RETALLACK, G.J., 1993, Late Ordovician paleosols of the Juniata Formation near Potters Mills, Pennsylvania. In S.G. Driese (editor), Paleosols, paleoclimate and paleoatmospheric CO_2; Paleozoic paleosols of Pennsylvania. University of Tennessee, Department of Geological Sciences, Studies in Geology, v. 22, p. 33-49

INTERNATIONAL ASSOCIATION OF GEOCHEMISTRY AND COSMOCHEMISTRY - 3RD INTERNATIONAL SYMPOSIUM ON GEOCHEMISTRY OF THE EARTH'S SURFACE

and

SEPM (SOCIETY FOR SEDIMENTARY GEOLOGY) FIELD TRIP

PALEOSOLS, PALEOCLIMATE AND PALEOATMOSPHERIC CO_2; PALEOZOIC PALEOSOLS OF CENTRAL PENNSYLVANIA

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DAY 1 STOP DESCRIPTIONS

STOP 1 - Late Ordovician Paleosols of the Juniata Formation Near Potters Mills, PA *by Gregory J. Retallack*

INTRODUCTION

A thick sequence of the Late Ordovician Juniata Formation is exposed in road cuts along a divided section of U.S. highway 322 east of Potters Mills and west of the long descent east to Milroy, Pennsylvania (Figs. 1-1, 1-2). These red beds include common sandstone paleochannels, divided by clayey and carbonate-bearing paleosols containing trace fossils of some of the earliest known land animals (Retallack and Feakes 1987; Retallack 1992a). The trace fossils are so common and well preserved here that it is not difficult to evaluate their field occurrence and some critical questions concerning them. Are the rocks marine or non-marine? Did the burrows form before, after or during soil formation? What kind of creatures formed the burrows? Laboratory studies of these paleosols and burrows have

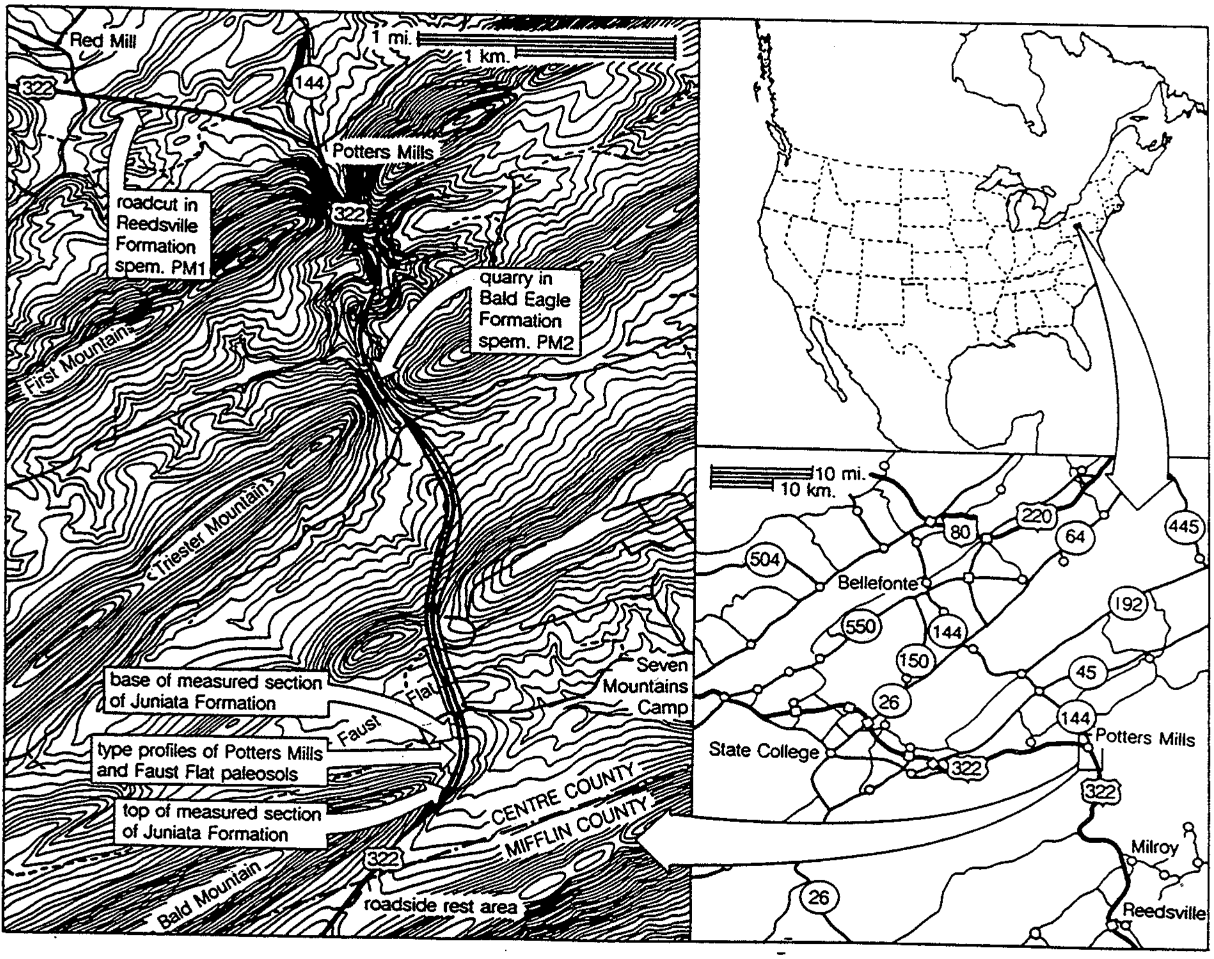

Figure 1-1 - Road map (lower right) and topographic map (left) for locality of Late Ordovician paleosols in the Juniata Formation near Potters Mills, Centre County, Pennsylvania. Contour interval is 20 feet.

clarified many of these questions (Feakes and Retallack 1988; Retallack 1992a), but there is no substitute for seeing them in the field for yourself.

A measured section of the Juniata Formation was made in 1985 (Fig. 1-2) on the western side of the western (eastbound) lanes of highway 322 beginning with strata dipping at 21° east from 100 m east of the junction with cross roads to Faust Flat and Seven Mountains Camp. This western part of the section is becoming progressively overgrown with crown vetch (*Coronilla varia* L.). Some 200 m east of the road junction the road cut is higher and the section includes the

