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I am submitting herewith a thesis written by Kevin Smith entitled "Influence of Illuviated Clays and Soil Cements on Hydraulic Conductivity in Sedimentary Saprolite." I have examined the final copy of this thesis for form and content and recommended that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.



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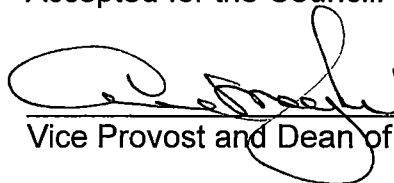
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Influence of Illuviated Clays and Soil Cements on Hydraulic Conductivity in Sedimentary Saprolite

A thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Kevin Harley Smith
December 2001

Acknowledgments

I would like to thank several people who have helped with this project. Miri Rietti-Shati for her input and company during three months of fieldwork. Without her help, this project would have most likely cost me another term and possibly my sanity. Cindy Stiles, for coming out to the field and constructing a soil profile for the KS-1 site. I would also like to thank the Anderson county NRCS office for their input and help in finding a landowner who would let me dig a rather large hole on his property. And of course, the landowner, Ferrell Moore, who was very kind and patient in letting me keep the pit open for three months.

I would also like to thank my advisors, Dr. Larry McKay, and Dr. Steve Driese, for helping me find a project that we all could enjoy working on, and for their help throughout this project. Thanks must also go to the third member of my committee, Dr. Mike Vepraskas, for making the long trips over from North Carolina to come to committee meetings and for adding his valuable comments.

Friends and family have also played a part in this project by giving their support and giving me distractions; you can't work all the time. Thanks Mom, Ryan, Dave, Steve, Milan, Settles, Camilo, and everyone else that I may be forgetting. And of course, the person who has to listen to me the most, Adrian Green, my girlfriend and best friend, who has to listen to me complain about my thesis, and brag about cycling, more than anyone. Thanks for her endless support and input on all of life's little struggles.

Financial support for this project was obtained through student grants-in-aid programs by AAPG, GSA, and Sigma Xi. Additional funding was supplied by the UT Center for Environmental Biotechnology and through an award to Drs. Larry Mckay and Steve Driese from the University of Tennessee professional development award program.

Abstract

A stepped pit was excavated to a depth of 3.4 meters in soil and saprolite formed from the Maryville Limestone (Middle Cambrian) at a site near Oak Ridge, TN. Field-scale measurements of hydraulic conductivity, K_{sat} and $K(\psi)$, and thin-section microscopy were used to test the hypothesis that illuviated clays and Fe/Mn cements are common occurrences in sedimentary saprolite and are responsible for the formation of a low K zone (depth <0.5-1.5 m) typically found in these materials. Results show that the onset of deposition of pedogenic clay and Fe/Mn oxides at about 60 to 100 cm depth corresponds to a two-orders-of-magnitude reduction in saturated hydraulic conductivity. Observations also indicate that accumulations of pedogenic clays and Fe/Mn oxides can occur to depths of at least 3 m, and that the relative amount of infilling in the deep saprolite does not correlate well to variations in hydraulic conductivity. The influence of lithology becomes increasingly important as one proceeds deeper into the section, because the frequency and nature (fractures vs. root holes) of the macropores varies according to lithology. Limestone-derived saprolite tends to have more frequent root holes and a higher abundance of pedogenic clay and Fe/Mn oxide infilling than shale/siltstone saprolite. However, variations in hydraulic conductivity tend to cross lithologic boundaries, indicating that variations in K depend on the interaction of a variety of factors, and suggesting that very complex flow systems are likely to develop in the saprolite. These

findings further our understanding of groundwater flow through the unsaturated zone in sedimentary saprolite, and have implications for agriculture, soil drainage, aquifer recharge, and contaminant migration in these materials.

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1. Introduction

A 65-100 km wide band of folded and faulted sedimentary rock, known as the Valley and Ridge Province, extends NE-SW along the western flank of the Appalachian Mountains. Throughout this area, including the portion in East Tennessee, the upper 1-15 m of the bedrock is highly weathered and fractured, forming a subsoil material referred to as saprolite. Saprolite is the result of extensive *in-situ* weathering of an existing parent rock, and has characteristics of both soil and rock. The original structure of the parent rock, including sedimentary layering and fractures is preserved, but the material also contains soil features such as high matrix porosity, translocation or illuviation of clays, precipitation of Fe/Mn oxides, and bioturbation (Dreier et al., 1987; Hatcher et al., 1992; Buol., 1994; Graham et al., 1994; Stolt and Baker, 1994; Richter and Markewitz, 1995). Although it is widespread in humid climates such as the southeastern United States, the physical and chemical characteristics of saprolite derived from sedimentary rock have not been extensively studied in the U.S. (Stolt and Baker, 1994). As a result, the hydrology of this type of subsoil is poorly understood, making predictions of surface runoff, aquifer recharge, soil water retention and transport of contaminants uncertain.

The only site where extensive research has been carried out on the hydrologic characteristics and behavior of sedimentary rock saprolite is at the U.S. Department of Energy's Oak Ridge Reservation (ORR) in eastern Tennessee. Researchers at Oak Ridge National Laboratory (ORNL) and other institutions carried out a series of field-based hydrologic investigations in the

saprolite and partially weathered bedrock at several sites on the ORR (Luxmoore et al., 1981; Watson and Luxmore, 1986; Drier et al., 1987; Moore, 1988, 1989; Wilson et al., 1988, 1989, 1990; Jardine et al., 1989, 1990; Luxmoore and Ferrand, 1993). Based on these previous studies, Solomon et al. (1992) developed a hydrologic conceptual model for the ORR. This model defined three hydrologic zones in the saprolite, the storm flow zone, the vadose zone, and the water table zone (Fig. 1). Perched water table conditions tend to develop in the upper 80-120 cm (the storm flow zone) during heavy rains, causing rapid down-slope 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 reaches the water table. Explanation for the cause of this variation in hydraulic conductivity was not offered, but a correlation between the approximate depth of the vegetated root zone and the storm-flow zone was suggested by Solomon (1992).

The existence of this rapid lateral flow (storm-flow) zone was confirmed by several field scale tracer experiments carried out at field research sites at ORR. Wilson et al. (1993) conducted an *in situ* tracer experiment in the upper meter of a "limey shale" saprolite (soil name-Montevallo; loamy-skeletal, mixed, subactive, thermic, shallow Typic Dystrudept (www.statlab.iastate.edu/soils/)) by releasing a bromide salt tracer through a buried line source during a rainstorm. The tracer was detected in a subsurface weir located 65 m down slope only 3.2 hrs after the release. Subsequent monitoring showed that the tracer concentration in the

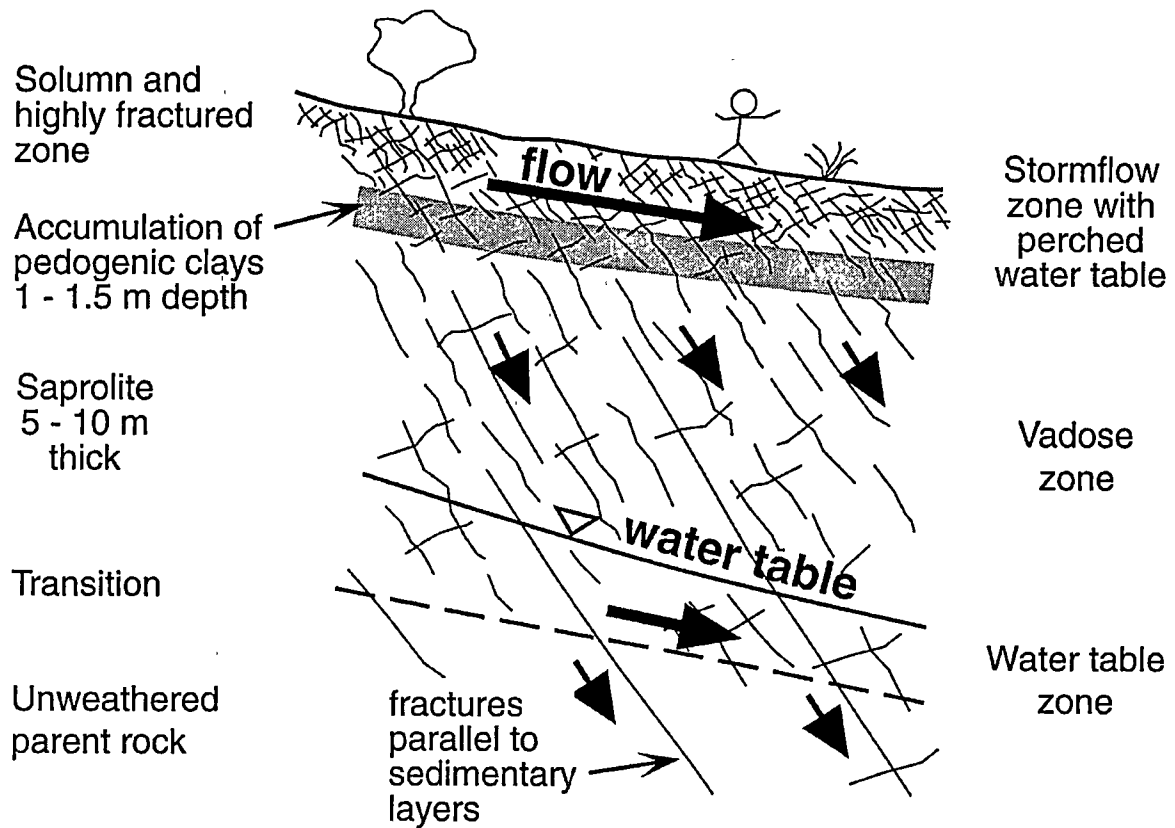


Figure 1. Conceptual model of lithology and hydrology of East Tennessee saprolite (From Driese et al., 2001, and modified after Solomon et al., 1992). Note: Long Arrows indicate high discharge rates, whereas short arrows indicate lower discharge rates.

weir was strongly influenced by individual precipitation events, indicating very fast lateral flow in the storm-flow zone. By comparison, downward migration of tracers in the saprolite immediately below the storm-flow zone was much slower, as demonstrated in another field experiment at ORR (Jardine et al. 1990). The investigators (Jardine et al., 1990) released a solution containing a bromide salt tracer at the top of an isolated *in-situ* 2 m² by 3 m deep pedon of "dolomitic shale" saprolite (soil name-Fullerton; fine, kaolinitic, thermic Typic Paleudults (www.statlab.iastate.edu/soils/)), and observed that the tracer did not penetrate below 120 cm depth during the 310 day duration of the experiment. However, additional field studies at a field site several km away showed that once infiltration did reach the water table, which typically occurs just above the saprolite-bedrock contact, it could also move rapidly down-slope (Lee et al., 1992; Shevenell et al., 1994; McKay et al. 1997 and 2000). Both the storm-flow zone and the upper portion of the water table zone are considered as potential rapid contaminant migration pathways at the ORR.

A modification of the ORR hydrologic conceptual model (Fig. 1) was recently proposed by Driese et al. (2001). This revised model was based on field and laboratory investigations at the ORR by Penfield (1999) indicating that many of the macropores and fractures in the saprolite from 50-250 cm depth were clogged with translocated or illuviated clays and Fe/Mn oxide accumulations. These infillings were so extensive that they were considered the most likely cause of the previously observed reduction in flow rate and hydraulic conductivity just below the storm-flow zone.

Investigators working in North Carolina in crystalline rock-derived saprolite also observed shallow zones of lower hydraulic conductivity, often occurring just below the soil-saprolite contact. In a study performed by Schoeneberger et al. (1995), minimum values of saturated hydraulic conductivity tended to occur at depths ranging from 50-100 cm. In another study, Vepraskas et al. (1996) observed a zone of low saturated hydraulic conductivity values just below the soil zone, and used thin section microscopy to ascertain the cause. They found that most fractures and macropores in this zone were plugged with illuviated clays, and concluded that the infillings, rather than differences in saprolite texture or structure, were responsible for the low hydraulic conductivity values. The zone of infilling was similar to those observed in the sedimentary rock saprolite by Penfield (1999) and Driese et al. (2001), and suggest that such zones are common features in saprolite.

The overall hypothesis for this study is that accumulations of pedogenic clays and mineral precipitates in the upper subsoil are common features in saprolite derived from sedimentary rock, and that they act as major controls on hydraulic conductivity and the development of shallow flow systems. This study tests 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 methods used for the study include: 1) excavation of a large, stepped test pit to allow for detailed field-scale pedologic and petrographic mapping of the soil and saprolite; 2) saturated and unsaturated hydraulic

conductivity measurements conducted with a tension-disc infiltrometer (TDI) and a compact constant head permeameter (CCHP); and 3) microscopic examination of soil and saprolite thin sections prepared from undisturbed pedons collected in the field to evaluate the depth-related distribution of pore infillings.

2. Description of Field Site

A research pit (KS-1) was excavated into saprolite developed from the Maryville Limestone of the Middle Cambrian Conasauga Group at a site approximately 10 km east of the city of Oak Ridge, TN (latitude 36°02.586N and longitude 84°04.677W). The site was chosen because it is close to the ORR (18.5 km) and is in a geologic and physiographic setting that is very similar to the setting at Special Waste Storage Area-7 (SWSA-7) at ORNL, where many of the previous saprolite field investigations were carried out and where undisturbed saprolite samples used for many laboratory-scale flow and transport experiments were collected (Watson and Luxmore, 1986; Moore, 1988, 1989; Wilson et al., 1988, 1989, 1990; Jardine et al., 1989, 1990; Luxmoore et al., 1981; Luxmoore and Ferrand, 1993; McKay et al., 1997; Cumbie and McKay, 1999; Dorsch and Katsube, 1999; Driese et al., 2001). The Maryville Limestone unit, which is equivalent to the Dismal Gap Formation on the ORR, is described by Srinivasan and Walker (1993) as a sequence of six alternating limestone and shale formations that formed in a shelf-margin type depositional environment. The lithologic variations reflect temporal changes in sedimentation rate, subsidence, and absolute sea-level change in the paleo-basin. Due to the complex nature of the depositional environment and lateral variation in lithology of the Maryville Limestone, on-site reconnaissance between the previous research sites located on the ORR and the field site described in this paper was needed. This reconnaissance showed only slight variation between the lithologies present at ORR and this site. Whereas, the ORR sites have noticeably more shale saprolite

lithologies present than limestone, the KS-1 site has approximately equal amounts of shale and limestone saprolite lithologies (soil name-Armuchee; Fine, mixed, semiactive, thermic Inceptic Hapludult (www.statlab.iastate.edu/soils/)).

The Maryville Limestone is overlain by the Nolichucky Shale (Upper Cambrian), and is underlain by the Rogersville Shale (Middle Cambrian). The rocks were deformed by compressional tectonic processes during the Alleghanian Orogeny, and crop out in imbricate thrust sheets that strike NE to SW, and dip SE (Hatcher et al, 1992). The climate of the region is humid temperate, and mean annual precipitation was 133 cm during the period 1954-1983. The wettest period lasts from January through March, when precipitation ranges from 13-16 cm/month. The driest period lasts from August through October, with precipitation ranging from 7-10 cm/month. It was during this driest time of the year that the pit was excavated, in August, and was open until mid November. During the time that the pit was open, rain only occurred once, for a two-day period, in late October. During this time no seepage of soil water from the walls of the pit into the basin was witnessed. The mean annual temperature is 15°C (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, oriented approximately perpendicular to strike (N60°E), and approximately parallel with the dip direction (20-25° SE). The opposing wall of the pit was stepped forming benches approximately 6 m long and 1-1.5 m wide, which served as level surfaces for carrying out infiltration tests (Fig. 2). Plastic tarps were used to cover these benches so as to minimize drying and to prevent infiltration from precipitation.

Lithology of the soil and saprolite exposed on the vertical pit face was characterized in the field using a combination of standard soil classification methods (Buol et al. 1997) and methods typically used in sedimentary rock classification (Driese et al. 2001). These methods included physical characterization of soil horizons and subhorizons, soil texture, root extent, animal burrows, Fe/Mn oxides, color, sedimentary structures, saprolite bedding thickness, fracture density, saprolite lithology, which is related to the lithology of the parent bedrock, and any other macroscopic features observed in the field.

Eighteen undisturbed samples ranging in size from 22 cm in diameter by 30 cm in length, to 10 cm in diameter by 5 cm in length, were collected approximately every 20 cm with depth, or at major changes in soil horizons or stratigraphic layers. These samples excavated from the pit face were allowed to

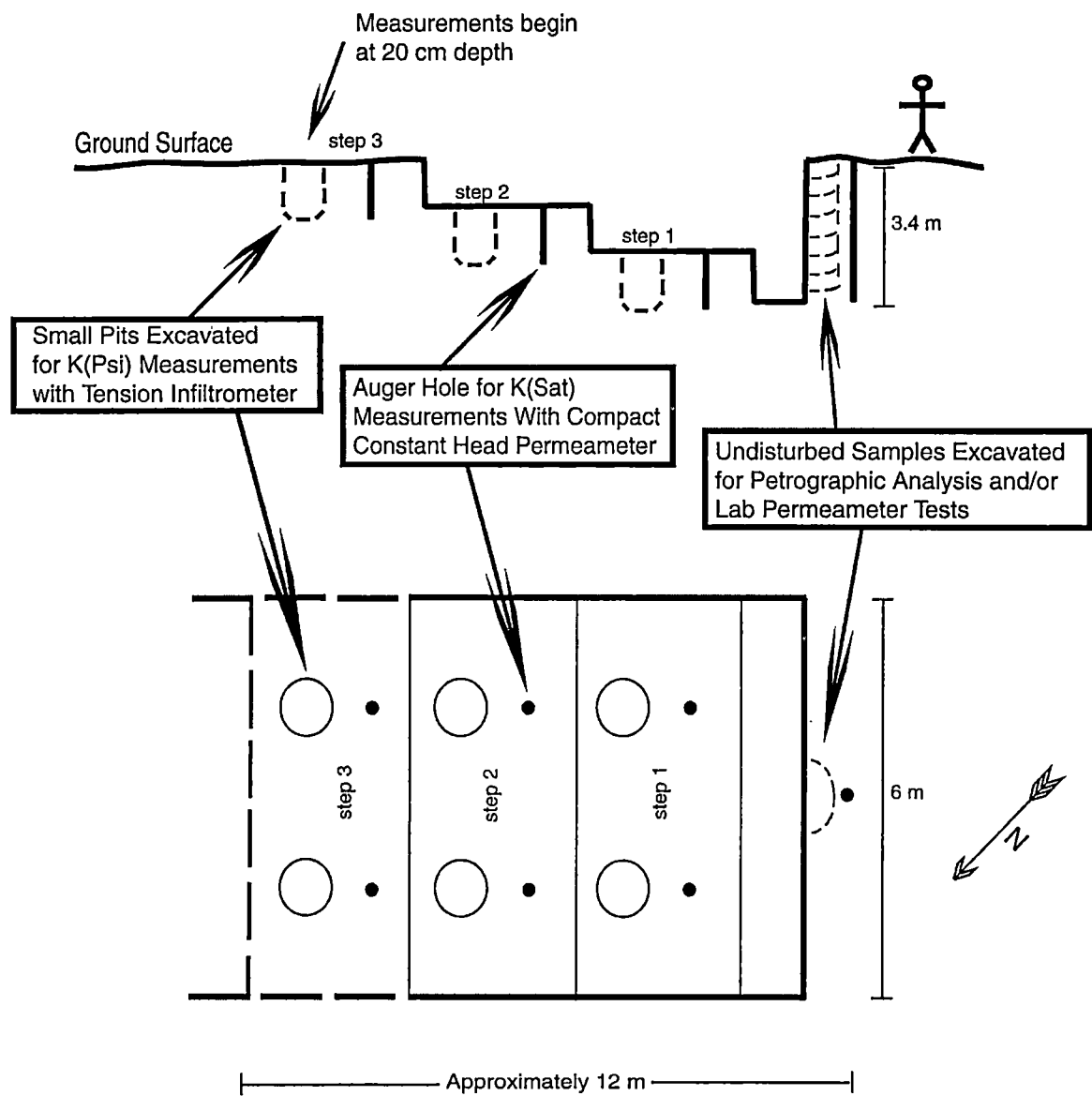


Figure 2. Schematic of pit layout (not to scale).

air dry and were sent to Spectrum Petrographic Inc. for preparation of petrographic thin sections. The thin sections were then examined using a petrographic microscope to determine the lithology, type and distribution of macropores, percentage of clay infillings, and percentage of Fe/Mn oxides present. The percentages of macropores, clay infillings, and Fe/Mn oxides were estimated using comparator charts (Folk et al., 1970) and then compared to measured profiles of saturated and unsaturated hydraulic conductivity. Digitized images were made from selected thin sections to visually show the extent of clay infilling of fractures and biopores.

