Holocene volcanic soils in the Mt. Gambier region, South Australia

Hiroshi Takesako[A], David J. Lowe[B], Jock Churchman[C] and David Chittleborough[D]

[A]School of Agriculture, Meiji University, Kawasaki, Kanagawa, Japan, Email takesako@isc.meiji.ac.jp
[B]Dept Earth and Ocean Sciences, School of Science and Engineering, University of Waikato, Hamilton, New Zealand, Email d.lowe@waikato.ac.nz
[C]School of Earth and Environmental Scs., University of Adelaide, Adelaide, SA, Australia, Email jock.churchman@adelaide.edu.au
[D]School of Earth and Environmental Scs., University of Adelaide, Adelaide, SA, Australia, Email david.chittleborough@adelaide.edu.au

Abstract
Volcanic soils derived from mid-Holocene basaltic tephra in the Mt. Gambier region of South Australia have developed in a xeric moisture regime. We studied two soils, one at Mt Gambier (MTG) and the other at nearby Mt Schank (MTS). Both volcanoes were active ca. 6000 cal. years ago. The MTG soil has a high content of $CaCO_3$ (incorporated during eruption through limestone) and other exotic materials intermixed with basaltic tephra containing low amounts of glass. The MTS soil is derived mainly from basaltic tephra with high glass content and much less $CaCO_3$ than at MTG. These parent mineralogies have led to markedly different clay compositions and chemical properties: the MTS soil contains abundant allophane (mainly) and ferrihydrite with few layer silicate clays, whereas the MTG soil is dominated by layer silicate clays and low allophane or ferrihydrite. Both soils are near neutral or alkaline. The MTS soil has a melanic horizon and andic properties and is classed as a Melanoxerand. The MTG soil has weak andic properties with insufficient glass to enable it to be classed in the Andisols, and is instead a Calcixeroll.

Key Words
Andic properties, Xerands, Xerolls, basaltic tephra, limestone, humus composition.

Introduction
The youngest volcanoes in Australia comprise the Mt Gambier (MTG) and Mt Schank (MTS) basalt complexes, ~10 km apart, in southeast South Australia. The area is characterised by xeric moisture and mesic temperature regimes. Volcanic soils and on around these complexes are derived mainly from basaltic tephra materials erupted ca. 6,000 cal. years ago. Tephra erupted from the craters at MTG contains considerable quantities of $CaCO_3$ and quartz, chert, and siliceous sponge spicules derived from thick Tertiary limestone, and calcareous sands, through which the basalt was erupted. Previous work has shown that glass content in MTG soils is comparatively low (<20%), and that much of the glass is altered. Tephra (scoria) from MTS contains much less exotic material (only from underlying calcareous sands) and has a higher glass content (≥50%), most unaltered. Volcanic crystals in both cases include olivine, labradorite, titanaugite, and Fe-Ti oxides (Lowe and Palmer 2005). Although the glass at both sites is basaltic, and hence low in SiO_2 (~50 wt %) and high in Al_2O_3 (~17 wt %), extra SiO_2 occurs at Mt Gambier by inclusion of the exotic minerals. We studied differences in physical, mineralogical, and chemical properties for two soils, one at MTG (near Blue Lake) and the other at MTS (on scoria). We also analysed humic materials because both soils have deep, dark A horizons.

Methods
Soil analytical methods were based on ISRIC (1986). Humus compositions were analyzed using the Nagoya method (Kumada 1987). Allophane and ferrihydrite contents were estimated from oxalate and pyrophosphate-soluble Al, Si, and Fe (Parfitt and Wilson 1985). Layer silicate clays were estimated using XRD.

Results
The MTS soil has physical properties typical of pedogenesis of tephra including low bulk density (≤0.7 g/cm^3) and low solid phases. A high porosity with warm, dry summers and moist winters accelerated the weathering of the material to form a relatively high clay content in upper horizons (~30%) in comparison with that of the MTG soil (~20%) (Table 1). Total soil analyses match the primary mineralogies: the MTS soil has a typical basaltic composition whereas the MTG soil has a high content of SiO_2 in upper horizons and a high content of CaO in lower horizons, commensurate with the incorporation of limestone and silica polymorphs into its parent material (Table 2). The 2Bk horizons have high base/Al ratios because of minimal losses of CaO by leaching compared with losses from upper horizons. A1 and A2 horizons of both soils have high soil organic

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Table 1. Physical properties.

