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SOILS OF THE PLIO-PLEISTOCENIC VOLCANIC DISTRICT OF MONTIFERRU (CENTRAL-WESTERN SARDINIA, ITALY)

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Introduction

Volcanic soils are widely spread in Sardinia (Italy), where they cover 11.6% of the island's surface (Aru *et al.,* 1991). These soils have been formed from various volcanic materials belonging to several volcanic cycles that occurred in different geological times.

An extensive Plio-Pleistocenic volcanic district is situated in the Montiferru area (central-western Sardinia). This district is characterised by domes of acid lava, acid tephra, and basaltic plateaux. Very limited data have previously been published about the soils of the Montiferru area, and limited research has been reported on soils that form in acid lava and tephra under similar conditions.

The aim of this study is to gain a better understanding of the key properties, variability, and classification of the soils formed from the Plio-Pleistocenic phonolitic lava and their intercalated tephra in the Montiferru area.

Materials and Methods

The study area is situated in central-western Sardinia (Italy), between 40°00' and 40°15' N and 8°27' and 8°42' E (Figure 1). Volcanic activity in this region started during the Oligocene with the deposition of the ignimbrites, with trachytic composition, which form the Montiferru rock basement. A second volcanic cycle, from Upper Pliocene to Middle Pleistocene, led to the accumulation of trachytic and phonolitic lava and tephra. The youngest volcanic products in the area are the basaltic lavas of the Middle-Upper Pleistocene (Assorgia *et al.,* 1978; Deriu *et al.,* 1981; Lecca *et al.,* 1997).

Our study focused on six pedons (Table 1), forming two soil sequences of three pedons each. The pedons were selected to represent soil development in the Plio-Pleistocenic phonolitic lava (sequence *A*) and in their intercalated tephra (sequence *B*) along two altitudinal transects. The sequence *B* includes a smaller range of altitudes with respect to sequence *A*, because tephra deposits are situated only at the higher elevations.

Vegetation in the area is in relation with the altitude. Above 900 m, the vegetation is mainly composed by grass species and low macchia. Between 900 and 600 m, natural and semi-natural woods and macchia are present. Below 600 m, vegetation is mainly composed by natural grasses and degraded macchia.

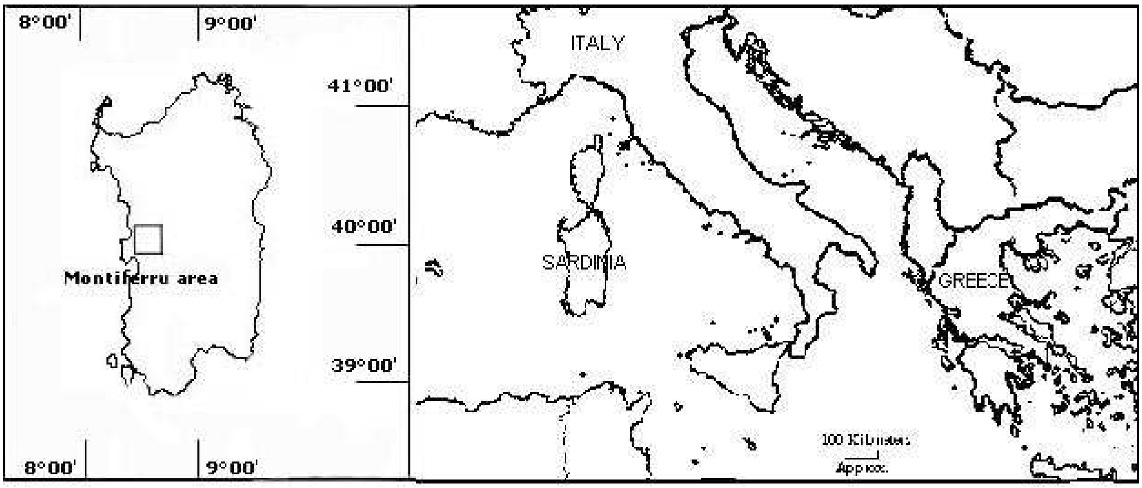

Figure 1. Western Mediterranean and location of the study area.

Elevations of pedons range from 1,050 to 172 m a.s.l. There are three climate stations close to the study area, placed at 241, 448 and 557 m a.s.l. They reveal that climate in the area change with altitude. Mean annual temperature ranges from 14.2°C of the highest climate station to 17.3°C of the lowest weather station (Sezione Autonoma per il Servizio Idrografico della Sardegna).

