Hydrogeology and pedology of saprolite formed from sedimentary rock, eastern Tennessee, USA

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Abstract

Groundwater flow in sedimentary rock saprolite, and in soils derived from this material, is strongly influenced by sedimentary layering and fractures inherited from the parent bedrock. The main objectives of this study were to determine whether parent bedrock lithology and infilling of fractures and other macropores with pedogenically derived clays and Fe/Mn oxides also play major roles in controlling hydraulic conductivity and groundwater flow. The study was carried out by measuring profiles of saturated and unsaturated hydraulic conductivity, $K_{sat}$ and $K(\psi)$, and comparing them to soil and saprolite pedology and lithology in a 3.4 m deep pit excavated in interbedded limestone and shale saprolite. In the depth interval of 50 to 100 cm, there was an abrupt decline in $K_{sat}$ and $K(0)$ by a factor of up to 250. This corresponds to the occurrence of a zone where almost all of the fractures and other macropores are occluded with pedogenic clays and Fe/Mn oxides. Below a depth of 100 cm, both degree of pore infilling and hydraulic conductivity tend to vary, with a spatial regularity that is similar to the thickness of sedimentary layering in the saprolite. However, variations in hydraulic conductivity do not always correspond to changes in lithology, suggesting that hydraulic conductivity is a result of the complex interaction of several factors, including parent bedrock lithology and the degree of infilling of the macropores. Similarities between hydrogeologic conditions at this site and at research sites in weathered sedimentary shale/siltstone and carbonate rock settings at the Oak Ridge Reservation in Tennessee and in weathered crystalline rock in North Carolina indicate that macropore infilling plays an important role in controlling hydraulic conductivity and groundwater flow for a variety of different types of parent bedrock.

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1. Introduction and review of previous sedimentary rock saprolite research

A 65–100 km wide belt of folded and faulted sedimentary rock, comprising the Valley and Ridge Province, extends NE–SW along the western flank of
the Appalachian Mountains in the eastern US (Thornbury, 1965; Colton, 1970). Throughout much of this area, including the portion in eastern Tennessee, the upper 1–15 m of the subsurface is a highly decomposed, usually fine-grained material, which is commonly referred to as saprolite (Becker, 1895). Saprolite is a material formed by extensive in situ weathering of an existing parent rock, which still retains geologic features from the parent rock (Bates and Jackson, 1987). In addition to bedrock features, such as sedimentary layering and tectonic fractures, saprolite often contains soil features such as high matrix porosity, translocated or illuvial clays, neo-formed clay minerals, Fe/Mn oxides, and marks of bioturbation (Dreier et al., 1987; Hatcher et al., 1992; Driese et al., 2001). Some authors maintain that a material must weather isovolumetrically (i.e., with little or no volume change) before it should be referred to as saprolite (Gardner, 1980, 1992, 2000; Velbel, 1990). In practice, materials that contain even a moderate degree of the parent bedrock character are often referred to as saprolite. Although saprolite is widespread in humid climates, such as in the southeastern US, the physical and chemical characteristics of saprolite derived from sedimentary rock have not been extensively studied (Stolt and Baker, 1994; Driese et al., 2001). As a result, the hydrology of this type of subsoil is poorly understood, making predictions of infiltration, soil water retention, surface runoff, aquifer recharge, and transport of contaminants uncertain.

The only site in the United States where extensive research has been carried out on the lithology and hydrology of highly weathered sedimentary rock is at the U.S. Department of Energy’s Oak Ridge Reservation (ORR) in eastern Tennessee. Most of the studies were carried out at four research sites (Melton Branch, Waste Area Grouping 5, Burial Ground 4, and West Bear Creek Valley) situated in weathered materials derived from calcite-rich shale or siltstone bedrock of the middle to upper Cambrian age Conasauga Group (Hatcher et al., 1992). Most of the studies were funded by the Department of Energy (DOE) and were related to efforts to clean up or control migration of hazardous and radioactive wastes from shallow waste burial pits located in these materials. The weathered material overlying the shale and siltstone is typically 1 to 10 m thick and retains a substantial amount of sedimentary layering and structure from the parent bedrock: Hence, it is referred to as saprolite (Dreier et al., 1987; Hatcher et al., 1992; Driese et al., 2001). Field studies in shale or siltstone saprolite at ORR include: pedologic and geologic characterization (Rothschild et al., 1984a,b; Dreier et al., 1987; Dorsch and Katsube, 1999; Driese et al., 2001); measurement of hydraulic properties of the column and upper C-horizon (Luxmoore et al., 1981b; Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988; Wilson et al., 1989); lateral flow and transport of solute tracers in the upper 1–2 m of the column and saprolite (Wilson et al., 1993); vertical infiltration and solute transport in a 3 m deep undisturbed pedon (Jardine, personal communication); solute or colloid tracer experiments in the saturated zone just above the saprolite–bedrock contact (Lee et al., 1992; Webster, 1996; Sanford et al., 1996; McKay et al., 1997, 2000); tracer experiments or monitoring of contaminant plumes in the partially weathered rock just below the saprolite–bedrock contact (Olsen et al., 1983; Shevenell et al., 1994; McCarthy et al., 1998a,b; Jardine et al., 1999; Lenczewski et al., 2003).