	Horizon	Depth (cm)	Munsell color	Bulk density (g/cm^3)	Three phase distributuion (%)			Particle size distribution (%)				Txture
					Solid	Liquid	Air	C. sand	F. sand	Silt	Clay	
Mt. Gambier	A1	0-20	10YR1.7/1	0.86	34.7	30.4	34.9	30.1	32.2	16.4	21.3	SCL
	A2	20-45	10YR2/1	0.97	38.8	27.4	33.8	35.9	31.2	13.6	19.3	SCL
	AB	45-60	10YR2/2	1.14	45.8	25.8	28.4	38.9	30.1	11.9	19.1	SCL
	Bw	60-75	10YR3/4	1.18	42.2	25.8	32.0	39.0	29.7	13.5	17.7	SCL
	2BCk	75-91	10YR4/3	1.33	50.2	23.6	26.2	48.2	30.1	10.8	10.8	LS
	2Ck1	91-130	10YR5/3	1.48	58.0	21.2	20.8	53.4	26.5	7.1	13.0	SL
	2Ck2	130-	10YR5/2	1.45	56.7	16.6	26.8	44.9	31.1	10.1	14.0	SL
Mt. Schank	A1	0-11	10YR1.7/1	0.52	22.4	40.6	37.0	26.4	17.8	26.2	29.6	LiC
	A2	11-22	10YR2/1	0.72	28.9	43.0	28.1	26.2	18.1	25.4	30.4	LiC
	AB	22-35	10YR2/3	0.72	26.6	40.8	32.6	29.3	20.2	23.5	27.1	LiC
	Bw	35-55	10YR4/4	0.66	24.9	36.6	38.5	39.3	24.3	20.0	16.4	LiC
	2A	55-75	10YR3/3	0.97	36.7	38.4	24.9	46.8	30.0	13.8	9.5	LS
	2C	75-100	10YR2/1	1.39	52.5	29.6	17.9	44.9	40.5	8.0	6.6	LS

Table 2. Total analysis of <2 mm fraction (% of 900 ^oC base).

	Horizon	SiO_2	Al_2O_3	Fe_2O_3	Ti_2O	MnO_2	CaO	MgO	K_2O	Na_2O	P_2O_5	SiO_2/Al_2O_3	$^aB/Al_2O_3$
Mt. Gambier	A1	75.34	8.45	5.55	1.13	0.07	4.92	2.03	1.07	0.69	0.75	15.1	1.94
	A2	81.42	6.84	4.83	0.93	0.06	2.41	1.50	0.85	0.63	0.53	20.2	1.48
	AB	81.57	7.43	4.90	0.96	0.06	1.65	1.50	0.87	0.59	0.48	18.6	1.17
	Bw	78.49	8.17	5.88	1.11	0.06	1.86	2.05	0.90	0.99	0.49	16.3	1.37
	2BCk	57.63	7.08	4.62	0.94	0.06	23.28	4.39	0.66	0.78	0.57	13.8	7.83
	2Ck1	59.15	6.60	4.16	0.80	0.05	22.69	4.68	0.62	0.76	0.49	15.2	8.34
	2Ck2	58.65	6.51	4.42	0.89	0.05	23.00	4.40	0.68	0.86	0.53	15.3	8.46
Mt. Schank	A1	51.14	12.89	12.73	3.15	0.17	6.83	7.20	1.04	1.52	3.35	6.7	2.66
	A2	49.51	13.44	13.42	3.30	0.18	6.81	7.61	1.01	1.60	3.12	6.3	2.63
	AB	47.72	14.65	14.17	3.50	0.17	6.67	7.80	0.96	1.56	2.80	5.5	2.42
	Bw	46.25	15.63	14.34	3.64	0.16	6.89	7.43	1.20	1.93	2.53	5.0	2.29
	2A	44.95	14.59	13.52	3.42	0.16	7.75	7.82	1.91	3.41	2.46	5.2	2.85
	2C	45.99	13.37	12.62	3.17	0.15	8.02	7.82	2.58	3.88	2.40	5.8	3.26

$^aB/Al_2O_3$: Base/Aluminum ratio;$(CaO+MgO+K_2O+Na_2O)/Al_2O_3$

matter contents (>10%), but a relatively lower content of N in the MTG soil relates to its high pH. The base saturation is >100% in horizons of the MTG soil, higher than for the MTS soil because of the limestone-bearing parent material. Values are also high in the MTS soil (~100%) because of the accumulation of bases by upward capillary movement during warm and dry summers. The values of phosphate absorption coefficients (equivalent to P retention) in horizons of the MTS soil are higher than those of the MTG soil because the MTS soil has much more allophane and ferrihydrite (Tables 3 and 4).

Table 3. Chemical properties.