Hydraulic conductivity measurements were made using a tension disc infiltrometer (TDI) for measuring $K(\psi)$, the unsaturated hydraulic conductivity, and a compact constant head permeameter (CCHP) for measuring K_{sat} , the saturated hydraulic conductivity (Amoozegar and Wilson, 1999). The measurements were carried out in hand-augered boreholes or hand-excavated pits, as shown in Fig. 2. In each of the boreholes or pits, four values of K_{sat} or $K(\psi)$ were typically measured, at depth intervals of 20 to 30 cm. These measurements were then compiled together to form hydraulic conductivity depth profiles, ranging from 20 cm to 300 cm depth below the ground surface. A final CCHP profile was measured in a borehole located behind the pit face (Fig. 2), with K_{sat} measurements ranging from 20 cm to 300 cm depth.

The tension-disc infiltrometer was used to measure infiltration rates on the flat bottom of the small hand-excavated pits. The excavations for the TDI

measurements were made by hand, using sharp-shooter shovels, picks, hand shovels, knives, and any other means necessary to obtain a flat, relatively undisturbed area. A layer of sand-sized quartz grains, approximately 1 cm thick, was placed between the bottom of the pit and the tension disk to ensure a good connection for hydraulic measurements. After each measurement, the small pits would be left open for approximately 24 hours, and then would be deepened by approximately 20 cm in preparation for the next measurement. This was repeated until the pits reached the depth of the next deepest bench. The CCHP measurements were carried out in boreholes that were constructed using a hand auger (7.62 cm diameter) and then were brushed with a nylon brush to minimize any smearing created during augering. After each measurement, the borehole was left open for approximately 24 hours and then the borehole was extended approximately 20 cm in preparation for the next measurement. This was repeated until the holes reached the depth of the next bench.

Three large columns of soil and saprolite, approximately 25 cm in diameter, were collected near the vertical face of the pit at depths of 19-49 cm, 80-110 cm, and 180-210 cm below the ground surface. The first of these columns was set up in a permeameter for measuring saturated hydraulic conductivity and carrying out pathogen tracer experiments, and the remaining columns will be set up and tested soon (Rietti-Shati, 2001). These columns have and will be subjected to constant flow rate tests at three to four rates per column. Hydraulic conductivity will then be calculated using Darcy's Law.

K_{sat} was calculated using the measured discharge values from the CCHP tests and the Glover solution (Amoozegar, 1989):

$$K_{sat} = \frac{Q \left[\sinh^{-1} \left(\frac{H}{r} \right) - \sqrt{\frac{r^2}{(H^2 + 1)}} + \frac{r}{H} \right]}{2\pi H^2} \quad (1)$$

where r is the radius of the borehole, H is the height of water in the borehole, and Q is the discharge obtained under steady-state flow conditions. Steady state was assumed to exist when four consecutive measurements of Q yielded equal values (≤ 0.1 cm variation) over a time period of 40 minutes. This would usually last 2-5 hours for each measurement in the sedimentary saprolite.

$K(\psi)$ was calculated using measured discharge values from the TDI tests and the simultaneous equation method presented by Ankeny et al. (1991):

$$Q(\Psi_1) = \left[\pi r^2 + \frac{4r}{A} \right] K(\Psi_1) \quad (2)$$

$$Q(\Psi_2) = \left[\pi r^2 + \frac{4r}{A} \right] K(\Psi_2) \quad (3)$$

$$\frac{[K(\Psi_1) - K(\Psi_2)]}{A} = \frac{\Delta \Psi [K(\Psi_1) - K(\Psi_2)]}{2} \quad (4)$$

where r is the radius of the tension disc in contact with the soil surface, $K(\psi_1)$ is the hydraulic conductivity at the lowest tension, $K(\psi_2)$ is the hydraulic conductivity at the next lowest tension, $Q(\psi_1)$ is the steady state discharge at the lowest tension, $Q(\psi_2)$ is the steady state discharge at the next lowest tension. A is defined as,

$$A = K(\Psi)/\phi(\Psi) = \text{constant} \quad (5)$$

where $K(\psi)$ is hydraulic conductivity at a reference surface water potential and $\phi(\psi)$ is the matric flux potential for the infiltration surface at a reference surface water potential. Equations 2, 3, and 4 yield three unknowns that can then be solved simultaneously for unsaturated hydraulic conductivity values using:

$$K(\Psi_1) = Q(\Psi_1) / \left[\pi r^2 + \frac{4r}{\left(\frac{2[Q(\Psi_1) - Q(\Psi_2)]}{\Delta\Psi[Q(\Psi_1) + Q(\Psi_2)]} \right)} \right] \quad (6)$$

$$K(\Psi_2) = Q(\Psi_2) / \left[\pi r^2 + \frac{4r}{\left(\frac{2[Q(\Psi_1) - Q(\Psi_2)]}{\Delta\Psi[Q(\Psi_1) + Q(\Psi_2)]} \right)} \right] \quad (7)$$

These equations were used for pairs of unconfined infiltration rates taken at different tensions. Steady state was assumed to exist when four consecutive measurements of Q were approximately equal (≤ 0.1 cm variation), over a period of 40 minutes; this would usually take 2-5 hours. In this study the equations were solved for tensions of 0 and 5 cm, and 5 and 14 cm. The measurements at three different tensions were carried out in exactly the same location, starting with the highest tension (14 cm) and then decreasing the tension to 5 cm, and finally to 0, which is essentially equal to K_{sat} .

4. Results

4.1 Field-scale lithologies

The soil profile 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 34 cm thick. These were underlain by clay loam saprolite BC and C-horizons that extend to the top of bedrock at approximately 3.4 m depth. A detailed soil profile description at the center of the vertical pit face is shown in Table 1. Thickness of the combined A and B-horizons vary with the lithology of the underlying saprolite (Fig. 3). The greatest combined A and B horizon thickness occurs above the limestone saprolite (approximately 50 cm), with thickness above the ribbon limestone saprolite and the shale saprolite of approximately 37 cm and 25 cm, respectively.

A map of the saprolite lithologies along the vertical pit face, which is oriented approximately parallel to the direction of maximum dip of sedimentary layering, is shown in Fig. 3. The BC and C-horizon consists 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 degrees. The shale/siltstone lithology represents approximately 33% of the saprolite exposed at the vertical pit face, while the limestone and ribbon limestone lithologies represent 26% and 41%, respectively (Appendix I). One thin layer (1 cm) of sandstone saprolite was observed below the shallowest ribbon-

Table 1. Soil and saprolite descriptions obtained from profile in the center of the vertical pit face (Fig. 3).

Horizon	Depth (cm)	Description
A	0-10	brown (10YR 5/3) silt loam; weak granular structure; loose; many fine and very fine roots, common medium and few coarse roots; common fine vesicular pores; 2% medium distinct (7.5YR 5/8) redox concentrations; clear smooth boundary.
BE	10-30	light yellowish brown (2.5Y 6/3)/brownish yellow (10YR 6/6) silt loam/loam; weak fine angular blocky structure; friable; common very fine roots; many very fine, common fine, and few vesicular pores, often infilled with insect and earthworm castings of A material; 4% medium distinct (7.5YR 5/8) redox concentrations; abrupt irregular boundary.
Bt	30-64	strong brown (7.5YR 5/6) clay loam; moderate medium angular blocky structure; firm; common very fine, few fine roots along ped faces; few fine vesicular pores; 5% distinct (10YR 7/6) medium shale saprorelicts; 2% distinct (10YR 2/1) medium iron/manganese concentrations; clear smooth boundary.
BC	64-91	strong brown (7.5YR 5/8) clay loam limestone saprolite; moderate medium angular blocky structure formed in part from inherited sedimentary bedding structure; firm; few fine roots along ped faces; 20% faint (7.5YR 4/6) coarse iron concentrations; 5% prominent (2.5Y 7/4) medium shale saprorelicts near bottom of horizon; 8% prominent (10YR 2/1) iron manganese concentrations along relict bedding and ped faces; clear smooth boundary. [ribbon limestone saprolite]
C1	91-112	strong brown (7.5YR 5/6) clay loam/shale saprolite; weak medium angular blocky structure; firm; few coarse and medium roots and relict roots along bedding; 25% faint (7.5YR 4/6) medium iron concentrations; 2% prominent (2.5Y 7/4) fine shale saprorelicts associated with 2Cr; 20% prominent (10YR 2/1) iron manganese concentrations on boundaries; abrupt smooth boundary. [ribbon limestone saprolite]
C2	112-340	laminated siltstone/shale saprolite mixed with limestone saprolite; reddish yellow (7.5YR 6/8) with common distinct (7.5YR 2.5/1) coatings along bedding planes. [ribbon limestone, limestone, and shale/siltstone saprolite]
Cr/R	340+	Partially weathered limestone; indicated by appearance of large, gray, unweathered rock fragments and substantial increase in resistance to excavation with backhoe. [Maryville limestone]

Note: The pit face is highly heterogeneous and this soil profile is a generality of what was observed in the field. Thin layers of shale, distributed throughout the pit are noticed to be more rock like than limestone at any given soil horizon.

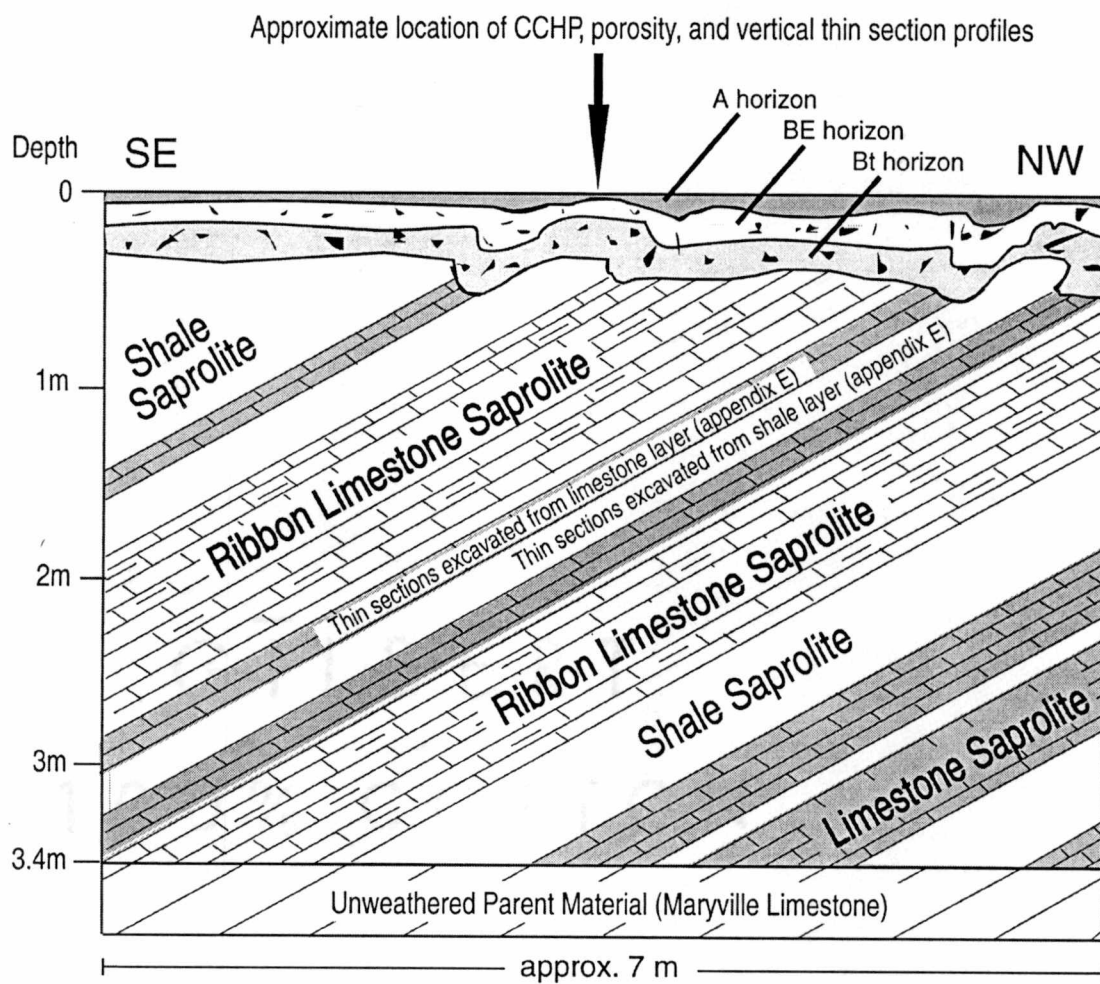


Figure 3. Map of vertical pit face showing soil horizons, and major stratigraphic units and bedding.

limestone layer, but is not depicted in Fig. 3. Sedimentary layering is very well preserved in the shale/siltstone and the ribbon limestone, and faint layering is visible in some of the limestone saprolite, indicating that volume losses during weathering were small.

Fractures were observed 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 meter), and more closely spaced (1-2 cm) than the bedding-perpendicular fractures (4-5 cm spacing and usually only a few centimeters in length). Together they appeared to form an interconnected network in the shale/siltstone saprolite. Fractures were also common in the ribbon limestone, although they were not as frequent or as extensive as in the shale/siltstone, and were only intermittently found in the massive limestone lithology. Fractures appeared more common in the shallow saprolite, but this is likely a function of moisture content (i.e. desiccation cracks) and/or stress relief.

Biopores (usually root holes) were visible in all saprolite lithologies down to the bottom of the pit (3.4 m). Biopores were the most common macropore in the massive limestone unit, with approximately twice as many biopores per unit area observed in this unit when compared to the ribbon limestone, and approximately 8 times more biopores than the shale/siltstone. The biopores were usually larger in the softer lithologies as well, with maximum diameters of 2.5 cm observed in the limestone and ribbon limestone, whereas the maximum diameter decreases

to approximately 0.05 cm for the shale/siltstone. A greater concentration of biopores was apparent closer to the ground surface (<50 cm), and is likely due to a higher density of tree and grass roots, and animal burrows. However, one macropore reaching 2 cm in diameter was found at approximately 1.5 m depth in the ribbon limestone saprolite, clearly indicating that large macropores are not restricted to these shallow depths.

The fractures and biopores described above often contained infillings or coatings of pedogenic clays or Fe/Mn oxides. For these macropores, 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 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 2 to 6 times more infillings being found in limestone and ribbon limestone, as compared to shale/siltstone. Most of these infillings (85%) were orange-red in color, indicating that oxidation occurred to the bottom of the pit at 3.4 m depth. Gray-green and black Fe/Mn oxide infillings were randomly spaced and less abundant (15%).

4.2 Hydraulic conductivity distribution

4.2.1 CCHP measurements

Vertical profiles of saturated hydraulic conductivity, K_{sat} , measured at three sites in the KS-1 pit using the CCHP equipment, are shown in Figs. 4 A, B and C. The profile of soil and saprolite lithology for the set of K_{sat} measurements located behind the center of the pit face is also shown on Fig. 4 C. In all three profiles, K_{sat} values are highest in the upper 40-60 cm (ranging from 2.5×10^{-6} to 1.5×10^{-5} m/s), and then decline by factors of up to 200 times within the next 40-60 cm. The zone of highest K_{sat} corresponds to the A- and upper portion of the B-horizons, which are both characterized by the frequent occurrence of biopores. The initial rapid decline in K_{sat} occurs in the lower B- and upper BC-horizons. Below a depth of 100 cm, the profiles indicate alternating layers, or zones, of higher and lower K_{sat} , each about 50-100 cm thick, which is approximately equal to the thickness of the major saprolite lithologies (Fig. 3). For the vertical profile measured at the center of the pit face (Fig. 4C), the lowest K_{sat} values tend to occur in the ribbon limestone saprolite lithology, which consists of closely spaced laminations of limestone and shale. Spreadsheets containing the CCHP field data, the calculations of K_{sat} and a comparison of values measured with the CCHP and the Guelph permeameter are shown in Appendices C and D.

