Pedogenesis in a fluvial terrace chronosequence in the Pacific Northwest, USA

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Abstract

We evaluated pedogenic properties in a river terrace chronosequence in the Oregon Coast Range with the purpose of identifying pathways and rates of soil genesis. Knowledge of time-dependent changes in soil properties enables approximations of residence times to be made for soils of unknown ages. We also used a mass balance analysis to determine how rates and forms of mass losses change over the course of soil development. Changes in soil properties observed in the soil chronosequence include an increase in profile thickness, soil redness, and accumulation of secondary minerals. Losses of weatherable minerals and total Si, Na, Ca, and K increase with terrace age. Fe is conserved in secondary crystalline oxides, and elemental Al is conserved in Al-Si clay minerals. The largest changes in soil physical and chemical properties occur within the first five terraces. The advancement of the weathering front to depths of nine meters in the two oldest terraces contributes to the large mass loss of Si.

Key Words

Quantitative pedogenesis, desilication, podzolization, marine terraces.

Introduction

Bockheim *et al.* (1992) developed a model of pedogenesis for the udic moisture regime (mean annual rainfall of 1900 mm), isomesic temperature regime (mean annual air temperature 11.7˚C) region of coastal Oregon, USA, from chronosequences of soils across flights of coastal marine terraces. The soils formed in surficial deposits of sand derived from in situ and reworked beach and beach face sediments under predominately Sitka spruce in the younger (80 to 125 ky) and Douglas-fir in the older (240 to >500 ky) terraces. The marine terrace model of Bockheim *et al.* (1992) suggests that in-situ clay formation and podzolization dominate early in pedogenesis, leading to development of Inceptisols and Spodosols; after intermediate periods of soil formation, podzolization and argilluviation act concurrently to form spodic and argillic horizons in soils classified as Ultisols; in late stages of soil development, argilluviation and clay neoformation are the dominant soil-forming processes and form strongly expressed Ultisols.

In this paper we test the general validity of this model in coastal Oregon, recognising that the soil sequences it is based on form in a quartz-rich, coarse-textured parent material, have relatively low temporal resolution, and receive high accessions of marine aerosols. Our test is based on morphological, chemical and mineralogical characterisation of a chronosequence of soils formed on fluvial terraces of the Siuslaw River in the Oregon Coast Range (OCR). A key question centres on the absence of Spodosols in the OCR chronosequence whereas this soil order features prominently in the coastal and marine terraces of Oregon and California and in the marine terrace model (Bockheim *et al.* 1992; Bockheim and Langley-Turnbaugh 1997; Langley-Turnbaugh and Bockheim 1997; 1998).

Methods

Site description

The OCR chronosequence comprises seven fluvial terraces formed along a ridge on the inside of a meander bend of the Siuslaw River in Lane County of western Oregon. The lower five terraces (T1 through T5, Table 1) have an obvious broad, planar form and are underlain by silty to sandy alluvium and some colluvium derived from Eocene Tyee sandstone. The highest two sites (T6 and T7) are terrace remnants recognisable only as benches in the ridge and denudation has removed the alluvial coverbeds, although deeply weathered soils persist. Ages of the two youngest terraces were determined by radiocarbon dating of detrital charcoal in the soil pits of Terraces 1 and 2; and, ages of the five other terraces were calculated using elevation above modern river valley and incision rate (Almond *et al.* 2007). The terraces range in age from several thousand to ~990 ky.

Table 1. Study site properties.

Terrace	Terrace age (ky)†	Elevation (m)‡	Depth of weathering (cm)	Soil suborder
T1	3.5	85.5	25	Psamment
T2	20	89.0	109	Udept
T3	69	94.3	260	Udult
T4	140	106.9	310	Udult
T5	200	117.6	460	Udult
T6	908	248.9	>910	Humult
T7	990	263.8	>1100	Humult

†Terrace ages and ‡elevations from Almond *et al.* 2007. Ages of terrace 1 and 2 determined from radiocarbon dating of detrital charcoal; ages of terraces 3 through 7 calculated from uplift rates and terrace elevations.

Field sampling

Soil pits were dug to at least 1.4 meters in the first five terraces, and roadside exposures were used in the two remnant and oldest terraces. Soils were described by genetic horizon using the standard methods (Milne *et al.* 1995) and sampled in 10 cm increments. An auger was used to collect samples deeper than the exposed pits either to the parent material or the maximum extent of the auger. Bulk density was calculated using a soil sleeve of known volume in the top two meters and a bucket auger of known volume in deeper locations.