	Horizon	pH			Org. C (g/kg)	Ino. C (g/kg)	T-N (g/kg)	C/N (org. C)	Humus (%)	CEC (cmol/kg)	Exchangeable cations (cmol/kg)				Base satu. (%)	P-Abs. coeffi.
		H_2O	KCl	NaF							Ca	Mg	K	Na		
Mt. Gambier	A1	8.08	7.36	9.55	72.7	2.6	2.2	33.0	12.53	45.00	57.57	5.03	5.53	10.22	174	1179
	A2	7.98	7.38	9.67	56.6	1.8	1.7	33.3	9.76	37.44	46.14	3.65	0.77	1.16	138	1074
	AB	7.93	7.31	9.81	35.9	nd	1.1	32.6	6.19	32.54	30.58	2.85	0.50	1.41	109	947
	Bw	7.98	7.18	9.88	19.0	nd	0.6	31.7	3.28	24.48	24.88	3.91	1.32	3.25	136	920
	2BCk	8.29	7.60	10.5	11.8	41.2	0.3	39.3	2.03	14.91	36.20	3.98	0.83	3.50	298	765
	2Ck1	8.46	7.71	10.7	8.1	40.8	0.2	40.5	1.40	13.39	34.65	3.99	1.27	3.92	327	638
	2Ck2	8.66	7.70	10.5	5.1	51.2	0.1	51.0	0.88	12.68	30.71	2.63	0.61	1.65	281	703
Mt Schank	A1	6.57	5.72	10.3	112.8	nd	8.2	13.8	19.45	58.28	32.02	12.08	4.54	2.16	87	1670
	A2	6.84	5.81	10.7	60.2	nd	4.1	14.7	10.38	42.36	26.08	7.26	2.97	2.00	91	1635
	AB	6.96	5.90	10.5	40.0	nd	3.1	12.9	6.90	37.73	23.70	6.07	3.89	4.92	102	1769
	Bw	7.26	6.16	10.4	16.6	nd	1.3	12.8	2.86	29.28	18.49	5.27	2.41	3.05	100	2157
	2A	7.69	6.49	10.3	21.9	nd	1.6	13.7	3.78	25.23	16.92	5.18	2.42	3.06	109	1216
	2C	7.70	6.68	9.94	5.0	nd	0.4	12.5	0.86	10.04	6.44	2.00	1.18	1.27	109	433

P-Abs. coeff., is Japanese traditional metod for p-retension. Max value is 2687mg P_2O_5/100g soil at pH 7.0, nd: not detected.

The dominant clay minerals in the MTG soil are kaolinite, smectite, illite, irregular mixed layer smectite-illite, minor kaolin-smectite (indicated by asymmetric 0.7nm peaks), all of which originated from the limestone, and in the MTS soil the main clay is allophane with subordinate ferrihydrite (Figure 1). Allophane formation in the MTS soil is governed by Si leaching from upper horizons during winter and early spring when precipitation is at a maximum and evaporation is low, thereby promoting the formation of Al-rich allophane (Al: Si ratios are ~1.6-1.9) (Table 4). Around 280 mm of water on average drains through upper horizons for typically three to ten weeks in this period (out of a total annual rainfall of ~700 mm) (Lowe and Palmer, 2005). The MTS soil fulfills the andic properties requirements of both Soil Taxonomy and WRB to qualify for Andisols (Andosols), but the MTG soil has only weak andic properties and insufficient glass (<~20% required) to meet the thresholds for Andisols (Table 4). At some other sites in the MTG area, however, some soils had sufficient glass to just meet criteria required for Andisols (Lowe and Palmer 2005)

Table 4. Selective dissolution analysis and allophane content.

	horizon	AOX (g/kg)			BDC (g/kg)		CPY (g/kg)		(Alo−Alp)/Sio	DSRO	SRO/	Ferrihyd
		Sio	Alo	Feo	Ald	Fed	Alp	Fep	(molar)	(%)	Clay(%)	rite(%)
Mt. Gambier	A1	2.36	3.96	5.38	2.88	14.15	0.93	0.57	1.33	1.4	6	9
	A2	3.06	5.39	6.28	2.44	15.35	1.08	0.74	1.47	1.9	10	11
	AB	2.59	4.97	7.02	1.33	13.18	1.31	0.84	1.47	1.6	8	12
	Bw	3.11	6.79	9.22	2.72	13.69	1.08	0.73	1.91	2.3	13	16
	2BCk	3.55	4.58	6.92	2.00	9.14	0.25	0.14	1.27	2.0	19	12
	2C1k	3.33	3.65	5.34	1.33	8.75	0.25	0.10	1.06	1.7	13	9
	2C2k	3.01	2.25	5.71	1.02	7.66	0.12	0.11	0.74	1.3	9	10
Mt. Schank	A1	12.91	26.89	11.38	5.22	16.93	3.89	0.92	1.85	9.2	31	19
	A2	15.51	30.56	13.60	5.04	16.57	3.13	0.90	1.84	11.0	36	23
	AB	21.51	38.62	15.70	5.34	23.17	2.58	0.66	1.74	14.8	54	27
	Bw	24.72	39.42	17.73	5.58	21.99	1.22	0.52	1.61	16.1	98	30
	2A	16.38	24.91	13.58	4.70	22.87	0.87	0.47	1.53	10.4	109	23
	2C	6.98	11.19	7.31	1.28	5.55	0.47	0.24	1.60	4.5	69	12

