1981). The bauxitic clays developed over the Nakobalevu Basalt at Colo-i-Suva were first described by Ibbotson (1960), as a commercial source of bauxite. In that report, no bauxitic profiles were described, and the terminology “laterite” and “lateritic profile” were not employed.

The most evident development of lateritisation was observed at the Nakobalevu K1 site. Access to the lateritic development was facilitated through trenches that had been dug within 50 metres of the K1 site and 70 metres from the K2 location for the construction of (now abandoned) communications buildings. The profiles showed all the characteristics and features of a now-accepted description (Ollier, 1994) of the lateritic profile. The Nakobalevu profile represents a deep-weathering profile formed over augite-olivine flows under humid tropical conditions; the geomorphological factors affecting this profile

Table 5. Particle Size Distribution Data (fine-earth, mm%) for the Nakobalevu Weathering Profiles.

					Sand Fractions											
Horiz	Depth (m).	Sand (2-0.05)	Silt (0.05-0.002)	Clay <0.002	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
K1-1	1.0	7	25	68	0	0	1	3	3	4	3	11	18	68	66	0.97
K1-2	2.0	18	17	65	0	4	10	3	1	17	16	5	14	65	62	0.95
K1-3	3.0	13	22	65	5	4	2	0	2	11	11	7	17	65	63	0.97
K1-4	4.0	21	26	53	4	8	5	2	2	19	17	14	16	53	51	0.96
K1-4.5	4.5	31	27	42	7	8	8	6	2	29	26	7	25	42	40	0.95
K2-1	1.0	30	29	41	3	9	11	3	4	26	25	15	19	41	39	0.95
K2-2	2.0	15	32	53	0	3	5	3	4	11	9	26	12	53	49	0.92
K2-3	3.0	10	37	53	0	3	4	1	2	8	7	11	29	53	47	0.89

Table 6. Mineralogy of powdered whole samples of Nakobalevu weathered materials.

				KAOL	GIBB	GOETH	MGT	HAEM	CHLOR	OTHER*
	Depth (m)									
K1	4 metres			XX	XXX	XXX	XX	X	X	X
	3 metres			XX	XXXX	XXX	X	X	X	X
	2 metres			XXX	XXXX	XXX	XX	X	X	X
	1 metre			XXX	XXX	XXX	X	X	X	X
K2	4 metres			XXX	XX	XX	XX	X	X	X
	3 metres			XXX	XXX	XX	XX	X	X	X
	2 metres			XXX	XXXX	XX	X	X	X	X
	1 metre			XXXX	XXXX	XX	X	X	X	X
	*In each of the metre horizons: minor augite, plagioclase (and magnetite grains)									

Abundance ranges: **XXXXX (50-80%)** **XXXX (30-50%)** **XXX (20-30%)** **XX (5-20%)** **X (trace)**

KAOL kaolinite **MGT magnetite** **GIBB Gibbsite** **HAEM haematite** **GOETH goethite** **CHLOR chlorite**

NB 1: Fresh rock mineralogy: augite (5-10%), plagioclase (labradorite) (10-40%), olivine (10-15%), magnetite (~5%)
NB 2: ICP analysis indicated the presence of Chromium (2000-3000 ppm) and Vanadium (750-850 ppm) in each horizon.

were described above, and the present climatic regime is *humid tropical* (average annual temperature 24^{o}C, average annual precipitation approximately 4000 mm). The basalt-derived soil at the K1 site (JBK-1) is described below, clearly approximating what is normally termed a tropical red loam (Uehara and Gillman, 1981); it was inferred that the soil formed as part of the weathering profile, soil cover was relatively undisturbed with minimal low-energy cultivation which appeared, in any case, to have ceased a long time ago, and the relatively young age of the flows (approximately 5.3 Ma) with no evidence of subsequent surficial magmatic activity in the immediate region.

A wide (~ 2 m) view of the Nakobalevu K1 profile was possible to a depth of approximately 2.5 metres. An upper, resorted-earth zone overlay a lower zone of saprolite, but there was no evidence of a stone-line often present where quartz veins exist (Ollier, 1984). The Munsell colour recorded for the resorted earth layer was 10 YR 3/4 (moist). The lower saprolite comprised a pallid zone of approximately 1.0-1.5 metres thickness overlain with (in the sections accessible to viewing) a mottled zone approximately 50 cm thick. A very-much dispersed and fragmental pisolitic horizon was observed as separating the resorted earth layer from the lower saprolite. The two saprolite zones (mottled and pallid) were often intermixed within the profile - evidence for several cycles of erosion and weathering on Nakobalevu in its short geological history. Both of these two saprolitic zones appeared as weathered rock *in situ*, without volume alteration, and of much lower density than the parent basalt. Munsell colours for the mottled segments ranged from 7.5 R 4/6 (red) to 7.5 R 5/3 (reddish brown) and 7.5 YR 4/4 (yellowish-brown); some bright red mottling patches were close to the 10 R 5/6 described by Ollier (1984).