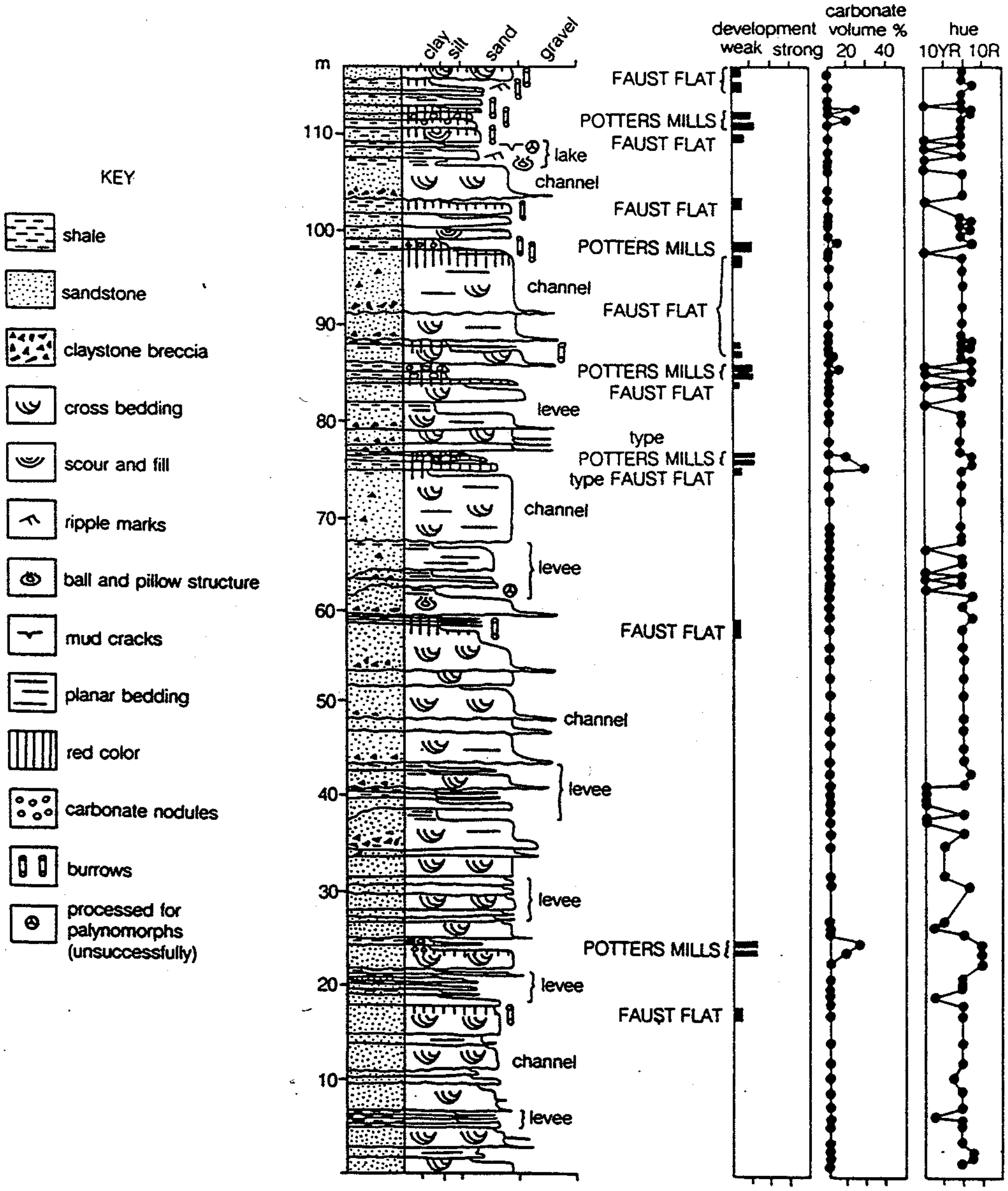

Figure 1-2 - A measured section of the Late Ordovician paleosols in the Juniata Formation near Potters Mills, Centre County, Pennsylvania. Paleoenvironmental interpretations of facies and paleosol series are shown, as well as estimates of the degree of development of the paleosols, percent area of carbonate nodules and Munsell hue (following scales of Retallack 1988, 1990).

type examples of the Potters Mills and Faust Flat clay paleosols (Fig. 1-3). The site is now marked by a small tree that began growing in the talus of excavations made in 1982. The measured section continues to the south to a point above the first excavated bench in the road cuts where the dip of the beds declines to almost horizontal. At this point high in the road cut are several additional meters of red Juniata Formation overlain by light colored sandstones of the basal Tuscarora Formation (Cotter 1982; Strother and Traverse 1979). Trace fossils are particularly easy to observe and collect in paleosols of the Juniata Formation near the excavated bench and in fallen blocks near this southern end of the measured section where the roadcut is highest.

GEOLOGICAL SETTING

The Juniata Formation represents the upper part of a thick clastic wedge that thins to the west into gray and green marine rocks (Drake *et al.* 1989). Red beds of the Juniata Formation have been interpreted as alluvial outwash of the high Taconic Mountains, a mixed sedimentary, metamorphic and plutonic folded mountain range that once existed to the east (Yeakel 1962; Meckel 1970). Paleogeographic reconstructions place the Potters Mills locality, which is stratigraphically high in the Juniata Formation, on the outwash plain at least 200 km east of marine rocks to the west and about 120 km west of the mountain front (Dennison 1976).

A variety of sedimentary structures within the purple-red sandstones of this outcrop confirm their fluvial origin (Cotter 1982). Stringers of intraformational breccia, trough cross bedding, and shallow scour-and-fill structures are common in the thick sandstones, which in

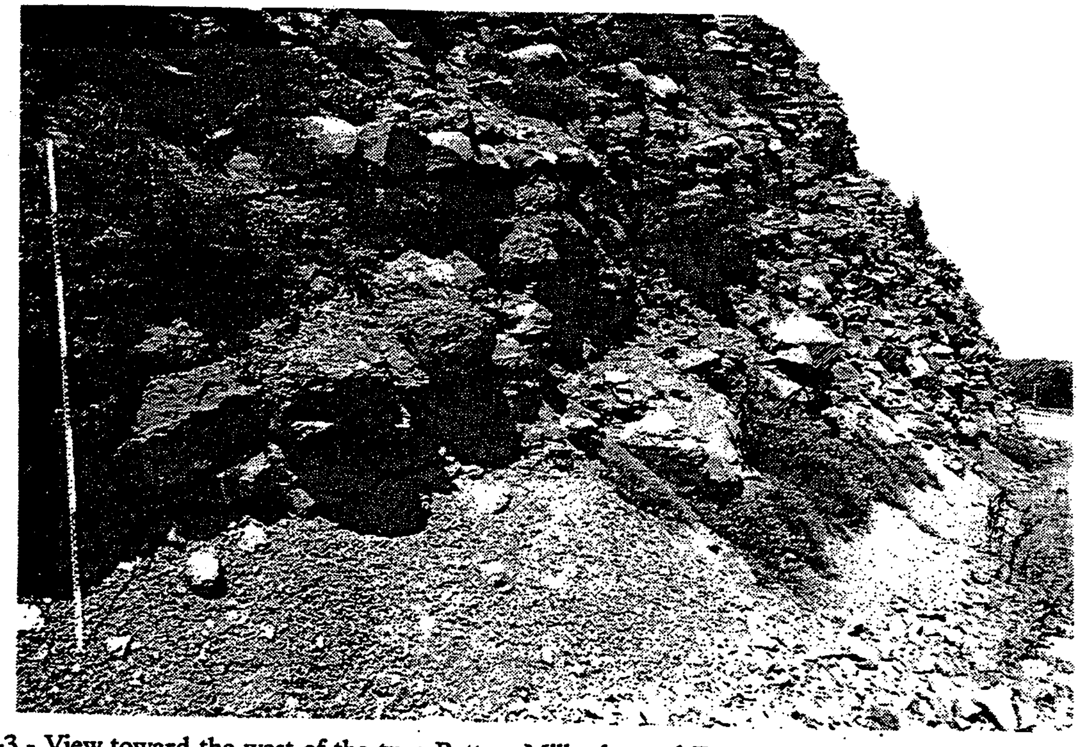

Figure 1-3 - View toward the west of the type Potters Mills clay and Faust Flat silty clay paleosols in roadcut exposures during 1982. The top of the Potters Mills clay is at the base of the upper black band on the staff, which is graduated in feet.

most cases appear tabular for the extent of their outcrop. There are places however, notably some 150 m south of the road junction, where the basal surface of a sandstone erodes steeply down for 30 to 40 cm into underlying units. These indications of asymmetric paleochannels are not so marked as in meandering river deposits, but are more than would be expected in braided streams. A loosely sinuous stream pattern is envisaged during deposition of this part of the Juniata Formation (Cotter 1978).

More definitive of the paleoenvironment of this formation are clayey red interbeds, which are in most cases interpreted as paleosols. Only a few fine-grained beds do not show some degree of ancient soil formation. Notable in this regard is a unit of gray shale with an horizon of soft sediment deformation (ball-and-pillow structure) at eye level near the southern end of the measured section where the strata are nearly horizontal in attitude. This facies is similar to lacustrine deposits. Nevertheless, it probably was not a permanent lake, because it lacks varves, fossils or chemical sediments.

