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Pre-Illinoian Glaciation and Landscape Evolution in the Cincinnati, Ohio/Northern Kentucky Region

John S. Nealon

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I, John S. Nealon , hereby submit this original work as part of the requirements for the degree of Doctor of Philosophy in Geology.

It is entitled:

Pre-Illinoian Glaciation and Landscape Evolution in the Cincinnati, Ohio / Northern Kentucky Region

Student's signature: John S Nealon

This work and its defense approved by:

Committee chair: Thomas Lowell, PhD

Committee member: C.Dale Elifrits, PhD

Mark J. Bowers

Committee member: Mark Bowers, PhD

Warren D Huff

Committee member: Warren Huff, PhD

Committee member: J Barry Maynard, PhD

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Committee Approval Form

Pre-Illinoian glaciation and landscape evolution in the Cincinnati, Ohio/northern Kentucky region

A dissertation submitted to the
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DOCTOR OF PHILOSOPHY (Ph.D.)
In the Department of Geology of the College of Arts and Sciences
By
John S. Nealon, P.E., P.G.
B.S., University of Missouri at Rolla, 1984
M.S., University of Illinois at Urbana-Champaign, 1989
March 29, 2013

Advisor: Thomas V. Lowell, Ph.D.
Committee Members: J. Barry Maynard, Ph.D.
Warren D. Huff, Ph.D.
Mark T. Bowers, Ph.D.
C. Dale Elifrits, Ph.D.

Abstract

The Quaternary evolution of northern Kentucky near Cincinnati Ohio is dominated by multiple glaciations and changing drainage pathways. One problematic feature is the so-called Deep Stage where a major valley system was eroded below modern base levels. Over 90 deep borings provide evidence for at least five pre-Wisconsinan glacial advances of the Laurentide ice margin that reached into northern Kentucky. Two of these advances are identified in the Northern Kentucky uplands. This indicates that the portion of the now-buried Deep Stage valley west of Boone County, Kentucky was in place at the time of the initial Laurentide ice sheet invasion into the region.

The diversion of fluvial pathways produced temporary lakes. The Burlington Clays of Boone County, Kentucky were deposited in an unnamed lake west of the Anderson Ferry Divide and were separate from the Claryville Clays, which were deposited in Lake Claryville east of the Divide. The Burlington and Claryville Clays were deposited in separate lakes and at separate times, with at least one interval in which they were the same lake. These lakes were fed by southerly sources; eventually, the composition of the Burlington Clays was affected by the encroaching Laurentide glacier.

Lake Claryville was drained part of the time via the Levee, Kentucky col and its associated spillways, and by extension, via the Old and existing Kentucky Rivers. The lake was also drained part of the time by cols in the Anderson Ferry Divide in and south of Walton, Kentucky, and by the Old Eagle River and the existing Eagle Creek. This study employed the glacial systems model (GSM) of Tarasov et al. (2012) to model the effects of ice advance and retreat and to model the relationships between the Levee spillway, the cols in and near Walton, and the advancing ice front during ice advance and retreat. Because of the significant differences in elevation of the Walton and Levee cols at and near the point of maximum ice advance, the Levee col was not used near the time of maximum ice advance. Rather, the Levee col was used when the ice front was far enough to the north that crustal flexure between Walton and Levee was either at a minimum or was reversed on the leading edge of the forebulge, in combination with the Walton col being at a higher, pre-erosion elevation.

The broad significance of this study is that it tapped a new subsurface record of pre-Illinoian glacial events in the midwestern United States. This record suggests that major elements of the present landscape remain from preglacial times.

Acknowledgements

Many thanks are due to the management of Thelen Associates, Inc. for their support of my dissertation work. In addition to office space, a computer, and the quintessential printer and copier, Thelen provided drilling, sampling, and laboratory test services, as well as access to valuable geotechnical exploration files that have been compiled over the last 42 years. Thelen management has also supplied much patience, interest, and encouragement over the past five years, which is also much appreciated, and without which the work could not have been completed.

I also thank the managers of Sanitation District No. 1 of Northern Kentucky, and of the Metropolitan Sewer District of Greater Cincinnati, for their permission to use valuable drilling and sampling data as part of this dissertation work. The final product could not have come together without it.

I also express sincere thanks to my advisor, Tom Lowell, who had the difficult task of teaching a geological engineer (who thought he had it all figured out) a thing or two about how a geologist thinks problems through and then formulates hypotheses that can be tested. Among Tom's first comments to me at the outset was his conclusion that he would need to teach this engineer how to think like a geologist, and that this would be no simple task. No problem, I thought. But he was right, and his patience, mentoring, friendship, and occasional sternness are much appreciated.

I would also like to thank the members of my committee for their assistance. Warren Huff shared his passion for clay mineralogy, and was the first one I spoke with about pursuing a Ph.D.

after we made a field trip out to a jobsite in Alexandria to see a landslide that had formed in the Claryville Clays. His enthusiasm and encouragement got the ball rolling. Barry Maynard was the department's graduate chairman when I started my program. He introduced me to Tom and helped my schooling plans take shape. His willingness to bring me into the department and to help me get started down this long road was valuable, as was his soil geochemistry expertise. Mark Bowers' patient encouragement and wise counsel about how to balance the responsibilities of work, home, Church, and schooling were timely and much needed. When the Church asked me to be the new Bishop and to take on the difficult and time-consuming responsibilities of leading a congregation, I knew who the first man was that I needed to go and see for counsel. Mark welcomed me into his office, shut the door, and gave me what might have been the single most critical and important half-hour of instruction that I'd had since I started the program, and it made a tremendous difference. Dale Elifrits was my undergraduate advisor when I received by bachelor's degree way back in 1984, when he had brown hair and I had…..well, hair. Dale's enthusiasm for teaching, learning, and geology are still contagious. I am glad he made his home here in Northern Kentucky, and am thankful for his encouragement and for three decades of friendship.

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Many thanks also go to my classmates at the University of Cincinnati, who cheerfully let an old guy infiltrate their ranks and take up their time and attention, all while trying to learn to think metric, think like a geologist, and fit in. The memories of four-day field trips, Halloween parties, and excursions to far-off places are priceless. I hope you learned a few things from me as well.

I need to express my eternal gratitude to the Lord as well. Our Heavenly Father is real, and has shown me His love, support, and awesome power time and again over these last five years. Without His help, I could not and cannot prevail.

Last but not least, I offer deep and heartfelt gratitude to Kim, my loving and faithful wife and best friend of almost 28 years, and to my children, all of whom have put up with my frustrations, long hours away from home, occasional bad moods, and endless happy ramblings about such diverse topics as orthogonal fractures, Platystrophia ponderosa, and highly plastic Claryville Clays. Kim has been especially patient, supportive, and encouraging. I deeply appreciate her behind-the-scenes cheering and support while I have enjoyed the limelight of a successful career and of successful schooling, which has included journeys to distant and exciting places like Iceland and the Greater Himalaya that she could only see in the photos and stories I brought back home. I love you more than I can say, Kim. Thank you for *everything*. This whole work is dedicated to you, because without you, I am nothing.

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CHAPTER ONE

INTRODUCTION AND BACKGROUND

OVERVIEW

The evolution of the Deep Stage valley was a significant event in the geologic history of the Greater Cincinnati Area. The pre-glacial Teays River system (Fig. 1) had been abandoned, and the Teays valley buried under glacial debris. The new Deep Stage alignment (and by extension, that of the present-day Ohio River that now occupies it) shortened the drainage path from Cincinnati, Ohio to the mouth of the Ohio at Cairo, Illinois from about 1,200 km to 600 km (745 to 373 mi). This shortening forced then-existing tributary streams to undergo incision as they adjusted their gradients to that of the new Ohio River, abandoning paleovalleys, terraces, and meander loops at higher levels above their deepening valleys (Andrews, 2006). The Greater Cincinnati region was perhaps changed the most because it was here that the headwaters of the Old Ohio River were extended eastward beyond the barrier of the Anderson Ferry topographic divide (Figs. 2 and 3), allowing drainage to flow due west from the Pittsburgh, Pennsylvania area to Cairo, Illinois and the Mississippi River.

Many previous workers have studied the history of glaciation and landscape evolution in the Greater Cincinnati Area. Their research has paid a good deal of attention to large-scale issues such as dismantling of the Teays River system (Teller [1970]); formation of the Deep Stage valley (Durrell [1961], Granger et al. [2001];) organization of the present-day Ohio, Licking, and Kentucky Rivers (Wayne [1952], Teller and Goldthwait [1991]); and formation of glacial Lake Claryville, which extended eastward from Kentucky's Anderson Ferry Divide across

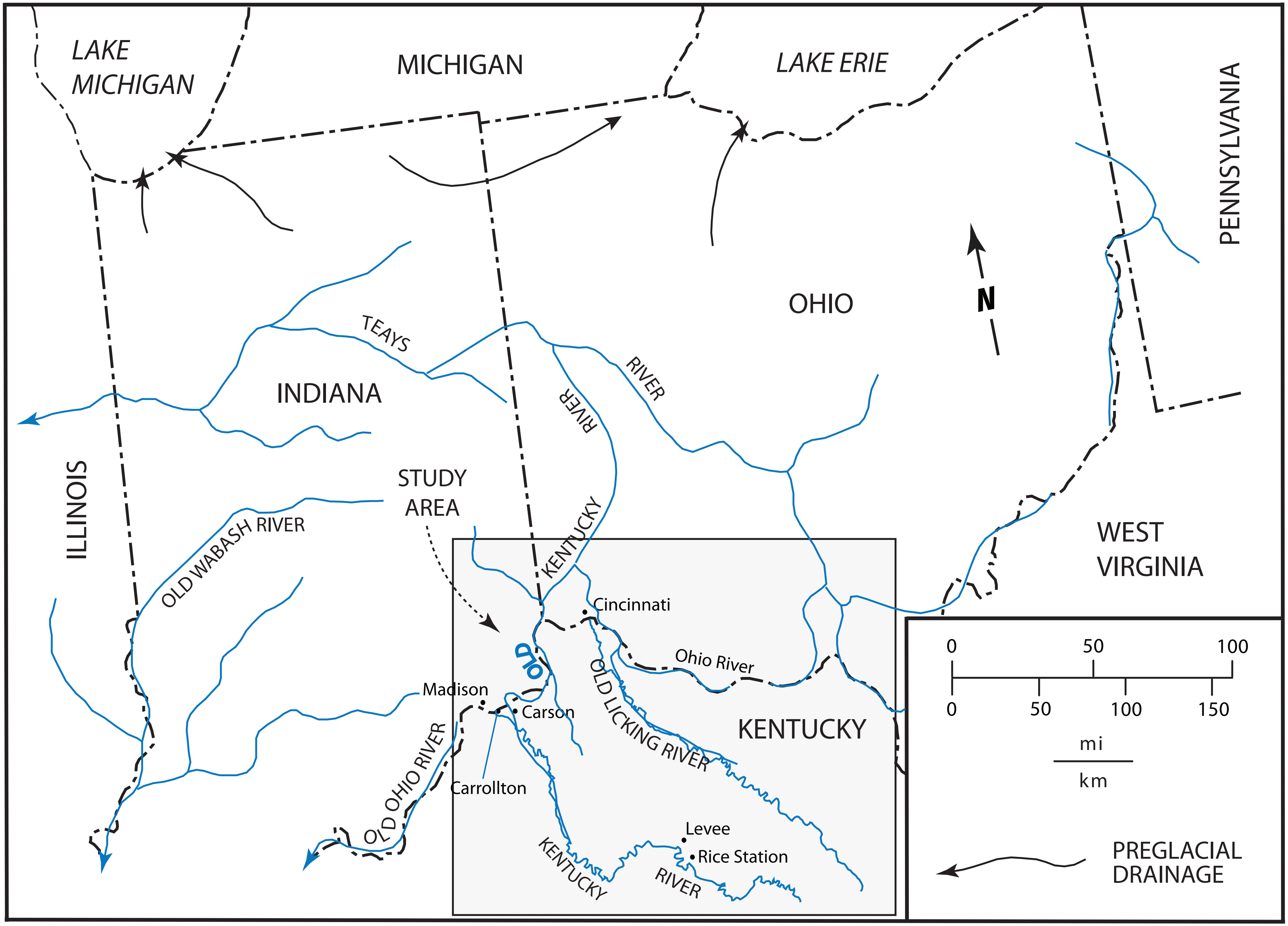
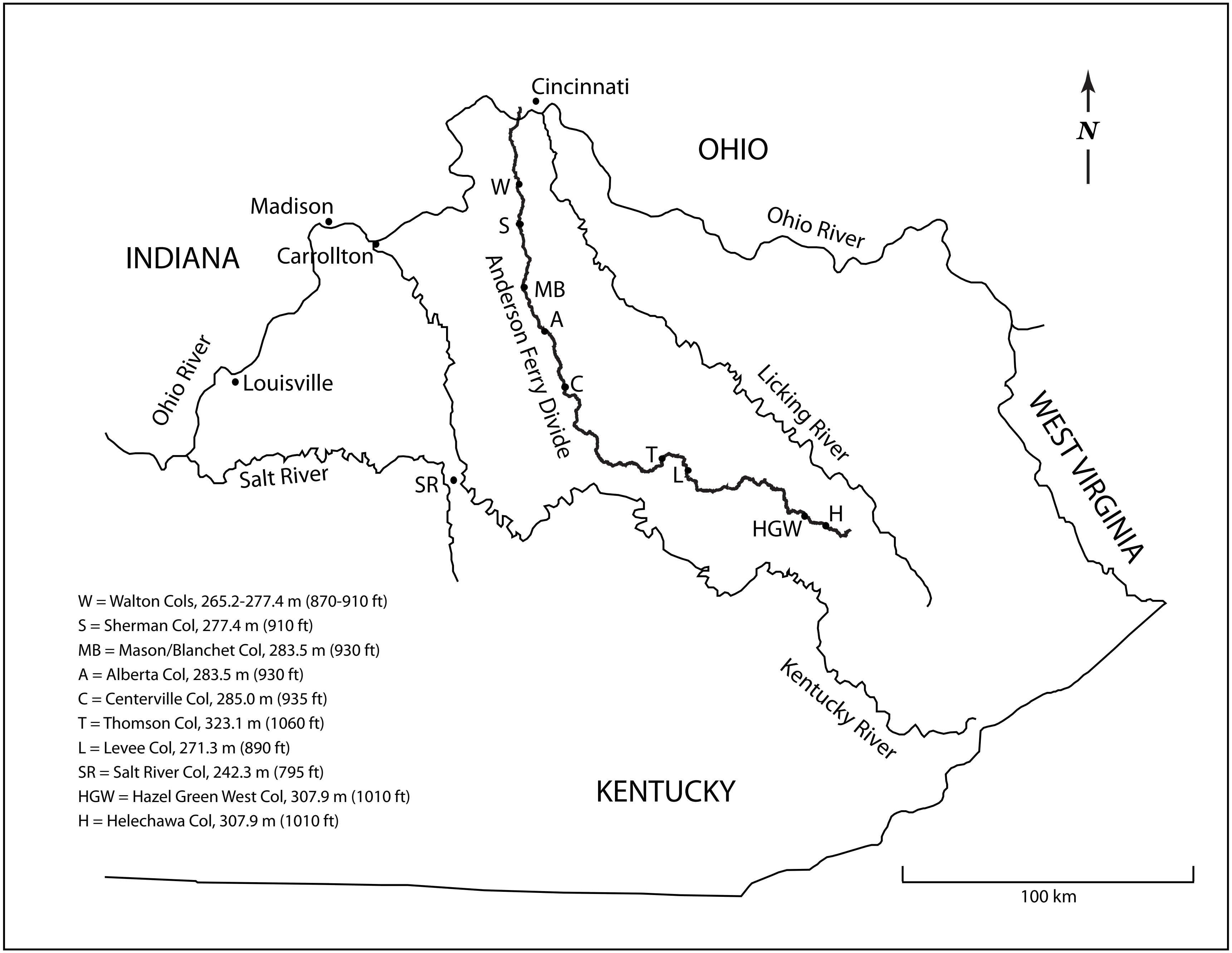


Figure 1. Map showing relationship of study area to Teays system drainage across West Virginia, Ohio, and Indiana (modified from Teller [1970]).



W = Walton Cols, 265.2-277.4 m (870-910 ft)
S = Sherman Col, 277.4 m (910 ft)
MB = Mason/Blanchet Col, 283.5 m (930 ft)
A = Alberta Col, 283.5 m (930 ft)
C = Centerville Col, 285.0 m (935 ft)
T = Thomson Col, 323.1 m (1060 ft)
L = Levee Col, 271.3 m (890 ft)
SR = Salt River Col, 242.3 m (795 ft)
HGW = Hazel Green West Col, 307.9 m (1010 ft)
H = Helechawa Col, 307.9 m (1010 ft)

Figure 2. Eastern Kentucky map showing locations of cols, rivers, and Anderson Ferry Divide discussed in text.

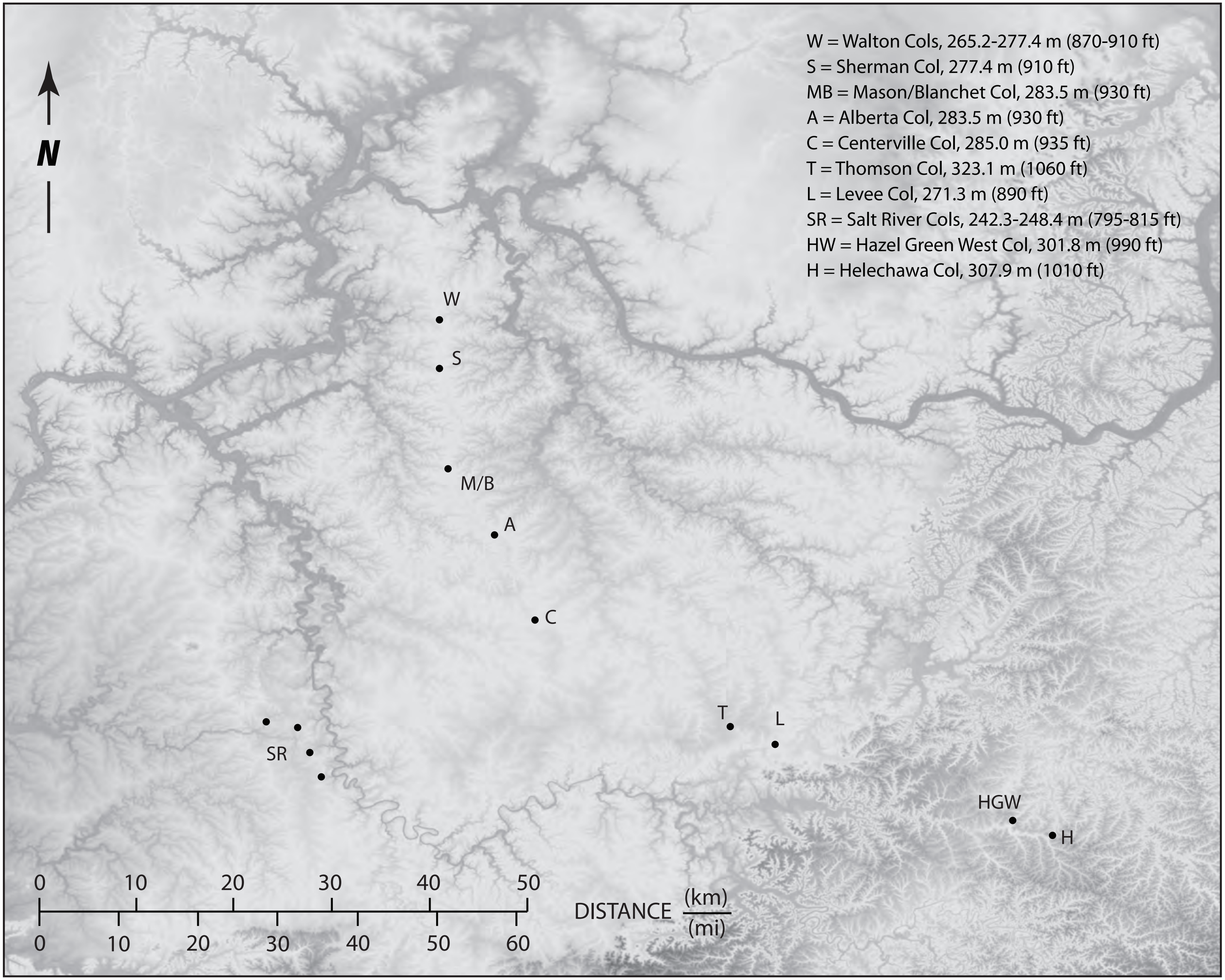


Figure 3. Digital elevation map showing locations of cols discussed in text.

northeastern Kentucky, southern Ohio, and into West Virginia (Andrews [2006]). Other research has also honed in on studies of the glacial materials that the Laurentide ice sheet and Lake Claryville left behind (Ettensohn [1970, 1974]).

The evolution of landscape and drainage on the west side of the Anderson Ferry Divide (hereafter referred to as "the Divide") in northern Kentucky has not been studied as extensively. This study has three major areas of focus that serve to develop and refine our existing knowledge of the events by which the Cincinnati region evolved from its preglacial condition, i.e., north-flowing drainage patterns developed on a shallow bedrock profile, to its present state, i.e., the west-flowing Ohio River cut deep into the topography. The first focus uses records of hundreds of geologic borings made in the Greater Cincinnati region over the past 40 years to introduce two new archives of northern Kentucky glacial materials and to expose and interpret the deep subsurface record in the region.

The first of these archives includes five clayey till units that exist near the Ohio River in western Boone County, Kentucky. The second of these archives includes lacustrine clays and interbedded clayey tills in the uplands of Boone County. In particular, this research has depended on a set of over 100 borings that were drilled in support of a major treatment facility in western Boone County, Kentucky north of Belleview, and a set of over 60 borings drilled across Boone County in support of a water conveyance tunnel connected to the plant. The general area of the treatment plant site is just north of the Cross Section B-B' location shown on Fig. 10. The portion of the tunnel alignment most relevant to this research is also shown on Fig. 10 as A-A', and is shown in detail on Figs. 22 and 23.

The second focus studies the effects of the glacier on the formation and drainage of temporary lakes in the Old Kentucky and Old Licking River basins. This focus is divided into two parts: 1) a study of the possible use of five cols (i.e., depressions in a ridge or divide) in the northern portion of the Anderson Ferry Divide to provide westward drainage for glacial Lake Claryville while the Laurentide ice sheet advanced to, and retreated from, its southern limit; and 2) a study of the role of isostatic crustal deflection during glaciation and deglaciation on the evolution of drainage in the Cincinnati region. The third focus is to characterize the provenance of the lake clays using X-ray diffraction (XRD) and X-ray fluorescence (XRD) techniques to look more closely at the mineralogy and geochemistry of northern Kentucky lacustrine clay materials on both sides of the Divide in order to compare and contrast them.

The results of study within these three major areas of focus has allowed 1) documentation of five glacial advances into northern Kentucky, and their timing relative to Deep Stage valley incision; 2) estimates of the magnitude and timing of crustal deflection, relative to the point of maximum glacial advance; and 3) characterization of the provenance of the Burlington and Claryville Clays, including an estimate of their relative ages. The three major focus areas and their results are developed in the following three chapters.

GEOLOGIC SETTING

In general, the area of study for this paper includes the Kentucky and Licking River basins, including their preglacial extensions into southwestern Ohio (Figs. 2 and 3). The Kentucky River basin to the west is separated from the Licking River basin to the east by a topographic

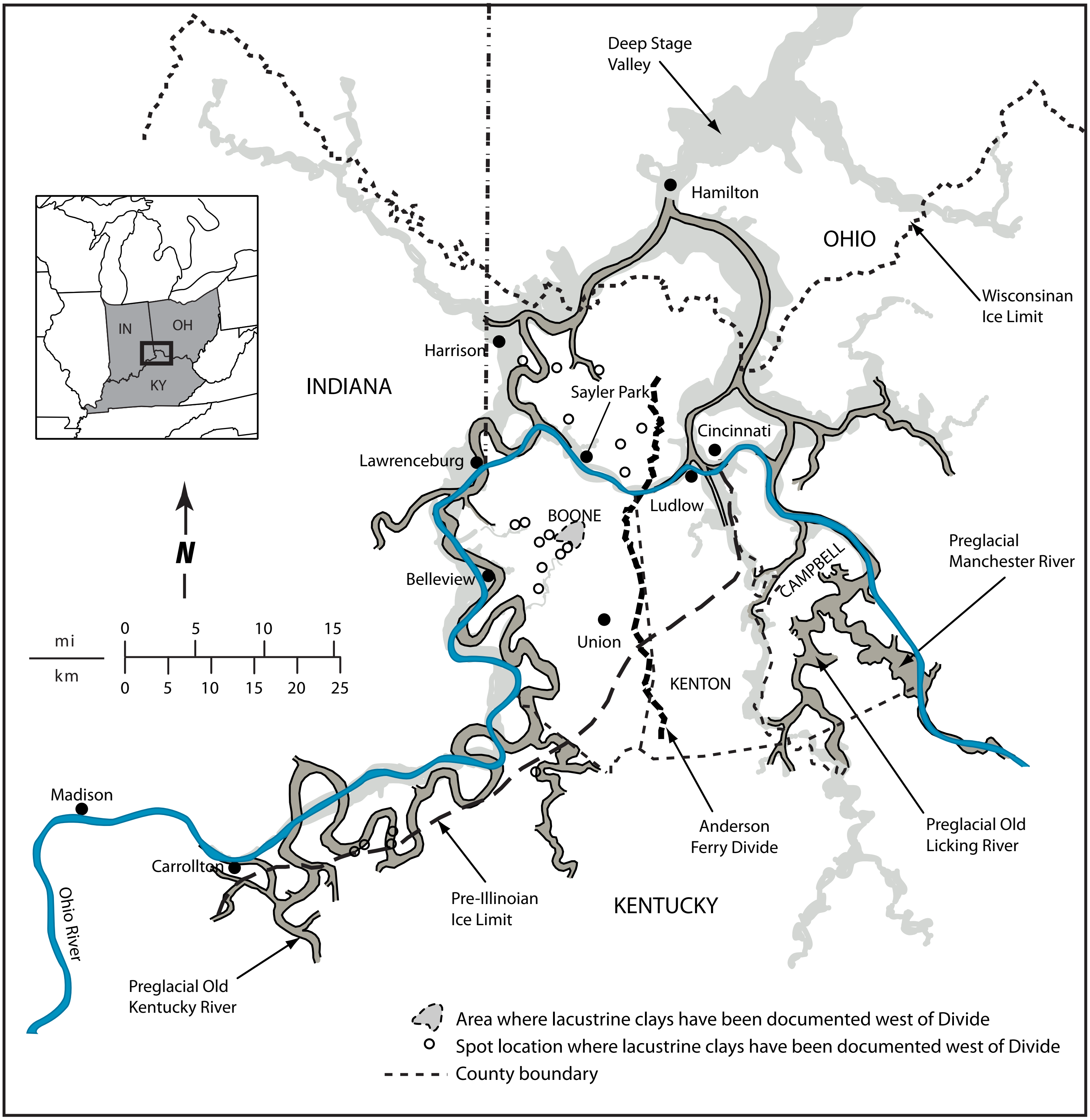


Figure 4. Map of northern Kentucky area showing features discussed in text.

divide known in the northern Kentucky area as the Anderson Ferry Divide, which has its northern terminus just south of Hamilton, Ohio. The northern Kentucky area is located south of Cincinnati, Ohio, and includes part of the margin of the maximum Laurentide ice sheet advance (Fig. 4).

Ohio and Kentucky are separated by the Ohio River and its underlying Deep Stage valley. Durrell (1961) refers to the "Deep Stage" as the westward-flowing drainage system formed by the breaching of divides between northward-flowing streams that were disrupted by southward-advancing ice (Fig. 2). The Deep Stage distinguishes itself from preglacial drainage in the Cincinnati region by its overall westward direction and by its greater width and depth of incision, likely caused by an increased volume of water from the combining of many watersheds and by the large volume of glacial meltwater it had to drain. The number of Laurentide ice sheet invasions is important because they altered the late Cenozoic landscape and created the landforms that exist today.

Cincinnati Region Geology

Cincinnati and Northern Kentucky are located over the axis of the Cincinnati Arch, a broad, gentle anticline extending from the Lexington, Kentucky area through the Greater Cincinnati area (Fig. 5). Erosion has exposed Ordovician rocks, chiefly thin- to medium-bedded limestones and shales, along the axis of the arch in the Greater Cincinnati area. Erosion has exposed Silurian, Devonian, Mississippian, and Pennsylvanian rocks on the east and west flanks of the arch.

NORTHWEST → SOUTHEAST

Maximum Thickness	>240 m	55 m	120 m	100 m	145 m	35 m	20 m	60 m	200 m	100 m	100 m	> 145 m
UNIT NAME	Pikeville Formation	Corbin Sandstone	Grundy Formation	Paragon Formation Slade Formation	Borden Formation Nada Member Cowbell Member Nancy Member	New Albany Shale	Boyle Dolomite	Crab Orchard Formation Brassfield Dolomite	Drakes Formation Bull Fork Formation Ashlock Formation Grant Lake Limestone Calloway Creek Limestone Garrard Siltstone	Kope / Clays Ferry Formation Point Pleasant Formation	Lexington Limestone	High Bridge Group Tyrone Formation Oregon Formation Camp Nelson Limestone
									Rich. Mays.	Edenian	Mohawkian	
	Pennsylvanian			Mississippian		Dev.		Sil.	Upper Ordovician			

Rich: Richmondian
Mays: Maysvillian

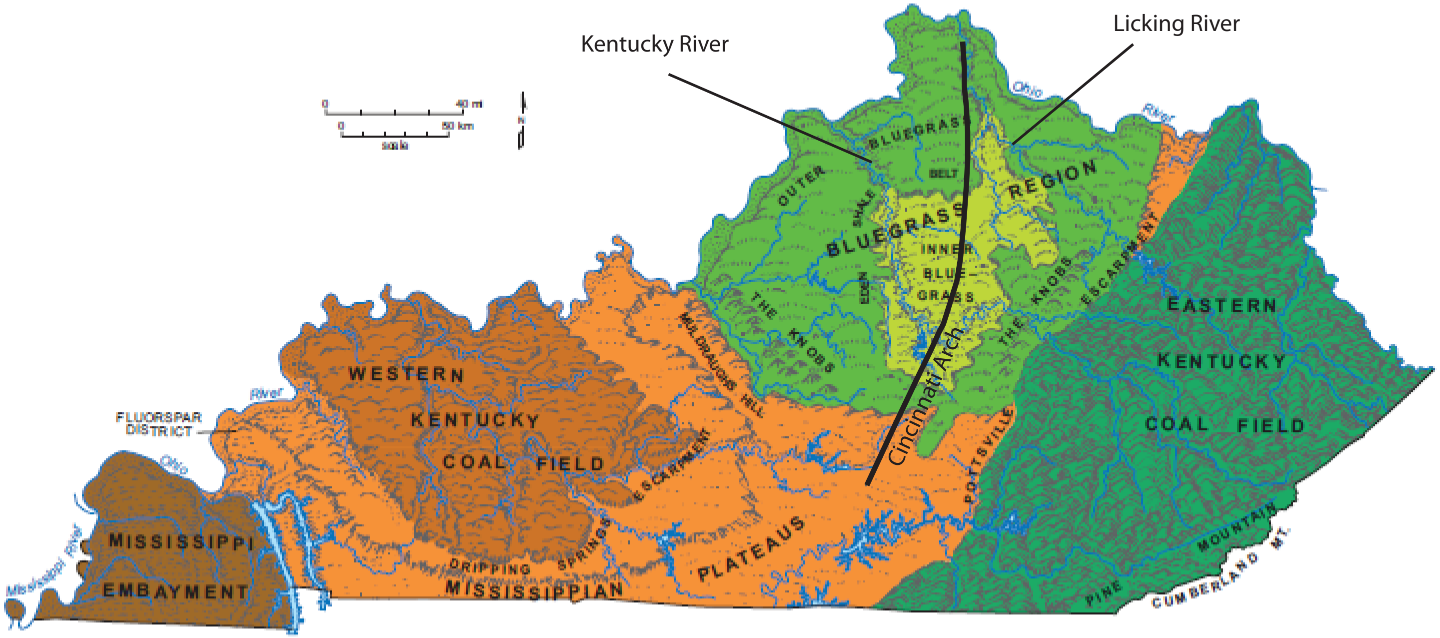


Figure 5. Geologic section (Andrews [2006]) and map of Kentucky physiographic provinces and Cincinnati Arch. TheKentucky and Licking Rivers have their headwaters in the Eastern Kentucky Coal Field, then pass through the Knobs, Inner Bluegrass, and Outer Bluegrass physiographic provinces on their way to the Ohio River (modified from Kentucky Geological Survey Map and Chart 25, Series XII, 2001).

The Deep Stage valley in the Cincinnati region was cut through the easily-eroded, thin- to medium-bedded limestones and shales of the Upper Ordovician Bull Fork, Fairview, Kope, and Point Pleasant Formations of the Outer Bluegrass physiographic province (Fig. 5). These are generally composed of 15 to 50 percent even bedded, thin- to medium-bedded limestone that is interbedded with silty, fissile shale. The Deep Stage has its floor in the Lexington Limestone.

The overburden soils filling the Deep Stage valley along the general Old Kentucky River alignment include interlayered outwash sands, outwash gravels, clayey tills, and colluvium (Figs. 6 and 7). Postglacial erosion and deposition have dissected and replaced some of the subsurface soils with alluvium and lacustrine soils. Blankets of eolian silt and fine sand have been deposited against hillsides in the Ohio River valley and the northern Kentucky uplands. In the uplands areas, the overburden soils are thinner and generally consist of eolian, alluvial, outwash, lacustrine, till, colluvial, and undivided drift soils (Gibbons [1972]).

The northern Kentucky area includes the Laurentide pre-Illinoian ice limit, but is south of the Wisconsinan ice limit (Fig. 4). Therefore, northern Kentucky contains pre-Wisconsinan tills as well as Wisconsinan outwash (Swadley [1972]), but contains no Wisconsinan tills.

Central Kentucky Geology

Because the effects of pre-Illinoian glaciation on the northern Kentucky area included the use of cols and spillways as far south as Levee, Kentucky, a description of the geology of the Kentucky and Licking River basins is appropriate. Much of the present-day Kentucky and Licking Rivers are cut into the easily-eroded, thin- to medium-bedded shale and limestone bedrock of the Outer

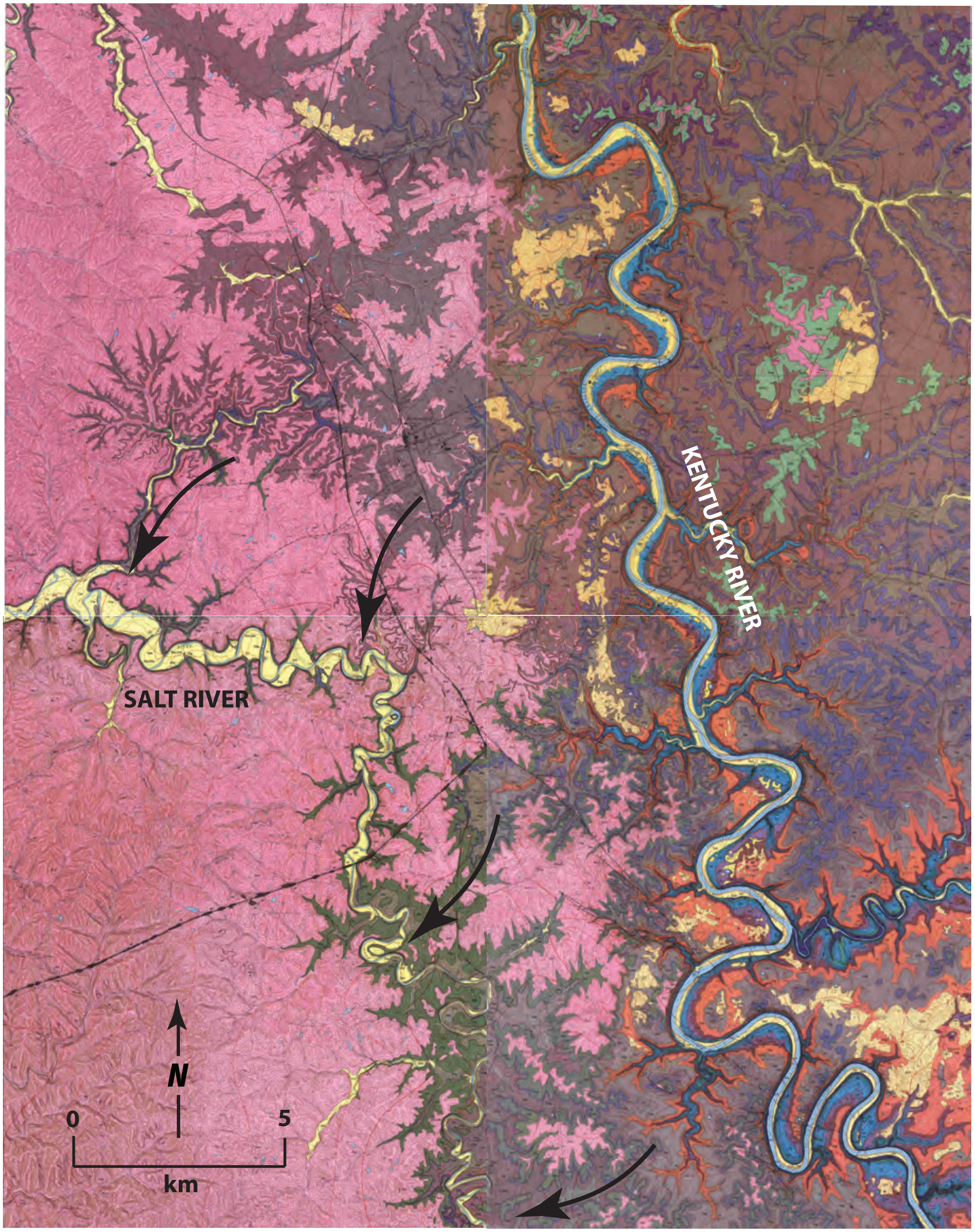


Figure 6. Paleochannels connecting captured, north-flowing tributary of Old Kentucky River with the existing Kentucky River valley near Lawrenceburg, Kentucky. The captured segment is now part of the west-flowing Salt River. The paleochannels have col elevations ranging from 242.3 to 248.4 m (795 to 815 ft). Andrews (2006) concluded that the capture of the Old Kentucky River tributary was contemporaneous with formation of the Levee spillway and diversion of Lake Claryville drainage down the Old Kentucky River and westward via the Salt River. Pink color at left delineates rocks of the Clays Ferry Formation. The darker colors to the right delineate rocks of the underlying Lexington Limestone. The blue color in the Kentucky River valley delineates rocks of the High Bridge Group. Modified from Cressman (1964, 1968, 1972, 1973).