The Nakobalevu regolith includes numerous corestones scattered throughout with generally narrow areas of regolith developed along the joints. The corestones are concentrically-layered, ca. 50 cm in diameter, orange-brown in colour and composed mostly of clay minerals. The boulder cores in the corestones show development of pisolites, dark-red in form, mostly still soft, generating a speckled effect. Ferrallitic semi-nodular aggregates and angular grits are common throughout both the pallid and mottled zones. The base of the regolith is irregular with a sharp contact to the first corestones.

Analysis of the soil horizons (Pedon JBK-1, see Appendix A, Table 7 and Bonato (1997)) showed the pisolitic material was predominantly gibbsite with associated goethite and some haematite, mainly in the form of coatings and small pieces of crust; the pisoliths measured 4 - 20 mm in length. Clayey material was almost totally kaolinite, and minor amounts of magnetite were also present.

The mottled areas consisted of a fine-grained uniform groundmass of kaolinite with oxides of aluminium and titanium, with abundant oxyhydroxides from olivine/augite weathering. Plagioclase was absent, but magnetite occurred with minor augite. Gibbsite and kaolinite predominated, with much of the gibbsite present in the form of nodular-type gravels.

The pallid zones were characterised by a depletion of iron, though most of the original basaltic textures and some of the original minerals remained. Plagioclase has altered almost entirely to kaolinite and abundant gibbsite, olivine formed coherent masses of iddingsite (seen in microscopic analysis of thin sections), and other iron present mobilised to form secondary oxyhydroxides (haematite, goethite); some of the magnetite has altered to haematite by surface/crack oxidation processes, but little-altered magnetite grains were also observed in the thin-sections, and obtained in the mineral separations. The pallid zone, although not uniform in the visually-accessible profiles, graded into the relatively fresh unaltered olivine-augite Nakobalevu Basalt; at the K1 site, the depth from soil surface to the sharp rock-saprolite interface approximated 4.5 metres.

3.4 Soil Genesis

Basalt-derived soils have been extensively investigated in a number of countries of the South Pacific including Samoa (Latham, 1979; Morrison, 1991; Schroth, 1970; Wright, 1963), the Cook Islands (Widdowson and Blakemore, 1977; Lee *et al*., 1979), Vanuatu (Quantin 1978) and Fiji (Morrison *et al*., 1986, 1987; Naidu *et al*., 1987). The soils range from young soils with high base saturation and intermediate pH (e.g., 5.7 - 6.5), to older more highly-leached and weathered soils of lower pH (4.8 - 5.6) and lower base saturation. Potassium tends to be deficient on these basalt-derived soils. In the hot, very wet environment of these soils, weathering proceeds very rapidly and the leaching can be accelerated; where volcanic ash is an addition, it becomes an important soil-forming factor (Morrison, 1991; Naidu *et al*., 1987).

Full site and profile descriptions for the Nakobalevu Pedon JBK-1 are given in the Appendix A. Laboratory data are presented in Table 7. The profile consists of a gritty loam over a thin gravely sand layer composed mainly of gibbsitic material. This in turn overlies a gritty clay loam loam and then more than 1 m of gritty clay. The gritty clay layer showed some evidence of illuviation (clay skins). The lower segment of the soil profile showed much evidence of weathered basalt in place.

The JBK-1 pedon proved difficult to classify as there is obvious evidence of at least two cycles of soil formation. Following the original Soil Taxonomy (Soil Survey Staff 1975), it was classified as a clayey, gibbsitic, isohyperthermic Typic Gibbsiorthox. When using the 1994 Keys to Soil Taxonomy (Soil Survey Staff, 1994) the sub-group classification could be Plinthic Acroperox. Using the second edition of Soil

Table 7. Laboratory Data for Soil Profile JBK-1.

