Soil Forming Processes in Vernal Pools of Northern California, Chico Area

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Abstract. Vernal pools and swales represent small yet complete ecosystems whose existence is threatened due to urban expansion and agricultural development. This study was conducted to evaluate and understand the unique biogeochemical processes occurring in these endangered ecosystems, in order to enhance preservation and mitigation efforts. Soils in the summit, rim, and basin geomorphic positions of four pools and one swale were investigated to correlate soil morphological properties to soil chemical and mineralogical properties. Processes were determined by solid-phase characterization, soil solution analysis, and in situ measurement of redox potential. The dominant soil processes are ferrolysis, organic matter accumulation, clay formation and translocation, duripan formation, and calcium carbonate accumulation. These seasonally episaturated wetlands exhibit cyclic oxidation and reduction of Fe and Mn (ferrolysis) resulting in low pH and accelerated weathering above the duripan. By-products of ferrolysis are bases and metal cations in solution which move downward and accumulate above the duripan as the pools dry. Oxidation of Fe and Mn creates the redoximorphic features of high chroma Fe mottles, and neutral Mn stains, concentrations, and masses. Organic matter accumulation was highest in the surface horizons (0-8 cm), ranging from 9.3 to 76.2 g kg^{-1}. Clay formation and translocation occurred in all geomorphic positions with thicker soil profiles in the summit position than either the rim or basin positions. Clay accumulation produced subsurface horizons enriched in clay (37-56 %). Duripan formation occurs as illuvial weathering products, dominantly silica with accessory iron oxides and calcium carbonate, cement a subsurface horizon to varying degrees.

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Introduction

Vernal pools and swales are episaturated (perched zone of saturation) seasonal wetlands that are characterized by a unique assemblage of vegetation and soils. The existence of vernal pools and their remarkable plant association was first published by Jepson (1925). Once a common feature in the Great Valley of California (Hoover, 1937), they are still abundant in various local regions (Holland and Jain, 1977; Holland, 1978). This is the case in the Chico area where they are frequently located in Pleistocene-age alluvium on river terraces and on Pliocene-age Tuscan Formation lahars (mudflows of pyroclastic materials), volcaniclastic sediments, and tuff (Saucedo and Wagner, 1992).

Vernal pools are widely distributed throughout the state of California (Holland and Jain, 1977), and they are frequently located in undulating micro relief or hogwallow topography (Nikiforoff, 1941; Broyles, 1987). They are underlain by an impervious layer such as a hardpan (Nikiforoff, 1941; Holland and Jain, 1977), a dense clay layer (Schlising and Sanders, 1982), a cemented mudflow (Jokerst, 1990) or a lithic contact (Weitkamp et al., 1996). The importance of suitable soil and hydrologic requirements for vernal pool species cannot be underestimated. The Mediterranean climate of California leads to winter and spring filling of the pools followed by a late spring to summer dry down. Even though vernal pools are dependent upon rains and runoff for their seasonality, the edaphic factors are more important than regional climate for affecting surrounding vegetation (Holland and Jain, 1977).

Vernal pools and swales represent small yet complete ecosystems that constitute “islands” in the surrounding grassland vegetation (Stebbins, 1976). The majority of vernal pool plant species are annuals, and a large portion are endemic to California vernal pools (Holland and Jain, 1977). Rarity and endemism exemplify these ecosystems as reservoirs of biodiversity for flora (Stone, 1990) and fauna (Alexander and Syrdahl, 1992; Baker et al., 1992; Gallagher, 1996; Gonzalez et al., 1996). Pool water chemistry, which is directly linked to soil chemistry, has a dramatic influence on aquatic invertebrate distribution (Gonzalez et al., 1996) and may have a tremendous impact on aquatic invertebrate endemism. The water holding capacity of vernal pools and vernal pool soils provides a buffer against regional flooding, ground water recharge in some cases, and transpirational needs for vegetation as the pools dry down. Another important, and frequently overlooked, aspect of vernal pool ecosystems is their ability to cycle nutrients. As in other freshwater wetland ecosystems, nitrogen and phosphorus inputs are assimilated by biota (Schlesinger, 1991), and the turnover of nutrients is controlled through biotic and redox interactions (Schlesinger, 1991; Mitsch and Gosselink, 1993). Thus, vernal pools perform functions similar to other freshwater wetlands.

Despite earlier investigations of vernal pool soil morphology, soil chemistry, and geomorphology, there remains a lack of detailed research on biogeochemical processes within these wetland ecosystems. The first extensive soils investigation of California vernal pools was conducted by Nikiforoff (1941) in the San Joaquin Valley. He described the mound to intermound micro relief (hogwallows), hardpans, claypans, seasonally standing water, and variations in soils from mound to intermound as integral components within vernal pool areas. A related study in Australia (Hallsworth et al., 1955) identified undulating micro relief as 'gilgai' whose existence was attributed to differential swelling of the subsoil compared to the topsoil. Statistical analysis revealed swelling to be significantly related to the clay content, the exchange capacity of the clay, the amount of sodium on the exchange complex, and an increase with depth of these three factors.

One of the first plant ecologists to recognize the importance of soils as an integral part of an ecosystem was Jack Major (1951). He extended Hans Jenny's conceptual model for soil formation to vegetation (Jenny, 1941). He theorized that specific properties of vegetation and the plant community (as well as soil) were a function of climate, parent material, relief, organisms or biota, all integrated over time (Major, 1951). Various studies have recognized that vegetation and soil gradients exist within vernal pools (Lathrop and Thorne, 1976; Bauder, 1987). The influence of soil chemical and physical factors on plant distribution was evaluated in vernal pools of eastern Washington (Crowe et al., 1994). In that study only topography and moisture gradients showed statistically significant relationships with vegetation distribution. A study of vernal pool pedogenesis in the Santa Rosa Ecological Preserve, Riverside County, California verified dramatic differences in soil physical and chemical properties with geomorphic position (Weitkamp et al., 1996).

An understanding of vernal pool soils is essential to the maintenance and preservation of these unique ecosystems. The objective of this study was to evaluate and understand the role of soils and their unique biogeochemical processes in these endangered ecosystems. Solid-phase characterization, soil solution analysis, and in situ measurement of redox potential were used to identify the dominant processes in these soil systems.

METHODS AND MATERIALS

Field Sites

One vernal pool (underlain by lahar) and one vernal swale (with duripan) were examined at the City of Chico's Doe Mill Preserve (DMP) (39^o 43' 30" N and 121^o 46' 45" W). This 6.1 ha (15 acres) preserve protects vernal pool habitat for the endangered Butte County Meadowfoam (*Limnanthes floccosa* ssp. *californica)*. It is located on an intermediate fan terrace with undulating micro relief, and elevations range from 79 to 82 m (260 to 270 ft). The soils have formed in the Pliocene Tuscan Formation lahars, pumicous tuff, and associated alluvium (Saucedo and Wagner, 1992).

