

CLAY AND ENGINEERING PROPERTIES OF THE STEEPLY DIPPING PIERRE
SHALE AND ADJACENT FORMATIONS ALONG THE FRONT RANGE
PIEDMONT, JEFFERSON AND DOUGLAS COUNTIES, COLORADO

by

Richard D. Johnson

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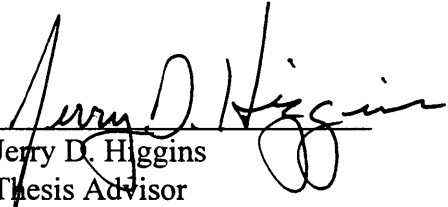
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Golden, Colorado


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ABSTRACT

Expansive clays in the steeply dipping Pierre Shale and adjacent formations are responsible for damage to residences, commercial structures, and infrastructure along the Front Range in Jefferson and Douglas Counties in central Colorado. The hazard is most severe in areas where these units are dipping greater than 30 degrees because of the differential movement of adjacent beds and has been termed "Heaving Bedrock" (Noe and Dodson, 1995). The differential movement has been attributed to differences in the abundances and composition of swelling clays.

The objective of this study is to determine the fundamental clay properties that govern the differential movement within the adjacent, steeply dipping beds. The clay properties examined include cation-exchange-capacity (CEC), mineralogy, and exchangeable cations. These clay properties are compared to engineering and index properties such as Atterberg Limits, suction, and grain-size distribution. There were 55 samples from 11 locations collected between 1992 and 1996 by the Colorado Geological Survey. The samples were collected at depths of 21 feet or less primarily from silty claystone and bentonite beds of the Pierre Shale. A second suite of samples (11 out of the 55) were taken from the Morrison Formation. A single bentonite sample was collected in Wyoming to compare with Colorado bentonites.

The clay mineralogy of the silty claystones are mainly dominated by mixed-layer illite/smectite, R=0 (27 to 70%) and discrete smectite (23 to 88%) with varying amounts of illite (3 to 21%), kaolinite (1 to 10%), and chlorite (0 to 1%). The bentonites are composed of relatively pure, discrete smectite.

The CEC for the silty claystones ranges from 59 to 134 milliequivalents per 100 grams of clay (meq/100g-clay) and averages 79 meq/100g-clay. The bentonites range

from 88 to 128 meq/100g-clay and average 113 meq/100g-clay. The exchangeable cations are dominated by calcium and magnesium in both the bentonites and silty claystones. The calcium ranges from 48 to 72%-milliequivalents (%-meq) (58%-meq average) and magnesium ranges from 23 to 42%-meq (33%-meq average) excluding samples from one section. Potassium composes a small portion, less than 5%-meq. The exchangeable sodium percentage (ESP) varies from 3 to 28%-meq and is closely tied to the bulk mineralogy.

A comparison of the results from two sampling sites where clay and engineering properties were known indicate that the fundamental controls on expansive behavior are percent smectite in the clay fraction and ESP. As the smectite percentage and/or ESP increases, so does the swell potential. Increases in ESP are directly related to the presence of gypsum in the bulk sample. The formation of gypsum results from the oxidation of pyrite. Pyrite oxidation generates acid which favors dissolution of carbonates and feldspars from the surrounding bedrock. As these reactions proceed, the concentrations of calcium (calcite), magnesium (dolomite), and sodium (albite) in solution increases. Calcium combines with the sulfate from pyrite oxidation to form gypsum, thus depleting the calcium concentration in solution. The low calcium concentration in solution and available sulfate causes the clay to release its exchangeable calcium. For the clay to maintain its charge balance, it must adsorb other cations such as magnesium and sodium, elevating the ESP and the expansive potential. In order for the aforementioned reactions to occur, pyrite must be twice as abundant as calcite in the bulk sample.

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Lastly, a special thank-you to my wife, Jodi Johnson, for her hours of editing and proofreading in the final weeks of this project, and George Breit for helping with the laboratory work and interpretation.

DEDICATION

I would like to dedicate this engineering report to Dr. George Breit of the United States Geological Survey. His expert advise and vast knowledge of the techniques presented in this report was greatly appreciated. His patience and willingness to assist in acquiring, interpreting, and presenting the information in this report was immeasurable.

INTRODUCTION

The Pierre Shale and adjacent formations, exposed along the Front Range in Jefferson and Douglas Counties near Denver, Colorado, are well known as the cause of swelling soil and heaving bedrock problems. These swelling and heaving problems cause more property damage than all other naturally occurring hazards combined within the State of Colorado, and millions of dollars are spent in Douglas County alone for repairs to private and state owned structures (Noe and Dodson, 1995).

The Pierre Shale and adjacent formations are steeply dipping along the Front Range in Jefferson and Douglas Counties, Colorado. The near-vertical character of the formations is partially responsible for the large differential movements that have been experienced by residential and commercial structures (Thompson, 1992). The term “Heaving Bedrock” is used to distinguish this problem from the more general hazards of swelling soils or swelling horizontal bedrock (Noe and Dodson, 1995). Steeply dipping, heaving bedrock has thin beds or layers in close proximity to each other exhibiting dissimilar swelling characteristics, causing differential movement of adjacent beds. Therefore, infrastructures may overlie multiple beds and may be damaged by the severely differential movement.

An area of substantial heaving bedrock problems has been defined within Jefferson County as the Designated Dipping Bedrock Area (DDBA) by the Colorado Geological Survey. The boundaries of this area are defined on the east where the bedrock dip equals 30° and on the west along the contact between the Graneros Shale and the Dakota Sandstone (Jefferson County GIS, 1997). A similar area has been defined in Douglas County and is called the Dipping Bedrock Overlay District (DBOD) (Noe and

Dodson, 1995). The samples analyzed and presented in this engineering report are collected from the Jefferson County DDBA or the Douglas County DBOD.

Purpose and Scope

The heaving bedrock problem within the Pierre Shale and adjacent formations is being studied by several investigators at the Colorado School of Mines, Colorado Geological Survey, and the University of Colorado using a wide variety of methods including chemical, engineering, geophysical, and remote sensing studies. The overall purpose of the study is to characterize and define the heaving problems within the Pierre Shale and adjacent formations along the Front Range of Colorado.

The specific objectives of this study are to determine the clay mineralogy, bulk mineralogy, cation-exchange-capacity (CEC), and dominant exchangeable cations and correlate these properties to: (1) cross-sections and heave features observed in the field, and (2) engineering and index properties such as swell potential, Atterberg limits, suction and clod tests, and grain-size distribution.

The engineering tests were performed by Aaron Bagley for his Master of Engineering report (Bagley, 1997). Results were exchanged between Bagley and the author so that each one could have a complete suite of test results.

GEOLOGY

The Pierre Shale and adjacent formations were deposited in a north-south trending trough nearly 1,000 miles across that extended from the Canadian arctic to the Gulf of Mexico (Schultz et al., 1980). This engineering report concerns the area west of Denver, Colorado, along the Front Range of the Rocky Mountains.

Regional Geology

The Pierre Shale, a prodelta shale (Bryant, 1993), is an extensive formation in the west-central interior of the United States and Canada and is composed of sandstone, siltstone, claystone, and bentonite beds that were deposited in the Cretaceous during the inundation of the Interior Cretaceous Seaway (Cobban et al., 1992). Due to the Laramide Orogeny during the early and mid Eocene Epoch, the Pierre Shale was turned vertical or near-vertical along the Rocky Mountain Front Range. In areas near the Dakota Hogback the formation can be vertical or overturned but towards the East it becomes nearly horizontal in the subsurface beneath the City of Denver.

The bentonites of the Pierre Shale are considered the most recognized active areas for heaving bedrock problems (Gill et al., 1996). In this report, a bentonite is defined as altered volcanic ash.

Site Geology and Sampling Locations

Figure 1 shows where the samples used in this study were collected. The sample sites are Bowles Church (BC), Fairway Vista (FV), Fairway Vista Apple-Green Bentonite (FVA), Green Mountain Partridge (GM), Pert's Park (PP), Roxborough Southdowns (RS), Roxborough Village, Filing 13 (R13), Roxborough Village, Filing 101 (R101), RV Trench (RV), Stanton Farms (SF), and a Wyoming Bentonite (WB) (not shown). The following sample and site descriptions were supplied by Dave Noe of the Colorado Geological Survey (Noe, 1997). The samples represent stratigraphically a large portion of the exposed Pierre Shale and Morrison Formation along the Front Range Piedmont (figure 2). The samples are presented from north to south with the exception of the Wyoming Bentonite (WB) (not shown).

Green Mountain Partridge (GM)

Figure 3 shows the location of a single sample (95043) that was collected north of Morrison Road, Jefferson County (SW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 31, T. 4 S., R. 69 W., Morrison Quadrangle). The sample is from the Pierre Shale in the upper transition zone between the *Baculites clinolobatus* (figure 2) and the top of the formation. The sample was collected from the east end of an exploratory trench, dug in 1995, to assess the heaving bedrock problem in a proposed subdivision.

The single sample is composed of a whitish, blocky, hard, 6-inch thick layer of rock that is flanked by "typical" gray siltstone from the upper transition zone. The bed has characteristics of a bentonite such as waviness, lenticular in shape, and evidence of internal shearing. It may be composed of a high percentage of calcite. The trench log

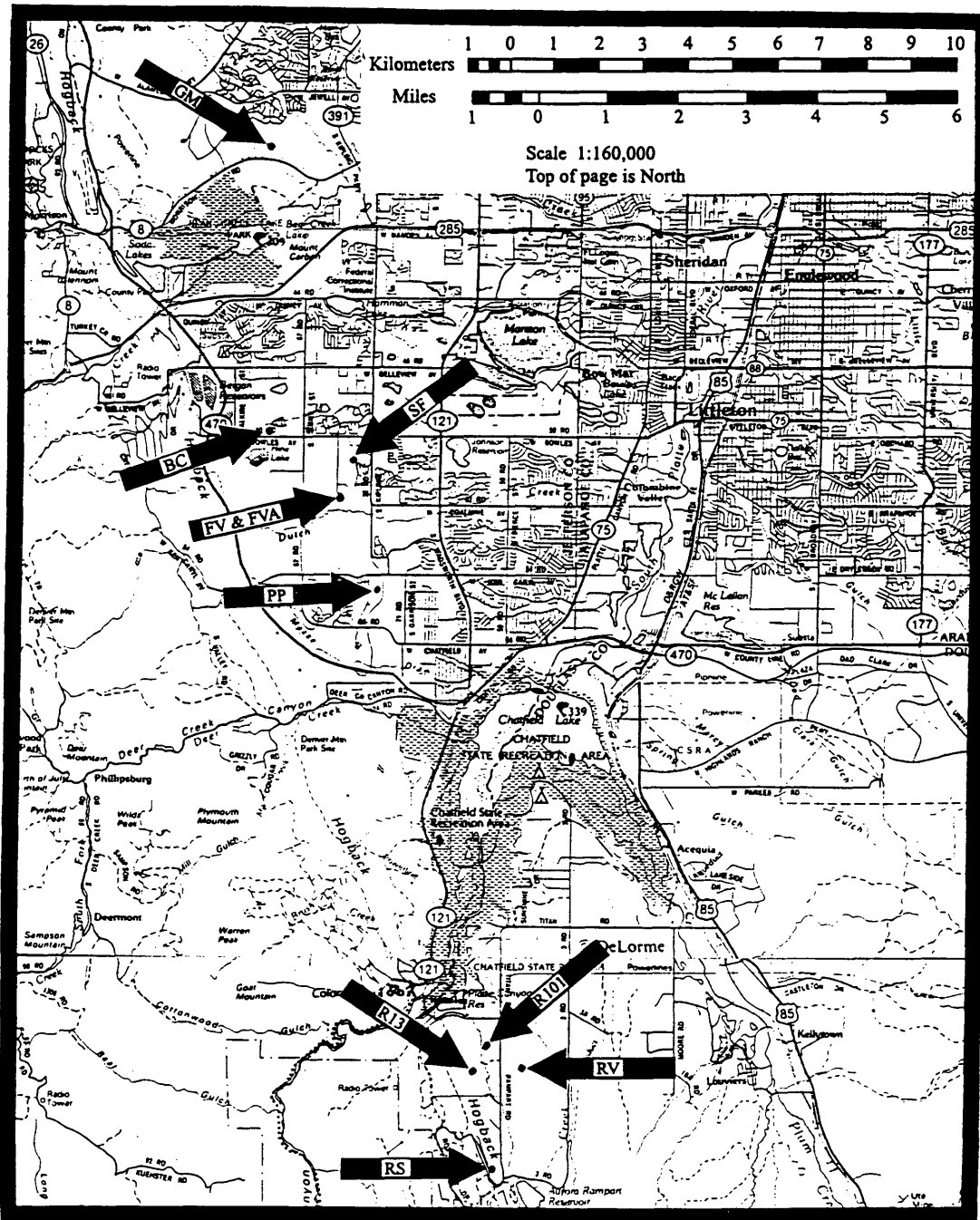


Figure 1. Sampling locations for study area indicated by ● : Green Mountain Patridge (GM); Bowles Church (BC); Stanton Farms (SF); Fairway Vista (FV); Fairway Vista Apple-Green Bentonite (FVA); Pert's Park (PP); Roxborough Village, Filing 101 (R101); Roxborough Village, Filing 13 (R13); RV Trench (RV); Roxborough Southdowns (RS).

CRETACEOUS STAGE		AMMONOID ZONE	SAMPLES	FORMATION	MEMBER	
Maastrichtian (part)	Middle	<i>Jeletzkytes nebrascensis</i> <i>Hoploscaphites nicolleti</i> <i>Hoploscaphites aff. nicolleti</i>	SF GM	Fox Hills Sandstone	— ? — — ? —	
	Lower	<i>Baculites clinolobatus</i> <i>Baculites grandis</i> <i>Baculites baculus</i> <i>Baculites eliasi</i>	PP FVA FV	Pierre Shale	Shale	
?	?	<i>Baculites jenseni</i> <i>Baculites reesidei</i> <i>Baculites cuneatus</i> <i>Baculites compressus</i> <i>Didymoceras cheyennense</i> <i>Exiteloceras jenneyi</i> <i>Didymoceras stevensoni</i> <i>Didymoceras nebrascense</i>	RV			
Campanian	Upper	<i>Baculites scotti</i>	R101 BC			Hygiene Sandstone Member
		<i>Baculites reduncus</i>				Shale
		<i>Baculites gregoryensis</i>				Muddy Buttes and Kremmling Sandstone Members
		<i>Baculites perplexus</i>				Shale
		<i>Baculites sp. (smooth)</i>				
	Middle	<i>Baculites asperiformis</i>	R13			Sharon Springs Member
		<i>Baculites mclearni</i>				Shale
		<i>Baculites obtusus</i>				
		<i>Baculites sp. (weak flank ribs)</i>				
		<i>Baculites sp. (smooth)</i>				
Lower	<i>Scaphites hippocrepis</i> III		Niobrara Formation (part)			
	<i>Scaphites hippocrepis</i> II					
	<i>Scaphites hippocrepis</i> I					
	<i>Scaphites leei</i> III					

Figure 2. Campanian and Maastrichtian ammonoid zones in the Western Interior of the United States in the Upper Cretaceous (modified from Cobban et al., 1992).

lists it as a “limey concretion zone” filled with “powdery, calcareous material” (Noe, 1997).

The upper transition zone contains few bentonites, and nearly all the layers that look like bentonites are severely altered by weathering. There is some question on whether such beds could have originally been bentonites and, if so, what happened to them? This sample is similar to 94001 from Stanton Farms (SF) (Noe, 1997).

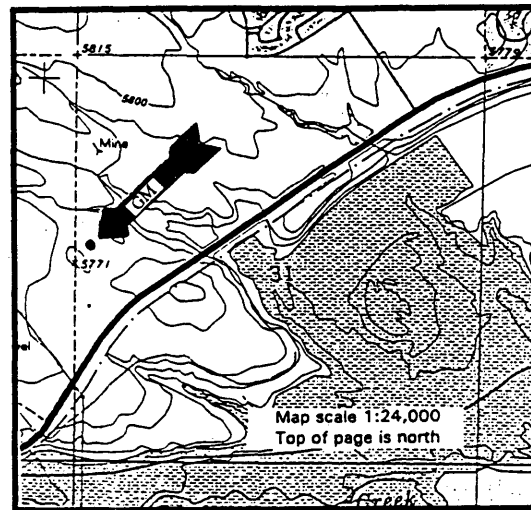


Figure 3. Green Mountain Pattridge (GM) sampling location (SW¹/₄NW¹/₄ sec. 31, T. 4 S., R. 69 W., Morrison Quadrangle) (Noe, 1997).

Bowles Church (BC)

The Bowles Church (BC) samples were collected at West Bowles Avenue near Wright Street, Jefferson County, Colorado (SE¹/₄SW¹/₄ sec. 17, T. 5 S., R. 69 W., Indian

Hills Quadrangle), (figure 4). The samples (numbers 96023-96031) were collected in 1996 at the northwest corner of a foundation excavation. These samples are from the upper shale unit of the Pierre Shale (upper Cretaceous), *Baculites scotti* (figure 2). The basement was overexcavated to a depth of 20 feet and the claystone bedrock was replaced with 10 feet of imported sand to mitigate heaving-bedrock hazards. Noe (1997) sampled the site after it was nearly backfilled.

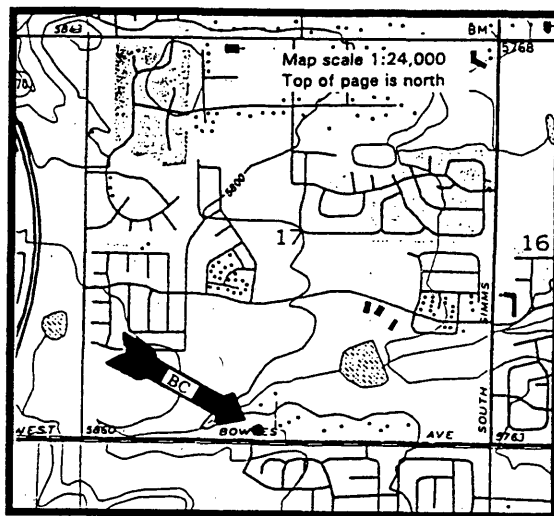


Figure 4. Bowles Church (BC) sampling location (SE¹/₄SW¹/₄ sec. 17, T. 5 S., R. 69 W., Indian Hills Quadrangle) (Noe, 1997).

The sample transect contains nine samples across an unusually thick (5.3 ft.) bentonite bed (figure 5). This bed is the thickest bentonite that has been reported from the Pierre Shale in Colorado. It was reported as being 10 feet thick at the base of the 20 foot excavation. The bentonite is light yellow-green except for the uppermost 1 foot, which is light gray, and has sharp basal and upper contacts, and appears unoxidized. The bed dips 70° to the east and strike appeared to conform with the regional trend (Noe, 1997).

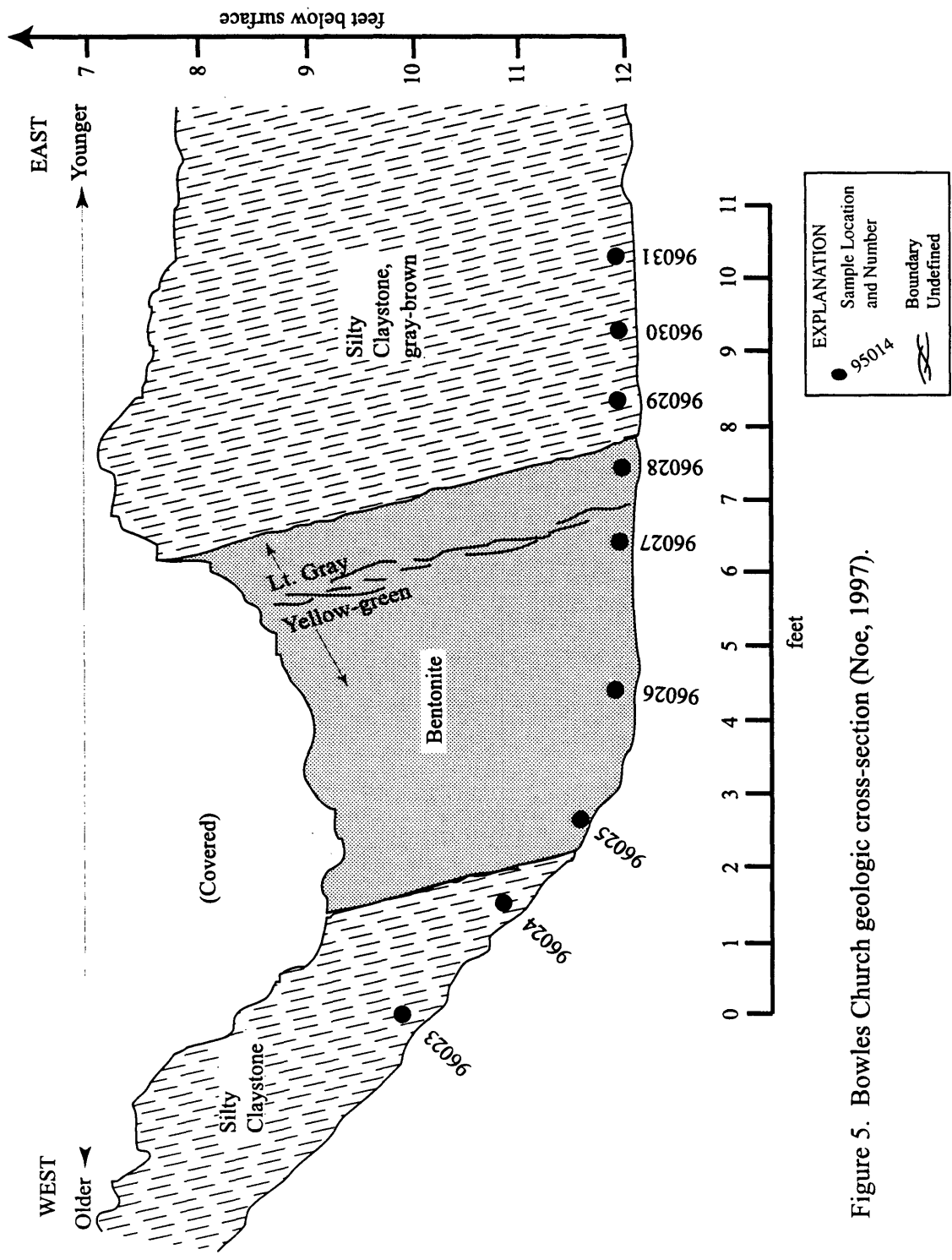


Figure 5. Bowles Church geologic cross-section (Noe, 1997).