PALEOSOL RECOGNITION

Paleosols in this exposure can be recognized in the field from their red color, clayey texture, sharply truncated tops with alteration down into bedded rocks, "hackly" and "massive" structure, and common small yellow carbonate nodules (Retallack 1985; Feakes and Retallack 1988). The hackly and massive appearance is from the development of soil clods (peds) defined by former cracks in the soil (now closed) and by clay coatings (now slickensided irregular surfaces), called argillans by soil scientists. The small nodular masses found in some profiles are weakly reactive to acid because they are dolomitic in composition. They are most prominent on weathered surfaces, where they are often partly dissolved and stained orange with ferric hydroxides. There also are abundant fossil burrows concentrated near the sharply truncated tops of the paleosols and decreasing in abundance downward into the profiles.

Another important observation that can be made in the field is the varying expression of these various features in each paleosol. The reddest, most clay-rich and bioturbated paleosols also include the most abundant carbonate nodules. On the other hand, some profiles are little more than bioturbated sediment. These field differences in degree of soil formation are thought to reflect the relative time available for soil formation, and are indicated using a relative scale of development (from Retallack 1990) by the width of the boxes in Figure 1-2.

Laboratory studies have confirmed identification of these clayey red bioturbated layers as paleosols. In thin section the paleosols compared with their parent alluvium are much more clayey and ferruginized with submicroscopic hematite. These pedogenic colloidal materials have developed at the expense of labile minerals such as mica and rock fragments (Fig. 1-4). There is no trace left of an original laminated fabric, but in its stead is the random aggregation of clay minerals into highly birefringent streaks that are characteristic of soils: microstructure called skelmosepic by Brewer (1976; Retallack 1985). This distinctive microfabric reflects the small scale stresses and reorientation of

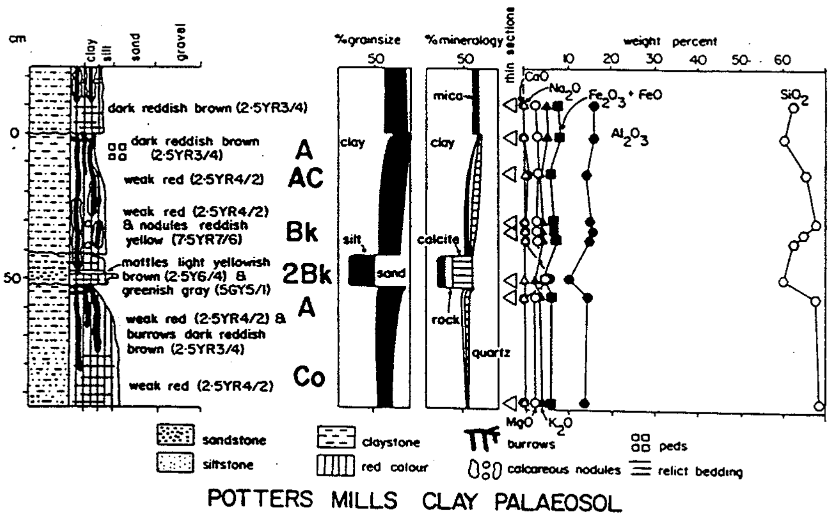

Figure 1-4 - Field appearance, petrographic and chemical appearance of the Potters Mills clay paleosol (above) and Faust Flat silty clay paleosol (below) near Potters Mills Pennsylvania. Specimen numbers from top down are UOR169 to 177 (from Retallack 1990).

soil during shrinking and swelling with wetting and drying, activity of soil fauna or other processes at low temperature and pressure (Retallack 1990). The carbonate nodules, though recrystallized, are replacive, as is usual for pedogenic carbonate (Wieder and Yaalon 1982).

The Potters Mills clay paleosol also shows a regular pattern of variation in chemical composition downward toward its parent alluvium, unlike the erratic pattern of chemical variation found in bedded sediments (Fig. 1-4). Molecular weathering ratios calculated from the weight percent of each oxide divided by its molecular weight can be used to evaluate possible soil-forming processes (Feakes and Retallack 1988), which include ferruginization due to oxidation (Fe_2O_3/FeO,SiO_2/Fe_2O_3)as well as clay formation (SiO_2/Al_2O_3)and leaching (Ba/Sr) due to hydrolysis (Fig. 1-5). A more rigorous assessment of the amount of chemical differentiation of these paleosols is compromised by uncertainties in the exact composition of layered alluvial parent material. This basic assumption has been ignored in some mass balance analyses of fluvial paleosols (Cerling and Quade 1992), but can be accommodated by using a range of compositions of a weakly developed paleosol as parent material for a better developed paleosol. The results of this analysis for the Potters Mills paleosol compared with the weakly developed Faust Flat paleosol (Fig. 1-6) show that the apparent weathering trends of desilication, and gains in alumina and iron are well in excess of likely variation in parent material composition. On the other hand, the degree of weathering demonstrated by these paleosols is much less profound than in other paleosols analyzed in this way (see for example, Grandstaff *et al.* 1986).

Also characteristic for paleosols are isotopic analysis of carbon from carbonate and organic matter from the Ordovician paleosols near Potters Mills (Table 1-1). Carbon of both organic matter and carbonate is isotopically much lighter in the paleosols than in demon-

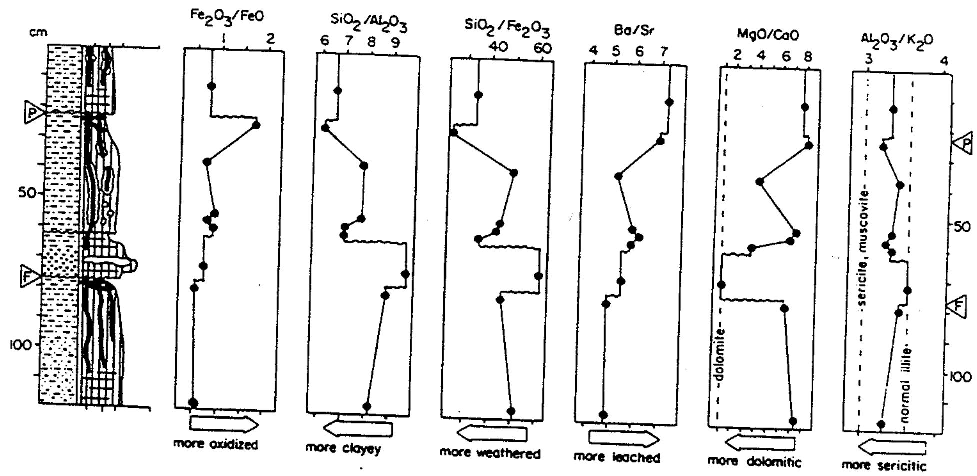

Figure 1-5 - Molecular weathering ratios and inferred weathering trends in the Potters Mills clay and Faust Flat silty clay paleosols, near Potters Mills, Pennsylvania (from Feakes and Retallack 1988).

strably marine carbonates of the underlying Bald Eagle Formation, which are interbedded with shales and sandstones containing brachiopods at the site sampled for isotopic results. Values of -4 to -6 ‰ for carbon in carbonate of the Potters Mills paleosols are very similar to those for paleosols of the Late Şilurian upper Bloomsburg Formation in Pennsylvania, and significantly lighter than values for near-marine paleosols of the lower Bloomsburg Formation in Pennsylvania (Mora *et al.* 1991; Driese *et al.* 1992).