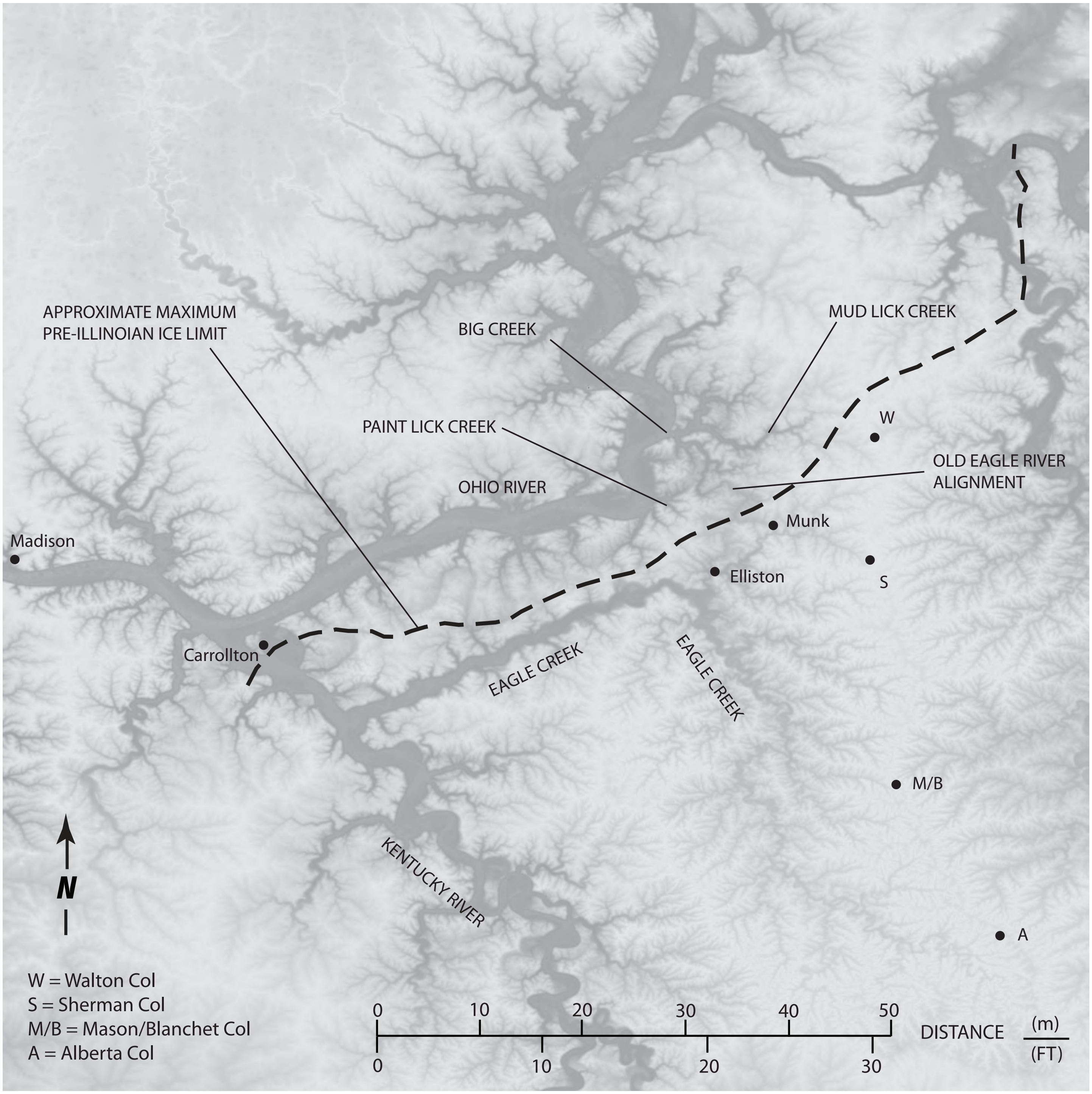


Figure 7. Digital elevation model showing location of Carrollton, Kentucky at the confluence of the Kentucky and Ohio Rivers. Also shown are the alignments of present-day Eagle Creek and of the Old Eagle River. Lake Claryville drainage flowed over the Walton col and to the Deep Stage valley via Mud Lick and Big Creeks until advancing ice crossed the Deep Stage and blocked Mud Lick Creek. Water then spilled over the south Mud Lick Creek valley crest and into the Old Eagle River valley. A col was breached just south of present-day Elliston, and the section of present-day Eagle Creek connecting the 90-degree bend south of Elliston with the Kentucky River carried drainage to the Kentucky and Ohio Rivers as an ice-marginal stream.

Bluegrass physiographic province (Kentucky Geological Survey [2001]; Fig. 5). They also cut through the massive limestones and dolomites of the Inner Bluegrass physiographic province. The rivers then pass back into the Outer Bluegrass again before winding through the Knobs physiographic province (Fig. 5), which is characterized by isolated, steeply-sloped, cone-shaped hills that are comprised of resistant Mississippian limestones underlain by less-resistant shales. The streams pass from the Knobs into the Eastern Kentucky Coal Field physiographic province to the southeast, which is characterized by Pennsylvanian coals, sandstones, and limestones.

Unconsolidated overburden materials south of the Cincinnati and northern Kentucky areas have been well documented by Andrews (2006), who discusses high-level fluvial deposits in abandoned meanders of the Old Kentucky River valley, as well as the Irvine Formation, composed of unconsolidated sand, gravel, and clay on upland terraces and broad hilltops in the vicinity of Irvine, Kentucky. Andrews (2006) reports that the Irvine Formation has an estimated age of 1.5 Ma.

PREVIOUS WORK ON PLEISTOCENE GEOLOGIC HISTORY

Summary

Laurentide glaciation affected much of the central Plains region of the United States. Boellstroff (1978) and Roy et al. (2004) identified at least seven pre-Illinoian ice advances in the central plains region of the United States, specifically in Iowa, Missouri, Kansas, and Nebraska. Based on paleomagnetic evidence, the presence of paleosols, and stratigraphic position relative to dated ash beds, two of these advances were >2 Ma; two were between 1.3 and 0.8 Ma; two were between 0.8 and 0.6 Ma; and the youngest was < 0.6 Ma (Fig. 8).

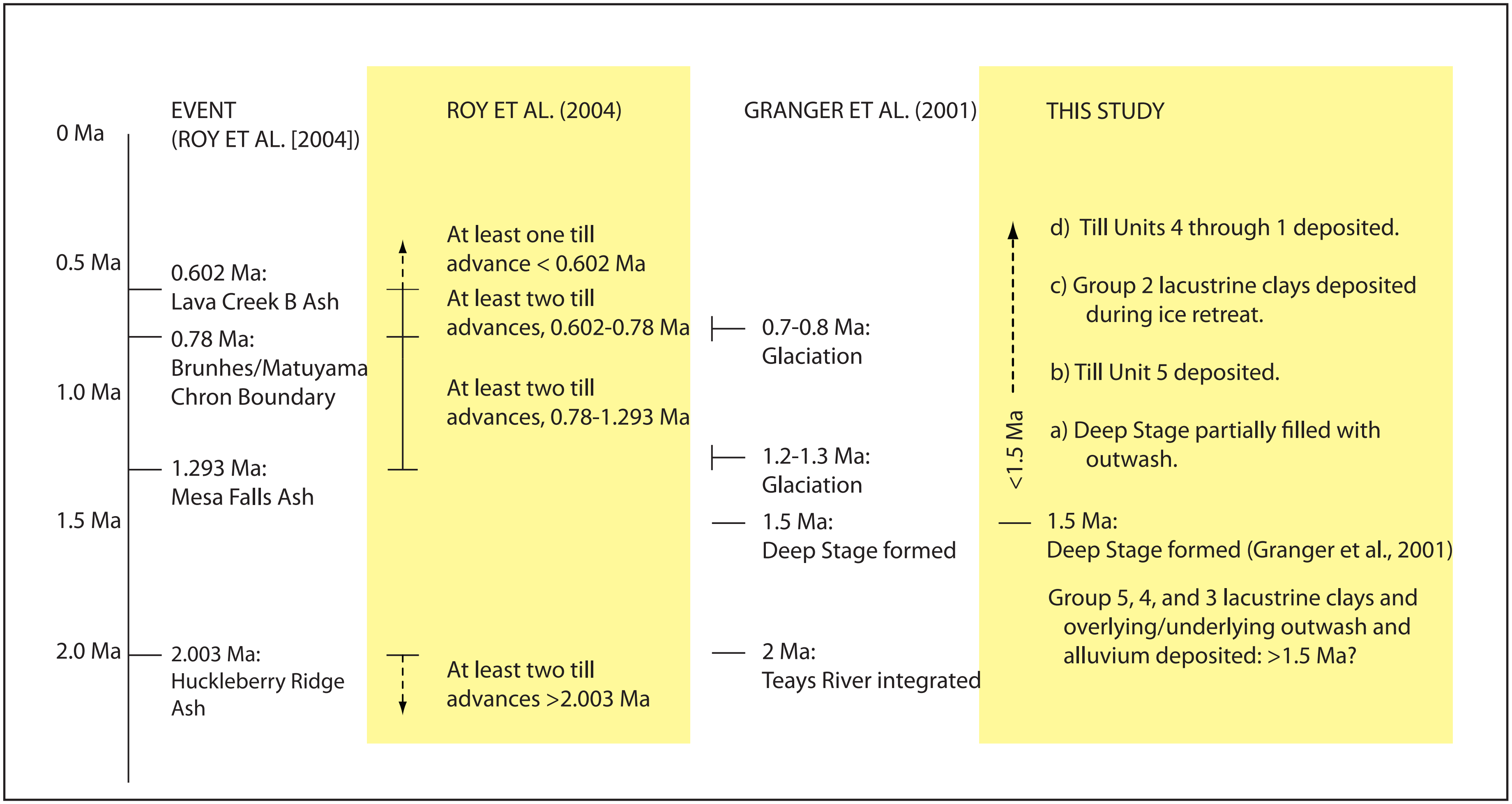


Figure 8. Summary of previous work relating to ages of glaciation in the central United States, compared to the results of this study.

The glaciations that affected the central Plains region affected the Cincinnati and northern Kentucky areas as well, as these areas are on the southern margin of Pleistocene glaciation. Coffey (1958, 1961), Durrell (1961), and Gray (1991) hypothesized that the Teays River itself was formed in response to disruption of preglacial northward drainage during a Laurentide ice advance that did not reach the southern ice limit. Granger et al. (2001) discuss a major incision event along the Green River, Kentucky at about 2 Ma that may have correlated with integration of the Teays River. Granger and Smith (2000) indicate that formation of the Deep Stage occurred along a later ice sheet margin near 1.5 Ma. Durrell [1961], Teller [1970, 1972, 1973], Swadley [1979], and Norton et al. [1983] concluded that the Deep Stage valley was downcut in response to invasion of glacial ice into northern Kentucky. Granger et al. (2001) indicated that subsequent glaciations are represented at Mammoth Cave by incision of the Green River at 1.2 to 1.3 Ma, and by aggradation at 0.7 to 0.8 Ma (Fig. 8).

Prior to the work of Granger et al. (2001), previous workers documented the relative timing of ice invasions into the Cincinnati region by assuming four major glaciations and following the classic sequence (from oldest to youngest) of Nebraskan, Kansan, Illinoian, and Wisconsinan in assigning ages. Norton et al. (1983) concluded that evidence of four major glaciations in the Cincinnati area may represent the maximum extent of only the major glaciations of several that may have occurred during the Quaternary, but that the “classic sequence” seemed to be reasonable for evaluating glacial effects. The terms “Nebraskan” and “Kansan” are generally no longer used; deposits previously referred to as Kansan or Nebraskan are now generally referred to as being pre-Illinoian (Mickelson and Colgan [2003]).

The Old Kentucky River west of the Divide, and the Old Licking and Manchester Rivers to the east (Fig. 4), were north-flowing streams that met in modern-day Hamilton, Ohio at the north end of the Divide (Teller [1970]). Following early Pleistocene blockage of north-flowing streams by the southward-moving Laurentide ice sheet, the waters of the Manchester and Old Licking Rivers were ponded against the Divide to the west, and formed a large, proglacial lake. Lake Claryville, called Lake Tight by Transeau (1941), extended eastward into northeastern Kentucky, southern Ohio, and West Virginia (Andrews [2006]). Erosion and downcutting across the cols separating the many inundated valleys of formerly north-flowing streams eventually formed the now-buried Deep Stage valley that is presently occupied by the underfit, present-day Ohio River (Durrell [1961]; Fig. 4). This allowed drainage east of the Anderson Ferry Divide to continue westward to the Mississippi River along a much shorter route.

Teller (1973) speculated that Lake Claryville drained to the west via flow through multiple small spillways formed in cols of the Anderson Ferry Divide. This drainage would have made its way westward over the Divide and eventually entered the Kentucky River basin. Andrews (2003, 2006) documented a major Lake Claryville spillway at Levee, Kentucky (Figs. 2 and 3), and demonstrated that drainage through this spillway helped form the present-day Kentucky River, which joined the preglacial Old Ohio River at Carrollton, Kentucky. While this spillway was active, Lake Claryville drainage could circumvent northern Kentucky by being diverted many kilometers to the south.

Ponding of the Old Kentucky River might have formed a significant lake as well on the western side of the Divide, except that drainage was diverted to the west via a set of paleochannels connecting the Old Kentucky River to a former tributary that had been captured by the Salt River near Lawrenceburg, Kentucky (Figs. 3 and 6), upstream of Carrollton (Cressman [1972, 1973]). Eventual breaching of a now-eroded col in the Carrollton, Kentucky area (Fig. 7) allowed drainage to eventually flow westward via the Old Ohio River valley, the headwaters of which were believed to be located near Madison, Indiana (Fowke [1900]; Wayne [1952]; Teller [1970, 1973]). Teller (1970) and Teller and Goldthwait (1991) suggested that the portion of the Old Kentucky River south of Carrollton may have been captured by the west-flowing Old Ohio River prior to glaciation as the Old Ohio River cut headward through the col between Carrollton and Madison.

Teller (1973) concluded that glacial ponding in the Old Kentucky River basin was short lived, while impoundment east of the Divide was of long duration. The presence of “scattered deposits of laminated (often varve-like) clay and silt” were noted in the uplands adjacent to the Old Kentucky and Old Licking River valleys (Fig. 4), and Teller (1973) stated that they might be the equivalent of the Claryville clays.

Swadley (1971b) mapped a section of the Old Kentucky River paleocourse in Boone County, Kentucky over which the old alluvium was overlain not by lacustrine deposits, but by pre-Illinoian outwash sands and gravels. At one location, these outwash deposits were mapped continuously between the old riverbed and the uplands at El. 262.1 m (860 ft) (Fig. 9). Swadley (1971b) reported outwash deposits north of Middle Creek in Boone County as high as El. 274.3 m (900 ft; Figs. 10 and 11); he reported that these deposits were up to 200+ ft thick.

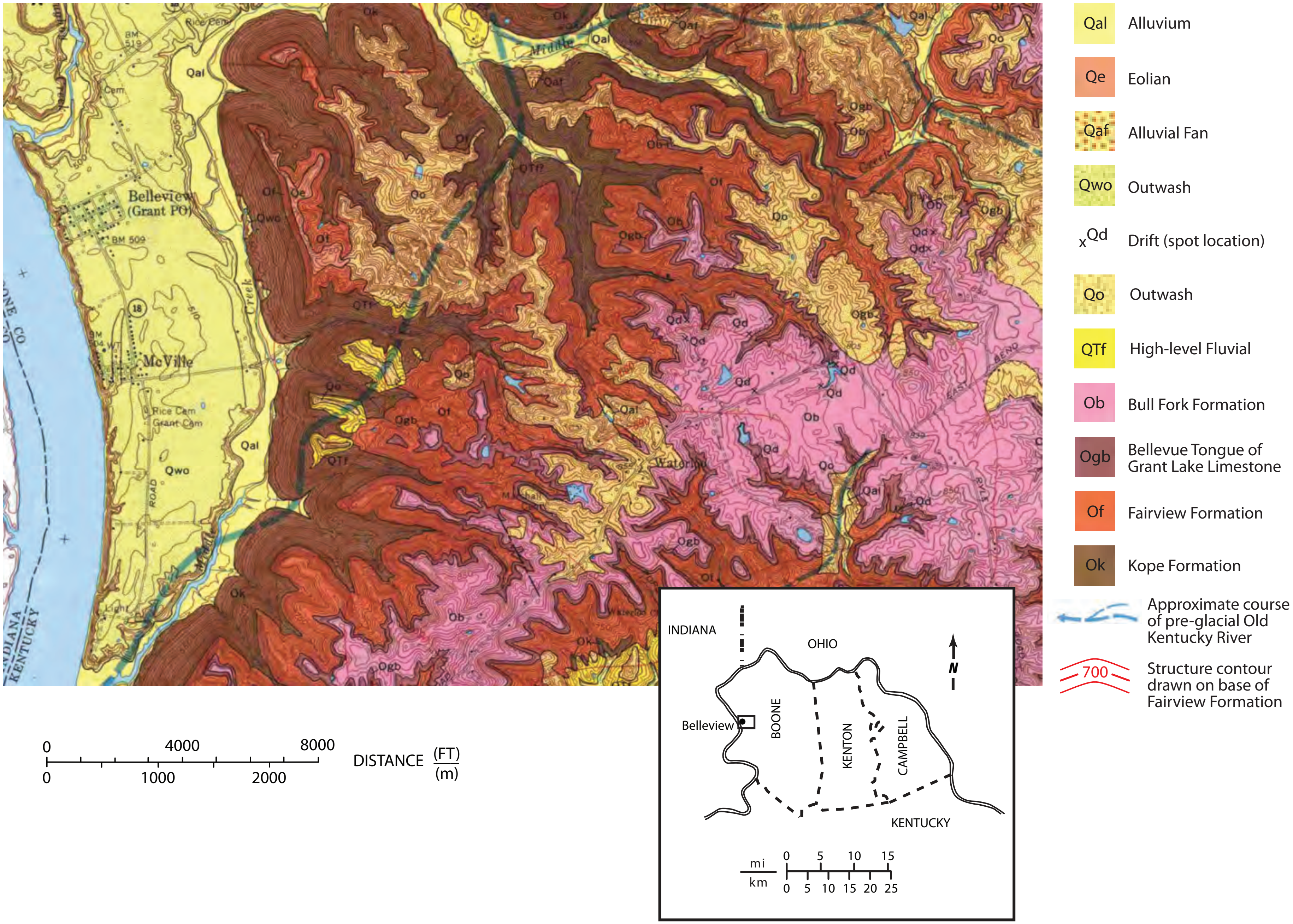


Figure 9. Section of geologic map showing one area where pre-Illinoian outwash extends continuously from Old Kentucky riverbed into uplands to El. 262.1 m (860 ft). Present-day Ohio River and community of Belleview, Kentucky at left of figure. Box on inset map shows location of geologic map (from Swadley 1971b).

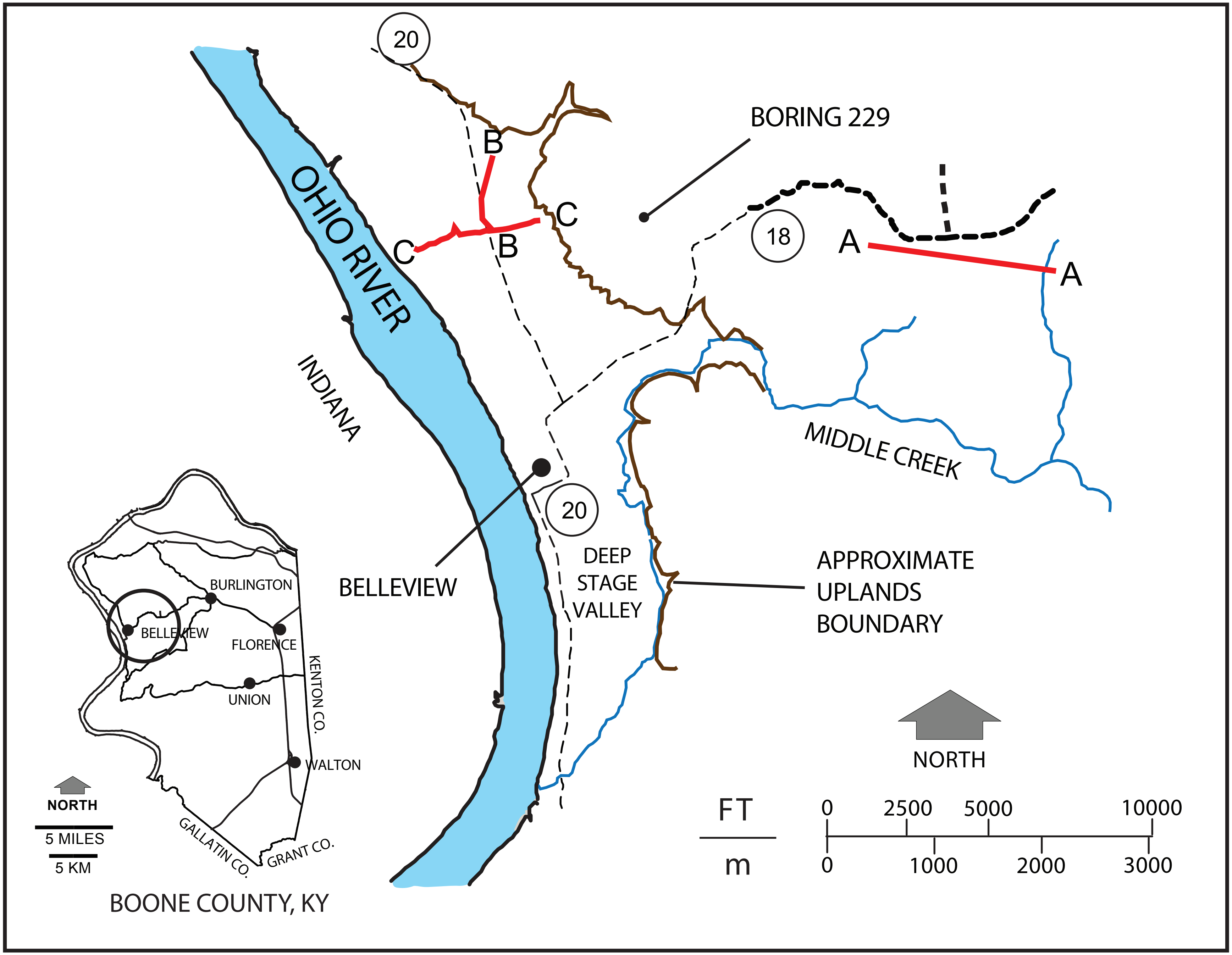
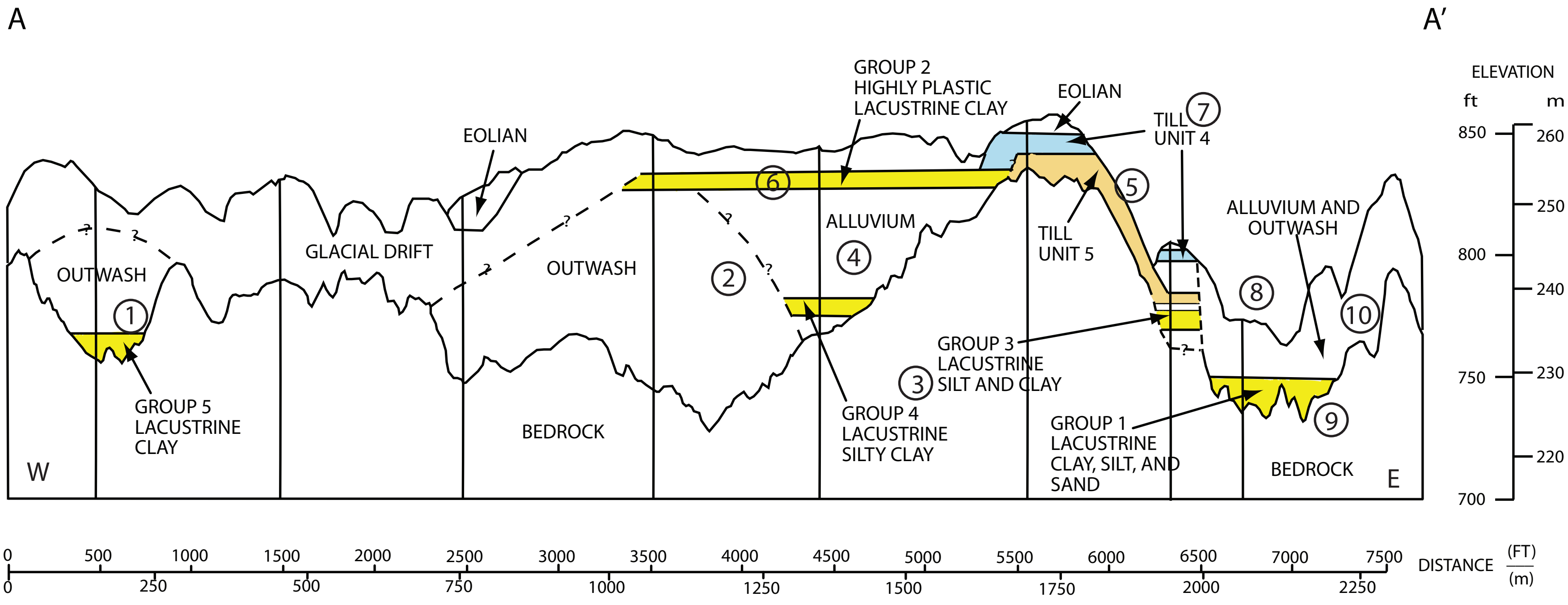


Figure 10. Plan of Boone County, Kentucky showing locations of cross sections A-A', B-B', and C-C', and cities. Circle at left shows detail location.



1) Group 5 lacustrine clay deposited in tributary valley to south-flowing, preglacial Old Kentucky River at west end of section.

2) Outwash fills tributary valleys and is subsequently eroded by streamflow.

3) Laminated, lacustrine silt and clay deposited at Group 3 and Group 4 locations following backup of drainage in Old Kentucky River tributary.

4) Group 3 and 4 lacustrine soils buried by deposition of alluvium.

5) Ice advance into northern Kentucky deposits Till Unit 5. Till Unit 5 may postdate the alluvium entirely, or may have been deposited in valley to west (4) above Group 4 and subsequently eroded prior to complete filling of valley with alluvium.

6) Laminated, highly plastic, Group 2 lacustrine clay deposited above alluvium-filled valley, and in widespread area to the north, likely in proglacial lake formed during retreat of ice that deposited Till Unit 5.

7) Ice advance into northern Kentucky deposits Till Unit 4. Ice overrode the Group 2 highly plastic, lacustrine clay and incorporated it into Till Unit 4, raising the till's plasticity where deposited to the east.

8) Further erosion of valley to the east.

9) Lacustrine soils deposited at Group 1 location.

10) Outwash and alluvium deposited over lacustrine deposits at Group 1 location.

Figure 11. Summary of depositional history of sediments encountered in borings drilled along cross section A-A′ (Fig. 10), in the northern Kentucky uplands of western Boone County north of Middle Creek. The clays labeled 'Group 2' once blanketed a large portion of the Boone County, Kentucky area west of the Anderson Ferry Divide.

The lacustrine clays of northern Kentucky were first described by Miller (1919). Those of Campbell County, Kentucky occurring roughly below El. 213.4 m (700 ft) were named the "Claryville Clays" by Durrell (1961). Ettensohn (1970) made an extensive study of the lacustrine clays throughout the preglacial river valleys and the uplands of the Greater Cincinnati Area on both sides of the Divide. The lake clays were described as being derived from two sources, one being a northern glacial ice source, and the other being the southerly sources that continued to enter the ponded lakes via north-flowing drainages. Ettensohn (1974) studied lacustrine sediments in the uplands west of the Anderson Ferry Divide and associated them with blockage of individual small streams, but not with formation of a single larger lake. Extensive lacustrine deposits documented in boreholes, roadcuts, and excavations since that time reveal the former existence of a proglacial lake in Boone County, Kentucky on the west side of the Divide. The relationship of these deposits to those of Lake Claryville has been unclear, although similar deposits west of the Divide and in Cincinnati, Ohio have been correlated to the Claryville Clays by Teller and Last (1981) (Fig. 4).

Clay Studies

Teller (1970, 1972, 1973) described northern Kentucky pre-Illinoian till fabric as being oriented northwest-southeast. Grain-size distributions distinguished Illinoian from pre-Illinoian tills to some degree, with the Illinoian being sandier and less clayey; he concluded that pre-Illinoian till exposures in the Greater Cincinnati Area are restricted to the uplands of Kenton, Boone, and Gallatin counties in Kentucky, and to the uplands of western Hamilton County in southwestern Ohio. Clay mineralogy also showed differences, with Illinoian tills exhibiting significantly more kaolinite and chlorite, and significantly less expandable minerals, than pre-Illinoian tills. Heavy mineral studies indicated that the ratio of hypersthene and epidote percentages (H/E) could be used to distinguish Illinoian and pre-Illinoian tills; H/E > 1 in Illinoian tills, and H/E < 1 in pre-Illinoian tills. Teller (1970) found that differences in the depth of carbonate leaching were also significant: where leaching depth exceeds 3.7 m (12 ft) (pre-Illinoian), the limestone/dolomite ratio exceeds 15:1, and where the leaching depth is 1.8-2.4 m (6-8 ft) (Illinoisan), the limestone/dolomite ratio is between 1:1 and 6:1. Teller's work was based on surface studies in the uplands, where exposures were subject to a strong weathering overprint.

The lacustrine clays of Campbell County occurring roughly below El. 213.4 m (700 ft) were named the "Claryville Clays" by Durrell (1961). Ettensohn (1970) summarized the work of others and made an extensive study of the lacustrine clays throughout the preglacial river valleys and the uplands of the Greater Cincinnati Area. He concluded that the large-scale ponding that occurred east of the Divide (i.e., that formed Lake Claryville) did not occur west of the Divide, but rather, that only local ponding of streams occurred to the west.

Ettensohn and Glass (1978) reported a probable depositional history of pre-Illinoian lacustrine clays sampled at two Cincinnati sites on the west side of the Anderson Ferry Divide (Fig. 1), based on clay mineral stratigraphy. They reported three depositional events at each site, having different clay mineral sources. The first involved deposition of clays contributed by the reworking of previously deposited stream alluvium. The second involved deposition of clays contributed by the northward-flowing drainage as it entered the growing ponded lake. The third involved deposition of clays contributed by the advancing ice sheet.

Based on clay mineralogy, sedimentary structures, and grain size, Teller and Last (1981) reported three lithologic units within a deposit of Claryville Clays sampled south of Alexandria, Kentucky on the east side of the Divide (Fig. 1), and correlated these three units with those of Ettensohn and Glass (1978).

In summary, previous work has documented that the Teays River system may have formed in response to glaciation that occurred at about 2 Ma, and that the Deep Stage was formed in response to a later glaciation that occurred at about 1.5 Ma. Prior to completion of Deep Stage integration, regional drainage collected in lakes and circumvented the northern Kentucky area by using the Levee spillway and the Kentucky River basin. Drainage in the northern Kentucky area after blockage of north-flowing streams but prior to organization of the Deep Stage has been touched on by previous workers, but has not been described extensively. The clayey tills occurring in the northern Kentucky uplands have also been studied and described, however, the relationship between the tills and the lacustrine deposits of northern Kentucky has not been clearly documented.

CHAPTER TWO

A TALE OF FIVE TILLS: A PRE-WISCONSINAN ARCHIVE IN THE DEEP STAGE VALLEY NEAR CINCINNATI, OHIO

OVERVIEW

An archive of glaciations in preserved in Deep Stage buried valley and adjacent uplands. Multiple borings provide evidence for at least five pre-Wisconsinan glacial advances of the Laurentide ice margin that reached into northern Kentucky. The advances are generally characterized by clayey till sheets separated by outwash, alluvium, and/or lacustrine deposits. Simple index classification tests (Atterberg limits plasticity tests) distinguish separate tills in the buried valley. Using these index tests, the tills can be distinguished based on their plasticity. Grain size distribution measurements were not useful in distinguishing individual till units. All five units are underlain by outwash and were inset to the Deep Stage valley. Based on stratigraphic relationships and on available index test data for uplands tills, the upper two units are identified in the nearby uplands. This indicates that the portion of the now-buried Deep Stage valley west of Boone County, Kentucky was in place at the time of the initial Laurentide ice sheet invasion into the region, suggesting that valley formation was based on then-existing topography and not on the presence of an ice margin.

Numerous deep boreholes have been drilled across a 2-km (1.2-mi) width of the now-buried Deep Stage valley in western Boone County, Kentucky, across the present-day Ohio River from Cincinnati, Ohio (Figs. 10 and 12). This study synthesizes these borings and other subsurface

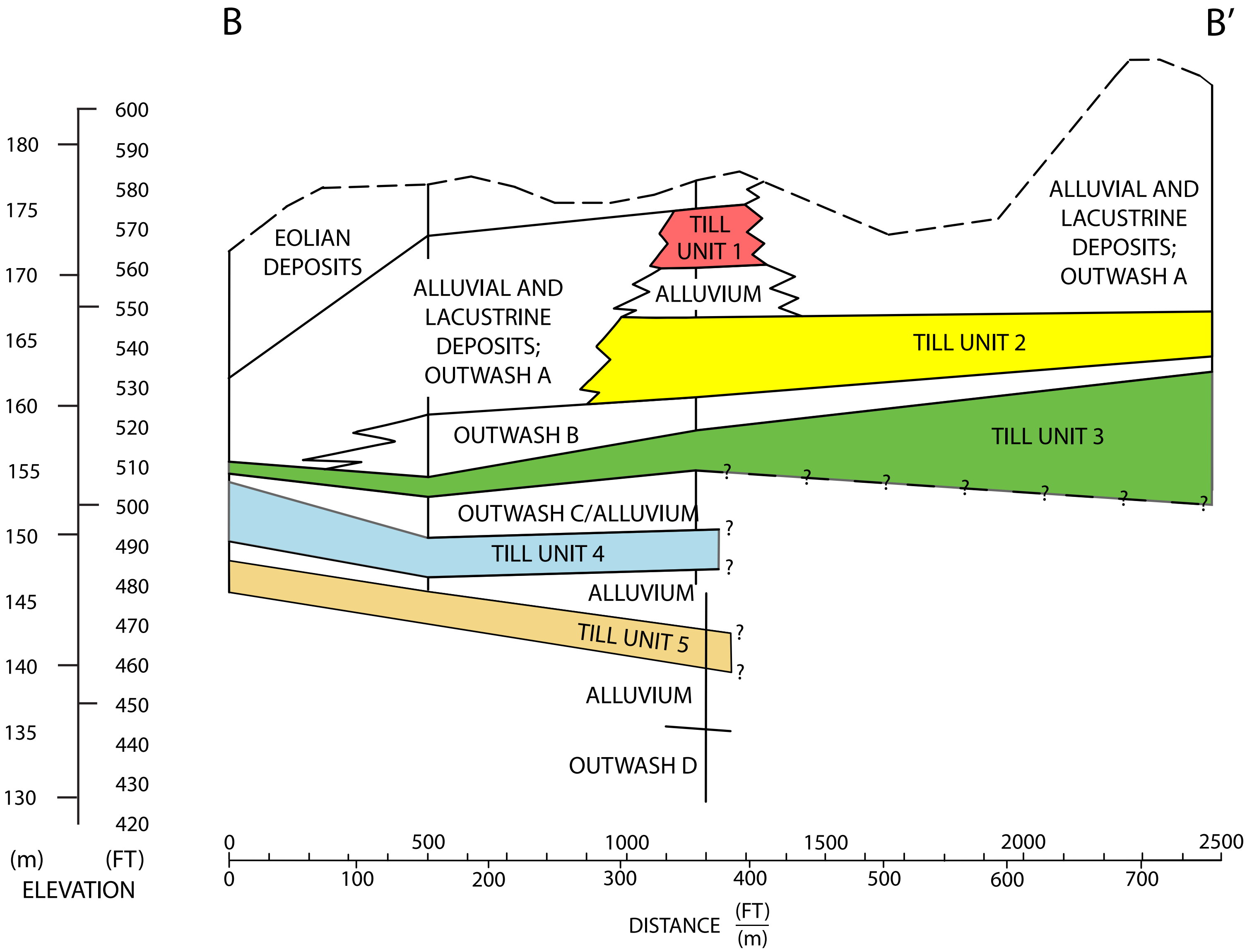


Figure 12. Geologic cross section B-B′ through Deep Stage valley infill materials, western Boone County, Kentucky. Cross section is based on the logs of 5 deep borings. Infill materials include clayey till and outwash deposits, alluvium, lacustrine deposits, and eolian silts and fine sands.

data obtained from boreholes drilled in Boone County over the past 40 years. They provide documentation, over a large area and over a wide range of elevations, of at least five pre-Wisconsinan glacial advances across the Deep Stage valley near the southern Laurentide ice margin (Figs 10, 12, and 13).