Two samples were taken below, four within, and three above the bentonite bed. The bedrock surrounding the bentonite was a gray-brown, silty claystone. The sampling was designed to investigate engineering and mineralogical changes within the bentonite bed and differences between the bentonite and surrounding claystone. In particular, it would be helpful to know if the basal contact is sharp and the upper contact is transitional (i.e., a mixing zone) (Noe, 1997).

Stanton Farms (SF)

Stanton Farms is located at the intersection of West Fair Avenue and South Oak Street, Jefferson County (SW¹/₄NE¹/₄ sec. 21, T. 5 S., R. 69 W., Littleton Quadrangle) as shown in figure 6. The sample (94001) is from the east end of trench 12 from the upper transition zone of the Pierre Shale between the *Baculites clinolobatus* (figure 2) zone and the top of the formation.

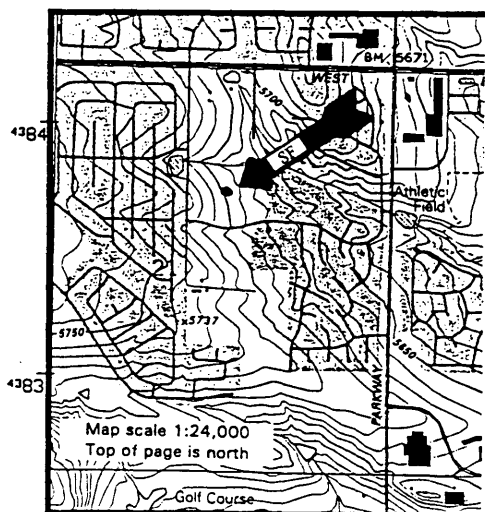


Figure 6. Stanton Farms (SF) sampling location (SW¹/₄NE¹/₄ sec. 21, T. 5 S., R. 69 W., Littleton Quadrangle) (Noe, 1997).

The exploratory trench was excavated in 1994 to assess the lithologies under a proposed subdivision for heaving bedrock hazards. The single sample consists of an unusual, whitish, blocky, hard, 8-inch thick layer of rock that is bounded by “typical” gray siltstone from the upper transition zone of the Pierre Shale (figure 7). The unusual bed has the gross appearance of a bentonite bed in that it shows signs of internal shearing such as waviness and pinching (Noe, 1997).

The sampling was designed to evaluate the mineralogical composition of this unknown material and to determine the mineralogy of any clay present. The upper transition zone of the Pierre Shale contains very few true bentonites (Noe, 1997). Nearly all beds similar in appearance to a bentonite are severely altered by weathering. This sample is similar to sample 95043 from the Green Mountain Partridge in that it appears to have been highly altered to caliche.

Fairway Vista (FV)

The Fairway Vista (FV) samples were collected at South Oak Circle near West Coal Mine Avenue, Jefferson County, Colorado (SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 21, T. 5 S., R. 69 W., Littleton Quadrangle), (figure 8). The samples (96009-96022) were collected from the south end of a foundation excavation in the upper shale member of the Pierre Shale in the *Baculites baculus* zone (figure 2) (Noe, 1997).

The site was excavated for a single-family dwelling in 1996. The basement was overexcavated to a depth of 16 feet, and the claystone bedrock was replaced with 10 feet of imported sand. Noe (1997) sampled the site after the backfill was completed and before the foundation was constructed.

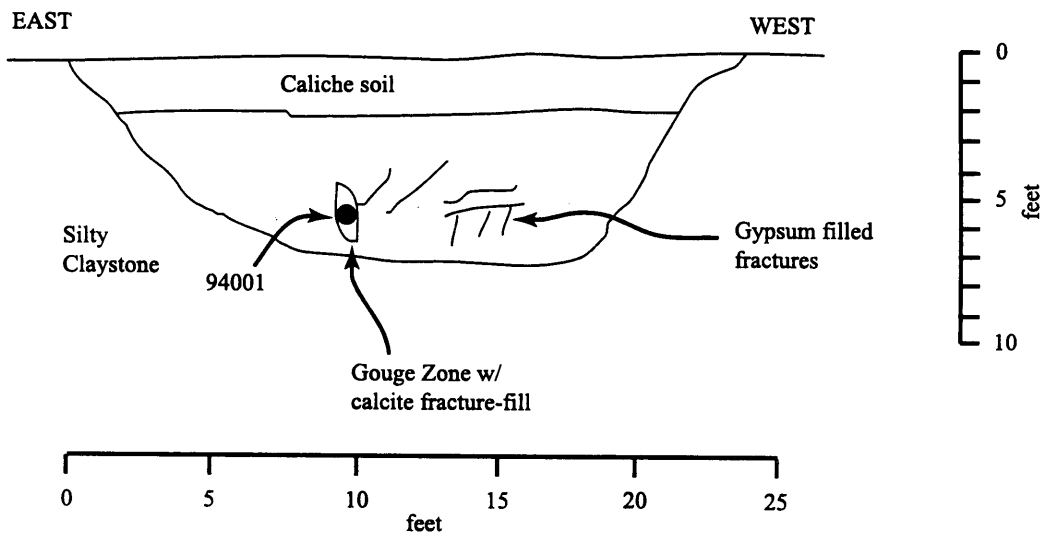


Figure 7. Stanton Farms geologic cross-section (Noe, 1997).

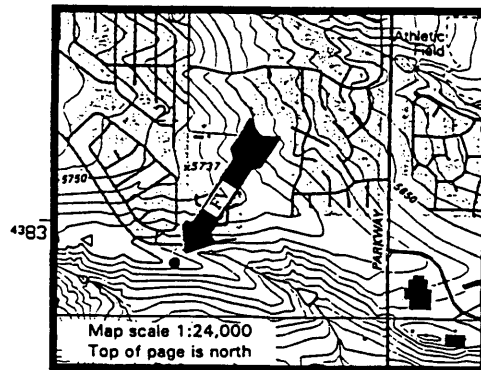


Figure 8. Fairway Vista (FV) sampling location (SE¹/₄SW¹/₄ sec. 21, T. 5 S., R. 69 W., Littleton Quadrangle) (Noe, 1997).

The sample transect contains 14 samples across a section of claystone with a single bentonite bed (figure 9). Sample 96015 is from the 6 inch thick, dark green-gray bentonite bed, which contains fibrous calcite seams and has a strike of N15°W and a dip of 80°E. A second sample in the transect (96022) is from a highly oxidized zone. The remaining 12 samples are from typical, gray-brown to yellow-brown, silty claystone. There are two obvious fracture sets with an average spacing between fractures of 0.5-1.0 feet that intersect the bentonite and rusty zone at approximately 45°. A few of the fractures contain gypsum infilling.

The sampling was designed to investigate a thin zone of potentially high heave-prone bentonite and a larger surrounding zone of moderately heave-prone claystone that are typical for this part of the Pierre Shale. Moderate to severe heaving has been observed in the residential subdivision immediately to the north along the strike of this and other bentonite beds. Questions to be answered are: (1) is the base of the bentonite sharp and the top transitional exhibiting mixing with respect to the surrounding claystone; (2) are samples from the claystone in the fractured zones more weathered than

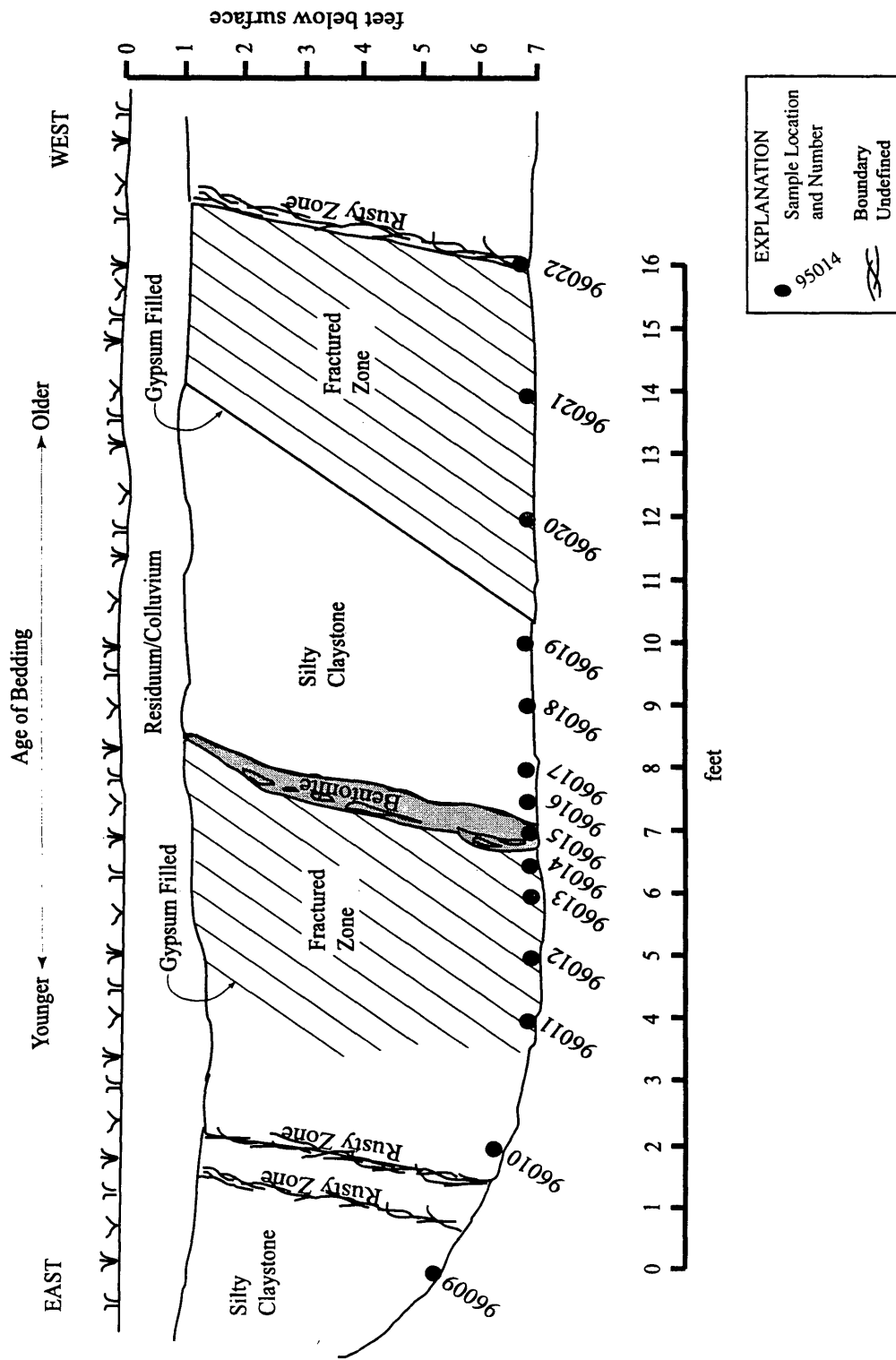


Figure 9. Fairway Vista geologic cross-section (Noe, 1997).

those from the less fractured claystone; and (3) if so, what affect does weathering have on the engineering and mineralogical properties (Noe, 1997)?

Fairway Vista “Apple-green Bentonite” (FVA)

The site (figure 10) is located south of West Coal Mine Avenue, Jefferson County, Colorado (SE $\frac{1}{4}$ SW $\frac{1}{4}$ sec. 21, T. 5 S., R. 69 W., Littleton Quadrangle). The single sample (93007) was taken from a graded cut area in the upper shale unit of the Pierre Shale between the *Baculites baculus* and *Baculites grandis* zones (figure 2) at the ground surface.

The site was graded in 1992 and remained unchanged until 1996. The sample is from a single, 3-inch thick bentonite bed locally referred to as “The Apple-Green Bentonite.” It has a distinctive greenish color, and similar bentonite beds have been noted along this zone in the Pierre Shale to the north.

The bentonite bed at this site heaved nearly 3 inches overnight after a typical thunder-shower that occurred 6 months after grading. Because the sample is small, it is to be used for mineralogical analysis only to determine if this bentonite bed has unique characteristics that would allow it to be identified at other locations (Noe, 1997).

Pert’s Park (PP)

The Pert’s Park suite of samples was taken from West Fairway Avenue at South Jellison Street, Jefferson County, Colorado (SW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 34, T. 5 S., R. 69 W., Littleton Quadrangle) as seen on figure 11. The samples (94002-94004) were taken from

the northwest corner of a foundation excavation and are from the upper shale unit of the Pierre Shale between the *Baculites baculus* and *Baculites grandis* zones (figure 2).

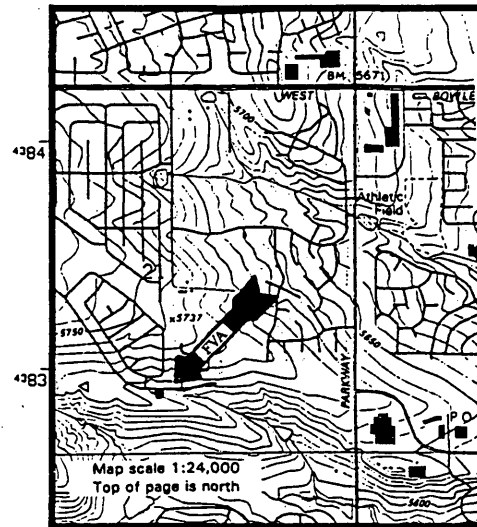


Figure 10. Fairway Vista "Apple-Green" Bentonite (FVA) sampling location (SE¹/₄SW¹/₄ sec. 21, T. 5 S., R. 69 W., Littleton Quadrangle) (Noe, 1997).

A house was constructed on this property in the late 1970s and was demolished a short time later because of significant heaving-bedrock damage. The site has a prominent heave feature running through the center of the area that continues for several blocks. The heave feature is one of the largest observed in the state of Colorado (over 1.5 feet of vertical displacement). The site has served as an informal park for years. In 1994, the site was sold and the new owner re-excavated a foundation coincident with the one from the original house. However, in 1997, the owner built a new house in the west half of the lot in hopes of avoiding the main heave zone.

The sample transect consists of three samples taken across a near-vertical shear zone along the major heave trend. The shear zone consists of braided pattern of

lenticular, calcite-filled fractures in “typical”-looking silty claystone (figure 12). One sample (94003) was taken from the center of the shear zone, and the other two samples (94002, 94004) symmetrically sampled the silty claystone on both sides of the shear zone.

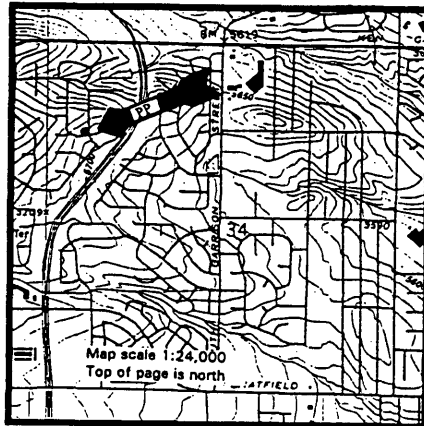


Figure 11. Pert's Park (PP) sampling location (SW¹/₄NW¹/₄ sec. 34, T. 5 S., R. 69 W., Littleton Quadrangle) (Noe, 1997).

Pert's Park is one of the few areas where a very large heave feature that has caused significant damage has been sampled. There are no recognized bentonite beds associated with the heave feature, and the shearing appears to be taking place between two similar-appearing bedrock blocks. It is postulated that the claystone properties and mineralogy from all three samples will be similar.

Roxborough Village, Filing 101 (R101)

Figure 13 shows the location of a single sample (93017) that was collected at Roxborough Village, Filing 101, north of Village Circle West and west of Rampart

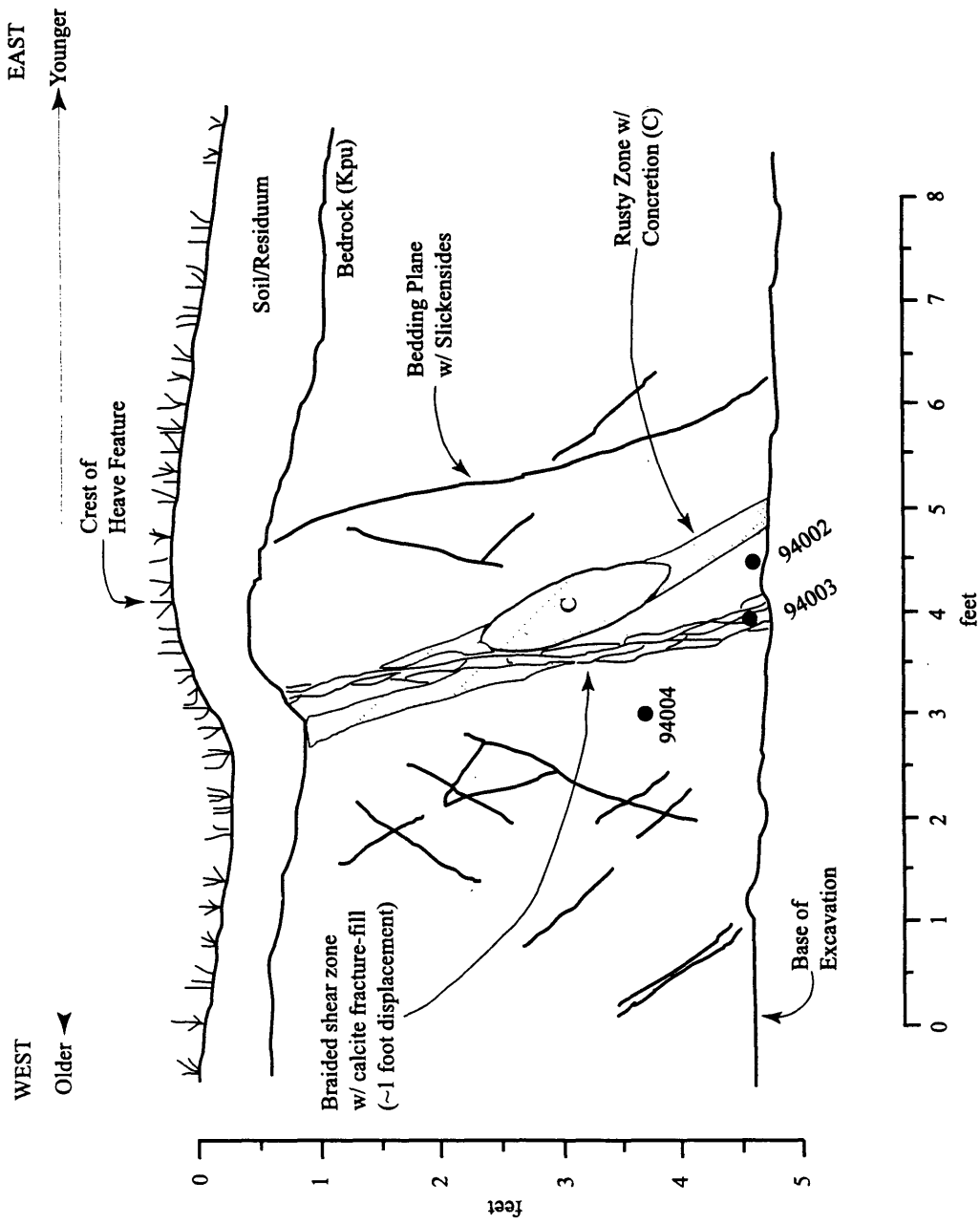


Figure 12. Pert's Park (PP) geologic cross-section (Noe, 1997).