The similar isotopic composition of dolomite and calcite from the same samples (Table 1-1) may be taken as evidence for dolomitization during soil formation as well as during formation of marine limestones of the Bald Eagle Formation. The greatest isotopic divergence between coexisting dolomite and calcite was in sandstone dividing the type Potters Mills and Faust Flat paleosols, which has a sparry carbonate cement (Fig. 1-4) similar to that of some groundwater calcretes (see Searl 1989). The pedogenic nodules in contrast have irregular margins and included small grains indicating that they have replaced clayey matrix in the manner usual for pedogenic nodules. They are however, recrystallized extensively (Retallack 1985; 1992a), and before these isotopic data were available, an origin by dolomitization of calcite during deep burial could still be

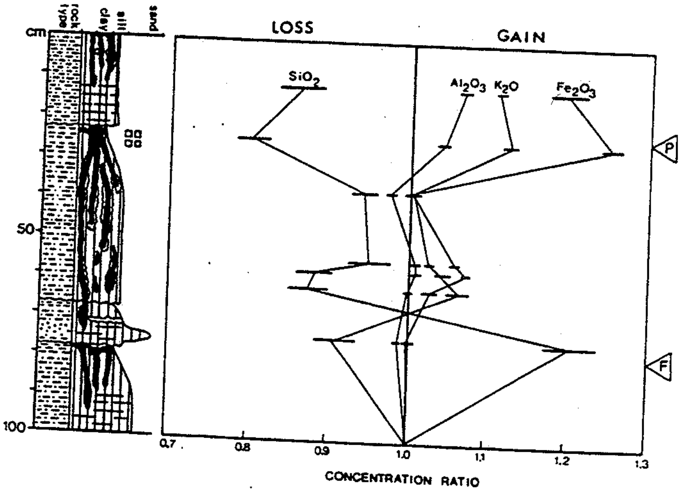

Figure 1-6 - Concentration ratios for selected oxides of the Potters Mills clay paleosol normalized to the range of values found in the less developed Faust Flat silty clay paleosol. This diagram represents the degree of soil formation of the better developed paleosol in advance of the weakly developed paleosol (from Feakes and Retallack 1988).

TABLE 1-1 - *Isotopic composition of organic matter and carbonate (‰) from Late Ordovician paleosols near Potters Mills, Pennsylvania.*

Unit	Horizon	Depth cm	Spem. No.	Organic $\delta^{13}C_{PDB}$	Calcite $\delta^{13}C_{PDB}$	Dolomit $\delta^{13}C_{PDB}$	Calcite $\delta^{18}O_{PDB}$	Dolomit $\delta^{18}O_{PDB}$
Potters Mills clay eroded phase paleosol	Bk	-25	R169	-	-6.93	-4.21*	-12.41	-11.68*
Potters Mills clay paleosol	Bk	-40	R172	-21.5*	-5.82	-4.31	-11.61	-11.45
	Bk	-50	R174	-	-4.13	-3.72	-11.44	-11.06
	Bk	-50	R174	-	-4.11	-3.72	-11.37	-11.10
	Ck	-55	R175	-6.7±.3*	-6.22	-4.34	-11.52	-11.43
Bald Eagle Formation marine limestone	-	-	PM2	-	+0.22	+0.48*	-9.78	-8.40*
	-	-	PM2	-	+0.27	+0.38*	-9.74	-9.05*
Reedsville Formation limestone	-	-	PM1	-	-8.49	-7.32	-11.13	-11.30

Note: These results were from carbonate nodules hand picked by C.R. Feakes or hand specimens of marine limestone, and were by Global Geochemistry Corporation, Canoga Park, California. Samples indicated * contained very small amounts of the analyzed fraction, and may have higher error (normally 0.1 or better). Depths are of the sample from the top of the paleosol in the detailed section of type Faust Flat and Potters Mills profiles 4 km east of Potters Mills. Bald Eagle Formation limestone is from the roadside quarry 1.2 km south east of Potters Mills and Reedsville Formation limestone from road cut 1.1 km northwest of Potters Mills, both on highway 322. Brachiopods were found associated with Bald Eagle limestone, but the Reedsville limestone was unfossiliferous, laminated and carbonaceous.

entertained (following arguments outlined by Zenger *et al.* 1980). Mississippian paleosols from Tennessee also were originally dolomitic, considering similar textural and isotopic evidence (Caudill *et al.* 1992). Low magnesium calcite is the most common carbonate forming in modern soils (Wright and Tucker 1991), but dolomite forms in some soils of exceptionally high base status (Doner and Lynn 1977; Botha and Hughes 1988).

ALTERATION AFTER BURIAL

Although these were indeed paleosols, it is equally clear that they have been altered considerably during burial. From the degree of alteration of conodonts (about CAI = 4) in Ordovician limestone of this area of Pennsylvania, burial depths were some 4.6-6.6 km and temperatures about 160-210°C (Epstein *et al.* 1977). This is compatible with the abundance of dioctahedral illite and trioctahedral chlorite in the Juniata Formation (Thompson 1970b) and the marked potash enrichment in the Potters Mills clay paleosol compared with surrounding alluvium (Figs. 1-5, 1-6). Such illitization is a widespread burial alteration of paleosols and other deeply buried sediments (Hearn and Sutter 1985; Retallack 1991a).

Compaction of the clayey upper parts of the paleosols is also a likely consequence of such deep burial, but subhorizontal burrows are compacted by less than a half and none of the vertical burrows have been obviously deformed into concertina-like shapes (Retallack 1985). Compaction can be calculated by the formula for sandstones of Sclater and Christie (1980) advocated by Baldwin and Butler (1985), as follows.

$$C = -0.5/[0.49/(e^{(D/3.7)})-1]$$

In this equation C is the degree of compaction as a fraction and D is the depth of burial in km. The constant 0.5 is the presumed original solidity (the complement of fractional porosity). This value is quite representative for soils, which have an average bulk density of about 1.3 g/cm^3 (Retallack 1990). In prior treatments of this problem (Retallack 1991b), the shale compaction curves of Baldwin and Butler (1985) were calibrated to a more reasonable solidity than the 0.2 value found in deep sea mud. The use of the sandstone curve is now thought more reasonable for both clayey and sandy parts of paleosols, because even clayey paleosols are in a sense like sandstones by virtue of their soil structure. Using burial depths of 4.6 to 6.6 km and these equations, these paleosols would be about 56-59% of their former thickness, a value compatible with the observed deformation of burrows.

These paleosols also have the vivid red color of deeply weathered tropical soils and sparse bluish-green mottles of partly waterlogged soils, yet show no petrographic or geochemical evidence of deep weathering or of gleization (Fig. 1-5). Both kinds of discoloration are common in paleosols (Retallack 1991a), and may have occurred early during burial by dehydration of ferric hydroxides to hematite and reduction of clayey matrix around anaerobically decayed organic matter. The original soils were more likely grayish brown in color.

PALEOENVIRONMENTAL IMPLICATIONS OF THE PALEOSOLS

The paleosols themselves offer additional information concerning the paleoenvironment of this ancient alluvial plain, and can be interpreted using two separate approaches. Identification of paleosols in modern soil classifications, such as the soil taxonomy of the Soil Conservation Service of the U.S. Department of Agriculture (Soil Survey Staff 1975) and the U.N.E.S.C.O.-sponsored Soil Map of the World (F.A.O. 1971-1981), is one useful way of locating analogous surface soils and soilscapes. The Potters Mills clay paleosol has been identified as an Ustropept of the U.S. taxonomy and as a Calcic Cambisol of the F.A.O. classification, and the Faust Flat silty clay paleosol as a Fluvent and Fluvisol respectively (Retallack 1985; Feakes and Retallack 1988). Fluvents and Fluvisols are such weakly developed soils that they reflect primarily a very short period of time available for soil formation: hundreds of years or less. Ustropepts and Calcic Cambisols are less widespread, forming on alluvial to rolling hilly landscapes that have been stable for periods of thousands to tens of thousands of years under woodland to wooded grassland in warm, subhumid to arid climates (Retallack 1990). Similar soils are known in several parts of the modern floodplains of the Indus and Ganges Rivers in India and Pakistan (for example, the Sultanpur Series soils of Ahmad *et al.* 1977), and similar paleosols in Miocene alluvium of the Siwalik Group of Pakistan and India (for example, the

Sonita paleosol series of Retallack 1991b).