AOxalate soluble Si, Al, Fe; CPyrophosphate soluble Al, Fe, Ca

BDithionite soluble Al, Fe; DSRO: Short Range Order minerals; mainly allophane

Humic acids for all soil horizons from both MTS and MTG soils are classified as “A type”, the most highly humified type (Figure 2). Properties associated with these humic acids in surface to subsurface horizons of both soil are very similar (Table 5). We found it difficult to distinguish beween the soils using ^{13}C solid NMR spectra (data not shown). The accumulation and high degree of humification of the soil organic matter in both soils are probably promoted by formation of Ca-humus complexes in the MTG soil and of Al-humus complexes in the MTS soil. It is possible that Aboriginal ‘fire-stick’ farming has promoted strong humification and ‘melanisation’ in upper horizons through the addition of charcoal from burning and from regular bracken fern growth that follows (Lowe and Palmer, 2005). The upper horizons of the MTS soil form a melanic horizon and those of the MTG soil a mollic horizon (Tables 4 and 5).

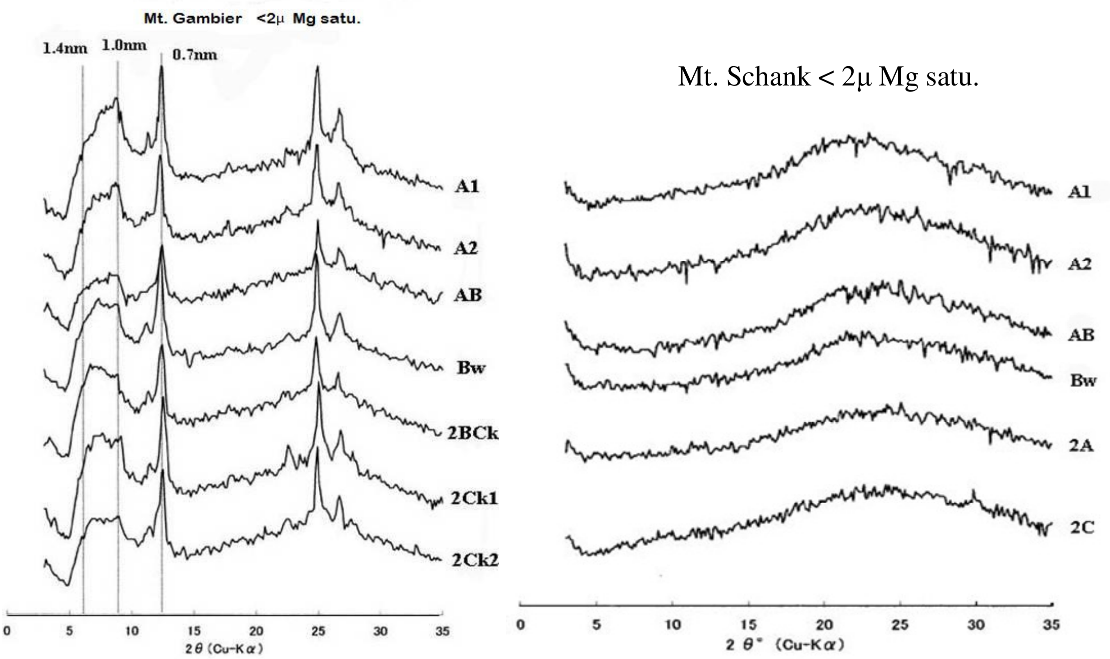

Figure 1. XRD patterns of Mg-saturated clay fractions.