Depth (cm)	Horizon	Size class and particle diameter (mm) – % Fine earth fraction (< 2 mm)									Ratio fine clay/ total clay	Coarse frag- ments (>2 mm) % of Whole soil
		Total										
		Sand (2-0.05)	Silt (0.05- (0.002)	Clay (<0.002)	(2-0.1)	Int. co.sa. (2-0.2)	Int.f. sa. (0.2- 0.02)	Int. silt (0.02- 0.002)	Clay (<0.002)	Fine clay (<0.0002)		
0-8	A	55	16	29	47	43	19	9	29			12
8-14	AC	71	10	19	66	62	12	7	19			35
14-54	2AB	35	17	48	32	27	13	12	48			15
54-100	2Bt	6	14	80	4	3	9	8	80			10
100-145	2Bt	10	23	67	8	9	8	16	67			8
145-196	2C	6	17	77	3	2	8	13	77			8

Depth (cm)	pH			CaCO$_3$ (%)	Organic matter			Phosphorus (ppm)		Phosphorus retention (%)	Acid oxalate (%)		
	H$_2$O 1:2.5	KCl 1:2.5	NaF 1:50		Carbon (%)	Nitrogen (%)	C/N	0.025M, H$_2$SO$_4$	Total		Al	Fe	Si
0-8	5.0	4.0			6.20					48	0.21	0.64	
8-14	5.1	4.3			1.02					30	0.09	0.18	
14-54	4.7	4.4			1.49					52	0.17	0.53	
54-100	4.5	4.8			0.61					79	0.20	0.22	
100-145	4.6	4.9			0.51					79	0.23	0.30	
145-196	4.5	4.5			0.46					80	0.16	0.08	

Depth (cm)	Cation Exchange											
	Exchangeable bases (meq/100 g)					Ext. acidity (pH 8.2) (meq/100)	CEC (meq/100 g)		Base Satn. (%)		KCl Extractable (meq/100g)	
	Ca	Mg	K	Na	Sum		NH$_4$OAc pH 7.0	Sum of cations pH 8.2	Sum of cations	NH$_4$OAc	H	Al
0-8	1.63	0.81	0.15	0.39	2.98	23.73	13.09	26.71	11	23	0.10	0
8-14	0.51	0.23	0.06	0.09	0.89	7.14	4.89	8.03	11	18	0.12	0
14-54	0.27	0.20	0.06	0.31	0.84	12.56	6.13	13.40	6	14	0.20	0
54-100	0.21	0.15	0.05	0.09	0.51	13.57	5.53	14.08	4	9	0.17	0
100-145	0.16	0.12	0.05	0.14	0.47	13.69	4.34	14.16	3	11	0.11	0
145-196	0.28	0.19	0.07	0.14	0.68	14.64	8.04	15.32	4	8	0.10	0

Depth (cm)	Bulk density (Mg/m^3)	15 bar Water retn. (% w/w)		Ratios to clay		CDB Al %	CDB Fe %	S(ppm)					
		Field moist	Air-dry	CEC NH$_4$OAc	15 bar water			Total	PO$_4$ Extrac.				
0-8	0.93	29.4	16.9	0.45	0.58	1.01	5.81						
8-14	0.87	9.5	7.1	0.26	0.37	0.60	4.74						
14-54	1.09	17.6	13.9	0.13	0.29	1.09	6.74						
54-100	1.17	39.8	25.6	0.07	0.32	1.29	10.56						
100-145	1.14	28.5	24.8	0.06	0.41	1.31	11.06						
145-196	n.d.	45.3	30.8	0.10	0.40	1.36	10.36						

Taxonomy (Soil Survey Staff, 1999), however, changes the classification significantly. The lower part of the profile exhibits a marked increase in clay content, but with limited evidence of illuviation. The oxic horizon was noted and found to correspond with the 14 - 54 cm horizon; the layers below this have too much inherent rock structure. The profile has an ochric epipedon and both a kandic and an oxic horizon, but the properties do not meet the requirements for an Oxisol, so this is in the Kandihumult great group (significant organic carbon content, with a kandic horizon). Subgroup assessment indicates there are no other sufficiently significant properties, leading to designation as a Typic Kandihumult, with the family modifiers of clayey, kaolinitic, isohyperthermic. This classification gives a clear indication of the highly weathered nature of the soil, with minimal base cations and weatherable minerals, but having appreciable organic matter in the upper horizons. It does not, however, indicate the gravelly nature of some of the upper layers, or evidence of more than one cycle of weathering.

As noted above, this pedon is dominated by kaolinite, gibbsite, with a high content of iron oxyhydroxides (goethite and hematite) and small amounts of residual minerals, such as, ilmenite, magnetite, and very small amounts of augite from the original augite-olivine basalt were present. No olivine or plagioclase was observed in the full two metres length of the soil profile. Thus the soil is dominated by variable charge minerals and possesses low permanent charge. The presence of significant gibbsitic material (in the form of nodules and broken gravels) is in accord with the conditions for this phenomenon as described by Fripiat and Herbillon (1971): free-drainage conditions, very high precipitation, and a position high above the water-table, to enable the rapid, and almost immediate removal of soluble weathering products particularly silica.