By comparison, only a few field studies at ORR investigated pedology or hydrology of soil and residuum material derived from weathering of the upper Cambrian age limestone and dolostone, which underlie about 50% of the ORR (Hatcher et al., 1992). The main location for research on weathered carbonate rocks at the ORR is the Walker Branch site, which is underlain by approximately 25 m of decomposed material derived from in situ weathering of Knox Group dolostone. Bedrock at the Walker Branch site contains some shale layers, but weathers to a material that retains much less parent bedrock structure than observed at the sites that are underlain by predominantly shale and siltstone bedrock (Wilson et al., 1989). Studies at this site include: measurement of hydraulic properties of the column and upper C-horizon (Luxmoore et al., 1981a,b; Wilson and Luxmoore, 1988; Wilson et al., 1989); vertical infiltration and solute transport in a 3 m deep undisturbed pedon (Jardine et al., 1989, 1990); influence of storm events on lateral flow and pore water chemistry in the upper 2 m of the column and
residuum (Luxmoore et al., 1990; Mulholland et al., 1990; Wilson et al., 1990).

An overall conceptual model of groundwater flow at ORR was developed by Moore (1988) and refined by Moore (1989) and Solomon et al. (1992). The model was based on results of many of the previously mentioned field studies carried out in the soil–saprolite–residuum at ORR, as well as on studies of streamflow (Huff et al., 1977; Huff and Frederick, 1984; Moore, 1992) and studies of the hydrogeology and geochemistry of the bedrock, including those by Tucci (1986), Haase et al. (1987), Moore et al. (1987), Webster and Bradley (1987), Connell and Bailey (1989), Dreier and Toran (1989), Jacobs (1989), and Bailey and Lee (1991). The most recent version of the ORR model (Solomon et al., 1992) noted that there were strong similarities in hydrologic characteristics and flow behavior in soils and decomposed materials derived from the shale/siltstone bedrock and the carbonate bedrock, even though there were substantial differences in the hydrogeology of the bedrock in these geologic settings. In weathered materials derived from both types of bedrock, they defined three hydrologic zones: the storm-flow zone, the vadose zone, and the water table zone. Perched water table conditions tend to develop in the upper 80–120 cm (the storm flow zone) during heavy rains, causing rapid downslope flow. Solomon et al. (1992) noted that hydraulic conductivity ($K$) values in the storm-flow zone were as much as three orders of magnitude greater than values measured in the underlying saprolite, and estimated that only about 10% of the infiltration entering the soil ever reached the water table. No explanation for the cause of this decrease in hydraulic conductivity was offered, but Solomon et al. (1992) suggested that there was a correlation between the approximate depth of the vegetated root zone and the storm-flow zone. Flow in the vadose zone, which is unsaturated for much of the year, is expected to be primarily downward. Flow in the water table zone, or saturated zone, was expected to have a significant lateral or downslope component, because of the steep topography and the contrast between the saprolite and the underlying, typically lower hydraulic conductivity, bedrock. Only a few measurements of hydraulic conductivity are available for saprolite below a depth of about 1.5 m (Solomon et al., 1992; Sanford and Moore, 1994), but they indicate that at least in some cases, $K_{sat}$ values tend to increase near the saprolite–bedrock transition.

The occurrence of rapid lateral flow in the storm-flow zone and the upper portion of the water table zone was confirmed by a series of field-scale experiments carried out at research sites at ORR. Wilson et al. (1993) conducted an in situ tracer experiment in the upper 100 cm of a “limy shale” saprolite (Montevallo series; loamy-skeletal, mixed, subactive, thermic, shallow Typic Dystrudept) by releasing a bromide salt tracer through a line source buried at a depth of 50 cm. The tracer was released during a rainstorm and was detected in a subsurface weir located 65 m down slope within 3.2 h of the release. Subsequent monitoring showed that the tracer concentration in the weir was strongly influenced by individual precipitation events, indicating very fast lateral flow in the storm-flow zone. Evidence of rapid lateral flow (i.e., high discharge rates in a subsurface weir, large changes in pore water chemistry) during storm events was also observed in the column and upper 2 m of the residuum at the Walker Branch site, which is situated on dolostone (Luxmoore et al., 1990; Mulholland et al., 1990; Wilson et al., 1990). By comparison, downward flow and migration of tracers in the shale/siltstone saprolite and the dolostone residuum immediately below the storm-flow zone was much slower, as demonstrated in vertical infiltration field experiments at both the Melton Branch and Walker Branch sites (Jardine, personal communication; Jardine et al., 1990).

Additional field tracer experiments, that involved adding solutes or colloids to wells in the deeper shale/siltstone saprolite at Burial Ground 4 (Webster, 1996; McKay et al., 1997) and at West Bear Creek Valley (Lee et al., 1992; McKay et al., 2000) and monitoring their down-slope movement, showed that once infiltration reached the water table, which typically occurs just above the saprolite–bedrock contact, it could also move very rapidly (<1 to 200 m/day). Both the storm-flow zone and the upper portion of the water table zone (especially where it includes the saprolite–bedrock transition zone) are considered as potential rapid contaminant migration pathways at the ORR.

Driese et al. (2001) recently proposed a modification to the soil and saprolite portion of the ORR hydrologic conceptual model, at least as it pertains to materials derived from shale and siltstone parent
material. This revised model was based on field and laboratory investigations at ORR by Penfield (1999) that showed many of the biopores and fractures in the saprolite from 50 to at least 250 cm depth (which was the maximum depth of excavation) were clogged with illuviated clays and Fe/Mn oxide accumulations. Although no hydraulic conductivity profiles were measured at this site, the infillings were so extensive that they were considered the most likely cause of the inhibited downward flow, which in turn can cause water table perching and subsequent rapid down-slope flow in the storm-flow zone.