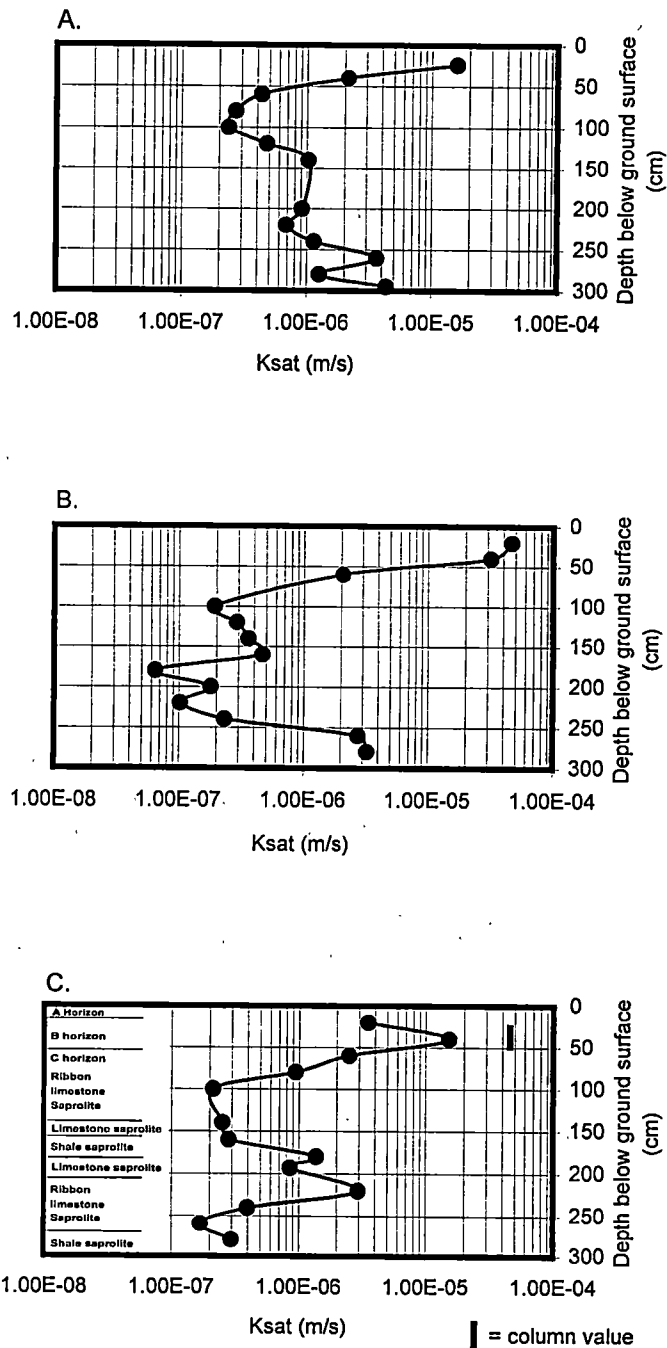


Figure 4. Ksat profiles measured at three locations in KS-1 pit. All values are measured with the CCHP, except for profile C, where values measured in laboratory using an undisturbed column sample is also included. A) North west side of pit steps. B) South east side of pit step. C) Continuous borehole located approximately 1 m behind the vertical pit face.

4.2.2 $K(0)$ and K_{sat} comparison

Vertical profiles of K_{sat} and $K(\psi)$ at 0 cm tension (essentially saturated K) from measurements taken on the northwest and southeast sides of the pit benches are shown on Figs. 5A and B. The K_{sat} and $K(0)$ values were measured at locations 1 m apart, along the strike of bedding, so at each depth they were expected to encounter approximately the same lithologies. The K_{sat} and $K(0)$ profiles generally had the same shape, but the K_{sat} values were usually lower by a factor of about 10. Theoretically, $K(0)$ and K_{sat} values measured at the same location should be identical for a homogeneous isotropic medium (Fetter, 1994). Local heterogeneity is likely responsible for some of the observed difference. For example, in the profiles in Fig. 5A, a large unweathered lens of limestone was encountered at 110 cm depth in the $K(0)$ profile but not in the K_{sat} profile. These types of variations, however, should not cause a systematic difference between K_{sat} and $K(0)$. Such a difference could occur if the vertical hydraulic conductivity was higher than the horizontal values, because the CCHP measurements were made in vertical boreholes, where inflow is largely horizontal, whereas the TDI was used on flat surfaces, where flow is largely vertical. It is more likely that the cause is due to differences in preparation of the saprolite surface prior to testing. A hand auger was used to prepare the holes for CCHP testing; this could have caused smearing around the annulus of the borehole. A borehole brush was used to alleviate this smearing but it is unsure whether this completely effective,

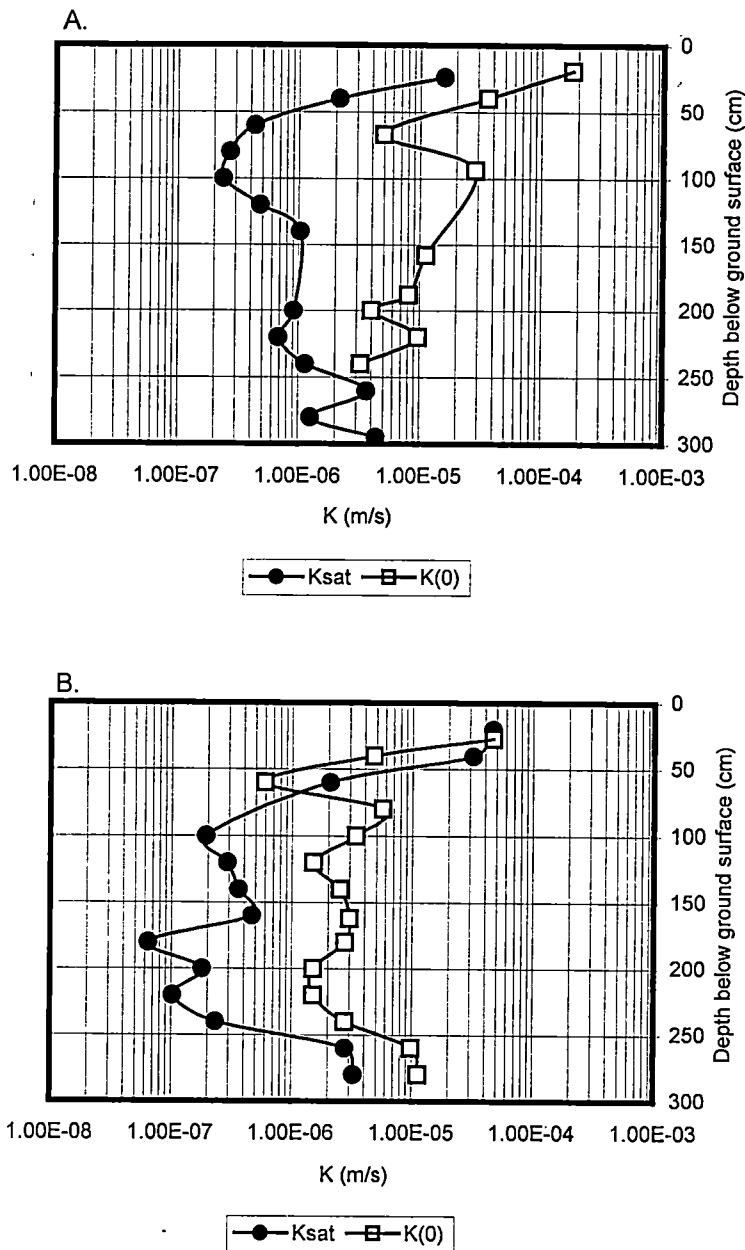


Figure 5. K profiles from two locations within KS-1 pit: A) Tension disc infiltrrometer (0 tension) and CCHP data comparison, Northwest side of pit steps. B) Tension disc infiltrrometer (0 tension) and CCHP data comparison, Southeast side of pit steps.

therefore, this remnant smearing could result in lower K_{sat} values for the CCHP.

The flat surfaces for the TDI tests were excavated with shovels and scrapers, which could open up some of the fractures, resulting in higher $K(0)$ values. It is possible that the actual hydraulic conductivity for this material lies somewhere between the values given in these two profiles.

4.2.3 $K(\psi)$ and $K(\psi)/K(0)$

Measured values of $K(\psi)$ at tensions of 5 and 14 cm were lower than values of $K(0)$ at the same measuring location, by factors ranging from 1.3 to 500 times (Appendix A). This is due to water flow at 5 and 14 cm tension being restricted to conducting pores less than or equal to 0.06 mm and 0.02 mm, respectively (pore size obtained by capillary theory). Small ratios of $K(\psi)/K(0)$ indicate the dominance of macropore flow, whereas ratios that approach one indicate that macropores are either absent or are filled with fine-grained material. Profiles of $K(\psi)/K(0)$ from both the northwest and southeast sides of the pit (Figs. 6A and B) indicate that macropores, most likely biopores and desiccation fractures, dominate flow in the upper 50 cm of the profile. This is followed by a rapid decrease in macropore flow at approximately 60 cm, and then a rapid increase in macropore flow from 80-100 cm (Figs. 6A and B) which corresponds to higher $K(0)$ values as shown on Fig. 5. Below 100-150 cm depth the $K(\psi)/K(0)$ profiles show less variability, indicating that although macropores may still be present, they are not as dominant as in the upper horizons.

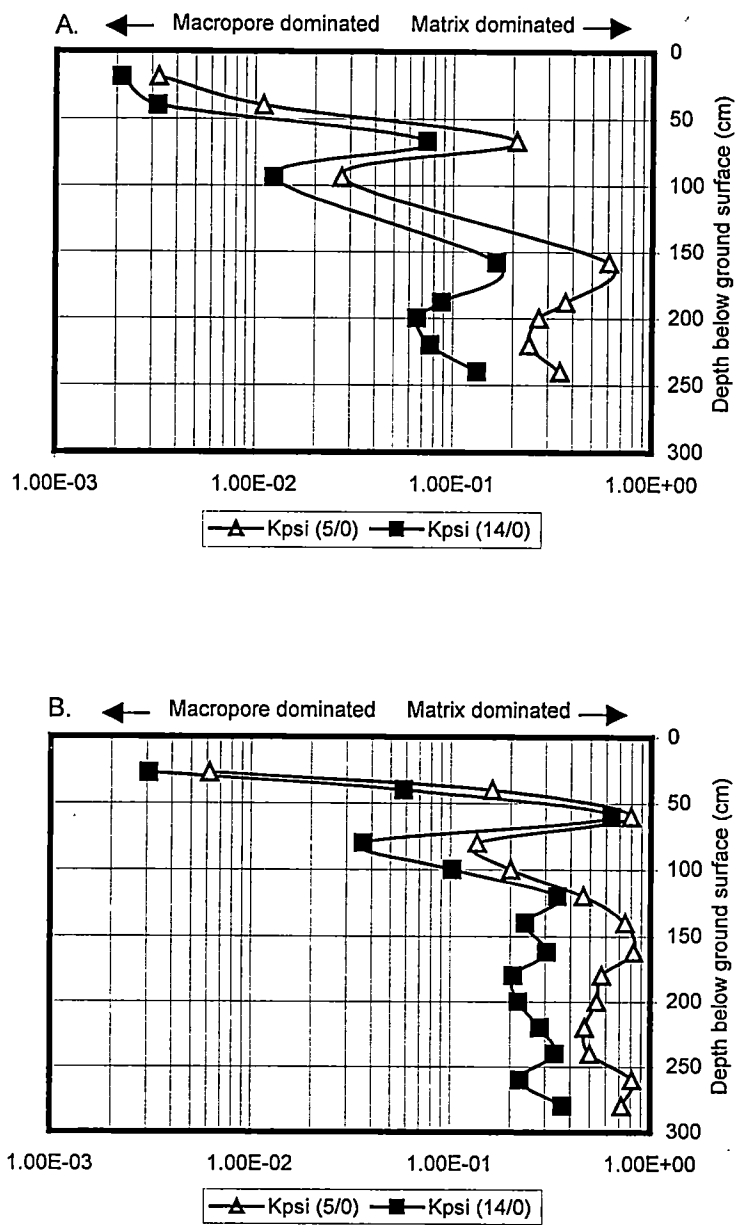


Figure 6. Ratio of $K(\Psi)/K(0)$ based on tension disc infiltrometer measurements at two locations within KS-1 pit: A) North west side of pit steps. B) South east side of pit steps.

4.2.4 Lab scale K_{sat}

Three large columns of soil and saprolite, approximately 25 cm in diameter and 30 cm in length, were collected close to the location of the CCHP measurements made behind the vertical face of the pit. The columns were collected at depths of 19-49 cm, 80-110 cm, and 180-210 cm below ground surface. K_{sat} results obtained from constant head permeameter tests carried out with the first of these columns (19-49 cm) yielded a value of 4.8×10^{-5} m/sec. This value is plotted on Fig. 4C and is approximately three times higher than the value measured with the CCHP at the same depths. This difference is small compared to the difference between the K_{sat} and $K(0)$ values (Fig. 5), and is well within the range of variability previously measured for K_{sat} values from saprolite at similar depths on the ORR (Driese et al., 2001).

4.3 Thin section lithologies

Thin sections collected from a vertical profile in the center of the pit face, and along two distinct sedimentary layers (Fig. 3), 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 excavated from the limestone layer at approximately 36 cm depth was classified as a Bt-horizon and has defining soil structure, whereas a thin section excavated from the shale layer at approximately

26 cm depth, was classified as a BC-horizon and has a clear saprolitic structure (Appendix E).

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 (Appendix E; Fig. 7). 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. 8). 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 lithologies. The shale/siltstone lithology, in contrast, exhibits a greater abundance of bedding-parallel and bedding-perpendicular fractures (Figs. 7 and 8). Detailed measurements of macropore aperture and porosity in the soil and saprolite thin sections were not carried out in this study. This is partially due to the occurrence of "artificial" porosity created during drying of the samples and preparation of the epoxy-impregnated thin sections. The fractures were particularly susceptible to disturbance, and it was common to see fractures in thin sections with apparent apertures of up to 5 mm, which were much larger than apertures observed in the field or in hand samples. Nevertheless, general observations were made from thin sections by estimating the percentage of macropores that existed as compared with the saprolite matrix. The assumption was made that all fractures

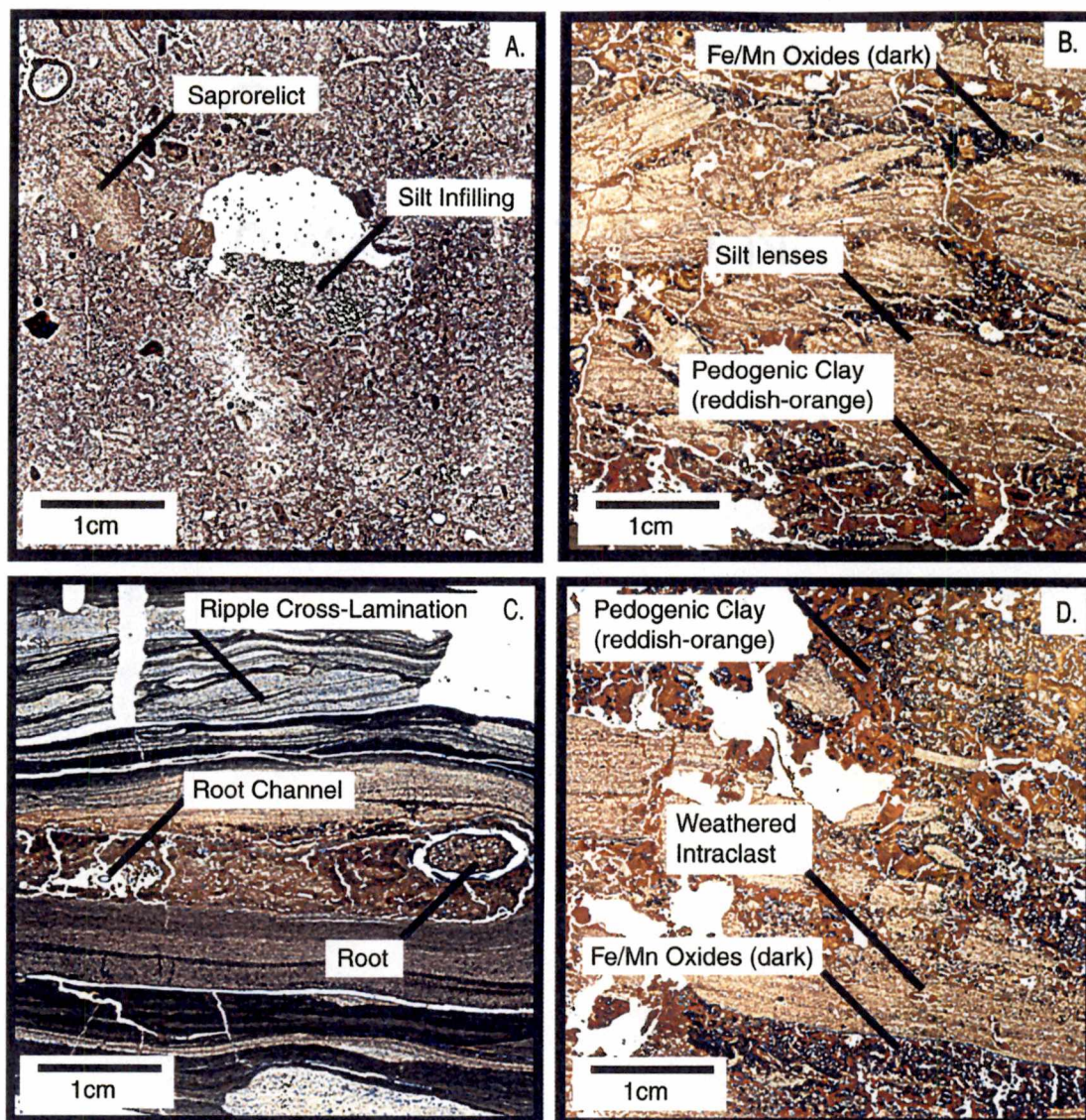


Figure 7. Micrographs of thin section samples from selected depths. Up orientation is towards top of page. Images photographed in plane-polarized light. A) 15 cm depth, silt loam soil with large bio-pore in center of section partially infilled with silt. B) 75 cm depth, limestone saprolite with silt intraclast lenses. Note: abundant pedogenic clay and Fe/Mn infilling. C) 183 cm depth, shale and siltstone saprolite with lens of clay-rich limestone saprolite in the center of section. Large root present in limestone lens. D) 262 cm depth, limestone saprolite with silt intraclast lenses. Note: Abundant pedogenic clay and Fe/Mn infilling.