Range Road, in Douglas County, Colorado (SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 35, T. 6 S., R. 69 W., Kassler Quadrangle). It is from the southwest side of a basement excavation in the Hygiene Sandstone Member (figure 2) of the Pierre Shale within the *Anipachydiscus complexus* zone (Noe, 1997). The site was excavated in 1993 to build a single-family dwelling. A conventional pier-and-grade-beam design was used with no overexcavation.

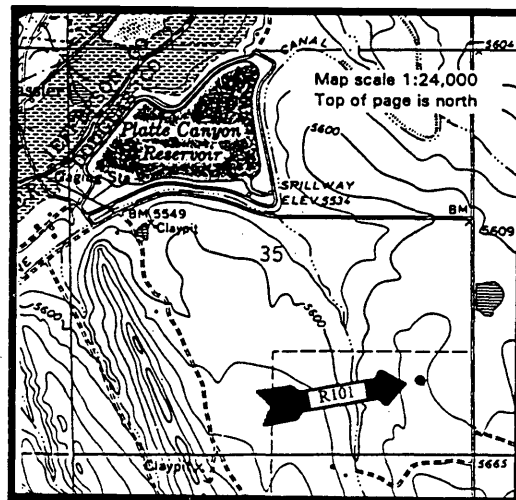


Figure 13. Roxborough Village, Filing 101 (R101) sampling location (SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 35, T. 6 S., R. 69 W., Kassler Quadrangle) (Noe, 1997).

The single sample is representative of a typical exposure of Hygiene Sandstone. At this location this unit is not a sandstone, but rather a sandy, clayey siltstone. The Hygiene is described as a sandstone in the Boulder County, Colorado, area. The Hygiene pinches out before reaching El Paso County, Colorado, and grades into a marine siltstone and claystone.

The sampling is designed to investigate one of the members of the Pierre Shale not commonly regarded as having heaving bedrock problems. It would be interesting to

compare the physical and mineralogical properties of this sample with those from more highly swell-prone claystones from the upper and lower shale units of the Pierre Shale.

Roxborough Village, Filing 13 (R13)

Roxborough Village, Filing 13 (R13) contains samples 93009-93014, which were collected inside of the northwest curve of the Village Circle West Road, Douglas County (NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 2, T. 7 S., R. 69 W., Kassler Quadrangle), (figure 14). The samples are from the lower shale unit of the Pierre Shale (Upper Cretaceous) between the base of the formation and the *Baculites asperiformis* zone (figure 2) (Noe, 1997).

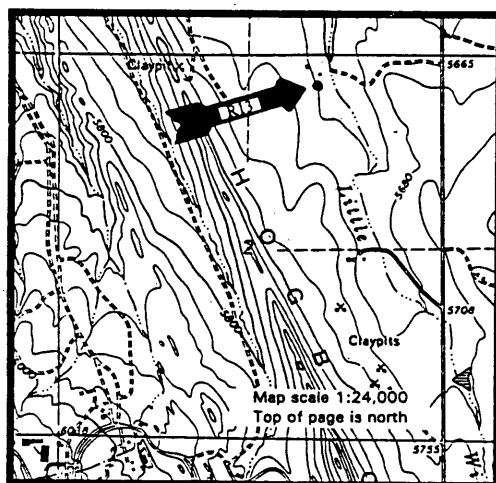


Figure 14. Roxborough Village, Filing 13 (R13) sampling location (NW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 2, T. 7 S., R. 69 W., Kassler Quadrangle) (Noe, 1997).

There are four bentonite beds, informally named B-1 through B-4, that were sampled along with two samples of typical silty claystone to either side of B-2 (figure 15). The beds are slightly to extremely overturned towards the northeast as a result of

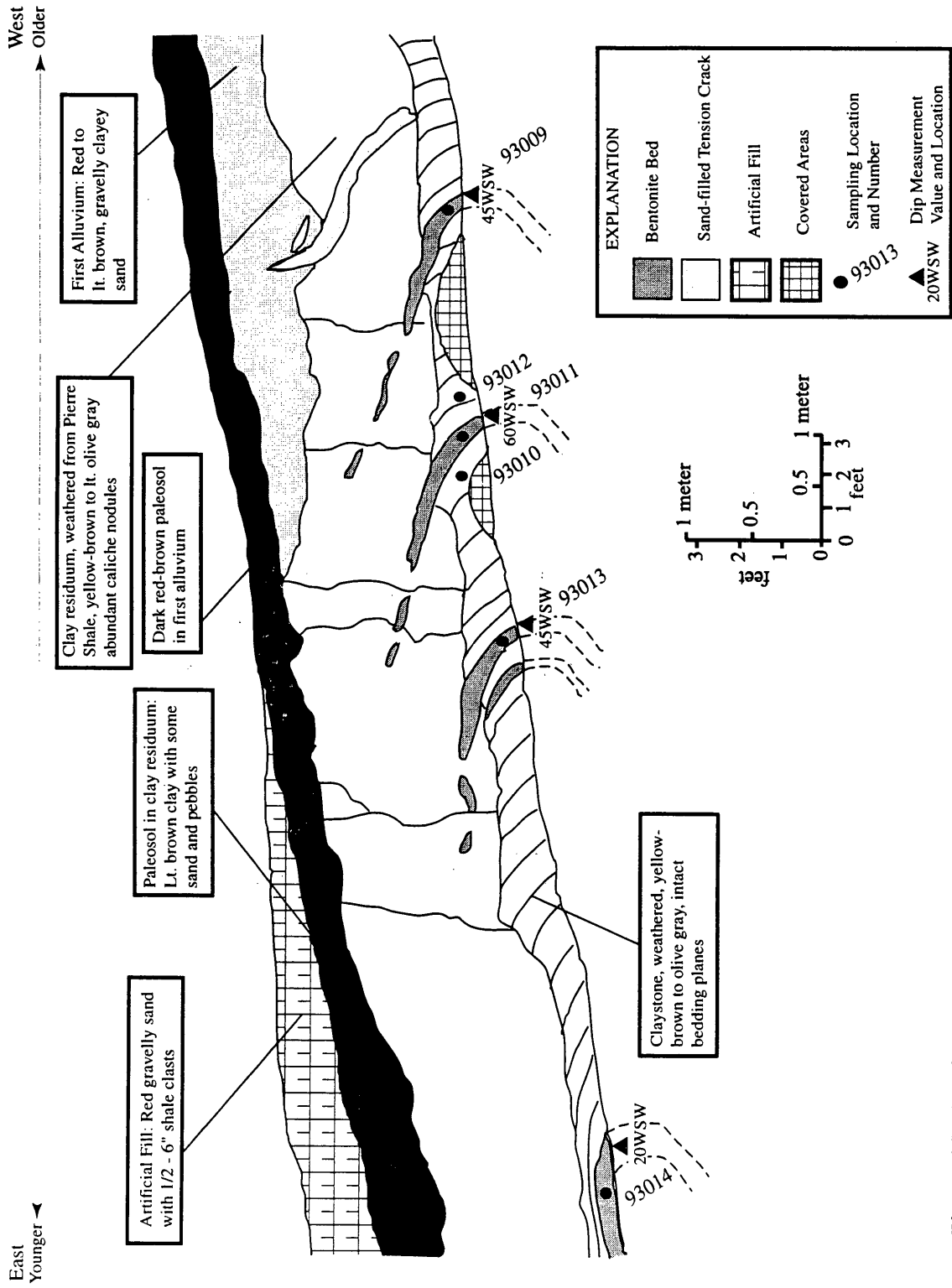


Figure 15. Roxborough Village, Filing 13 (R13) geologic cross-section (Noe, 1997).

gravity creep. As measured in an overexcavation in 1994, these beds dip normally at 70-80° northeast at depth and strike at N25W (Noe, 1997).

The sampling was designed to compare four successive bentonite beds with one another and with the surrounding claystone. These bentonites may differ from other bentonites due to the fact that gypsum and calcite are present in other heave-prone, upper shale units and are absent at this location. Gypsum and calcite are absent in the lower shale unit in general (Noe, 1997).

RV Trench (RV)

The RV Trench is located by the reservoir east of the Rampart Range Road, Douglas County (S¹/₂NW¹/₄ sec. 1, T. 7 S., R. 69 W., Kassler Quadrangle) as shown on figure 16. The sample suite (92027-92033) was taken at the base of a large trench in the upper shale unit of the Pierre Shale (*Exiteloceras jenneyi* zone, figure 2).

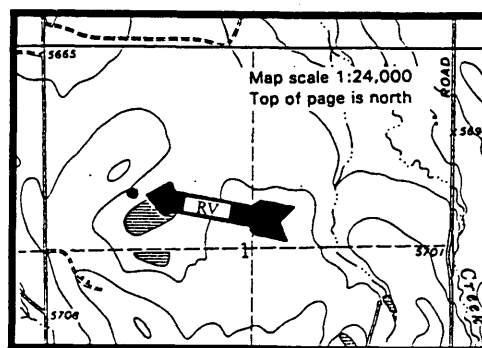


Figure 16. RV Trench (RV) sampling location (S¹/₂NW¹/₄ sec. 1, T. 7 S., R. 69 W., Kassler Quadrangle) (Noe, 1997).

The site was excavated in 1992 as a large, temporary ditch. Two months after the ditch was excavated, a typical summer thundershower caused near-instantaneous heaving along several geological features on the trench floor (figure 17). A neighborhood to the north has incurred extensive damage due to heaving bedrock. The larger heave features appear to align with zones containing bentonite beds (Noe, 1997).

The sample suite represents a transect across an incipient heave that occurred along a straight bedding plane in the claystone following the rainstorm. There was nearly 1 inch of offset observed in the bedrock blocks overnight. The bedrock above and below the heave is homogenous in appearance and consists of yellow-brown, iron oxide stained, silty claystone. It is postulated that the bedrock to either side of the heave will have essentially similar composition and properties.

Sample 92031 was taken from a different area of the trench and is a silty, yellow-brown claystone that may be bentonite. It was taken from a lenticular bed in the trench wall. The sample had a greasy texture and is slickensided on both sides. The significance of this sample is that the bentonite beds may be the foci of intense shearing movements that alter the shape of the bed.

Samples 92032 and 92033 are fragments of fracture-filling gypsum and calcite, respectively, taken from the trench spoils pile. The gypsum is typical of that found in high heave-prone shale. The calcite appears to be exclusively associated with the bentonites (Noe, 1997).

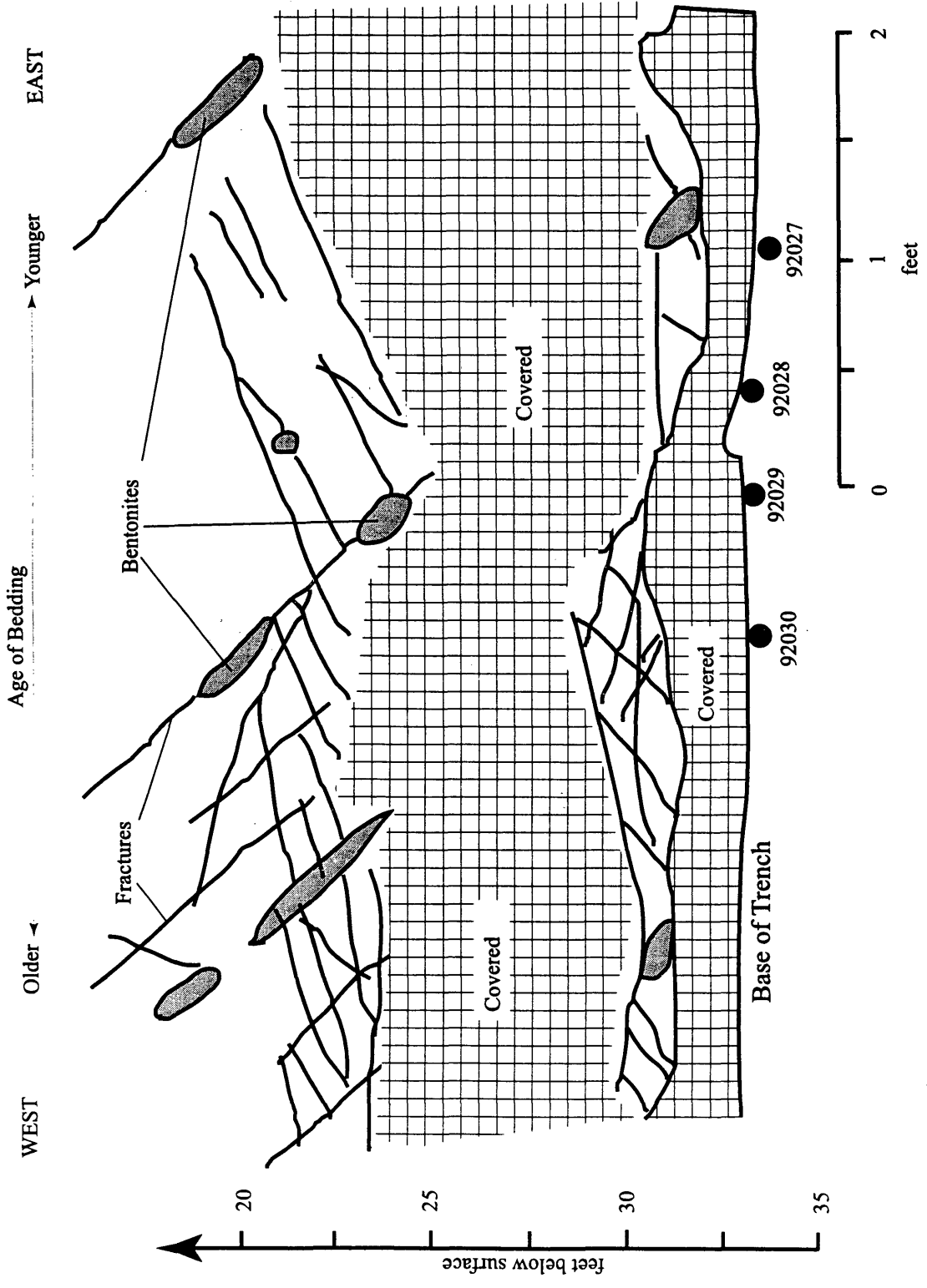


Figure 17. RV Trench (RV) geologic cross-section of wall (Noe, 1997).

Roxborough Southdowns (RS)

The Roxborough Southdowns (RS) samples are from the middle unit of the Morrison Formation (Upper Jurassic). The samples were collected at SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 11, T. 7 S., R. 69 W., Kassler Quadrangle (figure 18).

The site was excavated in 1995 to build a single-family house. The east side of the excavation was sampled. A conventional pier-and-grade-beam design was used with no overexcavation.

The sample transect contains eleven (95013-95023) samples across a variety of lithologies within the middle unit of the Morrison Formation which contains interbedded claystone, siltstone, and sandstone (figure 19). No bentonite were observed, but the lowermost claystone (samples 95013 and 95014) appears to be moderately expansive. The beds strike north-northeast and dip 50° to the northeast.

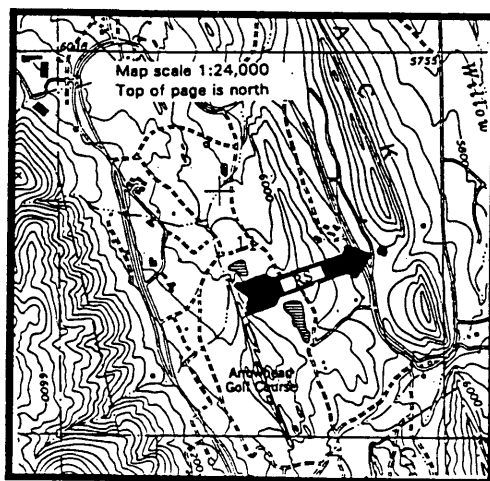


Figure 18. Roxborough Southdowns (RS) sampling location (SE $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 11, T. 7 S., R. 69 W., Kassler Quadrangle) (Noe, 1997).

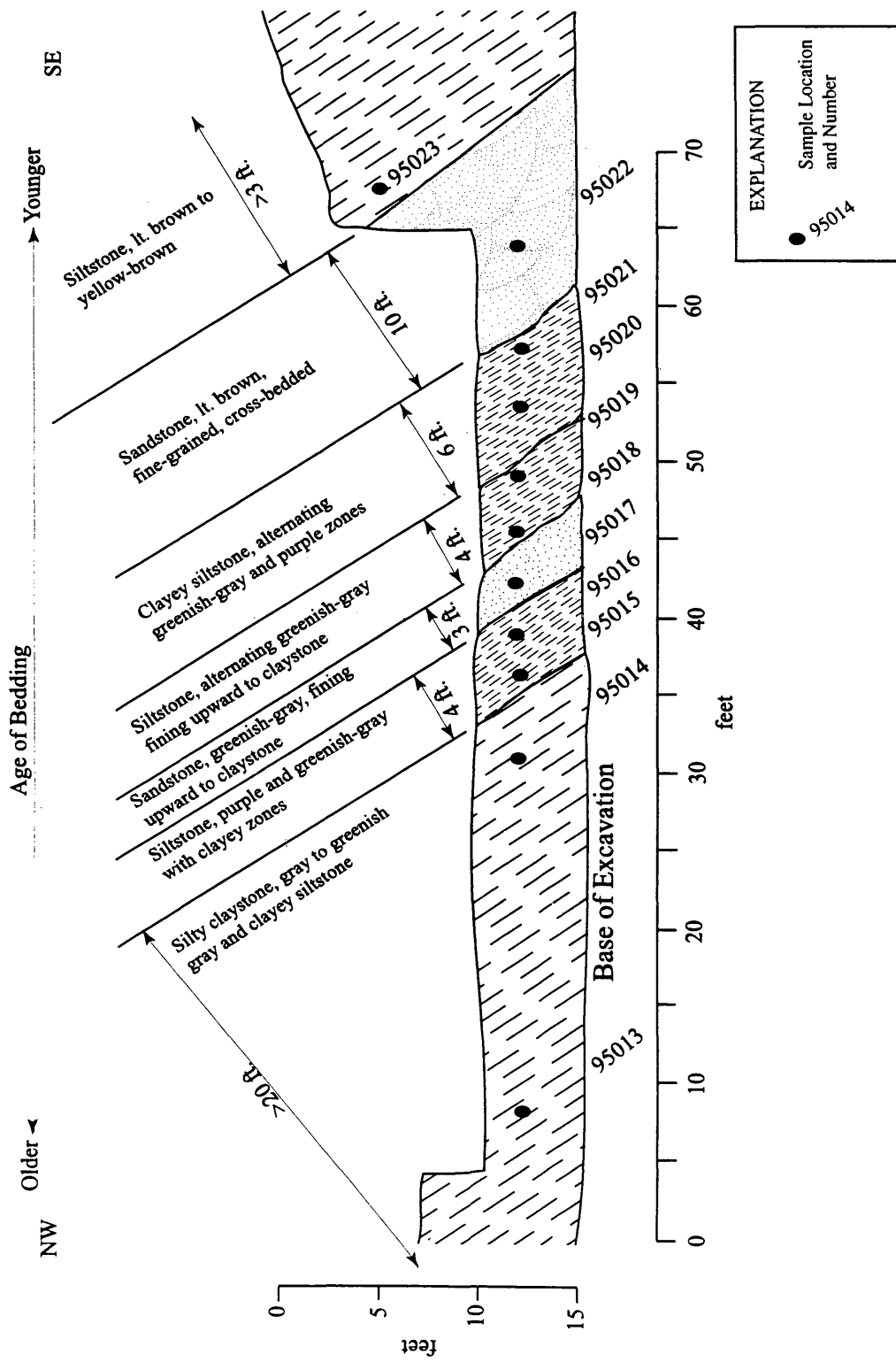


Figure 19. Roxborough Southdowns (RS) geologic cross-section (Noe, 1997).

The Morrison Formation is not known to have problems with heaving bedrock. This may be due to the fact that the Morrison Formation has a narrow outcrop and does not underlie housing and other developments. Houses are built over the Morrison on the west side of the Dakota hogback, but the streets are oriented parallel to the strike of the formation (an orientation that tends not to display heave features) (Noe, 1997).

The sample transect was chosen because it contains seven different lithologic units, all underlying a single house. The sandstone and claystone lithologies should show large variations in engineering properties and mineralogy.

Wyoming Bentonite Site (WB)

The Wyoming Bentonite Site is located 10 miles south of Lovell, 1 mile east of US Hwy 310, Bighorn County, Wyoming (S $\frac{1}{2}$ SE $\frac{1}{4}$ sec. 3, T. 54 N., R. 95 W., North Emblem Reservoir Quadrangle). The sample (94020) is from an outcrop in a hogback ridge beside the dirt road (see figure 20) from the Mowry Formation (Lower Cretaceous) stratigraphically older than the Pierre Shale.

The sample is typical of the very high-swelling sodium bentonites that are mined from the Bighorn Basin for commercial use. The outcrop exposure consists of a 1-inch thick outer rind of “popcorn” bentonite underlain by in-place, thinly interbedded bentonite and siltstone layers. The bentonite beds appear fresh as opposed to the siltstone layers, which appear to be oxidized. Only the pure bentonite was sampled (Noe, 1997).

Sample 94020 consists of white, unoxidized bentonite, peppered with minute black flecks. The sample contains both fresh and water-affected bentonite. The fresh bentonite is conchoidally fractured with sharp edges as opposed to the water-affected bentonite which has a “popcorn” texture. This bentonite is known to expand 2-3 times its

size when exposed to water, and remains intact as a marginally diffuse, colloidal mass (Noe, 1997).