Three vernal pools (with duripans) were examined at Wurlitzer Ranch Preserve (WRP) (39^o 51' 30" N and 121^o 57' 30" W). This is a 24.3 ha (60 acres) preserve that was created to mitigate loss of vernal pool wetlands and loss of habitat for the endangered Butte County Meadowfoam *(Limnanthes floccosa* ssp. *californica*), due to a housing development adjacent to Doe Mill Preserve (Kelley and Associates, 1992). The site is also located on an intermediate fan terrace with undulating micro relief, and elevations range from 56 to 64 m (185 to 210 ft). The soils have formed in the Red Bluff Formation and in the Modesto-Riverbank Formations (Saucedo and Wagner, 1992). The Red Bluff Formation is mixed early-Pleistocene alluvium composed of coarse red gravels with minor interbedded sands and silt derived from the Coast Ranges via the Sacramento River. The Modesto-Riverbank Formations are dominantly andesitic, late- to middle-Pleistocene alluvium composed of gravel, sand, silt, and clay derived from the Tuscan Formation via various streams.

The climate is Mediterranean with an average of 660 mm of precipitation occurring from late fall to early or mid spring. Annual precipitation was 1193 and 588 mm for the 1994-1995 and 1995-1996 water years, respectively (National Weather Service, 1995; 1996). The average annual air temperature is 16.7 ^{o}C with average monthly temperatures of 7.8 ^{o}C for January and 27.8 ^{o}C for July (National Weather Service, 1995; 1996).

Field Methods

A summit-rim-basin transect was sampled for four vernal pools and one vernal swale. The summit to basin transects ranged from 5 to 11 m and the vernal pools ranged in size from 34 m^2 to 70 m^2 (see Table 1). Fifteen pedons were described in open pits for the representative summit, rim and basin positions. Soils were classified according to the Soil Survey Staff (1996).

Redoximorphic features were described according to Vepraskas (1992). Bulk samples were taken from each morphologic horizon (Soil Survey Laboratory Staff, 1992).

In situ platinum electrodes were installed in two of the five transects. These were installed in triplicate at a depth of 5 cm and immediately above the duripan, for each geomorphic position (summit-rim-basin). The platinum electrodes were calibrated in Zobell's solution (Nordstrom, 1977) prior to installation. Field pH and Eh were measured for each geomorphic position throughout the rainy season. Field pH was measured by making an in situ saturated paste of the surface soil horizon (0-2 cm).

Laboratory Methods

Rainfall and vernal pool water samples were taken approximately every two weeks. Mineral nitrogen was monitored as nitrate and ammonium using ion chromatography. Total nitrogen and dissolved organic nitrogen were determined by persulfate oxidation and conductimetric quantification on a Carlson nitrogen analyzer (Yu et al., 1994). Solution pH was taken before filtration, and solution EC was taken after filtration through a 0.2 µm membrane filter.

Bulk density was measured on intact clods using the paraffin-coated clod method (Singer, 1986). Bulk samples were air dried, gently ground with a mortar and pestle, and sieved to remove coarse fragments (>2 mm). Particle size distribution was determined by the pipette method after organic matter removal with H_2O_2, Fe removal with sodium dithionite-citrate, carbonate removal with pH 5 sodium acetate on affected horizons, and Si removal with 0.1 *M* sodium hydroxide on affected horizons (Soil Survey Laboratory Staff, 1992). Soil pH was analyzed in 1:1, soil:water suspensions after a 30 min equilibration. Electrical conductivity was measured in saturated pastes after a 4 hour equilibration. Soils were extracted with dithionite-citrate to determine the quantity of organically bound, amorphous, and various crystalline oxide forms of Fe and Mn (Wada, 1989). Ammonium oxalate was used to selectively extract amorphous and organically bound Fe and Mn (Parfitt, 1989). Exchangeable bases were determined by displacement with 1 *M* NH_4OAc (Soil Survey Laboratory Staff, 1992). Cation-exchange capacity was measured by saturation with 1 *M* NH_4OAc buffered at pH 7, followed by displacement with 10% acidified NaCl (Soil Survey Laboratory Staff, 1992). The displaced NH_4 was quantified on a Carlson conductimetric nitrogen analyzer. The Ca, Mg, Na, K, Fe, and Mn concentrations in the above extracts were measured using an inductively coupled plasma spectrophotometer (ICP). Calcium carbonate was determined by the evolved gas method (Williams, 1948). Total C was determined by dry combustion of powdered samples. Organic C is the difference between total C and C contained in calcium carbonate. Surface and subsurface andesitic cobbles were qualitatively analyzed for mineralogy by x-ray diffraction of random powder mounts. The clay fraction (<2 mm) was qualitatively analyzed for mineralogy by x-ray diffraction of oriented mounts on glass slides saturated with Mg, Mg + glycerol, and K.

Results and Discussion

Pool, Swale, and Soil Morphology

The characteristics of the four vernal pools and one vernal swale are shown in Table 1. Each pool is approximately oval shaped, and the swale is sloped at 3-4 %. The change in elevation from summit to basin varies from 30 to 45 cm with maximum water depths between 15 and 28 cm. The pool at DMP is a flow-through pool, underlain by lahar, and the swale has a duripan that is closer to the surface in the basin (18 cm) than either the rim (34 cm) or the summit (80 cm) positions. All three pools at WRP are underlain by a duripan which is also closer to the surface in the basin positions. Pools #1 and #3 are ground water recharge pools while pool #2 is a flow-through pool. Thicker soil profiles are observed in the summit position compared to the rim and basin positions for the four pools with duripans and the one pool with the lithic contact. The pool #1 transect at WRP (Figure 1) will be used to exemplify representative soil and biogeochemical processes, with supporting data from the other transects used to highlight specific features as necessary.

Ferrolysis

The hydromorphic soil forming process of ferrolysis involves cyclic reduction and oxidation of iron, which leaches displaced base cations and accelerates mineral weathering (Brinkman, 1970). The seasonal nature of vernal pools creates repetitive cycles of anaerobic and aerobic conditions. During the reduction phase, soluble ferrous iron (Fe^{+2}) is formed which displaces base cations from the exchange capacity. These base cations are leached from the soil with bicarbonate formed by biotic respiration or concentrated at the depth of leaching (e.g., $CaCO_3$

Table 1. Physical properties of four vernal pools and one swale.

Location†	Size	Summit-basin Distance	Change in Elevation	Depth‡
DMP pool	34 m^2	5 m	45 cm	28 cm
DMP swale	3 m width	5 m	43 cm	20 cm
WRP #1	70 m^2	11 m	40 cm	25 cm
WRP #2	42 m^2	8 m	30 cm	18 cm
WRP #3	50 m^2	11 m	40 cm	15 cm

† DMP means Doe Mill Preserve, and WRP means Wurlitzer Ranch Preserve.

‡ Maximum depth of water.

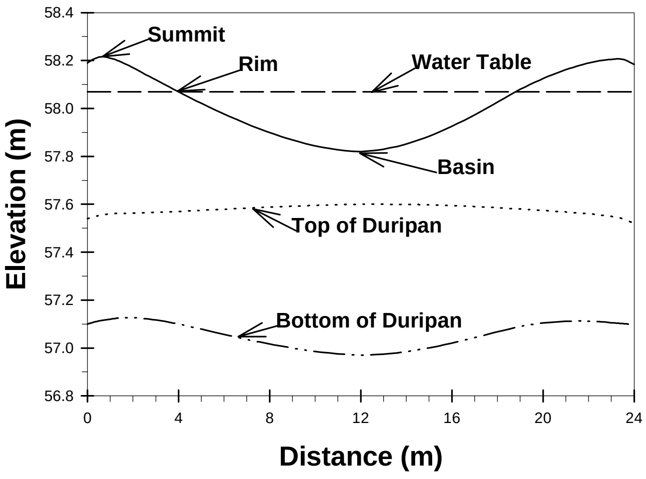

FIGURE 1. Cross section of WRP pool #1. showing surface, duripan, and maximum height of pool water. Summit, rim and basin position arrows indicate location of in situ platinum electrodes and approximate locations of pedons.

accumulation). Reduction reactions consume protons (H^+) resulting in an increase in soil pH during the period of reduction. Subsequent oxidation of exchangeable ferrous iron to ferric iron (Fe^{+3}) produces protons which acidify the soil and contributes to low base saturation. The low pH associated with the oxidation creates a harsh weathering environment (Brinkman, 1970; Van Breeman et al., 1983).