METHODS

The five till units documented in the available Deep Stage valley borings are easily distinguished based on stratigraphic relationships. Simple classification tests are used to establish till unit properties of these reference tills and then to attempt correlations with tills that occur across the uplands where intermediate units are missing.

Classification testing for this study consisted of Atterberg limits and particle-size distribution testing. The Atterberg limits and grain-size distributions were determined using American Society for Testing of Materials (ASTM) Standard Test Methods (ASTM [2010]). All testing was conducted in the materials testing laboratory of Thelen Associates, Inc. of Erlanger, Kentucky. Correlations between individual till units were based on groupings made on the basis of the test results.

Test results for this study were generated for 42 till samples obtained using subsurface materials sampled using one of three types of samplers: 76.2-mm (3-inch) diameter, thin-walled, Shelby tubes; a 50.8-mm (2-inch) outer diameter, split-barrel sampler; or a 76.2-mm (3-inch) outer diameter, split-barrel sampler. Thus, the maximum particle sizes that could be obtained were limited to 50.8 or 76.2 mm (2 or 3 inches). It is known that particles larger than 50.8 to 76.2 mm

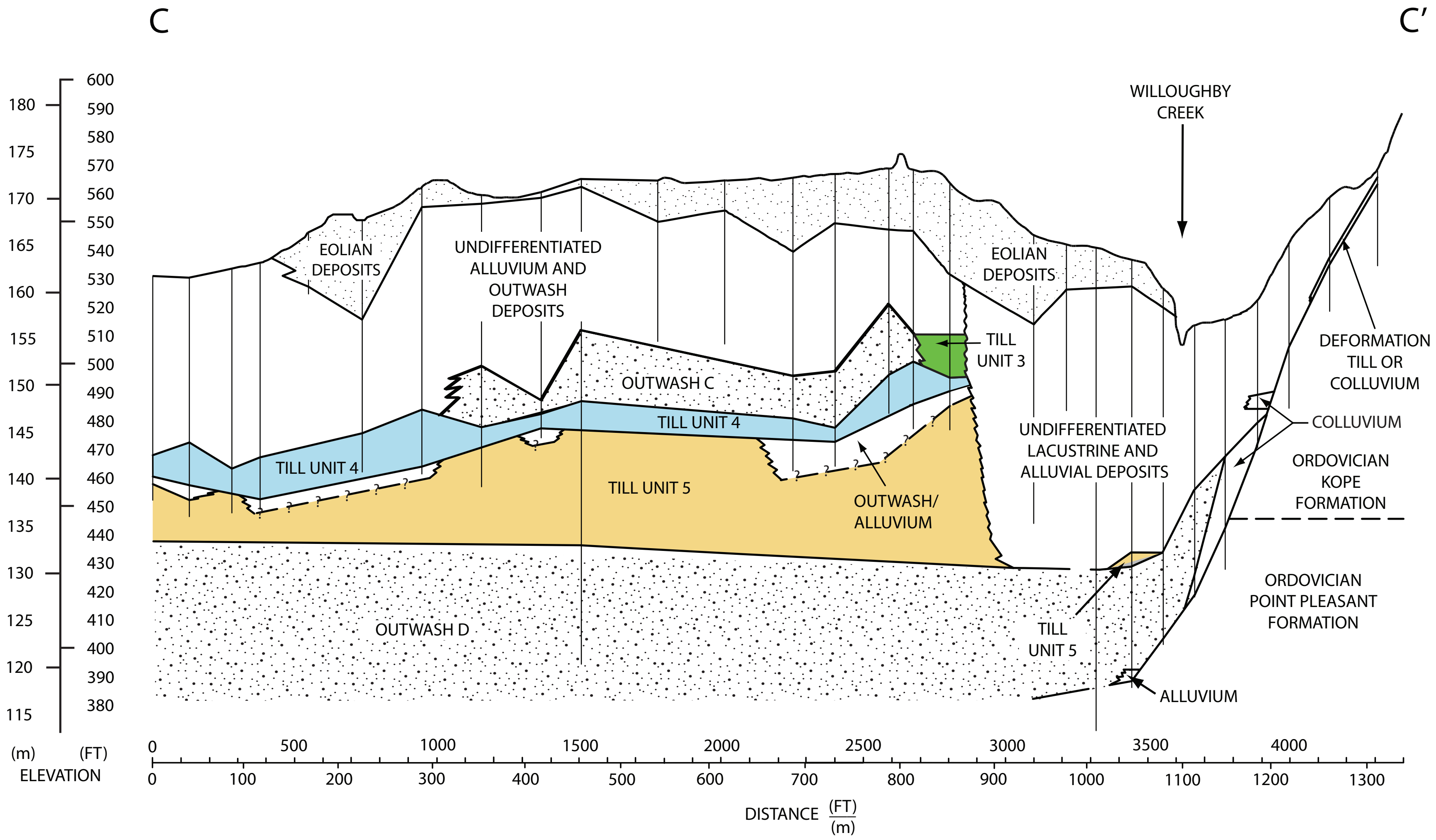


Figure 13. Geologic cross section C-C′ through Deep Stage valley infill materials, western Boone County, Kentucky. Cross section is based on the logs of 28 shallow and deep borings. Infill materials include clayey till and outwash deposits, alluvium, colluvium, lacustrine deposits, and eolian silts and fine sands.

(2 to 3 inches) exist in the tills and outwash deposits of northern Kentucky, and these could not be sampled. However, in a recent suite of testing, the maximum particle size noted in the clayey till units was generally less than 25.4 mm (1 inch). While it is believed that the samples obtained were representative of the matrix of the till material, it is acknowledged that larger particle sizes do exist.

Orientation of the Shelby tubes was required for remanent magnetism testing. The tube orientation was referenced to a temporary, surveyed datum. The tube was lowered into the borehole and pushed into the deposit slowly to obtain the oriented sample. The oriented Shelby tubes were placed in the tube extruder so that a thin blade could be used to lightly score the samples along the lines of orientation as they were being extruded.

Remanent magnetism studies of the clayey till from western Boone County were conducted at the University of Minnesota's Institute for Rock Magnetism (IRM). Remanent magnetism samples were obtained by pushing 12.7 mm x 12.7 mm x 12.7 mm (0.5 in x 0.5 in x 0.5 in), clear plastic boxes (provided by IRM) into the extruded Shelby tube sample at specific points along the scored line (Fig. 14).

RESULTS

The most important sections were obtained from Belleview, Kentucky and Sayler Park, Ohio, as well as in the northern Kentucky uplands. Belleview is located on the Ohio River south of Lawrenceburg, Indiana, while Sayler Park is located on the Ohio River upstream of Lawrenceburg and about 6.4 km (4 mi) downstream of the Anderson Ferry Divide (Fig. 4). The

Figure 14. Oriented Shelby tube sample of clayey till from Till Unit 5, obtained from a depth of 23.2 - 23.6 m (76.0 - 77.5 ft). Photo shows score line run down axis of sample during extrusion to mark the line of orientation. Remanent magnetism samples were obtained by pushing 12.7 mm x 12.7 mm x 12.7 mm (0.5 in x 0.5 in x 0.5 in), clear plastic boxes (provided by IRM) into the extruded Shelby tube sample at specific points along the scored line. Where necessary, the boxes were lightly driven into the sample using a rubber mallet. Also where necessary to avoid gravel particles in the till sample, the boxes were placed off of the scored line, and the offset was measured. The top and bottom faces of the boxes were marked with permanent marker as the boxes were cut from the sample, and the lids were then placed on the boxes. The scale is graded in units of 3.05 mm (0.01 ft).

properties of the various strata are reported in this section and correlated in the “Discussion” section. The till units are numbered from youngest to oldest as Till Units 1 through 5. The outwash deposits are lettered from youngest to oldest as Outwash A through D (Figs. 12 and 13).

Borings drilled in the Deep Stage valley west of Boone County show that much of the overburden materials generally consist of interlayered outwash sands and gravels and clayey tills. Closer to the Deep Stage valley sidewalls, colluvial wedges exist between the bedrock valley slopes and the valley infill materials (Fig. 13). Postglacial erosion and deposition have dissected and replaced some of the subsurface materials with alluvium and lacustrine materials. Blankets of eolian silts and sands have been deposited against hillsides in the Ohio River valley and the northern Kentucky uplands. In the uplands areas, the same overburden materials occur, but are much thinner. In addition, much of the northern Kentucky area is mantled by a stratum thought to be related in some way to glaciation, but for which a definite origin has not been established; this mantle is referred to on published geologic maps simply as “Qd” for Quaternary drift (Gibbons [1972]).

Outwash and Alluvium

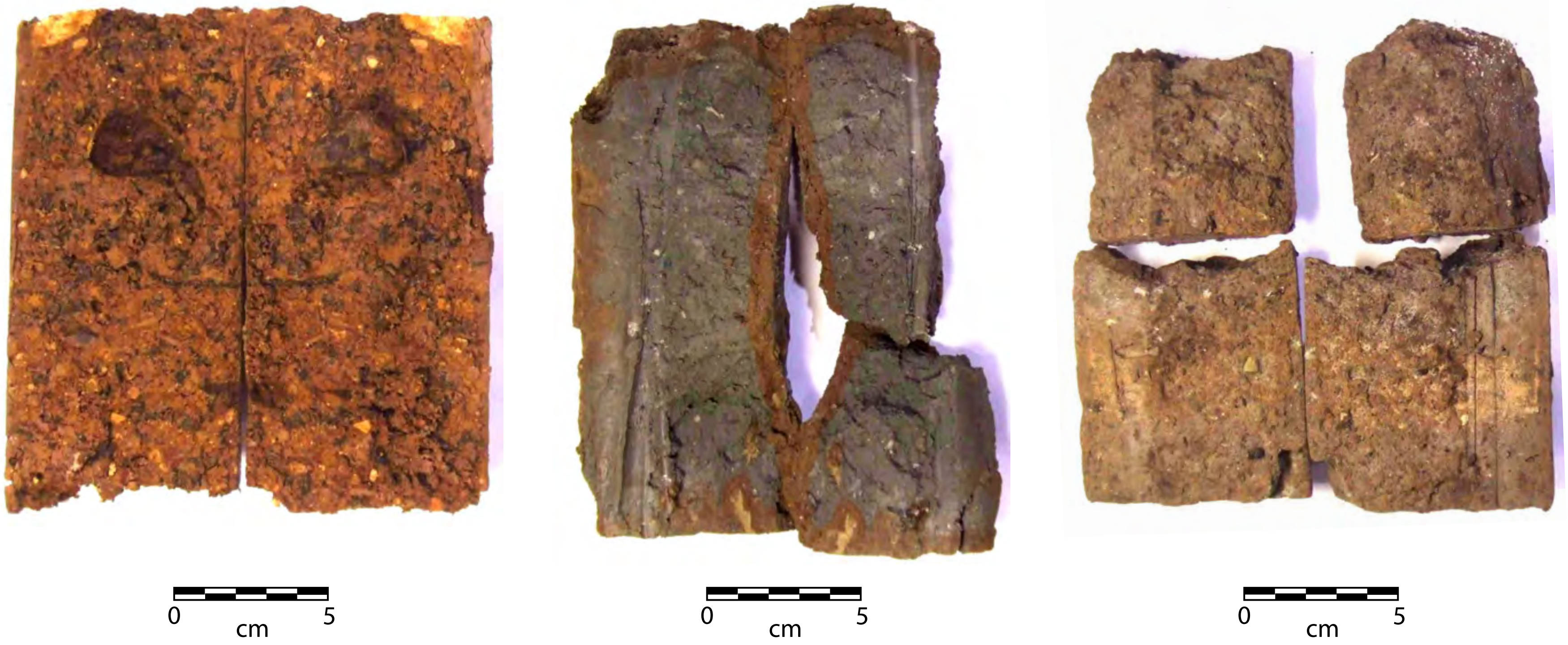
Four general zones of outwash have been documented in the western Boone County study area (Figs 12 and 13). These four outwash zones separate individual till units, and are therefore known to be of different ages. The deepest is referred to as Outwash D, which fills the bottom of the Deep Stage valley and underlies all five of the till units (Figs. 12 and 13). Outwash C occurs between Till Units 3 and 4, and Outwash B occurs between Till Units 2 and 3 (Fig. 12). All contain fine- to coarse-grained sand and gravel, although Outwash B contains fine- and fine- to medium-grained zones as well. The amounts of gravel and fines are variable. Cobbles and boulders are encountered mainly within Outwash C and D. The fourth outwash unit documented in the western Boone County study area (Outwash A) is the Wisconsinan outwash (Swadley [1972]), which is generally composed of silty fine sand and fine to medium sand, and which is significantly less dense than the other outwash units (Fig. 13).

Some alluvial and lacustrine materials are encountered between the tills as well. Water-transported sediments were interpreted as alluvium where they contained organic materials, were unsorted, or were not as well sorted as the outwash materials.

Deep Stage Valley Tills

In general, the tills in the Northern Kentucky area consist of sand-, silt-, and clay-sized particles (Fig. 15). The gravel content of tested samples is generally less than 4 percent, although this tends to increase nearer the base of the unit. The granular components are generally matrix-supported. Because it is roughly ½ to ¾ fines (i.e., passing the 75 μm [No. 200] sieve), the till behaves as a cohesive soil and is predominantly described in the records reviewed for this study as sandy, silty clay. Liquid limits are normally less than 40 percent, and moisture contents are generally less than 15 percent, owing to consolidation of the till under the weight of glacial ice.

The properties of the five till units documented within the now-buried Deep Stage valley west and north of Boone County (Fig. 10) are summarized in Table 1 below.



TILL UNIT 1
WESTERN BOONE COUNTY, KY
173.2 m (568.4 ft)

TILL UNIT 4
WESTERN BOONE COUNTY, KY

TILL UNIT 5
WESTERN BOONE COUNTY, KY
136.2 m (447.0 ft)

Figure 15. Photographs of Till Units 1, 4, and 5, collected from borings drilled in western Boone County, Kentucky. The clayey tills of the Greater Cincinnati Area are characterized by a medium stiff to very stiff consistency (i.e., typical unconfined compressive strengths between 1,000 and 5,000 pounds per square foot), and low plasticity. Till Unit 1 has a reddish tint, indicative of iron staining. The brown rind around the edges of the Till Unit 4 sample was caused by oxidation of the sample after recovery.

Till Unit 1 (the youngest) was encountered in only a single boring. Till Unit 2 was encountered in two borings and was separated from Unit 1 in these borings by up to 3.8 m (12.5 ft) of clayey, silty, and sandy alluvium. Till Unit 3 was encountered in seven borings and was separated from Unit 2 by 1.5 m (5.0 ft) to as much as 4.9 m (16.0 ft) of Outwash B. Till Unit 4 was separated from Unit 3 by 0.9 m (3.0 ft) to 10.7 m (35.0 ft) of Outwash C. The base of Till Unit 5 (the oldest) was encountered at elevations ranging from 133.1 to 137.0 m (436.8 to 449.4 ft).

TABLE 1. PROPERTIES OF DEEP STAGE VALLEY TILL UNITS SAMPLED NEAR BELLEVIEW, KENTUCKY

TILL UNIT	1	2	3	4	5
THICKNESS (m [ft])	4.6 (15.0)	2.3 - 6.1 (7.5 - 20.0)	0.9 - 9^+ (3.0 - 29.5^+)	0.6 - 7.6 (2.0 - 25.0)	1.5 - 3.0 (5.0 - 10.0)
NUMBER OF SAMPLES TESTED (SIEVE/ATTERBERG)	1/1	1/1	6/6	6/11	12/13
DESCRIPTION	Clayey sand	Sandy, clayey silt and sandy, silty clay	Silty clay and sandy, silty clay with gravel, rock fragments	Sandy, silty clay with variable amounts of sand, gravel	Sandy, silty clay with variable amounts of gravel
LIQUID LIMIT (%)	55	24	19-24	24-35	26-41
PLASTIC LIMIT (%)	30	16	15-17	13-22	14-22
PLASTICITY INDEX (%)	25	8	2-8	8-16	11-20
GRAVEL (%)	15	1	1-4	0-7	0-20
SAND (%)	42	31	30-48	33-44	31-65
FINES (%)	43	68	49-69	54-72	47-77

Some of the borings encountered clayey or sandy alluvial strata between Till Units 4 and 5, ranging from 0.3 m to more than 3.0 m (1.0 ft to more than 10.0 ft) thick, which indicated some passage of time between deposition of the tills above and below (Figs. 12 and 13). Other borings did not encounter any such separating strata, perhaps missing it because of the 1.5-m (5.0-ft) sampling interval. In these cases, Till Units 4 and 5 could not be separated based on visual inspection alone. The combined thickness of Till Units 4 and 5 was as great as 15.4 m (50.5 ft) in the borings.

One sample of Till Unit 5 obtained within 60 cm (2 ft) of its base contained 20 percent gravel and 46 percent sand, classifying the soil as clayey sand, and reflecting the influence of the granular outwash immediately below the till (Boring 251, Fig. 13).

Based on 36 grain size distribution results, till samples collected at Sayler Park could generally be distinguished from those obtained near Belleview, and samples collected from nearer the base of the till unit could be distinguished because of their proximity to the top of the underlying outwash. However, grain size distribution was not useful in distinguishing the individual till units (Fig. 16). The individual till units were distinguishable on the basis of plasticity (Fig 17). The plasticities of Till Units 4 and 5 overlapped over part of their range, but the highest values belonged to Unit 5, and the lowest belonged to Unit 4 (Fig. 17). Till Units 4 and 5 yielded the largest number of samples available for testing.

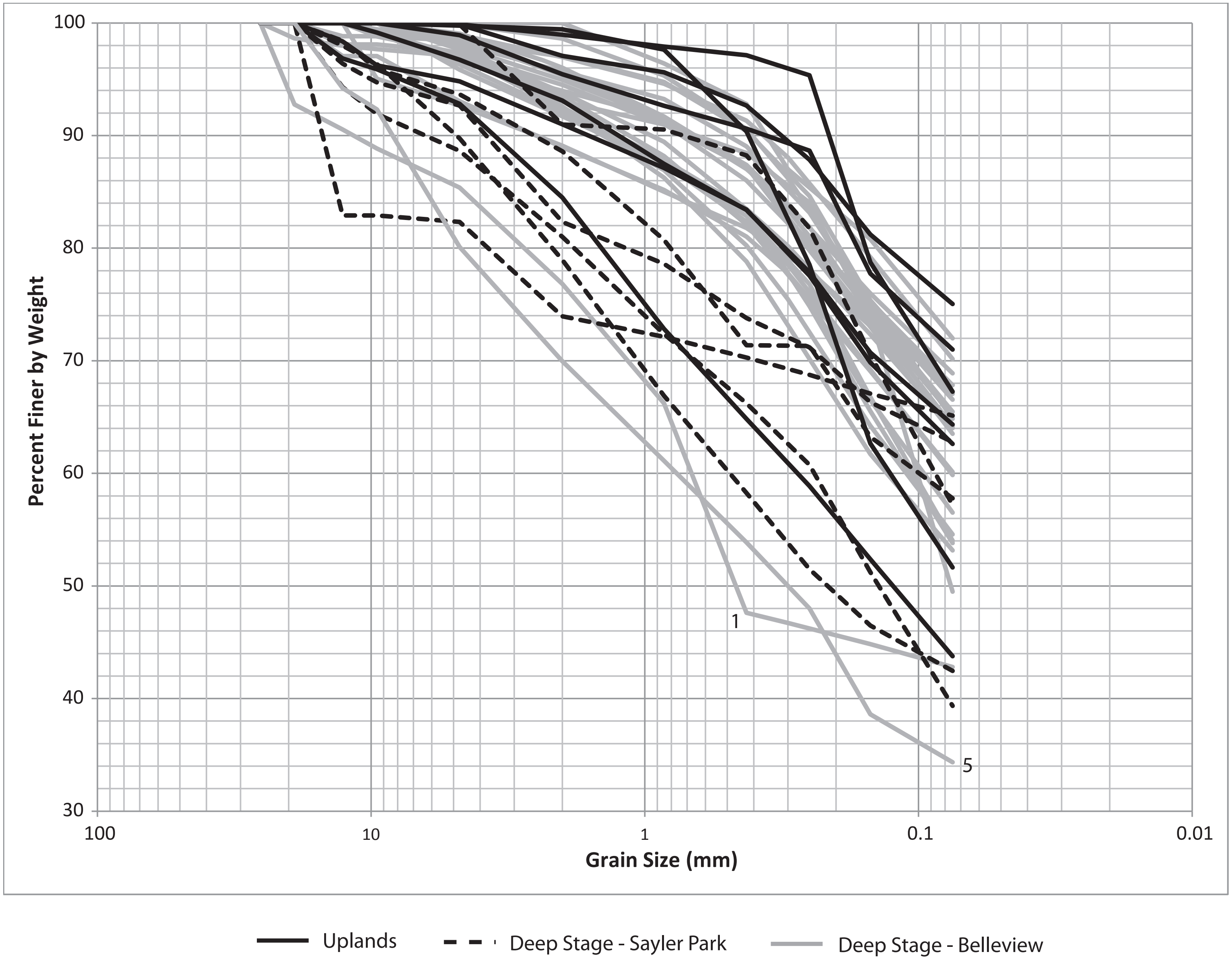


Figure 16. Grain-size distributions of 36 tested clayey till samples. Grain size distribution is not useful for distinguishing individual till units, although the grain-size distributions shown tend to distinguish the Sayler Park, Ohio tills from the remainder, and distinguish till samples taken from near the base of the unit (marked "1" and "5") where coarse-grained soils are more abundant. The Sayler Park till samples are from Till Units 3 and 4; the upland till samples are from Till Units 4 and 5. The large group of Deep Stage - Belleview till samples are from Till Units 1 through 5.

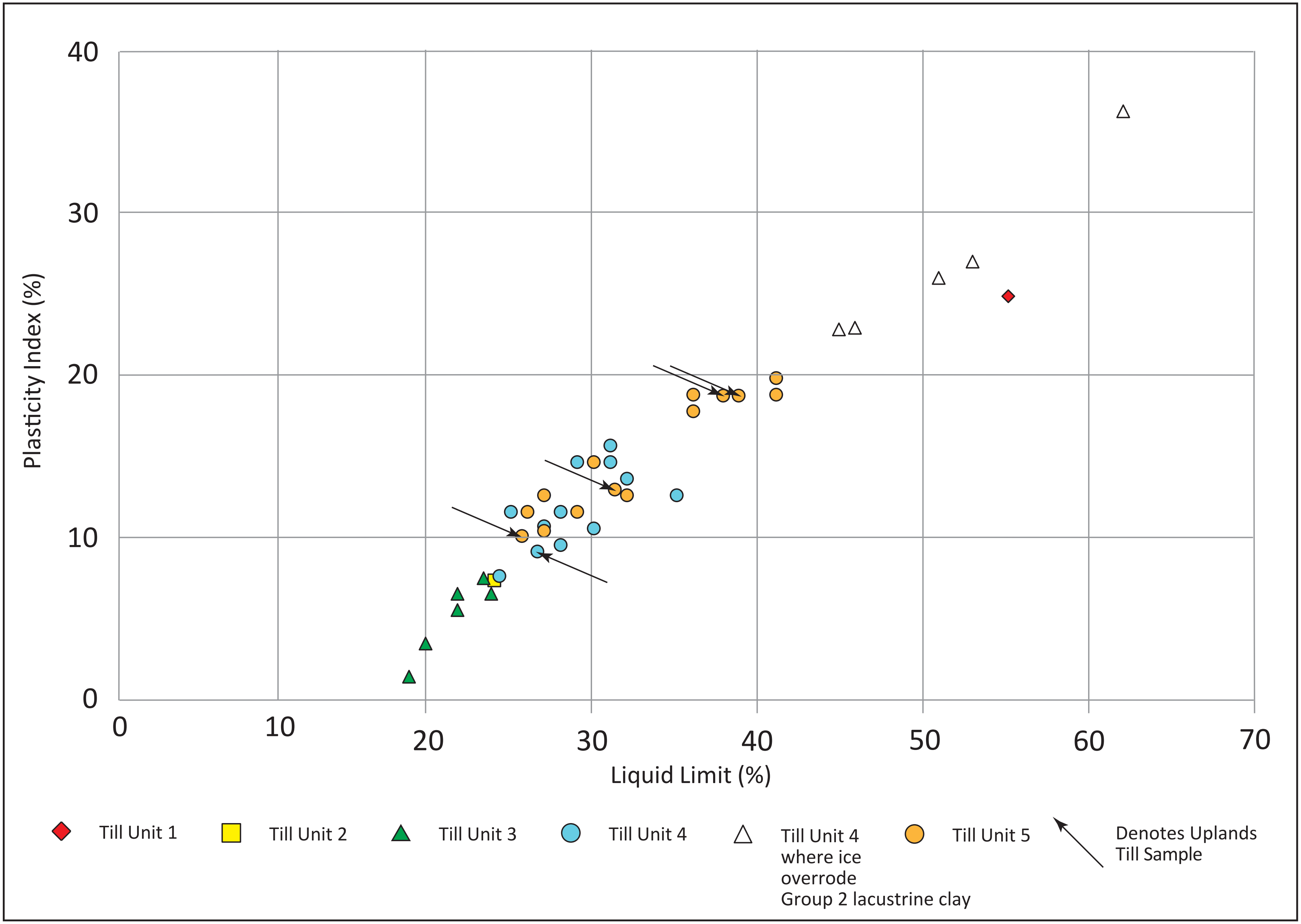


Figure 17. Plot of plasticity index vs. liquid limit, showing differences in plasticity of individual Deep Stage and northern Kentucky uplands till units.

Sayler Park is located over a northwest-flowing tributary of the main Deep Stage valley that flowed south-southwest from present-day Hamilton, Ohio through present-day Lawrenceburg (Durrell [1961]; Fig. 18). A set of borings drilled in this tributary encountered three buried secondary valleys that have apparent orientations normal to the tributary. The basal elevations of these secondary valleys range from 136.2 to 131.7 m (447 to 432 ft), higher in elevation than the floor of the main Deep Stage channel to which they are tributary. These valleys are filled as high as El. 168.9 m (554 ft). One of them is filled mostly with lacustrine clays, while the other two (Fig. 19) are filled with alluvium, colluvium, and clayey till. Two strata of till were encountered in three borings, at a basal elevation as low as El. 143.6 m (471 ft). Based on their Atterberg limits, the upper stratum exhibited Till Unit 3 characteristics. The lower portion of the lower till stratum corresponded to the range of plasticity values exhibited by Till Units 4 and 5, while the upper portion of the lower till stratum exhibited a higher plasticity, with liquid limits over 50 percent (Fig. 19).

Till has not been documented on the bedrock surface at the base of the Deep Stage valley between Hamilton, Ohio and Belleview, Kentucky. Several borings drilled along Section C-C' (Figs. 10 and 13) near Belleview, extended to or near the bedrock surface, encountered only outwash, alluvium, or valley-sidewall colluvium on the bedrock surface. The Sayler Park borings discussed above encountered the same (Fig. 19). Two borings extended to the bedrock in an abandoned Deep Stage meander in Hamilton, Ohio (Fig. 4) encountered 27.7 m (91 ft) of alluvium, lacustrine materials, and till underlain by 23.8 to 17.7 m (78 to 91 ft) of sand and gravel outwash above the bedrock surface. Teller (1973) and Swadley (1976) documented clayey till on the bedrock surface east of Carrollton, Kentucky (Fig. 4), but Teller (1973)

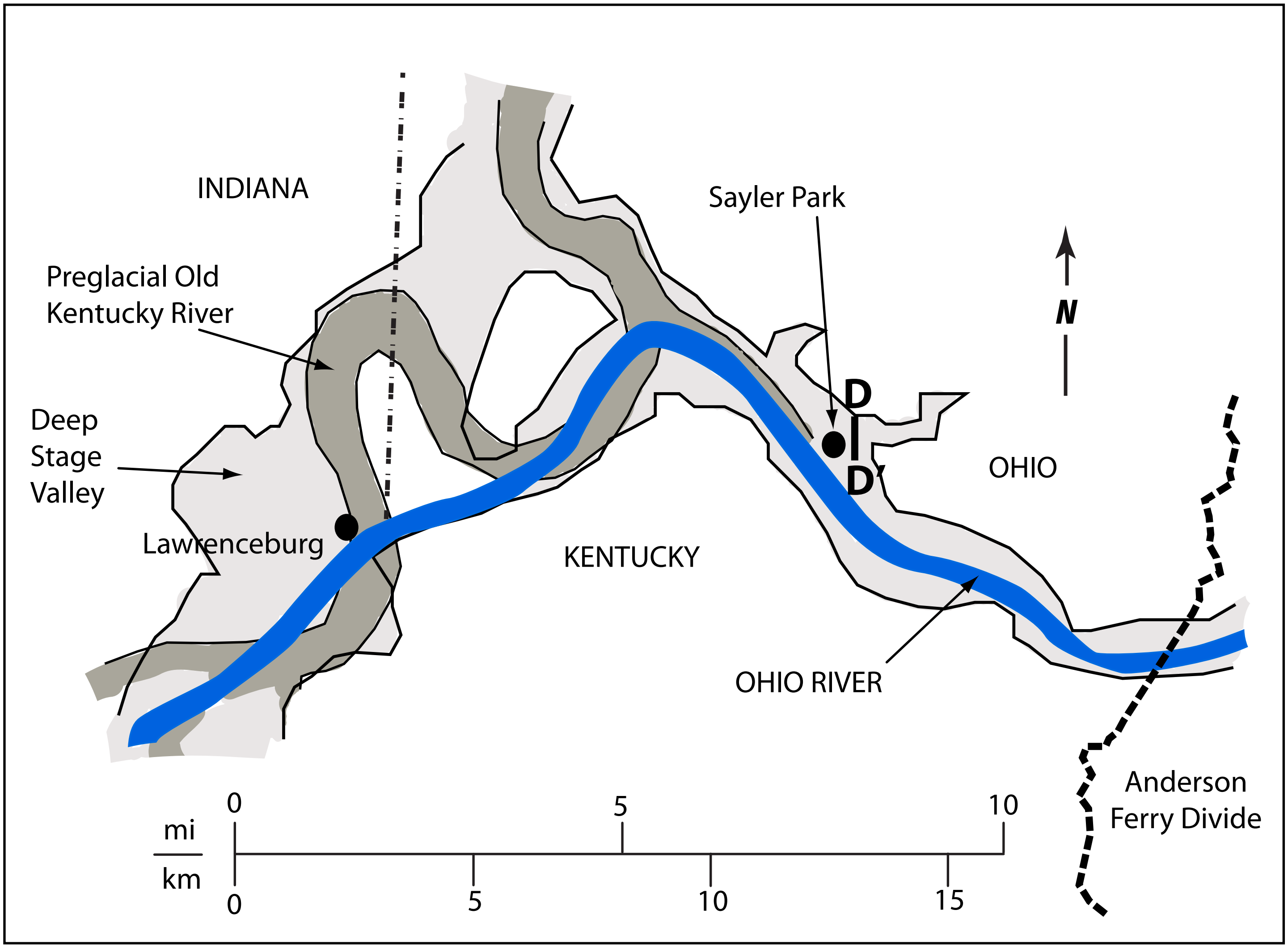


Figure 18. Site plan modified from Teller (1970) showing tributary of main Deep Stage valley in Sayler Park, Ohio area and location of cross section D-D'.

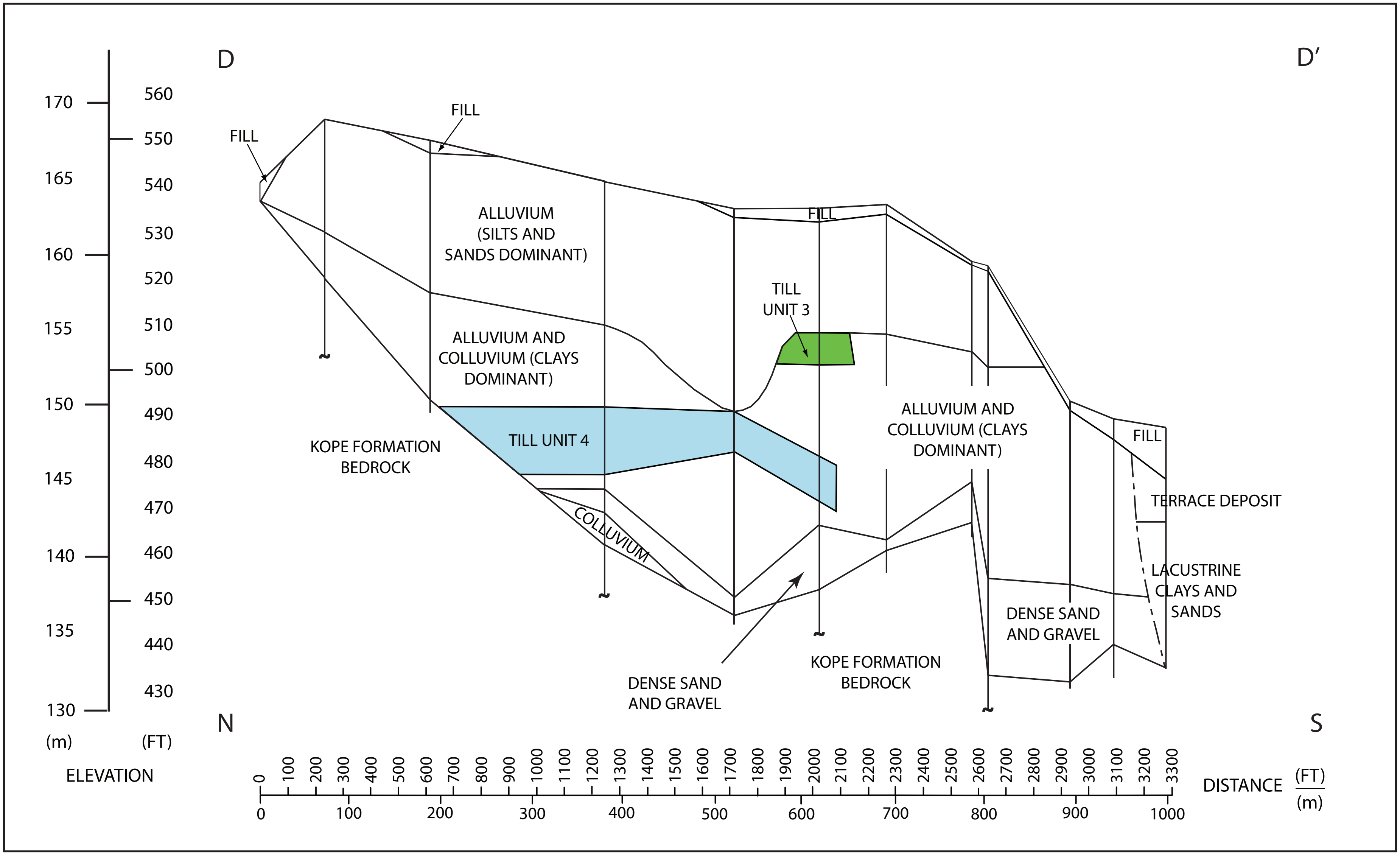


Figure 19. Cross section D-D′ in the Sayler Park, Ohio area.

demonstrated that this till was deposited by a lobe of ice that invaded the Carrollton area after the Ohio and Kentucky River valleys had been established (Fig. 20). All of these data support a hypothesis that the Deep Stage valley between Hamilton and Carrollton had been downcut and filled in with outwash prior to the arrival of glacial ice in the area.

Northern Kentucky Bedrock Uplands Tills

Tills have been identified in the northern Kentucky uplands (by the principal author) at elevations as high as 266.4 m (874 ft). This is consistent with till remnant elevations of 259.1-274.3 m (850-900 ft) noted at similar latitudes in southern Indiana (Gray [1988]).

Roughly 760 m (0.5 mi) east of the point where the bedrock uplands begin to rise above the Deep Stage valley infill sediments just north of Belleview, Kentucky, a boring drilled in the uplands (Boring 229, Figs. 10 and 21) encountered two strata of clayey till separated by 76.2 cm (2.5 ft) of outwash sand. The lower of the two till strata was 2.3 m (7.5 ft) thick, and rested on 3 m (10 ft) of very stiff clay overlying the bedrock surface. This lower till was made up of sandy, silty clay and clayey sand and, based on its liquid limit and plasticity index, exhibited Till Unit 5 characteristics. The upper of the two tills was 76.2 cm (2.3 ft) thick and rested on the outwash. This upper till was made up of clayey sand and, based on its liquid limit and plasticity index, exhibited Till Unit 4 characteristics (Fig. 21).