The overall hypothesis for this study is that accumulations of pedogenic clays and mineral precipitates in the upper portion of the subsoil (BC- and C-horizons) in fractures and biopores act as major controls on hydraulic conductivity and the development of shallow flow systems in areas underlain by sedimentary rock saprolite. The principal objective of the study was to test the hypothesis by systematically assessing and comparing both the degree of pore infilling caused by illuviated clays and Fe/Mn oxides, and the variability of hydraulic conductivity with depth in sedimentary rock saprolite at a typical site in eastern Tennessee. The influence of parent bedrock lithology is also considered by comparing profiles of hydraulic conductivity and lithology. A secondary objective is to compare the results of the study to the hydrologic conceptual model previously developed for sedimentary rock saprolite and residuum at the nearby Oak Ridge Reservation in Tennessee.

2. Description of field site

A research pit (KS-1) was excavated with a backhoe into saprolite developed from the Middle Cambrian-age Maryville Limestone, which is equivalent to the Dismal Gap Formation on the ORR (Srinivasan and Walker, 1993). The bedrock at outcrops near the site consists of massive limestone and ribbon limestone, interbedded with shale. The rock is deformed and fractured, with sedimentary bedding typically striking NE–SW and dipping to the SE (Hatcher et al., 1992). The site was located approximately 10 km east of the city of Oak Ridge, Tennessee (latitude 36°02.586′N and longitude 84°04.677′W) and is on a line directly along strike from some of the main shale/siltstone saprolite sites at the ORR. Because the bedrock at this site contains about equal amounts of terrigenous clastic and carbonate rock, it is expected to represent an intermediate between the shale/siltstone research sites and the dolostone research site at ORR. The soil at the KS-1 site is mapped as Armuchee series, which is a fine, mixed, semiactive, thermic Inceptic Hapludult (see http://ortho.ftw.nrcs.usda.gov/osd/osd.html). The climate of the region is humid temperate, and mean annual precipitation was 133 cm during the period 1954–1983 (Solomon et al., 1992).

3. Investigative methods

The KS-1 pit was excavated with a backhoe at a site located near the crest of a narrow ridge with a moderate slope (20%) to the SE, and a steeper slope (70%) to the NW. The pit was rectangular (12 m by 9 m), with a maximum depth of 3.4 m. One of the walls of the pit was vertical (Fig. 1), oriented approximately perpendicular to strike (N60°E), and approximately parallel with the bedding dip direction (20–25°SE). The opposing wall of the pit was stepped, forming benches approximately 6 m long and 1.5 m wide, which served as level surfaces for carrying out infiltration tests. Plastic tarps were used to cover these benches so as to minimize drying and to prevent infiltration from precipitation. The pit was excavated in August of 2000, during the driest time of the year, and was open until mid November. During this time, rain occurred only once and no seepage was observed in the excavation. A geologic section was also described based on observations at an outcrop of the bedrock at a site approximately 150 away from the pit.

Characteristics of the soil and saprolite exposed on the vertical pit face were described in the field using a combination of standard soil morphological description methods (Buol et al., 1997; Soil Survey Staff, 1998) and methods typically used in sedimentary rock description and classification (Driese et al., 2001). These methods included physical characterization of soil horizons and subsoil horizons, soil texture, root extent, animal burrows, Fe/Mn oxides, color, sedimentary structures, saprolite bedding thickness, fracture density, saprolite lithology (which is related to the
Undisturbed samples were collected from the pit face approximately every 20 cm with depth, or at major changes in soil horizons or stratigraphic layers. These samples were allowed to air dry and were commercially prepared into 5 by 7 cm thin sections. Thin sections were examined using a petrographic microscope to determine the lithology, type and distribution of macropores, percentage of pedogenic clays (which included clay infillings in macropores as well as neoformed and residual clays in matrix regions) and percentage of Fe/Mn oxides present were described according to the methods of Fitzpatrick (1993). Percentages of macropores, pedogenic clays, and Fe/Mn oxides were estimated using comparator charts (Folk et al., 1970) and then compared to measured profiles of saturated hydraulic conductivity. Photographic images were made from selected thin sections to visually show the extent of clay infilling of fractures and biopores. Bulk density values were measured on small (20–60 cm³) undisturbed sub-samples using the wax clod method (Blake and Hartge, 1986) and bulk porosity values were calculated using the bulk density values and assuming a specific gravity of 2.65 for the soil solids.