This sample was chosen for its high swelling characteristics due to its large affinity for water. It demonstrates a higher swell potential than any of the Colorado bentonites in the sample suite. Therefore, this sample represents the extreme in swelling characteristics to which the Colorado samples can be compared (Noe, 1997).

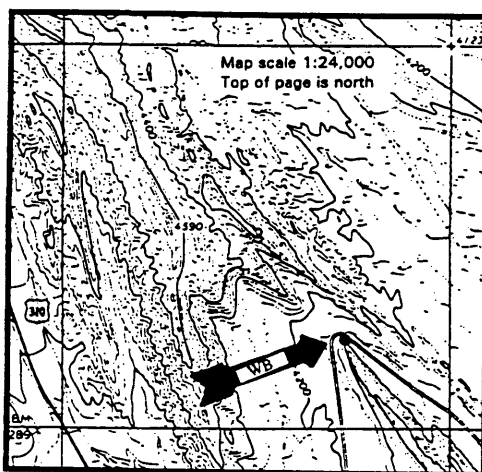


Figure 20. Wyoming Bentonite (WB) sampling location ($S^{1/2}SE^{1/4}$ sec. 3, T. 54 N., R. 95 W., North Emblem Reservoir Quadrangle) (Noe, 1997).

PREVIOUS STUDIES OF PIERRE SHALE MINERALOGY

Izett et al. (1971) studied the Pierre Shale near Kremmling, Colorado, and performed preliminary clay identification. Their main research objective was to correlate the formation to the east and west sides of the Rocky Mountains.

Schultz (1978) and Schultz et al. (1980) performed detailed clay identification, cation-exchange-capacity measurements, and chemical analysis of the Pierre Shale. Their study was located within the Northern Great Plains Region in Montana, Wyoming, and South Dakota. The data is extensive, but may not be comparable to the Pierre Shale near Denver, Colorado.

Tourtelot (1962) studied weathering behavior of the Pierre Shale, particularly the oxidation of iron sulfides. The study was done in the Great Plains Region of Montana and South Dakota.

Collins et al. (1988) discussed highway damage as a result of faulting within the Pierre Shale near Pierre, South Dakota. A section of their report detailed the clay mineralogy and possible cation type, but there were no quantitative measures of cation-exchange-capacity.

Nichols et al. (1991) investigated foundation problems related to heaving bedrock in the Pierre Shale, southwest of Denver, Colorado. A laboratory report was included (i.e., Eberl, 1991) that discussed the clay mineralogy and cation type, but there were no quantitative measurements of cation-exchange-capacity. The most recent work done on the Pierre Shale is by Gill et al. (1996). Their samples were collected southwest of Denver, Colorado. Clay mineralogy and cation-exchange-capacity measurements were performed on several samples.

Previous work shows that the dominant clay type in the Pierre is mixed-layered illite/smectite with minor amounts of kaolinite, discrete illite, and chlorite within the silty-claystone. Bentonite beds are mixed-layered illite/smectite and discrete smectite (Schultz et al., 1980). Schultz et al. (1980) estimates that the silty claystone beds consist of 69% mixed-layered illite/smectite with 45% (of 69%) of the layers being illite, 20% discrete illite, 4% chlorite, and 7% kaolinite by mass in the clay fraction.

There are discrepancies between publications in determining the cation-exchange-capacity and dominant exchangeable cation for the Pierre Shale. Schultz et al. (1980) show, by the 001 illite/smectite peak position (see Eberl, 1991), that the cation generally varies from a monovalent to a divalent cation. They performed quantitative cation exchange and found that the silty claystone has a cation-exchange-capacity of 30 milliequivalents per 100 grams of clay (meq/100g-clay) and 76 meq/100g-clay for the bentonite beds. Gill et al. (1996) performed cation-exchange-capacity measurements using 1 molar ammonia chloride. The silty claystone exhibited a 12.7 meq/100g-clay exchange capacity that were dominated by divalent cations. The bentonite samples had a 31.8 meq/100g-clay of exchange capacity that were also dominated by divalent cations.

METHODS

Samples were collected between 1992 and 1996 by the Colorado Geological Survey from excavations made during residential and commercial development within the study area. The Wyoming bentonite sample was collected from a road cut. Hand sampling was used with a variety of techniques. The most common technique was lateral, multi-bed sampling from the walls or floor of an excavation. Other techniques used were single sampling of known heave feature or bentonite and multi-sample collection around an asymmetrical heave feature.

The samples were stored in zip-lock bags. A large portion of the samples were kept in a humidity room (BC, FV, GM, RS, R13, R101, SF, WB) and the remaining samples were kept at ambient room conditions (RV, FVA, PP). It was assumed that weathering and therefore the oxidation of sulfides occurred prior to sampling and storage.

Sample Mineralogy

X-ray diffraction was used to determine clay and bulk sample mineralogy. The bulk mineralogy is quantified for each sample by using a quartz-ratio technique. The quartz ratio for a particular mineral phase is determined by dividing the height of the peak by the height of the quartz peak. The peaks used in this calculation are shown in table 1. The quartz ratio gives information about the x-ray diffraction pattern such as height without having to include all 55 patterns in this report. Approximately 50 grams of material was suspended in deionized water and rinsed three times, and then centrifuged to

a 1.0 micron-size fraction. It was then filtered with a 0.45 micron filter under a vacuum and transferred to a glass slide, producing an oriented clay mount (Drever, 1973). The mount was air-dried and scanned from 2° to 40° 2-theta (2θ) using a Scintag XDS-2000 X-ray Diffraction unit.

Table 1. Peak positions used in determining quartz ratios for each mineral phase.

Mineral Phase	Peak Position (d-spacing)
Quartz	3.35Å
Feldspar	3.18Å
Dolomite	2.89Å
Smectite	22.1Å
Illite	9.93Å
Calcite	3.02Å
Kaolinite	7.31Å
Gypsum	7.56Å

The oriented clay mount was then vapor-saturated at 50°C overnight with ethylene glycol and scanned a second time. The glycolation will expand the crystal lattice of any smectite clays, and the percent illite within the mixed-layered illite/smectite can be determined by using table 2 below (Moore and Reynolds, 1989).

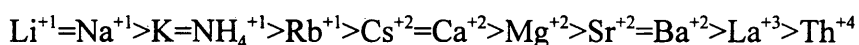
Two one-hour heat treatments were performed to the oriented clay mount. The first is a 350° Celsius treatment for quantitative techniques (that will be discussed later), and the second is a 550° Celsius treatment. The latter heat treatment causes the kaolinite structure to collapse and results in the absence of any kaolinite x-ray reflections. Dehydroxylation of hydroxide sheet within chlorite also occurs and causes weakening in the chlorite reflections. Therefore, if there is a reflection at 14.2 Å or 4.74 Å after the 550° Celsius heating, chlorite is present.

Table 2. The positions (CuK α) of useful reflections for estimating percent illite in illite/EG-smectite. (Moore and Reynolds, 1989)

% Illite	Reichweite	I_{001}/S_{002}		I_{002}/S_{003}		$^{\circ}\Delta 2\theta$
		d (Å)	$^{\circ}2\theta$	d (Å)	$^{\circ}2\theta$	
10	0	8.58	10.31	5.61	15.80	5.49
20	0	8.67	10.20	5.58	15.88	5.68
30	0	8.77	10.09	5.53	16.03	5.94
40	0	8.89	9.95	5.50	16.11	6.16
50	0	9.05	9.77	5.44	16.29	6.52
60	1	9.22	9.59	5.34	16.60	7.01
70	1	9.40	9.41	5.28	16.79	7.38
80	1	9.64	9.17	5.20	17.05	7.88
90	3	9.82	9.01	5.10	17.39	8.38

Cation-Exchange-Capacity (CEC)

A total cation exchange was performed using a 0.1 molar solution of strontium chloride. This method was selected because of the location of strontium on the lyotropic series (Bohn et al., 1985). The lyotropic series is:



Easily Replaced ----- > Hard to Replace

The lyotropic series defines the relative exchangeability of different cations in exchangeable sites in clay minerals. The order of cations is defined by valence and their hydrated radii. The higher the valence and smaller the hydrated radii, the more difficult it is to remove from the exchangeable site.

The procedure includes saturating approximately 0.2 to 0.5 grams of clay with three aliquots (~200 ml) of strontium chloride. After each of the three saturations the strontium chloride is saved. The strontium will remove all exchangeable cations from the clays replacing them with strontium. The procedure is discussed in appendix 1.

The final strontium chloride solution, containing various exchange cations from the clay, was analyzed by Perkin Elmer 3030 Atomic Absorption Spectrophotometer (AA). A calibration line was prepared by using known concentrations of sodium, calcium, magnesium, and potassium in a 0.1 Molar SrCl_2 solution to determine concentrations in the clay wash solutions.

The reproducibility of the cation exchange procedure (appendix 1) was determined by duplicating fourteen samples. A relative error between the two CEC measurements was calculated by taking the difference between the two values and dividing it by the mean. The relative errors of the total CEC for the fourteen samples were averaged. A portion of the CEC error is attributed to the analytical instrument used to analyze the cations in solution, a Perkin-Elmer 3030 Atomic Adsorption Spectrophotometer. Ten samples were chosen at random and their cation exchange solutions were reanalyzed. The error from these duplicate analyses were averaged in order to assess the analytical-instrument mean error.

There are problems associated with using strontium. Calcite in the sample will react with the strontium according to the reaction: $\text{CaCO}_3 + \text{Sr}^{+2} \rightarrow \text{SrCO}_3 + \text{Ca}^{+2}$. The reaction liberates calcium that did not originate from the clay surface and gives a higher calcium concentration in solution resulting in a elevated exchangeable calcium percentage. The reaction is favored because the solubility of SrCO_3 is much lower than that of CaCO_3 , the solubility-product constants (K_{sp}) are 5.6×10^{-10} and 4.8×10^{-9} , respectively.

Another general problem with measuring the cation-exchange-capacity of clays is the presence of quartz, which is a non-exchangeable phase. Therefore, the final clay mass measured is not only the clay, but also the non-exchangeable quartz. The affect of quartz and calcite was minimized by centrifuging to a less than 1.0 micron size fraction and checking for quartz and calcite by x-ray diffraction before the cation exchange was performed (appendix 1).

Quantitative Clay Mineralogy

Quantitative x-ray diffraction (XRD) was performed using the method developed by Schultz (1964) using Pierre Shale samples. The procedure is shown below in table 3 and 4 and figure 21. The set of equations contains three correction factors that are analytically determined.

Table 3. Equations for determining percentages of clay minerals from an x-ray diffraction pattern for samples from the Pierre Shale (from Schultz, 1964).

1. Measure the areas of the 7 angstrom (Å) air, the 10Å glycol, and the 10Å 350°C peaks; measure the heights of the 7Å air, the 10Å 350°C, the 14Å 550°C, and the 17Å glycol peaks.
2. Corrected 7Å peak area = $\frac{7\text{Å air peak area}}{1.4}$
3. Kaolinite + Chlorite (%) = $\frac{\text{Corrected } 7\text{Å peak area}}{\text{corrected } 7\text{Å peak area} + 10\text{Å } 350^\circ\text{C peak area}} * 100$
4. Chlorite (%) = $\frac{(\text{kaolinite} + \text{chlorite}) * 14\text{Å } 550^\circ\text{C peak height}}{1.5 * 7\text{Å peak height}}$
5. Kaolinite (%) = (kaolinite + chlorite) - chlorite
6. Illite (%) = $\frac{10\text{Å glycol peak area}}{\text{corrected } 7\text{Å peak area} + 10\text{Å } 350^\circ\text{C peak area}} * 100$
7. Smectite (%) = $\frac{17\text{Å glycol peak height}}{4.5 * 10\text{Å } 350^\circ\text{C peak height}} * (100 - \text{kaolinite} - \text{chlorite})$
8. Mixed-layer clay (%) = $100 - (\text{kaolinite} + \text{chlorite} + \text{illite} + \text{smectite})$

The first correction factor of 1.4 (step 2, table 3) is for correcting the kaolinite peak for differing degrees of crystallinity. The kaolinite of the Pierre Shale has a fairly uniform crystallinity (Schultz, 1964). This correction factor is the ratio of the air-dried 7A peak area to the 350°C heat-treated 10A peak area.

Table 4. Weight percentages of clay minerals for sample 96013.

Clay Mineral	Weight Percent
Mixed-layer I/S	55%
Smectite	38%
Illite	5%
Kaolinite	1%
Chlorite	1%

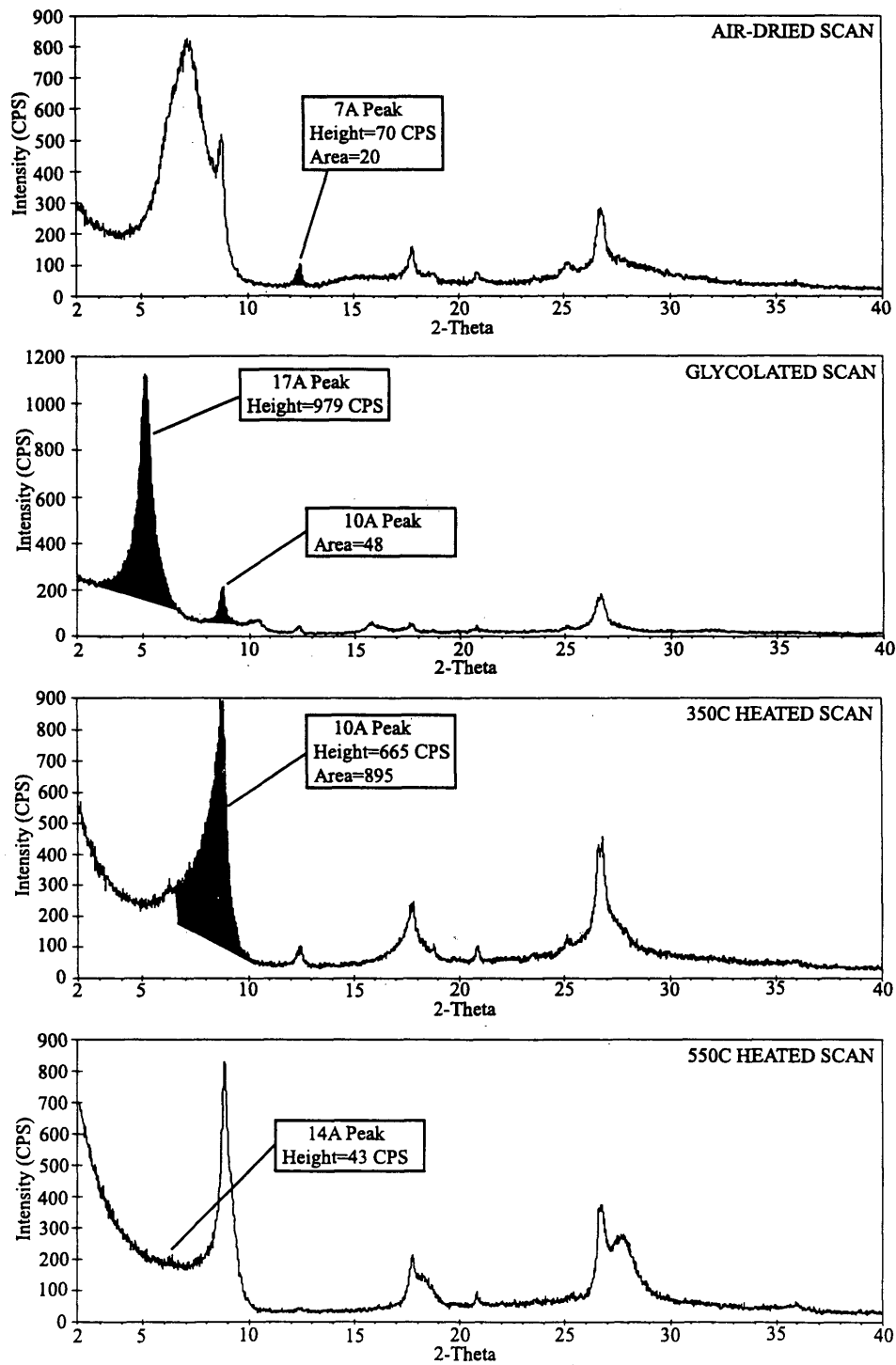


Figure 21. Example of peak measurements used in the quantitative calculations of clay mineralogy for sample 96013 from the Pierre Shale.

The corresponding correction factor for the samples was determined by making standard additions of kaolinite and illite and measuring the corresponding peak area increases for each addition. Kaolinite was chosen with a similar crystallinity to that of the Pierre Shale by using an area to height ratio. The kaolinite standard used for the samples from the Pierre Shale was a University of Missouri-Columbia, Clay Mineral Repository Standard Kga-1b, and the kaolinite standard for the Morrison Formation was a Ward's Natural Science Establishment, Inc. Standard H-9. The same illite standard, Marble Head Illite, was used for both formations. The correction factor was calculated by plotting the peak area versus weight percent added for both the kaolinite and illite additions, and the correction factor is the ratio of the kaolinite slope to the illite slope. The kaolinite correction factor for three Pierre Shale samples was determined and averaged 1.45, compared to 1.4 from Schultz (1964). The kaolinite correction factor for the Morrison Formation was determined to be 0.99.

The second correction factor of 1.5 (step 4, table 3) is for proportioning the 7A peak to the proper amounts of chlorite and kaolinite. The amount of decrease in height of the 7A peak, due to removal of chlorite, is equal to two-thirds ($2/3$) the height of the 14A chlorite peak at 14A after the 550°C heating. The chlorite correction factor was not determined for the samples because they contained less than a few percent chlorite.

The third correction factor of 4.5 (step 7, table 3) is to correct for the decrease in intensity for smectite after heating to 350°C. The correction factor is easily determined by taking the ratio of the peak heights of the glycolated 17A peak of smectite to the 350°C heated 9.8 - 10A peak of smectite. The correction factor calculated for the samples in this study averaged 3.8 as opposed to 4.5 from Schultz (1964), and the corresponding correction factor for the Morrison is 3.25.

Figure 21 shows the peaks that are measured for the quantitative procedure discussed above. The four x-ray diffraction patterns show the same sample after each of

the four treatments. The heights and areas were determined using a software package called “Jade” which was developed by Materials Data Incorporated (MDI).

Using the equations in table 3 and the corresponding values in figure 21, the weight percentages for the different clay minerals can be calculated, but first the correction factors of 1.4 and 4.5 must be changed to 1.45 and 3.82, respectively. Table 4 gives the calculated weight percentages for sample 96013 as an example.

RESULTS

The results of the study are presented in two sections. The first section presents the clay properties such as clay mineralogy, bulk mineralogy, cation-exchange-capacity, and dominant exchangeable cations for each location (figure 1) and how these properties correlate to the cross-sections, lithology, and engineering properties for each sample location. The second section presents the results that address the precision of the cation exchange capacity measurements. The data collected in this study are presented in their entirety in appendix 2.

Clay and Engineering Properties for Selected Sample Locations

Green Mountain Pattridge (GM)

A single sample (95043) was taken at the Green Mountain Pattridge, from a highly altered bentonite(?) bed. A value for CEC was not obtained because of the high concentration of fine-grained calcite in the less than 2 micron separate. The clay mineralogy of this sample consists of 95% discrete smectite, 4% mixed-layer illite/smectite (90% smectite layers), and 1% illite, yielding a total smectite percentage of 99%.

The bulk sample (95043) is composed of quartz, calcite (ratio to quartz equals 16.467), smectite (ratio to quartz equals 0.467), and kaolinite (ratio to quartz equals 0.267).

Bowles Church (BC)

Figure 22 shows: (a) CEC, (b) exchangeable cations, and (c) clay mineralogy of <2 um size fraction in relation to the Bowles Church (BC) cross-section. The strata was sampled above and below a 5.3 foot thick bentonite bed that was the dominant feature in the excavation. The first two samples (96023 and 96024) are silty claystones, stratigraphically below the bentonite. The next four samples were taken in the bentonite bed, and the final three were taken up-section from the bentonite. Figure 22a shows the cation-exchange-capacity (CEC) for the nine samples. The CEC for sample 96024, located just below the bentonite, is 85 milliequivalents per 100 grams of clay (meq/100g-clay) and jumps to 106 meq/100g-clay just inside the basal part of the bentonite.

The exchangeable cations on the clays in the silty claystones and the bentonite are dominated by the divalent cations of calcium and magnesium (figure 22b). Relative percentages of cations in the silty claystone samples average 52% calcium, 39% magnesium, 7% sodium and 2% potassium exchangeable cations. The bentonite samples have a similar exchange site chemistry, and on average consist of 55% calcium, 38% magnesium, 7% sodium, and 0% potassium exchangeable cations.