Another 3.7 to 4.0 km (2.3 to 2.5 mi) to the east, another till remnant was encountered in a set of borings drilled along cross section A-A’ (Figs. 10 and 11) north of Middle Creek, on a present-day uplands ridgetop situated above both ancient and modern valleys to the east and west. In one

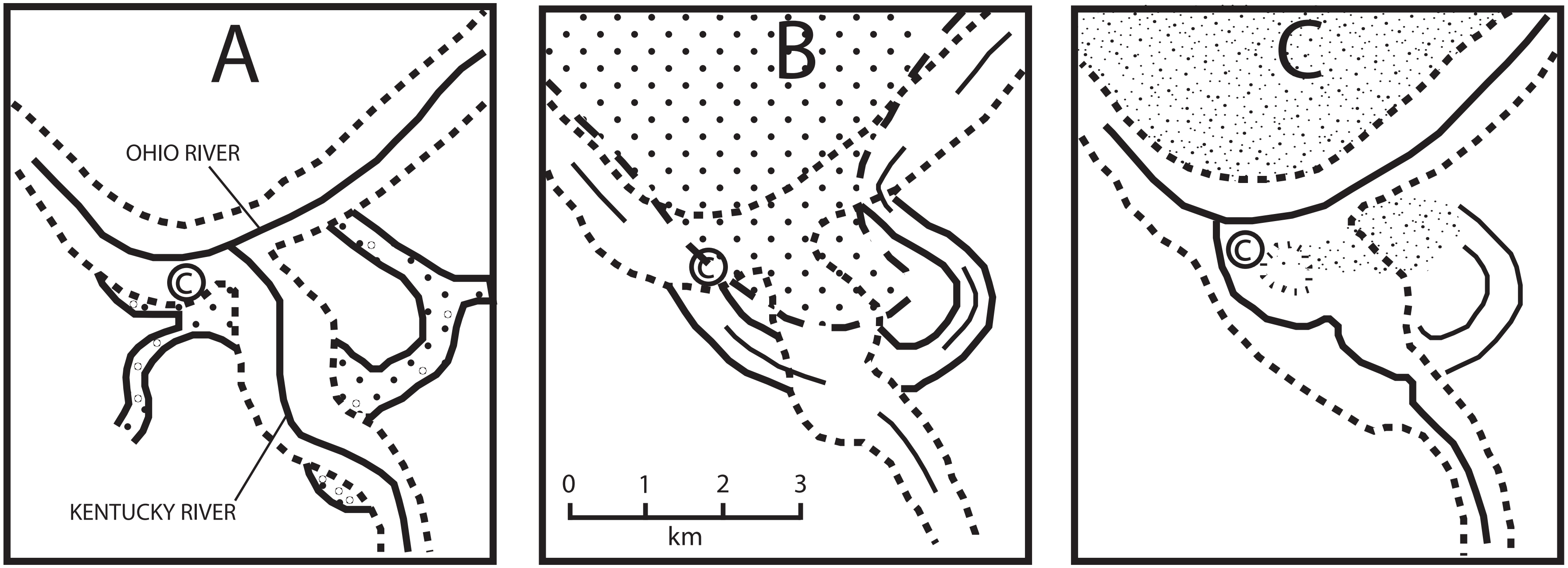


Figure 20. Sequence of events leading to present drainage conditions near Carrollton, Kentucky (indicated by circled 'C').
A: Pre-ice invasion conditions showing high-elevation Teays valleys (stippled); rivers entrenched at least to present levels.
B: Drainage at time of damming by ice; ice area stippled. C: Present conditions showing till (stippled) (after Teller, 1973).

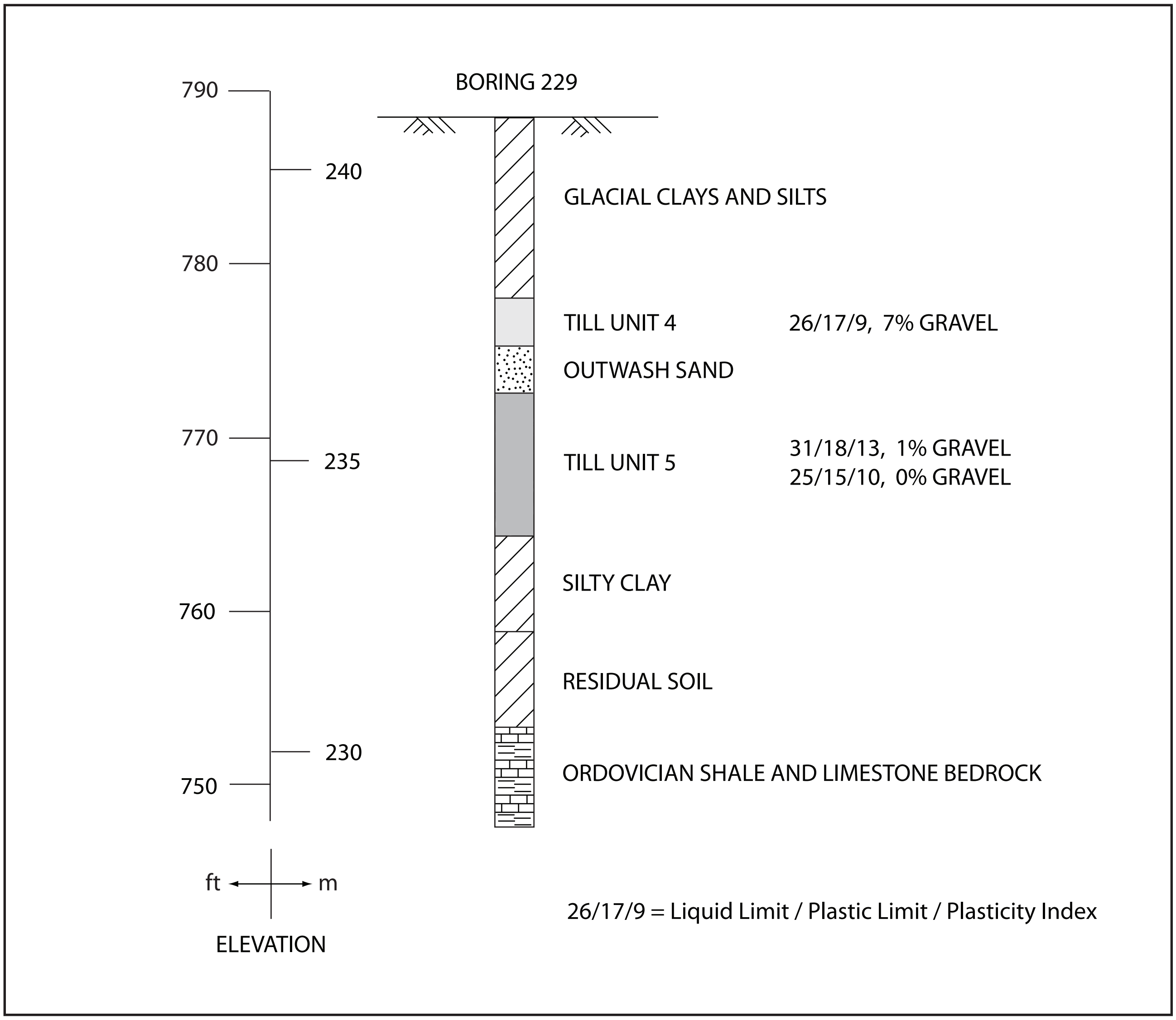


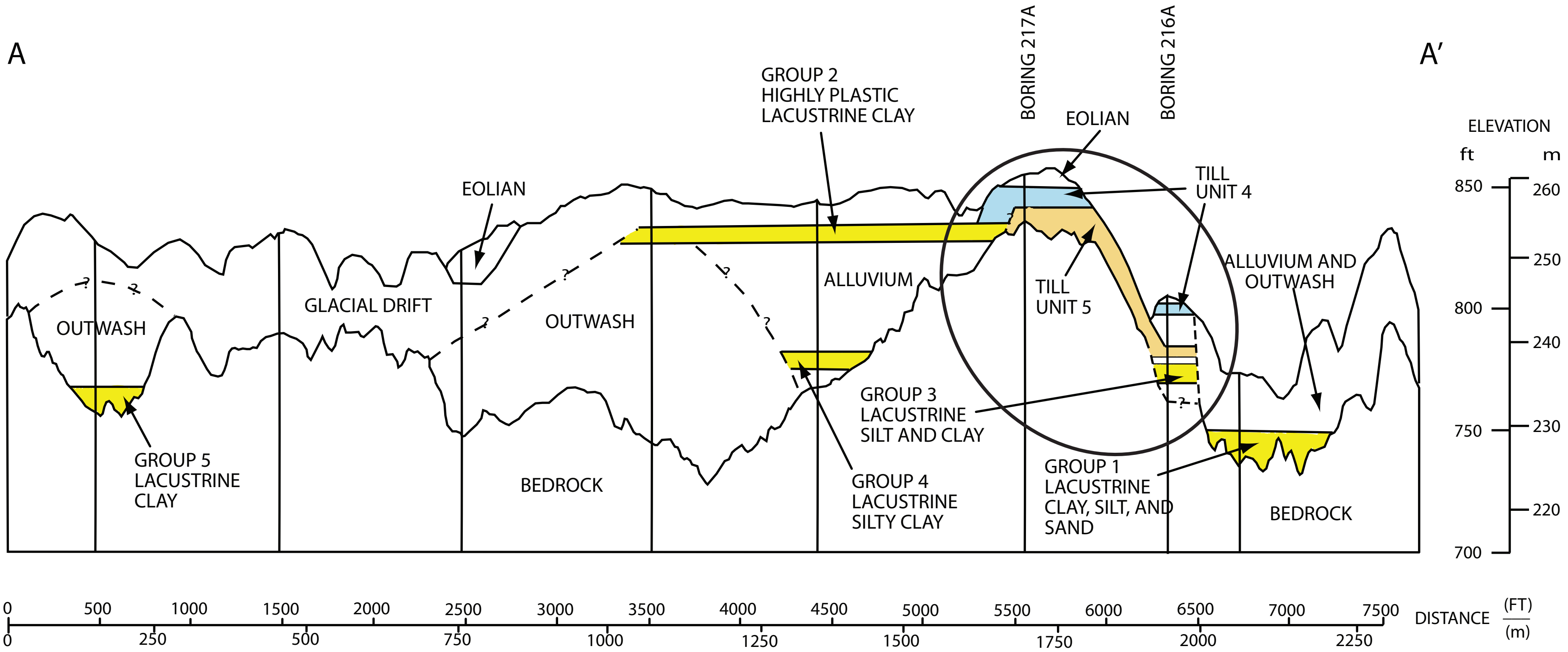
Figure 21. Boring 229 in the northern Kentucky uplands. The boring encountered two clayey till layers that, based on plasticity, are correlated with Till Units 4 and 5 from the Deep Stage valley near Belleview, indicating that the Deep Stage valley had already been downcut when the first ice advance reached and crossed the Deep Stage valley and invaded the northern Kentucky area.

of these borings (216A), two distinct till strata were encountered, separated by 3.8 m (12.5 ft) of clayey, fine- to coarse-grained outwash sand and gravel (Fig. 22). In the other boring (217A), the separating outwash sand was either not present or not encountered within the 1.52-m (5-ft) sampling interval. The liquid limit and plasticity index of the lower till stratum corresponds to the upper range of values exhibited by Till Unit 5. However, the liquid limit of the upper till stratum increases to over 50 percent, indicating a higher plasticity than that of Till Unit 4 as measured in the Deep Stage valley (Fig. 22).

Many of the remnant sediments in the Old Kentucky riverbed in Boone County are covered with outwash sand and gravel mapped by Swadley (1971a) as pre-Illinoian. In one instance, these outwash deposits are mapped continuously from El. 201.2 to 262.1 m (660 to 860 ft), i.e., from atop the Old Kentucky riverbed to a nearby ridgetop (Swadley [1971a]; Fig. 9), indicating that the outwash had, at one time, completely filled the valley and blanketed the ridgetops. This outwash is older than Till Unit 5 (Figs. 22 and 23), and suggests that not only had the Deep Stage valley been downcut and partially filled with outwash prior to the arrival of glacial ice in the area, but the Old Kentucky riverbed and the ridgetops above it had been blanketed with outwash prior to the arrival of glacial ice as well.

Lacustrine Materials

Northern Kentucky's lacustrine clays, sands, and silts feature prominently in deciphering the identities and relative ages of the upland tills due to their stratigraphic relationships and their effects on the plasticity of the till units. The plasticity of these clays is discussed here; Chapter



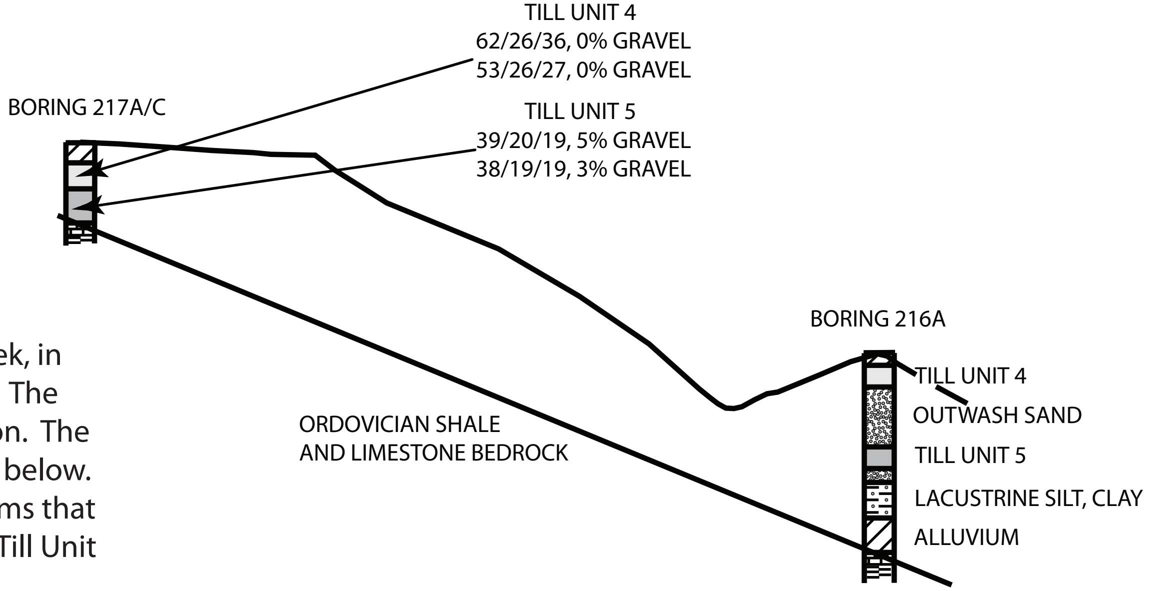
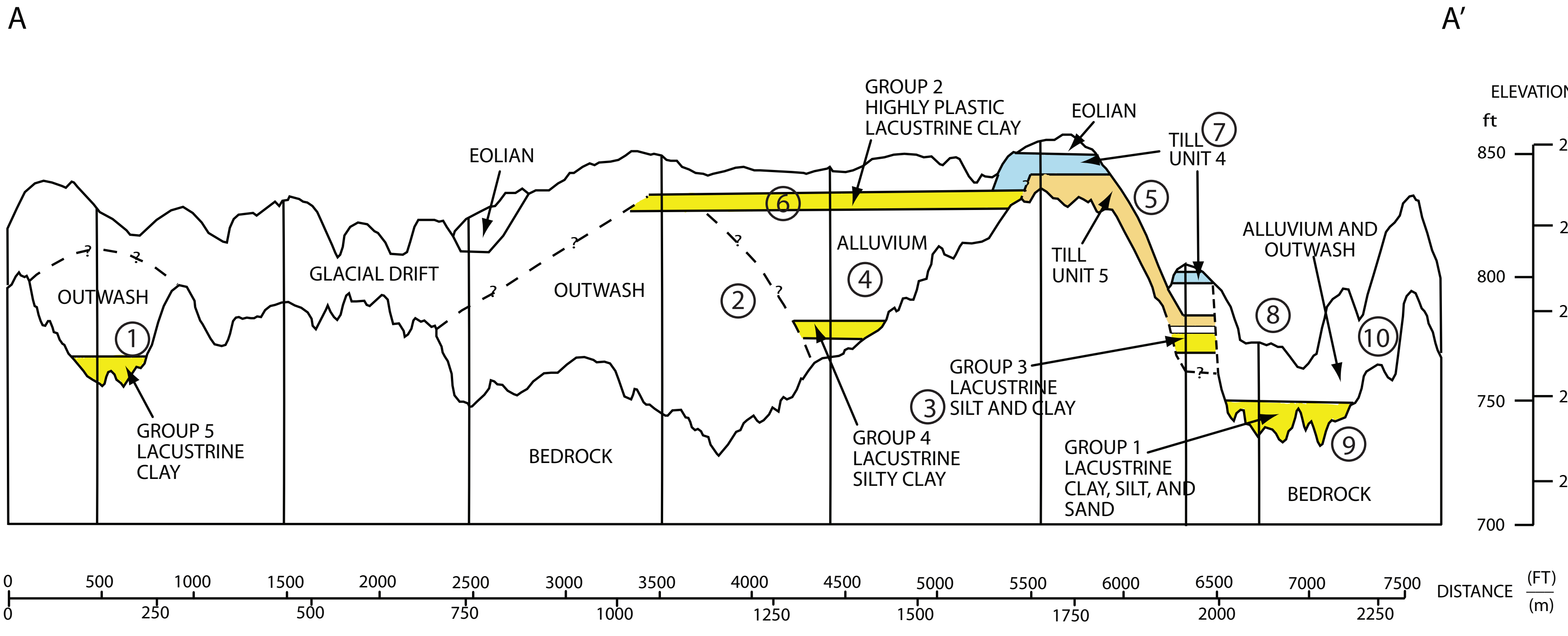


Figure 22. Cross section A-A' north of Middle Creek, in the uplands of western Boone County, Kentucky. The bedrock surface was delineated by seismic refraction. The ellipse indicates the location of the closeup section below. The marked increase in plasticity of Till Unit 4 confirms that the highly plastic Group 2 lacustrine clay postdates Till Unit 5 but predates Till Unit 4.



1) Group 5 lacustrine clay deposited in tributary valley to south-flowing, preglacial Old Kentucky River at west end of section.

2) Outwash fills tributary valleys and is subsequently eroded by streamflow.

3) Laminated, lacustrine silt and clay deposited at Group 3 and Group 4 locations following backup of drainage in Old Kentucky River tributary.

4) Group 3 and 4 lacustrine soils buried by deposition of alluvium.

5) Ice advance into northern Kentucky deposits Till Unit 5. Till Unit 5 may postdate the alluvium entirely, or may have been deposited in valley to west (4) above Group 4 and subsequently eroded prior to complete filling of valley with alluvium.

6) Laminated, highly plastic, Group 2 lacustrine clay deposited above alluvium-filled valley, and in widespread area to the north, likely in proglacial lake formed during retreat of ice that deposited Till Unit 5.

7) Ice advance into northern Kentucky deposits Till Unit 4. Ice overrode the Group 2 highly plastic, lacustrine clay and incorporated it into Till Unit 4, raising the till's plasticity where deposited to the east.

8) Further erosion of valley to the east.

9) Lacustrine soils deposited at Group 1 location.

10) Outwash deposited over lacustrine deposits at Group 1 location.

Figure 23. Summary of depositional history of sediments encountered in borings drilled along cross section A-A′ (Fig. 10), in the northern Kentucky uplands of western Boone County north of Middle Creek. This section helps relate the uplands till units to the Group 2 lacustrine clays that once blanketed a large portion of the Boone County, Kentucky and Cincinnati, Ohio areas.

Four describes the clay mineralogy and soil chemistry of these deposits in more detail.

Finely laminated, lacustrine materials occur in the Burlington (Fig. 24) area of Boone County and have been documented over a wide range of elevations. They are referred to herein as the Burlington Clays, and are separated into groups, each group (five total) having a specific location and elevation where it was encountered, and consisting of one or more separate strata. The five groups occur in a series of now-buried valleys located along cross section A-A (Fig. 11) north of the present-day Middle Creek valley (Fig. 10). These Middle Creek groups are numbered from youngest (1) to oldest (5). Groups 1, 3, 4, and 5 are 76 cm to 3.0 m (2.5 to 10.0 ft) thick, consist of sand, silt, silty clay, and highly plastic clay, and have been documented only in the buried valleys north of Middle Creek. Group 2 is distinctly different in that it is considerably thicker (up to 19.8 m [65 ft] thick), occurs over a large area of central to northern Boone County, extends into the Cincinnati area (Figs. 4 and 24, including the Middle Creek area), and consists of finely laminated, highly plastic clay.

The ranges of elevation over which the lacustrine deposits were encountered in available borings drilled in the Middle Creek area are shown in Table 2 below. Their depositional history is summarized in Figure 23.

Timing of Ice Advances

Remanent magnetism studies were conducted on Deep Stage valley till samples obtained using oriented, 76.2-mm (3-inch) diameter, thin-walled, Shelby tube samplers. The purpose was to

TABLE 2. LACUSTRINE MATERIAL GROUPS NORTH OF MIDDLE CREEK, FROM YOUNGEST (1) TO OLDEST (5)

LACUSTRINE GROUP	BORINGS SAMPLED	SAMPLING ELEVATION (m [ft])	DESCRIPTION
1D	216B	224.4 - 223.7 (736.4 - 733.9)	Gray finely laminated clayey silty sand
1C	216B	223.7 - 222.9 (733.9 - 731.4)	Gray finely laminated clay
1B	216B	222.9 - 220.6 (731.4 - 723.9)	Gray finely laminated clayey silt with organic odors
1A	216B	220.6 - 219.1 (723.9 - 718.9)	Gray finely laminated clay with organic odors
Till Unit 4 Deposited			
2C	Burlington Basement Excavation	244 (800)	Brown finely laminated clay with light blue silt partings
2B	209	261.3 – 256.7 (857.3 – 842.3)	Reddish brown laminated clay with trace gravel and variable sand
2A	104, 218, 219	251.6 - 249.1 (825.5 - 817.4)	Reddish brown laminated clay with trace gravel and variable sand
Till Unit 5 Deposited			
3B	216A	235.0 - 233.5 (771.0 - 766.0)	Gray thinly laminated clayey silt
3A	216A	233.5 - 232.7 (766.0 - 763.5)	Gray thinly laminated lean clay
4	218	235.6 - 234.4 (773.9 - 768.9)	Bluish gray laminated silty clay with trace fine gravel
Outwash Deposited			
5	222	231.2 (758.5)	Laminated highly plastic clay

establish whether the till samples had been deposited prior to or following the last major magnetic reversal at 0.78 Ma (Laj and Channell, 2007). The results of the remanent magnetism testing on samples of Till Unit 5 are presented on Figure 25. The results are plotted stereographically, with the demagnetization steps best-fit onto great circles. The great circles for Till Unit 5 are not well ordered, and indicate a magnetic declination of 66.8° +/-14.8º. These

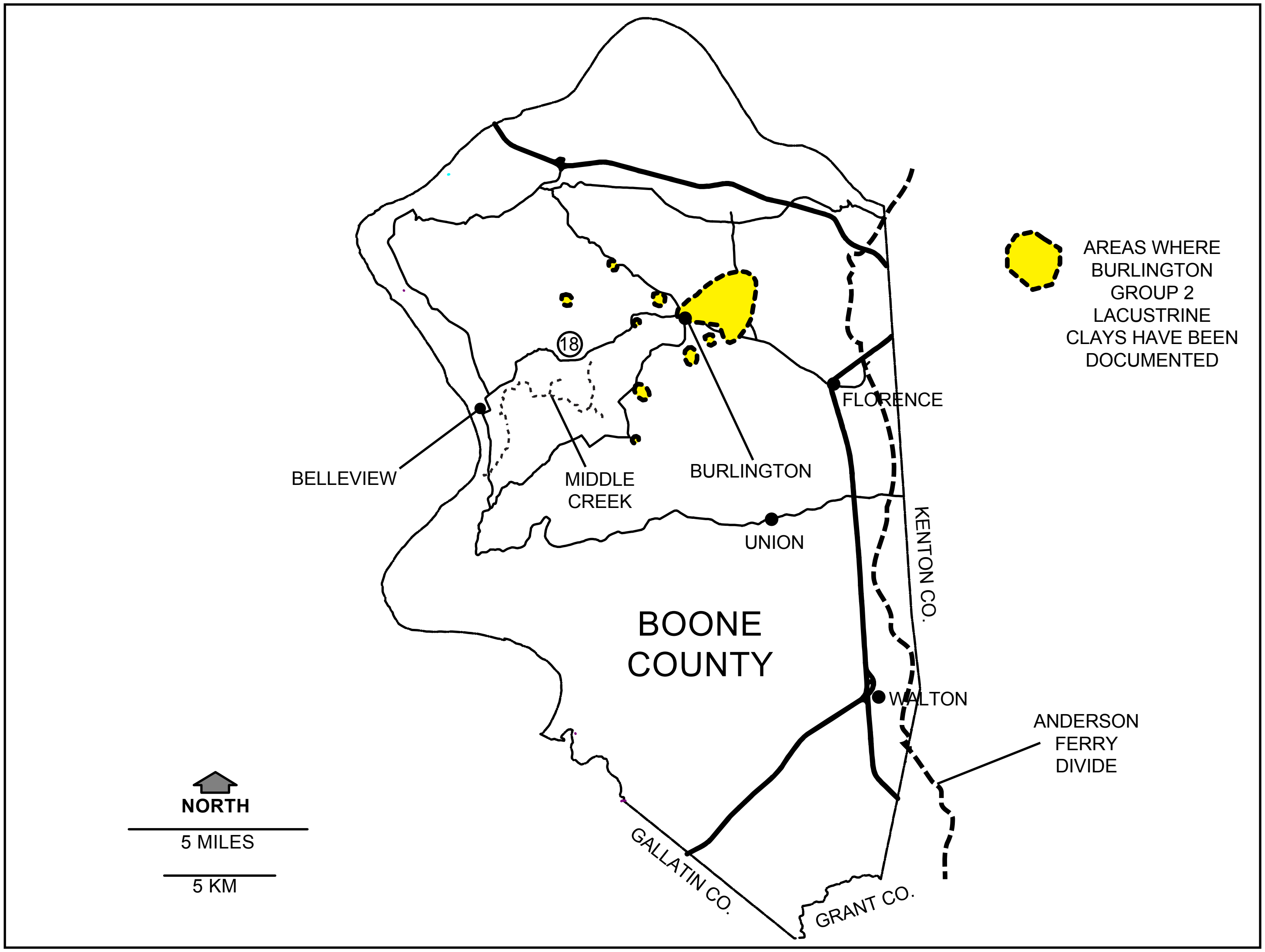


Figure 24. Areas in Boone County, Kentucky where Burlington Group 2 lacustrine clays have been documented. Burlington Group 1, 3, 4, and 5 lacustrine clays have only been documented between Middle Creek and Highway 18.

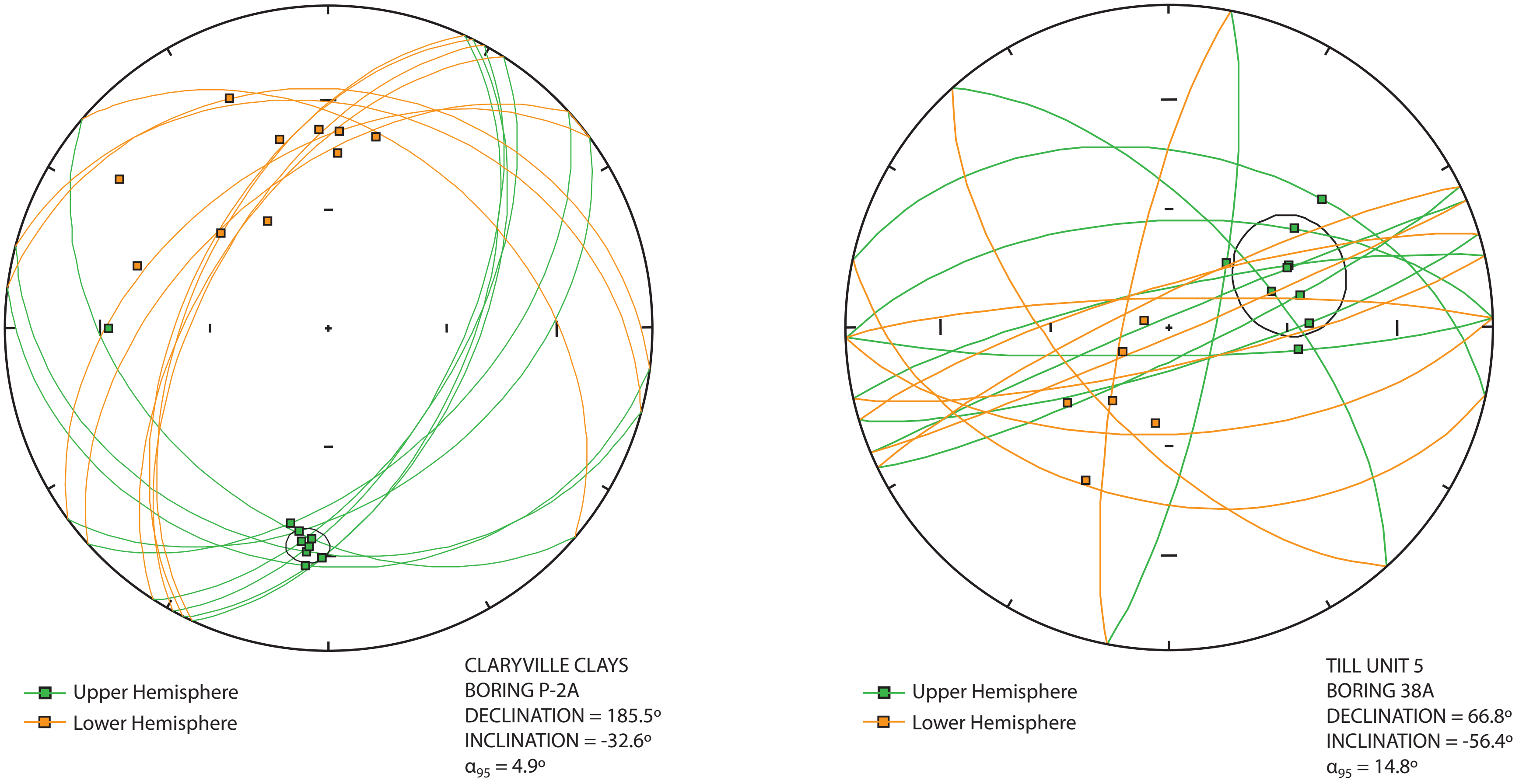


Figure 25. Remanent magnetism data collected on samples of basal Claryville Clay (L) and of Till Unit 5 (R). The Claryville Clay sample was obtained from a boring drilled southeast of Alexandria (Fig. 30). The Till Unit 5 sample was obtained from a boring drilled north of Section C-C' (Fig. 10). The Claryville Clay data show well-organized demagnetization circles and demonstrate conclusively that these clays were deposited during a period of reversed magnetic polarity, and that they are older than 780 ka. The Till Unit 5 data do not show well-organized demagnetization circles and do not correspond to any known periods of excursion from either normal or reversed polarity, and therefore, are not conclusive in terms of the age of the till.

results cannot be correlated to any known subchrons or magnetic excursions (Channell [2013]).

At some time following deposition of Till Unit 4, a valley was downcut to the east of Boring 216A (Fig. 22) and was subsequently filled with Group 1 lacustrine materials following blockage of its outlet. These lacustrine materials were subsequently buried by outwash that Swadley (1971c, 1972) mapped as pre-Illinoian. These lacustrine and outwash materials may have been associated with retreat of the ice that deposited Till Unit 4, or may be indicative of subsequent ice advances into the area.

Summary of Results

The individual tills are easy to distinguish where they occur in the Deep Stage valley because they are relatively flat and are generally separated by significant thicknesses of outwash or alluvium (Figs. 12 and 13). In addition, simple classification testing allows distinctions to be made on the basis of plasticity (Fig. 17). This has allowed Deep Stage Till Units 4 and 5 to be correlated with two till strata identified in the northern Kentucky uplands, as well as with northern Kentucky lacustrine deposits (Table 2).

DISCUSSION

Deep Stage Valley Tills

Till Unit 5, the deepest (and on the basis of stratigraphy, the oldest) till encountered within the Deep Stage valley, is underlain by at least 12.8 m (42 ft) of outwash sand and gravel (Fig. 13). This study presents evidence that tills were placed in the Deep Stage valley south of Hamilton, and that they postdate the downcutting of that valley. On the basis of plasticity, Till Units 4 and

5, the two oldest occurring in the Deep Stage valley, can be correlated with the oldest two tills occurring in the Northern Kentucky uplands. These findings indicate that incision of the Deep Stage valley south of Hamilton, Ohio and superposed over the general Old Kentucky River alignment occurred prior to the arrival of the glacial ice that invaded northern Kentucky.

Northern Kentucky Bedrock Uplands Tills and Lacustrine Clays

The two uplands till strata encountered in Boring 229 (Fig. 21) exhibit the plasticity characteristics of Deep Stage Till Units 4 and 5, including the characteristic of Till Unit 4 exhibiting a slightly lower liquid limit and plasticity index than that of Till Unit 5 (Figs. 17 and 21). Based on these similarities, these two uplands tills are correlated as Till Units 4 and 5. Further to the east and within the limits of the Group 2 lacustrine clays, the lower till stratum continued to exhibit the plasticity characteristics of Deep Stage Till Unit 5. However, once the limit of the Group 2 lacustrine clays is reached, the plasticity of the upper till stratum increases, and no longer exhibits the plasticity characteristics of Deep Stage Till Unit 4 (Fig. 22).

The upper portion of the lower till stratum encountered in the Sayler Park borings (Fig. 19) also exhibits higher plasticity than Till Unit 4 exhibits in the main Deep Stage valley. Sayler Park is downrange of Group 2 lacustrine clays documented in the Cincinnati area (Fig. 4), and therefore, the highly plastic Group 2 lacustrine clays were available as a source for Till Unit 4.

Based on the increased plasticity of the upper till stratum in Borings 217A and 217C (Fig. 22), the highly plastic, Group 2 lacustrine clays within this valley were not present at the time of the Till Unit 5 advance and therefore were not a source for Till Unit 5, but were present and were available as source material at the time of the later Till Unit 4 advance, and affected its plasticity by increasing it.

Timing of Deep Stage Incision

Granger et al. (2001) dated major river incisions at 2 Ma and at 1.5 Ma, suggesting that the first may have been associated with glaciation that caused the development of the Teays River but did not reach the Cincinnati area, and that the second was associated with a later glaciation that caused the development of the Deep Stage (Granger and Smith [2000]). Assuming that Laurentide glacial ice first reached the Cincinnati area at about 1.5 Ma, our conclusion that major portions of the Deep Stage valley in the Cincinnati area had already been downcut prior to the arrival of glacial ice in the area implies that the Deep Stage could have been downcut in less than 500 ka. This can be tested by estimation of erosion rates in similar strata.

The elevation of the preglacial Old Kentucky River is near 204.2 m (670 ft) where it is first intercepted by the Deep Stage valley near Carrollton, Kentucky; the lowest known elevation of the Deep Stage valley in the Cincinnati area is at 107.3 m (352 ft) across from Ludlow, Kentucky (Thelen [2012], Fig. 4). Almost 97 m (318 ft) of downcutting would have to have occurred in less than 500 ka, resulting in a minimum average downcutting rate of 194 mm/ka.

The bedrock underlying the Old Kentucky riverbed downstream of Carrollton belongs to the Kope Formation, composed of at least 85 percent shale that exhibits low slake durability, degrades quickly on exposure to water, and is easily erodible. Although erosion rates have not been estimated or measured for the Kope Formation itself, Howard (1997) has studied erosion rates for the Mancos Shale of Utah by the Fremont River based on cosmogenic dating of river terraces by Anderson et al. (1996). Howard (1997) describes the decomposition of unweathered Mancos Shale within a few tens of hours into loose, flaky chips when saturated with water; the author has seen Kope Formation shale behave in the same manner. Howard (1997) suggests a long-term average erosion rate of the Mancos Shale by the Fremont River of about 700 mm/ka. Assuming similar behavior by the Kope Formation, this erosion rate suggests that the downcutting of the Deep Stage valley through the Kope Formation (i.e., to roughly El. 138.7 m [455 ft]) could have occurred within 94 ka.

Andrews (2006) estimated an incision rate for the Kentucky River of 55 mm/ka. At an average incision rate of 55 mm/ka, the Deep Stage valley would have eroded through the Point Pleasant Formation and into the top of the Lexington Limestone from Els. 138.7 to 107.3 m (455 to 352 ft) in 571 ka, for a total of 94 ka + 571 ka = 665 ka. However, the 55 mm/ka erosion rate is for a geologic profile that includes over 100 m (328 ft) of High Bridge Group limestone and dolomite where the valley passes through the Inner Bluegrass physiographic province. This suggests that the erosion rate for the Point Pleasant and the upper portion of the Lexington Limestone, through which the Deep Stage valley was downcut, may be higher.

Based on these large incision rates, the Deep Stage valley could have been downcut within the 500 ka timespan between the organization of the Teays and Deep Stage valleys.

Timing of Glacial Advances

This study shows that at least seven Laurentide ice advances affected the Cincinnati region. The earliest advance(s) caused the downcutting of the Deep Stage valley by meltwater, and its subsequent filling with sand and gravel outwash. Five subsequent advances deposited Till Units 1 through 5 in the Deep Stage valley (the first two of these deposited Till Units 4 and 5 in the northern Kentucky uplands). The final advance deposited the Wisconsinan till to its location north of the present-day Ohio River. Six of these seven advances are known, on the basis of stratigraphy, to be pre-Wisconsinan in age, but remain undated.