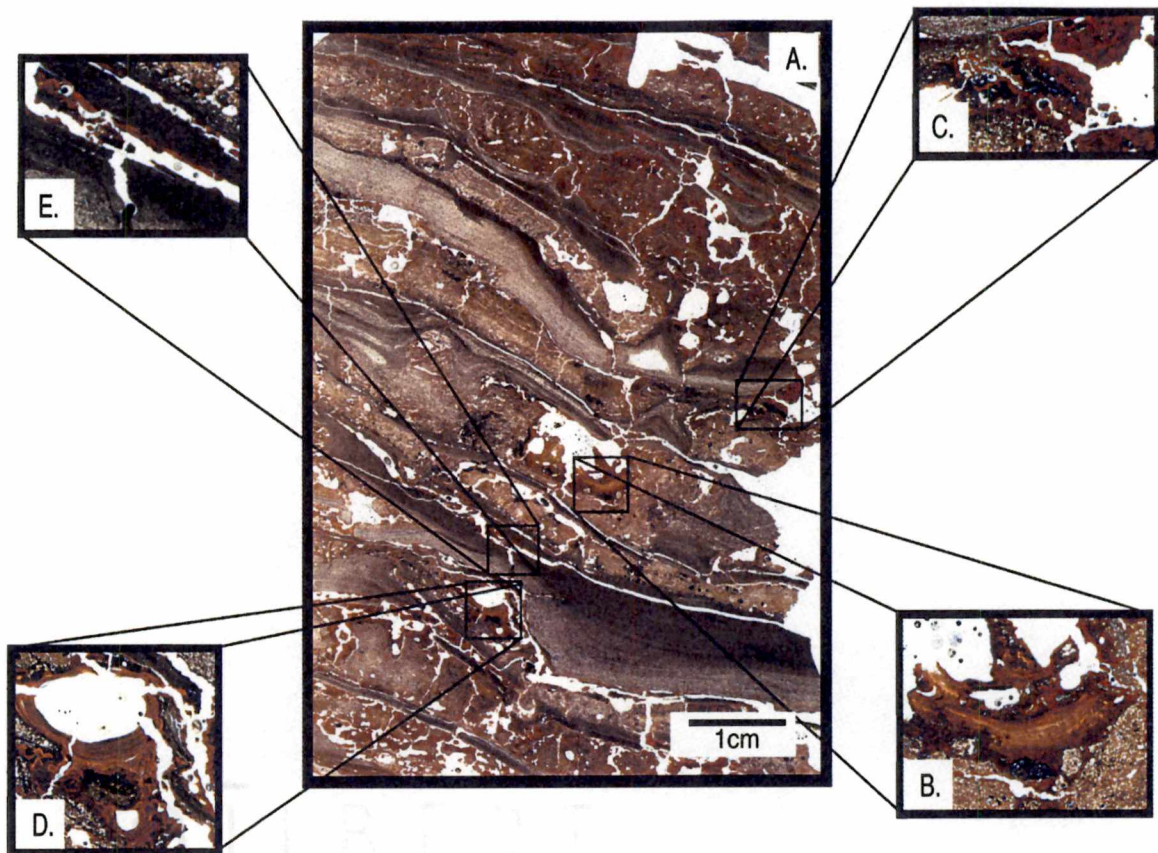


Figure 8. Micrograph of ribbon limestone thin section sample from 115 cm depth photographed in plane-polarized light. Up orientation is towards top of page. A) Complete thin section showing interbedding of limestone saprolite with silt intraclast lenses (ribbon limestone). B) Large biopore with abundant pedogenic clay infilling. Note: complex banding of deposits. C) Smaller pores infilled with Fe/Mn and pedogenic clay infillings. D) Large biopore partially infilled with pedogenic clay. Note: complex clay layer deposition from rim towards center of biopore. E) Bedding-parallel and bedding-perpendicular fractures. Note: pedogenic clay deposited on bedding-parallel fracture surfaces.

and biopores were present before drying, and that only an increase in fracture aperture has occurred. Based on these assumptions it was estimated about 10% of the bulk porosity consists of macropores in the limestone saprolite, whereas the percentage of macropores dropped to approximately 3% for the shale/siltstone saprolite.

Petrographic observations indicate that the limestone saprolite lithology contains more pedogenic clay and Fe/Mn oxides than the shale/siltstone saprolite lithology (Figs. 7 and 8). General observations made from thin sections (Table 2) were reinforced by quantitative investigations using visual comparator charts (Appendix G) (Fig. 9). These investigations show that thin sections lack illuviated clays from the soil surface down to the Bt-horizon (approximately 50 cm depth). Below the Bt-horizon, illuviated clays are observed to increase and decrease with a dependence on lithology (Fig. 9). The Fe/Mn oxide accumulation follows approximately the same pattern with a maximum attained in limestone lithologies and a minimum obtained above the Bt-horizon (Fig. 9). The limestone contains more intraclastic silt lenses, has a lower pedogenic clay and Fe/Mn oxide content than ribbon limestone containing fewer silt intraclast lenses. For example, the thin section from 75 cm depth has approximately 50% more silt lenses than were observed in the 200 and 250 cm depth thin sections (Appendix E), and this has a direct effect on the percentage of pedogenic clay and Fe/Mn oxides estimated in the depth profile (Fig. 9).

Table 2. Summary of saprolite porosity, macro-and micromorphology and their relationship to lithology. Note: ribbon limestone consists of limestone and shale/siltstone lithologies.

Lithology	Porosity	Macromorphology	Micromorphology
Limestone Saprolite	Porosity observed to be higher in thin section (10%). Bulk porosity observed to be higher using wax clod method (50-60%).	Frequent root holes, some animal burrows and bedding parallel or bedding orthogonal fractures observed. Fe/Mn oxide coatings found on most bedding parallel fractures. Clay infillings common in large pores and fractures.	Frequent circular pores with fewer fractures. Macropores ranged between 10 and 4000 μm diameter with a mean of approximately 400 μm . Clay and Fe/Mn infillings were abundant with a mean of 23% for clay and a mean of 12% for Fe/Mn oxides, compared to total slide area. Meniscus-type pendants and multiple coats of illuviated clays were observed in larger pores.
Shale/Siltstone Saprolite	Porosity observed to be lower in thin section (3%). Bulk porosity observed to be lower using wax clod method (20-45%).	Frequent bedding parallel and bedding orthogonal fractures observed, very few roots and animal burrows. Fe/Mn oxide coatings found on most bedding parallel fractures. Clay infillings found in some fractures.	Frequent fractures with fewer root holes. Macropores ranged between 10 μm and 4mm diameter or aperture with a mean of approximately 200 μm . Clay and Fe/Mn infillings were not abundant with a mean of 3% for clay and a mean of 2% for Fe/Mn oxides, compared to total slide area. Meniscus-type pendants and multiple coats of illuviated clays were observed in larger pores.

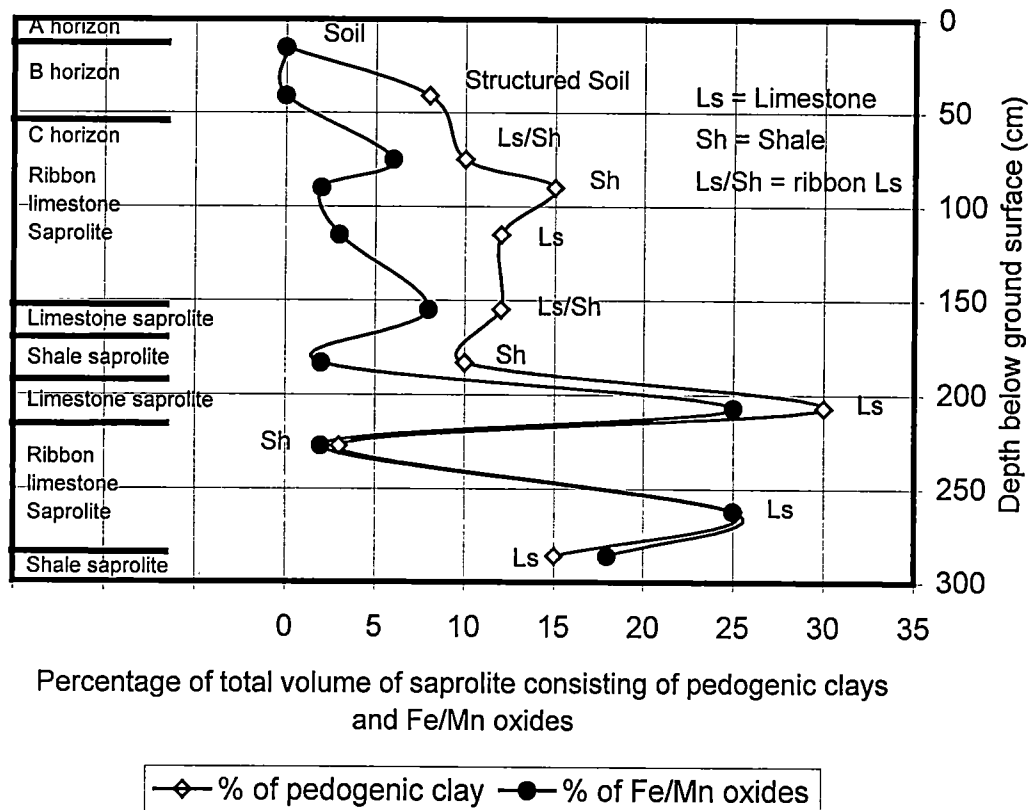


Figure 9. Percentage of clay and Fe/Mn oxides estimated from thin section micrographs and petrographic microscope (5 or 10 x) using visual image comparator charts. Note: Ls, Sh, and Ls/Sh are all thin section terms, whereas the stratigraphic column to the left in the figure utilizes field terms.

4.4 Bulk porosity

Thin section porosity observations were supplemented by bulk porosity measurements determined using the wax clod method on small, undisturbed samples (Blake and Hartge, 1986). Sample sizes ranged from 1 x 6 x 4 cm to 5 x 4 x 3 cm, and most of the samples did not contain large macropores (> 1mm diameter or aperture). The values are therefore representative of the porosity found in the matrix and the small macropores. The soil zone has the highest bulk porosity at approximately 62%, followed closely by the limestone saprolite, which has a bulk porosity of approximately 53% (Fig. 10). Bulk porosity of the shale/siltstone saprolite is lower and ranges between 20% and 45%.

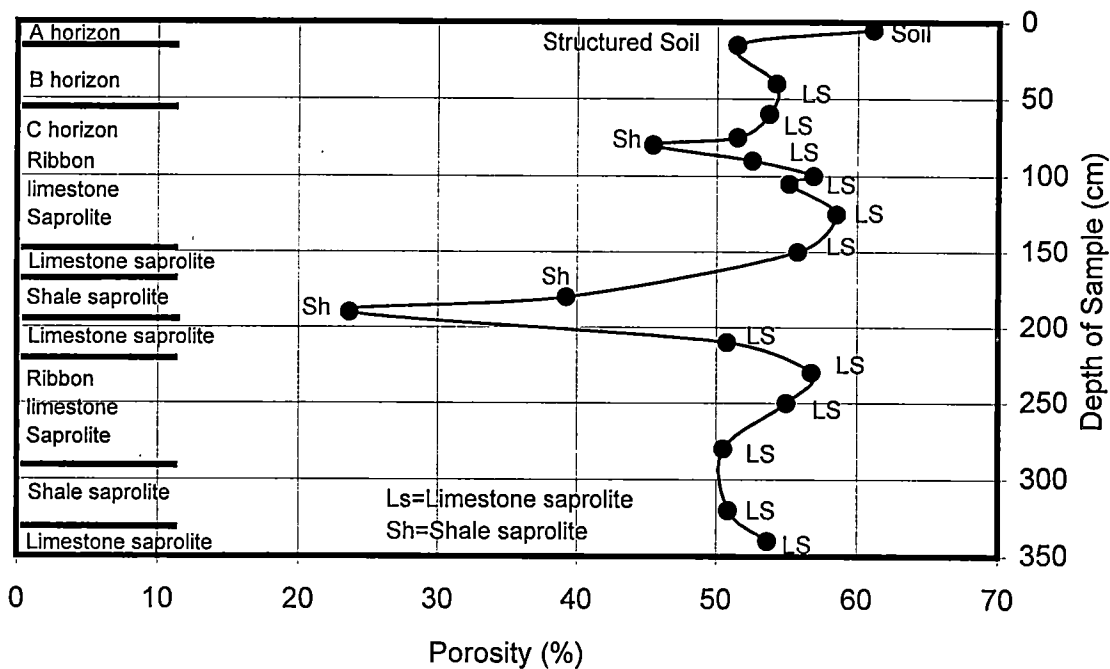


Figure 10. Bulk porosity data determined using paraffin-coated clods. Note: Ls, and Sh are small hand sample terms, whereas the stratigraphic column to the left in the figure utilizes field terms.

5. Discussion

5.1 Influence of saprolite lithology and pedogenic features on hydraulic conductivity

The results from all of the profiles of K_{sat} and $K(0)$ indicate that the highest hydraulic conductivity values occur in the A and BE horizons. Combined thickness of these horizons is strongly influenced by parent saprolite lithology, with A, BE, and Bt horizons approximately twice as thick in areas underlain by ribbon limestone or limestone saprolite, compared to areas underlain by shale/siltstone saprolite. Immediately below the BE-horizon there is a 30-80 cm thick layer of lower saturated hydraulic conductivity and higher $K(\psi)/K(0)$ values, indicating a reduction in the amount of macropore flow. This layer appears to occur in all of the saprolite lithologies and corresponds to the appearance of substantial infilling of macropores, mainly with pedogenic clays.

In the underlying saprolite (below approximately 100 cm depth) hydraulic conductivity varies in a way that suggests a lithologic control, with alternating higher and lower K_{sat} zones, similar in thickness to the major lithologic units. However, in the only case where profiles of K_{sat} and saprolite lithology were measured adjacent to one another (Fig. 4C), it appears that although the lowest values tended to occur more often in the ribbon limestone, the correlation between K_{sat} and lithology was weak. This may be partially due to the small number of K_{sat} measurements and/or the hydraulic influence of small interbeds within the dominant lithologies. The $K(\psi)/K(0)$ profiles (Fig. 6) also indicate

alternating zones of higher and lower amounts of macropore flow, although no lithologic data was collected at the location of these profiles.

The variations in hydraulic conductivity and $K(\psi)/K(0)$ observed in the BC and C-horizons are likely caused by a combination of variations in the frequency of occurrence of macropores, and in the degree of infilling of these features. Field observations showed a general trend towards fewer macropores with increasing depth, but also showed great differences in frequency of occurrence of fractures and root holes between different lithologies. Microscopic observations also showed substantial variability in the amount and type of macropore infilling materials (Fig. 9), which did not correlate well with variations in K_{sat} (Fig. 4C).

5.2. Comparison with previous hydrologic conceptual models

Conditions in the upper 50-150 cm of the soil and subsoil at the KS-1 site generally fit the hydrologic conceptual model developed for soil and sedimentary rock saprolite at the nearby Oak Ridge Reservation (Solomon et al., 1992; Driese et al., 2001). In both cases, the A and BE-horizons of the soil tend to have much higher hydraulic conductivity values (by a factor of up to 200), than the underlying lower Bt and upper BC-horizons. The sharp decline in hydraulic conductivity at both sites appears to be due to occlusion of most of the macropores with pedogenic clays. It is expected that at the KS-1 site, this zone of occlusion is sufficient to significantly inhibit downward flow, and could lead to the formation of a storm-flow zone, similar to what has been observed on the ORR (Solomon et al., 1992; Wilson et al., 1993).

There are substantial differences between conditions in the lower portion of the KS-1 saprolite (150 – 340 cm depth) relative to what has been observed, or inferred, for saprolite at ORR. This difference is likely 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) at the KS-1 site, relative to the ORR field sites. Field experiments at ORR (Lee et al., 1992; McKay et al. 1997 and 2000) indicated the presence of a fast-flow zone at the base of the saprolite, which is referred to as the water table zone in the Solomon et al. (1992) hydrologic conceptual model. However, at the ORR research sites, very little is known about hydraulic conductivity values in the vadose zone between the base of the upper B-horizons and the lowermost saprolite. The studies at the KS-1 site indicate that hydraulic conductivity in the saprolite is highly variable, and suggest that it is 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. This suggests that the water table zone shown on the ORR conceptual model is also likely very heterogeneous, and hence flow paths through this material are expected to be very complex.

A hydrologic conceptual model for the KS-1 site is shown on Fig. 11. The model is a modified version of the ORR conceptual model (Solomon et al., 1992; Driese et al., 2001), and incorporates the observed systematic variations in lithology, pore infilling and hydraulic conductivity. It is important to note that although variations in each of these factors were clearly visible in this study,

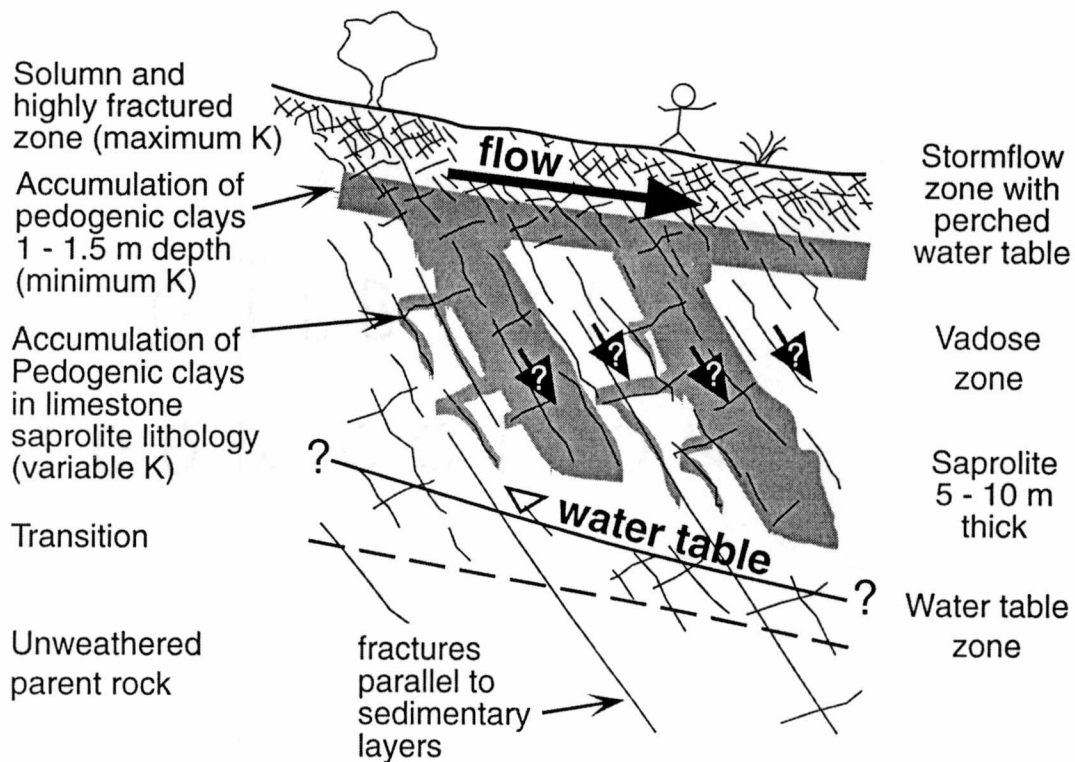


Figure 11: Revised conceptual model of hydrology and pedogenic clay distribution for East Tennessee sedimentary saprolite based on this study of the Maryville limestone saprolite. Note: Long arrows indicate high discharge rates, whereas short arrows indicate low discharge rates.

there is still substantial uncertainty in how they interact to control hydraulic conductivity. For example, a limestone saprolite layer containing numerous macropores, but with many of them occluded by pedogenic clay, might have the same hydraulic conductivity value as a shale/siltstone saprolite, containing fewer macropores, but with less infilling. Similarly, we do not have any data yet on how hydraulic conductivity values vary within a single lithologic layer.

Further comparison between the KS-1 site and a site in North Carolina indicate that correlations do exist in the lower B and upper BC and C-horizons despite saprolite lithologic differences. The North Carolina site has saprolite derived from crystalline bedrock whereas the KS-1 site has saprolite derived from sedimentary bedrock. Hydraulic conductivity and pedogenic clay observations made in the crystalline rock saprolite indicate that a minimum hydraulic conductivity (approximately 10^{-7} m/s) is reached at approximately 50 cm due to a clogging of macropores with pedogenic clays, which correlates well with observations made between the lower Bt and upper BC and C-horizons at the KS-1 site. Although no hydraulic conductivity measurements were available in the A and upper B-horizons in the North Carolina study, it is assumed that the reduction in hydraulic conductivity found at the North Carolina site could lead to perched water table conditions and the formation of a storm-flow zone similar to what has been observed at the ORR (Solomon et al., 1992; Wilson et al., 1993) and what is anticipated to occur at the KS-1 site.