The CEC/clay ratios indicate high kaolinitic clay contents, and the consequent engineering properties of the soil. The relatively low bulk density values (0.87 - 1.17 g/cm^3) are typical of highly weathered tropical soils with a low silt content. The close relationship between 1500kPa water retention and clay content is noted in this pedon, and in this instance, where the ratio of 1500 kPa water (on air-dry material) to measured clay exceeds 0.6, the 15-bar water data may be used to estimate the clay content by multiplying the percent water retained by 2.5 (Gangaiya *et al*., 1982).

4.0 Conclusions

Elemental mobilities in the weathering profiles of the Nakobalevu Basalt indicate a pattern common to the weathering of basic parent rock under conditions of the humid tropics - the rapid depletion by leaching of the alkali and alkaline earth elements, and the subsequent enrichment of aluminium and iron, and increase of hydration. At Nakobalevu, aluminium and iron enrichment is considerable, and strong lateritisation has occurred. Mineralogical studies confirm the elemental mobilities: a lateritic profile with fragmented crustal material composed predominantly of gibbsitic nodules and gravels, found in different sections of the profile, characterises the Nakobalevu sites, with kaolinite, and strongly goethitic - the demarcation of zones as mottled and pallid is also observable. The topographical environment is significant, with the Nakobalevu site providing the well-drained feature conducive to gibbsite formation. Since high amounts of crustal material are evidenced at Nakobalevu, it is suggested that this may well demonstrate the existence of earlier climates which were drier (than at present), and perhaps having lower mean annual temperature.

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Special Note

J.A. Bonato died in April 2012, while this manuscript was being drafted.

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Appendix A: Site and Profile descriptions for JBK-1.

Classification:	Typic Kandihumult, clayey, kaolinitic, isohyperthermic
Location:	Nakobalevu, SE Viti Levu, Fiji. Approximately 80 m SE of triangulation point on top of Mount Nakobalevu
Physiography:	2^o smooth SE facing (slope) from the triangulation point; altitude 460 m above mean sea level (a.m.s.l.)
Topography:	Very gentle slope from Nakobalevu peak
Drainage:	Site and profile well drained
Vegetation:	Was originally rainforest; cleared in part; site covered with ferns and assorted woody plants with little grass cover
Parent Material:	Nakobalevu basalt - an augite-olivine basalt flow
Climate:	Average annual temperature 23.5^{o}C; rainfall approximately 4000 mm annually with no dry season

Profile description

A 0-8 cm	Slightly moist; dark yellowish brown (10 YR 3/4) slightly gritty loam; combination of strongly developed medium subangular blocky and weakly developed fine granular; friable; not sticky; not plastic; abundant medium and fine roots; some earthworms and some ants; distinct smooth boundary,
AC 8-14	Slightly moist; dark brown (10 YR 4/3) gravelly gritty coarse sand; absence of structure; loose consistency; common fine and medium roots; gravels present are gibbsitic nodules; distinct slightly wavy boundary,
2AB 14-54	Moist; dark brown (7.5 YR 4/4) gritty slightly gravelly clay loam; weakly developed medium and fine granular structure; very friable; not sticky; not plastic; few medium and fine roots; a few, angular, weathered pieces of basalt; indistinct wavy boundary,
2Bt 54-145	Moist; 70% dark red (2.5 YR 3/4), 15% yellowish brown (10 YR 5/6) 15% dark reddish brown (5 YR 3/4) gritty clay; massive, but breaking into moderately developed medium and fine subangular blocky structure; firm; slightly sticky; slightly plastic; a few fine roots; some gravels present -small pieces of weathered

	basalt; few patchy clay skins on vertical ped faces; 10% of horizon made up of weathered basalt rocks completely weathered in terms of colour change, but still retaining mechanical strength; very few partly weathered (basalt) rocks; diffuse smooth boundary,
2C 145-190	Moist; yellowish red (5 YR 4/6) dark yellow-brown (10 YR 4/6) and grey gravelly gritty clay; weakly and moderately developed subangular blocky and granular structure; firm; slightly sticky; slightly plastic; gravels are partly weathered basalt pieces; rock structure present in approx. 50% of the horizon; absence of roots; no clay skins visible; distinct white pieces (about 1 mm diameter) are probably gibbsite.