Figure 22c shows the mineralogy of the clay fraction, including the percentage of discrete smectite, mixed-layered illite/smectite (I/S), and other clays (kaolinite + illite + chlorite). Figure 22c also shows the total percentage of smectite within the clay fraction; “total smectite” refers to the discrete smectite within the sample plus the smectite layers that are incorporated into a mixed-layer clay, usually illite/smectite. The two phases of smectite are totaled due to the fact that they both can expand upon wetting. The silty claystone samples are dominated by mixed-layer I/S and discrete smectite, averaging 47% and 47%, respectively, and contain lesser amounts of illite (4%), kaolinite (1%), and

chlorite (trace). The mixed-layer I/S on average is composed of 83% smectite layers and 17% illite layers. The clay fraction of the bentonites is composed entirely of discrete smectite. For this study, it was assumed that the clay phase in the bentonites is comprised entirely of discrete smectite because the x-ray diffraction data were not adequate to rule out the mixed-layer I/S with 0 to 10% illite layers.

The bulk mineralogy as determined by x-ray diffraction for the BC samples is shown in table 5. As shown, the silty claystone samples (96023, 96024, 96029-96031) are dominated by quartz, feldspar, and smectite. The bentonite samples (96025-96028) are exclusively smectite with an occasional trace of calcite.

Table 5. Bowles Church bulk mineralogy and quartz ratios from x-ray diffraction patterns; nd = not detected, cs = claystone, b = bentonite.

Sample	Mineral Phase							
	Quartz	Feldspar	Dolomite	Calcite	Gypsum	Smectit	Illite	Kaolinite
96023 cs	1	0.140	0.091	nd	nd	0.121	0.037	nd
96024 cs	1	0.237	0.158	nd	nd	0.128	0.035	nd
96025 b	nd	nd	nd	nd	nd	1	nd	nd
96026 b	nd	nd	nd	0.0804	nd	1	nd	nd
96027 b	nd	nd	nd	0.659	nd	1	nd	nd
96028 b	1	0.556	nd	nd	nd	8.519	nd	nd
96029 cs	1	0.172	0.039	nd	nd	0.212	0.025	nd
96030 cs	1	0.141	0.047	nd	nd	0.094	0.021	nd
96031 cs	1	0.132	nd	nd	nd	0.038	0.036	nd

The silty claystone samples (96023 and 96024) have CECs of 90 and 85 meq/100g-clay (figure 23a) and the corresponding clay percentages of 54 and 55 percent (figure 23b). The total smectite percentage was calculated by multiplying the total smectite percentage in the clay fraction (figure 22c) by the clay percentage in the whole rock (figure 23b). The resulting values are 45% (96023) and 46% (96024). The Atterberg Limits are shown in figure 23c. Sample 96023 has a liquid limit of 49% and a

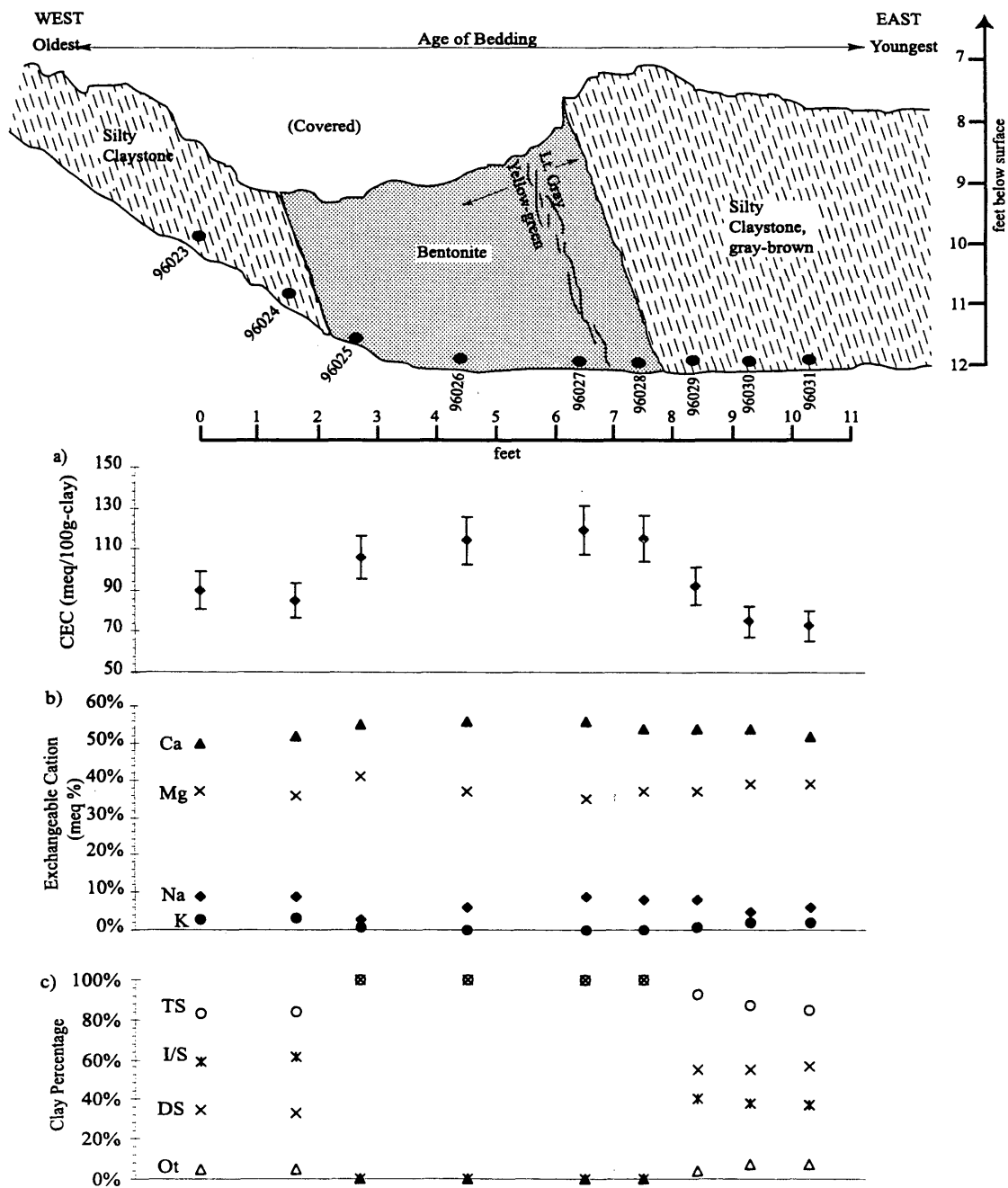


Figure 22. Clay properties for Bowles Church site (a) CEC, (b) Exchangeable Cations present, (c) Clay percentages in clay fraction: TS-Total Smectite, I/S-Mixed-layer illite/smectite, DS-Discrete smectite, Ot-Chlorite+Kaolinite+Illite.

plasticity index of 28%, and sample 96024 has a liquid limit of 44% and a plasticity index of 25%. Figure 23d shows the change in soil suction / change in water content, (h/w) and the swell category for each sample. Category I has the highest swell potential and V is the lowest (McKeen, 1992). Samples 96023 and 96024 are in categories II and III (high and moderate swell potential) with a h/w of -9.6 and -10.3, respectively.

The next four samples (96025-96028) are from the bentonite bed. The CECs average 114 meq/100g-clay. Because the bentonites are 100% discrete smectite (figure 22c), the percent clay and percent total smectite in the bulk sample are equal (figure 23b) and average 64%. The liquid limits for the bentonite samples averages 110% with a range from 99 to 122%, and the plasticity index averages 62% with a range from 50 to 71%. Figure 23d shows a dramatic jump in the h/w for the bentonites compared to the silty claystones. The category went to I (very high swell potential) with an average h/w of -3.4.

The last three samples (96029-96031) are silty claystones that are stratigraphically above the bentonite and are similar to samples 96023 and 96024. The CEC's average 80 meq/100g-clay (figure 23a) and the total smectite in the bulk sample ranges from 39 to 44% (figure 23b). The liquid limits are in the 50 to 55% range with the corresponding plasticity indices in the 31 to 37% range (figure 23c). The swell category for all three of the samples is a II (high swell potential) with an h/w of -9.0, -8.5, and -9.6, respectively (figure 23d).

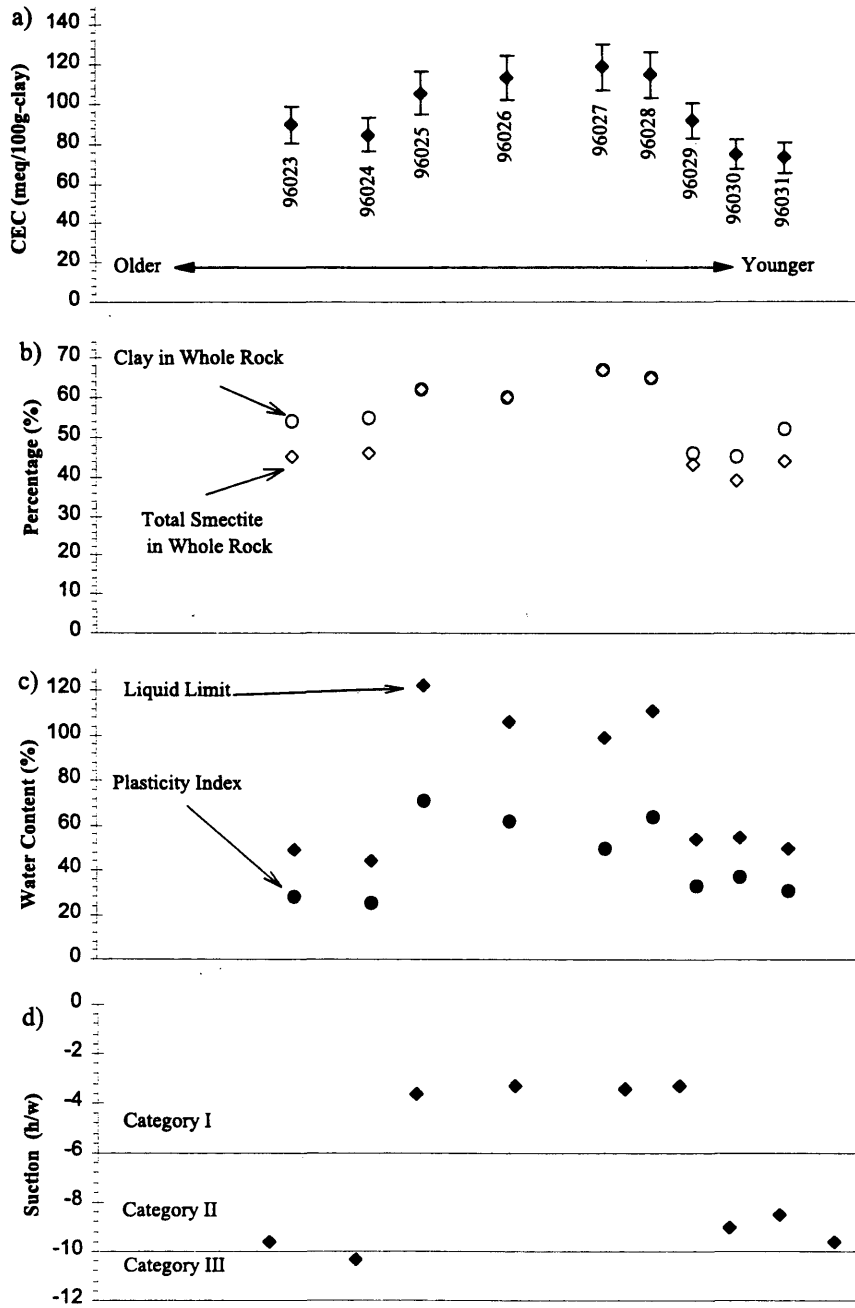


Figure 23. Bowles Church (BC) clay and engineering properties.

Stanton Farms (SF)

A single sample (94001) from Stanton Farms (SF) was taken from a gouge zone with calcite fracture-fill (figure 7). The sample was too small to conduct a cation exchange analysis.

The clay mineralogy of this sample is typical of a silty claystone from the Pierre Shale, having 62% total smectite with 39% discrete smectite and 30% mixed-layer illite/smectite (78% of layers are smectite), 21% illite, 10% kaolinite, and 0% chlorite. The bulk mineralogy of sample 94001 is dominated by calcite having a ratio to quartz of 3.657 followed by dolomite at 0.134, and smectite, illite, and feldspar all at 0.090.

Fairway Vista (FV)

The Fairway Vista (FV) cross-section (figure 9 and 24) contains 14 samples that were collected from the upper shale member of the Pierre Shale. Figure 24a shows the CEC for the FV cross-section. The bentonite bed is easily recognized by its much higher CEC of 117 meq/100g-clay (Sample 96015). The baseline CEC for the surrounding silty claystones average 71 meq/100g-clay. The sample immediately up section from the bentonite bed, sample 96014, shows a slight increase in the CEC (80 meq/100g-clay). There is an abrupt drop back to 71 meq/100g-clay (sample 96016) in the CEC below the bentonite.

Figure 24b shows the percentages of the cations found on the exchange sites. Fairway Vista suite averaged 22% exchangeable sodium. The potassium is consistent, 2-

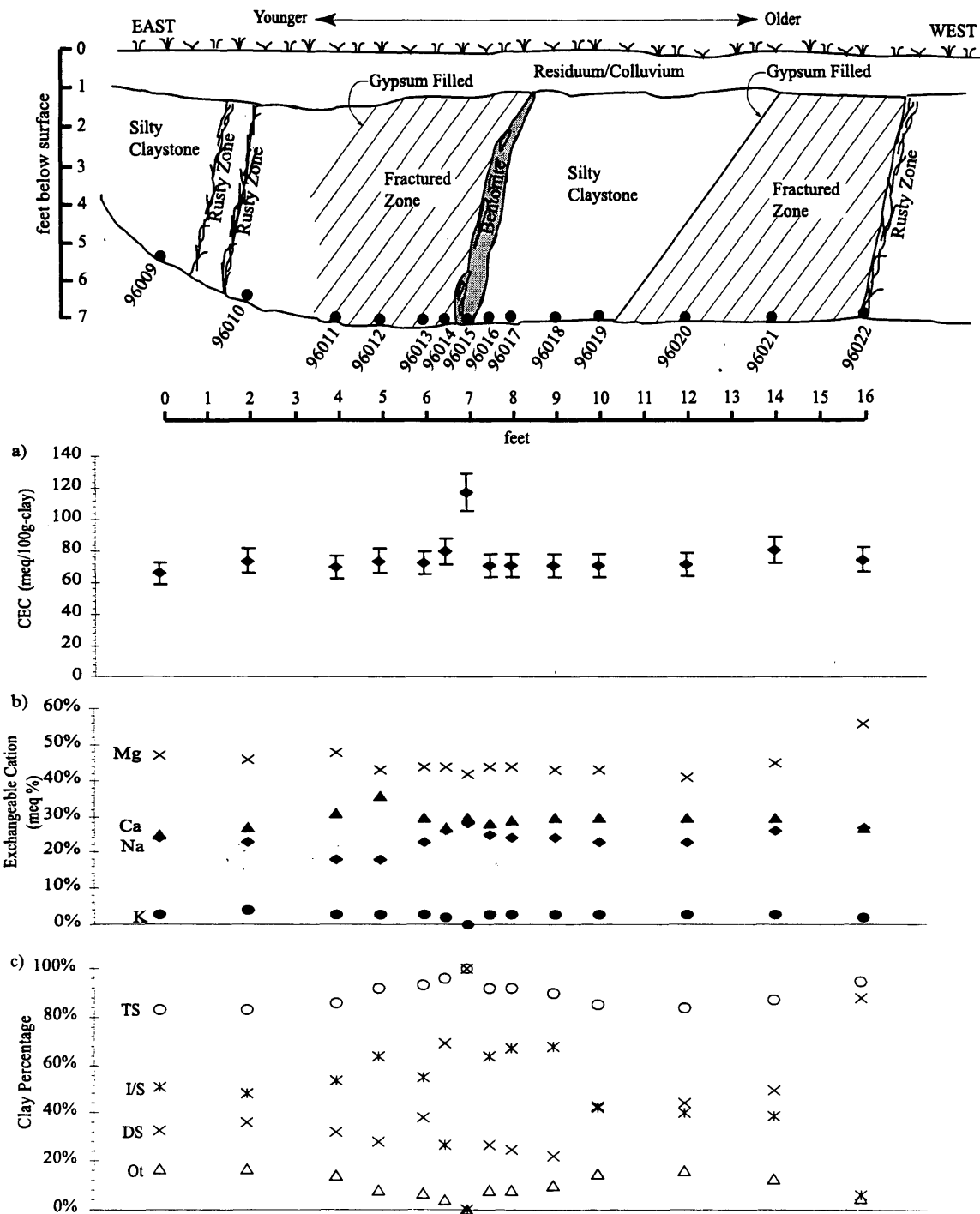


Figure 24. Clay properties for Fairway Vista site (a) CEC, (b) Exchangeable Cations present, (c) Clay percentages in clay fraction: TS-Total Smectite, I/S-Mixed-layer illite/smectite, DS-Discrete smectite, Ot-Chlorite+Kaolinite+Illite.

3% on the exchange sites with the exception of the bentonite, where potassium is consistently absent. The calcium and magnesium average 29% and 45%, respectively.

The clay mineralogy is outlined in figure 24c. The FV suite is dominated by discrete smectite and mixed-layer illite/smectite. For the silty claystones, the discrete smectite averaged 41% and the mixed-layer I/S averaged 48% (84% of the layers being smectite). The remaining phases were chlorite (1%), kaolinite (2%), and illite (9%), on average. The bentonite bed is 100% discrete smectite.

The bulk mineralogy of the FV samples is shown in table 6. The samples are dominated by quartz, feldspar, and smectite with small amounts of illite, kaolinite, gypsum, and calcite. It is important to note that samples 96015 (from the bentonite bed) and 96022 (from one of the rusty zones) are exceedingly high in gypsum (table 6).

Table 6. Fairway Vista bulk mineralogy and quartz ratios from x-ray diffraction patterns; nd = not detected, cs = claystone, b = bentonite.

Sample	Mineral Phase							
	Quartz	Feldspar	Dolomite	Calcite	Gypsum	Smectite	Illite	Kaolinite
96009 cs	1	0.091	0.060	nd	nd	0.120	0.046	0.025
96010 cs	1	0.113	0.076	0.051	nd	0.038	0.034	nd
96011 cs	1	0.090	0.046	0.017	0.050	0.125	0.042	nd
96012 cs	1	0.103	0.116	nd	0.048	0.048	0.042	nd
96013 cs	1	0.129	0.058	nd	nd	0.138	0.042	0.021
96014 cs	1	0.116	0.092	nd	nd	0.139	0.061	nd
96015 cs	nd	nd	nd	nd	1	0.396	nd	nd
96016 b	1	0.091	0.075	nd	nd	0.116	0.054	0.021
96017 cs	1	0.116	0.075	nd	nd	0.129	0.054	nd
96018 cs	1	0.110	0.050	nd	nd	0.113	0.042	nd
96019 cs	1	0.120	0.074	nd	nd	0.120	0.046	nd
96020 cs	1	0.106	0.046	nd	nd	0.079	0.046	nd
96021 cs	1	0.099	0.051	nd	nd	0.095	0.037	0.021
96022 cs	1	nd	nd	nd	21.565	0.478	nd	nd

Figure 25 shows the clay and engineering properties of the Fairway Vista (FV) sample suite. Figure 25a shows the CEC for the clay size fraction, which are the same data presented in figure 24a. Figure 25b is the percent clay and percent total smectite for the bulk samples. Only six of the samples are presented because the engineering data was not completed. The liquid limits and plasticity indices are presented in figure 25c. The single sample with a liquid limit of 115% is the bentonite. The two silty claystones (96014 and 96016) on either side of the bentonite shows slight increases in the liquid limit from approximately 75% to 82%.

Figure 25d shows the change in suction divided by the change in water content (h/w) for the FV samples. As seen, all the samples are in category I or II (category I is the most expansive; category V is the least expansive).

Fairway Vista “Apple-Green” Bentonite (FVA)

The Fairway Vista Apple-Green Bentonite (93007) is the only site where actual heaving was observed. The site heaved 3 inches overnight after a typical thundershower that occurred 6 months after grading of the area (Noe, 1997). The only data collected was the bulk mineralogy because it was a small sample.

The bulk mineralogy is different when compared to previously analyzed bentonites. The mineralogy is as follows: quartz, calcite (ratio of 0.155), feldspar (ratio of 0.090), dolomite (ratio of 0.067), illite (ratio of 0.034), and smectite (ratio of 0.025). Smectite is not typically the least abundant phase in a bentonite.

