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Late Miocene advent of tall grassland paleosols in Oregon

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Abstract

Paleosols in the late Miocene Rattlesnake Formation reveal three successive paleoclimatic regimens that can be dated using cumulative paleosol development prior to the radiometrically dated Rattlesnake Ash-Flow Tuff (7.05 Ma). The basal Rattlesnake Formation (ca. 7.5–7.3 Ma) has a suite of weakly calcareous paleosols indicating subhumid paleoclimate (800–1000 mm mean annual precipitation or MAP) and seasonal waterlogging. A shift at ca. 7.3 Ma to semi-arid paleoclimate (MAP 500–850) is indicated by paleosols with calcic horizons at depths of 105–85 cm. A second shift at ca. 7.2 Ma ushered in an assemblage of soils with shallow (36–53 cm) calcic horizons, indicating semi-arid conditions (MAP 200–600 mm) not much different from today. Along with the climatic shifts documented by the paleosols there also are substantial changes in alluvial architecture and paleotopography. The lower Rattlesnake Formation (ca. 7.5–7.2 Ma) was deposited by a stream flowing northeast in an ancestral John Day Valley. The upper part of the formation (ca. 7.2–7.1 Ma) was deposited within large alluvial fans shed from the growing anticline of Picture Gorge Basalt to the north. Stepwise changes in former vegetation can also be interpreted from paleosols. The basal Rattlesnake Formation (7.5–7.3 Ma) has a suite of paleosols with root traces, clay skins and manganese nodules like those of riparian woodland and seasonally waterlogged riparian meadow. The succeeding paleoclimatic sequence (7.3–7.2 Ma) includes the earliest known mollic paleosols with deep (>50 cm) calcareous nodules, interpreted as former soils of tall grassland. Also found are manganese-stained paleosols of seasonally waterlogged meadows, and weakly developed paleosols of early successional riparian vegetation. A later paleoclimatic sequence (7.2–7.1 Ma) includes desert shrubland paleosols, as well as paleosols of early successional riparian vegetation. Fossil bones and teeth found in many paleosols indicate coeval changes in mammalian faunas. The major shift from woodland to grassland at ca. 7.3 Ma introduced into this area tall grassland ecosystems, including large cursorial horses and pronghorns. Aridification continued with the shift to shrubland ca. 7.2 Ma (early Hemphillian), which corresponds to continent-wide mass extinction of most remaining browsing mammals from the Clarendonian Chronofauna.

Keywords: paleosols; paleoclimate; mammals; Miocene; Oregon

1. Introduction

The late Miocene (7 Ma) was a turning point in global climatic change toward cool, dry, glacial climates, unlike equable greenhouse climates of

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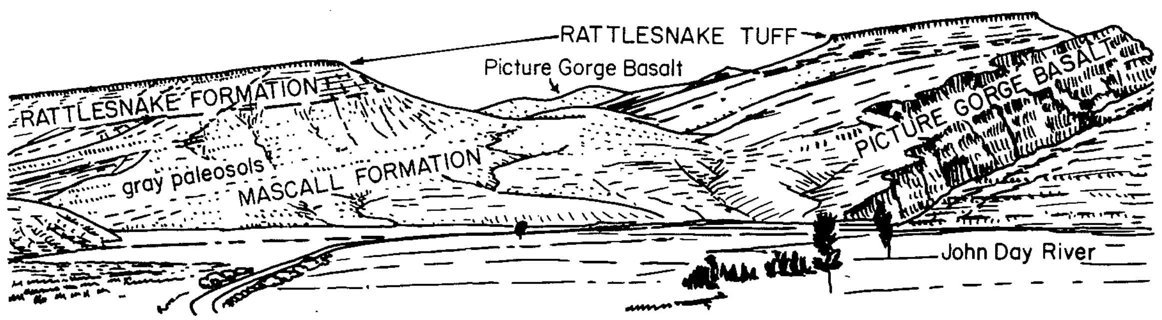

Fig. 1. Annotated sketch of the type area of the Rattlesnake Formation viewed from the east on the high terrace above Mascall Ranch, near Dayville, Oregon. Discordant dips indicate tectonic tilting during deposition of the Mascall and Rattlesnake Formations.

the earlier Cenozoic. This time is best known for the Messinian (7.2–5.3 Ma) salinity crisis, when the Mediterranean became a desert (Krijgsman et al., 1999), and global expansion of tall grasslands (Quade et al., 1995; Retallack, 1997a; Cerling et al., 1997). One could take the view that grasslands found opportunity in global climatic cooling and drying driven by Himalayan uplift (Raymo and Ruddiman, 1992), declining volume of oceanic thermohaline circulation (Flower and

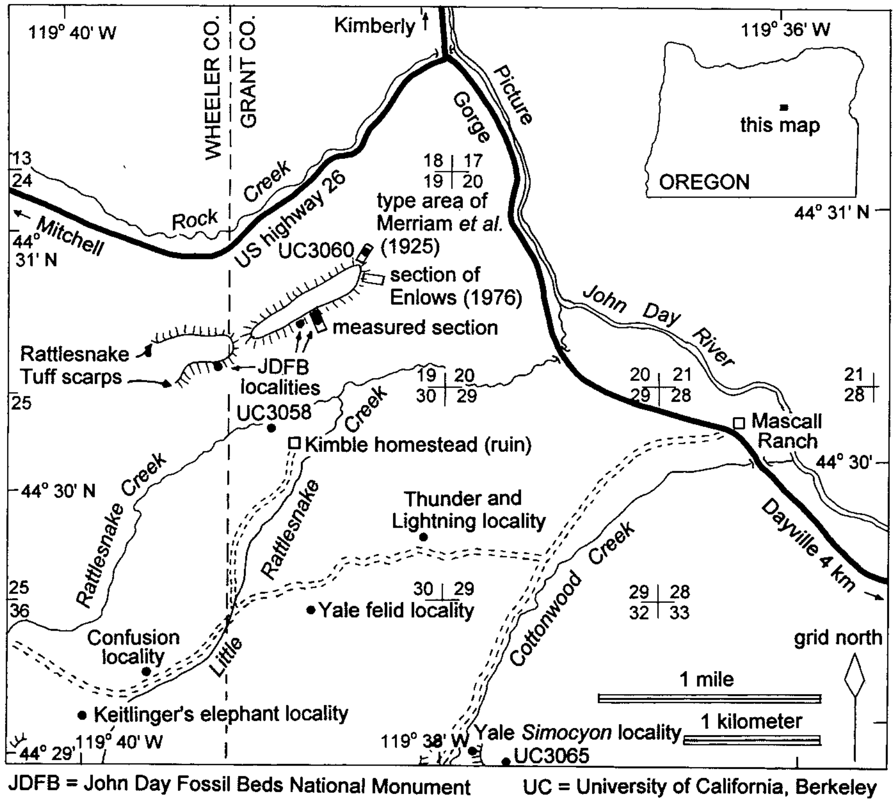

Fig. 2. Fossil localities and measured sections in the type area of the Rattlesnake Formation, near Dayville, Oregon. Numbered checks are for local map grid.

Kennett, 1994) and declining atmospheric levels of CO_2 (Cerling et al., 1997). An alternative hypothesis is appearance of tall grasslands by biological invasion and thresholds in plant–animal coevolution (Thomasson, 1985; Retallack, 1998a, 2001a). These hypotheses are examined here using evidence from paleosols in the late Miocene Rattlesnake Formation of central Oregon (Figs. 1 and 2) for the origin of tall grassland ecosystems.

Past approaches to the origin of grasslands included studies of fossil mammals and grasses (Jacobs et al., 1999), and the stable isotopic composition of fossil soils and mammals (Cerling et al., 1997). No fossil grasses are known from the Rattlesnake Formation in Oregon, although fossil grass pollen is widespread regionally in late Miocene rocks (Leopold and Denton, 1987). There is however a diverse fossil mammal fauna in paleosols of the Rattlesnake Formation, and these are hypsodont and cursorial ungulates typical of grassland habitats (Fremd et al., 1997). Oregon is too far north for C_4 grasses now, and probably always was (Cerling et al., 1997), so that isotopic studies of fossil soils and teeth in Oregon are not promising guides to the advent of grasslands there. Instead, two features of paleosols are emphasized here: their subsurface horizons of calcareous nodules and their distinctive surface horizons. Soils supporting sod-forming grasses have thick (>18 cm) surface horizons riddled with networks of fine (<2 mm) roots and abundant small (2–5 mm) rounded clods, dark with organic matter intimately mixed with clay (Pawluk and Bal, 1985; Buol et al., 1997). This distinctive surface horizon is called a mollic epipedon (Soil Survey Staff, 1998), and is recognizable in paleosols (Figs. 3 and 4: Ruhe, 1970; Retallack, 1997a,b; Wynn, 2000). Grassland soils of dry regions also develop subsurface horizons of calcareous nodules (Fig. 4). The depth within the profile to this calcic horizon shows a close relationship to mean annual precipitation (MAP) (Retallack, 1994; Caudill et al., 1996), within specific limits (Royer, 1999; Retallack, 2000), and this can be used to estimate former rainfall from paleosols once allowance is made for compromising factors such as burial compaction (Sheldon and Retallack, 2001). These and other features of paleosols also can be used to reconstruct the circumstances of Oregon's prehistoric grasslands.

2. Geological background

Late Miocene (early Hemphillian: Martin, 1983) fossil mammal beds west of Dayville in central Oregon (Figs. 1 and 2) were established as the type area of the Rattlesnake Formation by Merriam et al. (1925). Subsequently, Walker (1979,

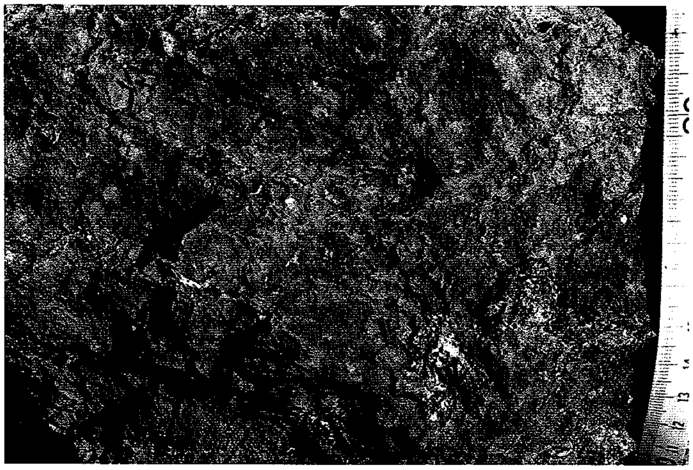

Fig. 3. Crumb peds in a late Miocene paleosol of the Rattlesnake Formation (Kalas paleosol at 10.3 m in Fig. 5). Tape is graduated in mm.