Laboratory analyses

All laboratory procedures were performed according to standard USDA methods (Soil Survey Staff 2004). Soils were air-dried and sieved to <2 mm at University of Oregon at Eugene. Representative subsets of samples were sent to ALS Chemex (Sparks, NV) for total elemental analysis and to University of California at Santa Barbara for soil physical and chemical analyses. Base cations were extracted at pH 7 with 1M NH_4oac and analysed by flame atomic absorption spectrometry. Cation exchange capacity (CEC-7) was determined with 1M KCl and a colorimetric autoanalyzer analyser. Electrical conductivity (mS/cm) and pH were measured on the supernatant of a 2:1 water to soil solution with handheld and bench-top meters. Soils were extracted for Fe and Al with 0.1M sodium pyrophosphate (McKeague 1967), 0.2M ammonium acid oxalic acid buffered at pH 3 (McKeague and Day 1966), and dithionite-citrate-bicarbonate (Mehra and Jackson 1960). Extracts were analysed by flame atomic absorption spectroscopy and correspond to the crystalline, non-crystalline, and organically-complexed Fe and Al oxides. Percent C and N were determined by the combustion method utilizing a Carla-Erba analyser after samples were ground to a fine mesh. Particle size distribution was determined by the pipette method on samples pre-treated for organic matter using H_2O_2 and for iron oxides using dithionite-citrate-bicarbonate (Jackson 1954). Sand fractions were wet sieved prior to sedimentation and prepared for analysis by XRD via random powder mounts. A qualitative analysis was performed using the relative intensities of diagnostic diffraction peaks to determine relative abundances of quartz, potassium feldspars, and plagioclase feldspars in sand-sized fractions (Moore and Reynolds 1997). Diffractograms were obtained with a Bruker D8 Advance diffractometer with a CuKα beam, scan range of 4° to 60° 2θ, step size of 0.015° 2θ, and step time of 0.5 seconds.

Results

Soils change from Entisols (T1) to Inceptisols (T2), to Ultisols (T3 and older). The most striking feature of soil morphological evolution is reddening. Soil hues are 2.5Y on T1 and progressively redden to 10R on the oldest two terraces (Figure 1). Reddening is associated with progressive increase in clay, expression of clay cutans, and formation of concretions. Strongly developed topsoils or surface organic (L, F, H) horizons are not strong features of any of the soils apart from a clear cumulate A horizon on T1.

Other than on T1, all soils are strongly acid, depleted in exchangeable base cations, and have low cation exchange capacities (Table 2). Pedogenic oxides of both Al and Fe accumulate over time and generally decrease in concentration with soil depth. Whereas pedogenic Al oxides comprise only a small fraction of total Al in all terraces, pedogenic Fe comprises an increasing amount of total Fe, with increasing degree of crystallinity, as soils age (Figure 2).

Table 2. Depth-weighted average chemical properties.

Terrace	pH	Soil Moisture ($\%, \theta_g$)	Ca	K	Na	Mg	CEC	Σ Cats
			----------------------------------		cmolc/kg		----------------------------------	
1	5.4	1.00	3.4	0.21	0.21	1.5	11.5	5.32
2	4.9	4.09	0.60	0.31	0.10	0.34	30.2	1.35
3	4.9	2.64	0.16	0.16	0.10	0.31	17.5	0.74
4	5.1	2.67	0.25	0.20	0.14	0.38	19.4	0.98
5	4.9	2.45	0.05	0.13	0.07	0.15	16.7	0.39
6	4.8	2.94	0.32	0.14	0.14	0.32	20.7	0.92
7	4.9	2.66	0.13	0.12	0.11	0.16	17.6	0.53

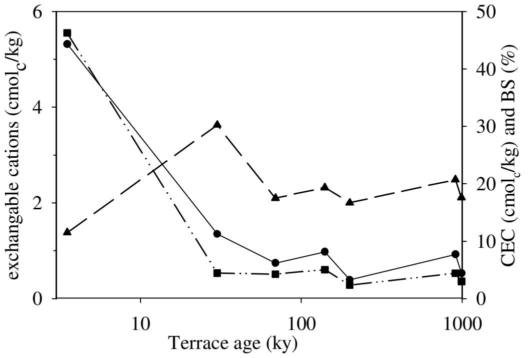

Figure 1. Chemical properties of B horizons. The youngest aside, all soils are depleted in exchangeable base cations (Σ cations, ●) and have low base saturations (BS, ■). Maximum cation exchange capacity (CEC, ▲) in the chronosequence soils occurs in terrace 2, and all others have relatively similar and low CECs.