Among the first researchers to identify this seasonal cycling of iron and manganese in flooded soils was Ponnamperuma (1963; 1964; 1966) during his research on rice fields. He developed Eh-pH stability diagrams for the reduced and oxidized forms of iron and manganese (Ponnamperuma et al., 1967; 1969). Research has subsequently verified many stability field diagrams (Eh-pH diagrams) for combined redox species in soils (Collins and Buol, 1970). When both reduced iron (Fe^{+2}) and manganese (Mn^{+2}) are present in the soil solution, iron oxidizes and precipitates sooner or at lower Eh-pH values compared to manganese.

Redox potential, or the oxidation-reduction potential, is a measure of electron availability, and it is measured as a voltage, Eh in millivolts (mV), that is necessary to prevent the flow of electrons between the environment and a reference electrode (Quispel, 1947; Bohn, 1971; Nordstrom, 1977). Redox potential in wetland soils can be used to quantify the tendency of the soil to oxidize or reduce substances (Faulkner and Richardson, 1989). As organic matter is oxidized (donates electrons) in anaerobic, waterlogged soils a sequence of reduction reactions (electron gains) occurs, and the redox potential drops (Mitsch and Gosselink, 1993). These oxidation and reduction reactions are microbially mediated through the consumption and production of oxygen and carbon dioxide (Paul and Clark, 1989). After the aerobic organisms consume oxygen present in the soil between approximately +600 to +400 mV, facultative and obligate anaerobes proliferate. They use oxidized soil components and organic matter as electron acceptors in their respiration and reduce the soil in the following sequence; disappearance of O_2 below +400 mV, disappearance of NO_3^- at +250 mV, appearance of Mn^{+2} at +225 mV, appearance of Fe^{+2} at +120 mV, disappearance of SO_4^{-2} at -75 to -150 mV, and the appearance of CH_4 at -250 to -350 mV (Mitsch and Gosselink, 1993). These redox potentials are not exact limits, as they are subject to the effects of temperature, pH, available organic matter, organic acids, saturation conditions, and the availability of reducible substrates. The additions of mineral nitrogen from the atmosphere, oxygen produced by photosynthesis from aquatic plants within the pools, and the abundance of manganese within the system (andesitic alluvium) tend to poise (buffer) the system preventing the reduction of iron until these substrates are consumed.

Within the monitored vernal pools, Eh values were sufficient to reduce nitrate, manganese, and sometimes iron. Platinum electrodes were used in situ in pool #1 for the 1995-96 season, and in pool #2 for the 1994-95 and 1995-96 seasons. The lowest Eh values were in the surface horizons at the 5 cm depth in the basin and rim positions. Pool #1 had the lowest Eh average values of +160 mV in the basin, +150 mV in the rim, and +210 mV in the summit for the 1995-96 season (Figure 2). Minimum Eh values in pool #2 were +150 mV in the basin, +260 mV in the rim, and +280 mV in the summit for the 1994-95 season compared to +160 mV in the basin, +120 mV in the rim, and +165 mV in the summit during the 1995-96 season.

These values indicate the tremendous spatial and temporal variability in redox processes and in reducible substrates within these ecosystems. The more acid soil conditions in the surface horizons, especially the basin and rim, shift the reduction to higher Eh values, which is consistent with theoretical stability diagrams (Collins and Buol, 1970; Ponnamperuma et al., 1967; 1969). In other words, reduction of iron and manganese occurs at higher Eh values in acid soils, such as those found at WRP and DMP. Consistent with the ferrolysis process is the inverse relationship of Eh and pH values (compare Figures 2 & 3). Reduction reactions consume protons increasing pH while oxidation reactions generate protons resulting in lower pH values (Brinkman, 1970; Van Breeman et al., 1983).

The effects of ferrolysis on vernal pools include accelerated mineral weathering which is verified by the dominance of the highly weathered kaolinitic (1:1) clays in the more reduced basin while mixed clay mineralogy (2:1 and 1:1 clays) is evidenced in the rim and summit (refer to soil taxonomy in Table 2). Additionally, the effects of ferrolysis include the release of bases, metal cations, and silicic acid into the soil solution for plant utilization, leaching of soluble constituents downward and to-

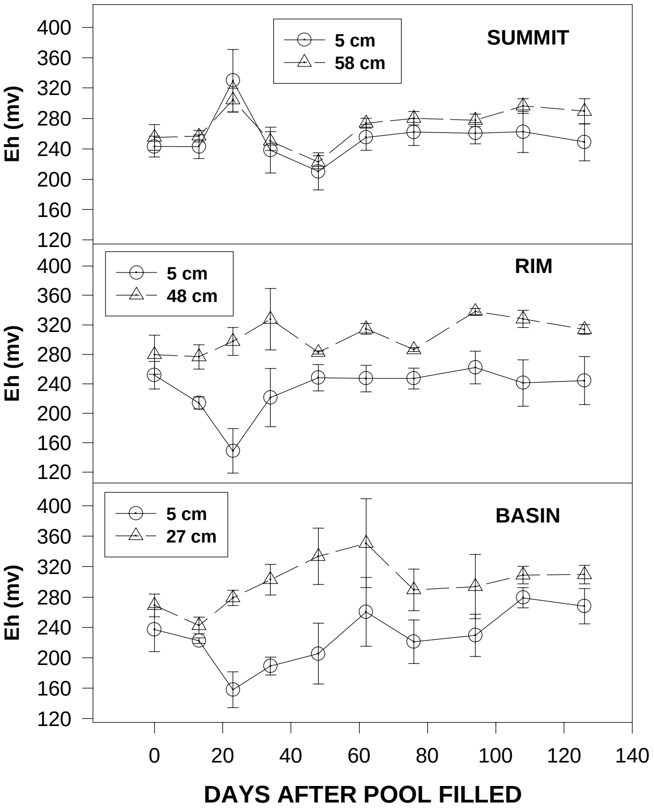

FIGURE 2. In situ Eh results for the summit-rim-basin transect of WRP pool #1. Platinum electrodes at 5 cm and above the duripan, in triplicate, were monitored from the initial filing to dry-down for 95-96 season. Note the lower levels in the rim and basin. Error bars represent standard deviations.