Fig. 4. Dark crumb surface (A horizon) and white nodular subsurface (Bk horizon) of the type Tatas paleosol in the late Miocene Rattlesnake Formation above the 'Confusion locality' (of Downs, 1956). Hammer for scale is below the dark upper portion of the paleosol center right.

1990) restricted this stratigraphic name to the ash-flow tuff only, but we accept both Rattlesnake Formation and its enclosed Rattlesnake Ash-Flow Tuff as valid stratigraphic names. The Rattlesnake Ash-Flow Tuff is now dated using single crystal $^{40}Ar/^{39}Ar$ laser fusion of K-feldspar at 7.05 ± 0.01 Ma (Streck et al., 1999).

The Rattlesnake Ash-Flow Tuff forms prominent scarps in the upper John Day Valley from Dayville to John Day. This is an enormous (130 km^3) rhyodacite covering some 9000 km^2 of central Oregon. Its original volume was probably 280 km^3 and original coverage some 30 000–40 000 km^2, erupted from a caldera now buried between Burns and Wagontire, some 120 km south of Dayville (Streck et al., 1999).

The type section of the Rattlesnake Formation is a succession of conglomerates and siltstones below the mesa-forming ash-flow tuff, but the formation includes conglomerates and siltstones overlying the ash-flow tuff in Cottonwood Creek and elsewhere within this general area (Fig. 2). In the type section the lower Rattlesnake Formation is 66 m thick, the Rattlesnake Ash-Flow Tuff 12 m, and the upper Rattlesnake Formation 113 m (Enlows, 1973, 1976).

The Rattlesnake Formation unconformably overlies the middle Miocene (Barstovian) Mascall Formation and is overlain by Quaternary alluvium, colluvium and pediment deposits (Fig. 1). The mesa-forming ash-flow tuff dips gently to the south, but not as steeply as the underlying Mascall Formation and Picture Gorge Basalt, indicating that the Rattlesnake Formation was deposited after uplift and folding of the underlying units (Stimac, 1996). Uplift and erosion of underlying basalts continued during deposition of the Rattlesnake Formation because most of the clasts in its fanglomerates are basaltic. Isopachs of both the conglomerates and the welded tuff show that the John Day Valley was a prominent erosional feature during deposition of the Rattlesnake Formation (Streck et al., 1999), as it has been ever since.

3. Materials and methods

A section of the Rattlesnake Formation was measured on Mascall Ranch in the steep slopes 2 km south of Picture Gorge (Figs. 2 and 5: NW1/4 SE1/4 NE1/4 SW1/4 section 19 T11S R26E Grant Co., UTM NAD27 11T E0289782m N4931979m at bottom and E0289750m N4932090m at top). The lower Rattlesnake Formation below the ash-flow tuff proved to be 77 m thick at this point. Enlows (1973, 1976) obtained a thickness of 66 m for equivalent strata 500 m to the north (Fig. 2: NE1/4 SW1/4 SW1/4 NE1/4 section 19 T11S R26E). Merriam et al. (1925) obtained a thickness of 69 m for these same strata 700 m to the north-

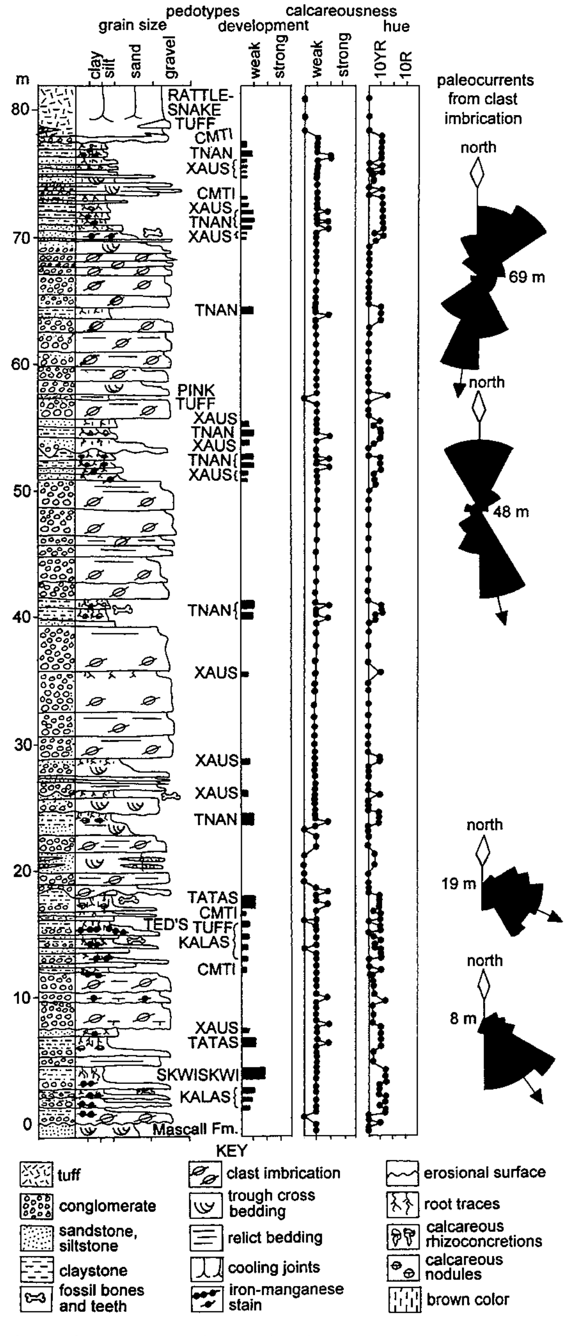

Fig. 5. Summary section and paleocurrents from clast imbrication in the lower Rattlesnake Formation. For explanations of pedotypes see Table 1. Scales of soil development, calcareousness and hue follow Retallack (1997b).

west (Fig. 2: NE1/4 NE1/4 SE1/4 NW1/4 section 19 T11S R26E). The uppermost silty tuffaceous beds beneath the Rattlesnake Ash-Flow Tuff thin and are eroded away to the north due to syndepositional uplift and folding of the underlying Picture Gorge Basalt (Fig. 1).

Each paleosol was examined, described and classified into a field scheme of pedotypes (Table 1). Depth of carbonate in the paleosols was measured as guides to former rainfall (Table 2). Weathering rind thickness was measured using vernier calipers accurate to 0.1 mm on freshly broken basalt pebbles within paleosols (Fig. 6) in order to determine their duration of soil formation by comparison with clast weathering in soils (Colman, 1986).

Many vertebrate fossils were found in the paleosols by National Parks staff and others, and these are noted on the measured section. Also visited and assessed were paleosols at vertebrate fossil localities of the University of California (Merriam et al., 1925), South Dakota School of Mines (Martin, 1983) and local resident Bruce Keitlinger (Fig. 2).

In addition, clast imbrication direction was measured to determine paleocurrents of paleochannel conglomerates and the paleogeographic setting of the paleosols. Imbrication was measured as the azimuth of maximal dip of the true upward dip of inclined pebbles. These new results are plotted as rose diagrams and vector means relative to magnetic north (Fig. 5).

Samples of selected paleosols were studied in petrographic thin sections. Counting of 500 points using a Swift Automatic Point Counter was used to establish grain size and mineral content of paleosol horizons, with an accuracy of about 2 vol% ($\pm 1\sigma$: van der Plas and Tobi, 1965; Murphy and Kemp, 1984). Clay mineral analyses were obtained from the automated Rigaku X-ray diffraction (XRD) at the University of Oregon, with normative clay mineral composition (Table 2) calculated from the traces using NEWMOD computer program (Reynolds, 1985). Chemical analyses by Intertek (Bondar-Clegg) of Vancouver, BC, Canada, used X-ray fluorescence for major and selected trace elements, and dichromate titration for ferrous iron. Bulk density was calculated from

Table 1
Pedotypes recognized in the Rattlesnake Formation in its type area, near Dayville

Pedotype	Meaning	Diagnosis	F.A.O. soil	USDA soil
Kalas	raccoon	Crumb-structured clayey brown (mollic) surface over black-spotted and veined (placic horizon)	Mollic Gleysol	Placaquand
Skwiskwi	brown	Granular-structured, brown (7.5YR) subsurface clayey (argillic) horizon	Humic Andisol	Eutric Fulvudand
Tatas	basket	Crumb-structured, brown, clayey–silty surface over deep (> 50 cm) calcareous nodules and calcareous rhizoconcretions	Calcic Kastanozem	Calciudoll
Cmti	new	Brown siltstone with relict bedding and root traces	Eutric Fluvisol	Fluvent
Xaus	root	Brown volcaniclastic sandstone with relict bedding and root traces	Calcaric Fluvisol	Psamment
Tnan	cliff	Brown (10YR–7.5YR), clayey–silty, granular–crumb-structured surface over shallow (< 50 cm) calcareous rhizoconcretions	Calcic Xerosol	Mollic Haplocalcid

paraffin-coated clods weighed in and out of water. These and other data are tabulated in a publicly available report (Retallack, 1999).

4. Alteration after burial

Environmental interpretation and classification of paleosols can be compromised by burial alteration during burial. For example, burial gleization of organic matter and burial reddening of iron hydroxide pigments are common alterations of paleosols (Retallack, 1991a,b), but there is little evidence of either in brown paleosols of the Rattlesnake Formation. Only one kind of paleosol (Tnan of Table 1) had a reddish brown hue that could in part be due to burial reddening of iron hydroxides, but no hematite was detected in XRD traces. Paleosols of the Rattlesnake Formation are friable, like Pleistocene paleosols of the area. Their patchy areas of micritic carbonate and chalcedony are like those of soils and paleosols (Wieder and Yaalon, 1982; Chadwick et al., 1987, 1995; Retallack and Alonso-Zarza, 1998), and unlike burial cements (Retallack, 1997b). Much of their dark color is due to amorphous iron–manganese stain of the kind found in waterlogged soils (Rahmatullah et al., 1990; McDaniel and Buol, 1991), unlike crystalline pyrolusite of burial diagenesis. In such settings, a dark and

Table 2
Depth to calcic horizon and estimated rainfall for paleosols of the Rattlesnake Formation

Pedotype	Level (m)	Calcic depth (cm)	Overburden (m)	Compaction (fraction)	Corrected calcic depth (cm)	Estimated MAP (mm)
Tnan	77	36	200	0.9332	39	367
Tnan	72	41	205	0.9321	44	395
Tnan	71	34	206	0.9319	36	355
Tnan	70	36	207	0.9317	39	367
Tnan	64	37	213	0.9304	40	373
Tnan	56	37	221	0.9287	40	373
Tnan	53	46	224	0.9280	50	424
Tnan	52	37	225	0.9280	40	374
Tnan	41	52	236	0.9254	56	457
Tnan	30	53	237	0.9252	57	463
Tnan	24	39	253	0.9219	42	387
Tatas	18	85	259	0.9206	92	619
Tatas	17	103	260	0.9204	111	691
Tatas	7	105	270	0.9183	114	700

Level is in the measured section (Fig. 5), overburden depth is from estimated thickness of overlying units, and compaction correction and MAP (standard deviation ± 141 mm) are from Retallack (1994, 1997a).