A second approach for interpreting paleoenvironment from paleosols is by means of the factor function approach. Numerous studies have been published on the relationship between environmental variables and soil features (e.g., Birkeland 1990; Retallack 1990; 1993). These studies can be used to interpret paleoenvironmental conditions from soil features.

Atmospheric Composition

The vivid red color and strong ferruginization of these alluvial paleosols are evidence of an oxidizing atmosphere. Unfortunately the parent material compositional reducing power (R of Holland 1984) for these paleosols is too low (R = 0.04-0.07) to be critical for tracking the oxygenation of the atmosphere. This low level of parent material compositional reducing power has been overwhelmed by atmospheric oxygenation levels since at least 2 billion years ago (Retallack 1990). Late Ordovician paleosols from Nova Scotia also are strongly ferruginized, but developed on andesite flows (R = 0.12). From these Nova Scotian paleosols, Feakes *et al.* (1989) argue for at least 0.04 atmospheres for the partial pressure of oxygen during the Late Ordovician, or about 0.2 times present atmospheric level of oxygen. This is sufficient to oxidize all of the iron of most igneous rocks, and more than enough account for the marked Ordovician ferruginization of the relatively iron-poor Juniata Formation near Potters Mills.

For estimating oxygenation from Late Ordovician paleosols of Nova Scotia, Feakes *et al.* (1989) used a figure of 10 times the present level (PAL) of carbon dioxide, which would be some 3000 ppmV. This assumption of elevated carbon dioxide levels is now supported by new isotopic results (Table 1-1) for the paleosols near Potters Mills, which have a very similar isotopic composition to Silurian paleosols of the upper Bloomsburg Formation in Pennsylvania. Mora *et al.* (1991) and Driese *et al.* (1992) have used the models of Cerling (1991) to calculate that these late Silurian paleosols formed under some 4200-6000 ppmV or 14-20 PAL atmospheric carbon dioxide. Similar arguments could be made from isotopic data on the paleosols at Potters Mills (Table 1-1) for some 5400-5800 ppmV or 18-19 PAL of carbon dioxide. This estimate assumes mean annual rainfall in the Ordovician of greater than 300 mm, which is indicated for these paleosols by their degree of bioturbation and depth of calcic horizon (Retallack 1985). It also assumes no waterlogging, which is compatible with the observed oxidation, ferruginization (Fig. 1-5) and depth of burrowing. Similar high levels of 4800 ppmV or 16 PAL of atmospheric carbon dioxide have been estimated from goethites of another Late Ordovician paleosol in Wisconsin by Yapp and Poths (1992).

These results are encouraging to general models of atmospheric evolution (Berner 1991; Kasting 1993), but not entirely without problems. Practical problems arise from the nature of the carbonate analyzed isotopically, whether pedogenic, groundwater or diagenetic in origin, and in this respect oxygen isotopic evidence for diagenetic alteration is troubling (Driese *et al.* 1992). For calculation of atmospheric oxidation, the heterogeneity of paleosol alluvial parent materials is a difficulty (Feakes and

Retallack 1988). There also are model dependent problems. Calculations for atmospheric oxidation assume minimal organic activity (Feakes *et al.* 1989), whereas those for carbon dioxide assume a carbon source from photosynthetic organisms using the Calvin cycle (C_3 pathway: Mora *et al.* 1991). Finally there are general problems, such as the well documented Late Ordovician glacial deposits of Africa (Bennacef *et al.* 1971). How could such extensive ice caps have grown in the greenhouse world indicated by paleosols? Could the glacial deposits be instead misidentified impact debris, as has been suggested for supposed Precambrian glacial rocks (Overbeck *et al.* 1993)?

Paleoclimate

One of the most robust of the environmental factor functions known for soils is the relationship between depth to the calcic horizon and mean annual rainfall. This should not be confused with the depth of leaching of carbonate in soils (as is apparent from Behrensmeyer and Willis 1992), which is a function of time for formation of the soil rather than only rainfall (Ruhe 1969). The relationship between mean annual precipitation and depth to carbonate has been demonstrated in the Great Plains (Jenny & Leonard 1935) and Mojave Desert of North America (Arkley 1963), on the Indo-Gangetic plains of Pakistan (Sehgal *et al.* 1968) and even on carbonatite-nephelinite airfall deposits of the Serengeti Plains of Tanzania (de Wit 1978). A recent compilation by Retallack (1993) showed that it holds also for soils in Argentina, Iraq, Iran, Kazachstan, Mongolia, Australia and New Zealand. In this global compilation, the relationship between depths (d in cm) and mean annual precipitation (P in mm) can be fitted with reasonable accuracy ($r = 0.79$ and $1\sigma = 141$ mm), by the following binomial equation.

$$P = 139.6-6.388d-0.01303d^2$$

Using this equation and the compaction factors already outlined for the Potters Mills clay paleosol with a Bk horizon now at a depth of 19 cm, but originally more like 32-34 cm, gives a mean annual rainfall of about 331 and 342 mm for the two burial thicknesses: both estimates ± 141 mm. There is no indication from molecular weathering ratios for sodium enrichment that would be expected during salinization found in soils of dry climate (less than 300 mm mean annual rainfall: Birkeland 1990). Thus a semiarid climate of some 300-500 mm per annum is indicated by the Potters Mills clay paleosol.

Use of this equation can be compromised by different atmospheric levels of carbon dioxide in the past, by erosion of the surface of paleosols and by compaction of the upper clayey part of paleosols during burial. The effects of compaction have been taken into account by using the formula of Sclater and Christie (1980). The problem of erosion of paleosols before burial can be mitigated by selecting profiles with well preserved surface horizons. The Potters Mills paleosol with its relatively complete burrow system buried by siltstone rather than a paleochannel sandstone (Retallack and Feakes 1987), was a better choice than other obviously eroded paleosols in this sequence. Some erosion already is incorporated in the variance of the modern data set, which includes rangelands abused by overgrazing and tillage (Retallack 1993). As already outlined Ordovician atmospheric levels of carbon dioxide are thought to have been much elevated compared to now, judging from recent work on isotopic composition of paleosol carbonate (Yapp and Poths 1992). This would have the effect of acidifying soils and creating carbonate horizons deeper in the soil (Mayer *et al.* 1988), all other factors being equal. However, the biotic factor was not equal in Ordovician soils compared with those of modern grasslands and deserts, in which biotic production of carbon dioxide can easily reach levels of ten times modern atmospheric levels of carbon dioxide postulated for the Ordovician atmosphere (Brook *et al.* 1983). Because presumed low carbon dioxide levels due to biota may have been compensated in a complex way by higher levels from the atmosphere, no correction has been applied to the estimation of rainfall here.

Seasonality of rainfall is also evident from the diffuse spread through the profiles of carbonate nodules, that in some cases show concretionary growth zones, very similar to features seen in modern and fossil soils of the monsoonal Indo-Gangetic Plains of India and Pakistan (Retallack 1991b). A strongly seasonal climate also is indicated for Ordovician Appalachia by Vertisol-like paleosols (Driese and Foreman 1992a; 1992b). The paleosols near Potters Mills do show some cracklike features, but none are clearly vertic, presumably because of the relatively silty and sandy composition of their parent material compared to the Vertisol-like Ordovician paleosols elsewhere.