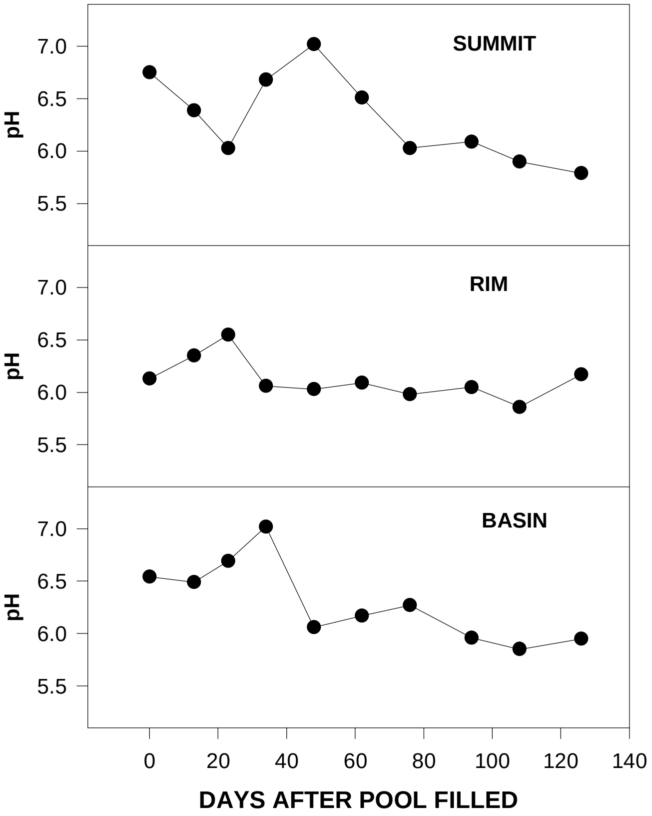

FIGURE 3. In situ pH from a saturated paste at 5 cm depth for the summit-rim-basin transect of WRP pool #1. The inverse relationship of pH and Eh is consistent with the ferrolysis process.

ward the basin, and upon dry-down and oxidation of the soil and the creation of redoximorphic features or redox concentrations (Soil Survey Staff, 1996). Depletions are zones of low chroma (2 or less) where Fe-Mn oxides, with or without clay, have been removed producing a reduced matrix having low chroma. The soils at WRP and DMP tend to have high amounts of dithionite extractable iron (Table 3) which obscure most visible depletions and colorize the soil matrix. Nevertheless, oxidation of Fe and Mn creates the redox concentrations of high chroma Fe mottles, and neutral Mn stains, concentrations, and masses (Table 3). Manganese stains, concentrations, and masses are distributed deeper within the soil profiles than Fe mottles, as Mn^{+2} is more mobile in the soil solution than Fe^{+2} (McDaniel and Buol, 1991) and Fe^{+2} oxidizes before Mn^{+2} (Collins and Buol, 1970). These redox features are diagnostic for identifying vernal pool soils as hydric soils (Vepraskas, 1992).

Organic Matter Accumulation

All the soil profiles examined show an accumulation of organic matter in the surface horizons above 20 cm, with the highest values in the 0-8 cm depth (Figure 4). Organic carbon concentrations in A horizons range from a low of 9.3 g kg^{-1} to a high of 76.2 g kg^{-1}. Concentrations of organic carbon in surface horizons of pool #1 were 60.8, 33.8, and 64.7 g kg^{-1} in the basin, rim and summit geomorphic positions, respectively (see Table 4). The lower concentrations measured in the rim position may result from erosional transport from this position, due to it having the maximum slope along the transect. Below a depth of 20 cm, organic carbon concentrations were generally less than 8 g kg^{-1}.

The vegetation at the two study sites is dominated by annual grasses and forbs (Kelley and Associates, 1991). The yearly turnover of annual vegetation produces surface litter and an abundance of dead roots in a shallow layer immediately below the soil surface (see Table 2). In some cases luxuriant algal mats form in the pools due to growth stimulated by nitrogen deposition via rainfall and dust. In these xeric grasslands where evapotranspiration exceeds precipitation, there is limited availability of water in the upper soil horizons to support microbial activity and organic matter decomposition during the summer. Furthermore, the seasonally anaerobic conditions of these wetlands inhibit organic matter decomposition during the winter and

TABLE 2. Physical and morphological properties of WRP vernal pool #1 soils.

Horizon	Depth	Color		------------ % ------------			Texture¶	Structure§	Bulk Density	Roots‡	Clay Films*ƒ*
		Dry	Moist	Sand	Silt	Clay					
Summit: fine, mixed, superactive, thermic Typic Durixeralf											
A	0-2	10YR 4/3	10YR 3/2	33.7	40.9	24.4	loam	1msbk	1.68	3vf	-
AB	2-10	7.5YR 5/4	7.5YR 3/4	31.4	44.8	23.8	loam	2csbk	2.23	3vf&1f	-
Bt1	10-30	7.5YR 5/4	5YR 3/3	28.5	43.6	27.9	clay loam	2msbk	2.24	2vf	2npo
Bt2	30-66	7.5YR 5/4	5YR 3/3	26.0	33.7	40.3	clay	3vcpr	2.30	2vf	3mkpf&po
2Btkqm	66-94	10YR 4/4	10YR 3/4	47.6	32.8	19.6	loam	3vcpl	2.22	-	-
2Btq	94-110	10YR 4/4	10YR 3/4	53.3	18.9	27.8	gscl	m	2.43	-	-
2BC	110-	10YR 4/4	7.5YR 4/4	63.2	16.5	20.3	gscl	m	2.04	-	-
Rim: fine, mixed, superactive, thermic Typic Durixeralf											
A	0-5	7.5YR 4/4	7YR 3/3	33.9	41.9	24.2	loam	2mpl	1.48	3vf	1npf
AB	5-12	7.5YR 4/4	5YR 3/2	33.3	43.1	23.6	loam	2m&csbk	2.05	2vf&1f	1mkpo
Bt1	12-24	7.5YR 4/4	7.5YR 3/4	22.9	39.7	37.4	clay loam	2cabk	2.29	2vf&1f	2mkpf&po
Bt2	24-50	7.5YR 4/4	5YR 3/3	21.3	37.5	41.2	clay	3cpr	2.28	2vf&1f	3kpf&po
2Btkqm	50-68	10YR 5/4	7.5YR 3/4	51.4	32.7	16.9	loam	3vcpl	2.19	1vf	3mkpf
2Btkq	68-97	7.5YR 4/4	7.5YR 3/4	45.2	24.0	30.8	scl	m	2.43	1vf	3mkpf
2BC	97-	7.5YR 4/4	5YR 3/3	50.8	19.1	30.1	vgscl	m	2.04	-	-
Basin: clayey, kaolinitic, thermic, shallow Aquic Durochrept											
A	0-5	7.5YR 5/4	7.5YR 3/4	22.8	40.3	36.9	clay loam	3mpl	1.66	3vf&1f	-
Bt	5-22	5YR 3/4	2.5YR 3/2	21.4	40.0	38.6	clay loam	3cpr	2.40	3vf	2mkpf&po
2Btkqm	22-34	10YR 4/4	7.5 YR3/4	62.9	23.2	13.9	cosl	3vcpl	2.10	-	3mkpf
2Btkq	34-53	10YR 3/6	5YR 3/3	58.4	20.9	20.6	scl	m	2.23	-	2nbr
2Btq	53-85	7.5YR 4/4	5YR 3/3	62.9	18.2	18.9	vgsl	m	2.11	-	2nbr
2BC	85-	7.5YR 4/4	5YR 3/3	64.7	16.7	18.6	vgsl	m	2.04	-	-

¶ gscl = gravelley (15-35%) sandy clay loam, scl = sandy clay loam, vgscl = very gravelley (35-60%) sandy clay loam, cosl = coarse sandy loam, vgsl = very gravelley (35-60%) sandy loam

§ 1 = weak, 2 = moderate, 3 = strong, f = fine, m = medium, c = coarse, vc = very coarse, sbk = subangular blocky, abk = angular blocky, pr = prismatic, pl = platy

‡ 1 = few, 2 = common, 3 = many, vf = very fine, f = fine

ƒ 1 = few (5-25%), 2 = common (25-50%), 3 = many (50-90%), n = thin, mk = moderately thick, k = thick, pf = ped faces, po = lining pores, br = bridges holding grains together

spring. These environmental conditions result in relatively slow decomposition rates and the accumulation of organic matter in the surface layers (Schlesinger, 1991).