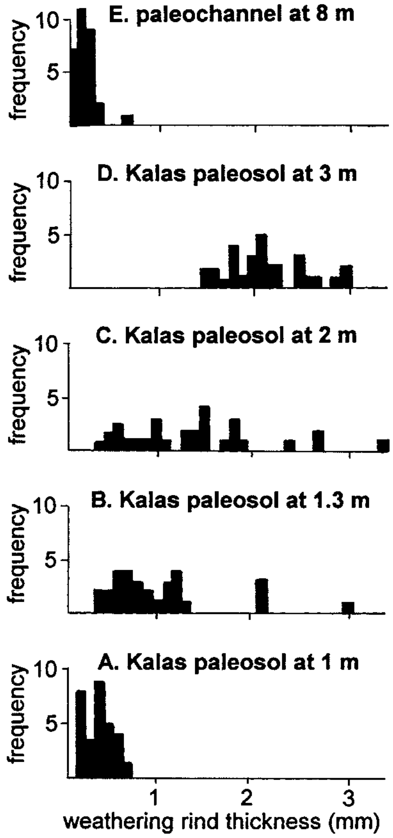

Fig. 6. Histograms of the thickness of weathering rinds on basalt pebbles in paleosols and a paleochannel of the lower Rattlesnake Formation.

organic surface horizon would also be expected, and it is likely that much organic matter has been lost from these profiles by decomposition during burial. Loss of organic matter is probably the most significant burial alteration of these paleosols. Considering a likely depth of burial of less than 200 m (Enlows, 1973, 1976), physical compaction would have been minimal (91–83% of original thickness) using standard compaction equations (Sheldon and Retallack, 2001). Significant clay diagenesis, such as illitization, is also unlikely considering diffuse peaks on X-ray diffractograms, which models using NEWMOD of Reynolds (1985) as abundant amorphous colloid (Table 3). Zeolitization is also not indicated by X-ray diffractograms. Paleosols of the Rattlesnake Formation lack the pervasive zeolitization and other alterations documented from underlying paleosols of the Mascall and John Day Formations (Retallack et al., 2000).

5. Pedotype recognition and classification

Paleosols in the Rattlesnake Formation are silty and brown, in striking contrast to associated gray basaltic conglomerates (Fig. 7). Paleosols also are abundant and diverse: 40 paleosols of six different pedotypes were found within a vertical thickness of 77 m (Fig. 5, Table 1). Pedotype names were used as objective field labels, and are part of a system of nomenclature for Cenozoic paleosols mapped both laterally and in vertical stratigraphic sections throughout central Oregon and Washington (Retallack et al., 2000). Because of the widespread use of local names for surface soils (Dyksterhuis, 1981) and geological formations (Enlows, 1973, 1976), pedotype names were chosen from the Sahaptin native American language (Rigsby, 1965; DeLancey et al., 1988). Profiles sampled for detailed study were in the main measured section, with exception of the type profile of the Tatas paleosol, which underlies a prominent tuff in bluffs above the 'Confusion locality' (of

Table 3
Clay mineral composition (vol% of <2 μm) of paleosol samples from the Rattlesnake Formation

Paleosol	Horizon	Level (m)	Specimen #	Amorphous	2–2 cell unit montmorillonite	2–3 cell unit montmorillonite	2–4 cell unit montmorillonite	2–5 cell unit montmorillonite	Kaolinite
Tnan	Bk	77	7624	76	–	9	9	–	6
Xaus	A	76	7627	74	–	13	5	3	5
Tatas	A	18	7608	90	–	–	–	10	–
Kalas	A	16	7616	83	–	–	–	17	–
Skwiskwi	Bt	4	7597	91	5.5	3.5	–	–	–
Kalas	A	3	7602	87	6.5	6.5	–	–	–

Fig. 7. Conglomerates (dark) and paleosols (light and silty) of the Rattlesnake Formation at a stratigraphic level of 18 m in the measured section (Fig. 5), but in exposures 1 km to the southwest of that section (NW1/4 SE1/4 SE1/4 SE1/4 section 24 T12S R25E, Wheeler County).

Downs, 1956) of the middle Miocene (15–16 Ma) Mascall Formation (Fig. 2: SE1/4 NE1/4 SW1/4 NE1/4 section 36 T12S R25E; Retallack, 1997a,b; Fremd et al., 1997). Only one of these pedotypes has previously been described: the Skwiskwi pedotype, with a type profile in the mid-Oligocene, upper Big Basin Member of the John Day Formation, in the Painted Hills, Oregon (Retallack et al., 2000), and other profiles in the middle Miocene Mascall Formation near Dayville (Bestland and Krull, 1997). Most Skwiskwi paleosols have a coarse granular texture and a brown to dark brown color (10YR), whereas the Skwiskwi slickensided variant paleosol in the Rattlesnake Formation has more prominent clay skins and slickensides, coarser ped structure, and a more reddish hue (7.5YR). The regional pedotypes are nongenetic field categories, but classification in soil taxonomies is necessarily interpretive, and may require laboratory data, as outlined in the following paragraphs.

The basal Rattlesnake Formation (0–4.7 m) has only two pedotypes (Kalas and Skwiskwi: Fig. 8), and forms a single fining-upwards sedimentary sequence (Fig. 5). The black-spotted clayey (Kalas) paleosols show little relict bedding and lack diagnostic horizons of moderately developed soils, narrowing the choice of soil orders in the US taxonomy to Inceptisols and Andisols (Soil Survey Staff, 1998). There is much amorphous colloid in Kalas paleosols (Table 3), as well as plagioclase crystals that are euhedral and zoned as if derived from airfall tuffs, rather than lath-shaped like those from basaltic rock fragments. Volcanic shards and pumice fragments are uncommon, but clay skins and plasma separations are evidence that these were more common in the parent material of the original soil than they have remained in the paleosols. These are all indications of Andisols rather than Inceptisols. Among Andisols, Kalas paleosols are most like Placaquands, because of their conspicuous iron–manganese stain, which is an indication of waterlogging (Rahmatullah et al., 1990; McDaniel and Buol, 1991). In the F.A.O. (1974) classification, soils with indications of waterlogging like Kalas paleosols are separated into the order Gleysol. Because of their presumed high base status (amorphous colloids and minor chemical weathering), crumb ped structure and abundant fine root traces, Kalas paleosols can be classified as Mollic Gleysols.

Thick, clayey, brown paleosols (Skwiskwi pedotype) have relict volcanic shards, abundant noncrystalline colloid, modest textural differentiation and lack alkali leaching (Fig. 8), as in Andisols of the US soil taxonomy (Soil Survey Staff, 1998) and Andosols of the F.A.O. world map of soils (F.A.O., 1974). They are non-calcareous and weathered of most volcanic shards, yet redder

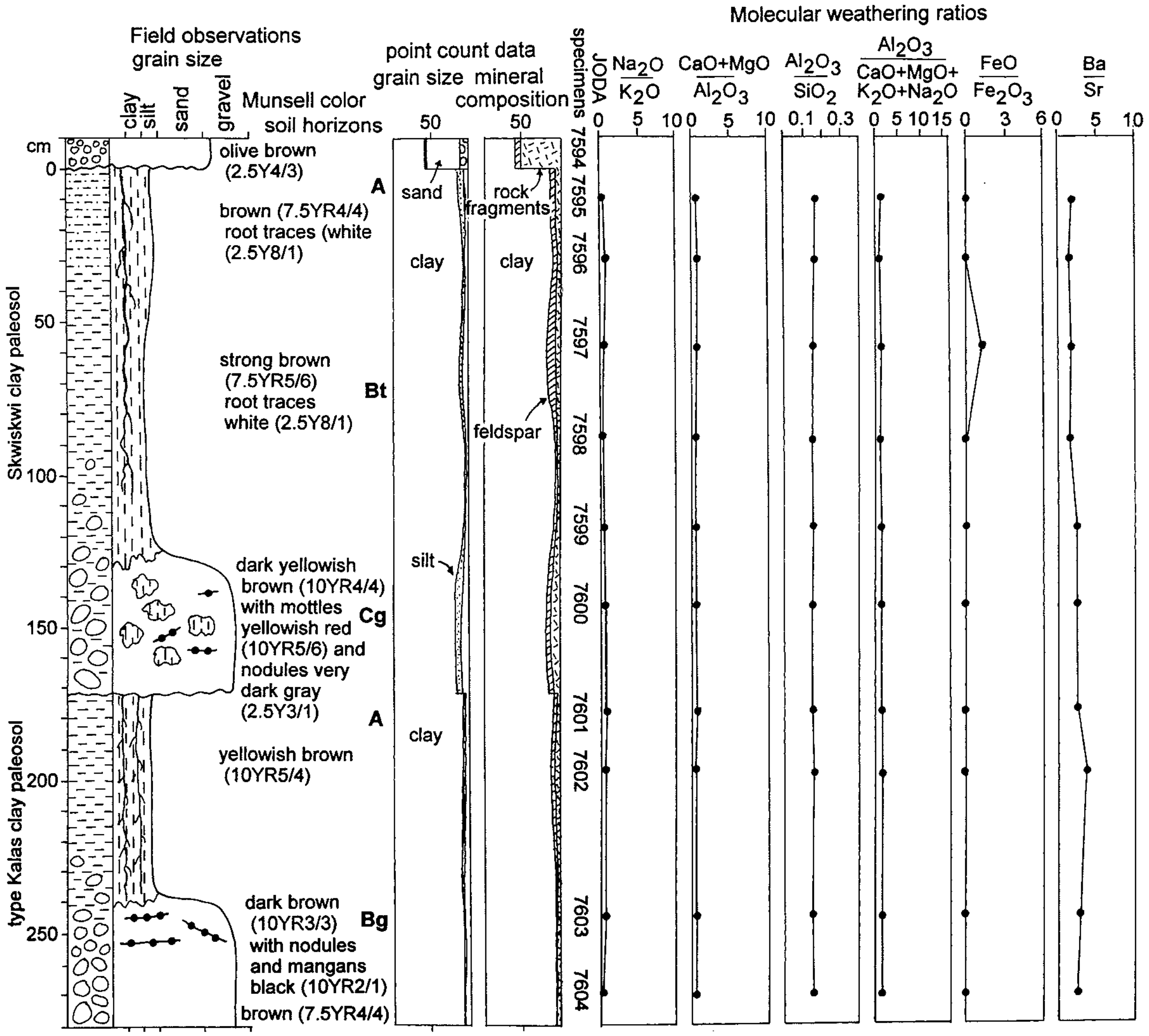

Fig. 8. Measured section, Munsell colors, soil horizons, grain size, mineral composition and selected molecular weathering ratios of the Skwiskwi clay and type Kalas clay paleosols at 2–5 m in the reference section of the lower Rattlesnake Formation. Lithological key as for Fig. 5.