Below the lower B and upper BC and C-horizons substantial differences occur between the KS-1 site and the North Carolina site. Hydraulic conductivity

increases in an almost linear trend from approximately 10^{-7} m/s at 50 cm depth to approximately 10^{-5} m/s at a depth of 300 cm. Pedogenic clay infillings show an inverse relationship, with approximately 50% less infilling present at 300 cm as compared to at a depth of 50 cm. Hydraulic conductivity for the KS-1 site has many pronounced inflections at these depths, whereas the North Carolina site has a subdued predictable change in K_{sat} when compared to pedogenic clay distribution. This difference is largely due to the homogeneity that exists in the crystalline saprolite when compared to the many sedimentary saprolite lithologies present at the KS-1 site.

6. Conclusions and Implications

The results of this study indicate that macropores are occluded with pedogenic clay and Fe/Mn oxides at a depth of 0.5 to 1 m. This decrease in hydraulic conductivity is found in all depth profiles regardless of lithology and can cause perched water table conditions that could result in a storm-flow zone as previously mentioned by Solomon et al. (1992). Below this 0.5 to 1 m low K zone pedogenic clay and hydraulic conductivity distribution varies, both being partly a function of lithology. Pedogenic clay is found to the bottom of this pit (3.4 m) and is largely confined to the limestone saprolite lithology, whereas, hydraulic conductivity seems to be randomly distributed due to influences of Pedogenic clay, Fe/Mn oxides, bulk porosity,, and random macropores.

As a result of these findings previous ORR and North Carolina research could be applied to this site, and possibly others for flow down to about 1 m; below this depth, hydrologic models to date should not be applied on a broad basis for interpreting hydrology of the saprolite in the sedimentary rocks comprising the Valley and Ridge province, or even to the Maryville Limestone specifically. Additional work must be done to examine the effect of differing lithology and possible influence on recharge before a working model can be put into place. However, this study and the hydrologic work performed in saprolite thus far should be considered when searching for appropriate storage locations for contaminants, such as hazardous waste sites and underground storage tanks. This is useful for predicting subsequent hydrologic behavior in this material before reaching the water table.

7. Suggestions for Future Research

Future work could use this study as an example for basic research methodology, but should consider applying it to different sites in different lithologies. Other considerations should be: 1) Employing geochemical analysis to determine if clay mineralogy and clay distribution with depth plays an important role in the observed storm-flow zone, i.e., clays in the storm flow zone may be more smectitic than clays deeper in the profile, 2) Excavating pits on different slope positions to determine if fluctuations in the storm-flow zone depth exist as a function of slope position, and, what consequences slope position has on pedogenic clay distribution deeper into the profile, 3) Excavating deeper pits to determine the extent of pedogenic clay distribution with depth and especially clay distribution above the water table, e.g., would a six meter pit have clay infillings occurring all the way down to the base of the pit?, 4) Conducting field infiltration tests using a pore coating dye, before pit excavation, in order to determine which pores are conductive, and more importantly, which lithologies are conductive, because thin sections do not always provide unequivocal evidence, and, 5) Better correlating hydraulic conductivity profiles to lithology.

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APPENDICES

Appendix A: Vertical Profiles of Hydraulic Conductivity

Tension Disc Infiltrometer

A series of hydraulic conductivity values, $K(\psi)$, at tensions of 0, 5, and 14 cm, were measured with the tension disc infiltrometer at depths from 20 to 300 cm, approximately 20 cm apart, below the ground surface.

Equations (Ankeny et al., 1991):

$$K(\Psi_1) = Q(\Psi_1) \left/ \left[\pi r^2 + \frac{4r}{\left(\frac{2[Q(\Psi_1) - Q(\Psi_2)]}{\Delta\Psi[Q(\Psi_1) + Q(\Psi_2)]} \right)} \right] \right.$$

$$K(\Psi_2) = Q(\Psi_2) \left/ \left[\pi r^2 + \frac{4r}{\left(\frac{2[Q(\Psi_1) - Q(\Psi_2)]}{\Delta\Psi[Q(\Psi_1) + Q(\Psi_2)]} \right)} \right] \right.$$

Where:

r = the radius of the tension disc in contact with the soil

$Q(\psi_1)$ = the steady state discharge at the lowest tension

$Q(\psi_2)$ = the steady state discharge at the next lowest tension

ψ = water tension (cm)

NW side of the pit

Depth = 19cm	Measurement # 3			
Material = Soil with sapro. Frag.				
<u>Q (Ψ1) (cm³/m)</u>	<u>Q(Ψ2) (cm³/m)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
339.33	1.1	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
1.080121969	0.00018002			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.003501412	5.83569E-07			

Depth = 19cm	Measurement # 3			
Material = Soil with sapro. Frag.				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.1	0.712	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.003536998	5.895E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002289402	3.81567E-07			
Depth = 40cm	Measurement # 7			
Material = Soil with sapro. Frag.				
<u>Q (Ψ1) (cm³/m)</u>	<u>Q(Ψ2) (cm³/m)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
68.575	0.77	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.21828178	3.63803E-05			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002450995	4.08499E-07			
Depth = 40cm	Measurement # 7			
Material = Soil with sapro. Frag.				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
0.77	0.218	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.002483195	4.13866E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.000703035	1.17172E-07			
Depth = 67cm	Measurement # 2			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
9.46	1.98	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.030116622	5.01944E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.006303479	1.05058E-06			

Depth = 67cm	Measurement # 2			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.98	0.698	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.006315553	1.05259E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002226392	3.71065E-07			
Depth = 94cm	Measurement # 5			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
53.92	1.47	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.171633588	2.86056E-05			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.00467918	7.79863E-07			
Depth = 94cm	Measurement # 5			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.47	0.669	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004698557	7.83093E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002138323	3.56387E-07			
Depth = 120cm	Measurement # 9			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
6.858	2.834	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.021836839	3.63947E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.009023856	1.50398E-06			

Depth = 120cm	Measurement # 9			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
2.834	0.654	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.009029309	1.50488E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002083687	3.47281E-07			
Depth = 158cm	Measurement # 1			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
21.28	13.01	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.067739442	1.12899E-05			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.041414011	6.90234E-06			
Depth = 158cm	Measurement # 1			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
13.01	3.55	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.041414021	6.90234E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.011300521	1.88342E-06			
Depth = 188cm	Measurement # 4			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
15.37	5.68	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.048927325	8.15455E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			

0.018081145	3.01352E-06			
Depth = 188cm	Measurement # 4			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
5.68	1.35	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.018084219	3.01404E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.004298186	7.16364E-07			
Depth = 200cm	Measurement # 8			
Material = Carbonate Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
7.494	2.035	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.023860003	3.97667E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.006479198	1.07987E-06			
Depth = 200cm	Measurement # 8			
Material = Carbonate Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
2.035	0.494	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.00648939	1.08157E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.001575311	2.62552E-07			
Depth = 220cm	Measurement # 10			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
18.444	4.493	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.058711461	9.78524E-06			

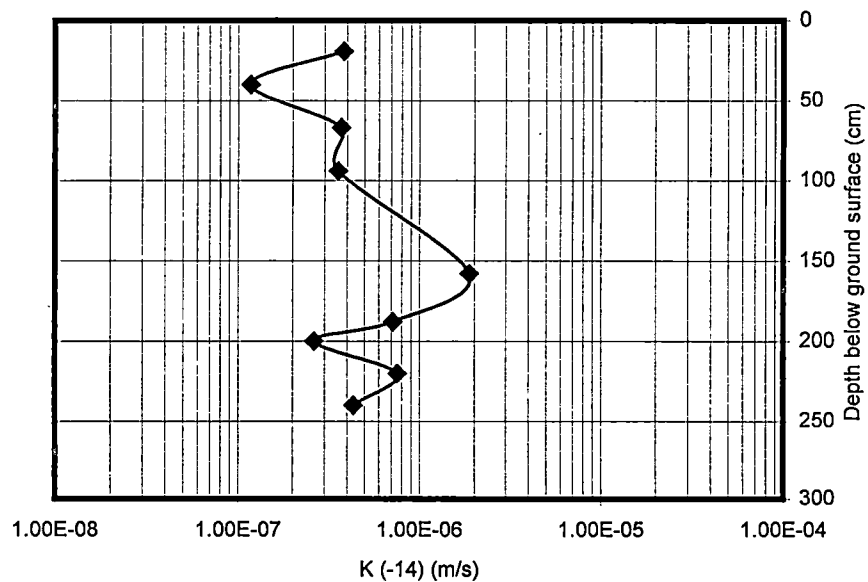
K (Ψ 2) (cm/min)	K (Ψ 2) (m/s)			
0.014302244	2.38371E-06			
Depth = 220cm	Measurement # 10			
Material = Carbonate/Shale Saprolite				
Q (Ψ 1) (cm ³ /min)	Q(Ψ 2) (cm ³ /min)	Disc Radius (cm)	Ψ 1	Ψ 2
4.493	1.424	10	5	14
K (Ψ 1) (cm/min)	K (Ψ 1) (m/s)			
0.014307248	2.38454E-06			
K (Ψ 2) (cm/min)	K (Ψ 2) (m/s)			
0.004534503	7.5575E-07			
Depth = 240cm	Measurement # 11			
Material = Mostly Carbonate Saprolite				
Q (Ψ 1) (cm ³ /min)	Q(Ψ 2) (cm ³ /min)	Disc Radius (cm)	Ψ 1	Ψ 2
6.148	2.136	10	0	5
K (Ψ 1) (cm/min)	K (Ψ 1) (m/s)			
0.019577208	3.26287E-06			
K (Ψ 2) (cm/min)	K (Ψ 2) (m/s)			
0.006801711	1.13362E-06			
Depth = 240cm	Measurement # 11			
Material = Mostly Carbonate Saprolite				
Q (Ψ 1) (cm ³ /min)	Q(Ψ 2) (cm ³ /min)	Disc Radius (cm)	Ψ 1	Ψ 2
2.136	0.814	10	5	14
K (Ψ 1) (cm/min)	K (Ψ 1) (m/s)			
0.006811459	1.13524E-06			
K (Ψ 2) (cm/min)	K (Ψ 2) (m/s)			
0.002595753	4.32625E-07			

Summary Table:

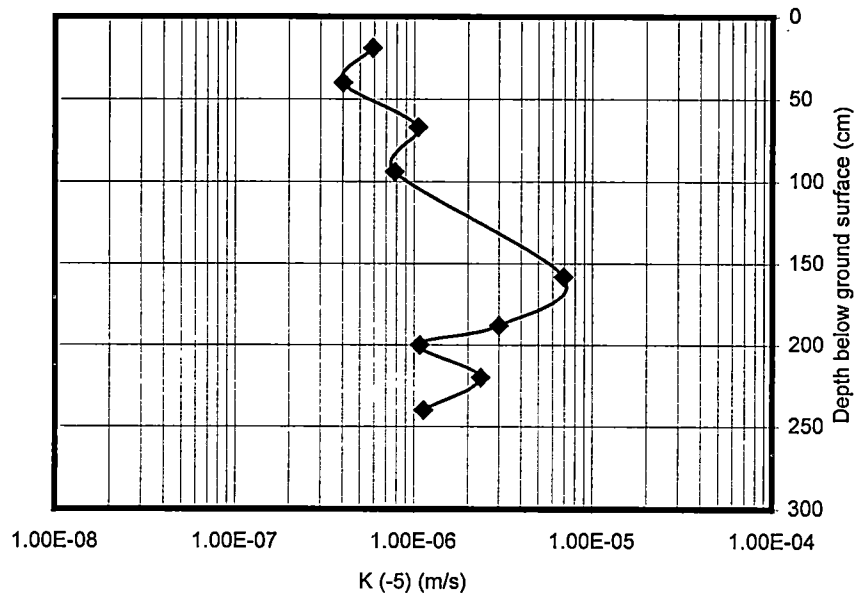
NW Side T.I. Data			
Depth	K (0) (m/s)	K (-5) (m/s)	K (-14) (m/s)
19	0.00018	5.87E-07	3.82E-07
40	3.64E-05	4.01E-07	1.17E-07
67	5.02E-06	1.05E-06	3.71E-07
94	2.86E-05	7.81E-07	3.56E-07
158	1.13E-05	6.90E-06	1.88E-06
188	8.15E-06	3.01E-06	7.16E-07
200	3.98E-06	1.08E-06	2.63E-07
220	9.79E-06	2.38E-06	7.56E-07
240	3.26E-06	1.13E-06	4.33E-07

Graphs:

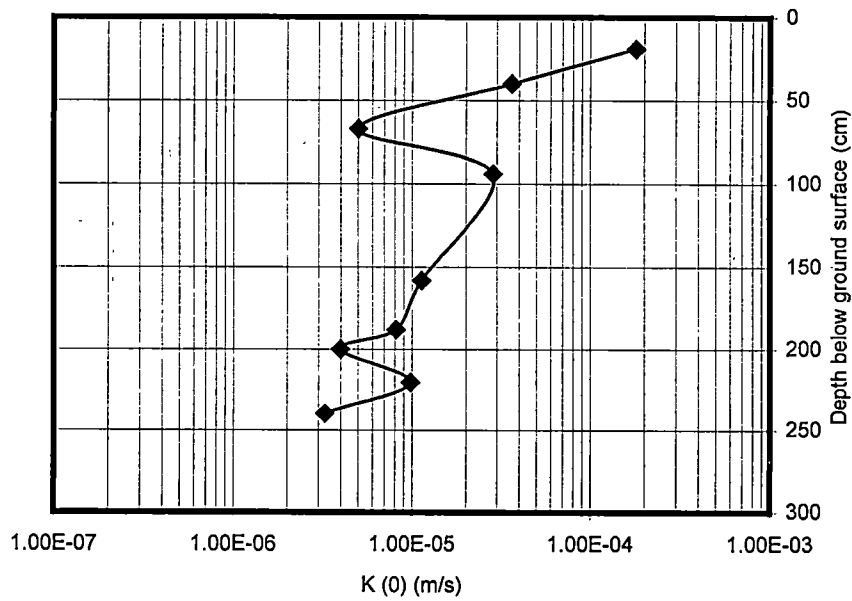
NW side of the pit, T.I. Data (14 cm tension)



NW side of the pit, T.I. Data (5 cm tension)



NW side of the pit, T.I. Data (0 cm tension)



SE Side of the pit				
Depth = 27cm	Measurement # 12			
Material = Soil with Saprolite Fragments				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
88.675	0.538	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.282261987	4.70437E-05			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.001712511	2.85419E-07			
Depth = 27cm	Measurement # 12			
Material = Soil with Saprolite Fragments				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
0.538	0.262	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.001769186	2.94864E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.000861574	1.43596E-07			
Depth = 40cm	Measurement # 14			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
8.98	1.45	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.028588887	4.76481E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.004616246	7.69374E-07			
Depth = 40cm	Measurement # 14			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.45	0.52	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			

0.004633386	7.72231E-07			
K (Ψ2) (cm/min)	K (Ψ2) (m/s)			
0.001661628	2.76938E-07			
Depth = 60cm	Measurement # 17			
Material = Shale Saprolite				
Q (Ψ1) (cm ³ /min)	Q(Ψ2) (cm ³ /min)	Disc Radius (cm)	Ψ1	Ψ2
1.09	0.872	10	0	5
K (Ψ1) (cm/min)	K (Ψ1) (m/s)			
0.003576033	5.96006E-07			
K (Ψ2) (cm/min)	K (Ψ2) (m/s)			
0.002860827	4.76804E-07			
Depth = 60cm	Measurement # 17			
Material = Shale Saprolite				
Q (Ψ1) (cm ³ /min)	Q(Ψ2) (cm ³ /min)	Disc Radius (cm)	Ψ1	Ψ2
0.872	0.698	10	5	14
K (Ψ1) (cm/min)	K (Ψ1) (m/s)			
0.002849446	4.74908E-07			
K (Ψ2) (cm/min)	K (Ψ2) (m/s)			
0.002280864	3.80144E-07			
Depth = 80cm	Measurement # 13			
Material = Mostly Shale Saprolite				
Q (Ψ1) (cm ³ /min)	Q(Ψ2) (cm ³ /min)	Disc Radius (cm)	Ψ1	Ψ2
10.641	1.453	10	0	5
K (Ψ1) (cm/min)	K (Ψ1) (m/s)			
0.033875265	5.64588E-06			
K (Ψ2) (cm/min)	K (Ψ2) (m/s)			
0.004625577	7.70929E-07			
Depth = 80cm	Measurement # 13			
Material = Mostly Shale Saprolite				
Q (Ψ1) (cm ³ /min)	Q(Ψ2) (cm ³ /min)	Disc Radius (cm)	Ψ1	Ψ2
1.453	0.387	10	5	14

<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004641786	7.73631E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.001236319	2.06053E-07			
Depth = 100cm	Measurement # 19			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
6.38	1.28	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.020314809	3.3858E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.004075698	6.79283E-07			
Depth = 100cm	Measurement # 19			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.28	0.65	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004098212	6.83035E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002081123	3.46854E-07			
Depth = 120cm	Measurement # 21			
Material = Mostly Shale Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
2.84	1.31	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.009058172	1.5097E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.004178241	6.96374E-07			
Depth = 120cm	Measurement # 21			
Material = Mostly Shale Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.31	0.97	10	5	14

<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004208263	7.01377E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.003116042	5.1934E-07			
Depth = 140cm	Measurement # 23			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
4.73	3.55	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.015075716	2.51262E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.011314755	1.88579E-06			
Depth = 140cm	Measurement # 23			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
3.55	1.13	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.011307072	1.88451E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.003599153	5.99859E-07			
Depth = 162cm	Measurement # 6			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
5.675	4.7	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.018086867	3.01448E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.014979432	2.49657E-06			
Depth = 162cm	Measurement # 6			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>

4.7	1.73	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.014966121	2.49435E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.005508806	9.18134E-07			
Depth = 180cm	Measurement # 15			
Material = Shale/Siltstone Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
5.2	2.98	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.016563742	2.76062E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.009492298	1.58205E-06			
Depth = 180cm	Measurement # 15			
Material = Shale/Siltstone Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
2.98	1.08	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.009494349	1.58239E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.003440905	5.73484E-07			
Depth = 200cm	Measurement # 16			
Material = Carbonate Saprolite				
<u>Q (Ψ1) (cm^3/min)</u>	<u>Q(Ψ2) (cm^3/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
2.84	1.54	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.009060268	1.51004E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.004912962	8.18827E-07			
Depth = 200cm	Measurement # 16			
Material = Carbonate Saprolite				