Saturated hydraulic conductivity values ($K_{sat}$) were measured using a compact constant head permeameter (CCHP), as described by Amoozegar (1989) and Amoozegar and Wilson (1999). Measurements were made by monitoring infiltration into 7.62 cm diameter boreholes, with the water level held constant at 10 cm above the base of the hole. Saturated hydraulic conductivity was calculated using the measured discharge values from the CCHP tests and the Glover model as outlined in Amoozegar (1989). The boreholes were swabbed with a nylon brush to attempt to remove any smearing created when the hole was advanced with a hand-auger. After each measurement, the borehole was left open for approximately 24 h and then was extended approximately 20 cm in preparation for the next measurement. Three profiles of $K_{sat}$ were meas-

Fig. 1. Schematic diagram of vertical pit face of site KS-1 weathering profile developed on Maryville Limestone in eastern Tennessee, showing soil horizons, saprolite lithologies, and bedding inherited from parent material.
ured using this procedure: one profile was located about 1.5 m behind the middle of the 3.4 m high vertical face of the pit, and the others were located at the NW and SE ends of the benches forming the opposite side of the pit. In the case of the profile behind the vertical face, measurements were made in the same borehole from depths of 20 to 280 cm. For the profiles on the benches, the measurements were made in a series of boreholes, each up to 1.5 m deep, located at the NW and SE ends of each bench. These were then combined to produce single \( K_{\text{sat}} \) profiles, from 20 to approximately 290 cm, for either end of the excavation.

Unsaturated hydraulic conductivity, \( K(\psi) \), was measured using a tension disc infiltrometer (TDI), which involves placing a porous disc in contact with a horizontal surface of the saprolite and then measuring the infiltration rate at different values of water tension. The method is described by Ankeny et al. (1991) and Amoozegar and Wilson (1999). Profiles of \( K(\psi) \) were measured at the NW and SE ends of the benches, about 1 m away from the above-mentioned profiles of \( K_{\text{sat}} \). The soil or saprolite surface was prepared by hand-excavation of a horizontal surface approximately 40 by 40 cm. A thin layer of sand was placed on the saprolite to ensure a good hydraulic connection with the 20 cm diameter infiltrometer disc. A constant water tension of 14 cm was initially applied to the disc and maintained until the flow rate was constant for at least 40 min. Tension was lowered to 5 cm and this procedure was repeated. The final measurement was carried out at zero tension. After each set of measurements, the surface was excavated another 20 cm and the process repeated. When the excavation reached about the depth of the next lowest bench, the apparatus was shifted over to the lower bench. In this manner, profiles of \( K(\psi) \) were measured from 20 to approximately 290 cm depth at the NW and SE ends of the pit. Unsaturated hydraulic conductivity values were calculated for tensions of 0, 5 and 14 cm using the simultaneous equation method presented by Ankeny et al. (1991).

4. Results

4.1. Field-scale lithologies

The soils at the KS-1 site consisted of a silt loam A-horizon, typically 10 cm thick, a silt loam/loam BE-horizon, typically 20 cm thick, and a clay loam Bt-horizon, typically 20 to 40 cm thick. These were underlain by clay loam BC- and C-horizons (saprolite) that extend to the top of hard bedrock at approximately 3.4 m depth (Table 1). Thickness of the combined A- and B-horizons vary with the lithology of the underlying saprolite. The greatest combined A- and B-horizon thickness occurs above the limestone saprolite (approximately 50 cm), with thicknesses above the ribbon limestone and the shale saprolites of about 37 and 25 cm, respectively.

A schematic map of the saprolite lithologies along the vertical pit face, which was oriented approximately parallel to the direction of maximum dip of sedimentary layering, is shown in Fig. 1. Designation of horizons was done according to the methods outlined in Soil Survey Staff (1998) and Cremeens (2000). The BC- and C-horizons consist of alternating layers of saprolite derived from shale/siltstone, massive limestone, and ribbon limestone (which is a thinly interbedded limestone and shale, with a characteristic undulating fabric). These layers vary in thickness from <1 cm to about 60 cm, and dip to the southeast at 20–25°. The shale/siltstone lithology represents approximately 33% of the saprolite exposed at the vertical pit face, whereas the limestone and ribbon limestone lithologies represent 26% and 41%, respectively. One thin layer (1 cm) of sandstone saprolite occurs beneath the lowest ribbon limestone layer, but is not depicted in Fig. 1. Sedimentary layering is very well preserved in the shale/siltstone and the ribbon limestone saprolite, and faint layering is visible in some of the limestone saprolite. The thickness, dip and general appearance of sedimentary layers in the saprolite were essentially the same as for the parent bedrock, as mapped at the outcrop 150 m away, indicating that the material weathered with very little change in volume.

Fractures occur in all of the different saprolite lithologies. These fractures, oriented parallel and perpendicular to sedimentary bedding, were the most common macropores in the shale/siltstone lithology, and were visible to the full 3.4 m depth of excavation. Bedding-parallel fractures tended to be longer (up to 1 m), and more closely spaced (1–2 cm) than the bedding-perpendicular fractures (4–5 cm spacing and commonly only a few cm in length). Together they appeared to form an interconnected network in the
Fractures were also common in the ribbon limestone, although they were not as common, nor as laterally extensive as in the shale/siltstone, and occurred only intermittently in the massive limestone saprolite. Soil structure (i.e., interpedal voids) was well developed in the BE- and Bt-horizons. The transition between well-developed soil structure and saprolite containing very little soil structure tended to be more abrupt in the shale lithologies than in the limestone lithologies.

Biopores (commonly root holes) were visible in the soils and in all saprolite lithologies down to the bottom of the pit (3.4 m). Biopores were the most common type of macropore in the massive limestone, with approximately twice as many biopores per unit area observed in this saprolite, when compared to the ribbon limestone, and approximately eight times more biopores than in the shale/siltstone. Biopores were typically larger in the limestone saprolite lithologies, which tended to be softer than the shale/siltstone saprolite. A maximum biopore diameter of 2.5 cm was observed in the limestone and ribbon limestone saprolite, whereas the maximum diameter in the shale/siltstone saprolite was approximately 0.05 cm. Almost all of the biopores in the shale/siltstone saprolite occurred along fracture surfaces or bedding planes, apparently because of the hard consistency of the intervening material. A greater frequency of biopores, especially larger biopores, occurred closer to the ground surface (<50 cm depth) in soils derived from all lithologies. However, one macropore about 2 cm in diameter occurred at approximately 1.5 m depth in the ribbon limestone saprolite, clearly indicating that large macropores are not restricted to shallow depths.