In many till sequences of only one glacial cycle (e.g., the late Wisconsin), there exist multiple clayey till strata and intervening gravel or sand layers. Many of the borings utilized for this study encountered layers of outwash and alluvium separating individual till units; these varied in thickness from 76 cm to 10.7 m (2.5 to 35 ft) where they were encountered and sampled, and represent some passage of time between ice advances. However, neither the length of time nor the extent of ice retreat between these advances can be determined. In some areas of the United States, distinct lithologies are represented in the sand, gravel, and cobbles of individual till strata that can be used to distinguish between different ice advances from different directions. For example, individual till strata deposited in the Manhattan, New York area have distinct colors and incorporate diagnostic indicator stones, depending on whether the ice advanced from the northwest or northeast over differing lithologies (Moss and Merguerian [2006]). This is not the case in western Cincinnati and Boone County, Kentucky, where the bedrock lithology consists mainly of interbedded shale and limestone.

The results of remanent magnetism testing performed on the Till Unit 5 samples are considered inconclusive. The magnetic orientations that had been established in the soil and bedrock materials forming the till were mechanically disrupted by particle reorientation during incorporation into, and transport by, the glacial ice. The stepwise demagnetization process discerned a general magnetic orientation within the till, but this could not be correlated to any known excursions occurring within Brunhes or Matuyama time (Fig. 11) that had been documented by Laj and Channell (2007).

CONCLUSIONS

Based on the results and discussion presented in this chapter, the following conclusions have been reached.

1) Incision of the portion of the Deep Stage valley extending south from Hamilton, Ohio along the general Old Kentucky River alignment occurred prior to invasion of glacial ice into northern Kentucky.

2) At least seven ice advances (six pre-Wisconsinan) have affected the Cincinnati region, the first being that which indirectly caused the incision of the Deep Stage valley by the erosive effects of its meltwater. Five of these ice advances are now known to have reached and crossed the Deep Stage valley south of Lawrenceburg.

3) At least two of the ice advances documented in the Deep Stage valley (associated with Till Units 4 and 5) continued into the northern Kentucky uplands. Whether Till Units 1

through 3 were deposited in the uplands and have since been eroded away, or were never present in the northern Kentucky uplands, cannot be determined at this time. However, deposition of lacustrine clays and outwash in a valley incised near Middle Creek some time after deposition of Till Unit 4 suggests that one or more additional ice advances occurred into northern Kentucky.

4) The Group 3, 4, and 5 lacustrine deposits are local to the area north of Middle Creek and represent multiple pondings of south-flowing stream valleys tributary to the Old Kentucky River. The thick, areally-extensive, Group 2 Burlington Clay was deposited in a proglacial lake occurring in the northern Kentucky uplands and extending into the Cincinnati area (Figs. 4 and 24). The lake was associated with the ice advances that deposited Till Units 4 and 5. The Group 1 Burlington Clays were laid down in a south-draining valley incised below Till Units 4 and 5, which likely provided drainage from the central Boone County area.

5) The highly plastic, Group 2 lacustrine clays altered the plasticity of Till Unit 4 where the advancing ice passed over and incorporated them into Till Unit 4.

6) Based on Granger et al's (2001) estimate of the age of Teays River incision at 2 Ma, and of Deep Stage incision at about 1.5 Ma, Till Units 1 through 5 are likely no older than 1.5 Ma.

CHAPTER THREE

THE EFFECTS OF ISOSTATIC CRUSTAL DEFLECTION ON THE ACTIVATION OF DRAINAGE COLS AND ON THE FORMATION OF TEMPORARY LAKES DURING GLACIATION AND DEGLACIATION OF THE CINCINNATI / NORTHERN KENTUCKY AREA

OVERVIEW

Isostatic crustal deflection affected the activation of drainage cols during glaciation and deglaciation of the Cincinnati and northern Kentucky areas, as well as the formation and drainage of temporary proglacial lakes (Andrews [2003, 2006]). Once glacial Lake Claryville formed on the east side of the Divide, it needed at least one outlet to allow drainage to the west. Andrews (2003, 2006) documented the existence of a major Lake Claryville spillway, complete with a network of paleovalleys, at Levee, Kentucky. However, other cols exist on the Anderson Ferry Divide at similar elevations to the Levee spillway col (Figs. 2 and 3), with isostatic crustal deflection caused by the weight of the advancing ice constantly changing the elevations of these cols relative to one another. The twofold purpose of this chapter is 1) to study the relationship between the Walton col in the northern portion of the Anderson Ferry Divide, and the Levee col farther south, in providing westward drainage for Lake Claryville while the Laurentide ice sheet caused isostatic crustal deflection during glaciation and deglaciation; and 2) to study the role of isostatic crustal deflection in the formation of the temporary lake in which the Burlington Clays were deposited.

ACTIVATION OF THE LEVEE SPILLWAY

The relationship between the Levee spillway and the cols has been studied as the ice sheet advanced southward and then retreated northward, causing isostatic flexure of the lithosphere. Andrews (2006) indicated that the Levee spillway col was the lowest point in elevation along the Divide separating the Old Kentucky and Old Licking River basins. However, a closer look at topography along the alignment of the Anderson Ferry Divide shows that the Walton col has a current elevation of 265.2 m (870 ft), or 6.1 m (20 ft) lower than the Levee spillway (Figs. 2 and 3), which challenges the conclusion of Andrews (2006). This is important because if the Levee spillway was not used to drain Lake Claryville, then alternative hypotheses must be developed for how the existing paleovalley network formed below the Levee col. The col elevations and the Ordovician bedrock formations in which they formed are shown in Table 3 below.

TABLE 3. COL NAMES, ELEVATIONS, AND BEDROCK FORMATIONS

COL NAME	ELEVATION (m [ft])	FORMATION	LITHOLOGY
Walton	265.2 (870)	Bull Fork	Interbedded shale (50%) and limestone (50%); (Swadley, 1969)
Sherman	277.4 (910)	Fairview	Interbedded shale (50%) and limestone (50%) (Swadley, 1969)
Mason/Blanchet	282.2 (926)	Kope/Clays Ferry Undivided	Interbedded shale (50%) and limestone (50%) (Wallace, 1976)
Alberta	289.6 (950)	Clays Ferry	Interbedded shale (50%) and limestone (50%); (Wallace, 1976)
Centerville	285.4 (935)	Millersburg Member, Lexington Limestone	Limestone lenses and nodules (70%), irregular beds; shale (30%) (Kanizay & Cressman, 1967)
Levee	271.3 (890)	Rowland Member, Drakes	Dolomitic, shaly and limey, silty mudstone (McDowell, 1978)

There are questions as to how the Levee col and spillway were activated, and how much they were used. The use of the Salt River paleochannels (Figs. 3 and 7) by the Old Kentucky River at Els. 242.3 to 248.4 m (795 to 815 ft), and the breaching of the col near Carrollton, Kentucky (Fig. 8) at an elevation lower than that, would not have allowed for Lake Claryville to eventually rise up to the level of the Levee spillway col at El. 271 m (890 ft). In addition, the approaching glacier isostatically depressed the Walton and Sherman col elevations far below that of the Levee col.

Three mechanisms may be considered by which Lake Claryville levels could have risen to the level of the Levee col. The first is that of damming of the Old Kentucky River by glacial ice, allowing water levels to rise in Lake Claryville by blocking them from access to the breached col that the upstream portion of the Old Kentucky River continued to drain out of. The second is that of damming of the Old Kentucky River by outwash deposits, which could have remained in place long after ice retreat, and which may have been in place at the time of a subsequent glacial advance. The third is adjustment of existing topography by isostatic crustal flexure caused by the weight of the advancing glacial ice.

METHODS

Crustal Flexure Models

Andrews (2006) presented and discussed a basic model of the effects of isostatic flexure caused by ice advance on regional drainage, based on equations presented in Turcotte and Schubert (1982). The model is based on a semi-infinite load, with a linear front, being placed on a homogeneous plate over an elastic foundation. This model (hereafter called the "simplified model") assumes a vertical load face and thus full ice thickness at the ice front, and estimates deflection of the lithosphere and aesthenosphere beneath the weight of a given thickness of ice. Both the height of, and the distance from the ice front to, the forebulge are also estimated. The forebulge occurs proximal to the ice front and results from elastic, frontal squeezing of the aesthenosphere. Andrews' (2006) purpose was not to determine the actual ice thickness or the actual magnitudes of lithospheric deflection, but simply to present the concept of isostatic flexure and to discuss the mechanism by which it occurs (Andrews [2011]). Pazzaglia and Gardner (1994) used a similar approach to study late Cenozoic flexural deflection of the middle U.S. Atlantic passive margin.

The simplified model is based on deflection of an ideal, homogeneous plate on an elastic medium in response to loading is defined by the following:

$$\mathrm{w} = h_a e^{(-\frac{x}{\alpha})} \left(\cos\left(\frac{x}{\alpha}\right) + \sin\left(\frac{x}{\alpha}\right)\right)$$

where α is a flexural parameter defined by:

$$\alpha = [4D/((\rho_m - 1)g)]^{-0.25}$$

The flexural rigidity of the plate (D) is related to elastic plate thickness (h), Poisson's ratio (ν), and Young's modulus (E) as follows:

$$D = Eh^3/(12(1-\nu^2))$$

Andrews (2006) assigned values of E = 70E+9 Pa, h = 35-40 km, D = 4E+23 N·m, and ν = 0.25. His values are in general agreement with those of Holzer (1979), who reviewed properties of the lithosphere and reported a Young's modulus of 0.68 Mbar (i.e., 68E+9 Pa); and with those of Pazzaglia and Gardner (1994), who studied orogenic flexural deflection of the crust and assigned values of h = 40 km, D = 4E+23 N·m, E = 70E+9 Pa, and ν = 0.25. Walcott (1970) estimated the lithospheric flexural rigidity as being on the order of 1.5 to 3.1E+23 N·m.

The plate is bent beyond the margins of the ice front, and a trough is formed proximal to the ice front. Proximal squeezing of the aesthenosphere forms a forebulge beyond the trough. The half-width of the trough is constrained by the flexural parameter as

$$x_o = 3\pi/4 * \alpha$$

The distance to the forebulge crest is also constrained by this flexural parameter, and is defined by

$$x_b = \pi * \alpha$$

The bulge height is directly related to the ice thickness:

$$w_b = -h_a e^{-t} = -0.0432\ h_a.$$

Tarasov et al. (2012) present a dynamic model for the deglaciation of the North American ice complex following Wisconsinan glaciation. Their method treats determination of past ice sheet evolution as a Bayesian statistical inference problem, and combines modeling and a large set of observations to generate probability distributions for past ice sheet evolution. Their glacial systems model (GSM) includes a three-dimensional, thermomechanically-coupled ice sheet model, visco-elastic bedrock response, a fully-coupled surface drainage solver, parameterized climate forcing, surface mass-balance and calving modules, and a gravitationally-self-consistent relative sea level solver (Tarasov et al., 2012). The GSM does not assume a vertical ice front, and thus allows the maximum ice thickness to occur well behind the ice front.

Although the GSM was constructed to consider the Wisconsinan deglaciation, the results may be used as a proxy for pre-Illinoian, isostatic crustal response to ice advance and retreat. The GSM has been run by Tarasov et al. (2012) at 500-year time intervals. The model results obtained at the 2,500-yr intervals of 16, 18.5, 21, 23.5, and 26 ka were considered; these would include the last glacial maximum (LGM) and the retreat of Wisconsinan ice from the Cincinnati region. The GSM grid cell resolution is 1.0° longitude and 0.5° latitude. The area over which the GSM was used encompassed 2.5° longitude and 2.0° latitude, or the area encompassed by 10 GSM grid cells. The visco-elastic solver is asynchronously coupled, with bed response computed at 100-year intervals using approximate 10° longitude by 5° latitude grid boxes, or roughly the area encompassed by 100 GSM grid cells. The coarseness of the visco-elastic response solver area, relative to the size of the study area, must be considered in interpreting the model results.

For a given time interval, the GSM provides surface topography (including the glacier) and ice thickness plots for the entire Laurentide ice sheet. For each time interval (i.e., 16, 18.5, 21, 23.5, and 26 ka), the ice thickness plot (h) was subtracted from the surface topography plot (z) to obtain a new ground surface topography plot (z-h) that accounted for crustal deformation but did not include the glacier. However, the GSM assumes a general ground surface profile that does not match existing topography. The GSM's 6 ka surface topography plot included neither ice nor effects of crustal loading from the glacier within the limits of the study area. Therefore, for each time interval, the 6 ka ground surface topography plot (z-h) was subtracted from that of each time interval's (z-h) in order to generate a new plot that represented only the difference in ground surface elevations within the study area resulting from crustal deformation at that particular time. This new elevation difference plot was then added to the present-day digital elevation model (DEM) of the study area. The resulting plot can be described as:

$$DEM + (Time_{(z-h)} - 6ka_{(z-h)}).$$

The ground surface elevations of specific latitude/longitude points could then be compared at different times as the glacier achieved its maximum southward extent within the study area and then retreated northward. This allowed observation of the surface elevation response to glaciation and deglaciation at different time stages within the northern Kentucky area. The use of different cols to provide Lake Claryville drainage could then be evaluated.

Spillway Flow

Because the Deep Stage valley was cut by a combination of north-flowing drainage and glacial meltwater, it may be useful to compare the Deep Stage valley's capacity to transmit water to the Walton and Levee cols' combined capacity to transmit it. (The Walton and Levee cols are chosen because they currently are the two lowest cols on the Divide.) The cols in the Anderson Ferry Divide had to drain Lake Claryville waters to the west until the Deep Stage valley was cut. Comparison of their capacities may shed light on whether or not the Walton and Levee cols were overmatched by glacial drainage. Even with isostatic crustal deflection lowering the elevation of the Walton col relative to that of the Levee col, perhaps water levels were able to rise to the elevation of the Levee col anyway if the capacity of the Walton col was overmatched.

Flow over natural cols may be modeled as stepped or trapezoidal notches (Fig. 26). If the dimensions of the spillway are known, then the capacity of the col can be estimated for a given water depth. For simplicity, the Walton (El. 264.9 m [869 ft]) and Levee cols (El. 272.5 m [894 ft] have been modeled as notched spillways (Codecogs [2013]) to determine their capacities with water heights up to El. 277.4 m (910 ft), which is the water height at which the Sherman col would be activated (based on current col elevations).

Based on a cross section of the Little Miami River's Deep Stage valley provided by Durrell (1961), the capacity of the Deep Stage valley may be estimated for a given depth of water as well, assuming a bottom elevation of 115.8 m (380 ft) and a channel-bottom width of 3,658 m (12,000 ft). Each col was modeled as a series of stepped notches (Fig. 26), although they could have been modeled as trapezoidal notches as well. The equation for flow capacity of the first stepped notch is

$$Q_1 = \frac{2}{3} * C_d * b_1 * \sqrt{2g} * {H_1}^{1.5}.$$

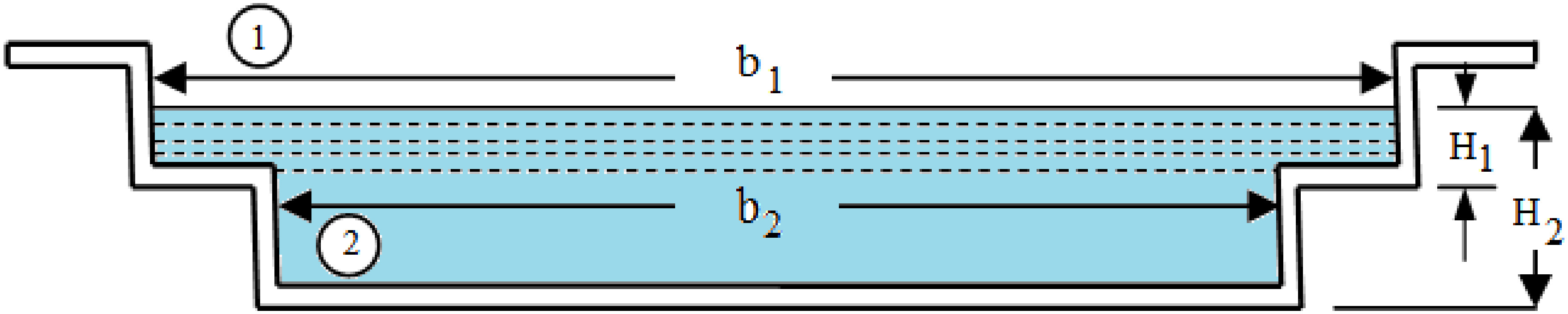


Figure 26. Walton and Levee cols modeled as stepped notches in order to estimate their flow capacity. The equation for the flow capacity of the first stepped notch is

$$Q = 2/3 * C_d * b_1 * (2g)^{1/2} * H_1^{1.5}.$$

The equation for the flow capacity of the second notch is

$$Q = 2/3 * C_d * b_2 * (2g)^{1/2} * (H_2^{1.5}. - H_1^{1.5)}.$$

The equation for the flow capacity of 'n' notches is

$$Q_T = Q_1 + Q_2 + ... + Q_n.$$

Q is flowrate in m^3/sec, C_d is a flow coefficient having a value of 0.6, *b* is the notch width in meters, *g* is the acceleration due to gravity, and *H* is the water head above the notch in meters.

The equation for flow capacity of the second notch is

$$Q_2 = \frac{2}{3} * C_d * b_2 * \sqrt{2g} * ({H_2}^{1.5} - {H_1}^{1.5}).$$

The equation for total flow capacity of n notches is

$$Q_{Total} = Q_1 + Q_2 + \ldots\ldots + Q_n.$$

Q is flowrate in m^3/sec, C_d is a flow coefficient that has a value of 0.6, b is the notch width in meters, g is acceleration due to gravity, and H is the water height above the notch in meters.

RESULTS

Crustal Flexure Models

The simplified model presented in Andrews (2006) assumed ice thicknesses of 1000 m and 1500 m (3281 and 4921 ft) in order to estimate possible lithospheric deflections south of the ice front. Using these ice thicknesses, the model generated deflections at the ice front itself of 303 to 455 m (994 to 1493 ft); a forebulge-crest-to-ice-front distance of 260 to 300 km (853 to 984 ft); and a forebulge height of 13 to 20 m (43 to 66 ft) (Andrews [2006]).

To provide a rough comparison between the results of the Tarasov et al. (2012) GSM with the simplified model, the GSM was first used to generate a profile of crustal depression with distance, for all time intervals, starting from the approximate southernmost point of maximum ice thickness at 51° north latitude (maximum ice thickness = 2,500 m [8,202 ft]). Data points were generated at 0.5-degree latitude intervals for each time interval. The simplified model was then used with the same maximum ice thickness to generate data points at the same distance intervals, starting at the vertical ice front. Both the GSM and simplified model results fit 6th-order polynomials having $R^2 > 0.98$, with the simplified model indicating ground surface elevations well below mean sea level. The results are shown on Fig. 27.

Using the Tarasov et al. (2012) GSM, the elevations of the Levee spillway col and the other cols listed in Table 3 have been estimated as a function of time (and by extension, proximity of the ice front). These elevations are shown in Table 4 below. For comparison purposes, the elevations of those locations at which the lacustrine clays have been encountered at the highest elevations on the east and west sides of the Divide (in Burlington and Alexandria, Kentucky, respectively) have been included. Figs. 28A through 28G show profiles of the estimated ground surface along the Divide with time, with the col locations marked.

It is noted that the GSM predicts maximum ice advance to a point about 10 km south of the Sherman, Kentucky col, which did not actually occur in the Wisconsinan glaciation. The actual southern limit of Wisconsinan glaciation is roughly 50 km (31 mi) north of Walton.

Spillway Flow

Using the method discussed above for estimation of spillway capacity, the Walton and Levee cols would have flow capacities of about 13,900 and 6,500 m^3/sec (491,000 and 229,500 ft^3/sec, respectively) with water heights up to El. 277.4 m (910 ft), based on current col elevations. Based on Durrell's (1961) cross section of the Little Miami River's Deep Stage valley, it would

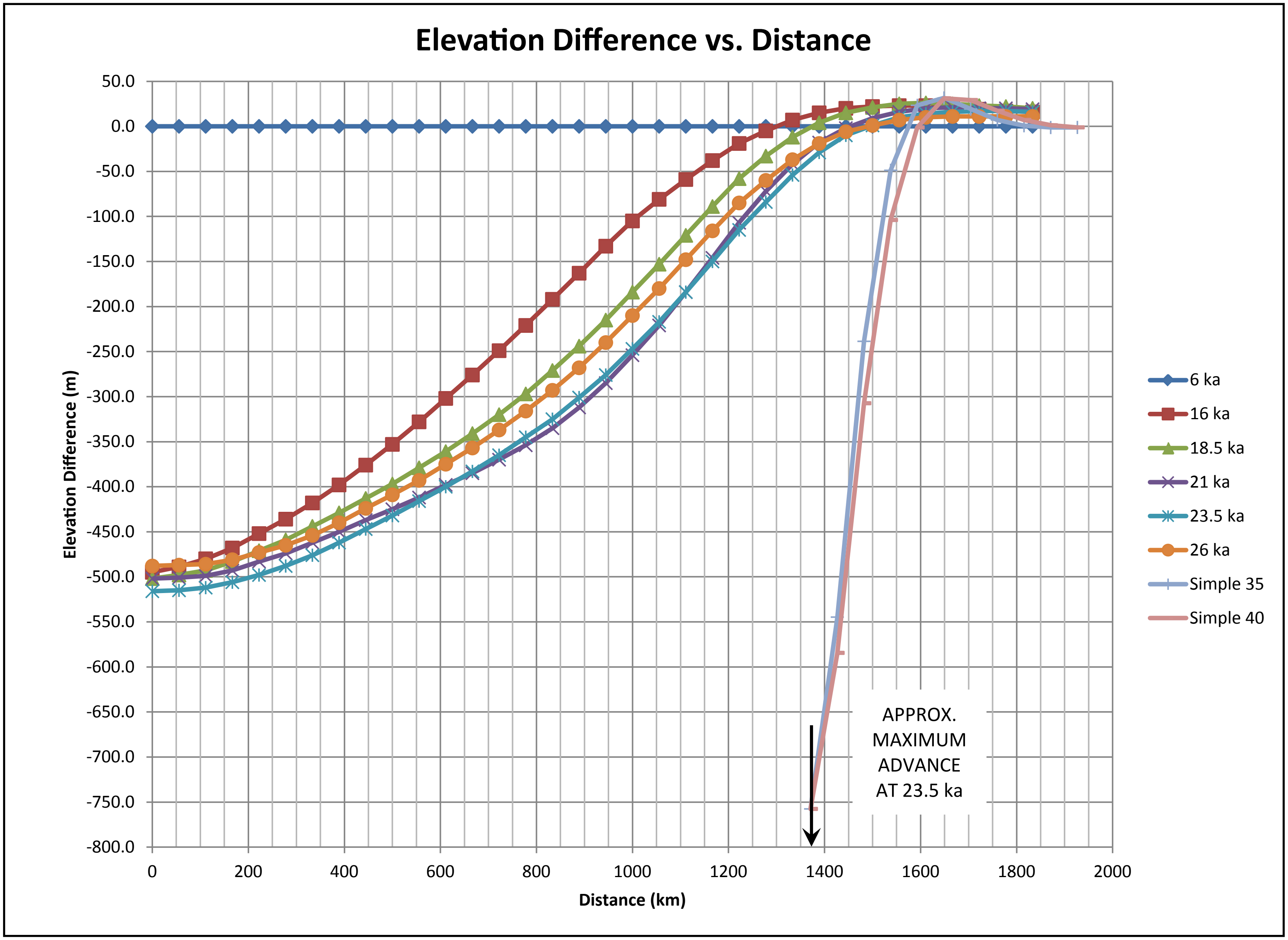


Figure 27. Plot showing ground surface elevation difference at time intervals of 16, 18.5, 21, 23.5, and 26 ka, relative to 6 ka (i.e., post-glacial) elevations, due to isostatic crustal deflection caused by advancing and retreating ice. For comparison, the data generated by the Simplified Model using lithosphere thicknesses of 35 and 40 km are included. Of the time intervals studied, the maximum ice advance and the maximum proglacial crustal deflections estimated by the GSM for the northern Kentucky area both occurred at 23.5 ka. The Simplified Model results are considered unreliable, in part, because they estimate ground surface deflections well below sea level at the ice front, owing to the simplifying assumption of a vertical ice front.

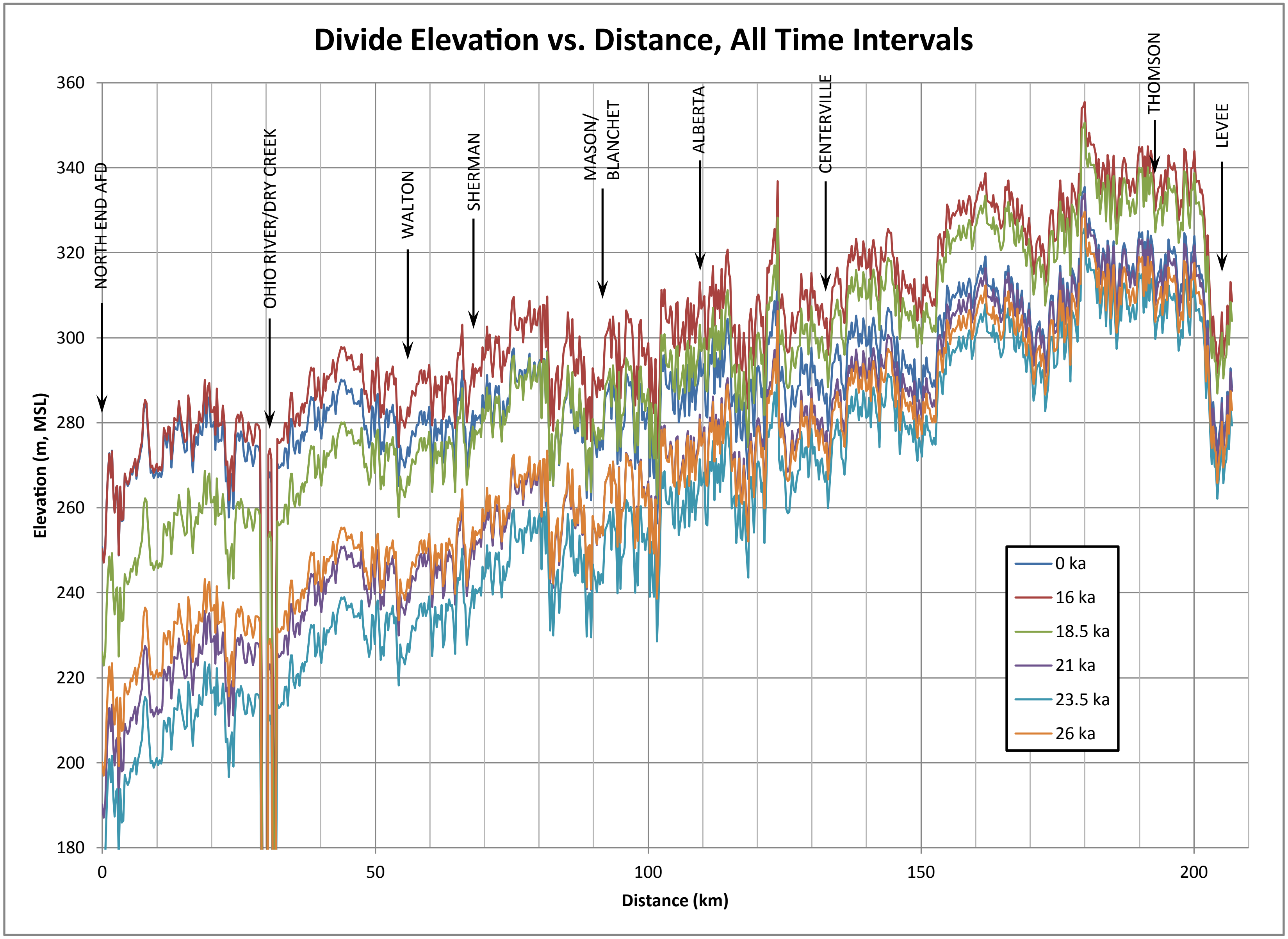


Figure 28A. Elevation vs. Distance plot along the Anderson Ferry Divide, from the north end of the Divide to the Levee col, for time intervals 0, 16, 18.5, 21, 23.5, and 26 ka. The plot shows the effects of isostatic deflection as glacier advances to its maximum at about 23.5 ka and then retreats.

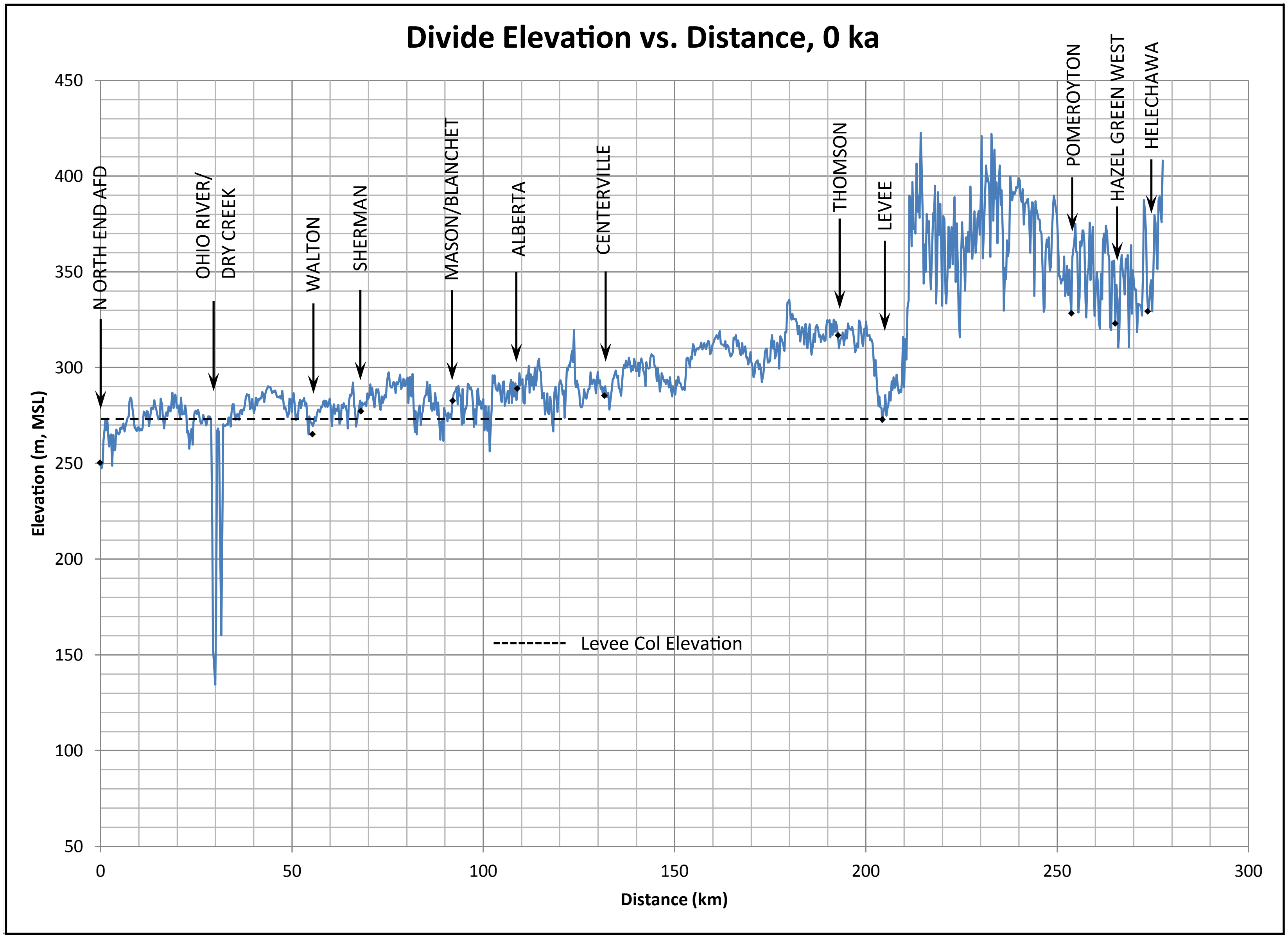


Figure 28B. Elevation vs. Distance plot along the Anderson Ferry Divide, from its north end to the Helechawa col, for time interval 0 ka (i.e., present day). Straight-line topographic profiles were generated between sampling points. Due to the sinuous nature of the divide and the frequency of sampling, the straight-line profiles between the sampling points incorporated the heads of drainages below the cols. This gives the appearance that the points shown as cols on this plot are not the lowest points on the divide, when in fact, they are. At the present time, the Levee col is 7.6 m (25 ft) higher in elevation than the Walton col. The digital elevation model cannot distinguish this 7.6-m (25-ft) difference because the Walton col was filled in for a railroad embankment.

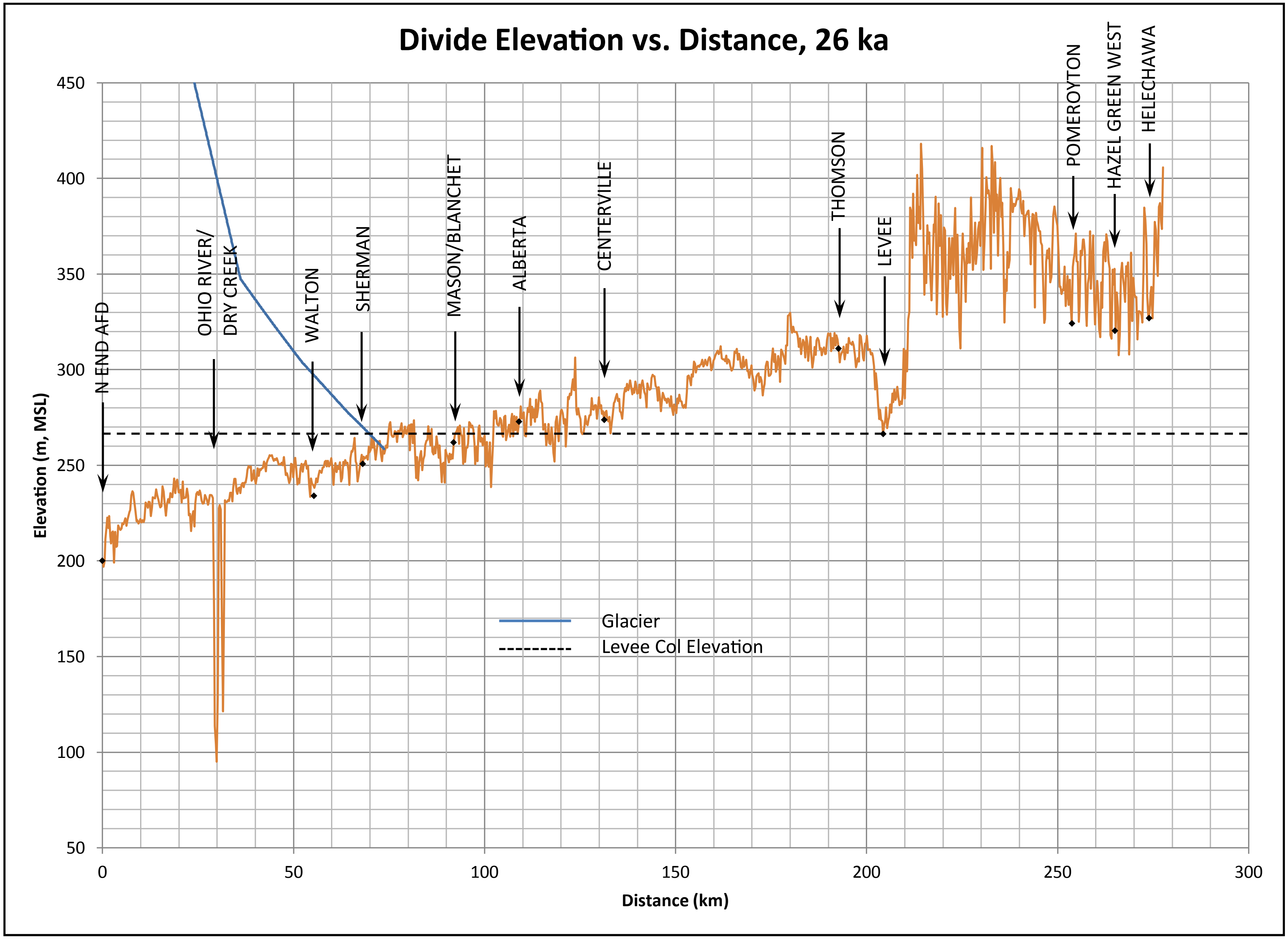


Figure 28C. Elevation vs. Distance plot along the Anderson Ferry Divide, from its north end to the Helechawa col, for time interval 26 ka, about 2,500 yr before maximum advance. The Walton, Sherman, and Mason/Blanchet cols were all lower than the Levee col, based on differences between present col elevations. The GSM estimates that the ice front was farther south than both the Walton and Sherman cols, which was the case west of the divide during pre-Illinoian advance. However, neither of these cols was actually covered, and both drained Lake Claryville until Mud Lick Creek (Fig. 7) was blocked by ice and prevented further use of the Walton col.