than, and not as dark as melanic soils, even though much organic carbon was probably lost during burial decomposition (Retallack, 1991a,b). Other Skwiskwi paleosols of the Mascall and John Day Formations (Bestland and Krull, 1997; Retallack et al., 2000) have a coarse granular ped structure, but Skwiskwi paleosols in the Rattlesnake Formation have blocky peds. They are best identified as Eutric Fulvudands (of Soil Survey Staff, 1998) or Humic Andisols (of F.A.O., 1974).

The lower Rattlesnake Formation (4.7–18.2 m) includes another fining-upwards sequence with a greater variety of paleosols (Tatas, Kalas and Xaus pedotypes). Tatas paleosols have thick, dark, crumb-textured surface horizons with abundant fine root traces, like those of grassland soils (Fig. 9). Tatas paleosols lack argillic horizons, albic horizons, gley mottling, freeze structures and limestone bedrock that characterize Mollisol suborders other than Udolls and Ustolls. Because of the great depth to the calcic horizon (85–105

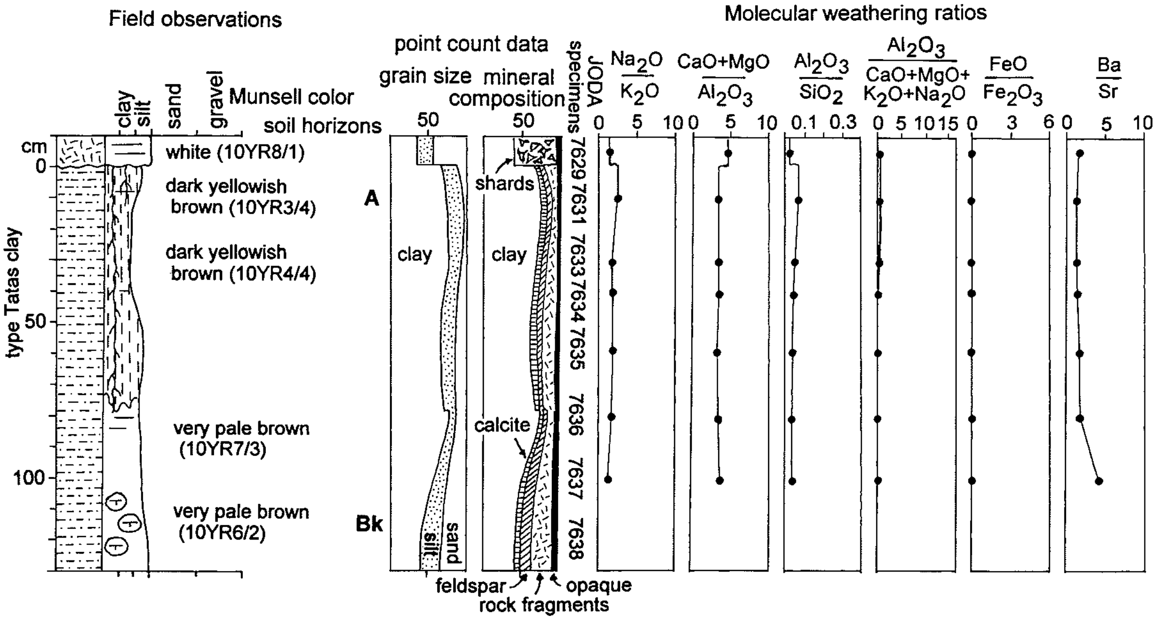

Fig. 9. Measured section, Munsell colors, soil horizons, grain size, mineral composition and selected molecular weathering ratios of the type Tatas clay paleosol above the Confusion locality in Little Rattlesnake Creek. The capping volcanic ash (Ted's Tuff) can be correlated to 16.5 m in the measured section (Figs. 11 and 12). Lithological key as for Fig. 5.

cm) of discrete micritic nodules, which would have been deeper (92–114 cm) in the original soil before burial compaction (Table 2), Tatas paleosols can be identified as Calciudolls (Soil Survey Staff, 1998). In the F.A.O. (1974) classification, Tatas paleosols are more calcareous than Phaeozems and less organic than Chernozems, and are best identified as Calcic Kastanozems.

Very weakly developed, sandy soils, with prominent relict bedding (Xaus paleosols; Fig. 10) are referred to the order Entisol of Soil Survey Staff (1998). Although these paleosols show weak manganese mottles attributable to waterlogging, the mottles are not sufficiently marked for Aquents. Because of their sandy texture, Xaus paleosols are better placed with Psamments than Fluvents. In the F.A.O. (1974) classification, Xaus paleosols are best regarded as Eutric Fluvisols, for much the same reasons.

Abundant relict bedding is also prominent in Cmti paleosols, which are more silty, clayey and reddish brown than Xaus paleosols (Fig. 10). They also were Entisols, probably Fluvents (Soil Survey Staff, 1998). Within the F.A.O. (1974) classification, they correspond to Calcaric Fluvisols.

The middle Rattlesnake Formation (18.2–77 m) contains yet another distinctive suite of paleosols of silty–sandy texture and generally more reddish hue (Tnan, Cmti and Xaus pedotypes). The best developed of these paleosols (Tnan pedotype) have subsurface accumulations of carbonate at depths of less than 1 m (Fig. 10), as in Aridisols of Soil Survey Staff (1998). The most obvious white glaebules in their subsurface are rhizoconcretions of chalcedony, with little intermixed micritic calcite. On the other hand, relict bedding has been destroyed to a degree much greater than in Entisols and Inceptisols. Tnan paleosols lack the clay content, ice disruption features, salts, pans and shallow bedrock of suborders other than Calcids, and as they lack petrocalcic horizons, are best regarded as Haplocalcids. In the F.A.O. (1974) classification, Tnan paleosols have more abundant fine root traces than Yermosols, and are best regarded as Calcic Xerosols.

An advantage of the F.A.O. classification is global coverage of soil maps useful for identifying

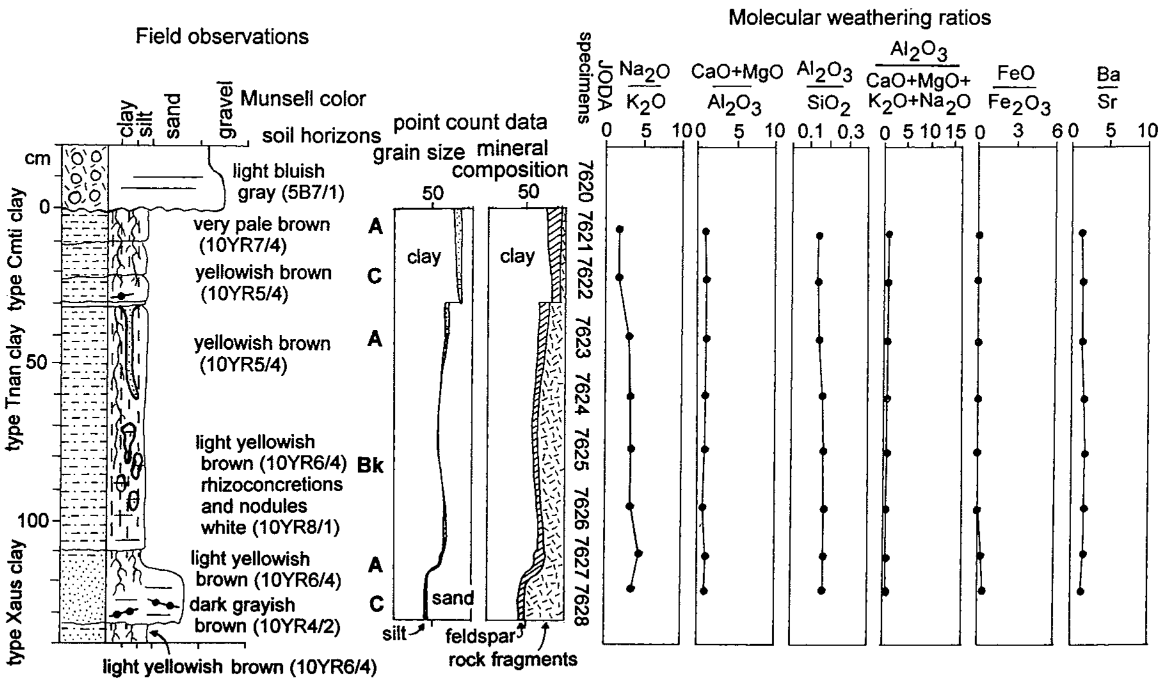

Fig. 10. Measured section, Munsell colors, soil horizons, grain size, mineral composition and selected molecular weathering ratios of the type Cmti clay, type Tnan clay and type Xaus sandy clay paleosols at 75–77 m in the reference section of the lower Rattlesnake Formation. Lithological key as for Fig. 5.

analogous modern soilscapes (F.A.O., 1975a,b). For example, the basal Rattlesnake Formation (0–4.7 m) has paleosols that can be characterized as Th(+Gm) in F.A.O. map code. The closest map unit in North and central America is Th1-2b(+L,Tv) in the volcanic uplands south and east of Mexico City, where vegetation is low deciduous forest grading into conifer forest at higher elevations (F.A.O., 1975b). Mean annual temperature (MAT) at Mexico City is 15.9°C, and MAP is 748 mm (Müller, 1982). The lower Rattlesnake Formation (4.7–18.2 m) has another suite of paleosols, of F.A.O. code Kk(+Gm,Jc,Je), most closely matched by map unit Kk2-2ab(+Gm) on loess and alluvium stretching from north of Amarillo, Texas, across the Oklahoma panhandle, to south of Dodge City, Kansas (F.A.O., 1975a). This is a region of tall to mixed prairie, with climate for Amarillo characterized by MAT 19.9°C and MAP 502 mm (Wood, 1996). In contrast, the middle Rattlesnake Formation (18.2–77 m) has a suite of paleosols not very different from soils in the Dayville area today (Dyksterhuis, 1981). There is also a large area of comparable soils in the F.A.O. maps (map code Xk5-2ab) under desert shrubland on volcanic ash of the Snake River Plain from near Idaho Falls west almost to Boise, Idaho (F.A.O., 1975a). Climate at Boise includes MAT 10.4°C and MAP 290 mm (Wood, 1996).