The large component of fine root detritus and their slow rates of decomposition are important factors in the accumulation of soil organic matter in temperate grasslands (Oades, 1988). This is observed in the pool #1 transect (see Table 2) with many (≥ 5 per cm^2) very fine (1 mm) roots throughout the A and Bt horizons of the basin; A horizon of the rim; and A and A B horizons of the summit. Common (1-5 per cm^2) very fine (1 mm) roots are seen below the surface horizons to the duripan. A few (<1 per cm^2) very fine (1 mm) roots penetrate the large, very coarse platy structure of the duripan in the rim position. Lower bulk density and smaller soil structural units are associated with the abundance of roots and higher organic carbon concentrations in the surface horizons (see Table 2). As the roots and organic carbon diminish in the clay enriched horizons and duripan at depth, the bulk density and structure size increase. Roots are distributed deeper within the thicker soil profiles of the summit and rim. Platy soil structure is common in the surface of the basin and rim; subangular blocky structure is common in the surface of the summit; and coarse to very coarse (>50 to >100 mm) prismatic structure is common in the clay enriched layer above the duripan in the rim and summit.

The inputs of nitrogen via rainfall and dust, were monitored at WRP for the 1994-95 and 1995-96 rainfall seasons. The total

TABLE 3. Extractable Fe and Mn distributions, mottles and colors, in WRP vernal pool #1 soils. The Fe_d and Mn_d were extracted with citrate-dithionite. The Fe_o and Mn_o were extracted with ammonium oxalate.

	--------------g kg^{-1}--------------			Fe		--------------g kg^{-1}--------------			Mn	
Horizon	Fe_d	Fe_o	Fe_o/Fe_d	mottles¶	Color-dry	Mn_d	Mn_o	Mn_o/Mn_d	mottles¶	Color-dry
Summit: fine, mixed, superactive, thermic Typic Durixeralf										
A	25.4	6.0	0.24	cld	7.5YR 5/8	1.2	0.9	0.75	cld	N 3/0
AB	29.1	6.9	0.24	clf&d	7.5YR 5/8	1.0	0.7	0.70	cld	N 3/0
Bt1	30.4	3.4	0.11	-	-	1.3	0.8	0.62	cld	N 3/0
Bt2	29.8	3.4	0.11	-	-	1.2	0.8	0.67	-	-
2Btkqm	15.6	2.2	0.14	m2d	7.5YR 5/8	0.7	0.4	0.57	cld	N 3/0
2Btq	14.4	2.0	0.14	-	-	0.6	0.4	0.67	-	-
2BC	12.1	2.3	0.19	-	-	0.5	0.3	0.60	-	-
Rim: fine, mixed, superactive, thermic Typic Durixeralf										
A	30.8	13.4	0.44	mld	7.5YR 6/8	1.0	0.8	0.80	-	-
AB	29.9	9.8	0.33	flf	7.5YR 5/8	1.2	1.1	0.92	cld	N 3/0
Bt1	31.4	8.6	0.27	flf	7.5YR 5/8	1.3	1.1	0.85	cld	N 3/0
Bt2	25.2	6.1	0.24	flf	7.5YR 5/8	1.2	0.9	0.75	cld	N 3/0
2Btkqm	14.8	3.7	0.25	c2d	2.5YR 4/8	0.7	0.6	0.86	cld	N 3/0
2Btkq	17.1	4.1	0.24	c2d	2.5YR 4/8	0.7	0.6	0.86	cld	N 3/0
2BC	19.3	5.6	0.32	c2d	2.5YR 4/8	0.6	0.5	0.83	-	N 3/0
Basin: clayey, kaolinitic, thermic, shallow Aquic Durochrept										
A	29.9	9.4	0.31	mld	7.5YR 6/8	1.1	1.0	0.91	cld	N 3/0
Bt	28.9	7.5	0.26	fi*f*&d	7.5YR 5/8	1.2	1.0	0.83	cld	N 3/0
2Btkqm	13.2	2.6	0.20	m2d&p	2.5YR 5/8	0.7	0.5	0.71	cld	N 3/0
2Btkq	12.6	4.7	0.37	clf&d	7.5YR 6/8	0.6	0.5	0.83	c2d	N 3/0
2Btq	13.4	5.4	0.40	c2d	2.5YR 4/8	0.5	0.5	1.00	c2d	N 3/0
2BC	13.6	5.7	0.42	-	-	0.5	0.5	1.00	-	-

¶ f = few (<2% of surface area), c = common (2-20% of surface area), m = many (>20% of surface area), 1 = fine (<5 mm diameter), 2 = medium (5-15 mm diameter), 3 = large (>15 mm diameter), *f* = faint, d = distinct, p = predominant.

nitrogen deposited in the 1994-95 season was 6.7 kg ha^{-1}. The nitrogen deposited via rainfall and dust is part of the global nitrogen cycle which includes significant components from fossil fuel combustion and agricultural practices (Schlesinger, 1991). This input of nitrogen into the ecosystem stimulates plant growth, and it is quickly converted to organic forms by biota. Figure 5 shows how the high levels of nitrate and ammonium are rapidly assimilated by biota within the pools into biomass and dissolved organic nitrogen (DON). The late season algal blooms are a direct result of those nutrient inputs. Note the increased DON in all the pools, and especially in grazed pool WRP #3 which also receives elevated inputs of nitrogen and phosphorous from cattle excrement.

Organic matter accumulation increases soil aeration, water retention, cation exchange capacity, helps maintain a uniform pH, and provides nutrient elements for plant growth upon mineralization. Another, and perhaps the most beneficial, function of these ecosystems is that plant and microbial uptake and immobilization of nitrogen lessens the potential loss of nitrate via denitrification and leaching. A study of vernal dams in northern hardwood forests has shown the importance of plant and microbial uptake in minimizing nitrate losses (Zak et al., 1990).

Clay Formation and Translocation

Clay concentrations in all soils ranged between 20 and 60% indicating that clay formation is a dominant process occurring in these soils (Figure 6). The formation of silicate clays occurs by alteration of existing primary or secondary minerals or from over saturation and precipitation from the soil solution. As the weathering intensity increases, 2:1 layer silicates are progressively altered to 1:1 layer silicates and finally to oxides of iron and aluminum (Bohn et al., 1985; Brady, 1990). The type of clay minerals produced is dependent upon the geologic nature of the parent material (Bohn et al., 1985; Buol et al., 1989; Brady, 1990; Evans, 1992) as well as climate, biota, relief, and time (Jenny, 1941). The soils at WRP developed in mixed allu-

Table 4. Soil chemical properties of WRP vernal pool #1 soils.