Paleotemperature is very difficult to assess from paleosols (Retallack 199lb). Pennsylvania is thought to have been in tropical latitudes during Ordovician time (Ziegler *et al.* 1979), and the degree of weathering and bioturbation of these paleosols is compatible with warm tropical weathering conditions.

Ordovician Life On Land

A critical question for interpretation of the abundant fossil burrows (Figs. 1-7A, B) in these red beds of the Juniata Formation is whether they represent biological activity before, during or after soil formation. A number of observations pertinent to this question can be made at the outcrop. The density of the burrows, particularly the subhorizontal ones, varies with other indices of soil formation, such as the abundance of clay skins and carbonate nodules, the intensity of red color, and the degree of destruction of relict bedding. Thus what appear to have been the best developed soils contain the most abundant burrows. Only the thicker red burrowed units also contain carbonate nodules, which are known from petrographic and isotopic evidence to have been pedogenic (Fig. 1-4, Table 1-1: Retallack 1985). These nodules are found isolated in the soil matrix as well as ensheathing some of the burrows. In the type Potters Mills clay paleosol 81 out of 157 burrows (61%) were ensheathed with carbonate. With a hand lens, it may be possible to verify in the field petrographic evidence that some nodules are cut by the burrow walls (Fig. 1-7C) and other nodules cut across filled burrow walls (Fig. 1-7D). This is the kind of distribution of carbonate expected if burrowing and nodule formation were occurring at the same time in a soil.

Alternatives to this interpretation include the idea than the burrows

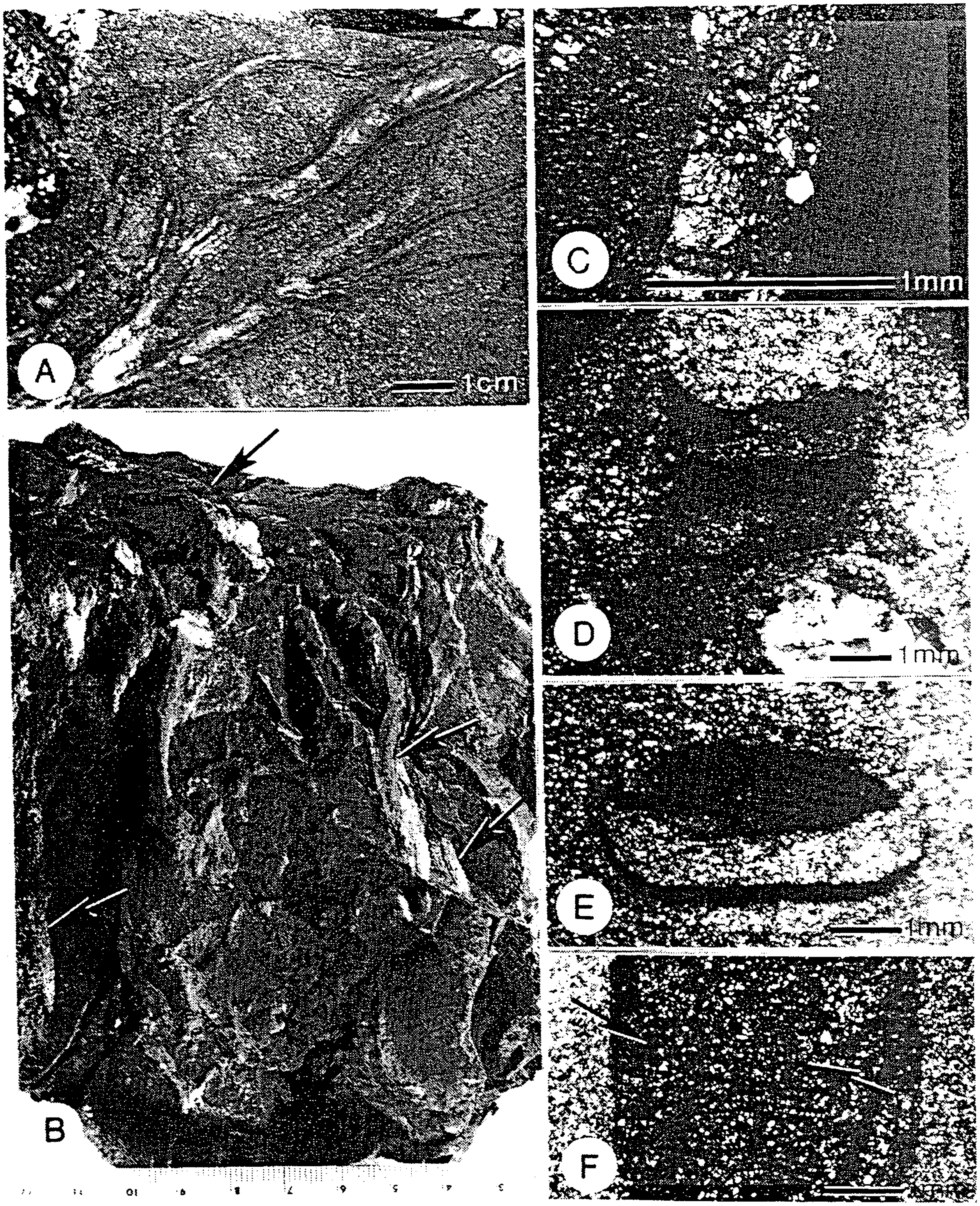

Figure 1-7 - Fossil burrows from Ordovician paleosols near Potters Mills. (A) subhorizontal burrows from paleosol surface; (B) subhorizontal (near top) and near vertical burrows (lower, all arrowed); C-F, optical photomicrographs showing truncation of carbonate by burrow wall; (C) burrow truncated by carbonate; (D) W-shaped backfills in longitudinal section, (D) and in cross section (E); and fecal pellets (F). Scale bars are in cm (A,B) and mm (C-F).

formed in a local lake or estuarine inundation of the floodplain, and were not destroyed by later soil formation. It is difficult to explain the variation in apparent soil development with burrow density in this way. Furthermore, the possible lacustrine gray and green shales, which can be observed near the top of the measured section where the dip is near horizontal, have relatively few trace fossils, and none of them are similar to the abundant burrows in the red beds. Marginal marine deposits of the Late Ordovician Bald Eagle Formation with rhynchonellid brachiopods (*Orthorhynchula-Ambonychia* community of Bretsky 1969) crop out in a roadside gravel quarry near this site, only 1 mile southeast of Potters Mills along highway 322 (Fig. 1-1). These interbedded carbonates, shales and sandstones (Thompson 1970a,b) also contain trace fossils, but they are less abundant and none are similar to the burrows in Juniata red beds. No fossil remains of aquatic or marine creatures have been found in the burrows of the red beds. Ostracods are especially conspicuous in their absence, because they are abundant in brackish water deposits of Ordovician and Silurian age in this region. Many of the trace fossils in the red beds are well preserved with sharp outlines and no evidence of collapse. One could argue that burrows would not be so readily destroyed in an Ordovician soil lacking large animals that are responsible for the fabric of many modern soils. However most burrows would have been somewhat collapsed or the clayey lining of their walls flaked off during a prolonged period of soil formation on a burrowed marine or lacustrine shale. From these observations it does not seem likely that the burrows predate soil formation.

Yet another idea is that soils formed subaerially and then were inundated by lake or lagoonal waters and an aquatic burrowing fauna. This idea is not supported by the mentioned trace fossil suites in nearby lacustrine and marginal marine facies. The burrows seen in the red beds are very distinct and more abundant than those in gray lake and estuarine deposits. Nor is it supported by the nature of the filling material of the burrows, which is uniformly red, highly oxidized material similar in chemical and mineralogical composition to the surrounding paleosol matrix. Such deep and complicated burrow systems in relatively impermeable shale would not have remained so oxidized during inundation. Pyritization or reduction of the burrow fills, and partial fill with gray estuarine or lacustrine shale would be expected following inundation of paleosols. There are some diffuse reduction spots and layers near the surface of some of the paleosols, but none filling the burrows, nor any rock or fossil trace of an omission sequence. At least one of the many burrowed surfaces should have preserved marine fossils or drab sediments if the sea or lakes had inundated this area with such frequency. The red burrows in paleosols near Potters Mills are very different texturally and chemically from pyritized and drab marine burrows into red Late Ordovician paleosols documented from Beans Gap, Tennessee (Driese and Foreman 1991).