Maximum temperatures of August vary in a very close range, while minimum temperatures of January show an higher relationship with the elevation. Mean annual rainfall in the area varies from 1,001 mm of the highest station to 527 mm of the lowest station (Sezione Autonoma per il Servizio Idrografico della Sardegna). The Soil Moisture Regime (Soil Survey Staff, 1998) is estimated to be Udic at elevations above 850 m, Ustic at elevations between 850 and 400 m, and Xeric at elevations below 400 m, while the Soil Temperature Regime is estimated to be Mesic at elevations above 750 m and Thermic at elevations below 750 m.

The pedons were described by standard soil survey methodology (Soil Survey Division Staff, 1993). Bulk soil samples were collected from each genetic horizon of each pedon for laboratory analyses. From the upper horizons undisturbed samples were collected with metal cylinders (Ministero delle Politiche Agricole e Forestali, 1997) for bulk density determination.

Bulk samples were air-dried and crushed to pass a 2-mm sieve. All analyses were performed on air-dried <2-mm soil according to the procedures published by Ministero delle Politiche Agricole e Forestali (2000) unless otherwise specified. Sand (2.0-0.02 mm), silt (0.020-0.002 mm), and clay (<0.002 mm) fractions were separated by pipette and sieving following pre-treatment with H_2O_2 to oxidise organic matter and dispersion aided by Na-hexametaphosphate.

Bulk density of field moist core samples was determined according to Ministero delle Politiche Agricole e Forestali (1997). Soil pH was measured by potentiometry in soil:solution suspensions of 1:2.5 H_2O, 1:2.5 1 *M* KCl, and 1:50 1 *M* NaF. Organic carbon (OC) was estimated by wet digestion with a modified Walkley-Black procedure.

Table 1. Selected site characteristics, locations, and time of deposition of parent materials for all pedons studied.

Pedon	Location	Geomorphic position	Elevation	Aspect	Slope	Vegetation	Parent material	Composition	Time of deposition	MAP‡	Average air temp.	
											Aug.	Jan.
			m asl†		%					mm	°C	
Sequence A												
6	M.te Urtigu	slope	1,005	ESE	10	natural grasses	lava flow	phonolitic	Upper Pliocene to Middle Pleistocene	1,001	25.6	7.6
12	Cuglieri	slope	730	WNW	50	degraded macchia	lava flow	tephritic-phonolitic	Upper Pliocene to Middle Pleistocene	740	25.3	9.2
11	S.ta Caterina	plain	172	NW	1	natural grasses	lava flow	phonolitic	Upper Pliocene to Middle Pleistocene	527	25.8	10.6
Sequence B												
7	M.te Entu	slope	980	ESE	20	low macchia	tephra deposits	phonolitic	Upper Pliocene to Middle Pleistocene	1,001	25.6	7.6
10	La Madonnina	slope	875	N	45	wood	tephra deposits	phonolitic	Upper Pliocene to Middle Pleistocene	1,001	25.6	7.6
9	Su Cantaru	slope	795	WSW	40	wood	tephra deposits	phonolitic	Upper Pliocene to Middle Pleistocene	1,001	25.6	7.6

† asl is above sea level.
‡ Mean annual precipitation.

Phosphate retention was quantified (Blakemore *et al.,* 1987). Iron, Al, and Si were extracted by Na-dithionite-citrate (Fe_d, Al_d, Si_d) and by NH_4-oxalate (Fe_o, Al_o, Si_o); Fe and Al were also extracted by Na-pyrophosphate (Fe_p, Al_p). Iron, Al, and Si in solution were determined by AAS. The allophane content was estimated from selective dissolution extracts (Parfitt, 1990).

Allophane Al/Si molar ratio was estimated from $(Al_o\text{-}Al_p)/Si_o$. Allophane was calculated by multiplying Si_o by a factor depending on the Al/Si molar ratio, assuming allophanes with Al/Si = 1 contain 20% Si_o and allophanes with Al/Si = 3.5 contain 6.25% Si_o. Intermediate Si_o contents of allophanes with intermediate Al/Si molar ratios were determined assuming a linear relationship between Si_o and Al/Si molar ratios of 1 and 3.5. Volcanic glass was identified in the sand fraction (2.0-0.02 mm) using a petrographic microscope (Soil Survey Laboratory Staff, 1996).