Horizon	pH	EC	Organic C	$CaCO_3$	CEC	Ca	Mg	Na	K	Ca/Mg
		dS m^{-1}	g kg^{-1}	g kg^{-1}	----------cmol (charge) kg^{-1}----------					
Summit: fine, mixed, superactive, thermic Typic Durixeralf										
A	6.2	0.20	64.7	1.0	29.0	13.4	7.5	0.1	1.2	1.8
AB	5.9	0.16	8.0	0.7	22.3	3.6	13.3	0.1	0.6	0.3
Bt1	6.4	0.06	6.1	0.6	22.1	8.9	6.5	0.1	0.3	1.4
Bt2	6.7	0.05	0.8	0.6	24.4	10.0	8.0	0.2	0.3	1.3
2Btkqm	7.5	0.04	0.2	10.8	24.6	10.5	8.9	0.3	0.2	1.2
2Btq	7.3	0.04	0.9	0.8	23.7	9.8	8.3	0.3	0.2	1.2
2BC	7.4	0.04	0.9	0.0	18.3	7.3	6.2	0.3	0.2	1.2
Rim: fine, mixed, superactive, thermic Typic Durixeralf										
A	5.7	0.09	33.8	0.0	21.5	6.9	5.0	0.1	0.6	1.4
AB	6.0	0.04	9.4	0.8	22.6	7.5	6.3	0.1	0.4	1.2
Bt1	6.8	0.06	5.7	0.4	27.8	9.9	9.2	0.2	0.4	1.1
Bt2	6.5	0.07	5.4	0.4	32.9	13.6	12.6	0.2	0.3	1.1
2Btkqm	7.8	0.02	0.5	3.8	25.2	13.2	11.6	0.4	0.2	1.1
2Btkq	7.8	0.22	0.1	16.6	24.7	15.3	11.2	0.3	0.2	1.4
2BC	8.0	0.06	0.6	0.6	20.9	9.3	8.6	0.4	0.2	1.1
Basin: clayey, kaolinitic, thermic, shallow Aquic Durochrept										
A	6.2	0.24	60.8	0.0	27.5	9.9	8.3	0.2	0.7	1.2
Bt	6.2	0.10	23.2	0.0	28.6	11.3	9.2	0.2	0.5	1.2
2Btkqm	8.1	0.14	0.7	44.4	26.5	22.5	9.6	0.3	0.5	2.3
2Btkq	8.1	0.07	2.6	18.0	28.8	14.9	7.8	0.3	0.4	1.9
2Btq	8.1	0.13	1.4	0.0	25.1	10.1	6.6	0.4	0.4	1.5
2BC	8.2	0.05	0.6	0.0	17.9	8.9	6.1	0.3	0.3	1.5

vium (with some inherited clays) from the Coast Ranges and dominantly andesitic alluvium (with some inherited clays) from the Tuscan Formation. The soils at DMP developed on the andesitic and basaltic Tuscan Formation lahars, pumicous tuff, and associated alluvium. The products of this mineral weathering not only include secondary clay minerals, but bases (Ca, Mg, K, and Na), metal cations (Fe and Mn), and aqueous silica or silicic acid (H_4SiO_4) (Bohn et al., 1985; Brady, 1990). The soluble bases are available for plant utilization as are certain metal cations. Extractable bases and base saturation (Table 4) indicate the relative availability of these major nutrients from the soil. The aqueous silica may reprecipitate as silicate clay minerals (Bohn et al., 1985; Brady, 1990) or move downward to the depth of leaching where it subsequently precipitates to form a duripan (Flach et al., 1969).

The translocation of silicate clays from an overlying horizon (eluviation) into a lower horizon results in accumulation of silicate clays (illuviation) (Soil Survey Staff, 1975; 1995). If the clay percentage and horizon thickness of the illuvial horizon are sufficient, along with the presence of clay films, skins, or bridges, then an argillic horizon is designated (Soil Survey Staff, 1996). Soils with argillic horizons are common in soils on stable landscapes in regions with a seasonal soil-water deficit (Avery, 1985). Clay translocation and accumulation is observed in the particle size distribution for all geomorphic positions of the WRP pool #1 transect (Table 2 and Figure 6). Clay content increases with depth to the duripan, and soils are more strongly developed in the summit compared to the rim and basin positions. A lateral gradient also exists as clay percentages increase closer to the soil surface in moving from the summit to basin position. This may be a function of the physical swelling and shrinking of the soil and/or detachment and transport of soil particles (erosion) which moves soil material toward the basin. Soils in the summit position have 41.3, 56.5, and 54.7% clay in argillic horizons for pools #1, #2 and #3, respectively. The summit is the most stable landscape position as indicated by the presence of the most strongly developed soil. In pool #1, the summit and rim soil profiles are classified as Typic Durixeralfs (having an argillic horizon) and the basin soil profile was classified as an Aquic Durochrept (no argillic horizon).

Clay skins are formed when the soil solution transports the suspended clays along with any organic matter and iron compounds to the depth of leaching (Buol and Hole, 1961). The absence of clay films in the surface horizons and the presence of thick clay

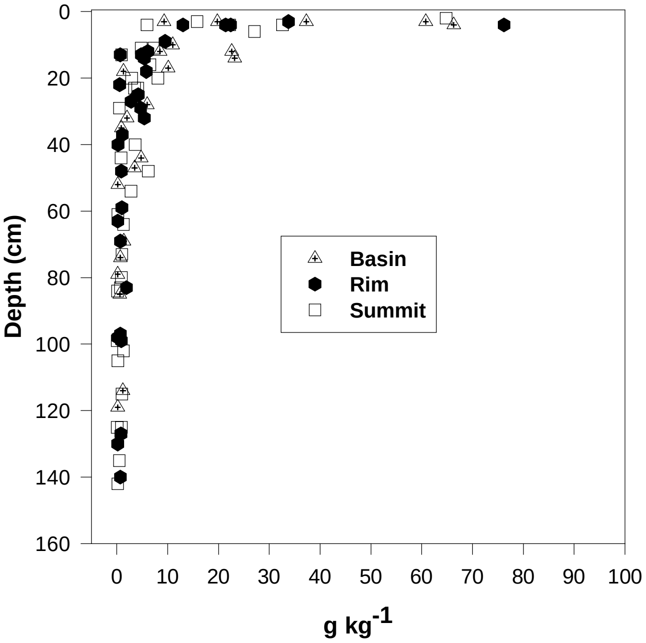

FIGURE 4. Grams of organic carbon per kilogram of dry soil, versus depth in cm. Highest accumulations in the surface horizons above 20 cm. These are average values from duplicate samples for the five summit-rim-basin transect, 15 pedons, and 91 horizons.

films beneath indicate a degrading zone above an accumulating zone (Bullock et al., 1974). The distribution of clay films in pool #1 verifies the translocation of clays (see Table 3). The summit has an absence of clay films in the degrading, eluvial A and AB horizons while common thin films occur in the Bt1 horizon and many moderately thick films occur in the Bt2 horizon above the duripan. The rim position soil has clay films throughout with the Bt2 having many thick films. The presence of clay films in the A horizons suggests that clay is also being laterally translocated down slope from the summit toward the basin position. The basin soil has no clay films in the degrading, eluvial A horizon, while common moderately thick films occur in the Bt horizon and many moderately thick films occur in the 2Btkqm horizon. Furthermore, clay films are observed throughout the duripans of the summit, rim, and basin soils as the soil solution transports clays to the depth of leaching.