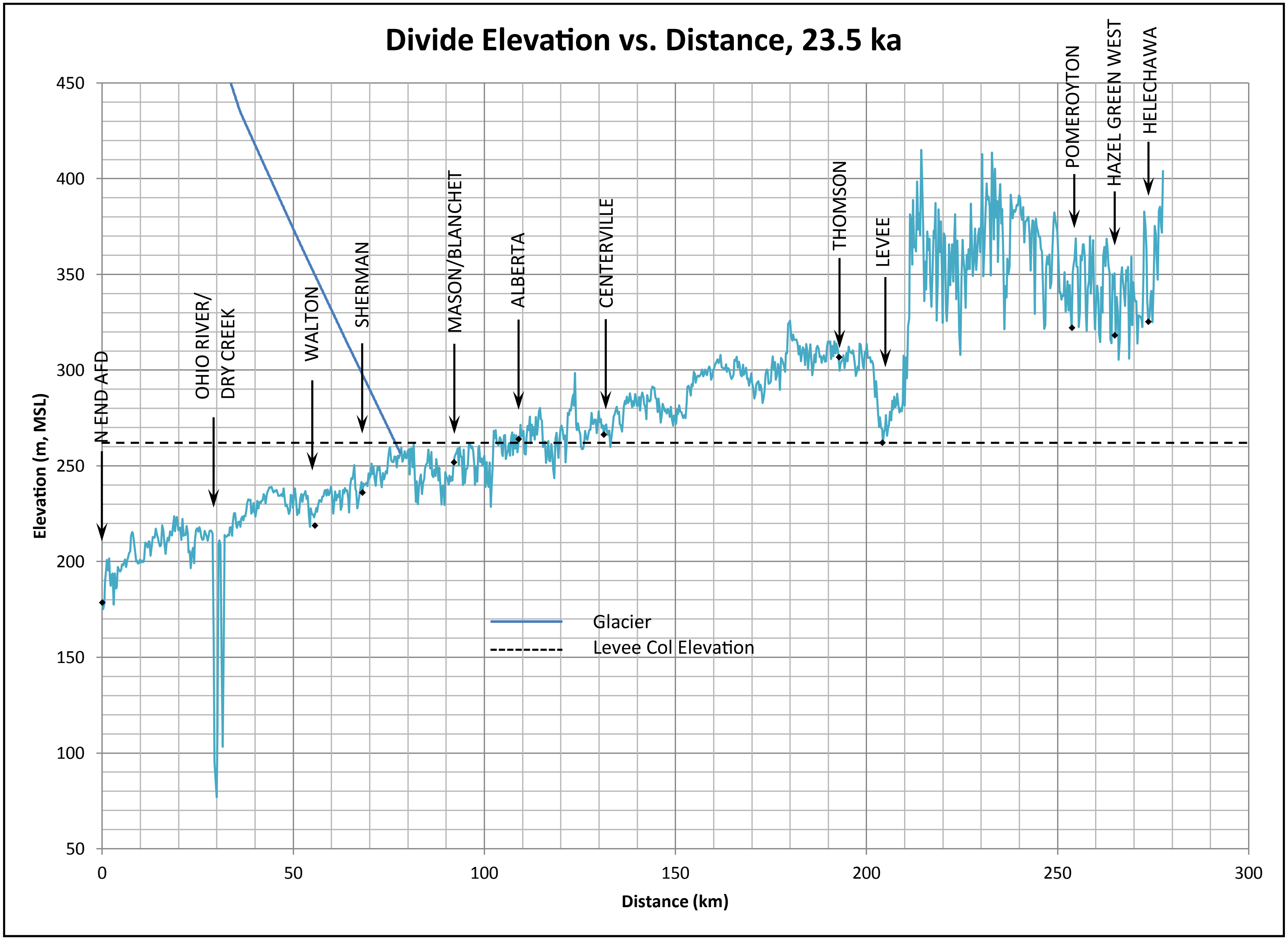


Figure 28D. Elevation vs. Distance plot along the Anderson Ferry Divide, from its north end to the Helechawa col, for time interval 23.5 ka, about the time of maximum advance. The Walton, Sherman, and Mason/Blanchet cols were all lower than the Levee col, based on differences between present col elevations. The GSM estimates that the ice front was farther south than both the Walton and Sherman cols, which was the case west of the divide during pre-Illinoian advance. However, neither of these cols was actually covered, and both drained Lake Claryville until Mud Lick Creek (Fig. 7) was blocked by ice and prevented further use of the Walton col. Among all of the time intervals studied, the GSM estimates maximum isostatic delfection in the northern Kentucky area at 23.5 ka.

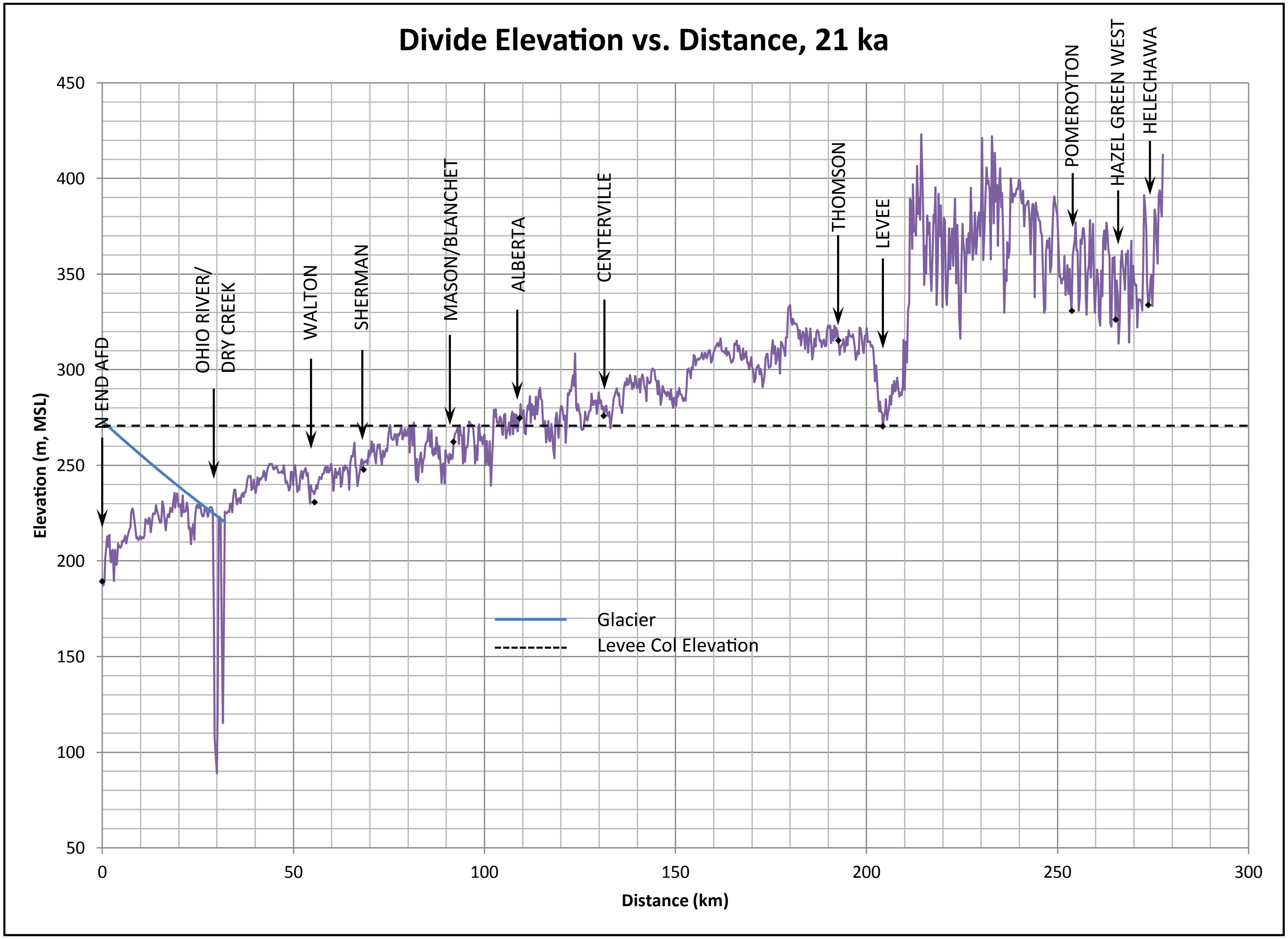


Figure 28E. Elevation vs. Distance plot along the Anderson Ferry Divide, from its north end to the Helechawa col, for time interval 21 ka, about 2,500 yr past maximum advance. The Walton, Sherman, and Mason/Blanchet cols were all still lower than the Levee col, based on differences between present col elevations, but the area was rebounding. Once the ice front retreated north of the Deep Stage valley, the Anderson Ferry Divide cols would no longer transmit Lake Claryville drainage.

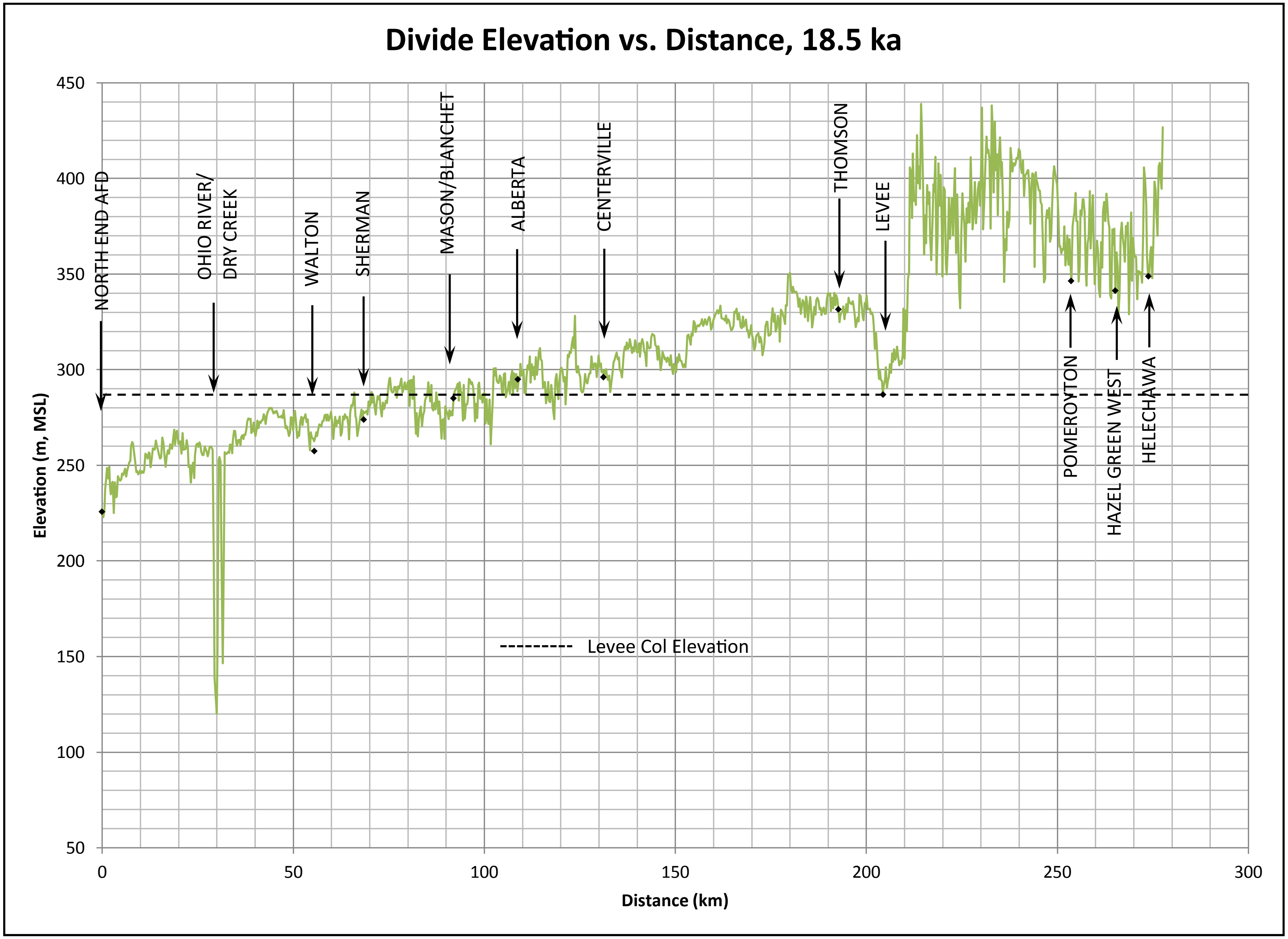


Figure 28F. Elevation vs. Distance plot along the Anderson Ferry Divide, from its north end to the Helechawa col, for time interval 18.5 ka. By the time of 5,000 yr after maximum advance, the Walton, Sherman, and Mason/Blanchet cols were still lower than the Levee col, based on the differences between present-day col elevations. However, assuming that the ice front was well north of the Deep Stage valley 5,000 yr past the time of maximum advance, the Anderson Ferry Divide cols would not have been transmitting Lake Claryville drainage at this point in time.

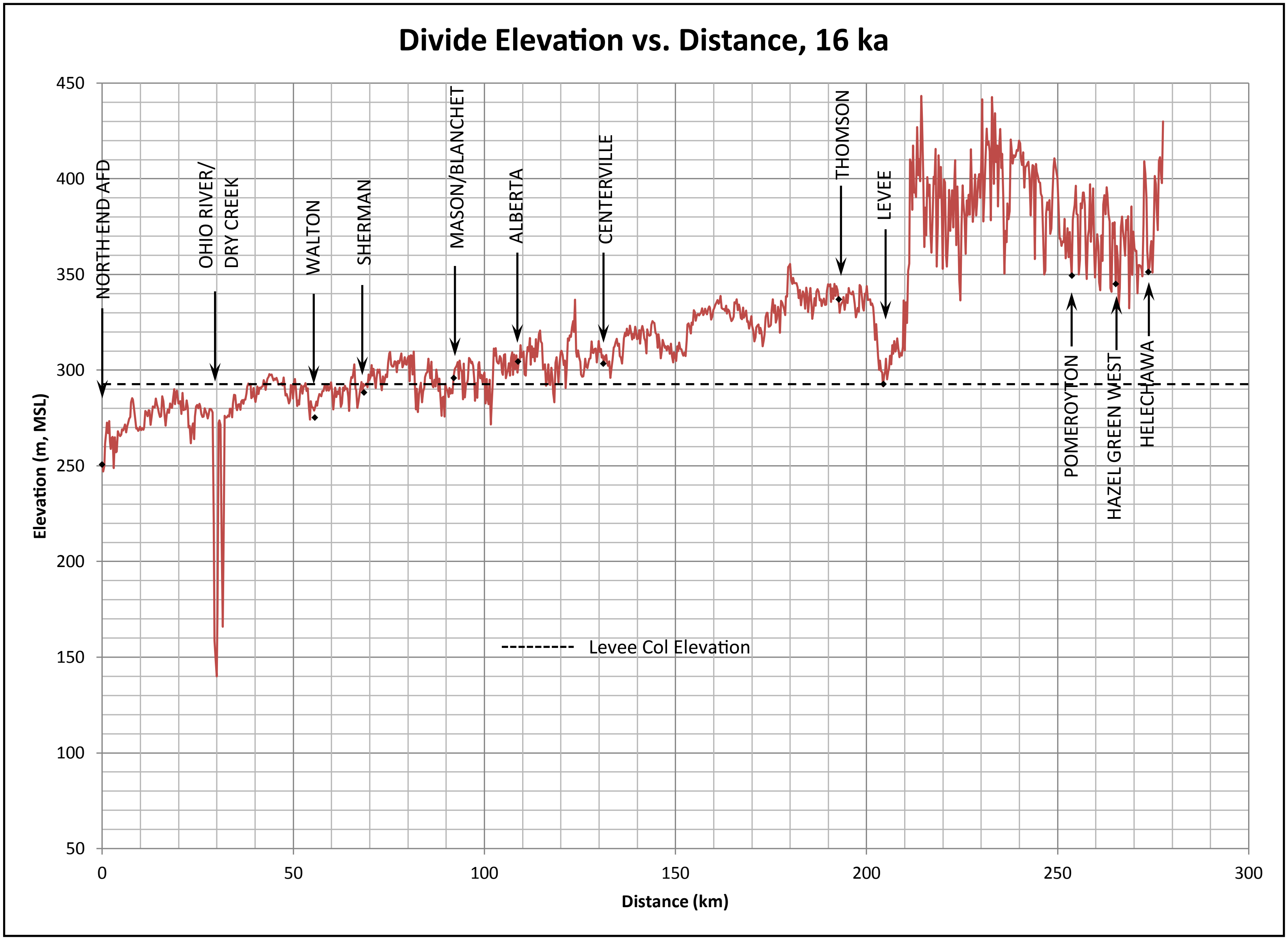


Figure 28G. Elevation vs. Distance plot along the Anderson Ferry Divide, from its north end to the Helechawa col, for time interval 16 ka. By the time of 7,500 yr after maximum advance, the Walton and Sherman cols were still lower than the Levee col, based on the differences between present-day col elevations. However, assuming that the ice front was well north of the Deep Stage valley 7,500 yr past the time of maximum advance, the Anderson Ferry Divide cols would not have been transmitting Lake Claryville drainage at this point in time.

pass this combined flow with a water depth of only 2.1 m (7.0 ft).

TABLE 4. ELEVATIONS OF SELECTED POINTS AT DIFFERENT STAGES OF GLACIATION AND DEGLACIATION (m [ft], MSL)

YEARS BEFORE RETURN TO NORMAL STATE	BURLINGTON HIGH LACUSTRINE CLAY	ALEXANDRIA HIGH LACUSTRINE CLAY	WALTON COL	SHERMAN COL	MASON/ BLANCHET COL	ALBERTA COL	CENTERVILLE COL	LEVEE SPILLWAY	LOWEST SALT RIVER COL
0	265.2 (870)	262.1 (860)	265.2 (870)	277.4 (910)	282.2 (926)	289.6 (950)	285.4 (936)	271.6 (891)	242.3 (795)
16,000	271.2 (890)	269.6 (885)	274.5 (901)	288.5 (947)	296.5 (973)	305.4 (1002)	303.1 (994)	291.7 (957)	262.5 (861)
18,500	252.2 (827)	251.5 (825)	258.3 (847)	273.8 (898)	284.8 (934)	295.4 (969)	295.3 (969)	286.9 (941)	258.0 (846)
21,000	221.5 (727)	222.1 (729)	230.6 (757)	247.9 (813)	262.1 (860)	274.3 (900)	276.2 (906)	270.2 (886)	242.3 (795)
23,500	209.5 (687)	210.2 (690)	218.9 (718)	236.4 (776)	251.0 (823)	263.8 (865)	266.6 (875)	262.1 (860)	233.5 (766)
26,000	227.1 (745)	226.7 (744)	234.0 (768)	250.2 (821)	262.2 (860)	273.2 (896)	273.6 (898)	265.9 (872)	237.1 (778)

DISCUSSION

Comparison of Models and Results

The homogeneous-plate-on-elastic-medium (i.e., simplified model) approach has several drawbacks as a glacial ice advance model. It assumes that the advancing ice can be approximated by a semi-infinite load that has a constant height and a linear front, and that the isostatic deflection response of the aesthenosphere at any given ice position is complete. The simplified model also does not account for climate chronologies; energy conservation within the ice; the physics of ice deformation; the superposition of responses brought about as the constantly-changing weight and distribution of ice induces new and changing loads to the aesthenosphere; and incomplete adjustment to any given crustal loading before different loads are imposed.

For about 60 percent of the maximum ice thickness generated by the GSM, the simplified model estimated deflections below sea level at the ice front. No evidence has been documented of marine incursion into the Old Ohio River valley as a result of lithospheric depression during glaciation (Andrews [2011]). The eustatic (globally averaged) sea level rise that occurred during the most recent glacial-interglacial transition from the Last Glacial Maximum to the Holocene has been estimated at or near 120 m (394 ft) (Jansen et al. [2007]; Shackleton [2000]; Waelbroeck et al. [2002]). Given that the elevation of the ancient Old Kentucky and Old Licking riverbeds is on the order of 189 m (620 ft) in the Northern Kentucky area, lithospheric deflection during glaciation could not exceed 120 m + 189 m = 309 m (1014 ft). Given the parameters used for the simplified model, lithospheric deflections of this magnitude would limit the maximum ice thickness at and near the vertical ice front to 1020 m (3346 ft). The assumptions of, and results generated by, the simplified model are unrealistic.

The GSM depicts the glacier as having a sloped face (Figs. 28C, 28D, and 28E), which causes the maximum ice thickness to be set well behind the ice front. This results in estimation of ground surface elevations well below sea level where the ice is thickest, and in estimation of ground surface elevations well above sea level at the ice front, which is expected. For the time intervals studied, the GSM estimates a maximum ice thickness of roughly 2,500 m (8,202 ft) at about 51° north latitude (just south of James Bay, Canada) with roughly 57 m (187 ft) of deflection at the ice front, and with a maximum forebulge height of 26 m (85 ft).

Comparison of Levee and Walton Col Elevations

Table 4 above shows the GSM estimates of col elevations as they existed at specific times during glaciation and deglaciation. These are shown graphically in Figure 28. For reference, they include cols at Thomson, Hazel Green, and Helechawa (Fig. 2). Based on the current elevations of the cols, and on those that would have existed during maximum glacial ice advance and during ice retreat, some generalizations can be made.

At no time in the process of ice advance and retreat were the Salt River cols at higher elevations than the Levee spillway (Table 4). Therefore, it would appear that Lake Claryville could only have risen high enough to use the Levee spillway following a cutoff from the Salt/Kentucky River paleochannels. The possibilities presented earlier were that this cutoff was accomplished by ice advance or by outwash damming. A potential problem with ice damming is that the GSM estimates that when the ice was at or south of the Deep Stage valley, the Walton col was depressed at least 31.7 m (104 ft) below the Levee col. This would appear to preclude ice damming from being the agent that allowed use of the Levee spillway, unless it could be demonstrated that the Walton col location was 31.7 m (104 ft) higher prior to glaciation.

However, a possibility is raised by comparison of the flow capacities of the cols with that of the Deep Stage valley, and by a closer look at Figure 28. Figure 28E indicates that at the time the ice front was at the Deep Stage valley, the Walton, Sherman, and Mason/Blanchet cols were all lower than the Levee col. Comparison of combined flow capacities, however, indicates that even with water levels 12.2 m (40 ft) deep at the Walton col and 4.9 m (16 ft) deep at the Levee col, their combined flow rate of 20,400 m^3/sec (720,500 ft^3/sec) amounts to a small percentage of the capacity of the Deep Stage valley that was cut by combined flows from north-flowing streams and glacial meltwater. For comparison, the Mississippi River near New Orleans achieved almost 66,500 m^3/sec (2,350,000 ft^3/sec) during the Flood of 1927 (U.S. Army Corps of Engineers [2013]).

The maximum water level attained in the Deep Stage valley, and thus the actual peak flow rate, during deglaciation is unknown. However, the significant difference in capacities suggests the possibility that more than one col was used to capacity at the same time during deglaciation, despite the great difference in elevations caused by crustal depression. Because the lake elevation had to be constant, however, the implication is that water levels would have been deep over the lowest cols. For instance, Fig. 28C and Table 4 indicate that for the Levee col to have been used near the point of maximum ice advance, water levels would need to have been 43.2 m (142 ft) above the base of the Walton col at 23.5 ka, and 31.9 m (104 ft) above the base of the Walton col at 26 ka. Water levels of this magnitude could not be supported.

Figure 9 demonstrates that at one point in time, outwash covered the Old Kentucky River alignment from the riverbed through elevations as high as 262.1 m (860 ft). As mentioned previously, Swadley (1971b) reported outwash deposits north of Middle Creek in Boone County as high as El. 274.3 m (900 ft; Fig. 11), that he reported to be up to 200+ ft thick. Outwash damming may also have allowed use of the Levee spillway for Lake Claryville drainage. An outwash dam as high as El. 273.3 m (900 ft) could have provided the required stream cutoff and caused Lake Claryville to rise up to the Levee spillway elevation while the glacier was not present. Even in this case, the Walton col would need to have been at a higher, pre-erosion elevation for the Levee col to be used.

Because of the significant differences in elevation of the Walton and Levee cols at and near the point of maximum ice advance, the Levee col was not used near the time of maximum ice advance. Rather, the Levee col was used when the ice front far enough to the north that crustal flexure between Walton and Levee was either at a minimum or was reversed on the leading edge of the forebulge, in combination with the Walton col being at a higher, pre-erosion elevation.

High-Level Lacustrine Deposition in Northern Kentucky and Southwest Cincinnati

In Campbell County, Kentucky, on the east side of the Anderson Ferry Divide, lacustrine clays have been documented overlying the Old Licking River alluvium at El. 191.1 m (627 ft) as part of the author’s work (Fig. 29). Gibbons (1971) has mapped lacustrine clays as high as El. 262.1 m (860 ft) in Alexandria, Campbell County, Kentucky. The principal author has sampled these clays where they occur at roughly El. 860 ft in Campbell County, and noted that they were not laminated, which could be consistent with deposition in shallow water subject to currents and turbidity. Table 4 indicates that the highest elevation at which the lacustrine clays occur in the Alexandria area was up to 8.5 m (28 ft) lower than the Walton col during maximum ice advance.

In Boone County, Kentucky and Hamilton County, Ohio, on the west side of the Anderson Ferry Divide, similar lacustrine clays (i.e., the Burlington Clays) have been documented overlying the Old Kentucky River alluvium at elevations as low as 210.3 m (690 ft) near Carrollton (Swadley

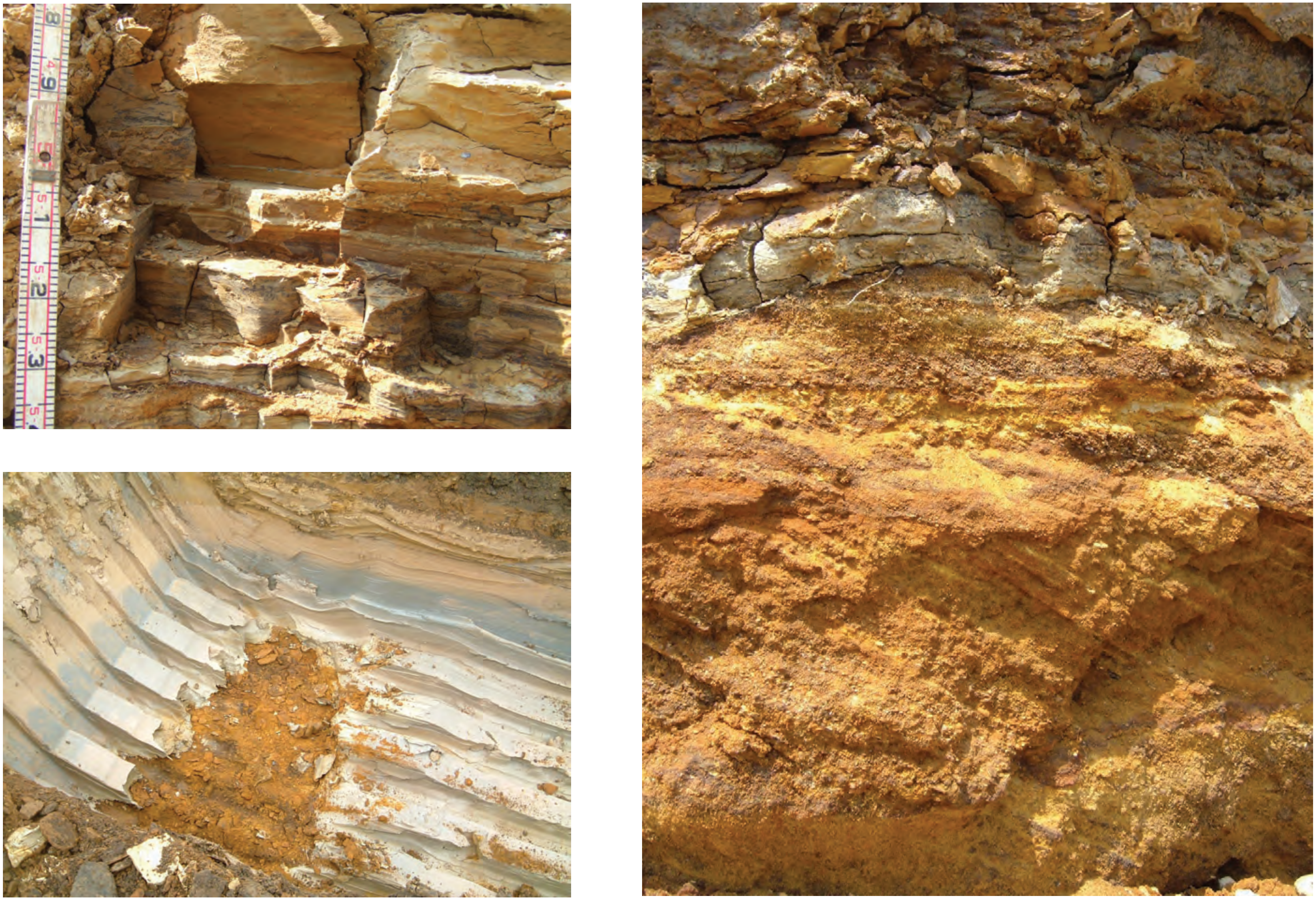


Figure 29. Claryville Clays at their contact with the Old Licking River alluvium, southeast of Alexandria, Kentucky (Fig. 30). The clays are finely laminated and highly plastic, with very high expansion potential. Basal clays in photo at bottom left were so soft and plastic that in places, the backhoe excavation was being sucked closed behind the backhoe bucket. Photos at bottom left and bottom right show contact with Old Licking River alluvium.

[1973b]), and as low as El. 192.0 m (630 ft) at Interstate 74's Ohio 128 exit (Ettensohn [1970]) (Fig. 4). Lacustrine clays have been documented in Boone County as high as El. 265.3 m (870.4 ft); this is about 3 m (10 ft) higher than the 262.1 m (860 ft) elevation documented by Ettensohn (1970)[1]. Thus the evidence indicates that the lacustrine clays occur up to similar altitudes on either side of the Anderson Ferry Divide. The Burlington Clays are discussed in greater detail in Chapter Four.

The mechanism by which lacustrine clay deposition occurred to such high elevations on the east side of the Divide is straightforward: the location where the highest lacustrine clay is documented in Campbell County (in Alexandria) was depressed at least 8.7 m (28 ft) below the Walton col at one point in time, which facilitated deposition (Table 4). The mechanism by which lacustrine deposition occurred at high elevations on the west side of the Divide is less straightforward. The lacustrine deposits encountered at the highest elevations (up to El. 265.3 m [870.4 ft] northeast of Burlington, Kentucky) are the Group 2 Burlington Clays, which are the thickest at about 13.7 m (45 ft), but which occur outside of known drainageways and in an area of the county not inundated by a blocked, north-flowing drainage. Based on the GSM, this area was depressed 9.1 m (30 ft) below the level of the Walton col at the time the ice front reached the Deep Stage. With the land surface depressed and tilted downwards to the north, and with the retreating ice front acting as a dam to the north, the Group 2 lacustrine clays were deposited on the west side of the Divide as high as El. 265.3 m (870.4 ft) in central and northern Boone County, and in the southwestern Cincinnati area.

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[1] Documentation provided by confidential test boring record in the files of Thelen Associates, Inc., Erlanger, KY.

CONCLUSIONS

Isostatic crustal deflection affected the activation of drainage cols during glaciation and deglaciation of the Cincinnati and northern Kentucky areas, as well as the formation and drainage of temporary proglacial lakes. This chapter compared two models of isostatic crustal flexure. The assumptions of, and results generated by, the simplified isostatic flexure model are unrealistic. The glacial systems model (GSM) of Tarasov et al. (2012) was used as a proxy for the response of the study area to pre-Illinoian glaciation. The results of this study, in combination with the results reported in Chapter Two, allow development of a more detailed accounting of the Pleistocene glacial history of the Cincinnati region.

The Levee col is not the lowest col on the Anderson Ferry Divide, as was reported by Andrews (2003, 2006). The Walton col is currently 7.6 m (25 ft) lower in elevation. The Walton col elevation was depressed as much as 43.2 m (142 ft) below that of the Levee during glaciation. An outwash dam as high as El. 273.3 m (900 ft) may have provided the required stream cutoff to allow Lake Claryville to rise up to, and remain at, the Levee spillway elevation while the glacier was not present. Even in this case, the Walton col would need to have been at a higher, pre-erosion elevation for the Levee col to be used.

Because of the significant differences in elevation of the Walton and Levee cols at and near the point of maximum ice advance, the Levee col was not used near the time of maximum ice advance. Rather, the Levee col was used when the ice front far enough to the north that crustal flexure between Walton and Levee was either at a minimum or was reversed on the leading edge of the forebulge, in combination with the Walton col being at a higher, pre-erosion elevation.

The lacustrine deposits encountered at the highest elevations west of the Divide (up to El. 265.3 m [870.4 ft] northeast of Burlington, Kentucky) occur outside of known drainageways and in an area of the county not inundated by a blocked, north-flowing drainage. With the land surface depressed and tilted downwards to the north by the glacier, and with the retreating ice front acting as a dam to the north, lacustrine clays were deposited on the west side of the Divide as high as El. 265.3 m (870.4 ft) in central and northern Boone County, and in the southwestern Cincinnati area.

CHAPTER FOUR

A COMPARISON OF THE BURLINGTON AND CLARYVILLE CLAYS: SOURCE STUDIES OF PRE-WISCONSINAN LACUSTRINE CLAYS IN BOONE AND CAMPBELL COUNTIES, KENTUCKY

OVERVIEW

This chapter documents the chemistry and clay mineralogy of the Burlington Clays, an archive of pre-Wisconsinan lacustrine clays in Boone County, Kentucky, and compares them to the Claryville Clays, across the Anderson Ferry Divide in Campbell County (Fig. 4). The purpose of this exercise has been to collect data that test these hypotheses: 1) that the Claryville and Burlington Clays were deposited in separate lakes and at separate times, except for at least one instance caused by isostatic crustal deflection in which they were deposited in a single lake; 2) that the groups and subgroups of the Burlington Clays were deposited at separate times, and 3) that the lakes were fed by southerly sources, but that eventually, the composition of the Burlington Clays was influenced by the encroaching glacier.

The Burlington Clays occur on the western side of the Divide and are, for the most part, separate from the Claryville Clays that were deposited on the eastern side in glacial Lake Claryville. They include the five groups of Boone County lacustrine materials documented in Chapter Two that are associated with the pre-Wisconsinan, Laurentide ice advance. Three of these groups (including their subgroups) have been examined for this study using X-ray diffraction (XRD) and X-ray fluorescence (XRF) methods. The Burlington and Claryville Clays are believed to have been deposited in separate lakes, except for a period of time (of unknown duration) when isostatic crustal depression caused the lakes to merge. The Claryville Clays and most of the Burlington Clays were deposited following the first ice advance into the northern Kentucky area, and are therefore pre-Illinoian.

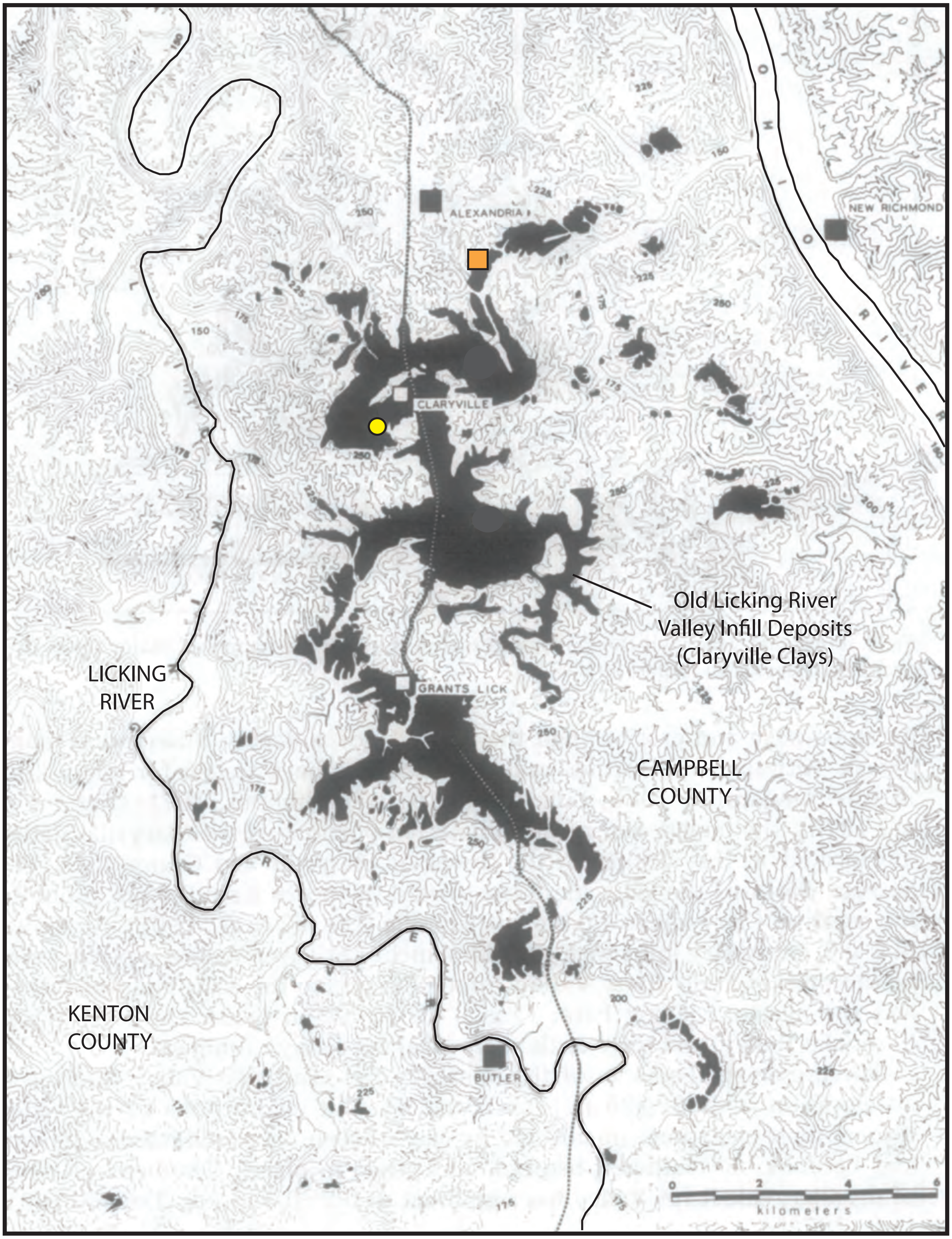
PREVIOUS WORK

Age of Claryville Clays

Regarding timing, Teller and Last (1981) dated a Claryville Clay deposit south of Alexandria, Kentucky (Fig. 30) at less than 690 ka using remanent magnetism methods, and concluded that the Claryville Clays must have been deposited prior to deposition of pre-Illinoian tills in the Cincinnati, Ohio area. Teller and Last (1981) cited Hoyer's (1972, 1976) determination that the Minford Clay in the headwaters of the Teays River system of southeastern Ohio had reversed polarity, and Bleuer's (1976) finding that pre-Illinoian clays in eastern Indiana also had reversed polarity, which had led these researchers to conclude that these clays were older than 690 ka. For this reason, Teller and Last (1981) concluded that the Claryville Clay did not represent the earliest period of glaciation in the region.