Results and Discussions

Pedons belonging to sequence *A* are very shallow to shallow and have very dark grey to dark brown A horizons, generally with subangular blocky structure (Table 2). The A horizon directly overlies an R horizon in pedon 11, whereas in pedons 6 and 12 the A horizons overlie a Bw horizon and a Cr horizon, respectively. Pedons belonging to sequence *B* are moderately deep and show profiles that are more developed than those of pedons of sequence *A* (Table 2).

They have black to dark grey A horizons with granular structure in the upper part (A1) and granular to subangular blocky structure in the lower part (A2), over thin Bw or BC horizons. The underlying C horizons are massive. Differences in soil profile development between pedons of sequences *A* and *B* are mainly due to the different parent materials of these soils. The thick tephra deposits, generally moderately coherent, are less resistant to weathering than the phonolitic lavas.

These results in the formation of deeper and more differentiated soils on tephra deposits. These soils may support wood type vegetation, while the shallow pedon 12 of sequence *A*, in similar climatic conditions, may support only a degraded macchia. Differences in vegetation cover have strongly influenced the A horizon characteristics. The pedons of sequence *B* are generally darker and the structure mainly tends to be granular. There are no significant morphological differences among pedons within each sequence.

The differences in texture among the pedons reflect their origin from different volcanic materials (Table 3). Horizons of pedons belonging to sequence *A* generally have lower clay content than horizons of pedons of sequence *B*. In pedons of sequence *A*, the texture becomes finer with decreasing elevations. Horizons of pedons of sequence *B* for which the data are available have oven-dry bulk densities 0.80 Mg m^{-3}, with the exception of the A2 horizon of pedon 7 (1.00 Mg m^{-3}) (Table 3).

This is typical for tephra derived soils at the weathering stage where a porous soil structure has developed, strongly influenced by noncrystalline materials and high soil organic matter concentrations (Wada, 1985; Shoji *et al.,* 1993).

Table 2. Selected morphological properties of all pedons

Horizon	Depth	Moist colour	Dry colour	Texture †	Structure ‡	Moist Consis-tence§	Roots¶	Lower boundary #
	Cm							
Sequence A								
Pedon 6								
A	0-8	10YR3/1	10YR4/2	ls	2f&msbk	fr	3f	as
Bw	8-20	10YR4/2	10YR5/3	ls	2f&msbk	fr	2f&m	as
R	20+	-	-	-	-	-	-	-
Pedon 12								
A1	0-2	10YR3/2	10YR4/2	sl	2fgr/2fsbk	vfr	3f	cs
A2	2-25	7,5YR3/2	10YR4/3	l	3m&csbk	vfr&fr	3f&m	aw
Cr	25-40	-	-	-	ma	-	-	ai
R	40+	-	-	-	-	-	-	-
Pedon 11								
A	0-31	7,5YR3/2	10YR5/3	l	3msbk/3mabk	fr	2f	aw
R	31+	-	-	-	-	-	-	-
Sequence B								
Pedon 7								
A1	0-8	10YR3/3	7.5YR3/2	l	2vfgr	vfr	3f&m	cw
A2	8-25	10YR2/1	10YR4/4	l	3f&msbk	vfr	3f&m	aw
BC	25-40	7.5YR4/2	10YR6/6	sl	1m&cabk	vfr	2f	cw
C1	40-70	7.5YR4/2	10YR7/4	sl	ma	vfi	1f	as
C2	70+	-	10YR8/3	ls	ma	vfi	1f	-
Pedon 10								
A1	0-30	10YR2,5/1	10YR4/2	l	2&3vf&f&m gr	vfr	3vf&m	cs
2A2	30-40	10YR2/1	10YR4/2,5	ls	2vf&f&mgr	vfr	3vf&m	cw
2Bw	40-54	10YR3/2	10YR5/3	ls	2f&mgr	fr	3f&m	as
2C1	54-80	10YR4/4	10YR7/4	sl	ma	vfi	0	gs
2C2	80+	10YR5/3	10YR7/3	sl	ma	efi	0	-
Pedon 9								
A1	0-4	10YR2/1	10YR2/1	ls	1vfgr	vfr	3f&m	aw
A2	4-10	10YR4/1	10YR4/2	l	3fgr/3msbk	vfr	3f&m	cw
Bw	10-40	10YR5/4	10YR4/4	sl	3fsbk	vfr	3f&m	cw
BC	40-75	2.5YR6/6	2.5YR6/6	l	1f&msbk	vfr	2f&m	gw
C	75-100	2.5YR6/4	2.5YR7/4	l	ma	vfr	2f&m	-