Soil classification
The MTS soil we studied is a Typic Melanoxerand in Soil Taxonomy and a Silandic, Melanic Andosol (Eutric, clayic) in the WRB system. (Thaptic Haploxerands were also reported at MTS by Lowe and Palmer 2005.) The MTG soil we studied is a Typic Calcixeroll in Soil Taxonomy and a Haplic Chernozem in the WRB system. (Both Humic Vitrixerands and Calcic Haploxerands were additionally reported at MTG by Lowe and Palmer 2005.) At a site midway between the two volcanic complexes, a soil on fine basaltic ash was classed as an Alfic Humic Vitrixerand by Lowe and Palmer (2005). Xerands make up only ~4% of Andisols and hence are rare globally because andisolization tends to be favoured by strong leaching in cool, udic moisture regimes. The Xerands in the Mt Gambier area are the only Andisols currently known in Australia (they are Andic, Chernic Tenosols in the Australian Soil Classification).

Table 5. Humus composition.

	Horizon	HT	HE	HE/HT(%)	a	b	PQ(%)	RF	⊿-logK
Mt Gambier	A1	137.1	67.5	49	51.4	16.1	76	112.7	0.557
	A2	92.0	57.7	63	44.9	12.8	78	131.0	0.538
	AB	85.1	42.0	49	28.7	13.4	68	136.9	0.530
	Bw	48.4	19.4	40	9.5	9.9	49	125.9	0.535
	2BCk	15.8	8.7	55	3.5	5.2	40	98.3	0.538
	2C1k	7.0	3.6	52	1.5	2.1	41	94.0	0.554
	2C2k	2.1	1.6	76	0.7	0.9	45	116.7	0.591
Mt. Schank	A1	222.9	94.1	42	64.9	29.2	69	88.1	0.623
	A2	137.7	64.2	47	40.0	24.2	62	156.2	0.512
	AB	96.2	39.6	41	19.8	19.8	50	138.8	0.552
	Bw	36.8	17.3	47	6.7	10.5	39	140.2	0.554
	2A	30.9	16.2	53	6.5	9.7	40	120.0	0.520
	2C	10.9	6.0	55	1.9	4.1	32	103.0	0.503

HT: total humus; ml of 0.1N $KMnO_4$ consumed by 1g soil. (converted rate using dry combastion is 1ml = 0.4mg C)
HE: extracted humus; the sum of 0.1N $KMnO_4$ (ml) consumed by HA and FA of the two extracts per 1g soil.
a and **b**: the amount of HA(humic acid) and FA(fuvic acid, respectively, calculated as ml of 0.1N $kMnO_4$ consumed by HA and FA of each extract corresponding to 1g soils.
PQ: a/(a+b) * 100; percent of HA in extracted humus(HA + FA)
RF: K600 * 1000/c; where c is ml of 0.1N $KMnO_4$ consumed by 30ml of HA solution used for determining absorption spectrum.
⊿-log K: log k 400 - log K 600, where K is the optical density at 400 or 600 nm

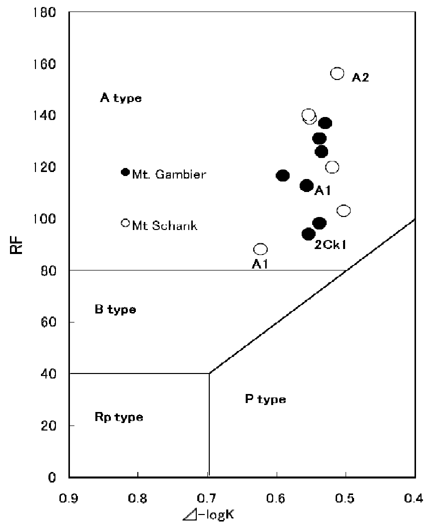

Figure 2. Classification diagram of humic acid

Conclusion
Contrasts in parent materials of two soils of similar mid-Holocene age at MTG and at MTS in southeast South Australia, which has a xeric moisture regime, have led to markedly different soil physico-chemical properties and clay compositions. Soils at MTS, on basaltic tephra (scoria) with common glass and relatively few limestone-derived minerals, contain much more allophane and ferrihydrite but few layer silicate clays. Soils at MTG, on basaltic tephra with intermixed limestone and other exotic materials including silica polymorphs, contain low allophane and ferrihydrite and abundant layer silicate clays including kaolinite, smectite, and illite. Organic matter in both soils is similar in accumulation and humification (both A type) and meets melanic or mollic epipedon requirements. The MTS soil in our study is Typic Melanoxerand (or Silandic, Melanic Andosol), and the MTG soil in our study is a Typic Calcixeroll (or Haplic Chernozem).

Selected reference
Lowe DJ, Palmer DJ (2005) Andisols of New Zealand and Australia. *Journal of Integrated Field Science* 2, 39-65.