The fractures and biopores described above commonly contained infillings or coatings of pedogenic slime. Fractures and biopores were also common in the ribbon limestone, although they were not as common, nor as laterally extensive as in the shale/siltstone, and occurred only intermittently in the massive limestone saprolite. Soil structure (i.e., interpedal voids) was well developed in the BE- and Bt-horizons. The transition between well-developed soil structure and saprolite containing very little soil structure tended to be more abrupt in the shale lithologies than in the limestone lithologies.

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clays or Fe/Mn oxides. It was generally not possible to visually determine whether the fractures were completely, or only partially infilled, because of the disturbance caused by excavation and shrinkage due to drying. For the root holes there was considerable variation, with some holes having little or no coating, and others completely infilled. These clay infillings and Fe/Mn oxides were irregularly distributed over the entire pit face below approximately 50 cm depth, with approximately two to six times more infillings occurring in limestone and ribbon limestone saprolite, as compared to shale/siltstone saprolite. Most of these infillings (85%) were higher-chroma colors, indicating oxidizing conditions to the bottom of the pit (3.4 m). Areas with low-chroma colors, indicating the occurrence of localized reducing conditions, were randomly spaced and constituted the remaining 15% of the infilled macropores.

4.2. Micromorphology and porosity

Thin sections collected from a vertical profile in the middle of the pit face (Fig. 1), and along two distinct sedimentary layers, indicate that pedogenic alteration is
far more intensive and extends to greater depth in the limestone saprolite, than in the shale/siltstone saprolite. This is responsible for the observed differences in thickness of the A- and B-horizons overlying the limestone and the shale/siltstone saprolite. For example, a thin section sampled from a weathered limestone layer at approximately 36 cm depth had defining soil structure (i.e., Bt-horizon), whereas a thin section prepared from a weathered shale layer directly above the previously mentioned sample had primarily saprolite rock structure (i.e., BC-horizon).

Thin sections from samples that were identified in the field as limestone or shale/siltstone saprolite were composed of mostly one lithology, but still showed some degree of complex interfingering of other lithologies (Fig. 2). Thin sections from the ribbon limestone saprolite showed that the material was composed of thin (0.1 to 1 cm) undulating interbeds of limestone and shale/siltstone (Fig. 3). Within the ribbon limestone, the limestone interbeds represented between 30% and 70% of the material.

The limestone saprolite and the limestone portion of the ribbon limestone unit tended to have a greater number of biopores, mainly root holes, observable in thin section than did the shale/siltstone saprolite (Fig. 4A,C,D,F). The shale/siltstone saprolite, in contrast, exhibited a greater abundance of bedding-parallel and bedding-perpendicular fractures (Fig. 4B,E). A dye tracer and fracture mapping experiment in shale saprolite from ORR showed that both bedding-parallel and bedding-perpendicular fractures were conductive to flow and that is likely the case at the KS-1 site.
Detailed measurements of macropore aperture and porosity in the soil and saprolite thin sections were not carried out due to the "artificial" porosity created during drying of the samples and preparation of the epoxy-impregnated thin sections (e.g., Fig. 4A, D and E). The fractures were particularly susceptible to shrinkage disturbance, and fractures in thin sections with apparent apertures of up to 5 mm were common, which were much larger than apertures observed in the field or in hand samples. Based on visual examination of the thin sections, and discounting the large openings that appeared due to desiccation, there was approximately three times as much open macroporosity (i.e., fractures and biopores that were not completely infilled) in the limestone saprolite as there was in the shale/siltstone saprolite.

Fig. 4. Photomicrographs of soil and saprolite showing macropores and macropore fillings. (A) One-centimeter-thick, illuviated clay deposit filling bedding-parallel fracture pores and biopores; note that clay is cross cut by younger generation of vertical and horizontal fractures lined with Fe oxides (plane-polarized light); 60 cm depth, Bt/BC-horizon transition. (B) Bedding-perpendicular fracture in very fine-grained sandstone saprolite, partially infilled with illuviated clay (plane-polarized light); 90 cm depth, BC-horizon. (C) Circular biopore partially infilled with microlaminate illuviated clay, in ribbon limestone saprolite; note that clay is thicker along bottom of pore (crossed-nicols); 115 cm depth, C1-horizon. (D) Circular biopore almost completely infilled with microlaminate illuviated clay and Fe/Mn oxides, in siltstone saprolite; porosity is enhanced by shrinkage during sample drying (crossed nicols); 155 cm depth, C2-horizon. (E) Bedding-parallel and bedding-perpendicular fracture pores lightly coated with pedogenic clay and Fe/Mn oxides, in siltstone/shale saprolite; note ovoid biopore at intersection between fractures sets (crossed nicols); 155 cm depth, C2-horizon. (F) Microlaminate illuviated clay filling biopore in limestone saprolite; note dendritic Fe/Mn staining of clay (plane-polarized light); 262 cm depth, C2-horizon.
Semi-quantitative estimates of the abundance of pedogenic clays and Fe/Mn oxides in the thin sections were made based on the percentage of the area of each thin section in which pedogenic clays or Fe/Mn oxides were the dominant material (Fig. 5). The estimates show that illuviated clays are rare from the soil surface down to the Bt-horizon (approximately 50 cm depth). Below the Bt-horizon, the abundance of illuviated clays and other pedogenic clays varies with depth and micro-scale lithology (Fig. 5). The Fe/Mn oxide abundance follows approximately the same pattern with low values estimated above the Bt-horizon and highly variable values in the deeper saprolite (Fig. 5). The lowest percentages of pedogenic clay and Fe/Mn occurred in the shale/siltstone saprolite and the shale/siltstone layers in the ribbon limestone saprolite, but there also appeared to be a trend towards higher values with increasing depth. The two highest estimates of pedogenic clay and Fe/Mn were at depths of 200 and 270 cm (Fig. 5).