† ls = loamy sand, sl = sandy loam, l = loam.
‡ A slash means that structure parts to the structure following the slash symbol. Grade: 1 = weak, 2 = moderate, 3 = strong; Size: vf = very fine, f = fine, m = medium, c = coarse; Kind: gr = granular, sbk = subangular blocky, abk = angular blocky, ma = massive.
§ vfr = very friable, fr = friable, vfi = very firm, efi = extremely firm.
¶ Abundance: 0 = none; 1 = few, 2 = common, 3 = many; Size: vf = very fine, f = fine, m = medium.
# Distinctness: a = abrupt, c = clear, g = gradual; Topography: s = smooth, w = wavy, i = irregular.

All horizons of pedons belonging to the sequence *A* for which the data are available have oven-dry bulk densities 1.03 Mg m^{-3} (Table 3). The highest value of 1.48 Mg m^{-3} is for the A horizon of pedon 11, which is located at 172 m a.s.l.

Table 3. Selected physical and chemical properties of all pedons.

Horizon	Depth	Sand*	Silt*	Clay *	Bulk density	pH H_2O	pH KCl	pH NaF	OC	Phosphate retention	Volcanic glass†
	cm		g kg^{-1}		Mg m^{-3}				g kg^{-1}	%	
Sequence A											
Pedon 6											
A	0-8	801	137	62	1.27	4.6	4.1	9.1	36	8	<5
Bw	8-20	840	110	50	1.18	5.0	4.2	9.2	19	9	<5
Pedon 12											
A1	0-2	524	366	110	1.03	5.7	5.0	10.7	59	45	<5
A2	2-25	486	403	111	-	6.2	5.0	10.6	33	34	<5
Pedon 11											
A	0-31	407	413	180	1.48	5.4	4.3	8.8	21	12	<5
Sequence B											
Pedon 7											
A1	0-8	355	437	208	0.61	6.2	4.8	10.7	48	52	<5
A2	8-25	451	419	130	1.00	6.2	4.7	11.2	24	58	<5
BC	25-40	524	357	119	-	6.4	4.6	11.2	8	48	<5
C1	40-70	619	327	54	-	6.0	4.4	11.0	3	36	<5
C2	70+	770	202	28	-	6.4	4.4	10.7	1	11	<5
Pedon 10											
A1	0-30	448	339	213	0.80	5.6	4.2	9.8	53	49	<5
2A2	30-40	746	231	23	0.79	5.7	4.3	11.8	43	84	<5
2Bw	40-54	780	202	18	0.79	5.5	4.2	12.0	43	82	<5
2C1	54-80	758	147	95	-	5.3	4.3	11.9	8	48	<5
2C2	80+	805	20	175	-	5.6	4.1	11.6	5	49	<5
Pedon 9											
A1	0-4	800	153	47	0.78	5.9	5.2	10.3	68	54	<5
A2	4-10	482	394	124	0.45	6.4	5.1	10.4	50	41	<5
Bw	10-40	693	252	55	-	6.0	4.4	11.3	16	60	<5
BC	40-75	388	494	118	-	5.5	4.0	11.0	6	40	<5
C	75-100	410	476	114	-	5.2	3.6	10.1	3	22	<5

*Sand: 2-0.02 mm; Silt: 0.02-0.002 mm; Clay: <0.002 mm.
†Volcanic glass of the 0.02-2.0 mm fraction.

Water pH values range from 4.6 to 6.2 in pedons of sequence *A*, and from 5.2 to 6.4 in pedons of sequence *B* (Table 3). The lowest values are for pedon 6, which is at 1,005 m a.s.l. where probably rainfall peaks the highest value. Potassium chloride pH is 0.5 to 1.2 units lower than pH(H_2O) in pedons of sequence *A* and 0.7 to 2.0 units lower than pH(H_2O) in pedons of sequence *B*.