<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.54	0.625	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004919543	8.19924E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.001996568	3.32761E-07			
Depth = 220cm	Measurement # 18			
Material = Ribbon Carbonate Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
2.84	1.34	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.009058403	1.50973E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.004274035	7.12339E-07			
Depth = 220cm	Measurement # 18			
Material = Ribbon Carbonate Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.34	0.8	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004291626	7.15271E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002562165	4.27027E-07			
Depth = 240cm	Measurement # 20			
Material = Mostly Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
5.2	2.6	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.016562527	2.76042E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.008281263	1.38021E-06			
Depth = 240cm	Measurement # 20			

Material = Mostly Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
2.6	1.74	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.008291778	1.38196E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.005549113	9.24852E-07			
Depth = 260cm	Measurement # 22			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
18.68	15.13	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.059466645	9.91111E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.048165436	8.02757E-06			
Depth = 260cm	Measurement # 22			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
15.13	4.21	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.04816194	8.02699E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.013401306	2.23355E-06			
Depth = 280cm	Measurement # 24			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
21.28	15.37	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.067740383	1.12901E-05			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.048927147	8.15452E-06			

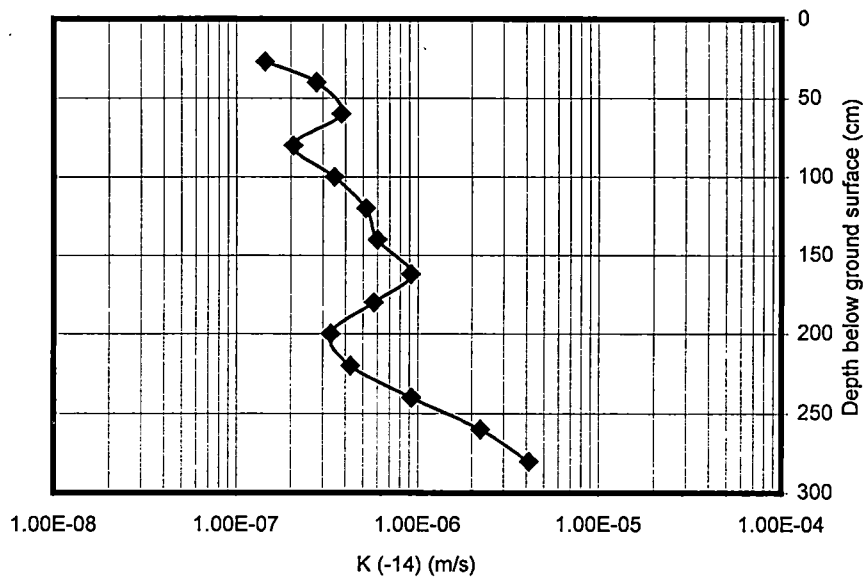
Depth = 280cm	Measurement # 24			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
15.37	7.8	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.048926244	8.15437E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.024829193	4.1382E-06			

Summary Table:

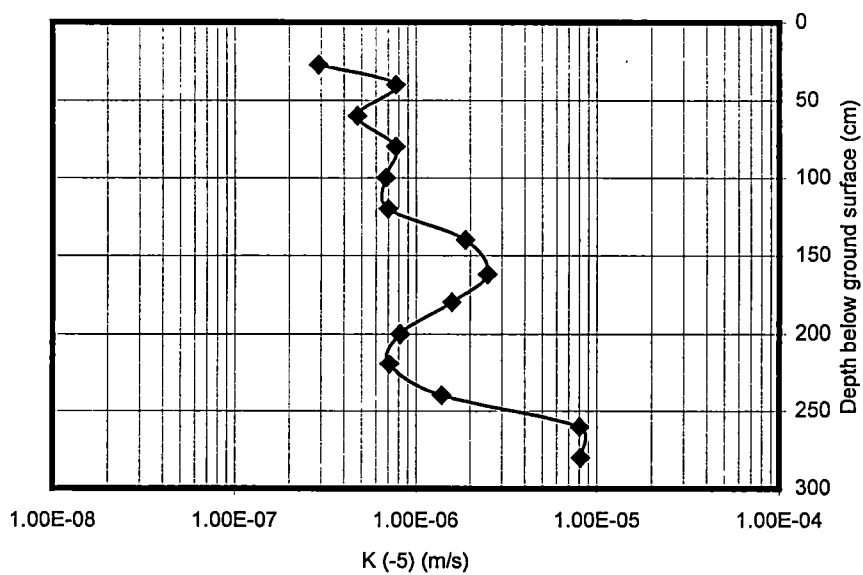
SE Side			
T.I. DATA			
<u>Depth</u>	<u>K (0) (m/s)</u>	<u>K (-5) (m/s)</u>	<u>K (-14) (m/s)</u>
27	4.70E-05	2.90E-07	1.44E-07
40	4.76E-06	7.71E-07	2.77E-07
60	5.96E-07	4.75E-07	3.80E-07
80	5.65E-06	7.71E-07	2.06E-07
100	3.39E-06	6.81E-07	3.47E-07
120	1.51E-06	7.00E-07	5.19E-07
140	2.51E-06	1.88E-06	5.99E-07
162	3.01E-06	2.49E-06	9.18E-07
180	2.76E-06	1.58E-06	5.73E-07
200	1.51E-06	8.18E-07	3.33E-07
220	1.51E-06	7.13E-07	4.27E-07
240	2.76E-06	1.38E-06	9.25E-07
260	9.91E-06	8.03E-06	2.23E-06
280	1.13E-05	8.15E-06	4.14E-06

Graphs:

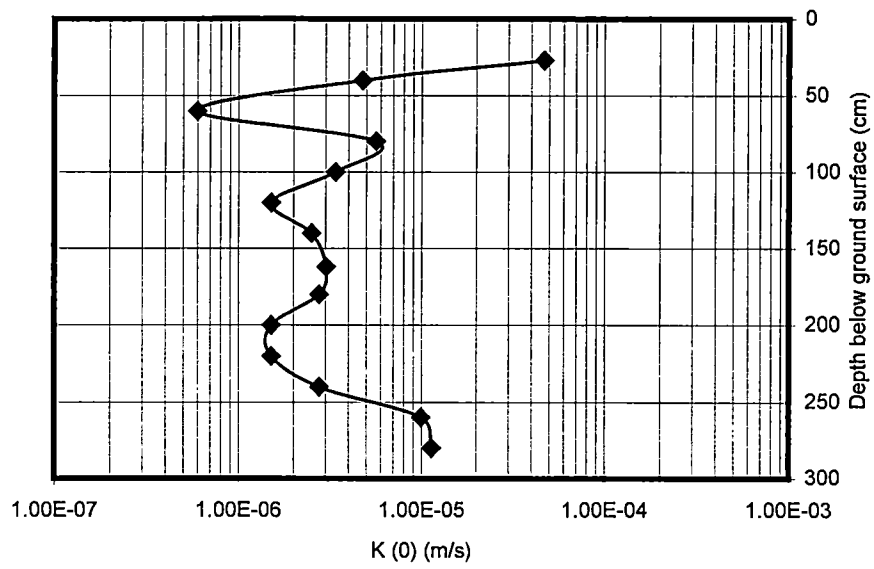
SE side of the pit, T.I. data (14 cm tension)



Left Side T.I. data (5 cm tension)



Left Side T.I. Data (0 cm tension)



Appendix B: Horizontal Variability of Hydraulic Conductivity

A series of hydraulic conductivity values, $K(\psi)$, at tensions of 0, 5, and 14cm, were measured with the tension disc infiltrometer at depths of 60 and 100 cm below ground surface to measure horizontal variability of hydraulic conductivity.

Equations (Ankeny et al., 1991):

$$K(\Psi_1) = Q(\Psi_1) / \left[\pi r^2 + \frac{4r}{\left(\frac{2[Q(\Psi_1) - Q(\Psi_2)]}{\Delta\Psi[Q(\Psi_1) + Q(\Psi_2)]} \right)} \right]$$

$$K(\Psi_2) = Q(\Psi_2) / \left[\pi r^2 + \frac{4r}{\left(\frac{2[Q(\Psi_1) - Q(\Psi_2)]}{\Delta\Psi[Q(\Psi_1) + Q(\Psi_2)]} \right)} \right]$$

Where:

r = the radius of the tension disc in contact with the soil

$Q(\psi_1)$ = the steady state discharge at the lowest tension

$Q(\psi_2)$ = the steady state discharge at the next lowest tension

ψ = water tension (cm)

Horizontal Measurements				
NW Side				
Depth = 100cm	Measurement # 19			
Material = Carbonate/Shale Saprolite				
$Q(\Psi_1)$ (cm ³ /min)	$Q(\Psi_2)$ (cm ³ /min)	Disc Radius (cm)	Ψ_1	Ψ_2
6.38	1.28	10	0	5
$K(\Psi_1)$ (cm/min)	$K(\Psi_1)$ (m/s)			
0.020314809	3.3858E-06			
$K(\Psi_2)$ (cm/min)	$K(\Psi_2)$ (m/s)			
0.004075698	6.79283E-07			

Depth = 100cm	Measurement # 19			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.28	0.65	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004098212	6.83035E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002081123	3.46854E-07			
Depth = 100cm	Measurement # 25			
Material = Shale/Carbonate Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.42	1.18	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004614154	7.69026E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.003834297	6.39049E-07			
Depth = 100cm	Measurement # 25			
Material = Shale/Carbonate Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.18	0.843	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.00379544	6.32573E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002711488	4.51915E-07			
Depth = 100cm	Measurement # 26			
Material = Carbonate Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
0.96	0.713	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.003152925	5.25487E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002341704	3.90284E-07			

Depth = 100cm	Measurement # 26			
Material = Carbonate Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
0.713	0.61	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.002393811	3.98969E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002048001	3.41334E-07			
Depth = 94cm	Measurement # 5			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
53.92	1.47	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.171633588	2.86056E-05			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.00467918	7.79863E-07			
Depth = 94cm	Measurement # 5			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.47	0.669	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004698557	7.83093E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002138323	3.56387E-07			
Depth = 60cm	Measurement # 17			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.09	0.872	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.003576033	5.96006E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002860827	4.76804E-07			

Depth = 60cm	Measurement # 17			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
0.872	0.698	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.002849446	4.74908E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.002280864	3.80144E-07			
Depth = 60cm	Measurement # 27			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
100.5	0.97	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.319902109	5.3317E-05			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.003087612	5.14602E-07			
Depth = 60cm	Measurement # 27			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
0.97	0.174	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.00311178	5.1863E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.000558196	9.30326E-08			
Depth = 60cm	Measurement # 28			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
5.21	1.43	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.016592376	2.7654E-06			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			

0.004554145	7.59024E-07			
Depth = 60cm	Measurement # 28			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.43	0.35	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004568646	7.61441E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.0011182	1.86367E-07			
Depth = 60cm	Measurement # 29			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
21.28	1.53	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.067738315	1.12897E-05			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.004870283	8.11714E-07			
Depth = 60cm	Measurement # 29			
Material = Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
1.53	1.02	10	5	14
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.004896779	8.1613E-07			
<u>K (Ψ2) (cm/min)</u>	<u>K (Ψ2) (m/s)</u>			
0.00326452	5.44087E-07			
Depth = 67cm	Measurement # 2			
Material = Carbonate/Shale Saprolite				
<u>Q (Ψ1) (cm³/min)</u>	<u>Q(Ψ2) (cm³/min)</u>	<u>Disc Radius (cm)</u>	<u>Ψ1</u>	<u>Ψ2</u>
9.46	1.98	10	0	5
<u>K (Ψ1) (cm/min)</u>	<u>K (Ψ1) (m/s)</u>			
0.030116622	5.01944E-06			

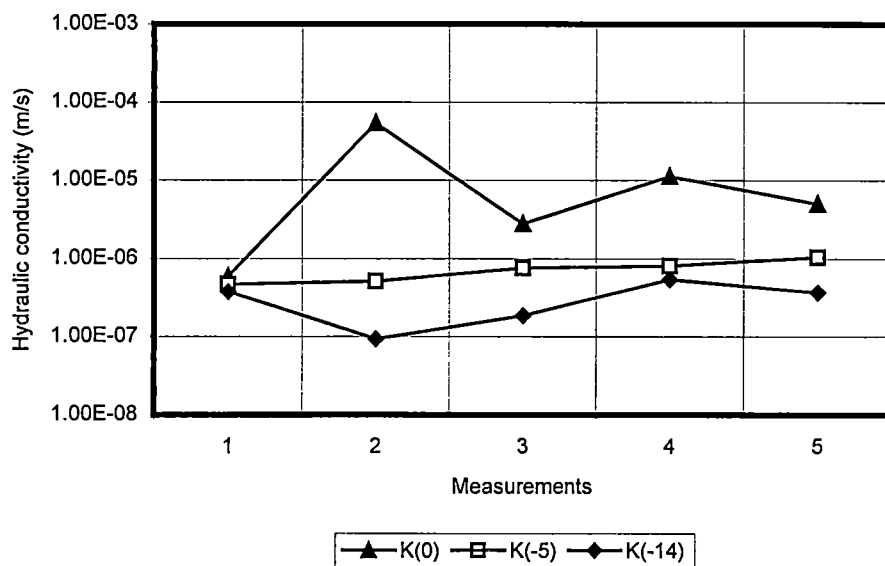
K (Ψ_2) (cm/min)	K (Ψ_2) (m/s)			
0.006303479	1.05058E-06			
Depth = 67cm	Measurement # 2			
Material = Carbonate/Shale Saprolite				
Q (Ψ_1) (cm ³ /min)	Q(Ψ_2) (cm ³ /min)	Disc Radius (cm)	Ψ_1	Ψ_2
1.98	0.698	10	5	14
K (Ψ_1) (cm/min)	K (Ψ_1) (m/s)			
0.006315553	1.05259E-06			
K (Ψ_2) (cm/min)	K (Ψ_2) (m/s)			
0.002226392	3.71065E-07			

Summary Table:

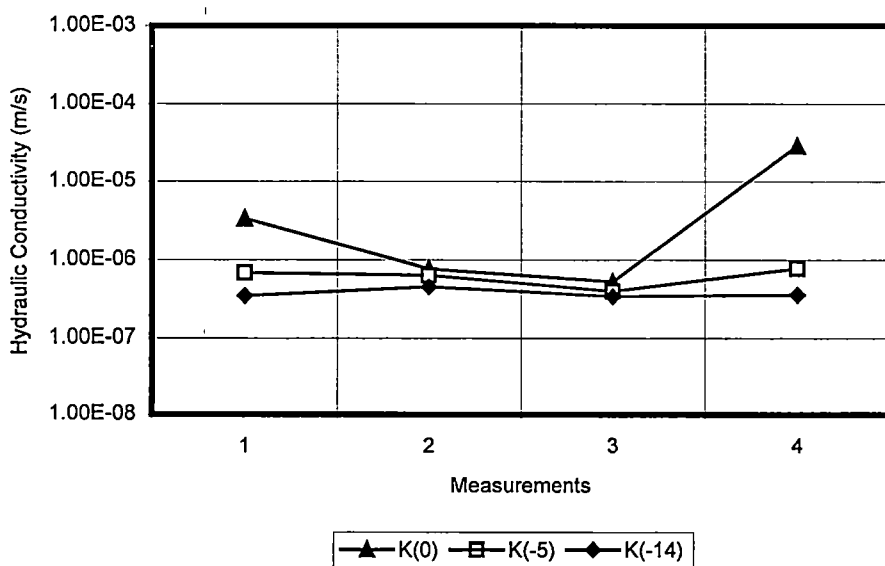
		Depth 100cm	
meas.	K (0) (m/s)	K (-5) (m/s)	K (-14) (m/s)
19	3.39E-06	6.81E-07	3.47E-07
25	7.69E-07	6.35E-07	4.52E-07
26	5.25E-07	3.94E-07	3.41E-07
5	2.86E-05	7.81E-07	3.56E-07
		Depth 60cm	
meas.	K (0) (m/s)	K (-5) (m/s)	K (-14) (m/s)
17	5.96E-07	4.75E-07	3.80E-07
27	5.33E-05	5.16E-07	9.30E-08
28	2.77E-06	7.60E-07	1.86E-07
29	1.12E-05	8.14E-07	5.44E-07
2	5.02E-06	1.05E-06	3.71E-07

Graphs:

Horizontal profile at 60 cm depth b.g.s.



Horizontal profile at 100 cm depth b.g.s.



Appendix C: Vertical Compact Constant Head Permeameter (CCHP) Profiles

A series of K_{sat} profiles measured with the CCHP from 20 cm to 300 cm depth below the ground surface, at intervals of approximately 20cm.