6. Paleoclimatic change

The different pedotype suites of the basal, lower, and middle Rattlesnake Formation correspond to three distinct paleoclimatic regimes, which can be reconstructed from a variety of paleosol features independent of pedotype classification. In the basal 4.7 m of the formation, black-spotted paleosols (Kalas) have iron–manganese nodules like those of waterlogged soils buffered from regional climate by groundwater (Rahmatullah et al., 1990; McDaniel and Buol, 1991), and so are not particularly informative about paleoclimate.

Some degree of precipitation seasonality is indicated by iron–manganese nodules formed in stagnant ground water, yet persistence of deeply penetrating root traces. Paleoclimate was not so strongly seasonal that any vertic structures were created in these, or more clayey associated paleosols (Skwiskwi). More paleoclimatic information comes from associated paleosols (Skwiskwi), which lack evidence of waterlogging, are leached of carbonate, and show weathered volcanic shards and feldspars to depths of a meter, as in western North American soils of climates more humid than 750 mm MAP (Retallack, 1994, 2000). Their smectite-dominated clays are like those of Hawaiian soils in climates drier than about 1000 mm (Sherman, 1952) and Californian soils drier than 500 mm (Barshad, 1966). At the drier end of this range, soils are more calcareous than these paleosols, and a range of 800–1000 mm MAP seems most likely for Skwiskwi paleosols. Their presumed high original humus levels and observed modest and shallow (1 m) weathering are more compatible with temperate than tropical conditions, and no ice wedges, or other indications of seasonal freezing were found.

The next distinct paleosol suite is in the lower Rattlesnake Formation (4.1–18.2 m) and is characterized by new kinds of paleosols (Tatas), which have carbonate nodules (calcic horizons) at depth. MAP can be related to depth to calcic horizon in modern soils by a formula (Retallack, 1994, 2000; Royer, 1999; Caudill et al., 1996), in which depth is adjusted to account for compaction by overburden (Sheldon and Retallack, 2001). None of the Tatas paleosols shows surficial erosion which might compromise these calculations: indeed the type profile has relict bedding indicating that its uppermost 10 cm received additions of sediment during formation (Fig. 9). Results of these calculations for paleosols of the lower Rattlesnake Formation are shown in Table 2. Tatas paleosol estimates range from 619 ± 141 to 700 ± 141 mm MAP, or roughly 500–850 mm. This represents a marked paleoclimatic drying, compared with estimates from paleosols lower in the formation. Seasonality of climate was also more marked, as indicated by concentrically banded rhizoconcretions of chalcedony and micrite in Tatas paleosols, unlike the clay-filled root traces lower in the formation (Kalas and Skwiskwi paleosols).

A third suite of paleosols dominated by another newly appearing pedotype (Tnan) was found from 18.2–77 m, and then to the top of the Rattlesnake Formation above the ash-flow tuff. Weakly developed paleosols (Xaus and Cmti) also are found at this stratigraphic level, but are not sufficiently developed to be guides to this third paleoclimatic regime. Tnan paleosols have sparse, small, carbonate nodules among more obvious chalcedony rhizoconcretions, and the depth to this incipient calcic horizon can be used as a proxy for MAP (Table 2), which was semi-arid (355–463 ± 141 mm, or roughly 200–600 mm). There is also evidence for climatic seasonality in banding of the chalcedony-micrite rhizoconcretions in Tnan paleosols. Comparable rhizoconcretions have been reported from Triassic paleosols in Antarctica (Retallack and Alonso-Zarza, 1998) and Mio–Pliocene paleosols in Nevada (Luft, 1966). Similar rhizoconcretionary banding also has been found in sagebrush and desert grassland soils of Nevada, which are seasonally snowy, with MAT 6–11°C and MAP 225–354 mm (Chadwick et al., 1987, 1995). This is not very different from current climate near Dayville, Oregon: seasonally snowy with only 90–150 frost free days, MAT 7–10°C and MAP 254–356 mm (Dyksterhuis, 1981). This is not to say that climate remained the same for the past 7.2 Ma. Paleosols are evidence of substantial and frequent subsequent paleoclimatic change (Retallack, 1997a; Busacca, 1998).

7. Vegetation change

The three successive paleoclimatic regimes noted in the Rattlesnake Formation correspond to three distinct mosaics of vegetation. The basal 4.7 m of Rattlesnake Formation includes several paleosols (Kalas), with a mix of thick and thin, shallowly spreading root traces, indicating a herbaceous cover (probably sedges or grasses), with scattered trees. This vegetation was mesic and riparian in character, considering the evidence from iron–manganese nodules for seasonal waterlogging (Rahmatullah et al., 1990; McDaniel and

Buol, 1991). A thick brown paleosol (Skwiskwi) at this stratigraphic level has both stout and fine root traces, which reach deeply into a well differentiated clay-rich subsurface horizon, as in forest soils. The dark brown color of the Skwiskwi paleosol implies high humus content (even more abundant before likely burial decomposition) and good ground cover. Its low alumina/bases ratios are indications of a fertile soil (Fig. 8). Such vegetation is compatible with identifications of sycamore (*Platanus*), elm (*Ulmus*), and willow (*Salix*) among fossil leaves from the lower Rattlesnake Formation near Dayville (Chaney, 1948a,b). Both sycamore and willow are common riparian trees, and may have dominated associated Kalas paleosols near streams. Elm would be a plausible dominant on soils like Skwiskwi paleosols, but the other genera would not have been excluded.

At a higher stratigraphic level within the lower Rattlesnake Formation (4.7–18.2 m), a change in vegetation is indicated by different paleosols (Tatas). Abundant fine root traces and scattered large rhizoconcretions (Fig. 11) in Tatas paleosols are evidence that they supported lightly wooded grassland. Furthermore, their thick, finely structured, laterally extensive surface horizons are indications that these were sod grasslands, with a substantial root mat and ground cover. The rainfall regime indicated by depth to calcic horizon (Table 2) is an indication of tall grassland, like that best known in the central Great Plains of North America (Jenny, 1980). Tatas paleosols are evidence for the oldest tall grasslands yet known in the USA (Retallack, 1997a). Comparable paleosols become common during the late Miocene (7 Ma) in the North American Great Plains, Argentine pampas, East African rifts and Indo-Gangetic plains (Retallack, 1997a, 1998a; Quade et al., 1995).

A variety of other paleosols associated with Tatas paleosols in the lower Rattlesnake Formation (4.7–18.2 m) reveal a mosaic of vegetation. Black-spotted (Kalas) profiles probably supported riparian woodland, as noted above. Root traces in weakly developed paleosols (Xaus and Cmti) are evidence for both trees and shrubs, probably early in ecological succession to colonize ground disturbed by, and deposited from, floodwaters. These riparian pole woodlands of levees (Cmti) and sand bars (Xaus) were slightly better drained than nearby clayey riparian swales (Kalas).

Within the middle Rattlesnake Formation (18.2–77 m), a new regime of vegetation is indicated by different paleosols again (Tnan). Fossil root systems are preserved in Tnan paleosols as little-distorted black pedotubules, which in deeper levels of the paleosols are encrusted with banded

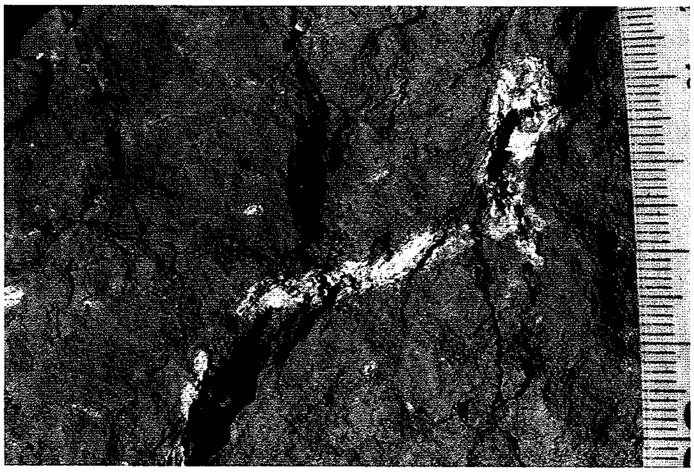

Fig. 11. Chalcedony-calcite rhizoconcretion in Tatas paleosol at 18 m in section (Fig. 5) of late Miocene Rattlesnake Formation. Tape is graduated in mm.

chalcedony and micrite. Fine, near-vertical root traces, like the adventitious roots of grasses, are common, as well as stout, branching roots, like those of woody shrubs. Large root traces like those of trees were also seen, but were uncommon. Tnan paleosols lack both the fine root density and crumb structure of Tatas paleosols, and their grasses were probably bunch grasses rather than sod-formers. These observations together with the limited chemical weathering and shallow calcic horizons of Tnan paleosols are suggestive of arid to semi-arid wooded shrubland. Tnan paleosols are similar to the Hack loam soil in this area today (Dyksterhuis, 1981), which is vegetated by sage (*Artemisia rigida*), juniper (*Juniperus occidentalis*), and wheatgrass (*Agropyron spicatum*: Franklin and Dyrness, 1973). Bunch grasses are common in this vegetation, giving the alternate name of shrub steppe (Leopold and Denton, 1987). Such desert vegetation has been assumed to be of Quaternary origin largely because of its poor paleobotanical record (Axelrod, 1989), but such arid oxidizing environments are not conducive to plant preservation (Retallack, 1998b). Although it is not known whether the particular species now forming the wooded shrublands of central Oregon ranged back to the late Miocene, Tnan paleosols are evidence for ecologically comparable vegetation at that time. With subsequent paleoclimatic fluctuation, vegetation alternated between shrubland, grassland and woodland, as indicated by Plio–Pleistocene fossil soils, phytoliths, pollen and mammals of the Pacific Northwest (Rensberger and Barnosky, 1993; Busacca, 1998; Blinnikov, 1999).