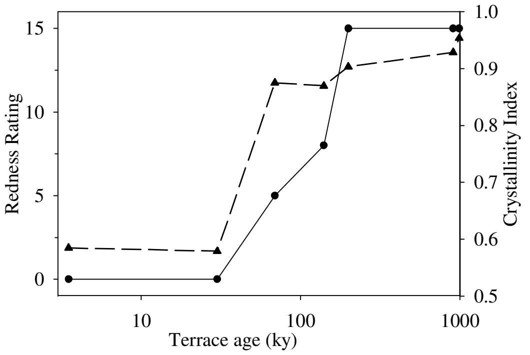

Figure 2. Crystallinity and redness ratings of B horizons. Crystallinity (●) was calculated as [1-(Fe_{ox}/Fe_{dcb})]. Redness rating (▲) was calculated from field-moist colors as [(10-H)x(C/V] where H is hue, C is chroma, and V is value, and H was converted from Munsell hues of 10R, 2.5YR, 5YR, 7.5YR, and 10YR to 0, 2.5, 5, 7.5, and 10, respectively (Torrent *et al.* 1983).

Temporal mineralogical changes of the sand fraction include an increase in the abundance of quartz at the expense of plagioclase and K-feldspars on increasingly older terraces. Soil chemical and physical properties, pedogenic Fe- and Al-oxide contents, sand mineralogy, and bulk-soil elemental analyses suggest progressive pedogenesis results in transformation of the primary minerals muscovite, biotite, Mg-chlorites, andesine, plagioclase feldspars, and K-feldspars to gibbsite, hematite, goethite, vermiculite, smectite, and kaolinite.

The dominant effects of pedogenesis are (1) depletion of Si, Na, Ca, K, and Mg; (2) conservation and redistribution of Al and Fe; and (3) transformation of Al and Fe from the parent material to secondary pedogenic oxides. Losses of Si represent the largest and most progressive net elemental depletion. Losses range from -28.7 g/cm^2 at 40 ky to -219 g/cm^2 by 990 ky. In contrast, Na and Ca losses are supply-limited and reach maximum depletion by 140 ky with net elemental losses of 5.62g/cm^2 and 3.41 g/cm^2, respectively. Maximum elemental depletion of K and Mg is reached by 200 ky, and losses subsequently lessen with age. Mineral analyses corroborate mass-balance results of Na and Ca removal with increasing age, and shifts of Si, Mg, and K from sand to clay-sized particles. Overall, the chronosequence data suggest a shift from depletion of bases and acidification as the dominant processes for the first 200 ky, to production and redistribution of secondary oxides and clay minerals thereafter, whilst Si is continually leached.

Conclusion

Important differences between the pedogenic evolution of the soils on marine terraces described by Bockheim *at al.* (1992) and our river terrace sequence include (1) an absence of Spodosols and (2) a rapid accumulation of clay in our chronosequence. After only 20 ky, B horizons contain >30% clay; in contrast, 105 ky is required to form this amount of clay in well-drained marine terrace soil sequence. The soil parent materials derived from the Tyee formation contain an abundance of pre-weathered and easily-weatherable minerals and the fluvial deposition processes have resulted in less textural and mineralogical sorting than the beach and eolian processes forming the parent materials of the marine terrace soils. Clays inherited from the parent material and formed by weathering appear to have a moderating effect on podzolization, allowing clay – Fe oxide complexes to form, and inhibiting strong redistribution of Fe and Al characteristic of podzolization. We speculate that as Fe oxides accumulate, organic chelating agents become saturated with Fe and are rendered immobile. Relatively rapid organic matter turnover in the dry, warm environment then prevents these compounds from accumulating. The net result is a pedogenic pathway that favours the accumulation of Fe oxides and clay. The pedogenic pathways represented by the coastal marine terrace chronosequences and the OCR chronosequence therefore probably reflect a bifurcation resulting from a subtle shift in the balance of formation of complexing organic compounds and secondary Fe oxides and clays. The shift in this balance may result from any combination of subtle differences in vegetation, marine aerosol inputs, parent materials, and bioturbation regimes.

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