Source Materials

Marshall (2011) and Welch (2007) analyzed samples of Kope Formation shale and limestone to investigate their source materials by plotting the ratios of Zr/TiO_2 vs. Nb/Y as per the method of Winchester and Floyd (1977). For comparison, Marshall (2011) also analyzed samples of siltstones from the Garrard and Clays Ferry Formations at locations south of the Greater



● CLARYVILLE CLAY SITE SAMPLED AND TESTED BY TELLER AND LAST (1981)

■ CLARYVILLE CLAY SITE SAMPLED AND TESTED FOR THIS STUDY

Figure 30. Map showing general locations of Claryville Clay infill deposits in the Old Licking River valley, as well as sampling locations discussed in the text (modified from Teller and Last, 1981).

Cincinnati Area, as well as secondary concretions sampled from within the Kope Formation shales in northern Kentucky. Their work demonstrated that the source materials for the Ordovician shales and siltstones deposited between the Cincinnati, Ohio and Lexington, Kentucky areas were largely of andesitic composition, and that the source materials for the Kope Formation limestones were largely of rhyodacitic and rhyolitic composition.

Jacobi and Longo (2008) studied the use of the thorium/uranium ratio as an indicator of hydrocarbon source rock. They reported that Th/U ratios greater than 2 are indicative of excess carbon associated with petroleum hydrocarbons and coal. The higher ratio indicates that oxidizing conditions are prevalent, in which uranium becomes soluble and mobile and is readily removed, whereas thorium is not redox sensitive and will remain (Jacobi and Longo [2008]). Based on the XRF data, Th/U ratios can be calculated for the Burlington and Claryville Clays to help evaluate the possibility that coal-bearing rocks of the East Kentucky Coal Field have acted as source materials for the Burlington and Claryville Clays.

METHODS

Samples of Burlington Clay Group 1, 2, and 5 lacustrine materials occurring in Boone County, Kentucky (i.e., from the west side of the Divide) were tested for this study (Fig. 24). The samples were obtained from a basement excavation in Burlington, Kentucky as well as from borings using either 76.2-mm (3-inch) diameter, thin-walled, Shelby tubes or a 50.8-mm (2-inch) outer diameter, split-barrel sampler.

Samples of Claryville Clays from Campbell County, Kentucky (i.e., from the east side of the Divide) were obtained from a boring drilled southwest of Alexandria, Kentucky (Fig. 30). Sampling techniques included use of a 50.8-mm (2-inch) outer diameter, split-barrel sampler and oriented, 76.2-mm (3-inch) diameter, thin-walled, Shelby tubes (Fig. 31). Oriented samples were obtained from the Claryville Clays for remanent magnetism testing in the same manner as described previously for the till (Fig. 32).

Remanent magnetism studies of the Claryville Clays from Alexandria were conducted at the University of Minnesota's Institute for Rock Magnetism (IRM).

X-ray diffraction and X-ray fluorescence testing were performed at the University of Cincinnati. All X-ray diffraction samples were subjected to mechanical disaggregation, and then allowed to settle to obtain the spherical equivalent of the <2µ fraction. Clays were removed from the pipetted suspension using a centrifuge, and were then smeared onto glass petrographic slides to achieve maximum particle orientation. X-ray diffraction testing was completed using a Siemens D-500 x-ray diffractometer, using CuKα radiation with Ni filtration. Runs were made at 2° per minute at 40 kV and 30 ma, with 2θ ranging from 2° to 32°. All samples were studied in their untreated, glycolated, and heated (350° C) forms. All XRD traces generated for this study are included in Appendix A.

Clay mineral percentages were estimated from the x-ray diffraction plots by comparing various ratios of peak areas measured within each diffraction tracing, and by using weighting factors calculated from mineral-standard data provided by Underwood and Pickering (1996) for

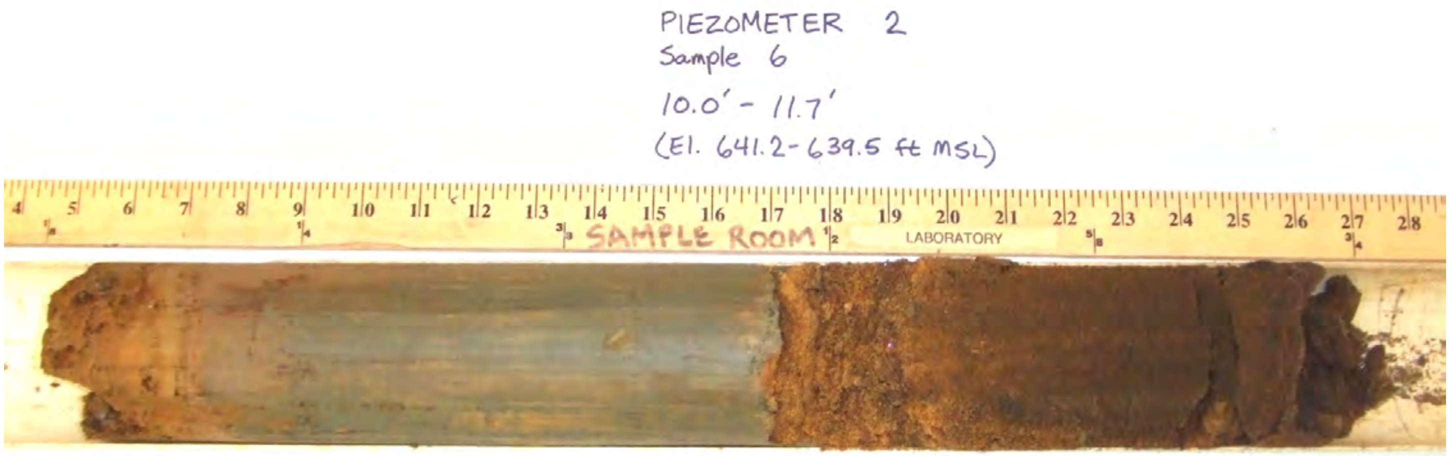


Figure 31. Shelby tube sample of Claryville Clay at its contact with the Old Licking River alluvium.

Figure 32. Oriented Shelby tube sample of Claryville Clay, obtained from a depth of 3.1 - 3.4 m (10.1 - 11.1 ft) from a site southeast of Alexandria, Campbell County, Kentucky (Fig. 30). Photo shows score line run down axis of sample during extrusion to mark the line of orientation. Remanent magnetism samples were obtained by pushing 12.7 mm x 12.7 mm x 12.7 mm (0.5 in x 0.5 in x 0.5 in), clear plastic boxes into the extruded Shelby tube sample at specific points along the scored line. Where necessary, the boxes were lightly driven into the sample using a rubber mallet. The top and bottom faces of the boxes were marked with permanent marker as the boxes were cut from the sample, and the lids were then placed on the boxes. The scale is graded in units of 3.05 mm (0.01 ft).

smectite, illite, chlorite-kaolinite, and mixed-layer illite-smectite. Peak areas were measured directly from the diffraction tracings using a planimeter.

XRF testing was completed using a 3070 wavelength dispersive X-ray fluorescence spectrometer to analyze pressed powder samples for Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, MnO_2, Na_2O, P_2O_5, SiO_2, TiO_2, Ba, Co, Cr, Cu, Mo, Nb, Ni, Pb, Rb, Sr, Th, U, V, Y, Zn, and Zr. A portion of each sample was heated to 1000° C for one hour to determine the LOI values. Intensity data were converted to weight percentage (wt%) or parts per million (ppm) using simple and multiple regressions applied to United States Geological Survey and Japan Geological Survey rock standards and LOI data.

A principal component analysis (PCA) was performed using the XRF results. The PCA used an orthogonal transformation to transform the 26 original variables (10 major compounds and 16 trace elements) measured for each sample into new, uncorrelated variables (axes), called the principal components, which are linear combinations of the original variables. The new axes lie along the directions of maximum variance. PCA allows variation in a data set to be accounted for as concisely as possible (Shrestha et al. [2008]; Davis [2002]; Wikipedia [2013]). The PCA was performed on the XRF data using the PC-ORD software program (McCune and Mefford [2006]) and an Excel spreadsheet following normalization of each data subset.

RESULTS

Clay Mineralogy and Geochemistry

The XRD and XRF testing on the Burlington and Claryville Clays provided interesting and important results, summarized by these four key points: 1) Illite is the dominant clay mineral; 2) some of the Burlington Clays contain non-clay minerals that the Claryville Clays do not; 3) the Claryville Clays and the Burlington Clay groups and subgroups exhibit different degrees of carbonate leaching; and 4) Th/U ratios are greater than 2.

The dominant clay mineral in all of the tested groups was illite, with lesser amounts of expandables (i.e., illite/smectite and mixed-layer chlorite/smectite), and kaolinite. The Burlington Clays exhibited higher percentages of kaolinite than did the Claryville Clays, although Group 1 exhibited almost none. Quartz was present in all of the tested samples in significant amounts (Huff [2013]).

The Group 2 Burlington Clays have been subdivided into three layers based on stratigraphy (Table 2). Groups 2A and 2B generally consisted of reddish brown, finely laminated clay with small amounts of sand and gravel. Group 2C generally consisted of brown, finely laminated clay with light blue silt partings (Fig. 33). These light blue partings have not been documented within the Claryville Clays, but have been documented in lacustrine clays found overlying the Old Kentucky River alluvium (Ettensohn [1974]). Groups 2B and 2C contained less expandable clay minerals than Groups 1, 2A, and 5.

Figure 33. Burlington Group 2C lacustrine clays from basement excavation in Burlington, Kentucky. Note the pale blue silt partings that have been documented here and elsewhere in the Old Kentucky River valley (Ettensohn, 1974). Also note the fine laminae. These clays are highly plastic and can exhibit very high expansion potential.

All of the Burlington Clay groups except for 2A and 5 exhibited calcite and dolomite in their XRD traces. Group 1 also exhibited albite, plagioclase, and other feldspars. The Claryville Clay samples contained none of these non-clay minerals except for very small amounts of feldspars, and exhibited lepidocrocite (γ-FeO[OH]), an iron oxide, in two samples.

The clay mineral percentages (based on the XRD results) are summarized in Tables 5 and 6 below. The results of the XRF trace element and major compound analyses are summarized in Tables 7 and 8 below. The XRD traces are included in the Appendix.

A principal component analysis (PCA) was performed using the XRF results. The purpose of the PCA was to determine if the resulting data plot would present the results in specific clusters or groups that would allow a determination to be made as to whether or not the Burlington and Claryville Clays had different source areas. The PCA plot for Axes 1 and 2 is presented as Figure 34; the plot showed clustered groupings among the Burlington Clay data.

Bivariate plots comparing selected trace elements and major compounds were also made for the purpose of determining if the resulting data plots would present the results in specific clusters or groups that would allow a determination to be made as to whether or not the Burlington and Claryville Clays had different source areas. A plot of $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$ vs. Sr is presented as Figure 35. A plot of Th/Sr vs. Al_2O_3/CaO is presented as Figure 36. These plots also showed clustered groupings among the Burlington Clay data as well as between the Burlington and Claryville data. The Group 1 and Group 2A sample clusters are highlighted on Figs. 35 and 36 for easier identification.

TABLE 5. CLAY MINERAL PERCENTAGES IN TESTED BURLINGTON CLAYS

Sample	Group	Illite (%)	Mixed-Layer Chlorite/Smectite (%)	Kaolinite (%)	Lepidocrocite (%)	Other Non-Clay Minerals*
B-216B 22.5-24	1	82	15	3	0	
B-216B 27.5-29	1	67	33	0	0	C, D
B-216B 30-31.5	1	73	27	0	0	A, C, D, F
B-216B 32.5-34	1	84	16	0	0	C, D, F
B-216B 35-36.5	1	81	19	0	0	C, D
B-104 17.5-19	2A	69	25	6	0	
B-218 12.5-14	2A	66	26	8	0	
B-219 15-16.5	2A	64	28	8	0	
B-219 17.5-18	2A	77	17	6	0	
B-209 10-11.5	2B	84	9	7	0	C, D
B-209 12.5-14	2B	82	7	11	0	C, D
B-209 15-16.5	2B	75	12	13	0	C, D
B-209 17.5-19	2B	84	10	6	0	C, D
B-209 20-21.5	2B	83	11	6	0	D, F
B-209 22.5-24	2B	83	10	7	0	C, D
B-209 25-26.5	2B	85	7	8	0	D
Burlington Basement	2C	87	9	4	0	C, D
B-222 60-61.5	5	75	17	8	0	

*A = Albite
C = Calcite
D = Dolomite
F = Feldspars

TABLE 6. CLAY MINERAL PERCENTAGES IN TESTED CLARYVILLE CLAYS

Sample	Group	Illite (%)	Mixed-Layer Chlorite/Smectite (%)	Kaolinite (%)	Lepidocrocite (%)	Other Non-Clay Minerals
P-2A 2.5	N/A	78	17	4	1	
P-2A 3.6	N/A	73	23	4	0	
P-2A 4.55	N/A	65	32	3	0	
P-2A 5.6	N/A	72	22	6	0	
P-2A 6.5	N/A	71	25	4	0	
P-2A 7.65	N/A	64	20	3	13	
P-2A 8.6	N/A	58	40	2	0	
P-2A 9.4	N/A	80	15	5	0	
P-2A 10.7	N/A	76	18	6	0	
P-2A 11.1	N/A	75	18	7	0	
Dendramis (2007)	N/A	81	13	6	0	

Following the methods of Marshall (2011) and Welch (2007), the XRF results were used to plot Zr/TiO_2 vs. Nb/Y on the Winchester and Floyd (1977) plot to investigate possible source materials of the Burlington and Claryville Clays. This plot is included as Figure 37. The purpose of this exercise is not to identify the actual source of the clays, but rather to test for differences from the results of Marshall (2011) and Welch (2007).

Figure 38 shows Th/U ratios for the Burlington and Claryville Clays. Only the Burlington Clay Group 5 sample did not yield a Th/U ratio greater than 2. The ratios varied from 1.8 to almost 9.0, with the majority of values greater than 3.3.

TABLE 7. X-RAY FLUORESCENCE TRACE ELEMENT RESULTS FOR BURLINGTON AND CLARYVILLE CLAYS

Sample	Group	Elev (m)	Elev (ft)	Ba (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Mo (ppm)	Nb (ppm)	Ni (ppm)	Pb (ppm)	Rb (ppm)	Sr (ppm)	Th (ppm)	TiO2 (%)	U (ppm)	V (ppm)	Y (ppm)	Zn (ppm)	Zr (ppm)
B-216B 22.5-24	B - 1	223.2	732.4	334	24	72	39	3.1	11	45	16	130	125	10	0.74	4.21	143	27	92	127
B-216B 27.5-29	B - 1	221.7	727.4	331	14	32	29	5.0	12	25	13	76	202	6	0.55	2.69	57	27	48	287
B-216B 30-31.5	B - 1	221.0	724.9	414	12	40	31	5.8	14	29	13	88	187	7	0.64	2.85	72	29	56	262
B-216B 32.5-34	B - 1	220.2	722.4	402	12	48	37	5.0	16	36	18	124	162	11	0.75	5.21	106	31	81	195
B-216B 35-36.5	B - 1	219.4	719.9	457	18	80	43	4.7	12	43	17	154	133	10	0.73	4.33	145	30	108	140
B-104 17.5-19	B - 2A	250.1	820.6	814	21	97	41	2.9	16	54	19	226	129	15	0.87	1.71	210	30	104	163
B-218 12.5-14	B - 2A	249.5	818.4	668	28	106	40	4.4	13	62	20	198	120	15	0.77	4.01	221	42	100	143
B-219 15-16.5	B - 2A	251.2	824	624	27	91	41	4.6	16	54	19	198	124	17	0.88	2.18	182	44	114	211
B-219 17.5-18	B - 2A	250.4	821.5	615	29	96	41	5.2	15	49	19	206	116	13	0.83	1.58	195	34	101	175
B-209 10-11.5	B - 2B	261.3	857.3	521	20	82	39	4.5	16	51	20	188	128	13	0.88	2.56	176	32	96	155
B-209 12.5-14	B - 2B	260.5	854.8	469	21	84	39	5.8	14	53	23	185	122	12	0.82	3.51	175	30	94	147
B-209 15-16.5	B - 2B	259.8	852.3	595	20	89	43	4.1	17	53	21	215	139	16	0.85	4.37	185	32	94	158
B-209 17.5-19	B - 2B	259.0	849.8	511	23	88	43	2.4	14	54	19	215	144	16	0.73	4.80	185	30	95	145
B-209 20-21.5	B - 2B	258.3	847.3	455	16	93	52	4.9	17	57	22	200	133	15	0.89	3.94	185	34	114	179
B-209 22.5-24	B - 2B	257.5	844.8	478	14	94	40	2.8	14	51	20	229	146	16	0.79	3.91	201	30	91	150
B-209 25-26.5	B - 2B	256.7	842.3	449	14	88	42	4.0	16	54	23	204	150	14	0.84	3.74	173	32	95	173
Burlington Bsmt.	B - 2C	243.8	800			93			15			179	117	11	0.66		556	40		122
B-222 60-61.5	B - 5	231.2	758.5	440	19	70	43	4.0	16	43	15	148	142	12	0.82	6.50	136	28	92	187
P-2A 2.5	C	197.7	648.7	444	24	69	37	5.7	23	45	15	179	107	18	1.05	3.33	143	40	95	278
P-2A 3.6	C	197.4	647.6	471	24	84	44	3.2	16	53	19	230	126	18	0.83	3.53	201	33	115	193
P-2A 4.55	C	197.1	646.6	429	24	83	41	4.0	19	50	15	207	106	19	1.00	3.83	165	39	109	214
P-2A 5.6	C	196.8	645.6	491	27	103	41	4.8	19	49	17	177	95	17	1.07	4.23	187	43	108	167
P-2A 6.5	C	196.5	644.7	530	28	73	36	5.2	24	43	21	190	107	19	1.14	4.19	165	37	97	210
P-2A 7.65	C	196.1	643.5	489	25	80	33	10.3	17	45	17	147	84	15	1.05	3.09	155	37	90	166
P-2A 8.6	C	195.9	642.6	506	25	73	36	7.7	24	42	22	183	105	21	1.11	4.11	142	39	93	263
P-2A 9.4	C	195.6	641.8	517	22	113	41	6.7	12	48	19	226	132	17	0.72	2.52	234	31	103	144
P-2A 10.7	C	195.2	640.5	510	27	103	44	5.1	17	53	24	237	141	20	0.88	3.21	226	35	109	182
P-2A 11.1	C	195.1	640.1	438	23	104	40	5.8	13	51	16	209	115	15	0.80	3.60	223	35	106	146

TABLE 8. X-RAY FLUORESCENCE MAJOR COMPOUND RESULTS FOR BURLINGTON AND CLARYVILLE CLAYS

Sample	Group	Elev (m)	Elev (ft)	Fe_2O_3 (%)	MnO_2 (%)	TiO_2 (%)	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	K_2O (%)	P_2O_5 (%)	MgO (%)	Na_2O (%)	LOI (%)
B-216B 22.5-24	B - 1	223.24	732.4	11.87	0.104	0.75	45.9	13.9	6.19	3.35	0.144	2.95	0.34	14.34
B-216B 27.5-29	B - 1	221.71	727.4	4.96	0.071	0.75	49.1	10.9	12.26	2.05	0.302	4.05	0.49	13.97
B-216B 30-31.5	B - 1	220.95	724.9	4.98	0.077	0.78	52.4	10.9	10.45	2.19	0.199	3.42	0.40	13.29
B-216B 32.5-34	B - 1	220.19	722.4	6.09	0.086	0.86	51.7	13.1	8.14	2.98	0.166	3.09	0.37	12.78
B-216B 35-36.5	B - 1	219.43	719.9	9.56	0.158	0.79	49.5	15.6	5.11	3.70	0.136	3.26	0.38	11.88
B-104 17.5-19	B - 2A	250.12	820.6	6.72	0.087	0.91	54.1	20.9	1.79	4.87	0.114	1.92	0.62	8.33
B-218 12.5-14	B - 2A	249.45	818.4	9.40	0.148	0.80	52.4	20.0	1.53	4.35	0.140	2.38	0.58	8.79
B-219 15-16.5	B - 2A	251.16	824	6.33	0.127	0.94	56.0	20.2	1.52	4.37	0.171	1.86	0.64	8.08
B-219 17.5-18	B - 2A	250.40	821.5	8.19	0.070	0.90	53.8	20.1	1.64	4.66	0.182	2.13	0.69	7.92
B-209 10-11.5	B - 2B	261.31	857.3	8.71	0.081	0.96	50.2	18.1	3.90	4.42	0.083	2.66	0.50	10.63
B-209 12.5-14	B - 2B	260.55	854.8	9.50	0.117	0.89	48.9	17.4	4.77	4.45	0.088	2.79	0.39	11.02
B-209 15-16.5	B - 2B	259.78	852.3	6.83	0.065	0.95	50.4	19.4	4.10	4.72	0.069	2.65	0.49	10.73
B-209 17.5-19	B - 2B	259.02	849.8	6.37	0.048	0.80	48.2	19.2	4.74	4.91	0.071	3.45	0.44	12.05
B-209 20-21.5	B - 2B	258.26	847.3	6.76	0.047	0.96	50.7	19.8	3.06	4.71	0.169	2.74	0.65	10.42
B-209 22.5-24	B - 2B	257.50	844.8	6.54	0.053	0.83	50.2	19.8	3.35	5.21	0.085	2.70	0.51	10.97
B-209 25-26.5	B - 2B	256.74	842.3	5.69	0.051	0.92	50.0	20.1	3.80	4.86	0.140	2.98	0.59	11.03
Burlington	B - 2C	243.84	800	6.80	0.052			6.6						
B-222 60-61.5	B - 5	231.19	758.5	6.97	0.157	0.92	53.9	15.4	5.49	3.47	0.161	2.27	0.36	10.78
P-2A 2.5	C	197.73	648.7	5.61	0.071	1.17	58.2	18.4	1.41	4.07	0.193	2.05	0.78	7.85
P-2A 3.6	C	197.39	647.6	5.38	0.043	0.89	52.9	21.8	1.86	4.95	0.163	2.04	0.66	9.58
P-2A 4.55	C	197.09	646.6	5.88	0.047	1.08	53.8	20.2	1.72	4.48	0.198	2.19	0.74	9.60
P-2A 5.6	C	196.78	645.6	9.18	0.271	1.00	57.0	15.7	0.35	4.13	0.175	1.76	0.47	9.69
P-2A 6.5	C	196.51	644.7	5.37	0.307	1.20	62.4	16.0	0.45	4.13	0.091	1.76	0.43	7.78
P-2A 7.65	C	196.14	643.5	10.56	0.722	0.89	62.1	10.4	0.73	3.29	0.226	1.905	0.07	9.42
P-2A 8.6	C	195.87	642.6	5.14	0.052	1.15	60.3	17.5	1.30	3.72	0.190	1.27	0.70	8.10
P-2A 9.4	C	195.62	641.8	8.37	0.178	0.71	50.0	21.0	1.35	5.29	0.204	2.25	0.54	10.44
P-2A 10.7	C	195.23	640.5	6.23	0.035	0.88	52.5	21.5	1.72	5.03	0.124	1.56	0.59	10.04
P-2A 11.1	C	195.10	640.1	10.00	0.032	0.77	49.2	20.3	1.51	4.84	0.181	1.78	0.65	10.86

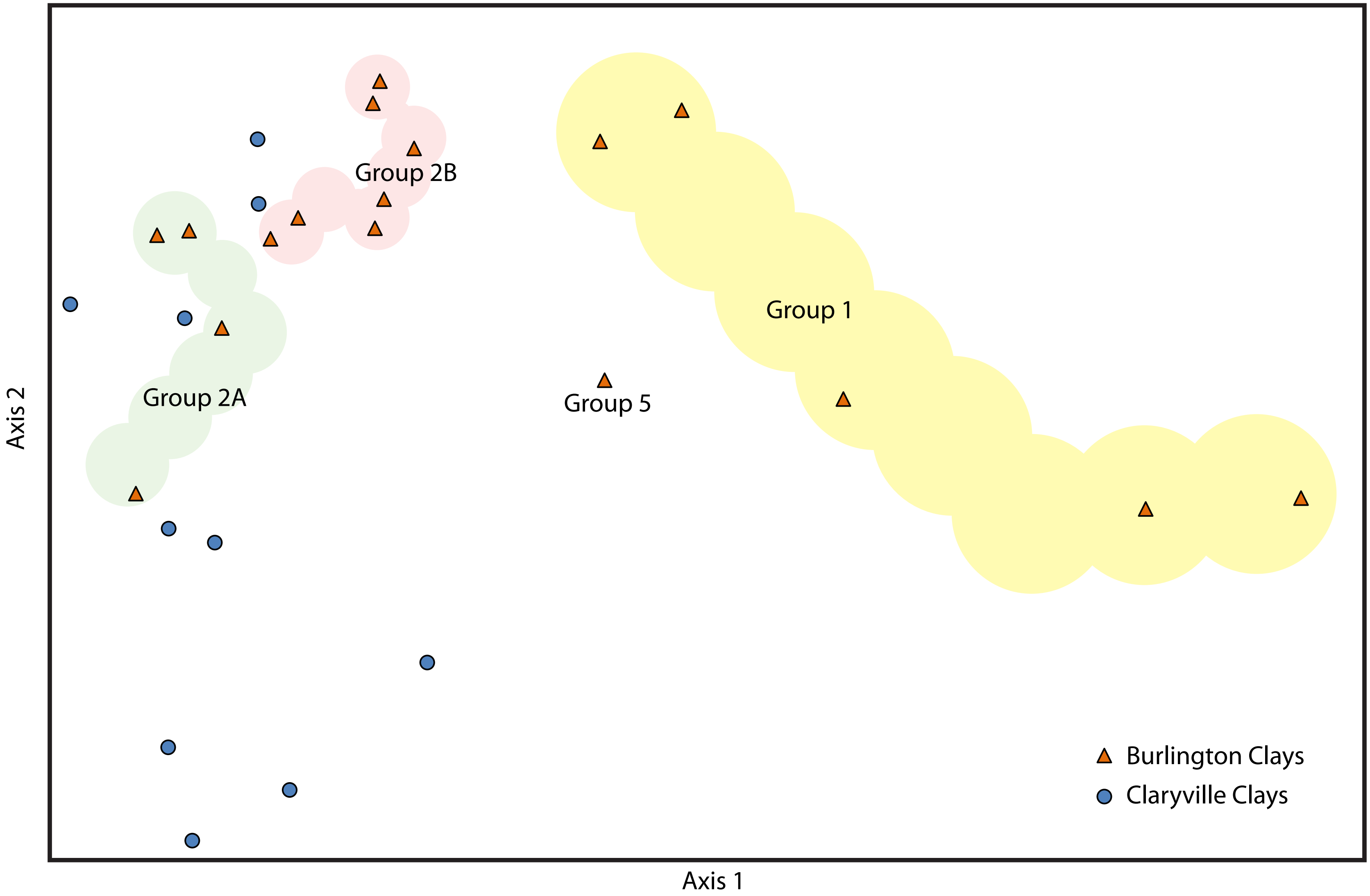


Figure 34. Principal component analysis (PCA) of X-ray fluorescence (XRF) major and trace element data, Burlington and Claryville Clays. An orthogonal transformation converted a set of 27 possibly correlated values (10 major compounds and 17 trace elements) for each sample into a set of linearly uncorrelated values called *principal components*, which are the eigenvectors of the 27 X 27 variance/covariance matrix. The first principal component (Axis 1) has the largest possible variance, and accounts for as much of the variability in the data as possible. The second component (Axis 2) has the highest variance possible under the constraint that it be orthogonal to, i.e., uncorrelated with, the first component. Thus, the PCA highlights differences in the data (Davis [2002]; Wikipedia [2013]). The PCA shows separation of Group 1 Burlington Clay samples from the remainder, and separate clusters of Group 2A and 2B samples. Group 2A is clustered within the Claryville Clay sample group, a relationship also seen on Figs. 35 and 36. The colors merely serve to highlight the data clusters within each group.

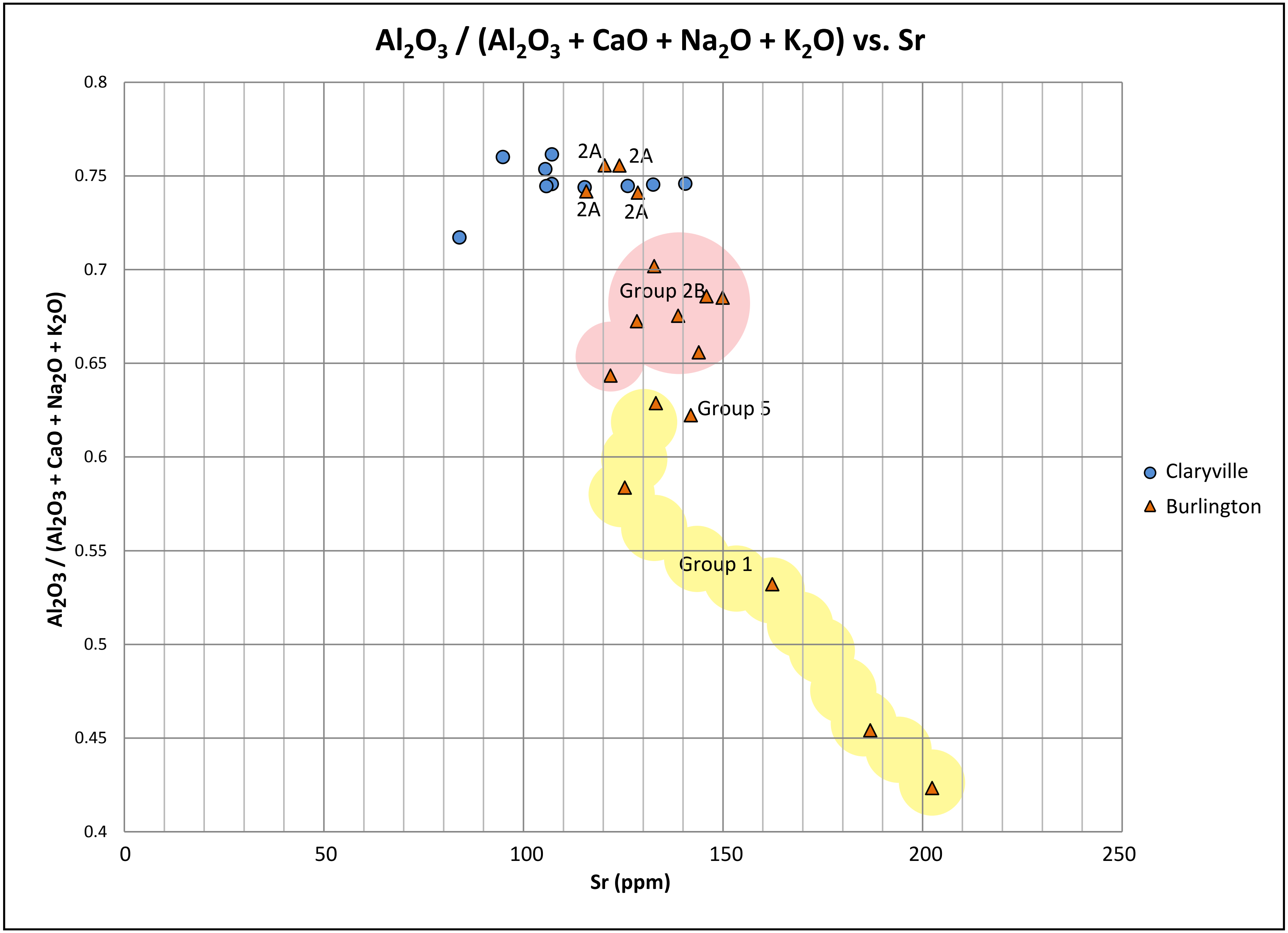


Figure 35. Plot of $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$ vs. Sr. Higher values of $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$ and lower values of Sr are indicative of carbonate leaching and, hence, more weathering. Based on this, the graph suggests that the Claryville Clays are similar in leaching to Burlington Clay Group 2A, and more leached than Groups 5, 2B, and 1. The Group 5 clays are overlain by pre-Illinoian outwash that is heavily calcite ($CaCO_3$) cemented, which has increased the Group 5 CaO content and thus decreased the ratio $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$, making the sample appear to be less leached of carbonate.

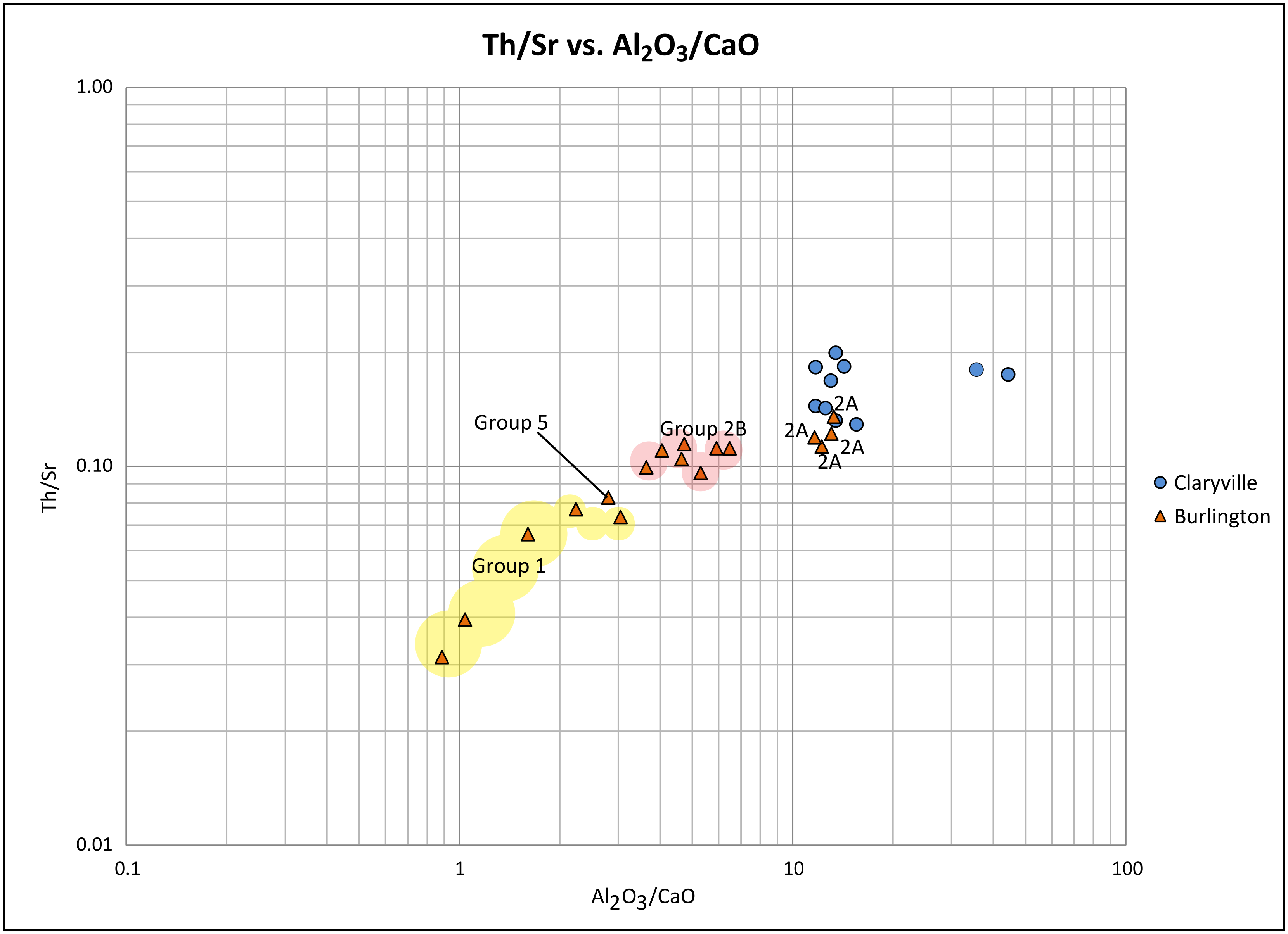


Figure 36. Plot of (Th/Sr) vs. (Al_2O_3/CaO). Th acts as a proxy for Al (both are insoluble) while Sr acts as a proxy for Ca (both are soluble). Higher values of Al_2O_3/CaO and higher values of Th/Sr are indicative of carbonate leaching and, hence, more weathering. Based on this, the graph suggests that the Claryville Clays are weathered to a similar extent as Burlington Clay Group 2A, and are weathered more than Groups 5, 2B, and 1. The Group 5 clays are overlain by pre-Illinoian outwash that is heavily calcite ($CaCO_3$) cemented, which has increased the Group 5 CaO content and thus decreased the ratios of Al_2O_3/CaO and Th/Sr, suggesting that the sample is less weathered.