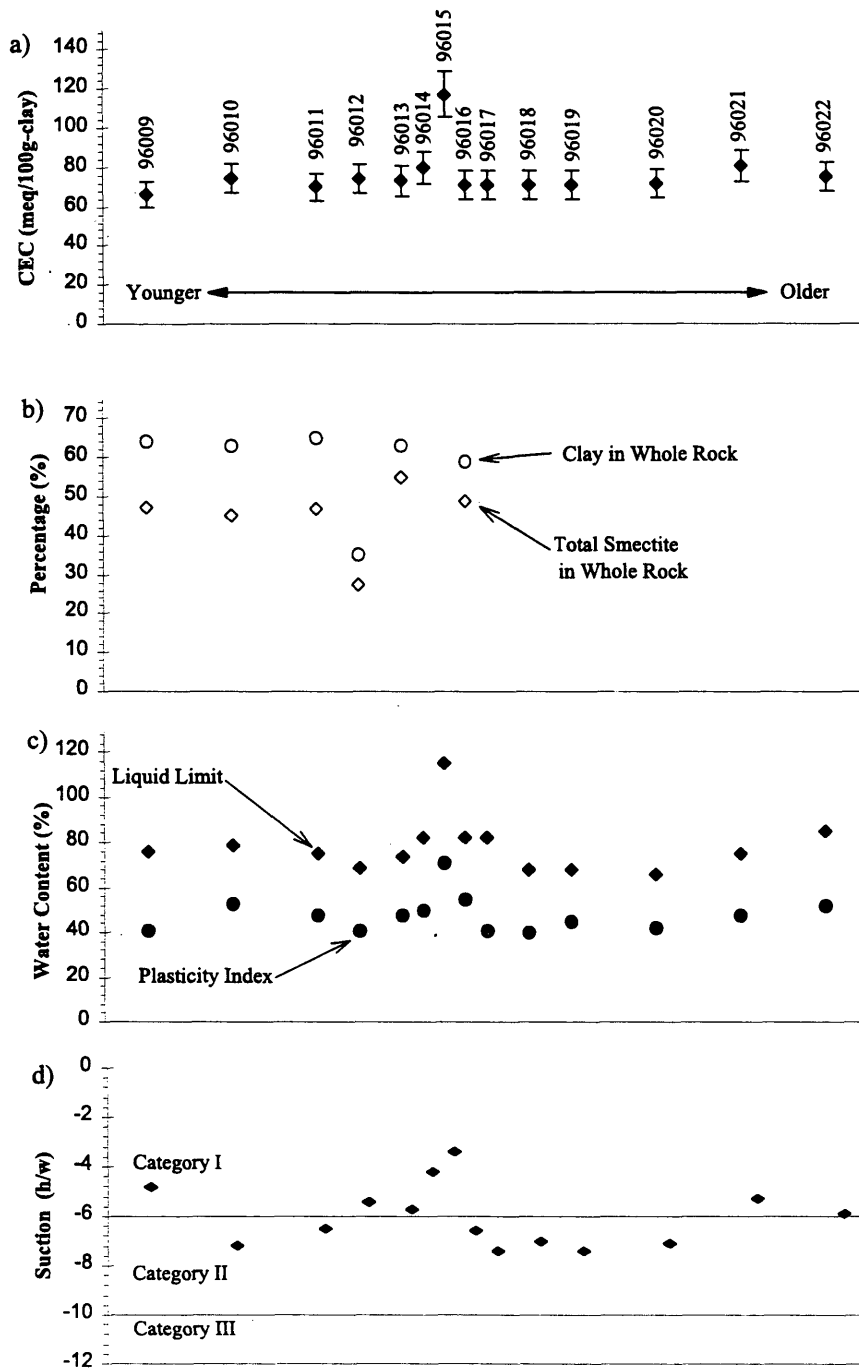


Figure 25. Fairway Vista (FV) clay and engineering properties.

Pert's Park (PP)

The samples from Pert's Park (PP) were collected from one of the largest asymmetrical heaves observed in Colorado. The suite contains three samples (94002-94004) transecting a near vertical reverse shear zone (figure 12) perpendicular to the heave feature. Sample 94003 was taken from the center of the shear zone.

The CEC for each of the samples is highly variable as shown in figure 26a. From west to east through the shear zone, the CEC starts at 97meq/100g-clay (94004) to 134meq/100g-clay (94003) to 79meq/100g (94002).

The exchangeable cations also vary among samples (figure 26b). Sample 94004 contains 57% calcium, 3% sodium, 36% magnesium, and 4% potassium. The sample within the shear zone (94003) has 61% calcium, 12% sodium, 25% magnesium, and 2% potassium on the exchange sites. The sample on the east side of the shear zone (94002) has 48% calcium, 14% sodium, 36% magnesium, and 3% potassium on the exchange sites.

The clay mineralogy of the three samples is nearly identical, as shown in figure 26c. The total smectite ranges from 79% (94002) to 83% (94004) with sample 94003 falling in the middle at 82%. The total smectite is dominated by a discrete smectite phase which varies only 3% for the three samples, from 54 to 57%. The next most abundant phase is a mixed-layer I/S and only varies 3%, from 29 to 32%, with the percentage of smectite layers ranging from 83 to 87%.

The bulk mineralogy of the PP samples (table 7) are typical of siltstones in the Pierre Shale. The only distinctive mineral component in slightly higher abundance than normal is calcite.

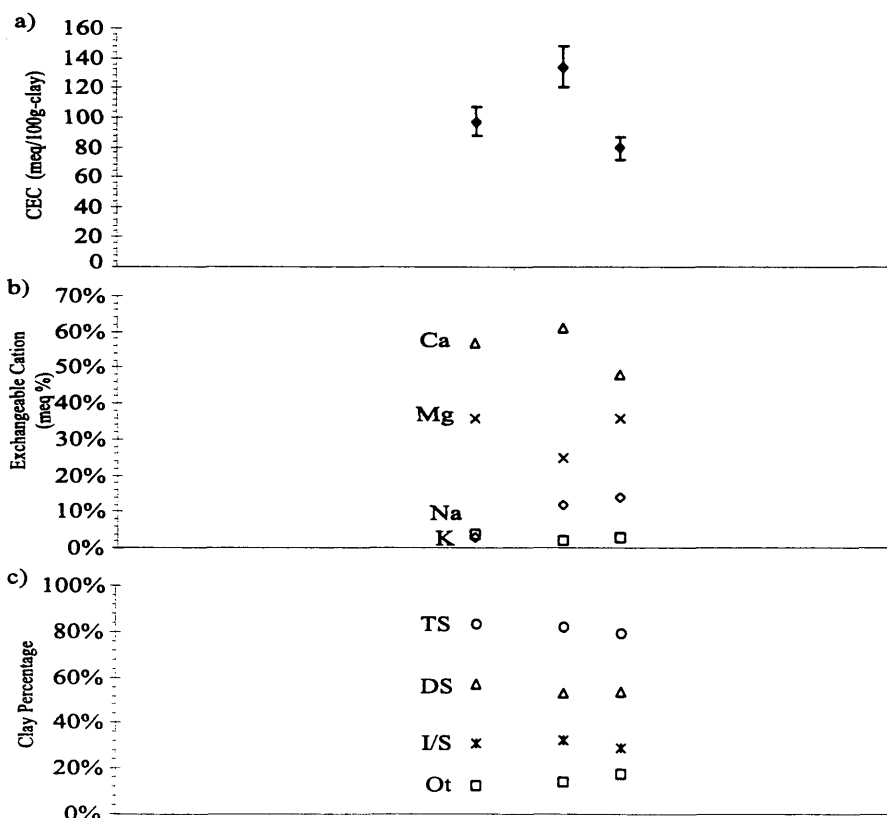
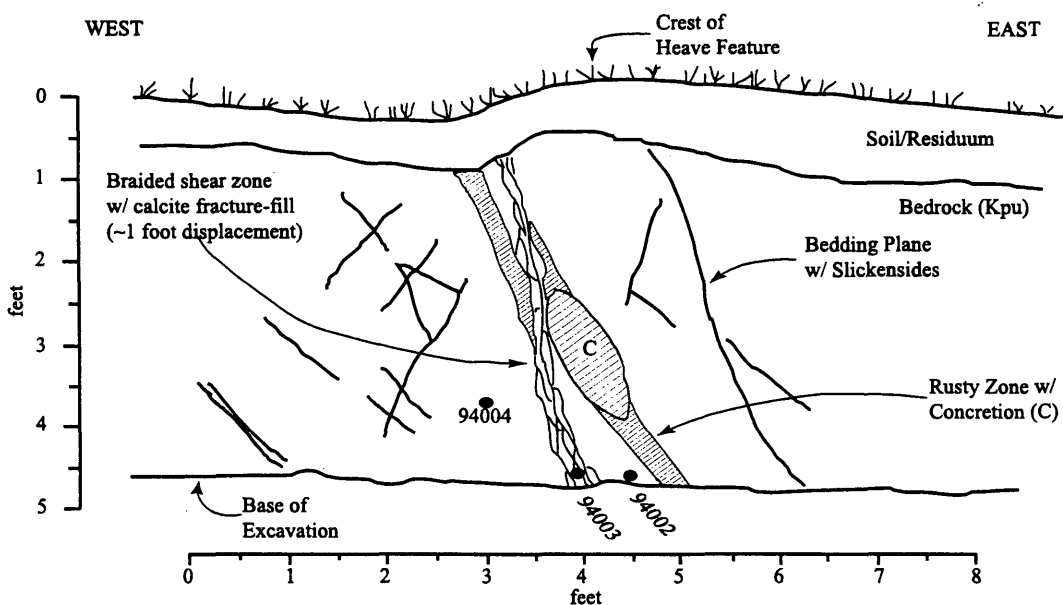


Figure 26. Clay properties for Pert's Park site (a) CEC, (b) Exchangeable Cations present, (c) Clay percentages in clay fraction: TS-Total Smectite, I/S-Mixed-layer illite/smectite, DS-Discrete smectite, Ot-Chlorite+Kaolinite+Illite.

Table 7. Pert's Park bulk mineralogy and quartz ratios from x-ray diffraction patterns; nd = not detected, cs = claystone, b = bentonite.

Sample	Mineral Phase							
	Quartz	Feldspar	Dolomite	Calcite	Gypsum	Smectite	Illite	Kaolinite
94002 cs	1	0.074	0.093	nd	nd	0.112	0.062	nd
94003 cs	1	0.380	0.070	0.628	nd	0.103	0.041	nd
94004 cs	1	0.070	0.120	0.160	nd	0.112	0.050	nd

Roxborough Village, Filing 101 (R101)

A single sample (93017) was collected for the Roxborough Village, Filing 101 (R101) sample suite from the Hygiene Sandstone, a low expansive member of the Pierre Shale. The CEC for this sample is 111meq/100g-clay having 4% sodium, 3% potassium, 63% calcium, and 29% magnesium on the exchange sites. The clay mineralogy is composed of 33% discrete smectite, 43% mixed-layer illite/smectite (with 78% smectite layers), 20% illite, 3% kaolinite, and 1% chlorite. The total smectite calculates to be 67% of the clay fraction.

The bulk mineralogy of sample 93017 is typical of a Pierre Shale silty claystone in this study. The phases and corresponding ratios are as follows: quartz (1), dolomite (0.111), feldspar (0.107), smectite (0.070), illite (0.041), and calcite (0.027).

Roxborough Village, Filing 13 (R13)

The Roxborough Village, Filing 13 (R13) suite is from Douglas County (figure 14). At this site, slope creep has acted on the beds causing them to overturn from down-

slope movement. Therefore, much of the deformation that is observed in figure 15 is attributed to down-slope movement and not exclusively to the heaving bedrock.

The suite contains 6 samples from the lower shale unit of the Pierre Shale (figure 15). Figure 27a shown below is the CEC for the 6 samples. The bentonite beds are samples 93014, 93011, 93013, and 93009. These samples have notably higher CEC's than the silty claystones (from 112meq/100g-clay to 120meq/100g-clay) with the exception of sample 93014 at 88meq/100g-clay (figure 27a). The CEC for this bentonite is similar to the CEC for the surrounding silty claystones.

The exchangeable cations (figure 27b) are similar for all the samples in this suite. The calcium averages 65 percent, ranging from 50 to 72 percent. The magnesium is lower than calcium with an average value of 29 percent, ranging from 23 to 42 percent. Sodium and potassium are very low averaging 5 percent and 1 percent, respectively.

Four out of the six samples in this suite are bentonites and are easily distinguished by their clay mineralogy (figure 27c). The bentonites have a typical composition of 100 percent discrete smectite (which also equals 100 percent total smectite). The two siltstones have a total smectite composition near 85 percent, of which, about 74 percent on average is discrete smectite. The mixed-layer I/S in the siltstones averages 15% with 84% of the layers being smectite. The silty claystones contain 10% illite, 2% kaolinite, and 0% chlorite, on average.

The bulk mineralogy of the Roxborough Village (R13) bentonites (93009, 93011, 93013, 93014) differs from previously discussed bentonites because they are not entirely composed of smectite and gypsum (table 8). They contain quartz, feldspar, and in some samples, gypsum.

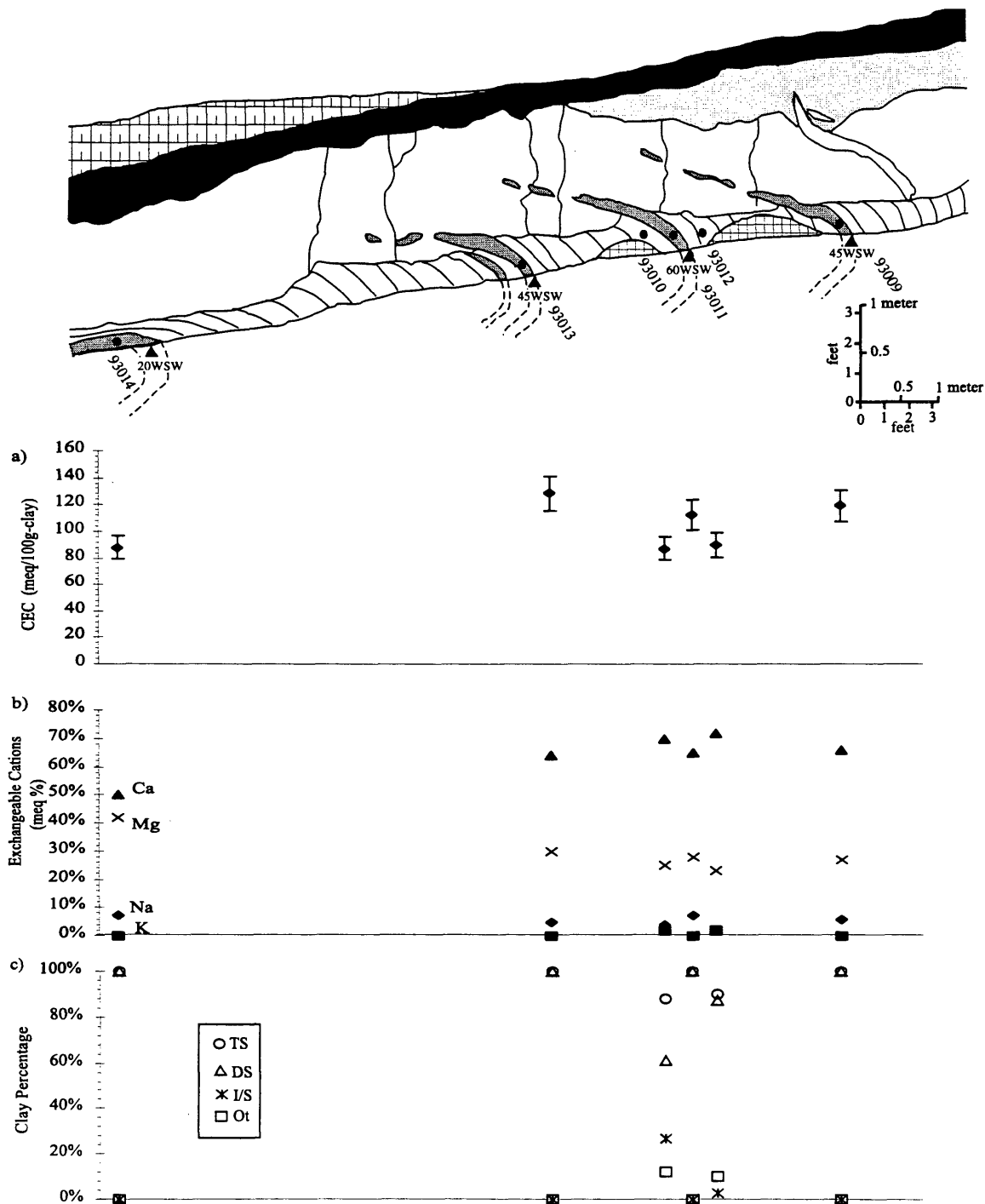


Figure 27. Clay properties for Roxborough Village, Filing 13 site (a) CEC, (b) Exchangeable Cations, (c) Clay percentages in clay fraction: TS-Total Smectite, I/S-Mixed-layer illite/smectite, DS-Discrete smectite, Ot-Chlorite+Kaolinite+Illite.

Table 8. Roxborough Village, Filing 13 bulk mineralogy and quartz ratios from x-ray diffraction patterns; nd = not detected, cs = claystone, b = bentonite.

Sample	Mineral Phase							
	Quartz	Feldspar	Dolomite	Calcite	Gypsum	Smectite	Illite	Kaolinite
93009 b	1	nd	nd	3.524	nd	10.952	nd	nd
93010 cs	1	0.065	0.108	0.029	nd	0.108	0.038	nd
93011 b	1	nd	nd	nd	nd	3.096	nd	nd
93012 cs	1	0.084	0.113	0.029	0.172	0.167	0.046	nd
93013 b	1	0.382	0.794	1.059	1.882	6.500	nd	nd
93014 b	1	0.541	nd	4.973	nd	12.162	nd	nd

RV Trench (RV)

There were a total of seven samples taken from the RV site. Four samples (92027-92030) were taken on the trench floor (figure 17), two on the east side of the heave and two on the west side. Sample 92031 was taken from a single lenticular, severely sheared bentonite bed not shown on figure 28. The other two samples were taken from material excavated from the trench and are typical of the gypsum and calcite fracture fills in the area (not shown on figure 28), and only bulk mineralogy was determined for these samples.

The CEC (figure 28a) shows that the samples (92027-92030) differ only slightly from 59 to 62 meq/100g-clay. Figure 28b shows the cations on the clays are almost identical with calcium at 54 to 61 percent, magnesium at 32 to 36 percent, sodium at 3 to 7 percent, and potassium at 4 percent. The CEC of the single sample (92031) is 85 meq/100g-clay with 6% from sodium, 1% from potassium, 63% from calcium, and 30% from magnesium.

The clay mineralogy among samples 92027-92030 is similar (figure 28c). The samples are dominated by mixed-layer illite/smectite (averaging 68%) with 89% of the

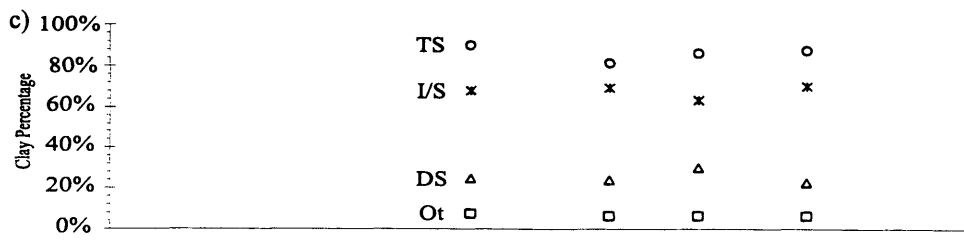
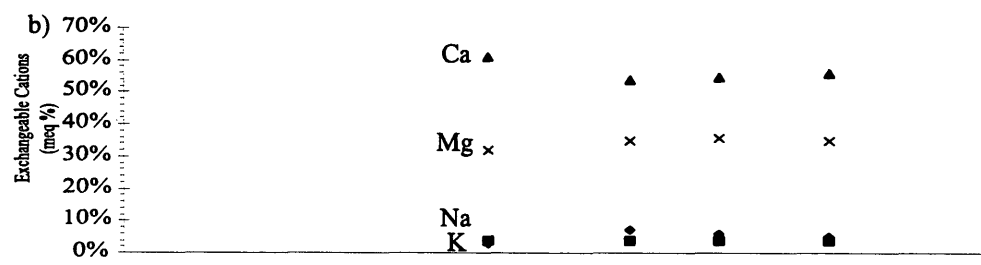
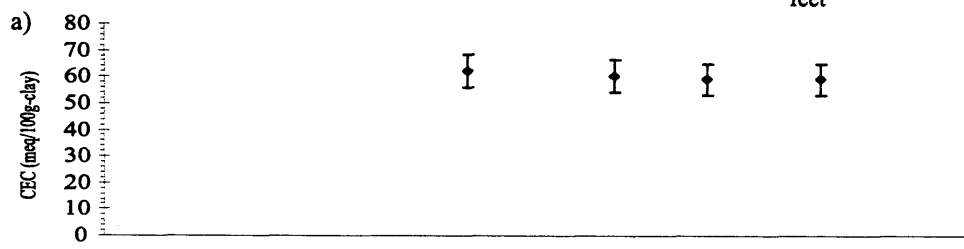
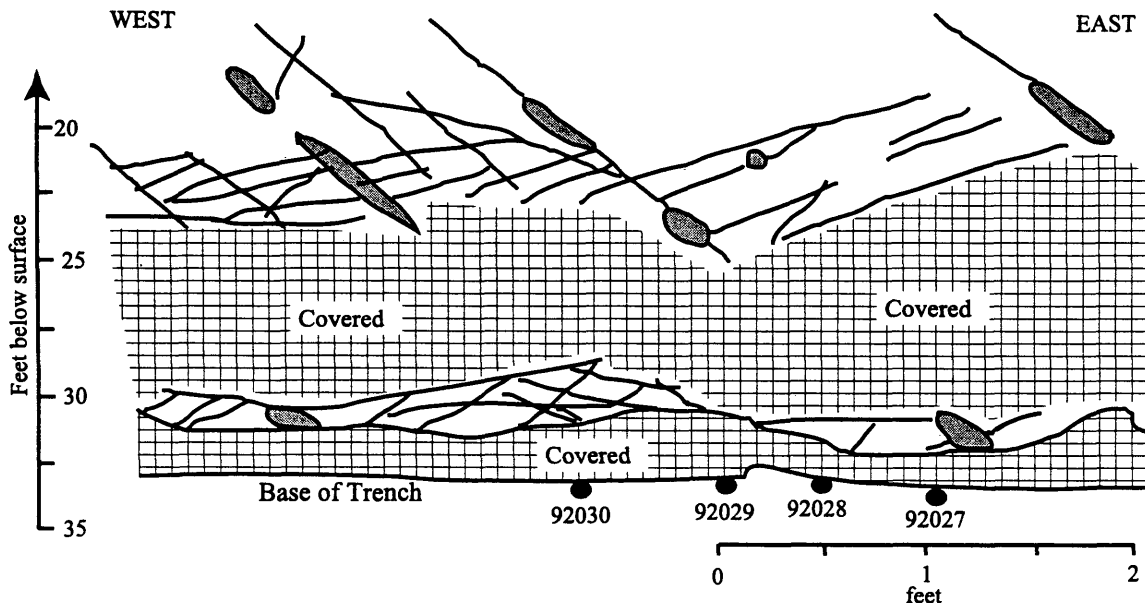


Figure 28. Clay properties for RV Trench site (a) CEC, (b) Exchangeable Cations, (c) Clay percentages in clay fraction: TS-Total Smectite, I/S-Mixed-layer illite/smectite, DS-Discrete smectite, Ot-Chlorite+Kaolinite+Illite.

layers being smectite. The RV samples contain a total smectite percentage of 86%, on average, in conjunction with the discrete smectite averaging 26%. The mineralogy of sample 92031 is comprised of 100% discrete smectite, which is typical for bentonite from the Pierre Shale.