Equation (Amoozegar, 1989):

$$K_{sat} = \frac{Q \left[\sinh^{-1} \left(\frac{H}{r} \right) - \sqrt{\frac{r^2}{H^2 + 1}} + \frac{r}{H} \right]}{2\pi H^2}$$

Where:

r = the radius of the borehole

H = the height of water in the borehole

Q = the discharge obtained under steady-state flow conditions

	NW side of pit				
Depth = 24cm	Measurement # A1	09/18/2000			
Material = Soil with saprolite fragments					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
49	10	3		0.092	1.5269E-05
52.5	10	3		0.098	1.636E-05
52.5	10	3		0.098	1.636E-05
				K (avg) (m/s)=	1.5996E-05
Depth = 40cm	Measurement # A4	09/19/2000			
Material = Soil with saprolite fragments					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
7.4	11	3		0.012	2.0223E-06
8	11	3		0.013	2.1863E-06
8.2	11	3		0.013	2.2409E-06

				K (avg) (m/s)=	2.1498E-06
Depth = 60cm	Measurement # A5	09/27/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
2.2	13.5	3		0.003	4.5054E-07
2	13.5	3		0.002	4.0958E-07
2.2	13.5	3		0.003	4.5054E-07
				K (avg) (m/s)=	4.3688E-07
Depth = 80cm	Measurement # A7	09/20/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
1.4	14	3		0.002	2.7214E-07
1.4	14	3		0.002	2.7214E-07
1.4	14	3		0.002	2.7214E-07
				K (avg) (m/s)=	2.7214E-07
Depth = 100cm	Measurement # A11	09/28/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
0.6	9	3		0.001	2.1566E-07
0.8	9	3		0.002	2.8755E-07
0.6	9	3		0.001	2.1566E-07
				K (avg) (m/s)=	2.3962E-07
Depth = 120cm	Measurement # A15	10/02/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
1.8	12	3		0.003	4.3562E-07
2	12	3		0.003	4.8403E-07

2.2	12	3		0.003	5.3243E-07
				K (avg) (m/s)=	4.8403E-07
Depth = 140cm	Measurement # A18	10/03/2000			
Material = Saprolite, Fragmented					
<u>Q (cm^3/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
2	7.5	3		0.005	9.1494E-07
2.6	7.5	3		0.007	1.1894E-06
2.2	7.5	3		0.006	1.0064E-06
				K (avg) (m/s)=	1.0369E-06
Depth = 200cm	Measurement # A2	09/18/2000			
Material = Saprolite, Fragmented					
<u>Q (cm^3/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
4	13	3		0.005	8.6445E-07
4.4	13	3		0.006	9.509E-07
4.4	13	3		0.006	9.509E-07
				K (avg) (m/s)=	9.2208E-07
Depth = 220cm	Measurement # A3	09/19/2000			
Material = Saprolite, Fragmented					
<u>Q (cm^3/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
3.8	15	3		0.004	6.6862E-07
4	15	3		0.004	7.0381E-07
4	15	3		0.004	7.0381E-07
				K (avg) (m/s)=	6.9208E-07
Depth = 240cm	Measurement # A6	09/20/2000			

Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
6.6	15	3		0.007	1.1613E-06
6.6	15	3		0.007	1.1613E-06
6.4	15	3		0.007	1.1261E-06
				K (avg) (m/s)=	1.1496E-06
Depth = 260cm	Measurement # A8	09/27/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
18.9	14	3		0.022	3.6739E-06
18.9	14	3		0.022	3.6739E-06
18.9	14	3		0.022	3.6739E-06
				K (avg) (m/s)=	3.6739E-06
Depth = 280cm	Measurement # A12	09/28/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
3.4	9.5	3		0.007	1.1361E-06
4	9.5	3		0.008	1.3366E-06
4	9.5	3		0.008	1.3366E-06
				K (avg) (m/s)=	1.2697E-06
Depth = 295cm	Measurement # A16	10/02/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
15.75	11	3		0.026	4.3042E-06
15.75	11	3		0.026	4.3042E-06
16.8	11	3		0.028	4.5912E-06
				K (avg) (m/s)=	4.3999E-06

Summary Table:

NW side of pit	
Depth Below Ground surface	Ksat (m/s)
24	1.60E-05
40	2.15E-06
60	4.37E-07
80	2.72E-07
100	2.40E-07
120	4.84E-07
140	1.04E-06
200	9.22E-07
220	6.92E-07
240	1.15E-06
260	3.67E-06
280	1.27E-06
295	4.40E-06

	SE side of Pit				
Depth = 20cm	Measurement # A9	09/27/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
140.7	9.5	3		0.282	4.7014E-05
138.6	9.5	3		0.278	4.6312E-05
140.7	9.5	3		0.282	4.7014E-05
				K (avg) (m/s)=	4.678E-05
Depth = 40cm	Measurement # A14	09/28/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
105	10	3		0.196	3.2719E-05
100.8	10	3		0.188	3.1411E-05

102.9	10	3		0.192	3.2065E-05
				K (avg) (m/s)=	3.2065E-05
Depth = 60cm	Measurement # A19	10/03/2000			
Material = Saprolite, Fragmented					
<u>Q (cm^3/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
7.2	11	3		0.012	1.9676E-06
7.6	11	3		0.012	2.077E-06
8	11	3		0.013	2.1863E-06
				K (avg) (m/s)=	2.077E-06
Depth = 100cm	Measurement # A21	10/04/2000			
Material = Saprolite, Fragmented					
<u>Q (cm^3/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
1	14	3		0.001	1.9439E-07
1	14	3		0.001	1.9439E-07
1	14	3		0.001	1.9439E-07
				K (avg) (m/s)=	1.9439E-07
Depth = 120cm	Measurement # A23	10/06/2000			
Material = Saprolite, Fragmented					
<u>Q (cm^3/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
1.6	15	3		0.002	2.8153E-07
1.6	15	3		0.002	2.8153E-07
1.8	15	3		0.002	3.1672E-07
				K (avg) (m/s)=	2.9326E-07
Depth = 140cm	Measurement # A24	10/09/2000			
Material = Saprolite, Fragmented					

<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
2	14	3		0.002	3.8877E-07
1.8	14	3		0.002	3.4989E-07
1.8	14	3		0.002	3.4989E-07
				K (avg) (m/s)=	3.6285E-07
Depth = 160cm	Measurement # A25	10/09/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
2.6	15	3		0.003	4.5748E-07
2.8	15	3		0.003	4.9267E-07
2.6	15	3		0.003	4.5748E-07
				K (avg) (m/s)=	4.6921E-07
Depth = 180cm	Measurement # A26	10/10/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
0.6	14	3		0.001	1.1663E-07
0.2	14	3		0.000	3.8877E-08
0.2	14	3		0.000	3.8877E-08
				K (avg) (m/s)=	6.4795E-08
Depth = 200cm	Measurement # A10	09/27/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
1	14	3		0.001	1.9439E-07
1	14	3		0.001	1.9439E-07
0.8	14	3		0.001	1.5551E-07
				K (avg) (m/s)=	1.8143E-07

Depth = 220cm	Measurement # A13	09/28/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
1.2	20	3		0.001	1.3803E-07
1.2	20	3		0.001	1.3803E-07
1	20	3		0.001	1.1502E-07
				K (avg) (m/s)=	1.3036E-07
Depth = 240cm	Measurement # A17	10/02/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
1.4	15	3		0.001	2.4633E-07
1.2	15	3		0.001	2.1114E-07
1.4	15	3		0.001	2.4633E-07
				K (avg) (m/s)=	2.346E-07
Depth = 260cm	Measurement # A20	10/03/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
15.75	15	3		0.017	2.7713E-06
15.75	15	3		0.017	2.7713E-06
15.75	15	3		0.017	2.7713E-06
				K (avg) (m/s)=	2.7713E-06
Depth = 280cm	Measurement # A22	10/04/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
10.5	10	3		0.020	3.2719E-06
10.5	10	3		0.020	3.2719E-06
10.5	10	3		0.020	3.2719E-06

				K (avg) (m/s)=	3.2719E-06

Summary Table:

SE side of pit	
Depth Below Ground surface	Ksat (m/s)
20	4.68E-05
40	3.21E-05
60	2.08E-06
100	1.94E-07
120	2.93E-07
140	3.63E-07
160	4.69E-07
180	6.48E-08
200	1.81E-07
220	1.03E-07
240	2.35E-07
260	2.77E-06
280	3.27E-06

	Behind Pit Face				
Depth = 20cm	Measurement # A34	10/23/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
25.2	18	3		0.020	3.3928E-06
27.3	18	3		0.022	3.6755E-06
26.3	18	3		0.021	3.5409E-06
				K (avg) (m/s)=	3.5364E-06
Depth = 40cm	Measurement # A37	10/25/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
85.1	15	3		0.090	1.4974E-05

86.1	15	3		0.091	1.515E-05
87.2	15	3		0.092	1.5343E-05
				K (avg) (m/s)=	1.5155E-05
Depth = 60cm	Measurement # A39	10/30/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
19.95	19	3		0.015	2.4781E-06
19.95	19	3		0.015	2.4781E-06
21	19	3		0.016	2.6085E-06
				K (avg) (m/s)=	2.5216E-06
Depth = 80cm	Measurement # A40	10/31/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
5.8	16.5	3		0.005	8.8797E-07
6.2	16.5	3		0.006	9.492E-07
6.6	16.5	3		0.006	1.0104E-06
				K (avg) (m/s)=	9.492E-07
Depth = 100cm	Measurement # A41	11/01/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
2	21	3		0.001	2.1373E-07
2	21	3		0.001	2.1373E-07
2	21	3		0.001	2.1373E-07
				K (avg) (m/s)=	2.1373E-07
Depth = 120cm	Measurement # A32	10/19/2000			

Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
36.75	8	3		0.093	1.545E-05
35.7	8	3		0.090	1.5008E-05
35.7	8	3		0.090	1.5008E-05
				K (avg) (m/s)=	1.5155E-05
Depth = 140cm	Measurement # A33	10/23/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
0.8	10.5	3		0.001	2.3315E-07
0.8	10.5	3		0.001	2.3315E-07
1	10.5	3		0.002	2.9144E-07
				K (avg) (m/s)=	2.5258E-07
Depth = 160cm	Measurement # A35	10/24/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
0.6	6	3		0.002	3.6496E-07
0.2	6	3		0.001	1.2165E-07
0.6	6	3		0.002	3.6496E-07
				K (avg) (m/s)=	2.8386E-07
Depth = 180cm	Measurement # A36	10/25/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
5	11	3		0.008	1.3664E-06
5	11	3		0.008	1.3664E-06
5.2	11	3		0.009	1.4211E-06
				K (avg) (m/s)=	1.3846E-06

Depth = 193cm	Measurement # A38	10/30/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
3.2	11	3		0.005	8.7451E-07
3.2	11	3		0.005	8.7451E-07
3	11	3		0.005	8.1985E-07
				K (avg) (m/s)=	8.5629E-07
Depth = 220cm	Measurement # A43	11/28/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
18.9	16	3		0.018	3.0271E-06
15.8	16	3		0.015	2.5306E-06
21	16	3		0.020	3.3634E-06
				K (avg) (m/s)=	2.9737E-06
Depth = 240cm	Measurement # A44	11/18/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
4	22	3		0.002	3.9835E-07
4	22	3		0.002	3.9835E-07
4	22	3		0.002	3.9835E-07
				K (avg) (m/s)=	3.9835E-07
Depth = 260cm	Measurement # A45	11/18/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
1.6	27	3		0.001	1.1633E-07
3.4	27	3		0.001	2.4721E-07
2	27	3		0.001	1.4542E-07

				K (avg) (m/s)=	1.6965E-07
Depth = 280cm	Measurement # A46	11/18/2000			
Material = Saprolite, Fragmented					
<u>Q (cm^3/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
4.4	26	3		0.002	3.3918E-07
3.6	26	3		0.002	2.7751E-07
3.6	26	3		0.002	2.7751E-07
				K (avg) (m/s)=	2.9807E-07

Summary Table:

Behind Pit CCHP DATA	
Depth Below Ground surface	Ksat (m/s)
20	3.54E-06
40	1.53E-05
60	2.52E-06
80	9.49E-07
100	2.14E-07
140	2.53E-07
160	2.84E-07
180	1.38E-06
193	8.56E-07
220	2.97E-06
240	3.98E-07
260	1.70E-07
280	2.98E-07

Appendix D: Comparison Between CCHP and Guelph Permeameter

Comparison between CCHP and Guelph permeameter using the same methods, i.e. the same borehole, same equation (below), and approximately the same constant head.

Equation (Amoozegar, 1989).

$$K_{sat} = \frac{Q \left[\sinh^{-1} \left(\frac{H}{r} \right) - \sqrt{\frac{r^2}{H^2 + 1}} + \frac{r}{H} \right]}{2\pi H^2}$$

Where:

r = the radius of the borehole

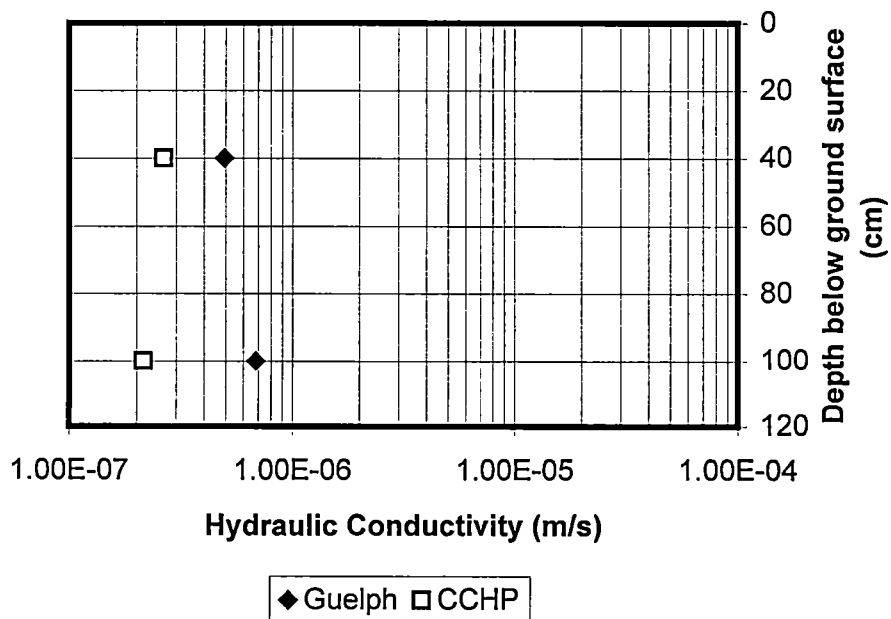
H = the height of water in the borehole

Q = the discharge obtained under steady-state flow conditions

Comparative measurements with CCHP and quelph permeameter					
Depth = 100cm	Measurement # A41	11/01/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
2	21	3		0.001	2.1373E-07
2	21	3		0.001	2.1373E-07
2	21	3		0.001	2.1373E-07
				K (avg) (m/s)=	2.1373E-07
Depth = 100cm	Measurement # G2	11/01/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
7.09	23	3		0.004	6.5985E-07
7.8	23	3		0.004	7.2593E-07
7.09	23	3		0.004	6.5985E-07
				K (avg) (m/s)=	6.8188E-07
Depth = 40cm	Measurement # A42	11/01/2000			
Material = Saprolite, Fragmented					

<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
2.2	17	3		0.002	3.2234E-07
1.6	17	3		0.001	2.3443E-07
1.6	17	3		0.001	2.3443E-07
				K (avg) (m/s)=	2.6373E-07
Depth = 40cm	Measurement # G1	11/01/2000			
Material = Saprolite, Fragmented					
<u>Q (cm³/min)</u>	<u>H (cm)</u>	<u>r (cm)</u>		<u>K (cm/min)</u>	<u>K (m/s)</u>
3.55	16	3		0.003	5.6858E-07
2.84	16	3		0.003	4.5486E-07
2.84	16	3		0.003	4.5486E-07
				K (avg) (m/s)=	4.9277E-07

Comparative study between Guelph and CCHP



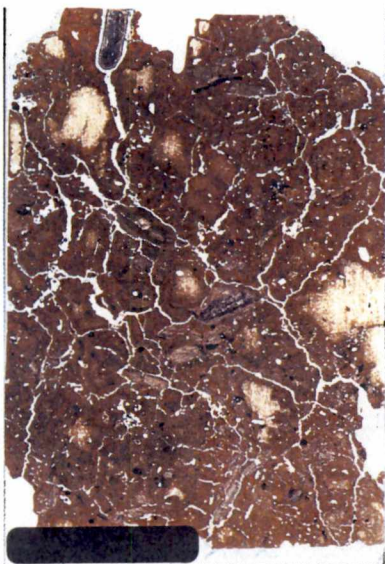
Appendix E: Thin Section Micrographs

All thin sections are 7.5 cm by 5 cm, images shown below are approximately 1:1. Up orientation is towards the top of the page. All images were scanned in on a flat-bed scanner with transparency attachment.

E.1. Thin sections were collected from a vertical sampling profile on the pit face, as shown on figure 6.



11-18 cm depth, Soil horizon EB, Silt Loam soil depicted in Figure 7 A.



38-45 cm depth, Soil horizon Bt, Clay Loam soil.



72-79 cm depth, BC horizon, ribbon limestone saprolite with abundant intraclastic silt lenses and shale/siltstone saprolite depicted in Figure 7 B.



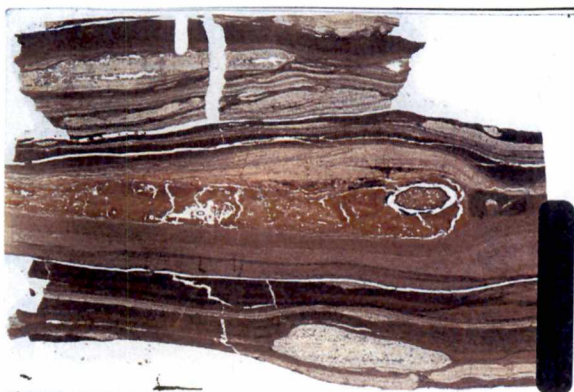
87-94 cm depth, C1 horizon, limestone saprolite and shale/siltstone saprolite.



112-119 cm depth, C1 horizon, ribbon limestone saprolite depicted in Figure 8.



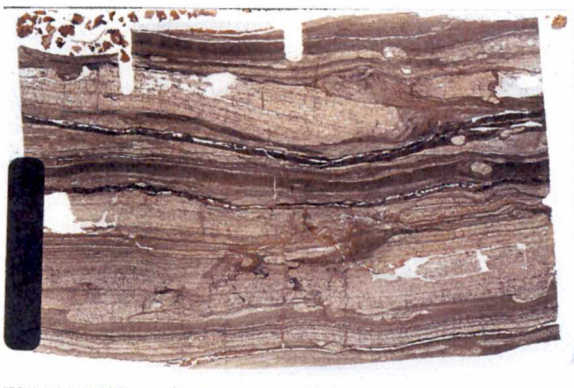
152-159 cm depth, C2 horizon, Shale/siltstone saprolite and ribbon limestone with abundant silt intraclasts.



182-185 cm depth, C2 horizon, shale/siltstone saprolite with layer of limestone saprolite in the center. Note. Root in the limestone saprolite. Depicted in Figure 7 C.



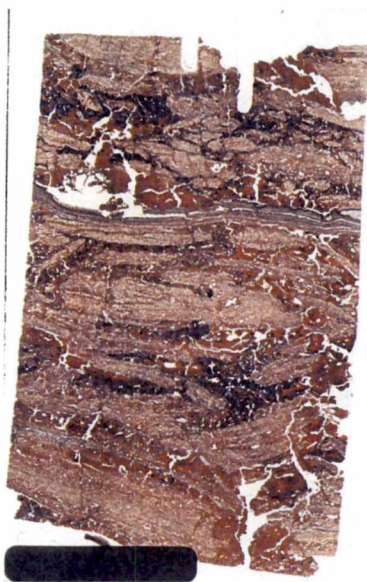
205-208 cm depth, C2 horizon, ribbon limestone saprolite with some silt lenses.



225-228 cm depth, C2 horizon, shale/siltstone saprolite.



259-267 cm depth, C2 horizon, ribbon limestone saprolite with some silt lenses as depicted in Figure 7 D.



283-290 cm depth, C2 horizon, ribbon limestone with abundant silt intraclasts.

E.2. Carbonate thin sections extracted from 2nd shallowest ribbon limestone layer shown in Figure 3.



33-40 cm depth, Bt horizon.



57-64 cm depth, BC horizon, ribbon limestone saprolite.

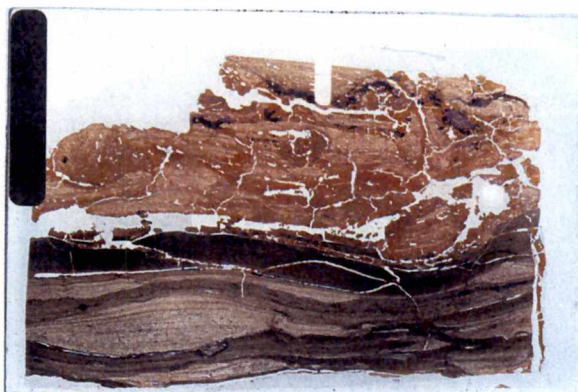


91-98 cm depth, BC horizon, ribbon limestone saprolite.