The resulting morphology indicates an accumulating clay layer at depth above the relatively impermeable duripan. The clay layer and duripan are closer to the surface in the basin, than either the rim or summit positions. The summit profile is more developed with a greater clay percentage at depth than either the rim or basin. This clay layer creates a zone of low water and root permeability that contributes to maintaining episaturation in these ecosystems, as well as providing water holding capacity for vegetation utilization after pools dry down.

Duripan Formation

A duripan is a diagnostic subsurface horizon that is cemented by silica so that less than 50% of the volume of air dry fragments slake in water or prolonged soaking in acid (HCl) (Soil Survey Staff, 1996). Duripans vary in their degree of silica cementation, and they frequently contain accessory cementing agents, primarily iron oxides and calcium carbonate (Flach et al., 1969; Soil Survey Staff, 1996). Duripans are widespread across the western United States in sub-humid Mediterranean and arid climates (Flach et al., 1969; Chadwick et al., 1987b; Boettinger and Southard, 1990). They tend to occur on extremely old landscape components such as remnant alluvial fans along the western foothills of the Sierra Nevada (Flach et al., 1969). Duripans have formed on geomorphic surfaces ranging from late-Pliocene to Holocene in age, and they occur in soils formed from a wide range of geologic materials (Flach et al., 1969; Torrent et al., 1980; Chadwick et al., 1987a).

Silica cements are derived from the rapid weathering of volcanic glass and amorphous materials rich in silica (Soil Survey Staff, 1975; Chadwick et al., 1987a) or from the prolonged weathering of silicate minerals, such as feldspars and ferromagnesian minerals (Flach et al., 1969; Torrent et al., 1980; Boettinger and Southard, 1991). Opaline silica is the major constituent of the pedogenic cement (Flach et al., 1969;

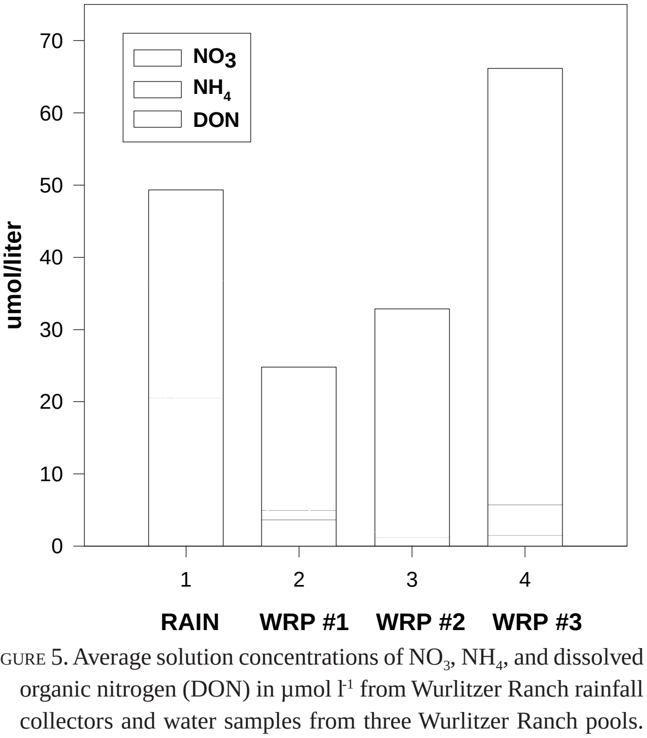

FIGURE 5. Average solution concentrations of NO_3, NH_4, and dissolved organic nitrogen (DON) in µmol l^{-1} from Wurlitzer Ranch rainfall collectors and water samples from three Wurlitzer Ranch pools. This is from the 94-95 season. Note the reduced levels of NO_3 and NH_4 and increased levels of DON in all the pools. DON is greatest in WRP #3, a grazed pool.

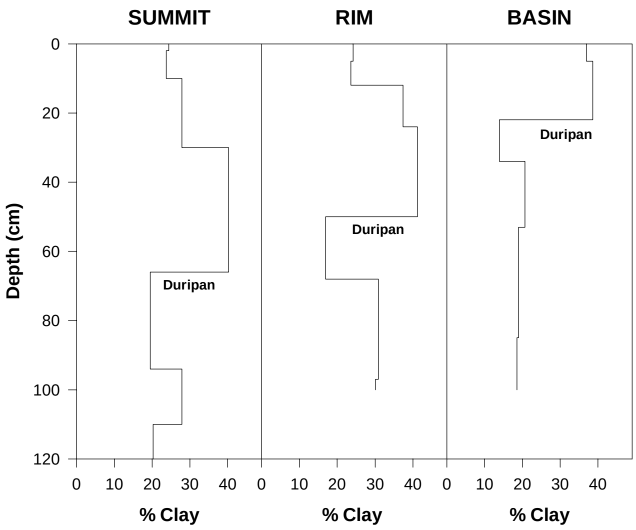

Figure 6. Percent clay versus depth in cm. for the summit-rim-basin transect of WRP pool #1. Note the greater clay accumulation and deeper profile above the duripan in the summit than either the rim and basin positions.

Chadwick et al., 1987b). As weathering releases silica into the soil solution, it is translocated to the depth of leaching where it precipitates upon soil dehydration (Flach et al., 1969; Chadwick et al., 1987b). The silica accumulates in and around mineral grains, where it cements clay particles preventing their expansion and contraction upon wetting and drying and dispersion by water. Continued development leads to formation of a well developed pan having platy morphology that acts as an effective barrier to downward water movement and root penetration (Flach et al., 1969; Soil Survey Staff, 1975).

Both study sites are located on older alluvial fan terraces, whose soils occur in formations that range in age from early-Pleistocene (WRP) to early-Pliocene (DMP). The mineralogy of both sites is dominated by the andesitic Tuscan Formation and its alluvium; the WRP site has the additional influence of mixed mineralogy alluvium from the Coast Range. The Tuscan Formation consists of lahars (mudflows), volcanic flows, and pumiceous tuff (rhyolitic consolidated rock formed by volcanic eruptions) (Saucedo and Wagner, 1992). The dominant mineralogy of the Tuscan Formation lavas is andesite, rich in plagioclase feldspars and ferromagnesian minerals, with pumiceous (high in amorphous silica) welded ash deposits occasionally interlayered (Lydon, 1967). XRD analysis of andesitic cobbles from WRP identified the following minerals: plagioclase feldspar $(Ca,Na)Al(Si,Al)Si_2O_8$; hornblende $(Ca,Na)_{2-3}(Mg,Fe,Al)_{5-}Si_6(Si,Al)_2O_{22}(OH)_2$; augite $Ca(Fe,Mg)Si_2O_6$; and minor amounts of magnetite Fe_3O_4. These minerals along with possible ash deposits and reworked alluvium comprising the Tuscan Formation certainly provide the substrate for duripan genesis.

The duripans in the WRP pool #1 transect are extremely developed with very coarse platy morphology in the 2Btkqm horizons of all geomorphic positions (basin-rim-summit) (Table 2). Silica enrichment exists below the platy portion of the duripan in all positions: 63 cm thick in the basin (22 - 85 cm; Btkqm, 2Btkq, 2Btq horizons), 47 cm thick in the rim (50 - 97 cm; 2Btkqm and 2Btkq horizons), and 46 cm thick in the summit (64 - 110 cm; 2Btkqm and 2Btkq horizons). The morphologic letter designation "m" denotes greater than 90% induration (hardened) and the letter "q" denotes silica affected horizons (Soil Survey Staff, 1996). The "q" designation may or may not be at least 50 % indurated, but in this case all horizons designated with "q" are more than 50% indurated, hence meeting the definition of a duripan. The silica is accumulating to a greater degree in the basin position compared to the rim and summit positions, as is indicated by its thickness.