Bulk porosity, measured using small (20–60 cm³) undisturbed samples of soil and saprolite, were highest at the base of the A-horizon, with a value of approximately 62% at a depth of 10 cm. Values in the B-horizon and in the limestone saprolite, to a depth of 340 cm, were similar, ranging from 50% to 58%. Bulk porosity values in the shale/siltstone saprolite varied from 23% to 45%. Most of the samples contained very few open fractures or biopores, so the measured bulk porosity values are mainly representative of a combination of the fine-grained matrix and the pedogenic pore infilling materials.

4.3. Hydraulic conductivity distribution

In all three profiles of \( K_{\text{sat}} \) the values are highest in the upper 40–60 cm of the soil (ranging from \( 2 \times 10^{-7} \) to \( 5 \times 10^{-5} \) m/s), and then decline by a factor of up to 250 times within the next 40–60 cm (Fig. 6). The zone of highest \( K_{\text{sat}} \) values corresponds to the A- and upper portion of the B-horizon, which are both characterized by the common occurrence of numerous biopores and well-defined soil structure. The rapid decline in \( K_{\text{sat}} \) occurs mostly in the BC-horizon and corresponds to the disappearance of soil structure and the first occurrence of infilling of macropores with pedogenic

![Fig. 5. Percentage of Fe/Mn oxides and pedogenic clays (illuviated clays, neoformed clays and residual clays) estimated from thin section micrographs and petrographic microscope (5x or 10x) using visual image comparator charts. Lithologies indicated on graph refer to the dominant micro-lithology of the thin section.](https://example.com/fig5.png)
clays and Fe/Mn oxides. From a depth of 100 to 150 cm all of the $K_{\text{sat}}$ values, except one, are less than $5 \times 10^{-5}$ m/s. Below a depth of 150 cm, the $K_{\text{sat}}$ values are generally low, but vary over a much wider range than did the values from 100 to 150 cm depth. For the profiles measured on the NW and SE ends of the benches, there is a substantial increase (7–30 times) in $K_{\text{sat}}$ from 250 to 300 cm depth, but it is not clear whether this represents a general increase in $K_{\text{sat}}$ with depth, or just another variation in the profile. The patterns of all three profiles suggest alternating 50–100 cm thick layers of higher and lower $K_{\text{sat}}$, which is approximately the thickness of the major variations in parent bedrock lithology. However, for the middle profile, which is the only one with detailed lithologic data, the $K_{\text{sat}}$ variations tend to cut across lithologic boundaries. This suggests that either $K_{\text{sat}}$ is not exclusively controlled by lithology, or there are some differences in lithology between the vertical pit face and the $K_{\text{sat}}$ profile, which was located 1.5 m behind the pit face.

Profiles of $K(0)$ measured with the TDI and $K_{\text{sat}}$ measured with the CCCP at both the NW and SE ends of the benches (Fig. 7A and B) show similar trends, with high values of $K(0)$ in the upper 20 to 30 cm ($5 \times 10^{-5}$ to $2 \times 10^{-4}$ m/s) and a sharp decline (by a factor of 40 to 80 times) from 20 to 60 cm depth. The sharp decline in $K(0)$ occurred at slightly shallower depth than the decline in $K_{\text{sat}}$ and the zone of minimum $K$-values was much thinner. Below a depth of 60 cm, the $K(0)$ values vary substantially, and in both cases give the impression of alternating layers of higher and lower hydraulic conductivity. For the SE profile (Fig. 7B), the pattern of variation of $K(0)$ is similar to the variation in $K_{\text{sat}}$, which was measured in a borehole located approximately 1 m away. For the NW profile (Fig. 7A), there was less similarity between the $K(0)$ and $K_{\text{sat}}$ profiles.