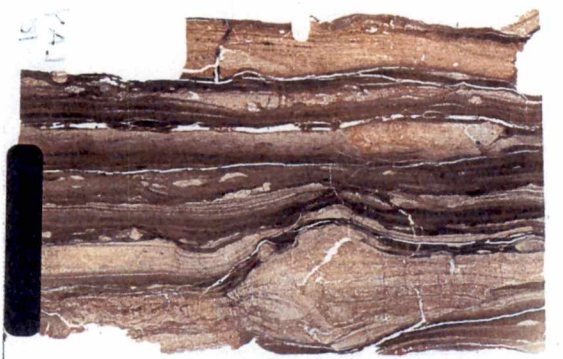
E.2. Shale thin sections extracted from 4th shallowest shale layer shown in Figure 3.



24-27 cm depth, BC horizon, shale/siltstone saprorelicts.



64-67 cm depth, BC and C1 horizon, ribbon limestone saprolite with silt lenses and shale/siltstone saprolite.



96-99 cm depth, C1 horizon, shale/siltstone saprolite.



115-122 cm depth, C2 horizon, shale/siltstone saprolite.

Appendix F: Porosity Data

Porosity calculated using the wax clod method.

Equations (Blake and Hartge, 1986):

$$\text{Bulk Density} = \frac{(P_w \times W_{cd})}{\left[W_{cp} - W_{cw} + W_p - \left(W_p \left(\frac{P_w}{P_p} \right) \right) \right]}$$

$$\text{Porosity} = 100 \left(\frac{1 - \text{Bulk Density}}{2.65} \right)$$

Where:

P_w = Density of Water

W_{cd} = Weight of oven-dried clod in air

W_{cp} = Weight of coated clod in air

W_{cw} = Weight of coated clod in water

W_p = Weight of paraffin in air

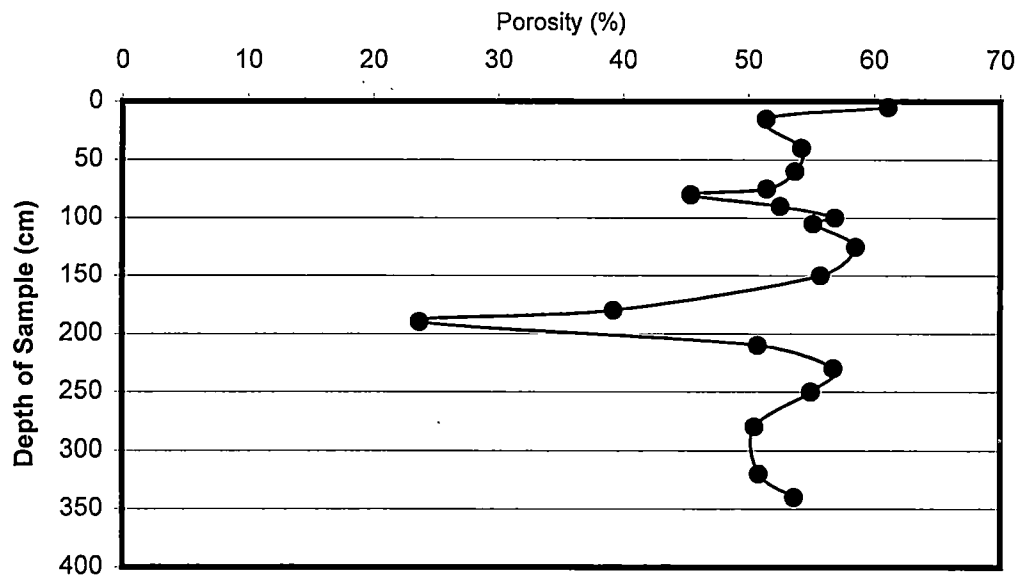
P_p = Density of paraffin

Behind pit
face
porosity

Sample # (depth (cm))	W_{cd}	W_{cp}	$W_p =$ $W_{cp} - W_{cd}$	W_{cw}	P_w	P_p	Bulk Density	Porosity	Depth (cm)
5	15.404	18.323	2.920	3.123	1	0.922	1.030	61.127	5
15	34.464	38.276	3.812	11.174	1	0.922	1.287	51.435	15
40	27.063	31.350	4.287	8.672	1	0.922	1.213	54.237	40
60	17.053	20.137	3.085	5.966	1	0.922	1.226	53.741	60
75	30.235	33.969	3.735	10.137	1	0.922	1.286	51.484	75
80	37.394	41.545	4.152	15.326	1	0.922	1.446	45.451	80
90	24.929	28.479	3.550	8.352	1	0.922	1.257	52.554	90
100	23.309	26.316	3.007	5.655	1	0.922	1.142	56.897	100
105	15.763	17.867	2.105	4.414	1	0.922	1.187	55.196	105
125	47.249	55.436	8.187	11.727	1	0.922	1.098	58.551	125
150	29.624	33.611	3.987	7.993	1	0.922	1.172	55.781	150
180	52.797	56.677	3.880	23.552	1	0.922	1.610	39.253	180

190	41.914	44.368	2.454	23.435	1	0.922		2.022	23.684	190
210	2.088	2.806	0.718	1.145	1	0.922		1.305	50.763	210
230	10.079	11.875	1.796	2.921	1	0.922		1.145	56.790	230
250	32.844	36.346	3.502	8.507	1	0.922		1.192	55.001	250
280	53.816	59.413	5.597	17.897	1	0.922		1.311	50.520	280
320	45.871	50.964	5.093	15.307	1	0.922		1.302	50.861	320
340	19.196	21.883	2.687	6.024	1	0.922		1.228	53.660	340

Porosity data for undisturbed samples collected from vertical pit face (see Fig. 6)



Appendix G: Thin section observations

Thin section observations made using visual comparator charts and ruler applied to digital images and microscope observations.

Depth (cm)	Lithology	Macropore dist.	Macropore mean	% macropores	% of clay (ped)	% Fe/Mn
15	soil	0.03-9 mm	0.3 mm	20	0	0
41	soil/sapro	0.01-2 mm	0.2 mm	20	8	0
75	Ls 70%	0.01-4 mm	0.2 mm	18	15	8
	Sh 30%	0.01-4 mm	0.2 mm	18	2	0
90	Ls 40%	0.02-1.5 mm	0.7 mm	6	35	2
	Sh 60%	0.01-0.2 mm	1 mm	3	3	2
115	Ls 50%	0.01-3 mm	0.5 mm	20	20	4
	Sh 50%	0.01-9 mm	0.3 mm	10	3	2
155	Ls 70%	0.01-2 mm	0.6 mm	6	15	10
	Sh 30%	0.01-2 mm	0.2 mm	4	3	1
183	Ls 25%	0.02-4 mm	0.3 mm	15	25	2
	Sh 75%	0.01-1.5 mm	0.1 mm	5	1	2
207	Ls sapro.	0.01-9 mm	0.4 mm	10	30	25
227	Sh sapro.	0.01-5 mm	0.2 mm	3	3	2
262	Ls sapro.	0.01-7 mm	0.4 mm	10	25	25
286	Ls sapro.	0.01-4 mm	0.5 mm	10	15	18

Graph is figure 9.

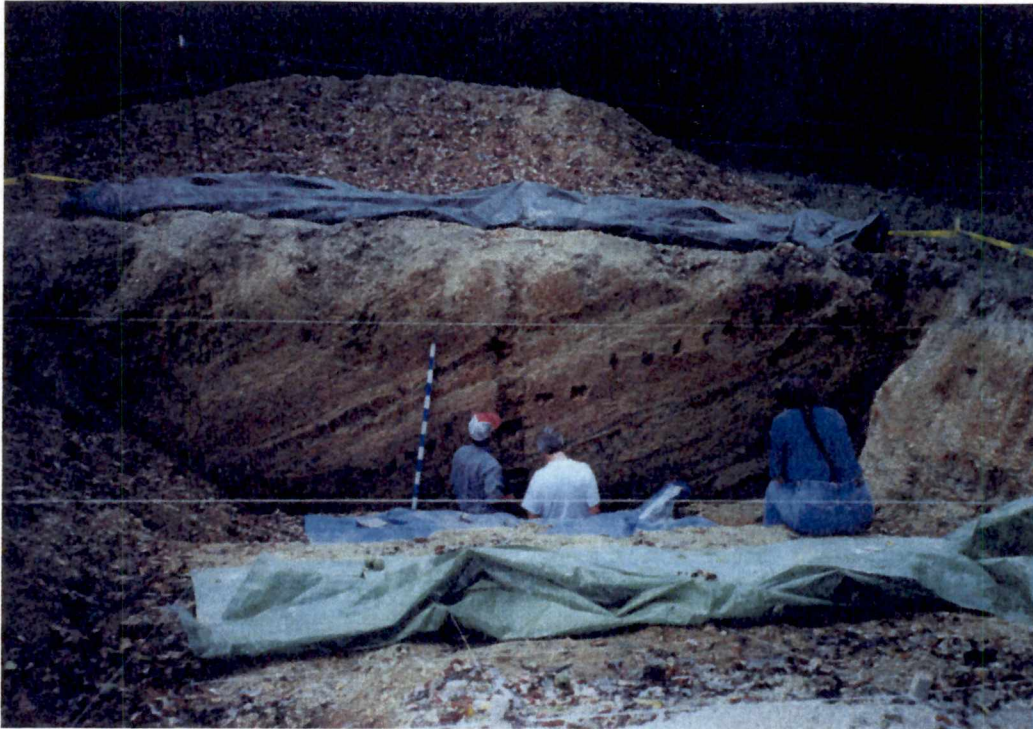
Appendix H: Field Pictures



Picture looking down-slope from pit to schrader road. Note Jeep parked down at road, middle of the photograph.



Picture looking up slope. Pit was later excavated at the top of the hill.



Picture showing vertical pit face and lithologies present. Note: workers are standing at the back of the pit to examine lithologies.



Close up of pit face, center and NW side. Field of view approximately 3.5 m.



Close up of pit face, center and SE side. Field of view approximately 3 m.



Typical column excavated to be cut down and later sent off to be thin sectioned.



Typical array of fracturing, photograph is mostly shale saprolite.



Unweathered limestone lens present under pit step 2. This lens inhibited some TDI measurements. Field of view is approximately 2 m.



Typical photograph off saprolite fragments during pit excavation.

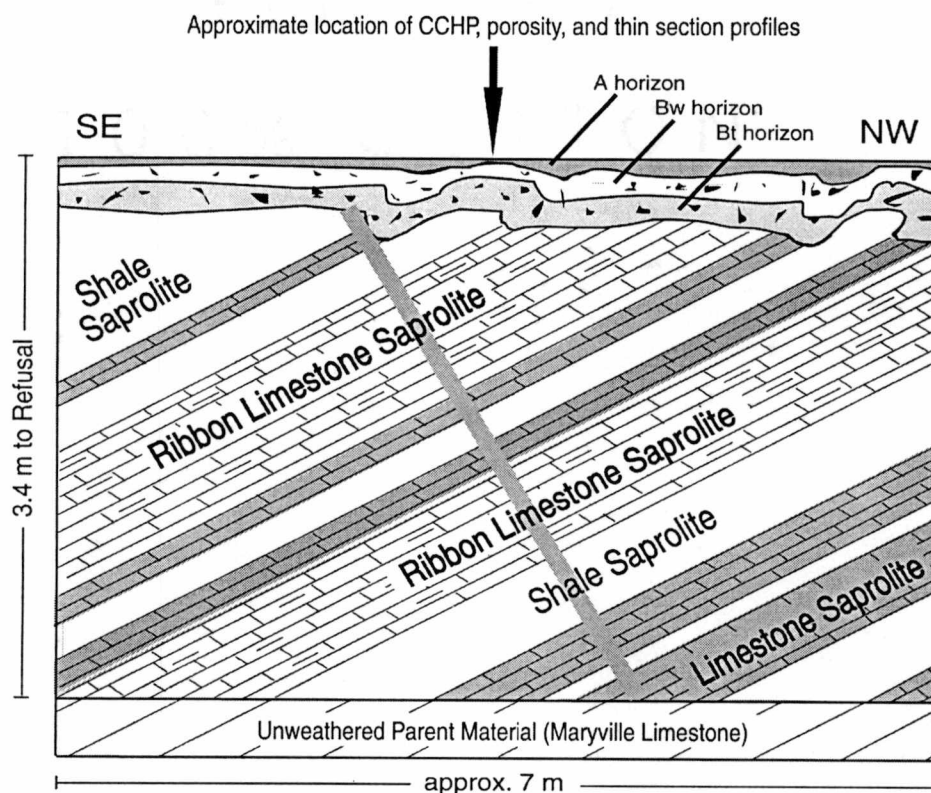


Typical CCHP set up during field measurements.



Typical TDI set up during field measurements.

Appendix I: Calculation of the percentage of stratigraphic units that influence K measurements.



 = Location of strat profile for % of lithology present that influences K measurements.

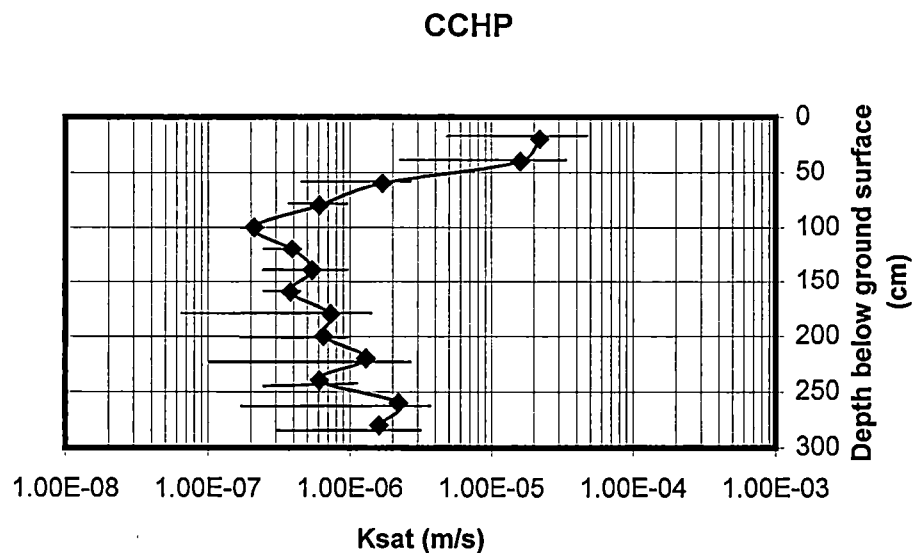
	Limestone	Ribbon Limestone	Shale
	0.6	1.85	0.27
	0.85	2.23	1.25
	0.4		0.50
	0.4		0.7
	0.36		0.65
Total (cm)	2.61	4.08	3.37
Percentage	26%	41%	33%

Appendix J: Mean Hydraulic conductivity profiles of K_{sat} and $K(\psi)$.

All K_{sat} profiles measured with the CCHP are averaged with depth and are presented with error bars corresponding to the greatest difference between measurements.

CCHP			
Error bars			
mean	depth	Plus	Minus
2.20E-05	20	4.70E-05	3.50E-06
1.60E-05	40	3.20E-05	2.15E-06
1.70E-06	60	2.50E-06	4.40E-07
6.10E-07	80	9.50E-07	2.70E-07
2.10E-07	100	2.40E-07	1.90E-07
3.90E-07	120	4.80E-07	2.90E-07
5.40E-07	140	1.00E-06	2.50E-07
3.80E-07	160	4.70E-07	2.80E-07
7.30E-07	180	1.40E-06	6.50E-08
6.50E-07	200	9.20E-07	1.80E-07
1.30E-06	220	3.00E-06	1.00E-07
6.10E-07	240	1.20E-06	2.40E-07
2.20E-06	260	3.70E-06	1.70E-07
1.60E-06	280	3.30E-06	3.00E-07

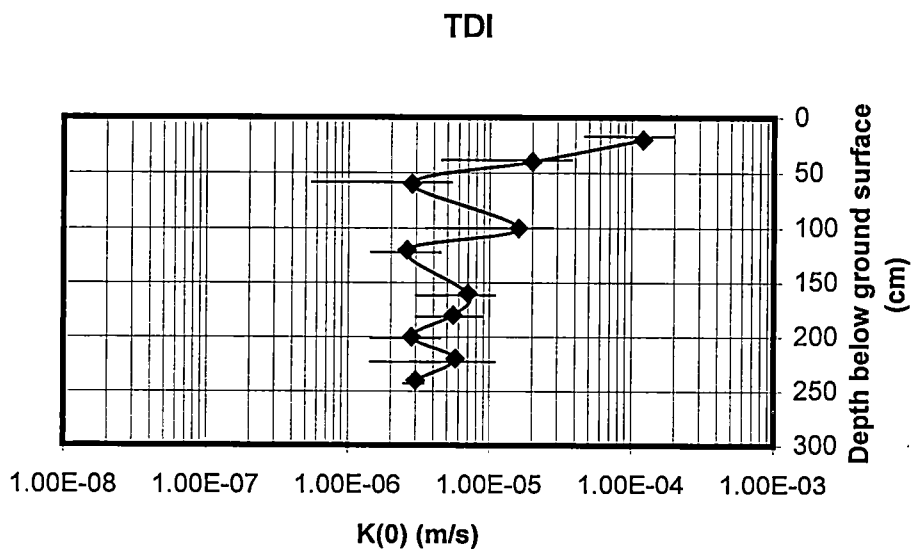
Graph:



All $K(0)$ profiles measured with the TDI are averaged with depth and are presented with error bars corresponding to the greatest difference between measurements.

TDI			
		Error bars	
mean	depth	plus	minus
1.20E-04	20	2.00E-04	4.70E-05
2.00E-05	40	3.60E-05	4.80E-06
2.80E-06	60	5.00E-06	6.00E-07
1.60E-05	100	2.90E-05	3.40E-06
2.60E-06	120	3.60E-06	1.50E-06
7.00E-06	160	1.10E-05	3.00E-06
5.50E-06	180	8.20E-06	2.80E-06
2.80E-06	200	4.00E-06	1.50E-06
5.70E-06	220	9.80E-06	1.50E-06
3.00E-06	240	3.30E-06	2.80E-06

Graph:



VITA

Kevin Harley Smith was born on January 23, 1974, in Decatur, Georgia, where he spent the first four years of his life. After age four his family moved to Alabama where he lived in Fort Payne, Huntsville, Guntersville, Gadsden, and Tuscaloosa. After graduating from Southside High School in Gadsden, Kevin moved to Tuscaloosa, to attend the University of Alabama. He started with thoughts of transferring to Auburn University to pursue a degree in forestry. This was short lived, and he stayed at U of A for two years as an undeclared undergraduate. After the first two years he had thoughts of going into Civil Engineering but while fulfilling his natural science requirements he decided Geology was the degree that best suited his interests. While taking classes in geology he decided to go for a double BS, Geology and Environmental Science. After receiving a BS in Geology and a BS in Environmental Science he made the choice to attend graduate school at the University of Tennessee in August of 1999. After obtaining his Masters of Science in geology in August of 2001 he moved to Durango, Colorado, to pursue a career in the Geological Sciences.