Also in the middle Rattlesnake Formation are weakly developed paleosols (Cmti and Xaus pedotypes). Some Xaus paleosols preserve fluvial sedimentary structures including imbricated gravels and trough cross-bedding within the profile. They represent colonization by woody vegetation of sandy channel bars and streamsides. The iron–manganese staining of many Xaus paleosols is evidence of waterlogging in fluvial lowlands, though not so marked as in paleosols lower in the sequence (Kalas and Skwiskwi). Cmti profiles have relict bedding and fossil root traces of trees and shrubs, but unlike the Xaus profiles, Cmti profiles have only scattered iron–manganese spots and were more oxidized, and so less subject to seasonal waterlogging. Vegetation of Cmti paleosols was probably riparian pole woodland of streamside levees and terraces more elevated than the sand bar and point bar pole woodlands of Xaus paleosols.

8. Changing mammalian adaptations

There is evidence from fossils found in paleosols for changes in mammal faunas as the Rattlesnake Formation accumulated. A variety of fragmentary bones and teeth have been found in Kalas paleosols of the basal 4.7 m of the formation. A partial molar of a gomphothere (*Gomphotherium* sp. indet. following Lambert and Shoshani, 1998) with manganiferous staining was found in Kalas paleosols at the base of the Rattlesnake Formation by local resident Bruce Keitlinger in the valley of Little Rattlesnake Creek (Fig. 2: NE1/4 NW1/4 NE1/4 SW1/4 section 36 T12S R25E, Wheeler County). In the South Dakota School of Mines 'Thunder and Lightning' locality (Fig. 2: SE1/4 NW1/4 NW1/4 section 29 T12S R26E, Grant County; Martin, 1983; Fremd et al., 1997), a sequence of Kalas paleosols is identical to that from 1 to 5 m in the measured section (Fig. 5). Screening of this site has yielded frog (*Rana* sp. indet.), turtle scute (*Chelonia* gen et sp. indet), bat (Vespertilionidae gen et sp. indet. cf. *Myotis*), mouse (*Peromyscus* sp. indet.), rhino (*Teleoceras* sp. indet.), peccary (*Myohyus longirostris*) and camel (*Hemiauchenia* sp. cf. *H. vera*: Martin, 1983; Wright, 1998). Nearby water is indicated by the frog, grasses or sedges by the grazing hypsodont rhino, and trees by the camel.

Confirmation of grasslands of the lower Rattlesnake Formation (4.7–18.2 m) comes from discovery of a tooth and astragalus of the large, hypsodont and cursorial horse (*Pliohippus spectans*) in a Tatas paleosol at 18 m in the measured section (Fig. 5). These large horses were probably grazers (MacFadden et al., 1999; MacFadden, 2000). An incisor of a squirrel (*Spermophilus gidleyi*) was found in a Kalas paleosol at a level equivalent to 13 m in the measured section (Fig. 5), but

1 km to the southwest. Comparable living ground squirrels live in a variety of vegetation types, but require a supply of small seeds from herbaceous vegetation.

Paleosols of the middle Rattlesnake Formation (18.2–77 m) have yielded a variety of mammal fossils. Enlows (1976) records hipparionine three-toed horse teeth (*Neohipparion leptode* as revised by MacFadden, 1998) from 1 m beneath the ash-flow tuff in what is here recognized as a Tnan paleosol. Yet another fossiliferous Tnan paleosol less than 1 m below the Rattlesnake Ash-Flow Tuff yielded the holotype jaw of the procyonid *Simocyon marshi* in nearby Cottonwood Creek (Fig. 2: Baskin, 1998a). Another locality with only Tnan paleosols exposed (Fig. 2: NW1/4 NE1/4 NE1/4 NW1/4 section 31 T12S R26E) yielded a big cat (felid or nimravid) now in the Yale collections (YPM40265: Martin, 1998a,b). Berkeley locality 3060 in the type section of the Rattlesnake Formation (Merriam et al., 1925) is in Tnan paleosols (correlatable with 25 m in Fig. 5), and has yielded horse (*Pliohippus spectans*), rhino (*Teleoceras fossiger*, name after Prothero, 1998) and peccary (*Mylohyus longirostris*, name after Wright, 1998). A partial skull of the hippo-like grazing rhino (*T. fossiger*) was excavated from the silty upper part of a Xaus paleosol at a level of 70 m in measured section, but 200 m south of the section line. Also from Xaus paleosols in the measured section are molars of beaver (*Dipoides* sp. cf. *D. stirtoni*, 29 m), and of peccary (*M. longirostris*, 51 m). Rhinos and peccaries are compatible with riparian pole woodland, but horses indicate persistence of open rangeland.

9. Changing fluvial regimen

Alluvial architecture changes also with the three distinct suites of paleosols in the basal (0–4.7 m), lower (4.7–18.2 m) and middle (18.2–77 m) Rattlesnake Formation. At the base of the section, a moderately developed paleosol (Skwiskwi) caps a fining-upwards cycle with its base in weakly developed paleosols (Kalas) and interbedded conglomerates. This is probably a point bar cycle of a meandering stream. The basal, thin (0.3–0.5 m) paleochannel conglomerate of the Rattlesnake Formation fills an erosional landscape cut into the underlying Mascall Formation (Fig. 1). Our paleocurrent measurements from clast imbrication (Fig. 5) show that these streams flowed southeast down the axis of the late Miocene John Day Valley revealed by Rattlesnake Ash-Flow Tuff isopachs (Streck et al., 1999). This is the opposite direction to the flow of the modern John Day River, and predates excavation of the current outlet through Picture Gorge.

Within the lower Rattlesnake Formation (4.7–18.2 m) conglomerates are thicker (2 m), and coarser-grained (many boulders), but still show southeasterly paleocurrents and fining-upwards sequences that culminate in moderately developed paleosols (Tatas). Unlike associated paleosols, Tatas paleosols lack any evidence of waterlogging, and their deeply penetrating root traces, calcareous rhizoconcretions and calcareous nodules indicate good drainage for most of the year. Tatas paleosols formed on floodplains and low terraces away from stream margins and also remote from creeks and alluvial fans building from tributary valleys of the main drainage. The strong imbrication of associated basaltic paleochannel conglomerates and their wide lateral extent is evidence of change in fluvial regimen to braided and loosely sinuous streams of considerable power.

Yet another shift in fluvial regimen is represented by the middle Rattlesnake Formation (18.2–77 m), where conglomerate beds are much thicker than before (each about 10 m thick), with gradational fining-upwards trends culminating in siltstones with paleosols (mainly Tnan pedotype). Furthermore, paleocurrents indicated by pebble imbrication shift from easterly to southerly (Fig. 5). These changes in facies and paleocurrents record progradation of gravelly alluvial fans from highlands of Columbia River Basalt to the north (fanglomerate facies of Enlows, 1973, 1976). The best developed paleosols in this part of the formation (Tnan) represent those parts of alluvial fans distant from channels, where suspended load and airfall has softened the gravelly surface of fan channel tracts. Associated weakly developed paleosols (Xaus and Cmti) formed along the riparian fringe of alluvial fan channels.

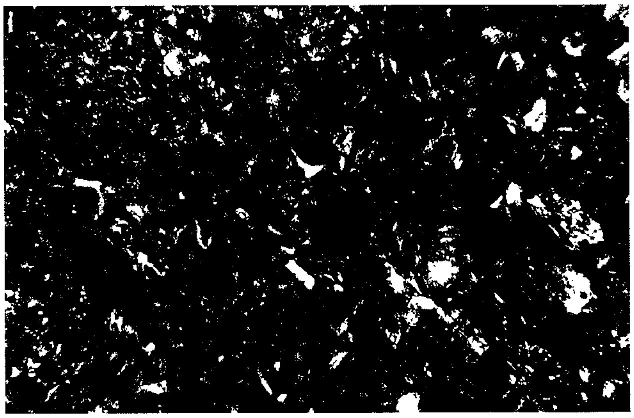

Fig. 12. Petrographic thin section under crossed nicols or the surface (A) horizon of the type Tatas clay paleosol, showing volcanic shards, feldspar and ellipsoidal crumb peds. Field of view is 7 mm across.

10. Changing sediment sources and parent materials

There is evidence that both source terranes and paleosol parent material changed during deposition of the Rattlesnake Formation, in ways compatible with interpreted shifts in paleoclimate and former vegetation. Three separate sources of materials include basaltic gravel, fresh volcanic airfall ash, and volcaniclastic redeposited sediments of the Mascall and underlying Cenozoic formations.

The Picture Gorge Basalt of the Columbia River Basalt Group is a tholeiitic flood basalt, typically 40% plagioclase, 35% clinopyroxene, 8% glass, 5% olivine, and 5% iron oxides (Robinson, 1973). Pebbles of basalt dominate conglomerates of the Rattlesnake Formation, which become more thick and coarse-grained up-section as paleoclimate became drier and vegetation sparser allowing progradation of alluvial fans from tectonically uplifted hills of basalt to the north (Fig. 1). Basaltic pebbles were the most voluminous part of parent materials for Kalas paleosols, but basalt clasts in these paleosols have remained fresh within thin weathering rinds (Fig. 6), and so played a minor role in weathering.

A second source of material was sandy to clayey volcaniclastic sediment of rhyodacitic bulk composition from erosion of the underlying Mascall and John Day Formations (Bestland and Krull, 1997). This was a large component of the fine-grained upper parts of paleochannel deposits and associated Xaus paleosols. Quartz is very rare in these sandy sediments and paleosols, so that quartzose local Paleozoic and Mesozoic basement to the south was probably not well exposed at the time.