The discovery of such evidence of burrowing organisms on land during the late Ordovician was a surprise (Retallack and Feakes 1987), because the established fossil record of terrestrial animals begins in the Silurian with a diversity of arachnids and myriapods (Shear 1991; Gray and Shear 1992). A fossil of one of these Ordovician burrowers would be an invaluable guide to their biological affinities, but is unlikely to be recovered from such oxidized paleosols (Retallack 1984). Nevertheless, the burrows and their soils can reveal some aspects of the nature of the beasts. They were evidently capable of withstanding dry soil conditions, judging from the associated pedogenic carbonate. Some burrows include fecal pellets with a distinct ferruginized margin, as an indication that the animal excreted solid feces that dried out (Fig. 1-7E). Other burrows are filled with backfill structures of alternating siltstone and claystone, and some of these show W-shaped outlines (Fig. 1-7F, G), indicative of a bilaterally symmetrical organism. The burrows are roughly tubular with diameters ranging from 2 to 21 mm, and the size distribution of the burrows includes distinct parasitic modes (Fig. 1-8), as if this was an animal like an arthropod that grew in distinct increments or moult stages. Data were pooled from both subhorizontal and vertical burrows, which were found to be interconnected in the field (Retallack and Feakes 1987), and modes in the pooled data can be shown to be significant using the Komolgorov-Smirnov test (Kopaska-Merkel 1988; pers. comm. 1988). An additional set of measurements taken on a subsequent visit to the site and included in the new compilation presented here (Fig. 1-8), shows that modes for vertical and subhorizontal subsets of the data are also statistically distinct. These various constraints are most compatible with a millipede-like animal excavating these burrows (Retallack and Feakes 1987), and similar burrows and fecal pellets are known to be produced by living millipedes (Romell 1935; Paulusse and Jeanson 1977).

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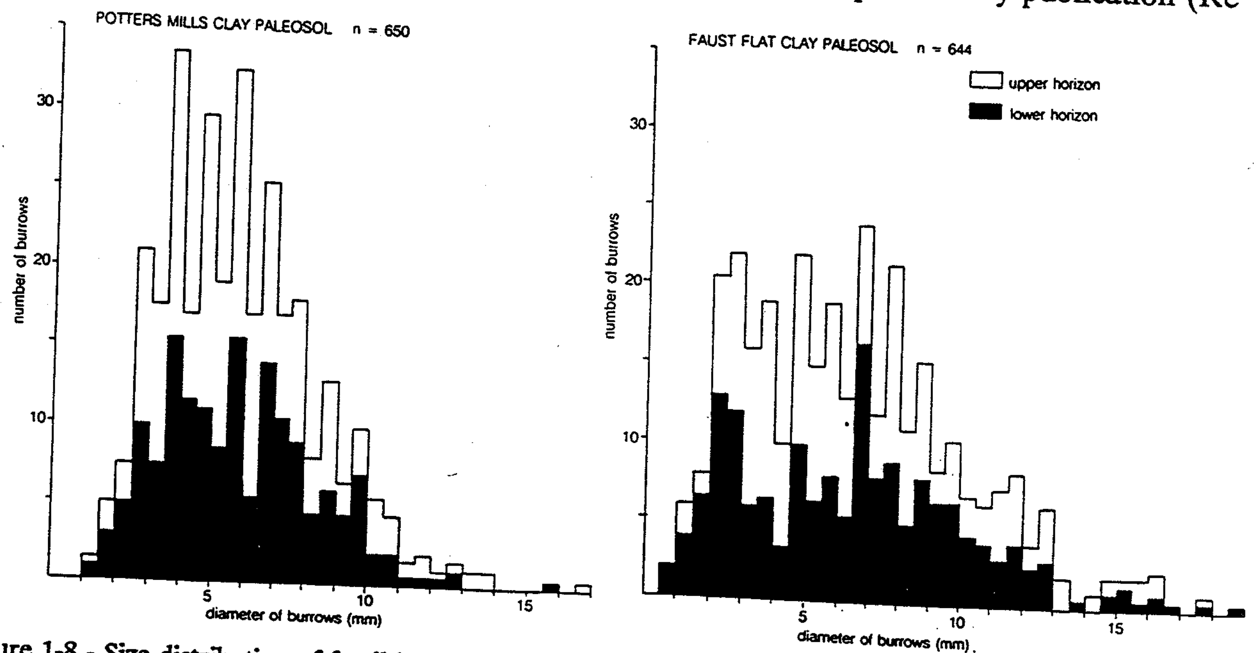

Figure 1-8 - Size distribution of fossil burrows from Ordovician type Potters Mills clay (left) and Faust Flat silty clay (right) paleosols near Potters Mills, Pennsylvania. This compilation includes measurements additional to those reported by Retallack and Feakes (1987).

-tallack 1985), these trace fossils were assigned to the ichnogenera *Skolithos* and *Planolites*, but subsequent serial sectioning of the burrow systems demonstrated that the horizontal and vertical components form a single burrow system (Retallack and Feakes 1987). For this and other reasons the burrows should be referred to a new ichnogenus.

The abundant burrows and isotopically light organic matter (Table 1-1) in these paleosols imply some kind of vegetable fodder on land. This is unlikely to have been a microbial earth, because trace elements normally complexed with organic matter (P, Li, Nb, Ni, Sr, Y) are depleted near the surface of the Potters Mills clay (Feakes and Retallack 1988). Vegetation was more likely a loose litter of more substantial plants similar to a polsterlands of lichens or bryophytes (Retallack 1992b). Rooted or rhizomatous plants are unlikely to have been present, if the lack of root-like traces in these paleosols can be trusted. There is independent evidence elsewhere for bryophyte-like spores as ancient as Middle Ordovician (Llanvirnian: Gray 1985; 1991), although none have been found even in the gray shales of this outcrop (Fig. 1-2: J. Gray, pers. comm. 1985). The parent plants of these distinctive spores have not yet been found as megafossils.

Parent Material

One problem for precise chemical characterization of Ordovician paleosols near Potters Mills is their heterogeneous alluvial parent material (Feakes and Retallack 1988). Claystone breccias in the bases of some of the paleochannels (Fig. 1-2) are evidence that soils of the floodplain were eroded and mixed with material from the mountainous Taconic uplands to the east (Meckel 1970; Dennison 1976). Some of the observed fining-upwards variation in grain size in these paleosols could be in part products of deposition from waning flood flows, as is better understood in geologically younger fluvial deposits (Cotter 1978). These parent material effects can account for part of the inverse covariation of silica and alumina in these soils, but not the distribution of oxidized iron and carbonates (Feakes and Retallack 1988).

Paleotopographic Setting

The degree of oxidation and development of the Potters Mills clay are indications that it formed on moderately well drained parts of the landscape (Feakes and Retallack 1988). Presumably this would have been on an alluvial terrace, perhaps no more than a meter or so above water table. The Potters Mills clay paleosol is chemically and petrographically most like soils of the elevated alluvial fans (bhabhar region) rather than the marshy bottomlands (dhankar or terai) in the sub-Himalayan outwash plains of India and Pakistan (Retallack 1991b). The Faust Flat paleosols in contrast, probably occupied lower terraces and point bars close to stream channels, where their development was curtailed by frequent flooding. Most of the red Juniata Formation represents a facies comparable to sediments of the north Indian bhabhar, whereas the underlying and interfingering drab-colored Bald Eagle Formation can be compared with dhankar and terai sediments of the Indo-Gangetic lowlands.