Moreover, pedons belonging to sequence *B* have pH(NaF) values generally >10.0, with the exception of the A1 horizon of pedon 10, which can be indicative of amorphous material (Shoji and Ono, 1978). In sequence *A*, only pedon 12 shows pH(NaF) values >10.0. Organic C concentrations are highest in the surface horizons and decrease with depth in all soils (Table 3). In pedons 9 and 10, located under wood, appreciable amounts of organic C are also present in the Bw horizons.

The lowest concentration of organic C is for pedon 11, which is located at 172 m a.s.l. under natural grasses. Phosphate retention is higher in pedons belonging to sequence *B*, generally with values ranging from 36% to 84% (Table 3). Only the C2 horizon of pedon 7 and the C horizon of pedon 9 have phosphate retention <25%. In pedons of sequence *A*, phosphate retention is >25% only in pedon 12. Volcanic glass is always <5% of the 0.02-2.0 mm fraction of all pedons (Table 3).

Selective dissolution results (Table 4) show that generally, with the only exception of pedon 6, concentrations of Fe_d are higher than Fe_o and Fe_p, indicating that considerable amounts of Fe released from the weathering of Fe-bearing minerals are transformed into more or less crystalline Fe-oxides.

This is reflected also by the Fe_o/Fe_d ratio, which is related to the degree of crystallinity of the iron oxides (Schwertmann, 1985) and shows values 0.50, with the only exception of pedon 6 where the poorly crystalline fraction of Fe-oxides is dominant, probably due to the colder and more humid climate.

Concentrations of Fe_o are generally higher than Fe_p. The Fe_p/Fe_o ratios of pedons belonging to sequence *A* are generally lower than the Fe_p/Fe_o ratios of pedons of sequence *B*. These Fe_p/Fe_o ratios are suggesting that in pedons of sequence *A* the noncrystalline form of Fe is generally ferrihydrite as opposed to organically bound Fe, whereas in pedons of sequence *B* it is the opposite. Aluminium oxalate values of A and Bw horizons of pedons belonging to sequence *B* are ranging between 7.0 and 18.6 g kg^{-1}, while Al_o values of horizons of pedons belonging to sequence *A* are 6.5 g kg^{-1}.

The A and Bw horizons of the studied pedons have Al_p/Al_o ratios ranging from 0.36 to 1.0 (ratios >1.0, like for horizons Bw of pedon 6 and A2 of pedon 12, are likely due to a significant fraction of the colloidal Al passing the filter), which reflect the occurrence of a consistent fraction of organically bound Al. Acid-oxalate Al (Al_o) and Si (Si_o), together with pyrophosphate extractable Al (Al_p), are used to estimate the Al/Si molar ratio of the short-range-order Al-Si material and the contents of allophane and imogolite (Dahlgren, 1994).

Allophane data should be used with caution in the case of Al/Si molar ratios considerably lower than one and greater than two, because allophane and imogolite structures with these compositions have never been isolated from soils (Dahlgren, 1994). Only for the A1, BC and C1 horizons of pedon 7 and the A1 and A2 horizons of pedon 9 the Al/Si molar ratio values are in the range to estimate allophane content. Estimated allophane concentrations in these horizons are 4%.

Pedons of sequence *A* do not satisfy the criteria for andic soil properties (Soil Survey Staff, 1998) because of their to low phosphate retention, $Al_o + 0.5\ Fe_o$, and volcanic glass content. Moreover, all pedons of sequence *A* have bulk density values 1.03 Mg m^{-3}. Pedons of sequence *B* do not satisfy the criteria for andic soil properties only for their volcanic glass content <5%.

According to Soil Survey Staff (1998) pedons of sequence *A* classify as Lithic Udipsamment (pedon 6), Lithic Dystrustept (pedon 12), and Humic Lithic Dystroxerept (pedon 11). All the three pedons of sequence *B* classify as Andic Dystrudepts. The Andic Great Group is due to bulk densities 1.00 Mg m^{-3} and to $Al_o + 0.5\ Fe_o$ contents >1.0% throughout horizons with a total thickness 18 cm within 75 cm of the mineral soil surface.