The $K(0)$ values for both the NW and SE profiles (Fig. 7A and B) were approximately 3 to 20 times higher than the $K_{\text{sat}}$ values. The differences in the neighboring $K(0)$ and $K_{\text{sat}}$ profiles is likely partly due to local heterogeneity, but the large shift between the two types of measurements may be due to factors related to the measurement methods. The sides of the augered boreholes in which the $K_{\text{sat}}$ values were measured were likely affected to some degree by “smearing” that can close or infill many of the fractures or biopores, and thereby reduce infiltration rates. The sides of the holes were roughened with a
stiff brush to try to remove the smeared zone, but the effectiveness of this treatment is difficult to evaluate. By comparison, the horizontal surfaces used for the \( K(0) \) tests were hand-excavated and cleaned with a trowel and knife, which appeared to be a more effective method for removing surface disturbance in this material. As well, there was a tendency for the fractures to open-up slightly due to drying and stress-relief before the \( K(0) \) measurements were carried out, which would tend to increase the measured values. The measurements may also be affected by anisotropy of hydraulic conductivity in the soil and saprolite. The \( K_{\text{sat}} \) values were based on measurements of predominantly horizontal flow through the vertical sides of the borehole, whereas the \( K(0) \) values were based on measurements of predominantly vertical flow from the tension disc infiltrometer. With the existing data it is not possible to distinguish between the influence of smearing and anisotropy, but both types of measurements show the same general trends (i.e., a sharp decline in hydraulic conductivity in the BC-horizon and then variable hydraulic conductivity in the deeper saprolite).

Profiles of ratios of \( K(\psi)/K(0) \) at tensions, \( \psi \), of 5 and 14 cm are shown in Fig. 8. These ratios provide a measure of the relative influence of macropores (i.e., fractures, biopores, or soil structure) on hydraulic conductivity. If a fine-grained material contains pores that are all about the same size, a small increase in soil tension (a few centimeters) has little affect on hydraulic conductivity, and the ratio of \( K(\psi)/K(0) \) remains close to unity. By comparison, a fine-grained material containing numerous macropores will experience large decreases in \( K(\psi)/K(0) \) with increasing tension, because these pores drain readily and hence play a minor role in unsaturated flow. For both the

![Fig. 7. Profiles of \( K_{\text{sat}} \), measured with CCCP and \( K(0) \), measured with a tension disc infiltrometer for (A) NW profile, and (B) SE profile.](image-url)
NW and SE profiles (Fig. 8), low values of $K(\psi)/K(0)$ were measured at depths of 20–40 cm, indicating an abundance of large, open macropores. As depth increased, the ratios increased by factors of 40 to 200 times, and reached a peak at about 60 cm depth. This is the same interval over which the sharp decline in $K(0)$ was observed and indicates an abrupt decrease in flow through macropores. Below a depth of 60 cm, both profiles showed alternating increases and decreases in $K(\psi)/K(0)$ ratio, although none were as large as the initial decrease from 20 to 60 cm depth. The variations in $K(\psi)/K(0)$ typically occur over intervals of 50–100 cm depth, which are similar to the variations observed in $K_{sat}$ and $K(0)$ and are about the same as the typical thickness of lithologic units in the saprolite.

5. Discussion and conclusions

5.1. Influence of pedogenic features and parent bedrock lithology on hydraulic conductivity

The abundance of macropores, which occurred to the full 3.4 m depth of the excavation in all lithologies, suggest that they, rather than the fine pores in the...
saprolite matrix, govern flow during saturated or nearly saturated conditions. This is supported by the $K(\psi)/K(0)$ measurements (Fig. 8), which indicate a high proportion of macropore-dominated flow in many areas. The initial sharp decline in $K_{\text{sat}}$ and $K(0)$, and the increase in $K(\psi)/K(0)$ from 50 to 100 cm depth (Figs. 6–8) are almost certainly due to a decrease in soil structure and concomitant clogging of the remaining macropores with pedogenic clays and Fe/Mn oxides. These observations are consistent with the main hypothesis of this study. However, below a depth of 100 cm there was substantial variation in both the amount of pedogenic pore infilling material present (Fig. 5) and the hydraulic properties of the material (Figs. 6–8), but there did not appear to be any correlation between them. The reduction in $K_{\text{sat}}$ in the lower Bt- and upper BC-horizons is similar to that observed in profiles measured in crystalline rock saprolite in North Carolina in studies by Schoeneberger et al. (1995) and Vepraskas et al. (1996). In the crystalline rock saprolite, there was typically a substantial increase in $K_{\text{sat}}$ below this zone of occlusion. Vepraskas et al. (1996) examined thin sections of the crystalline rock saprolite and concluded that the infilling of fractures and macropores with illuviated clays in a well-defined zone was responsible for the decrease and subsequent increase of hydraulic conductivity with depth. This is similar in many respects to the zone of macropore occlusion. This suggests that zones of macropore infilling and corresponding decreases in hydraulic conductivity are likely common features of humid, temperate region saprolite, regardless of the origin of the parent material.

The periodicity of variations in hydraulic conductivity profiles in the saprolite were about the same as the thickness of layers in the parent bedrock material, but the variations tended to cut across lithologic boundaries. This may partly be a function of the relatively small number of hydraulic conductivity measurements and the small scale of many of the lithologic variations. On first glance, the much greater frequency of biopores and more extensive accumulation of pedogenic materials in the limestone saprolite, relative to the shale saprolite, could suggest the likelihood of greater flow through the limestone. However, this may be an artifact of the weathering characteristics of the two materials. Laboratory measurements of $K_{\text{sat}}$ in 11 large (typically 25 cm diameter by 25 to 40 cm long) undisturbed columns of interbedded shale/siltstone, limestone and sandstone saprolite from 100 to 220 cm depth at a site at the ORR showed up to 3 orders of magnitude variability in values measured in different samples, but there were no discernable clusters of values for individual lithologies (Driese et al., 2001).