Samples 92027-92030 have a similar bulk mineralogy (table 9) as other silty claystones in the Pierre Shale and are very consistent within this suite with dolomite varying the most from 0.099 to 0.063 ratio to quartz. Sample 92031 has a typical bentonite mineral composition of quartz (1) and smectite (2.52). Samples 92032 and 92033 are samples of fracture fills. Sample 92032 is gypsum fracture-fill taken from the Pierre Shale, and sample 92033 is a calcite fracture-fill also taken from the Pierre Shale.

Table 9. RV Trench bulk mineralogy and quartz ratios from x-ray diffraction patterns; nd = not detected, cs = claystone, b = bentonite, ff = fracture fill.

Sample	Mineral Phase							
	Quartz	Feldspar	Dolomite	Calcite	Gypsum	Smectite	Illite	Kaolinite
92027 cs	1	0.109	0.099	nd	nd	0.117	0.046	0.036
92028 cs	1	0.109	0.092	nd	nd	0.121	0.054	0.038
92029 cs	1	0.143	0.063	nd	nd	0.177	0.067	0.029
92030 cs	1	0.135	0.071	nd	nd	0.097	0.067	0.038
92031 b	1	nd	nd	nd	nd	2.521	nd	nd
92032 ff	1	nd	nd	nd	18.370	0.222	nd	nd
92033 ff	nd	nd	nd	1	nd	0.012	nd	nd

Roxborough Southdowns (RS)

Roxborough Southdowns (RS) is the only suite of samples analyzed that are from the Morrison Formation (figure 19). The 11 samples were collected from 7 well-defined stratigraphic units which include siltstones, clayey siltstones, and sandstones. Figure 29a shows the CEC for the RS samples. The samples show large variations from within the

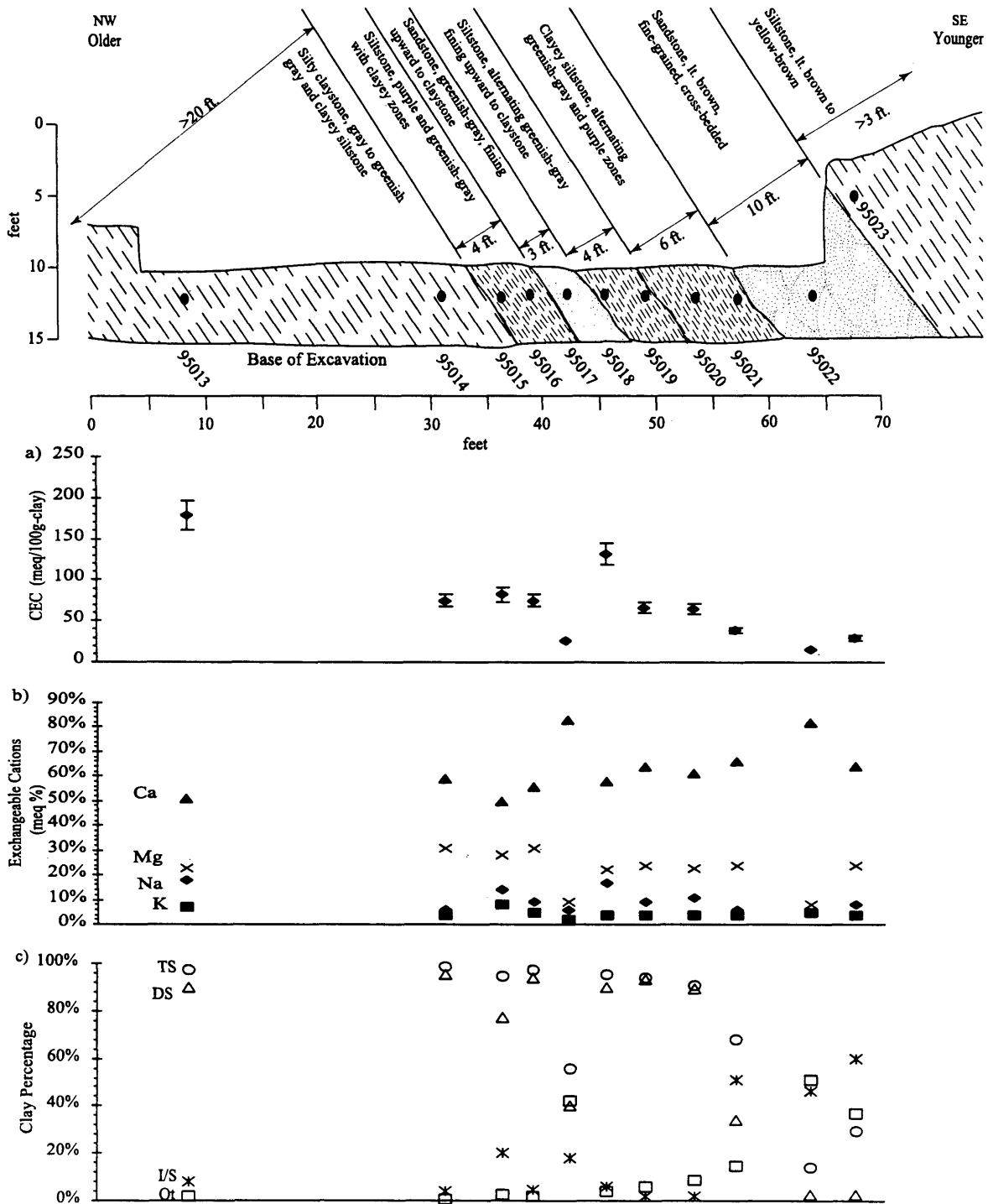


Figure 29. Clay properties for Roxborough Southdowns site (a) CEC, (b) Exchangeable Cations present, (c) Clay percentages in clay fraction: TS-Total Smectite, I/S-Mixed-layer illite/smectite, DS-Discrete smectite, Ot-Chlorite+Kaolinite+Illite.

same bed, such as samples 95013 and 95014 with CEC's of 178 to 75 meq/100g-clay, respectively. The siltstones are in the 40 to 82 meq/100g-clay range with two anomalous highs (samples 95013 and 95018) and one low (sample 95023). The sandstones are expectantly low at 31 meq/100g-clay (95017) and 26 meq/100g-clay (95022).

The exchangeable cations are dominated by calcium at 50 to 66 percent for the siltstones (figure 29b) with the two sandstones at 83 and 82 percent. The magnesium is consistent through the suite at 22 to 31 percent for the siltstone samples, but the two sandstones are unusually depleted in magnesium with 9 and 8 percent. The sodium varies from 5 percent (sample 95022) to 18 percent (sample 95013) with an average of 10 percent. The potassium is low and varies very little from sample to sample, averaging only 5 percent.

The clay mineralogy is highly variable for the suite, as shown in figure 29c. Samples 95013-95020 have a large percentage of total smectite (discrete smectite plus smectite in mixed-layer I/S) averaging 96%, excluding the sandstone (sample 95017). There is an abrupt drop in total smectite at sample 95021 (to 68%) and continues to drop at samples 95022 and 95023. It is of particular interest that the "Other" clays (Chlorite+Kaolinite+Illite) dominate the clay mineralogy; discrete smectite has decreased to 3 percent for samples 95022 and 95023. Mixed-layer I/S increases in samples 95021, 95022, and 95023 from 8% (with 91% smectite layers) to 52% (with 45% smectite layers), on average.

The Morrison Formation bulk mineralogy (table 10) is different from the Pierre Shale. The Morrison Formation samples are mainly smectite with lesser amounts of feldspar. Dolomite and gypsum were absent from these samples.

Table 10. Roxborough Southdowns bulk mineralogy and quartz ratios from x-ray diffraction patterns; nd = not detected, sl = siltstone, st = sandstone.

Sample	Mineral Phase							
	Quartz	Feldspar	Dolomite	Calcite	Gypsum	Smectite	Illite	Kaolinite
95013 sl	1	0.058	nd	nd	nd	0.244	nd	nd
95014 sl	1	nd	nd	nd	nd	0.691	0.043	nd
96015 sl	1	nd	nd	nd	nd	0.283	0.030	0.017
95016 sl	1	nd	nd	nd	nd	0.342	nd	0.058
95017 st	1	0.028	nd	0.106	nd	nd	nd	0.008
95018 sl	1	nd	nd	nd	nd	0.189	nd	0.033
95019 sl	1	nd	nd	nd	nd	0.300	nd	0.054
95020 sl	1	0.058	nd	nd	nd	0.215	0.019	0.050
95021 sl	1	0.050	nd	nd	nd	0.033	nd	0.075
95022 st	1	0.016	nd	nd	nd	nd	nd	0.020
95023 sl	1	0.053	nd	nd	nd	0.016	0.029	0.065

Wyoming Bentonite (WB)

The single sample of Wyoming Bentonite (WB) is typical of the sodium-rich bentonite that is mined in the Bighorn Basin of Wyoming. The CEC for this sample is 100meq/100g-clay, which is not dissimilar to the bentonites of the Pierre Shale.

The exchangeable cations are very diagnostic for this sample. It has an exchangeable sodium percentage of 79%, calcium at 5%, magnesium at 15%, and potassium at 1%. The clay mineralogy is composed entirely of discrete smectite, which is very similar to the bentonites of the Pierre Shale.

The WB sample has a bulk mineralogy of mainly smectite (ratio to quartz of 1.453) with lesser amounts of feldspar at a quartz ratio of 1.260. Other minor constituents included calcite at 0.253 and illite at 0.180.

Reproducibility of Cation Exchange

Fourteen analysis were duplicated in order to determine an error in the total CEC. The average error was determined to be 9.5% and is reflected in the error bars on all the CEC plots. The error in CEC is small relative to the variability observed in the samples.

A portion of the CEC error in the cation exchange procedure is attributed to the analytical instrument. Ten samples were chosen at random and their cation exchange solutions were reanalyzed. The analytical error for the ten samples averaged 2.3%. So, 2.3 of the 9.5% error in the total cation exchange procedure is attributed to the Atomic Adsorption Spectrophotometer and the calibration line technique. The heterogeneity of the samples can also introduce error into reproducing the cation exchange.

DISCUSSION

Clay properties give insight into the mechanisms that control the engineering properties and, in turn, the location and severity of potential heaving bedrock. The clay mineralogy within the Pierre Shale is spatially and stratigraphically uniform.

Cation-exchange-capacity (CEC), exchangeable sodium percentage (ESP), and percent smectite are fundamental properties that control the degree to which the clay minerals swell (Mitchell, 1993). Variations in ESP are directly related to the degree of weathering that alters the bulk mineralogy.

Depositional mixing of clay minerals was observed at bentonite beds. Silty claystones stratigraphically above bentonite beds show increases in the percentage of discrete smectite and CEC, indicating that fluvial mixing or continued ash-fall during the deposition of the subsequent silty claystone beds did occur.

The RV Trench (RV) location was observed to heave before sampling. The clay properties are very consistent across the heave feature.

Clay Mineralogy

The clay mineralogy of the silty claystones within the Pierre Shale are relatively uniform, both spatially and stratigraphically. The Pert's Park (PP) samples are located 1.5 miles away from the Fairway Vista samples (figure 1), but the two locations are stratigraphically equivalent (figure 2). The total smectite in the PP suite averages 81% with a standard deviation of 2.1% (table 11). The total smectite at FV averages 89% with

a standard deviation of 0.05%. The difference between the two averages is only 9.4% (table 11). The mixed-layer illite/smectite clay phase does vary between locations and averages 31% (84% smectite layers) at PP and 48% (84% smectite layers) at FV.

Discrete smectite is similar to mixed-layer illite/smectite in its abundance. The averages are 55% and 41%, respectively, with a difference of 14%, illustrating that samples taken at similar stratigraphic horizons but spatially removed have near similar clay mineralogical composition with variations of less than 15%.

Table 11. Clay mineralogy (averages) of selected cross-sections.

Stratigraphic Interval	Sampling Location	Total Smectite	Mixed-layer illite/smectite	Discrete smectite
Upper Pierre Shale	PP	81%	31%	55%
Upper Pierre Shale	FV	89%	48%	41%
Middle Pierre Shale	BC	86%	47%	47%

The Bowles Church (BC) silty claystone samples are stratigraphically older than the Fairway Vista (FV) claystone samples (figure 2) and are spatially 1.6 miles apart (figure 1). The total smectite for BC averages 86% (table 11) with a standard deviation of 0.04, and the FV claystones average 89% with a standard deviation of 0.05%, a difference of only 3.4%. The mixed-layer illite/smectite and discrete smectite show a similar relationship. Mixed-layer illite/smectite averages 47% (BC) and 48% (FV). Discrete smectite averages 47% (BC) and 41% (FV) (table 11). Samples taken from different stratigraphic horizons within the Pierre Shale exhibit similar clay mineralogical compositions. In this case, the Fairway Vista and Bowles Church suites show less than a 7% difference in clay mineralogy for all phases.

Bentonites from the Pierre Shale studied in this report (11 out of 55 the samples) have identical clay mineralogy and are composed entirely of discrete smectite. The

bentonites are assumed to originate from deposition of volcanic ash during volcanic eruptions. The only variations that were observed are the thickness and bulk mineralogy. The thickness is controlled by the duration of the ash fall event. The variations in bulk mineralogy are discussed below.

Variations in the Exchangeable Sodium Percentage (ESP)

The ESP varies stratigraphically within the Pierre Shale as shown in table 12. The Upper Campanian section Pierre Shale (figure 2) containing samples from SF, GM, PP, FVA, and FV have higher exchangeable sodium percentages, above 10% on average (table 12). In the Middle Campanian section of the Pierre Shale, near the Hygiene Sandstone Member, the ESP drops below 10%. Samples from RV, R101, BC, and R13 have an average ESP of 7% or less (table 12).

Table 12. Properties of bentonites from selected cross-sections.

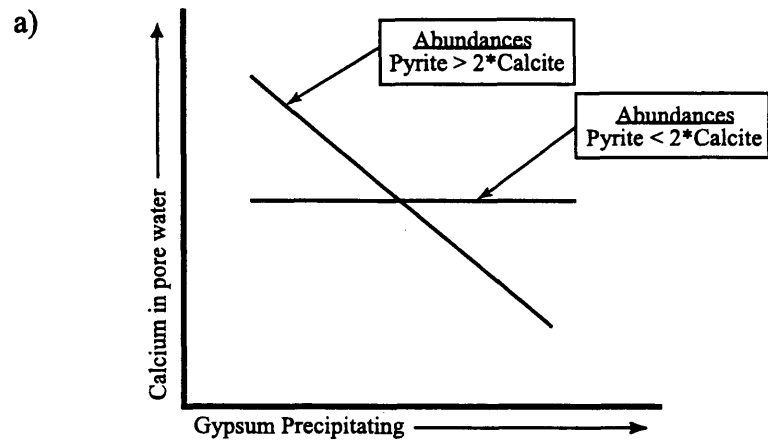
Stratigraphic Interval	Sampling Location	Average ESP	Gypsum	Calcite	Dolomite
Upper Pierre Shale	FV	24%	Present	Absent	Absent
Middle Pierre Shale	RV	5%	Absent	Absent	Absent
Middle Pierre Shale	BC	7%	Absent	Present	Absent
Lower Pierre Shale	R13	5%	Present	Present	Present

Gypsum formation appears to alter the exchangeable cations within the clays. For example, FV section has a higher average ESP than the BC section (table 12). A distinct difference between the two cross-sections is that the bentonite in the FV section contains gypsum (table 12) in the bulk sample as opposed to the BC section where gypsum is

absent (table 12). This may be explained by the oxidation of pyrite (FeS_2), which forms sulfuric acid and Fe^{+2} in solution. The Fe^{+2} oxidizes to Fe^{+3} and forms ferric oxyhydroxides (yellow in hand sample and usually amorphous) and more sulfuric acid (figure 30b). Tourtelot (1962) studied the weathering of the Pierre Shale in Montana and South Dakota. He stated that, "Sulfide minerals, such as pyrite and marcasite, in the rock are oxidized to sulfate compounds at a very early stage in the weathering of an outcrop....Pyrite is nearly always present in unweathered rocks of the Pierre Shale and equivalent units." The sulfuric acid dissolves carbonates (calcite and dolomite) and feldspars (albite). The bulk mineralogy of samples in this study contained no detectable pyrite, which indicates that oxidation has occurred.

Magnesium, calcium and sodium ions are released into solution during the dissolution of calcite, dolomite, and albite; thereby increasing pore water concentrations. The calcium reacts with the sulfate to form gypsum, depleting the calcium in the pore water (figure 30b). Tourtelot (1962) states that, "Sulfate ions brought near the surface of the outcrop by capillary movements of water form relatively insoluble calcium sulfate," (gypsum) "if calcium ions are present." If the exchangeable cations on the clay surface are in at least local equilibrium with the pore water, then as the calcium is depleted from the pore water, the clay releases calcium from the exchange sites and replaces it with more-abundant sodium and magnesium ions. This results in higher exchangeable sodium and magnesium percentages.

Figure 22b shows that the BC section averages 54% exchangeable calcium, 37% exchangeable magnesium, and 6% exchangeable sodium. Figure 24b shows that the FV section averages 29% calcium (lower), 45% magnesium (higher), and 24% sodium (higher), indicating that the calcium has been replaced by magnesium and sodium. Along with the higher ESP, the liquid limit and plasticity index is elevated (figure 25c), and an increase in the change in suction divided by the change in water content (h/w) is shown in



b)

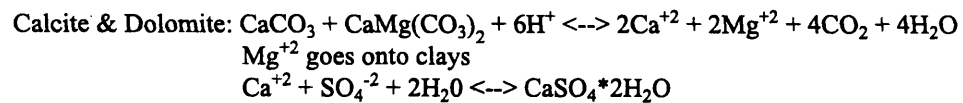
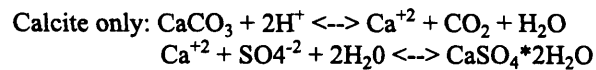
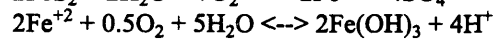
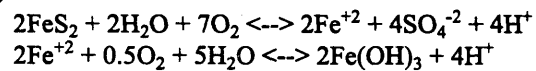


Figure 30. a) Schematic diagram of pyrite and calcite controlling the formation of gypsum, b) Reactions showing the process by which gypsum forms.

figure 25d. Accordingly, these samples have a higher swell category designation and higher swell potential (McKeen, 1992).

Controls on Gypsum Formation

The gypsum formation reaction (figure 30b) is partially controlled by the molar abundances of pyrite and carbonates (calcite and dolomite) in the whole rock. If pyrite concentrations are higher than twice that of calcite in the bulk sample, then the oxidation of pyrite will dissolve all the available calcite, resulting in the precipitation of gypsum and depletion of calcium in the pore water. This was observed at the FV site. If the bulk sample is dominated by calcite, then the pore water calcium concentration will remain constant during the formation of gypsum, which does not affect the exchangeable cations. This was observed at the R13 site. Table 11 shows that the R13 section contains gypsum, but the ESP is low (averaging only 5%). The presence of calcite demonstrates that twice the molar abundance of calcite compared to pyrite prior to weathering, therefore, there is no affect on the clay exchange sites. Figure 30a shows a schematic diagram of the concentration of calcium in the pore water as gypsum forms for these two situations. The stoichiometry for the reactions is shown in figure 30b.