A third source of material was fresh, vitric and pumiceous volcanic airfall ash (Fig. 12) from contemporaneous eruptions to the south and east (Streck et al., 1999). Two little weathered, vitric tuffs were found in the measured section (at 17 and 67 m in Fig. 5). Like the well known Rattlesnake Ash-Flow Tuff, these tuffaceous volcanic components were rhyodacitic in chemical composition, with a large portion arriving as shards (vitric and non-crystalline: Enlows, 1973, 1976). This fresh volcanic component dominated local soil chemistry, considering the persistence of so much amorphous colloid in these paleosols, reflected in diffuse, broad XRD peaks and modeling by NEWMOD (Table 3). The proportion of this parent material varies with pedotype. Most Kalas paleosols have an appreciable thickness of these clayey and silty materials on top of a basal conglomeratic layer. The Skwiskwi paleosol has little basaltic gravel deep within the profile, and consists almost entirely of clay and colloid derived from the weathering of rhyodacitic volcanic ash, as indicated by shard remnants deep within the profile. Tatas paleosols also have little basaltic gravel, and consist almost entirely of clay and colloid derived from the weathering of rhyodacitic volcanic ash. Shards and feldspar persist within these paleosols (Fig. 12), and indicate a parent material primarily of airfall volcanic ash. Coarse (up to 3 cm) pumice fragments in the type Tatas clay (correlatable to 16.5 m in Fig. 5) and Tatas clay silty variant (18 m in Fig. 5) paleosols are evidence of large Plinian eruptions creating a relatively pure and homogeneous parent material. Both profiles also show redeposition of the surface 10 cm by wind and water, which introduced some basaltic granules. Cmti and Tnan paleosols also formed on airfall volcanic ash, but in most cases this is mixed with volcaniclastic sediments, derived in large part from erosion of the earlier Miocene Mascall Formation. The increased abundance of little weathered volcanic shards up-section may reflect climatic drying as well as increased supply.

11. Time for formation

Rates of sediment accumulation and geological age of different parts of the Rattlesnake Formation can be inferred from estimates of the time for formation of the paleosols by comparison with comparable surface soils and soil features (Table 4). For example, the measured thickness of weathering rinds on basalt clasts in Kalas paleosols (Fig. 6) can be compared with rind thickness of surface soils of known exposure age (Colman, 1986). All measured clasts were excavated by trenching this steep outcrop, in order to avoid modern weathering. The times estimated from rind thickness are thus durations of soil formation for the paleosols before Miocene burial. The oxidation rinds are simple reddened gradients (diffusion sesquans) that show no chemical reduction or other burial alteration. Also measured was the thickness of weathering rinds in paleochannel basaltic clasts, which can be as much as 0.5 mm. This presumably reflects ancient soil development that liberated clasts from upland soils to streams and then parent material to the paleosols. Mean rind thickness of basalt clasts in Kalas paleosols varies from 0.6 to 2 mm. Assuming a subhumid climate comparable to modern McCall, Idaho (other chronofunctions of Colman, 1986 give slightly different results), and subtracting a likely prior thickness of 0.5 mm (Fig. 6), gives estimates of about 9, 32–35 and 139 ka for the Kalas paleosols at 1, 2, and 3 m respectively within the first of the three paleoclimatic regimens (ca. 7.5–7.3 Ma). These are long times compared with the profile differentiation and degree of clay weathering observed, and should be considered maximal likely estimates.

Other indices for duration of soil formation, such as thickness, clay accumulation and abundance of clay skins, can be used for other pedotypes. The increase in clay in the Bt horizon of the Skwiskwi pedotype is comparable to that seen in soils between the 2.2–4.6-ka Organ I and 8–15-ka Isaacks Ranch surfaces on alluvial fans in the desert near Las Cruces, New Mexico (Gile et al., 1966, 1981), and between the 10-ka lower Modesto and 40-ka upper Modesto surface in the San Joaquin Valley of California (Harden, 1990). In tropical, humid, highland New Guinea, volcanic shards are destroyed in soils older than 8–27 ka (Ruxton, 1968). A reasonable time for formation of the Skwiskwi paleosol considering its clay content and few relict shards is 10–40 ka.

Tatas paleosols are weakly to moderately developed. Primary structures such as bedding are sparse and much disrupted, clay skins are scattered and calcareous nodules remain diffuse. Such a degree of clay accumulation is between that seen in the 3-ka post-Modesto II terrace and the 10-ka upper Modesto terrace in the San Joaquin Valley of California (Harden, 1990). Such a degree of carbonate accumulation is between that seen in the 2.2–4.6-ka Organ I soil and the 8–15-ka Isaacks Ranch soil near Las Cruces, New Mexico (Gile et al., 1981). Another constraint is given by the persistence of volcanic shards, which in tropical, humid, highland New Guinea are destroyed in soils older than 8–27 ka (Ruxton, 1968). Some 5–10 ka is a likely time for formation of Tatas paleosols.

Tnan paleosols are weakly to moderately developed, their calcareous nodules larger and more conspicuous than in weakly developed soils such as the 2.2–4.6-ka Organ I soil, but not so large and well defined as in moderately developed soils such as the 8–15-ka Isaacks Ranch soil near Las

Table 4
Paleoenvironmental interpretation of paleosols from the late Miocene Rattlesnake Formation

Pedotype	Paleoclimate	Ancient vegetation	Former animals	Paleotopography	Parent material	Time for formation
Kalas	not indicative of climate	seasonally waterlogged riparian meadow	frog (*Rana* sp.), bat (*Myotis* sp.), mouse (*Peromyscus* sp.), squirrel (*Spermophilus gidleyi*), gomphothere (*Gomphotherium* sp. indet.), rhino (*Teleoceras* sp.), peccary (*Mylohyus longirostris*), camel (*Hemiauchenia* sp. cf. *H. vera*)	swales in lowland channel tract	basaltic conglomerate and rhyodacitic redeposited volcanic ash	9–139 ka
Skwiskwi	800–1000 mm MAP	riparian woodland	none found	lowland stream banks and levees	rhyodacitic redeposited volcanic ash	10–40 ka
Tatas	500–850 mm MAP, seasonally dry	tall wooded grassland	monodactyl horse (*Pliohippus spectans*), squirrel (*Spermophilus gidleyi*)	high terraces of floodplains	redeposited rhyodacitic volcanic ash	5–10 ka
Cmti	not indicative of climate	riparian colonizing grassland	insect burrows	dry silty swales in channels of alluvial fan	redeposited rhyodacitic volcanic ash	10–100 yr
Xaus	not indicative of climate	riparian colonizing shrubland	beaver (*Dipoides* sp. cf. *D. stirtoni*), rhino (*Teleoceras fossiger*), peccary (*Mylohyus longirostris*)	banks and bars in channels of alluvial fan	rhyodacitic volcaniclastic sand and gravel	10–100 yr
Tnan	200–600 mm mean annual rainfall, seasonally dry	dry wooded shrubland	procyonid (*Simocyon marshi*), small (3 cm diameter) rodent burrow, three-toed horse (*Neohipparion leptode*), monodactyl horse (*Pliohippus spectans*), rhino (*Teleoceras fossiger*)	stable interfluves of alluvial fan	redeposited rhyodacitic volcanic ash	5–10 ka

Cruces, New Mexico (Gile et al., 1966, 1981). Tnan paleosols thus represent some 5–10 ka of soil formation.

Very weakly developed paleosols such as Cmti and Xaus profiles represent only a few seasons of plant growth and iron–manganese mottling on freshly deposited sandy alluvium. Such soils form over intervals of about 10–100 yr.

Using these estimates (Table 4) for soil formation, the rock accumulation rate can be seen to have increased dramatically though time from 0.02 mm/yr for the basal Rattlesnake Formation (0–4.7 m), to 0.08 mm/yr for the lower part of the formation (4.7–18.2 m) and 0.52 mm/yr for the middle part of the formation (18.2–77 m). Also available from these data are estimates of the geological age of different parts of the formation, relative to the radiometric date of 7.05 Ma for the Rattlesnake Ash-Flow Tuff. Using paleosol data, the base of the formation in the type area should be ca. 7.5 Ma, the climatic change at 4.7 m in the section at 7.3 Ma and the paleoclimatic change at 18.2 m in the section at 7.2 Ma.

12. Late Miocene advent of tall grasslands in central Oregon

Evidence from paleosols, together with indications from paleocurrents, sedimentology, geological structure and paleontology, allow reconstruction of the paleoenvironment of the Rattlesnake Formation at two critical times during the late Miocene: ca. 7.3 Ma (Fig. 13) and ca. 7.1 Ma (Fig. 14). Our interest in this sequence of paleosols was stimulated by the prospect of documenting what appeared to be, from reconnaissance study of many Oregon paleosols (Retallack, 1997a), some of the earliest tall grassland paleosols in North America. With new insights on a variety of paleoenvironmental variables from paleosols, there is the prospect of evaluating plausible causes for the evolution of tall grasslands, such as declining atmospheric CO_2, decreasing rainfall, local tectonic or volcanic activity, or plant–animal coevolution.

The idea that declining global CO_2 content of the atmosphere promoted grasslands came largely from isotopic studies. Lowland tropical grasses now use the Hatch-Slack or C_4 photosynthetic pathway, have isotopically heavy carbon and thrive under conditions of low atmospheric CO_2. In contrast, the Calvin-Benson or C_3 photosynthetic pathway of trees, shrubs, and cool-climate to montane grasses creates isotopically light carbon and is less conservative of CO_2 (Quade et al., 1995; Cerling et al., 1997). A late Miocene (7 Ma) shift to isotopically heavy carbon in pedogenic nodules and mammalian teeth has now been found in the USA, Bolivia, Argentina, Kenya, and Pakistan (Wang et al., 1994; Kingston et al., 1994; Morgan et al., 1994; Quade et al., 1995; MacFadden et al., 1994; Latorre et al., 1997), but not in Oregon or northern North America where C_4 plants have never been demonstrated (Cerling et al., 1997). The inferred rise in C_4 vegetation in paleotropical regions was not necessarily the first appearance of grasslands, because isotopic studies of grazing mammal teeth and phytoliths have shown that C_3 grasses were widespread during the early Miocene (MacFadden, 2000). Global lowering of atmospheric CO_2 partial pressure is inferred because C_4 plants have a competitive advantage when CO_2 becomes limiting at less than 500 ppmV (Cerling et al., 1997). Confirmation of CO_2 drawdown at 7 Ma comes from a rise in oceanic alkalinity (pH from 7.4 to 8.2) from boron isotopes ($\delta^{11}B$) in marine foraminifera (Spivack et al., 1993; Pearson and Palmer, 1999) and reduction of atmospheric CO_2 partial pressure from some 350 ± 40 to 280 ± 25 ppmV from stomatal distribution of fossil oak and *Ginkgo* leaves (van der Burgh et al., 1993; Retallack, 2001a). Consistently low values of atmospheric CO_2 throughout the Miocene are revealed by studies of the isotopic composition of peats in Germany (Utescher et al., 2000) and of planktonic algal carbon in deep sea sediments of the Pacific Ocean (Pagani et al., 1999). Paleoclimatic shifts inferred in our sequence from subhumid woodland to semi-arid shrubland are much greater than can be attributed to changes in atmospheric CO_2 abundance comparable with Pleistocene glacial–interglacial fluctuation of this greenhouse gas (Busacca, 1998).