It is likely that both the degree of infilling with pedogenic materials and the lithology of the parent bedrock influence hydraulic conductivity in the saprolite. Both of these factors influence the size, frequency and degree of interconnection of the “open” portion of the fractures and biopores, which, in turn, control hydraulic conductivity. Direct measurement of the characteristics of the open macropores was not carried out in this study, because of the very small size of many of the macropores (relative to field observation methods), and because of disturbance caused by stress-relief, drying and grinding during preparation of the petrographic thin sections.

5.2. Comparison with ORR hydrologic conceptual model

Results of the study at the KS-1 site are in most respects consistent with previous findings at research sites in sedimentary rock saprolite at the nearby Oak Ridge Reservation and generally support the soil and saprolite portion of the ORR hydrologic conceptual model (Solomon et al., 1992). A revised hydrologic conceptual model for sedimentary rock saprolite, which is based on the present study, and the previously discussed ORR model (Solomon et al., 1992; Driese et al., 2001), is presented in Fig. 9 and discussed below. The principal difference between the revised model and the previous versions is the recognition that the infilling of macropores with pedogenic materials, which extends to greater depth than observed at the ORR, is not the only important factor influencing hydraulic conductivity and subsurface flow. Parent bedrock lithology plays an important role in controlling the frequency of occurrence of macropores and lithologic layering has a periodicity...
similar to that observed in the $K_{\text{sat}}$ and $K(\psi)$ profiles, suggesting that it is also influencing flow.

The high $K_{\text{sat}}$ values observed in the upper 50 cm of the soil and the underlying sharp decline in values from 50 to 100 cm depth at the KS-1 site, are expected to sufficiently inhibit downward flow to cause perched water table conditions during large storm events. Although the investigations at the KS-1 site were not designed for monitoring storm-flow, it is likely that there is an active storm-flow zone at this site (as depicted in Fig. 9), with rapid down-slope flow similar to what has been observed at several sites at the ORR (Luxmoore et al., 1990; Wilson et al., 1990, 1993). The cause of this abrupt decline in $K_{\text{sat}}$ values is almost certainly the decrease in soil structure and the observed clogging of macropores with pedogenic clays and Fe/Mn oxides, and is consistent with the observations of extensive pore clogging at the base of the storm-flow zone by Driese et al. (2001) at the Melton Branch site at the ORR. Extensive pedogenic pore infillings were also observed in this depth interval in thin sections from another ORR site (weathered Nolichucky Shale from a site in West Bear Creek Valley), so it appears that this is a common feature of sedimentary rock saprolite (Driese, unpublished data).

The investigations at the KS-1 site indicate that the hydrology and pedology of the saprolite underlying the storm-flow zone (i.e., the vadose zone on Fig. 9) is much more complex than indicated in previous versions of the ORR conceptual model (Solomon et al., 1992; Driese et al., 2001). This recognition is due, at least in part, to the availability of a more detailed set of hydraulic conductivity measurements and lithologic observations (at the macro- and micro-scale) for the KS-1 site, than for most of the ORR field sites. The studies at the KS-1 site indicate that hydraulic conductivity in the saprolite below the initial zone of macropore occlusion is highly variable and is likely controlled by a complex combination of factors, including the lithology of the parent bedrock, the nature of the macropores (i.e., fractures versus root holes), and the degree of infilling with pedogenic clays and Fe/Mn oxides.

From this study, it is not clear whether the zone of increased hydraulic conductivity observed near the saprolite bedrock contact at the West Bear Creek Valley site at the ORR (Sanford and Moore, 1994) is a common feature in sedimentary rock saprolite. Two of the three $K_{\text{sat}}$ profiles at the KS-1 site indicated a substantial increase (by factors of 7–30) in values near

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**Fig. 9.** Combined hydrologic–lithologic–pedologic conceptual model for limestone–shale sedimentary rock saprolite based on observations from KS-1 site and on investigations previously carried out at the Oak Ridge Reservation, TN (principally, Moore, 1988; Solomon et al., 1992; Driese et al., 2001).
the bottom of the 300 cm deep profiles, but it was not clear whether this was a significant trend, or just another variation similar to those observed higher in the profile. However, even without an increase in $K_{sat}$ in the lower saprolite, it is likely that lateral or downslope flow during saturated conditions would be much faster in the saprolite than in the underlying bedrock, because of the differences in occurrence of fractures and biopores.

The hydrologic conceptual model described above is useful, but has several important limitations. The main limitations are that it is based on studies from only a few sites: the KS-1 site (this paper) and four main sites at ORR (Melton Branch, Walker Branch, West Bear Creek Valley and Burial Ground 4). These sites are all within approximately 20 km of one another and are all in similar types of sedimentary rocks (mixtures of limestone–dolostone and shale/siltstone), with similar tectonic histories. Before the conceptual model can be more widely applied, there is a need to examine saprolite hydrology and pedology in other sedimentary rocks, particularly in “end-member” examples, such as relatively homogenous stratigraphic units of limestone, shale and sandstone. The role of rock structure also needs to be examined and this could be done by comparing saprolite developed from flat-lying, relatively un-deformed sedimentary rocks with saprolite developed from faulted and folded rocks, like those found at ORR and the KS-1 site. Sedimentary rock saprolite is widespread in many humid, temperate areas and further development of conceptual models could prove very valuable in addressing concerns as diverse as monitoring contaminant migration from landfills, design and placement of sewage infiltration systems, predicting surface runoff or aquifer recharge, and optimization of irrigation systems.

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