When these duripans formed still remains a question, since a substantial amount of silica needs to accumulate through mineral weathering, translocation, and precipitation upon soil dehydration. There is some evidence of Holocene (<10 ka) silification where volcanic glass is a major source of silica for cementation (Chadwick et al., 1989). However the climatic fluctuations since the mid-Pleistocene (Spaulding and Graumlich, 1986) may have created a wetter climate producing and distributing clays deep in the profile, followed by a drier climate creating a duripan and protecting the lower part of the profile from further weathering (Torrent et al., 1980). Nonetheless, these duripans are an integral component of vernal pool ecosystems due to their role in creating a perched water table, restricting downward root growth, accumulating weathering products, and reducing the volume of soil in which pedogenesis and plant growth can effectively take place.

Calcium Carbonate Accumulation

One of the by-products of pedogenesis that can have a significant effect on vernal pool ecosystems is the accumulation of calcium carbonate. In many arid and semiarid regions $CaCO_3$ may be a secondary cementing agent in duripans, if carbonates are present in sufficient amounts (Flach et al., 1969; Soil Survey Staff, 1975). Calcium can originate from eolian dust (Gile et al., 1966), carbonate containing parent materials (Flach et al., 1969), and weathering of Ca-feldspars and other Ca-bearing minerals (Chesworth, 1992). Carbonates originate primarily from CO_2 produced by root and microbial respiration. Pedogenic carbonates form as calcium and carbonates become concentrated and precipitate from the soil solution as the soil profile dries (Gile et al., 1966; Flach et al., 1969). The zone of pedogenic carbonate accumulation indicates the effective leaching depth within the soil profile (Arkley, 1963; Flach et al., 1969).

The soils in the WRP pool #1 transect (see Figure 7, Table 4) have accumulated calcium carbonate which increases in a downward gradient to the duripan and a lateral gradient toward the basin. Calcium along with the other base cations (e.g., Mg, K, Na) are weathered from primary minerals in these soils. They are assimilated by plants and other biota as essential nutrients while releasing CO_2 and HCO_3^- to the soil environment. As the pools dry down and the soils dehydrate, calcium carbonates and other soluble components (Fe^{+2}, Mn^{+2}, and aqueous SiO_2) move downward in the profile and precipitate.

The duripan in the basin position contains the greatest amount of calcium carbonate (44 g kg^{-1}) with strong effervescence in the 2Btkqm and 2Btkq horizons and >20% of the surface area covered with segregated masses in the 2Btkqm. The 2Btkqm horizon of the rim had 16 g $CaCO_3$ kg^{-1} soil with >20% of the surface area exhibiting carbonate filaments or threads; the 2Btkqm of the summit had 18 g $CaCO_3$ kg^{-1} soil with < 20% of the surface area exhibiting carbonate filaments and disseminated masses.

Calcium carbonates are distributed in minor amounts throughout the soils of the summit and rim positions. This indicates greater amounts of biological activity in the deeper soil profiles than that which occurs in the basin. Additionally, calcium carbonate is an auxiliary cementing agent of these duripans which accumulates more slowly in soils with high clay percentages (Flach et al., 1969; Gile and Grossman, 1979). Overlying the duripan in all geomorphic positions are thicker clay enriched horizons which have a direct influence on pedogenic processes. The summit and rim positions, with deeper profiles and thicker clay enriched horizons, display a deeper accumulation of calcium carbonate over the thinner profile of the basin.

CONCLUSIONS

This study of vernal pool pedogenesis shows that the dominant soil forming processes are ferrolysis, organic matter accumulation, clay formation and translocation, duripan formation, and calcium carbonate accumulation. These processes create a three dimensional biogeochemical environment that strongly influences hydrologic properties and nutrient cycling. The distinct seasonality of these wetland ecosystems results in alternating conditions of reduction and oxidation within the soil profile. This process, termed ferrolysis, accelerates mineral weathering and releases base cations (Ca, Mg, Na, K), metals and silicon for biotic assimilation and secondary mineral formation. Diagnostic for wetland status are the high chroma iron mottles, near neutral Mn stains, masses, and concretions, and low chroma depletions which are generated by redox processes. High concentrations of secondary iron oxides (> 20 g kg^{-1}) tend to mask field observations of low chroma depletions.

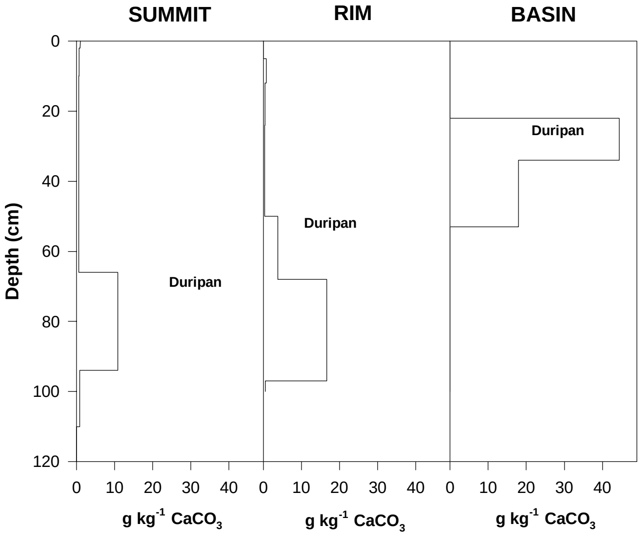

FIGURE 7. Grams of $CaCO_3$ per kilogram of dry soil, versus depth for the summit-rim-basin transect of WRP pool #1. $CaCO_3$ is moving downward in the profiles to the depth of leaching, the duripan. $CaCO_3$ is also moving laterally toward the basin and accumulating there in greater concentrations.

Organic matter accumulates preferentially in the surface horizons (0 - 20 cm) as increasing bulk density and seasonally anaerobic conditions inhibit deep root development. Carbonates, clays and silica are translocated to the effective leaching depth where they accumulate to form the duripan with its associated Fe, Mn, carbonates and clay enrichments. The high concentrations of aqueous Mn^{2+} and Fe^{2+} during saturated conditions may be toxic to certain plants and required for others, such as *Limnanthes floccosa* ssp. *californica*. These edaphic controls may provide a refuge for competition sensitive plants that can tolerate the effects of ferrolysis. Certainly, the relationship between nutrient availability/potential toxicity and specific vegetation requires further study.

The unique assemblage of soil properties which includes the clay enriched argillic horizons, duripans, and shallow lithic contact in mudflow pools, plays a critical role in nutrient cycling in vernal pool ecosystems. These soil features create seasonal episaturation which stores water and associated nutrients for vegetation utilization during the pool dry down. Mineral nitrogen additions to vernal pool waters are quickly assimilated by biota (often by algae) and reducing conditions in the upper soil layers lead to denitrification. Attempts to construct vernal pools must mimic these natural soil features to provide the unique assemblage of nutrient availability, water-holding capacity and redox conditions which characterize endemic plant and animal habitat. Further research on nutrient cycling is required on both reconstructed and natural vernal pools in order better understand and preserve these endangered ecosystems.

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