Other plausible causes of grassland expansion

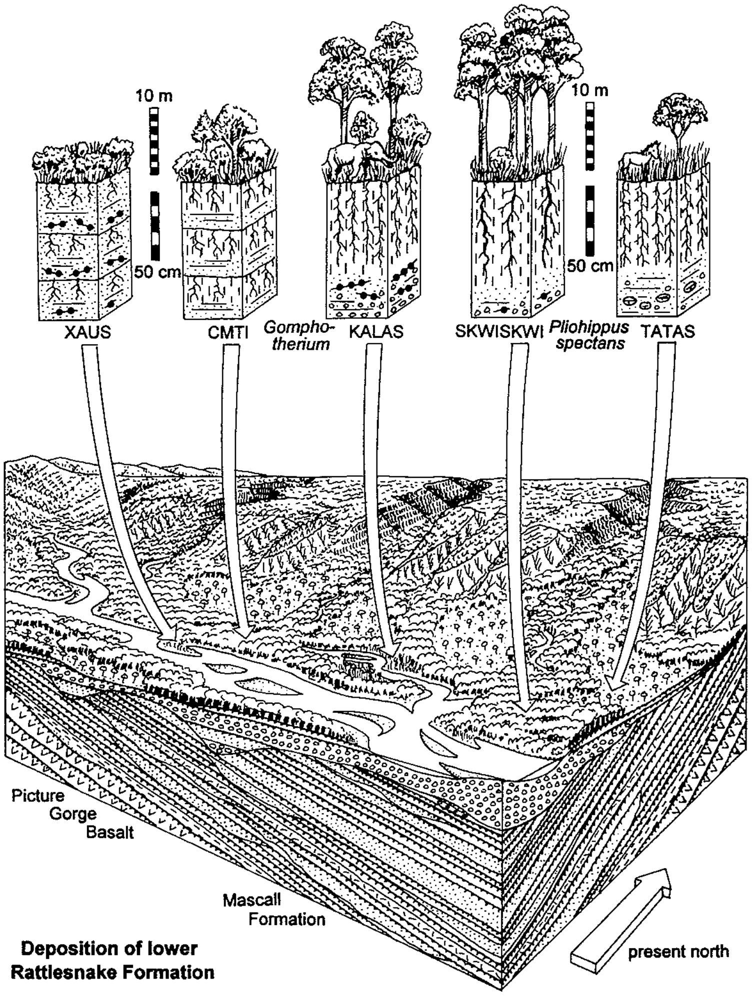

Fig. 13. Reconstruction of the area near Picture Gorge, west of Dayville during the late Miocene (7.3 Ma) accumulation of the Rattlesnake Formation. Lithological key as for Fig. 5.

include mountain uplift (Quade and Cerling, 1995) and waning oceanic thermohaline circulation (Flower and Kennett, 1994). Although Panamanian isthmus closure may have had global paleoclimatic repercussions, this was at 3.1–3.5 Ma, well after deposition of the Rattlesnake Formation. Furthermore, Carribean island arcs had deflected oceanic circulation from this region since the Eocene (Iturralde-Vinent and MacPhee, 1999; Marincovich, 2000). The appearance of tall grasslands in central Oregon does not appear to be cued to local volcanic or tectonic activity either. Cascadian volcanism and its rain shadow in eastern Oregon can be traced back at least 40 Ma (late Eocene: Retallack et al., 2000), and the interval from 6 to 9 Ma was a lull in volcanic activity in the central Cascades (McBirney et al., 1978). The most profound local tectonic event was creation of the hilly basal unconformity of the Rattlesnake Formation, yet paleosols immediately above this level are not strikingly different from those of the underlying Mascall Formation (Bestland and Krull, 1997). The most profound volcanic event was eruption of the massive Rattlesnake Ash-Flow Tuff, yet assemblages of paleosols indicate similar climate and vegetation both

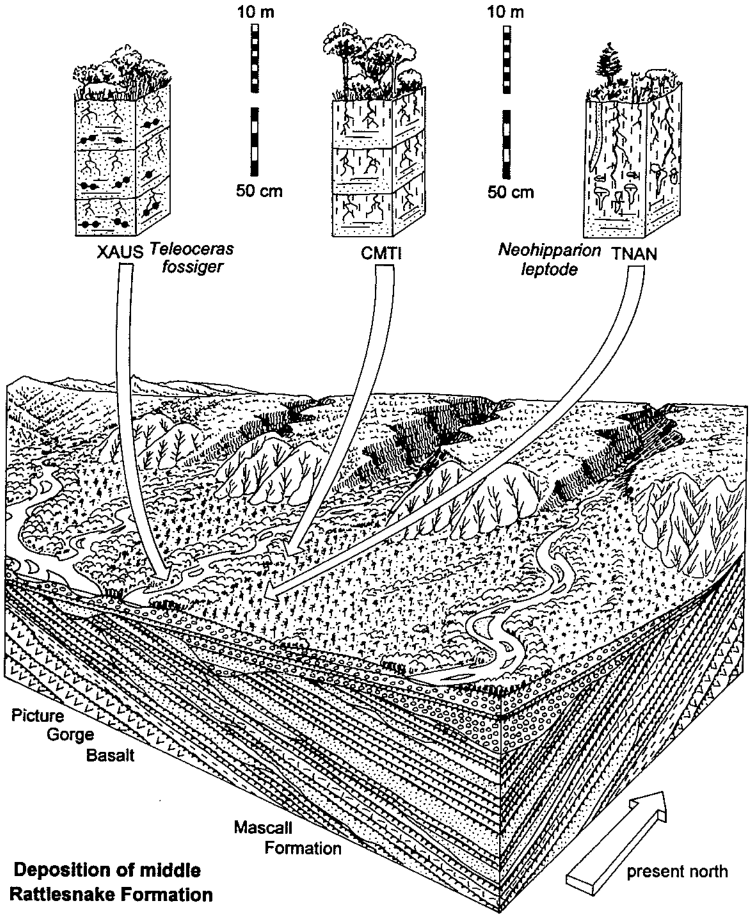

Fig. 14. Reconstruction of the area near Picture Gorge, west of Dayville during the late Miocene (7.1 Ma) accumulation of the Rattlesnake Formation. Lithological key as for Fig. 5.

before and after this regionally catastrophic eruption.

Another idea for the origin of grasslands, often tied to changes in mountain uplift, volcanic activity or ocean currents, is the idea that grasslands evolved in response to dry or monsoonal climates of the late Miocene (Quade et al., 1989; Pagani et al., 1999). In apparent support of this idea, paleosols of the Rattlesnake Formation show paleoclimatic drying and increased seasonality from subhumid woodlands to semi-arid grasslands. Furthermore, paleoclimatic drying continued with a clear overshoot to arid conditions comparable to the present day. However, there is no evidence of extreme of monsoonal precipitation, which forms a suite of soil features not found in paleosols of the Rattlesnake Formation (Retallack, 1991b). Taking a longer view of the whole Cenozoic, paleosols and other proxy records reveal many other paleoclimatic wet–dry cycles uncorrelated with grassland advances in either Oregon or the North American Great Plains (Retallack, 1997a). Paleosols with the fine roots and structure of sod grassland soils first appear during the early to middle Miocene in paleosols with calcic horizons at depths of 40 cm or less, but such paleosols with calcic horizons as deep as 1 m do not appear until the late Miocene. This observation can be interpreted as evidence for regional expansion of grasslands at about 7 Ma into wetter climatic regions, so that the ecotone between grassland and woodland was shifted from the 400-mm isohyet to near the 750-mm isohyet encompassing the current area of tall grasslands (Retallack, 1997a). Sod-forming tall grasslands thus replaced pre-existing dry woodlands during late Miocene time (ca. 7 Ma), dramatically expanding their climatic and geographic range to displace dry woodlands formerly living in the 400–750-mm isohyet belt. From this broader perspective grasslands were not filling in regions too dry or seasonal for trees, but expanding their range into wetter and less seasonal regions.

Another plausible explanation for late Miocene expansion of tall grasslands is the original insight of Kovalevsky (1873) that grasslands are a product of the coevolution of grasses and grazers (Stebbins, 1981; Thomasson, 1985; Retallack, 2001b). Grasses are uniquely equipped to withstand grazers with their sod of matted roots, underground rhizomes, silicified leaves and telescoped meristems. Grazers with their hard hooves and tall crowned teeth are uniquely equipped to exploit open grassy habitats (Janis, 1995; MacFadden et al., 1999). Late Miocene evolutionary radiations are known for many grassland creatures in addition to ungulate mammals, including grasses (Thomasson, 1979, 1987; Jacobs et al., 1999), daisies (Singh, 1988), legumes (Axelrod, 1992), dung beetles (Retallack, 1990), bees (Burnham, 1978), colubrid snakes (Rage, 1984), and passerine birds (Unwin, 1988). The late Miocene can be viewed as a significant threshold in the protracted evolutionary arms race between grasses and grazers, during which modern tall grasslands and large, cursorial, hypsodont grazers appeared in the wake of the most important extinction of mammals in the last 30 Ma (Webb, 1984). The major shift from woodland, through grassland mosaic to desert shrubland here documented from 7.3 to 7.2 Ma (early Hemphillian) corresponds in time to continent-wide extinction of most remaining browsers in the Clarendonian Chronofauna of large mammals: complete losses of oreodonts, moschids, dromomerycids, merycodontine antilocaprids, and gomphotheres, and much reduced diversity of camels, peccaries, rhinos and horses (Stanley, 1997; Lander, 1998; Webb, 1998; Lambert and Shoshani, 1998; MacFadden, 1998; Prothero, 1998; Janis and Manning, 1998a,b; Wright, 1998; Honey et al., 1998). At the same time there was an evolutionary radiation of North American pronghorns (antilocaprines: Janis and Manning, 1998b) and stipid grasses (Thomasson, 1979). Many of the distinctive carnivores of the Rattlesnake Formation were freshly immigrant from cool temperate Eurasia: the martenlike *Lutravus halli*, the procyonid *Simocyon marshi* and the bear *Indarctos oregonensis* (Baskin, 1998a,b; Hunt, 1998). This was a major reorganization of North American biota, with a clear unidirectional result of more grassland than ever before. In any given locality, as in central Oregon, grasslands came and went with changing paleoclimate and soils, but despite this near chaotic background of tectonic, oceanic, and paleoclimatic oscillations, tall grasslands arrived and stayed in subhumid regions throughout the world.

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