The BC, RV, and R13 sections are interpreted to have been calcite-dominated systems because of the presence of calcite after weathering (table 12) and the lack of sulfides to produce gypsum. The FV section was a sulfide-dominated system before weathering because of the presence of gypsum after the oxidation of pyrite.

Bedrock depth also controls the oxidation of sulfides and the formation of gypsum. Tourtelot (1962) shows that insoluble sulfur (sulfides) in the Pierre Shale increase at depths greater than 10 feet. The sulfides are oxidized at depths less than 10

feet resulting in the formation of gypsum. The BC section was sampled at a depth of 12 feet, and the FV section was sampled at a depth of 7 feet. The deeper section (BC) did not show signs of gypsum formation because the sulfides may have not yet oxidized and are probably in small amounts not detectable by x-ray diffraction. Tourtelot performed his study on flat-lying Pierre Shale. The highly fractured, steeply dipping Pierre Shale along the Front Range may represent a different situation because water can penetrate deeper, causing the oxidation of sulfides to occur at a greater depth.

Mixing Zones at Bentonites

The silty claystones stratigraphically above (i.e. younger than) the bentonites show signs of mixing with the bentonites. This could be caused by continued ash-fall during the deposition of the siltstones or reworking of the already deposited ash. Figure 24a shows the CEC for the FV section. Sample 96014 shows a slight increase in CEC just above (east of) the bentonite, and sample 96016 shows an abrupt drop at the base of the bentonite. The total smectite (TS) in figure 24c shows a similar trend, and this trend is also observed in the suction (figure 25d). The suction data, CEC, and percentage of pure smectite suggests that these mixing zones, stratigraphically above the bentonites, have a slightly higher potential for heaving because of the increased pure smectite content from weathering of the volcanic ash. This phenomenon could explain the asymmetry of some of the heaves that have been observed in the field (Gill et al., 1996).

Heave Feature due to Shear

The RV Trench (RV) was observed to heave (2 inches) before sampling (Noe, 1997). The clay properties of the four samples that transect the observed heave are nearly identical. Figure 28a-c shows each sample to have nearly the same properties, including CEC, mineralogy, and exchangeable cations. The sampling at this site was constrained to the basal surface of the trench. These results would indicate that subsurface mechanisms are controlling the differential heaving in this area. The engineering data for these samples is not completed at this time but in the future can be found in Aaron Bagley's Master of Engineering report.

CONCLUSIONS

The clay properties of the Pierre Shale samples are spatially and stratigraphically similar. The clay mineralogy of the silty claystones are mainly dominated by mixed-layer illite/smectite (averages 49% with a standard deviation of 14.9%) which is dominated by discrete smectite (average: 82%, standard deviation: 7.7%) with varying amounts of illite (from 3 to 21%), kaolinite (from 1 to 10%), and chlorite (from 0 to 1%). The bentonites are purely discrete smectite.

The cation-exchange-capacities (CEC) for the silty claystones ranges from 59 to 134 meq/100g-clay and average 79 meq/100g-clay. The CEC for the bentonites ranges from 88 to 128 meq/100g-clay, averaging 113 meq/100g-clay.

The exchangeable cations are dominated by calcium and magnesium in both the bentonites and silty claystones. The calcium is in the 48 to 72% range (58% average) and magnesium ranges from 23 to 42% (33% average), excluding samples from Fairway Vista which are discussed below. Potassium comprises a small portion, less than 5%. The exchangeable sodium percentage (ESP) is quite variable (3 to 28%) and is closely tied to the bulk mineralogy as discussed below.

Variations in bulk mineralogy give insight into the relative abundances of the major exchangeable cations (calcium, magnesium, and sodium). These cations are interpreted to be influenced by the oxidation of sulfides, which produce sulfuric acid and sulfate ions in solution that, in-turn, dissolve carbonates and feldspars. This causes the concentrations in solution of calcium, magnesium, and sodium to increase. The calcium combines with the sulfate to form gypsum, therefore depleting the calcium concentration in solution. The low calcium concentration in solution forces the clay to release its exchangeable calcium. In order for the clay to maintain its charge balance, it must absorb

other cations such as magnesium and sodium. This effect can be observed by comparing the Bowles Church and Fairway Vista samples. The Bowles Church samples do not contain gypsum (table 5) and have low exchangeable sodium (3-9%) and magnesium (35-41%) and high exchangeable calcium (50-56%). The bentonite in the Fairway Vista section (sample 96015) contains gypsum (table 6) and the exchangeable sodium is 28%. The ESP for the entire section does not fall below 18%. The exchangeable calcium is depleted to less than 37% and magnesium is concentrated to greater than 40%.

The bulk mineralogy of the silty claystones from the Pierre Shale are mostly composed of quartz, feldspars, and clay minerals. Minor contributors are calcite, gypsum, and dolomite. The bentonites are almost entirely clay minerals (discrete smectite) with varying amounts of calcite and gypsum as minor constituents.

The clay mineralogy of the Wyoming bentonite sample is identical to bentonite samples from the Pierre Shale (100% discrete smectite). The Wyoming bentonite has very high concentrations of exchangeable sodium compared to a bentonite from the Pierre Shale. The ESP for the Wyoming bentonite is 79% compared to less than 30% for all the Pierre Shale samples studied. The sample has a plastic limit of 29% and a liquid limit of 480% (plasticity index of 451%) (Bagley, 1997).

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APPENDIX 1

The cation exchange procedure used for this report is outlined below. This procedure has never been published and was acquired through personal communication (Breit, 1996). It is not standard practice for the United States Geological Survey.

Cation Exchange Procedure

1. The sample is allowed to soak in deionized (DI) water for a minimum of three days. After three days, it is wet sieved through a 45 micron (μm) screen. The $>45\mu\text{m}$ fraction can be discarded and the $<45\mu\text{m}$ fraction is retained for the rest of the procedure.
2. The sample is washed three (3) times by suspending the less than 45 micron material in DI water and centrifuging to less than 0.10 μm size fraction, and then decanting (discard) the clear fluid. After each wash, the less than 45 micron material must be completely suspended in DI water. (Throughout this procedure, a wash or rinse cycle refers to centrifuging a sample to a 0.1 μm size fraction and suspending the material in the specified solution.)
3. Using a high frequency ultrasonic bath, sonify the sample for four (4) minutes.
4. Allow samples to remain undisturbed for five (5) minutes and note if flocculation occurs.

5. If sample flocculates, then it must be washed at least two (2) more times, see step one (2). The sample is then re-sonified and observed after five minutes. If flocculation persists then the sample must be washed until flocculation is no longer evident.
6. The sample is then centrifuged to a 1 micron size fraction for the clay separation.
7. Decant approximately two-thirds ($2/3$) of the suspended material into another centrifuge bottle.
8. Replace the decanted fluid from the centrifuge bottle containing the less than 45 micron size fraction with DI water and suspend material.
9. Again, centrifuge the less than 45 micron material to the 1 micron size fraction.
10. Decant approximately two-thirds ($2/3$) of the suspended material into the same centrifuge bottle as before.
11. Again, centrifuge the previously decanted 1 micron material to a 1 micron size fraction and decant as much fluid as possible into another centrifuge bottle, without disturbing any of the solids at the bottom.
12. Personal experience suggests taking the darkest sample, or the one with the most solids settling to the bottom, and preparing one oriented clay mount.

13. Scan the mount from $20^{\circ}2\theta$ to $27^{\circ}2\theta$. This will cover the two major quartz and calcite peaks. The counts per second for the $26.6^{\circ}2\theta$ should be under 300cps. Remember; there may be a clay peak at $\sim 26.6^{\circ}2\theta$ and it may not be possible to totally remove it. Use your judgment on whether it is a clay or quartz reflection. (I am using a step scan with a $0.02^{\circ}2\theta$ step and a two (2) second dwell time. A similar continuous scan can be calculated.)
14. If the quartz and/or calcite counts are too high, then the samples must be centrifuged again to a 1 micron size. I suggest either doubling the time, increasing the rotations per minute, or both. It is a good idea to bring as many samples through the process as possible and not just work with one. I usually work with six because that is what a typical centrifuge can hold.
15. Proceed when the quartz peak is at an acceptable level.
16. Prepare oriented clay mounts. (2-3 mounts)
17. Dry 20 ml of the clay suspension and weigh the clay. The mass of clay per unit volume of suspension can be determined.
18. To assure that the cation concentrations are large enough to analytically measure, there should be a minimum of 0.2 grams and a maximum of 1.0 grams used in the cation exchange. Samples suspected of having a low CEC should be closer to the 1.0 gram and vice versa for a high CEC.

19. The volume of 0.1 molar strontium chloride (SrCl_2) used in the cation exchange is determined by assuming CEC for the clay and calculating the corresponding milliequivalents (meq) per milliliter (ml) of exchange capacity.
20. The volume of SrCl_2 added at each rinse should be able to exchange ten (10) times the exchange capacity of the clay.
21. Combine the calculated volumes of clay and SrCl_2 in a centrifuge bottle. The samples cannot be allowed to evaporate during the cation exchange because it causes changes in concentration. Agitate and allow to sit overnight.
22. After allowing the clay and SrCl_2 to sit overnight, agitate and centrifuge all the clay to the bottom ($<0.1\mu\text{m}$).
23. Decant the clear SrCl_2 solution off from above the clay being careful not to remove any solids. Save the SrCl_2 , this is what will be analyzed. It is not important to save all the solution, but the total volume and the volume saved must be known.
24. Add a new volume of SrCl_2 to the clay, allowing it to sit overnight each time. Save all or a portion of the decanted solution.
25. After three (3) SrCl_2 washings, the samples are washed three (3) times with DI water. Check for residual chlorine in the decanted solution by adding silver nitrate. Residual chlorine means that there is also residual strontium that must be removed. A white precipitate will form with the presence of chlorine. If chlorine is present then the sample must be washed with DI water a fourth time and checked again. Continue

washing until no chlorine is detected. Caution, silver is highly toxic and should not be dumped down the drain.

26. After washing the samples with DI water, the clay must be dried and weighed.
27. The clay used in the cation exchange can be acid digested using hydrofluoric and nitric acids. The solution will be analyzed for strontium. The milliequivalents of strontium should be equal to that of the milliequivalents measured in the cation exchange solution. If the values are equal then we are assured that complete exchange occurred.

APPENDIX 2

Appendix 2 contains the complete data of the 55 samples that were analyzed for this report. The sampling location refers to: Bowles Church (BC), Fairway Vista (FV), Wyoming Bentonite (WB), RV Trench (RV), Roxborough Southdowns (RS), Fairway Vista “Apple-Green” Bentonite (FVA), Roxborough Village Filing 13 (R13), Roxborough Village Filing 101 (R101), Stanton Farms (SF), Pert’s Park (PP), and Green Mountain Partridge (GM). Table 1 shows the cation-exchange-capacity (CEC) and the exchangeable cation percentages. Table 2 shows the clay mineralogy, where I/S represents illite/smectite. Table 3 shows the bulk for the samples. For all tables, NA stands for not applicable.

Table 1. Sample #	Sampling Location	CEC (meq/100g-clay)	Exchangeable Cations			
			Na (% meq)	K (% meq)	Ca (% meq)	Mg (% meq)
96023	BC	90	9%	3%	50%	37%
96024	BC	85	9%	3%	52%	36%
96025	BC	106	3%	1%	55%	41%
96026	BC	114	6%	0%	56%	37%
96027	BC	119	9%	0%	56%	35%
96028	BC	115	8%	0%	54%	37%
96029	BC	92	8%	1%	54%	37%
96030	BC	75	5%	2%	54%	39%
96031	BC	73	6%	2%	52%	39%
96009	FV	66	24%	3%	25%	47%
96010	FV	74	23%	4%	27%	46%
96011	FV	70	18%	3%	31%	48%
96012	FV	74	18%	3%	36%	43%
96013	FV	73	23%	3%	30%	44%
96014	FV	80	26%	2%	27%	44%
96015	FV	117	28%	0%	30%	42%
96016	FV	71	25%	3%	28%	44%
96017	FV	71	24%	3%	29%	44%
96018	FV	71	24%	3%	30%	43%
96019	FV	71	23%	3%	30%	43%
96020	FV	72	23%	3%	30%	41%
96021	FV	81	26%	3%	30%	45%
96022	FV	75	27%	2%	27%	56%
94020	WB	100	79%	1%	5%	15%
92027	RV	59	5%	4%	56%	35%
92028	RV	59	6%	4%	55%	36%
92029	RV	60	7%	4%	54%	35%
92030	RV	62	3%	4%	61%	32%
92031	RV	85	6%	1%	63%	30%
92032	RV	No CEC	NA	NA	NA	NA
92033	RV	No CEC	NA	NA	NA	NA
95013	RS	178	18%	7%	51%	23%
95014	RS	75	6%	4%	59%	31%
95015	RS	82	14%	8%	50%	28%
95016	RS	75	9%	5%	56%	31%
95017	RS	296	6%	2%	83%	9%
95018	RS	132	17%	4%	58%	22%
95019	RS	66	9%	4%	64%	24%
95020	RS	65	11%	4%	61%	23%
95021	RS	39	6%	4%	66%	24%
95022	RS	26	5%	5%	82%	8%
95023	RS	29	8%	4%	64%	24%
93007	FVA	No CEC	NA	NA	NA	NA
93009	R13	119	6%	0%	66%	27%
93010	R13	87	4%	2%	70%	25%
93011	R13	112	7%	0%	65%	28%
93012	R13	90	2%	2%	72%	23%
93013	R13	128	5%	0%	64%	30%
93014	R13	88	7%	0%	50%	42%
93017	R101	111	4%	3%	63%	29%
94001	SF	No CEC	NA	NA	NA	NA
94002	PP	79	14%	3%	48%	36%
94003	PP	134	12%	2%	61%	25%
94004	PP	97	3%	4%	57%	36%
95043	GM	No CEC	NA	NA	NA	NA

Table 2. Sample #	Sampling Location	Clay Percentages in Clay Fraction					
		Chlorite	Kaolinite	Discrete Illite	Discrete Smectite	Mixed-layer I/S	Illite in I/S
96023	BC	trace	1%	4%	35%	59%	20%
96024	BC	trace	2%	3%	33%	61%	18%
96025	BC	0%	0%	0%	100%	0%	NA
96026	BC	0%	0%	0%	100%	0%	NA
96027	BC	0%	0%	0%	100%	0%	NA
96028	BC	0%	0%	0%	100%	0%	NA
96029	BC	0%	1%	3%	55%	40%	8%
96030	BC	0%	2%	5%	55%	38%	15%
96031	BC	0%	1%	6%	56%	37%	23%
96009	FV	1%	3%	13%	33%	51%	17%
96010	FV	1%	3%	13%	36%	48%	22%
96011	FV	1%	2%	11%	32%	54%	25%
96012	FV	1%	1%	6%	28%	64%	22%
96013	FV	1%	1%	5%	38%	55%	10%
96014	FV	trace	1%	3%	69%	27%	6%
96015	FV	0%	0%	0%	100%	0%	NA
96016	FV	trace	1%	7%	27%	64%	13%
96017	FV	trace	1%	7%	25%	67%	20%
96018	FV	1%	1%	8%	22%	68%	8%
96019	FV	trace	1%	14%	43%	42%	17%
96020	FV	1%	1%	14%	44%	40%	15%
96021	FV	1%	2%	10%	50%	39%	21%
96022	FV	0%	1%	4%	88%	6%	6%
94020	WB	0%	0%	0%	100%	0%	NA
92027	RV	0%	3%	4%	23%	70%	8%
92028	RV	0%	3%	4%	30%	63%	12%
92029	RV	0%	2%	4%	24%	69%	18%
92030	RV	0%	2%	4%	25%	68%	6%
92031	RV	0%	0%	0%	100%	0%	NA
92032	RV	NA	NA	NA	NA	NA	NA
92033	RV	NA	NA	NA	NA	NA	NA
95013	RS	0%	1%	1%	90%	8%	7%
95014	RS	0%	0%	1%	95%	4%	6%
95015	RS	0%	1%	2%	77%	20%	11%
95016	RS	0%	1%	1%	94%	5%	10%
95017	RS	2%	36%	4%	40%	18%	13%
95018	RS	1%	2%	1%	90%	6%	7%
95019	RS	0%	2%	4%	93%	2%	9%
95020	RS	1%	3%	5%	89%	2%	9%
95021	RS	0%	5%	10%	34%	51%	34%
95022	RS	0%	22%	29%	3%	46%	76%
95023	RS	0%	9%	28%	3%	60%	56%
93007	FVA	NA	NA	NA	NA	NA	NA
93009	R13	0%	0%	0%	100%	0%	NA
93010	R13	trace	1%	11%	61%	27%	22%
93011	R13	0%	trace	0%	100%	0%	NA
93012	R13	0%	2%	8%	87%	3%	10%
93013	R13	0%	0%	0%	100%	0%	NA
93014	R13	0%	0%	0%	100%	0%	NA
93017	R101	1%	3%	20%	33%	43%	22%
94001	SF	0%	10%	21%	39%	30%	22%
94002	PP	0%	2%	14%	54%	29%	17%
94003	PP	0%	1%	13%	53%	32%	13%
94004	PP	0%	2%	10%	57%	31%	17%
95043	GM	0%	trace	1%	95%	4%	10%

Table 3. Sampling		
Sample #	Location	Bulk Mineralogy
96023	BC	Quartz, Feldspar, Smectite, Dolomite, Illite
96024	BC	Quartz, Feldspar, Smectite, Dolomite, Illite, Calcite
96025	BC	Smectite
96026	BC	Smectite, Calcite
96027	BC	Smectite, Calcite, Quartz
96028	BC	Smectite, Quartz, Feldspar
96029	BC	Quartz, Smectite, Feldspar, Dolomite, Illite
96030	BC	Quartz, Feldspar, Smectite, Dolomite, Illite
96031	BC	Quartz, Feldspar, Smectite, Illite
96009	FV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
96010	FV	Quartz, Feldspar, Dolomite, Smectite, Illite
96011	FV	Quartz, Smectite, Feldspar, Gypsum, Dolomite, Illite, Calcite
96012	FV	Quartz, Dolomite, Gypsum, Feldspar, Calcite, Smectite, Illite
96013	FV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
96014	FV	Quartz, Smectite, Feldspar, Dolomite, Calcite, Illite
96015	FV	Gypsum, Smectite
96016	FV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
96017	FV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
96018	FV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
96019	FV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
96020	FV	Quartz, Smectite, Feldspar, Illite, Dolomite
96021	FV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
96022	FV	Gypsum, Quartz, Smectite
94020	WB	Smectite, Feldspar, Quartz, Calcite, Illite
92027	RV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
92028	RV	Quartz, Smectite, Feldspar, Dolomite, Illite, Kaolinite
92029	RV	Quartz, Smectite, Illite, Dolomite
92030	RV	Quartz, Feldspar, Smectite, Dolomite, Illite, Kaolinite
92031	RV	Smectite, Quartz
92032	RV	Gypsum, Quartz, Smectite
92033	RV	Calcite, Smectite
95013	RS	Quartz, Smectite
95014	RS	Quartz, Smectite, Illite
95015	RS	Quartz, Smectite, Illite, Kaolinite
95016	RS	Quartz, Smectite, Kaolinite
95017	RS	Quartz, Feldspar, Kaolinite, Smectite
95018	RS	Quartz, Smectite, Kaolinite
95019	RS	Quartz, Smectite, Kaolinite
95020	RS	Quartz, Smectite, Kaolinite, Feldspar, Illite
95021	RS	Quartz, Kaolinite, Feldspar, Smectite
95022	RS	Quartz, Kaolinite
95023	RS	Quartz, Kaolinite, Feldspar, Illite, Dolomite, Smectite
93007	FVA	Quartz, Calcite, Feldspar, Dolomite, Illite, Smectite
93009	R13	Smectite, Calcite, Quartz
93010	R13	Quartz, Dolomite, Smectite, Feldspar, Illite, Calcite
93011	R13	Smectite, Quartz
93012	R13	Quartz, Gypsum, Smectite, Dolomite, Feldspar, Illite, Kaolinite
93013	R13	Smectite, Gypsum, Quartz, Feldspar
93014	R13	Smectite, Calcite, Quartz, Feldspar, Kaolinite
93017	R101	Quartz, Dolomite, Feldspar, Smectite, Illite, Calcite, Kaolinite
94001	SF	Calcite, Quartz, Dolomite, Feldspar, Smectite, Illite
94002	PP	Quartz, Smectite, Dolomite, Feldspar, Illite, Kaolinite
94003	PP	Quartz, Calcite, Feldspar, Smectite, Dolomite, Illite, Kaolinite
94004	PP	Quartz, Calcite, Smectite, Dolomite, Feldspar, Illite, Kaolinite
95043	GM	Calcite, Quartz, Smectite, Kaolinite