Table 4. Results of selective dissolution analysis of <2-mm soil of all pedons

Horizon	Depth	Fe_d	Fe_o	Fe_p	Al_d	Al_o	Al_p	Si_d	Si_o	Fe_o/Fe_d	Fe_p/Fe_o	Al_p/Al_o	$(Al_o - Al_p)/Si_o$ molar ratio	All.†	Al_o + 0.5 Fe_o
	cm					g kg^{-1}								%	
Sequence A															
Pedon 6															
A	0-8	5.8	3.7	2.0	0.8	1.9	1.7	3.4	0.6	0.67	0.55	0.89	0.35	ND	0.38
Bw	8-20	6.3	6.3	2.6	0.4	0.6	0.7	3.4	0.4	1.01	0.41	1.14	0.00	ND	0.37
Pedon 12															
A1	0-2	7.3	1.2	0.4	3.4	6.5	3.0	6.9	16.3	0.17	0.33	0.46	0.23	ND	0.71
A2	2-25	9.7	3.0	1.9	3.2	1.0	4.6	6.7	13.3	0.31	0.63	4.57	0.00	ND	0.25
Pedon 11															
A	0-31	13.6	5.2	2.4	0.6	5.4	2.7	5.5	10.5	0.38	0.47	0.49	0.27	ND	0.80
Sequence B															
Pedon 7															
A1	0-8	20.9	8.0	0.0	4.7	16.4	6.3	6.0	3.9	0.38	0.00	0.38	2.72	4	1.94
A2	8-25	19.7	7.3	4.4	4.0	18.6	6.6	4.5	2.4	0.37	0.60	0.36	5.30	ND	2.04
BC	25-40	15.3	3.8	5.6	6.1	15.3	10.1	9.9	2.9	0.25	1.47	0.67	1.81	2	1.72
C1	40-70	15.1	3.4	3.3	5.4	8.6	6.8	9.0	2.5	0.22	0.98	0.79	0.76	1	1.20
C2	70+	6.5	0.3	0.2	1.6	0.6	0.4	5.0	1.2	0.04	0.68	0.68	0.17	ND	0.08
Pedon 10															
A1	0-30	13.1	4.6	5.5	5.2	9.6	8.0	7.1	14.9	0.35	1.19	0.84	0.11	ND	1.19
2A2	30-40	12.0	5.8	5.9	9.6	16.8	13.0	8.2	9.1	0.48	1.01	0.78	0.43	ND	1.97
2Bw	40-54	9.6	4.8	4.6	9.9	17.1	11.8	7.7	12.8	0.50	0.95	0.69	0.44	ND	1.96
2C1	54-80	6.5	1.4	0.8	3.9	11.4	2.7	4.3	20.8	0.23	0.56	0.23	0.44	ND	1.22
2C2	80+	7.5	2.2	0.8	2.7	0.7	2.0	0.5	9.8	0.30	0.38	2.74	0.00	ND	0.18
Pedon 9															
A1	0-4	7.3	1.8	0.9	3.5	9.7	3.5	1.8	2.0	0.24	0.51	0.37	3.19	2	1.06
A2	4-10	7.4	2.1	1.9	2.7	7.0	2.9	3.4	5.0	0.29	0.88	0.41	0.86	<1	0.81
Bw	10-40	7.9	3.5	3.0	3.0	11.7	7.8	3.5	11.7	0.45	0.84	0.68	0.35	ND	1.35
BC	40-75	3.1	0.6	0.4	0.8	6.4	2.9	4.6	6.9	0.20	0.73	0.46	0.53	ND	0.09
C	75-100	3.4	0.6	0.0	0.3	2.8	0.6	6.1	3.6	0.17	0.07	0.18	0.65	ND	0.06

† All. = allophane, Si_o method (Parfitt, 1990).

Conclusions

The two studied soil sequences are strongly different in their morphological, physical, and chemical properties. The different nature of parent materials has played a significant role in determining the different pedological trends of these soils. In the very shallow and shallow soils of sequence *A*, formed from phonolithic lavas, the formation of short-range-order aluminosilicates is limited. In contrast, pedogenesis in the moderately deep soils of sequence *B*, formed from phonolithic tephra, induced the formation of a considerable amount of short-range-order aluminosilicates, with a consistent fraction of organically bound Fe and Al.

Differences in climate, due to different elevation a.s.l., seems to be responsible for pH(H_2O), organic carbon, and selective dissolution data variations within pedons of sequence *A*. For soils of sequence *B* there are no significant climatic differences, due to the small difference in elevation between the three pedons. Nevertheless, variations, among the three pedons, in selective dissolution data concerning Fe and Al could be related with small climatic changes.

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