Duration Of Soil Formation

In the qualitative scale of Retallack (1988; 1990), the Potters Mills clay paleosol is weakly developed and the Faust Flat clay is very weakly developed. The Faust Flat profiles probably represent less than 100 years or so of soil formation. The calcic horizon of the Potters Mills clay is differentiated only to a modest extent (Stage I of Gile *et al.* 1966 or stage 1 of Wieder and Yaalon 1982). A comparable development of nodules and clay skins to that seen in the Potters Mills clay paleosol is seen in surface soils of the Indo-Gangetic Plains after about 400 to 4500 years (Ahmad *et al.* 1977; Courty and Féderoff 1985). This order of magnitude of time is represented by this degree of soil formation in many parts of the world (Birkeland 1990).

The short time for formation of the paleosols and their separation by great thicknesses of fluvial sandstone are indications of relatively rapid accumulation of this sequence, compared with other thick submontane alluvial fan sequences such as the Late Silurian Bloomsburg Formation of Pennsylvania, the Late Devonian Catskill magnafacies of upper New York state and the Siwalik Group of Pakistan (Retallack 1990). Using 100 years for Faust Flat and 4000 years for Potters Mills profiles, the measured sequence (Fig. 1-2) accumulated at a rate of 249 cm/ka, which is appreciably faster than 34-71 cm/ka estimated in a similar fashion from paleosols in the Miocene Siwalik Group of Pakistan (Retallack 1991b). The increased dominance and development of paleosols in comparable molasse sequences through geological time, like long-term changes toward meandering rather than braided streams (Cotter 1978), may reflect the evolution of a firmer grip on the landscape by increasingly bulky and complex terrestrial ecosystems.

CONCLUSIONS

That red clayey beds in the Juniata Formation were soils on Ordovician land surfaces (Fig. 1-9) is indicated by the distribution of clay skins, carbonate nodules, and burrows, and by variations in petrographic, chemical and isotopic composition of these distinctive layers. These paleosols are strongly ferruginized, and so compatible with estimates from other paleosols for atmospheric oxygen levels approaching that in the modern atmosphere, and certainly more than 0.2 PAL (present atmospheric level). The isotopically light carbon of pedogenic nodules in the paleosols indicate elevated atmospheric levels of carbon dioxide (5400-5800 ppmV or 18-19 PAL). The depth of the calcic horizon in the paleosols, adjusted for likely compaction is evidence of a semiarid climate (300-500 mm per annum). There is also some evidence, better expressed in other Ordovician paleosols, for seasonality of rainfall, perhaps like that endured by similar monsoonal soils of the Indo-Gangetic Plains of Pakistan and India. Abundant burrows in the paleosols are evidence of millipede-like animals, which may have fed on bryophyte-like plants known only from fossil spores. These paleosols were well drained and droughty, and formed on terraces and streamsides of alluvial fans issuing from a major folded mountain range to the east (Fig. 1-9). Their parent material was quartzo-feldspathic outwash from these mountains of sedimentary and metamorphic rocks, and included much redeposited soil material. The paleosols are weakly developed, and so are evidence of a rapid rate of fluvial aggradation.

The identification of clayey, nodular, burrowed horizons in the Juniata Formation near Potters Mills as buried soils has ramifications for understanding many aspects of Late Ordovician environments on land. A soil is not just dirt beneath our feet, but a physico-chemical reaction front to the environment and a fundamental part of terrestrial ecosystems. Similarly, paleosols are not merely buried soils, but barometers of former atmospheric oxygen and carbon dioxide partial pressures, rain gauges of past climates, trace fossils of ancient ecosystems, indicators of paleotopography, records of the parent material for soil development, and tachometers of alluvial sedimentation. They deserve our continued attention.

ACKNOWLEDGMENTS

Lynn Feakes was instrumental in helping get this project off the ground in

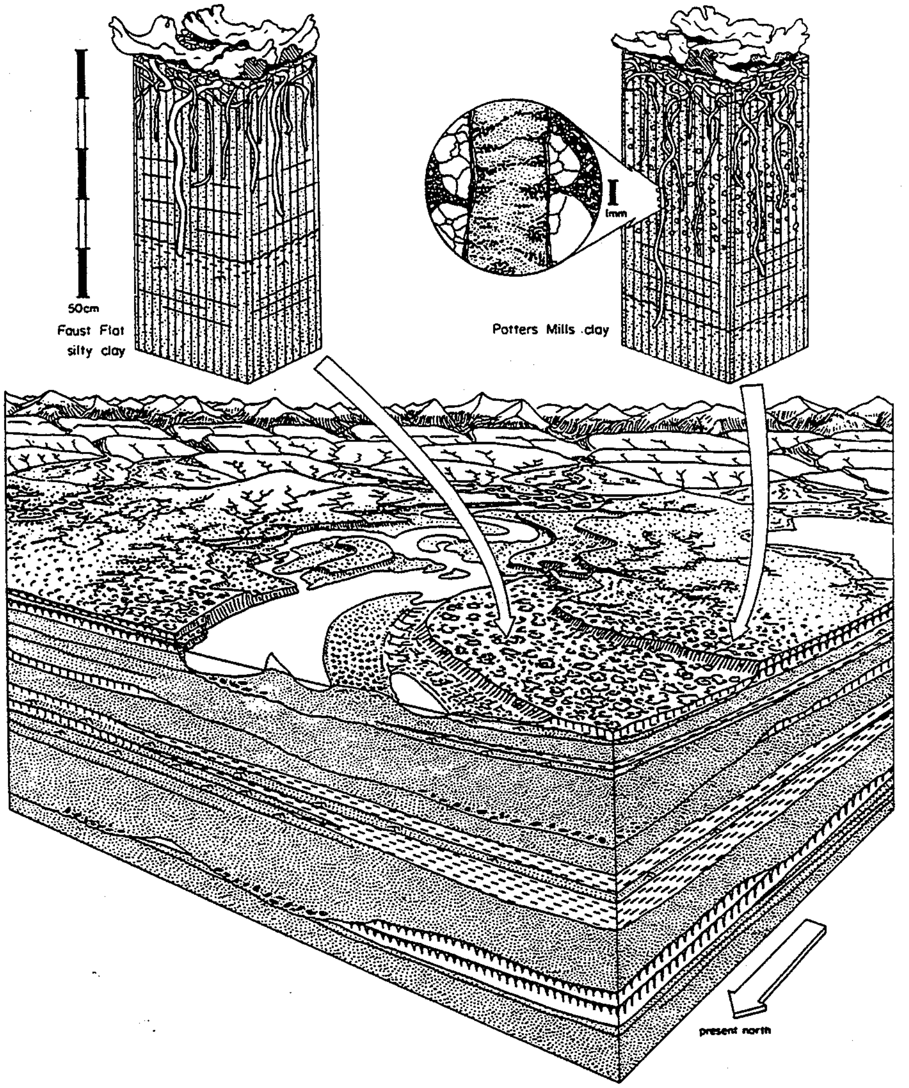

Figure 1-9 - A reconstruction of the Potters Mills area during the Late Ordovician. Vegetation shown is conjectural and similar to that hypothesized by Gray and Shear (1992). It represents the maximum likely biomass compatible with soil formation (from Feakes and Retallack 1988).

its early stages, and in attracting funding from the society of Sigma Xi. It is also a pleasure to acknowledge helpful discussions with V.P. Wright, S.G. Driese, C.I. Mora, and H.D. Holland. Thanks also are due to S.G. Driese for organizing publication of this excursion guide.

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