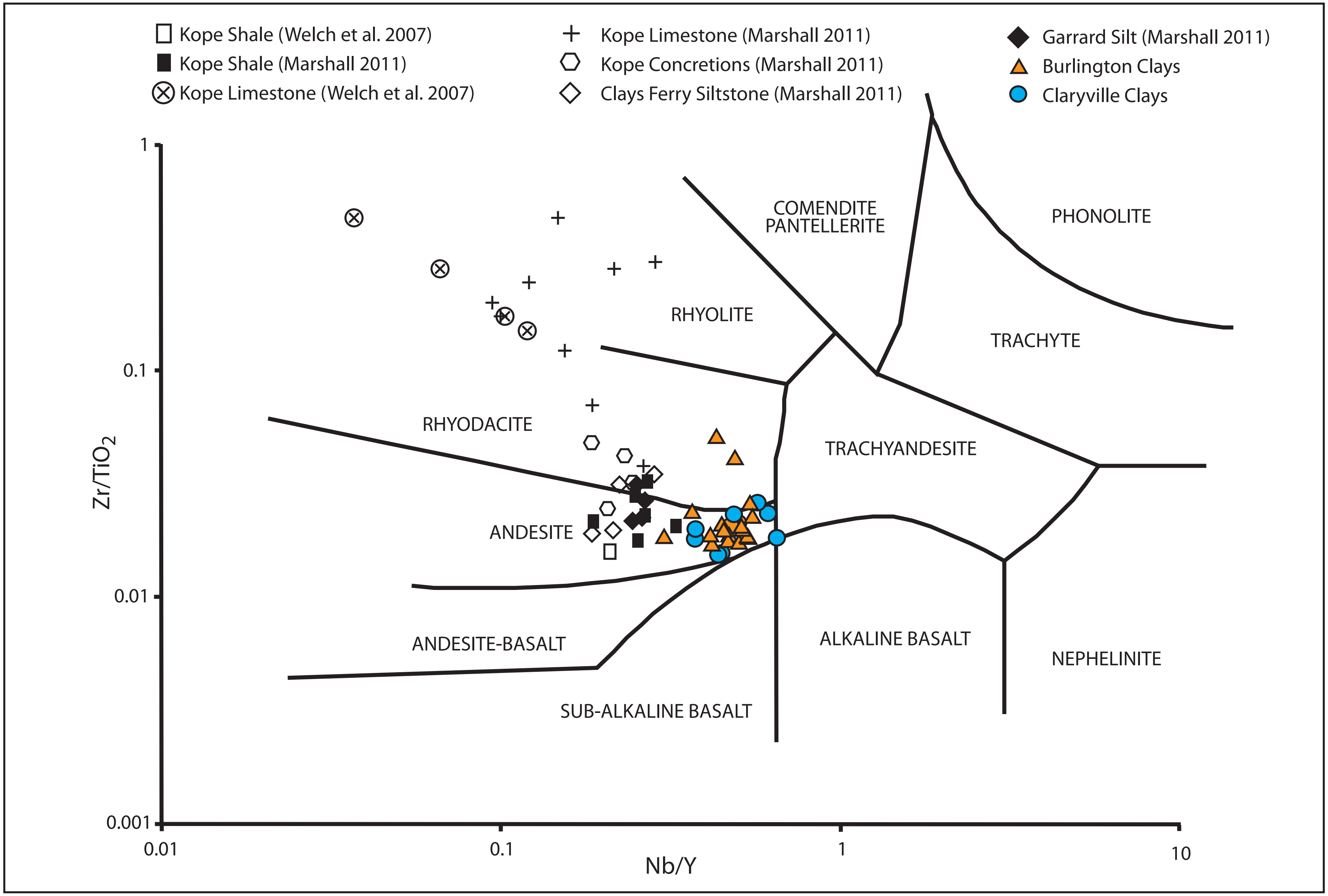


Figure 37. Plot of (Zr/TiO_2) vs. (Nb/Y) for the Claryville and Burlington Clays, set against the realms of volcanic rock origin established by Winchester and Floyd (1977). Titanium is highly associated with mafic rocks, and Zr with felsic rocks. Nb is associated with higher alkali content and Y is not (Marshall, 2011). Welch et al. (2007) and Marshall (2011) demonstrated that the shales and siltstones of the Kope Formation, the Garrard Silt, and the Clays Ferry Siltstone, all of which are exposed on the Cincinnati Arch between the northern Kentucky area and Lexington, Kentucky, are of andesitic origin. The above plot shows that the Claryville and Burlington Clays, while somewhat more alkaline, have the same (or similar) origin as local shales and siltstones, and were likely derived from them as source materials. The two Burlington Clay samples in the rhyodacite region are from Group 1, and may have had Kope limestone or concretions as their source.

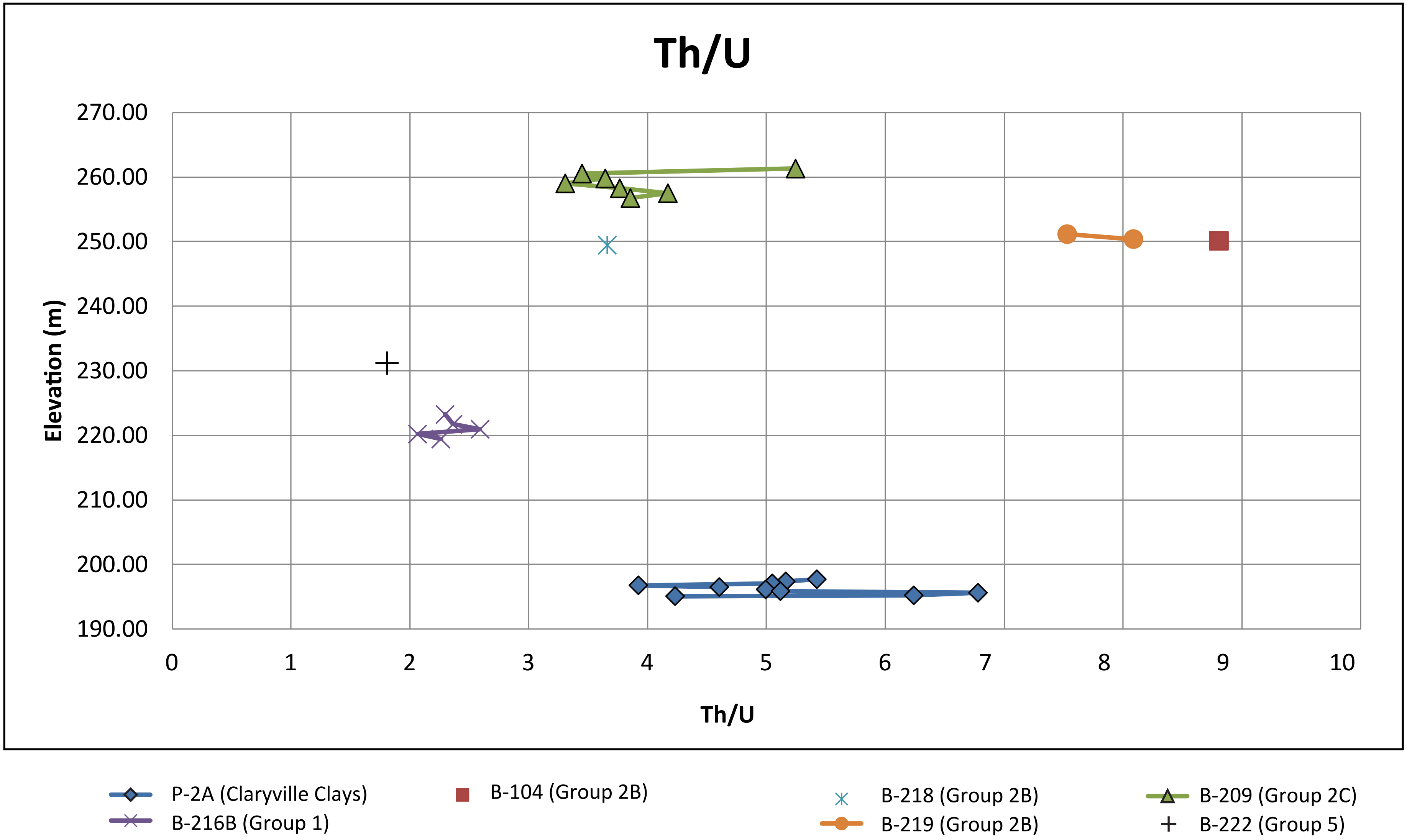


Figure 38. Ratio of Th/U shown as a function of the elevations above mean sea level at which the samples occurred. Th/U ratios greater than 2 are indicative of excess carbon associated with petroleum hydrocarbons and coal. The higher ratio indicates that oxidizing conditions are prevalent, in which uranium becomes soluble and mobile and is readily removed, while thorium is not redox sensitive and will remain (Jacobi and Longo, 2008). The ratios here suggest the influence of coal-bearing rocks in both the Old Kentucky and Old Licking River watersheds as source materials for the lacustrine clays.

Remanent Magnetism Testing

The results of the remanent magnetism testing on the Claryville Clay samples are presented on Figure 25. The results are plotted stereographically, with the demagnetization steps best-fit onto great circles. The great circles for the Claryville Clays are well ordered, and indicate a magnetic declination of 185.5º +/- 4.9º.

DISCUSSION

Similarites and Differences Among the Burlington and Claryville Clays

The PCA plot (Fig. 34) identifies clustered groups among the Burlington Clays. The Group 1 clays are fairly isolated at one side of the plot. Although closer together, similar clusters can be discerned for the Group 2A and 2B Burlington Clays. The Group 2A Burlington Clays occur within the Claryville Clay grouping. The Group 5 sample point appears to be fairly isolated as well, although it is difficult to draw a strong conclusion based on a single data point. The plot indicates that the Burlington Clay groups are distinct, and suggests that they may have been deposited at different times and under different circumstances. The plot also suggests that the Group 2A Burlington Clays share a common source with the Claryville Clays.

The Group 1, 2B and 2C Burlington Clays (i.e., the youngest tested) exhibited calcite, dolomite, albite, plagioclase, and other feldspars on their XRD traces; Groups 2A and 5 (i.e., the oldest tested) exhibited none of these non-clay minerals. The basal Claryville Clays exhibited traces of feldspars, but not in significant amounts. All of the clays contained significant amounts of quartz (Huff [2013]). These minerals were present in rock flour transported by the moving glacier. This is a strong indicator that following deposition of Group 2A, the ice front was close enough to the Greater Cincinnati area to affect the composition of the Burlington Clays (and to a much lesser extent, the Claryville Clays) by contributing meltwater containing the rock flour.

The absence of these non-clay minerals in Group 2A is unexpected, considering that the Group 2A Burlington Clays contained small amounts of sand and fine gravel that were likely rafted into place, strongly suggesting close proximity to the ice front. It is possible that some of these non-clay minerals were once present in the Group 2A clays, but that weathering has since removed them. It is also possible that the ice that was affecting the composition of the Group 2A clays approached from a different direction and did not contain these minerals. Because the Group 5 clays were deposited upon the initial blockage of north-flowing drainage when no glacier was in close proximity, they would not be expected to contain any of the rock-flour minerals contributed by the glacier.

Degrees of Leaching of Burlington and Claryville Clays

Among the bivariate plots made to compare different trace elements and major compounds for this study, those most useful for segregating the data made use of Th, Sr, and CaO. Th acts as a proxy for Al; both are insoluble. Sr acts as a proxy for Ca; both are soluble. With increased time of surface or groundwater exposure, clays can be expected to exhibit decreasing amounts of CaO and Sr as their carbonate is leached out, whereas clays subjected to less exposure will exhibit greater amounts of CaO and Sr. The inference that lower Ca and Sr indicate more leaching is only valid for wet (e.g., periglacial) climates.

The plots of $Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)$ vs. Sr and Th/Sr vs. Al_2O_3/CaO (Figs. 35 and 36) show lesser ratios of these parameters among the Claryville Clays than among the Burlington Clays, indicating that the Claryville Clays have been leached to a greater extent. The overlap of the Group 2A Burlington Clays at one end of the Claryville grouping on Figs. 35 and 36 suggests that the Group 2A clays and the basal Claryville Clays have a similar exposure history, and may correlate in age.

Using the same logic, the plot also suggests that the Group 2A Burlington Clays are more weathered than the Group 2B clays. The Burlington basement sample (Group 2C) could not be plotted on Figs. 35 and 36 because it was not tested for Al_2O_3 or CaO. However, the Th/Sr ratio for the Group 2C clay (0.095) would place it between the Group 2B and Group 1 clusters on Figs. 35 and 36, suggesting that the Group 2A Burlington clays are the most weathered, and the Group 2C clays are the least weathered. With one exception discussed below, the degrees of leaching (and thus weathering) of the tested Burlington Clay groups also follow their stratigraphic order of age. Among Groups 2A, 2B, and 1, the oldest unit is Group 2A, and the youngest unit is Group 1.

The Group 5 clay sample exhibits an intermediate level of weathering on Figs. 35 and 36. However, the Group 5 lacustrine clay is located in a buried valley bottom (Fig. 11) below a granular outwash deposit that was noted during drilling and sampling to be heavily cemented with calcite. Leaching of the carbonate from this outwash has likely increased the amount of carbonate in the Group 5 clay, making it appear less weathered on the basis of carbonate content.

Age of Claryville and Burlington Clays

The purpose of the remanent magnetism study conducted on the Claryville Clay samples was to establish whether they had been deposited prior to or following the last major magnetic reversal at 0.78 Ma (Laj and Channell, 2007). Teller (2011) has indicated that the results of Teller and Last (1981) are in question, given the quality of remanent magnetism testing at that time, and given the advances that have since been made in the technology since. The results of remanent magnetism testing performed on the 10 basal Claryville Clay samples clearly indicates reversed polarity and demonstrates that the basal Claryville Clays were deposited no later than 780 ka, and are in fact pre-Illinoian (Fig. 25). This refutes the conclusion of Teller and Last (1981) that the age of the Claryville Clays is less than 690 ka.

Based on the correlation of degree of leaching to stratigraphic age shown between the Claryville and Group 2A Burlington Clays in Figures 35 and 36, it may be concluded that Burlington Groups 2A and 3 through 5 are all older than 780 ka.

Source Materials

The work of Marshall (2011) and Welch (2007) showed that the sources for local shales and siltstones are largely of andesitic origin. Plotting the ratios of Zr/TiO_2 vs. Nb/Y for the Burlington and Claryville Clays on the bedrock origins chart of Winchester and Floyd (1977) shows that their sources are also largely of andesitic origin. This suggests that local shales and siltstones acted as source materials for the Burlington and Claryville Clays (Fig. 37).

Titanium is highly associated with mafic rocks, and Zr with felsic rocks. Nb is associated with higher alkali content and Y is not (Marshall, 2011). Welch et al. (2007) and Marshall (2011) demonstrated that the shales and siltstones of the Kope Formation, the Garrard Silt, and the Clays Ferry Siltstone, all of which are exposed on the Cincinnati Arch between the northern Kentucky area and Lexington, Kentucky, are of andesitic origin. Figure 37 shows that the Claryville and Burlington Clays, while somewhat more alkaline, have the same origin as local shales and siltstones, and were derived from them as source materials. The two Burlington Clay samples in the rhyodacite region are from Group 1, and may have had Kope limestone or concretions as their source.

Most of the lacustrine clay samples tested for this study exhibited Th/U ratios greater than 3.3 (Fig. 38). (Jacobi and Longo [2008]). Th/U ranged from 1.8 to 9.0 for the Burlington Clays, and 4.0 to 6.7 for the Claryville Clays. The highest Th/U ratios found (7.8 to 8.8) were for the Group 2A clays sampled in Borings 104 and 219 (Fig. 22). The Kentucky and Licking Rivers rise in the Pennsylvanian rocks of the Eastern Kentucky Coal Field. The Th/U ratios suggest that coal-bearing Pennsylvanian rocks in both the Kentucky and Licking River watersheds also acted as source materials for the lacustrine clays.

CONCLUSIONS

The evidence presented in this chapter supports the hypotheses set out in the Overview section, namely, 1) that the Claryville and Burlington Clays were deposited in separate lakes and at separate times, except for at least one instance in which isostatic crustal deflection caused the lakes to merge; 2) that the groups and subgroups of the Burlington Clays were deposited at separate times, and 3) that the lakes were fed by southerly sources, but that eventually, the composition of the Burlington Clays (and to a much lesser extent, the Claryville Clays) was influenced by the encroaching glacier.

The first two hypotheses are supported by three lines of evidence. The first is that the Burlington and Claryville Clays, for the most part, clustered separately on the PCA and bivariate plots presented in Figs. 34, 35, and 36. The separate clustering suggests that the Claryville and Burlington Clays, as well as the Burlington Clay subgroups, had different source areas. The second line of evidence is the degree of carbonate leaching, which suggests varying degrees of weathering of the groups and subgroups. The third line of evidence is that the Claryville Clay and Group 2A Burlington Clay data overlap on Figs. 34, 35, and 36, suggesting that they had similar source areas and degrees of weathering, and were likely deposited in the same lake.

The third hypothesis (that the lakes were fed by southerly sources, but that eventually, the composition of the Burlington Clays was influenced by the encroaching glacier) is first supported by evidence from the XRF testing. The Zr/TiO_2 vs. Nb/Y plot and the Th/U plot lead to a conclusion that the composition of the Claryville and Burlington Clays was largely derived from the shales and siltstones of the Outer and Inner Bluegrass provinces, but was also influenced by the Pennsylvanian coals and bedrock of the Eastern Kentucky Coal Field.

The XRD test results provide evidence that the composition of the Burlington Clays was eventually influenced by the glacier. The Group 5 and 2A Burlington Clays exhibited no calcite, dolomite, albite, plagioclase, or other feldspars on their XRD traces. The Group 2B, 2C, and 1

Burlington Clays strongly exhibit some or all of these on their XRD traces. These non-clay minerals were contributed to the lake in which the Burlington Clays were deposited by runoff from the ice. The approach of the glacier was heralded by the appearance of small amounts of rafted sand and gravel in the Group 2A clays; the glacier began to influence the composition of the Burlington Clays themselves starting with Group 2B.

Based on stratigraphy, the Group 5 clays are the oldest of the Burlington Clays. They were deposited as a result of the initial blockage of the north-flowing drainage, and no glacier was present to exert any influence; thus, the Group 5 XRD trace showed none of the calcite, dolomite, albite, plagioclase, or other feldspars that would appear in younger Burlington Clay samples when the ice front was in close proximity to the lake. By extension, it may be hypothesized that testing of the Group 4 and 3 lacustrine clays would show no glacier influence there either.

The results of remanent magnetism testing clearly show that the basal Claryville Clays were deposited during a period of reversed magnetic polarity, and are therefore older than 780 ka. This refutes the conclusions of Teller and Last (1981) that the age of the Claryville Clays is less than 690 ka, and that they do not represent the earliest period of glaciation in the region. Based on the correlation of degree of leaching to stratigraphic age shown between the Claryville and Group 2A Burlington Clays in Figures 35 and 36, Burlington Groups 2A and 3 through 5 are all older than 780 ka.

EPILOGUE

CONCLUSIONS OF THIS STUDY

This study has resulted in 1) documentation of five glacial advances into northern Kentucky, and their timing relative to Deep Stage valley incision; 2) estimates of the magnitude and timing of crustal deflection, relative to the point of maximum glacial advance; and 3) characterization of the provenance of the Burlington and Claryville Clays, including an estimate of their relative ages and degrees of weathering.

The main conclusions of this study are the following:

1. Incision of the portion of the Deep Stage valley extending south from Hamilton, Ohio along the general Old Kentucky River alignment occurred *prior* to invasion of glacial ice into northern Kentucky. At least six pre-Wisconsinan ice advances eventually affected the Cincinnati region, the first being that which caused the incision of the Deep Stage valley by the erosive effects of its meltwater. Five of these ice advances are now known to have reached and crossed the Deep Stage valley south of Lawrenceburg. At least two of those five ice advances continued into the northern Kentucky uplands. Based on Granger et al's (2001) estimate of the age of Teays River incision at 2 Ma, and of Deep Stage incision at about 1.5 Ma, the oldest of these tills is no older than 1.5 Ma.

2. The Burlington Clays were deposited in central and northern Boone County, and in southwestern Cincinnati, as a result of multiple pondings of south-flowing stream valleys tributary to the Old Kentucky River, and as a result of the formation of an areally-extensive, proglacial lake occurring in the northern Kentucky uplands and extending into the Cincinnati area. With the land surface depressed and tilted downwards to the north by the glacier, and with the retreating ice front acting as a dam to the north, lacustrine clays were deposited on the west side of the Divide as high as El. 265.3 m (870.4 ft) in central and northern Boone County, and in the southwestern Cincinnati area. The youngest of the documented Burlington Clays was laid down in a north-south-oriented valley that likely provided drainage from the central Boone County area.

3. The Burlington and Claryville Clays were deposited in separate lakes and at separate times, with at least one interval in which they were the same lake. These lakes were fed by southerly sources; but eventually, the composition of the Burlington Clays was affected by the encroaching glacier.

4. The Levee col and spillways, and by extension, the Old and existing Kentucky Rivers, divided the work of draining Lake Claryville with the Walton col, and by extension, the Old Eagle River and the existing Eagle Creek. This study used the glacial systems model (GSM) of Tarasov et al. (2012) to model the effects of ice advance and retreat and to model the relationships between the Levee spillway, the cols in and near Walton, and the advancing ice front during ice advance and retreat.

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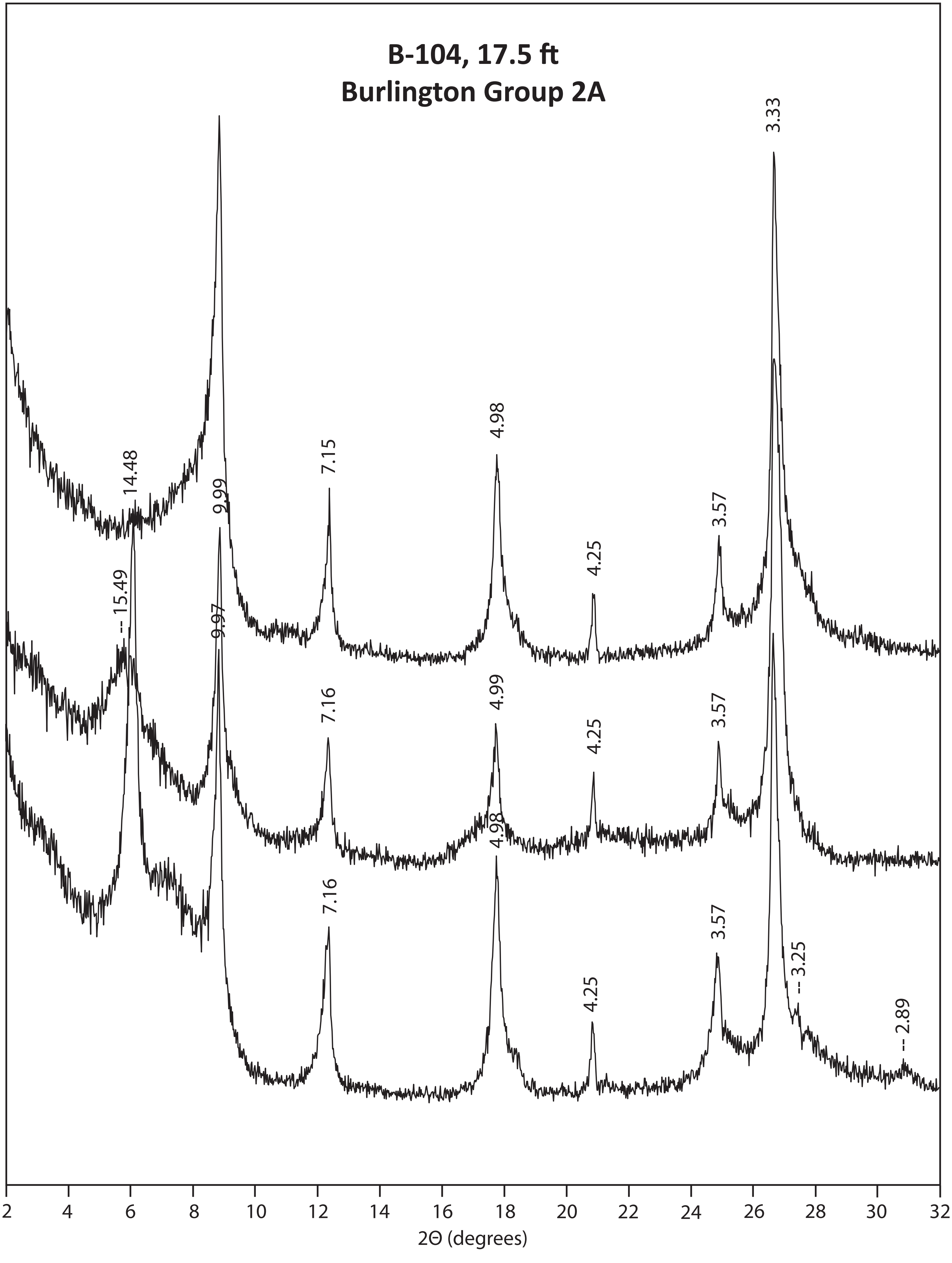
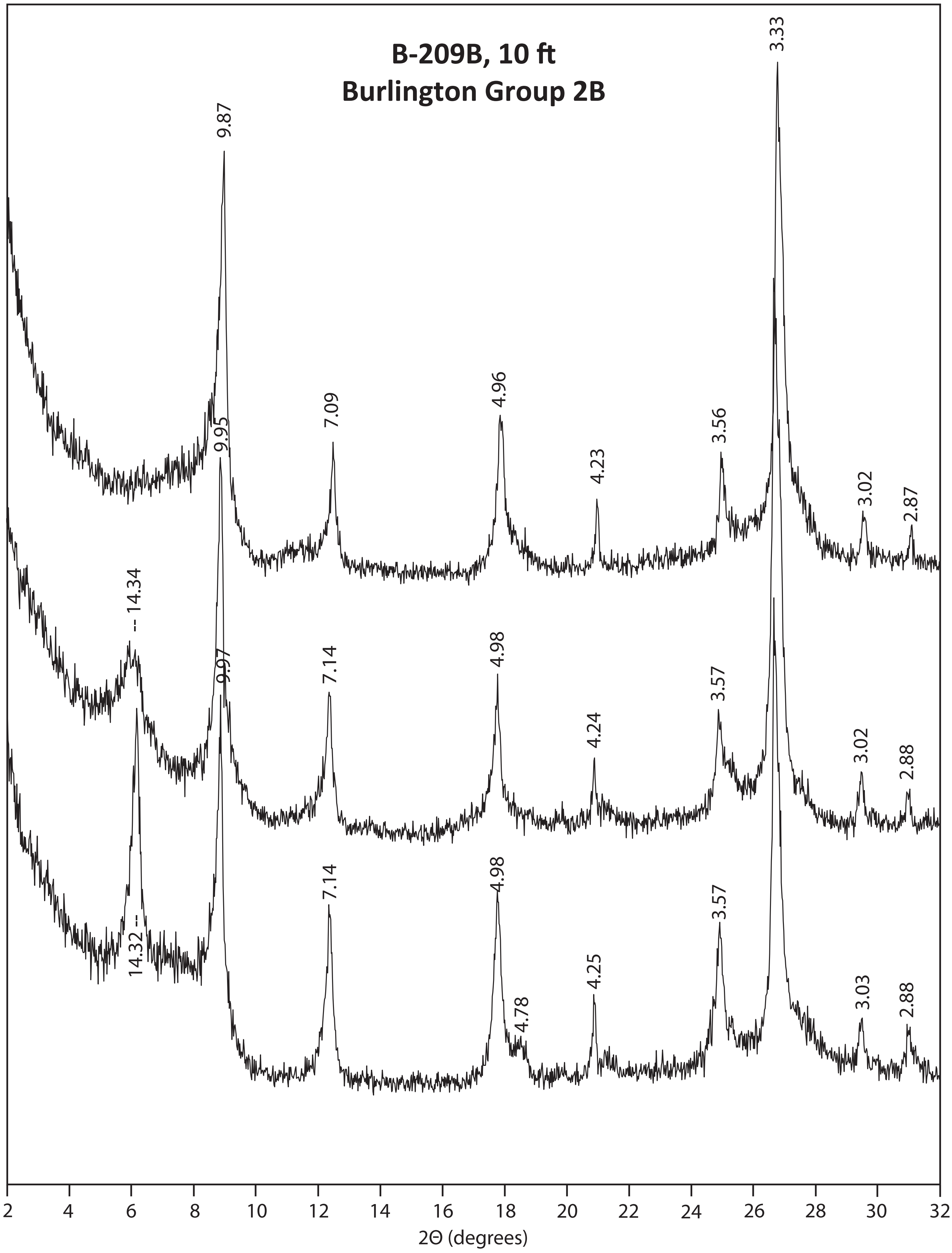
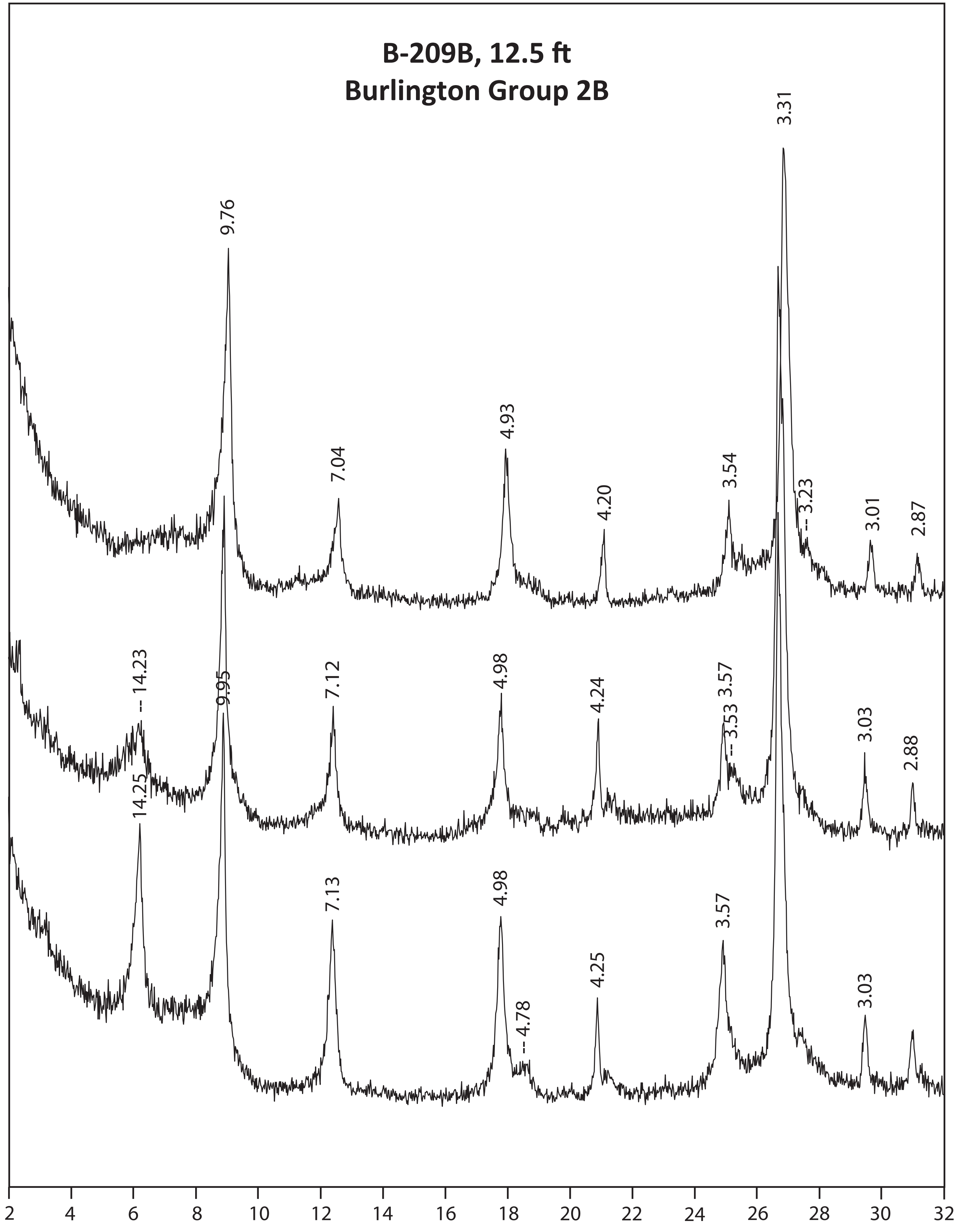
APPENDIX

X-RAY DIFFRACTION TRACES

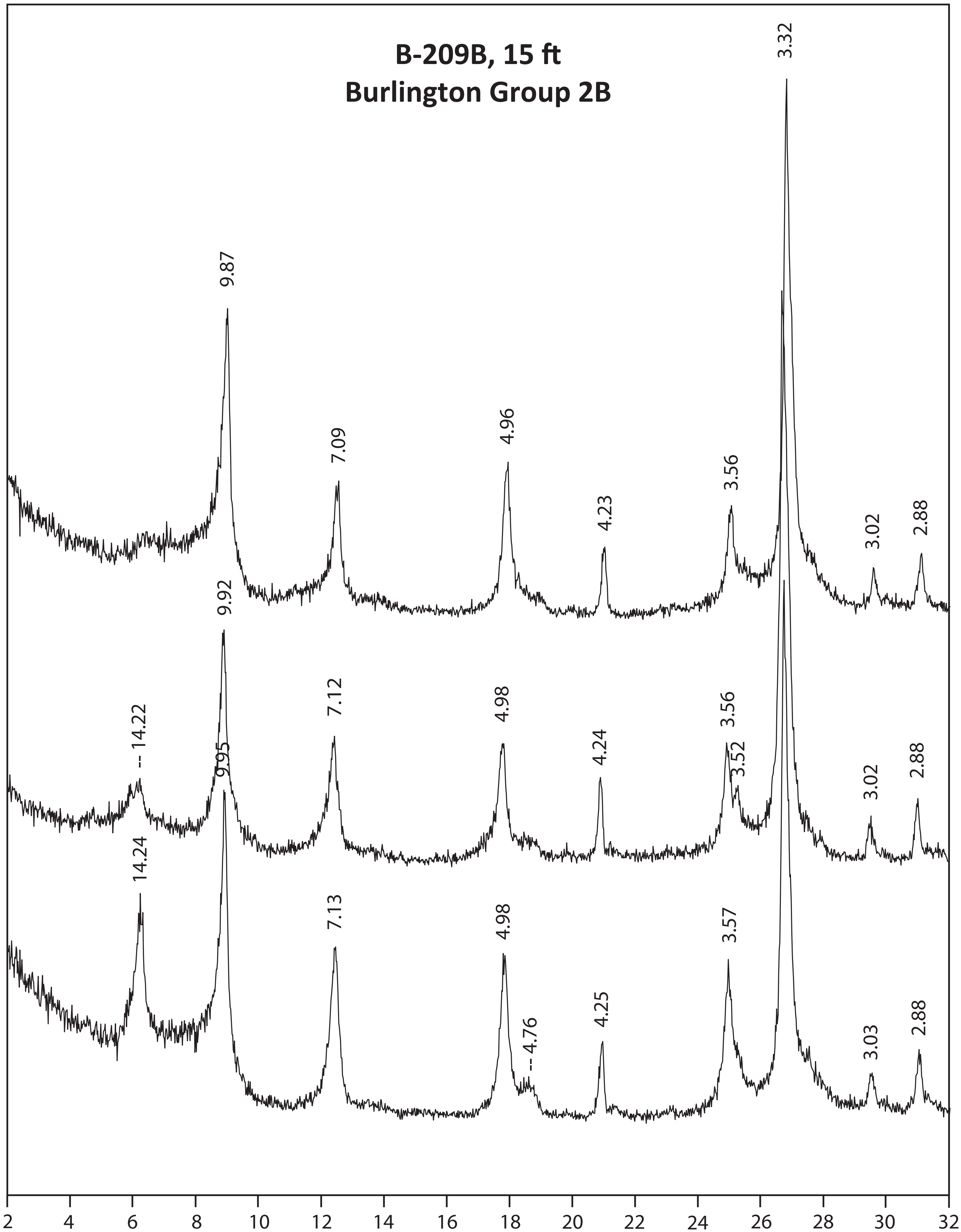
B-104, 17.5 ft
Burlington Group 2A




B-209B, 10 ft
Burlington Group 2B
9.87
7.09
4.96
4.23
3.56
3.33
3.02
2.87
14.34
9.95
7.14
4.98
4.24
3.57
3.02
2.88
14.32
9.97
7.14
4.98
4.78
4.25
3.57
3.03
2.88
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)

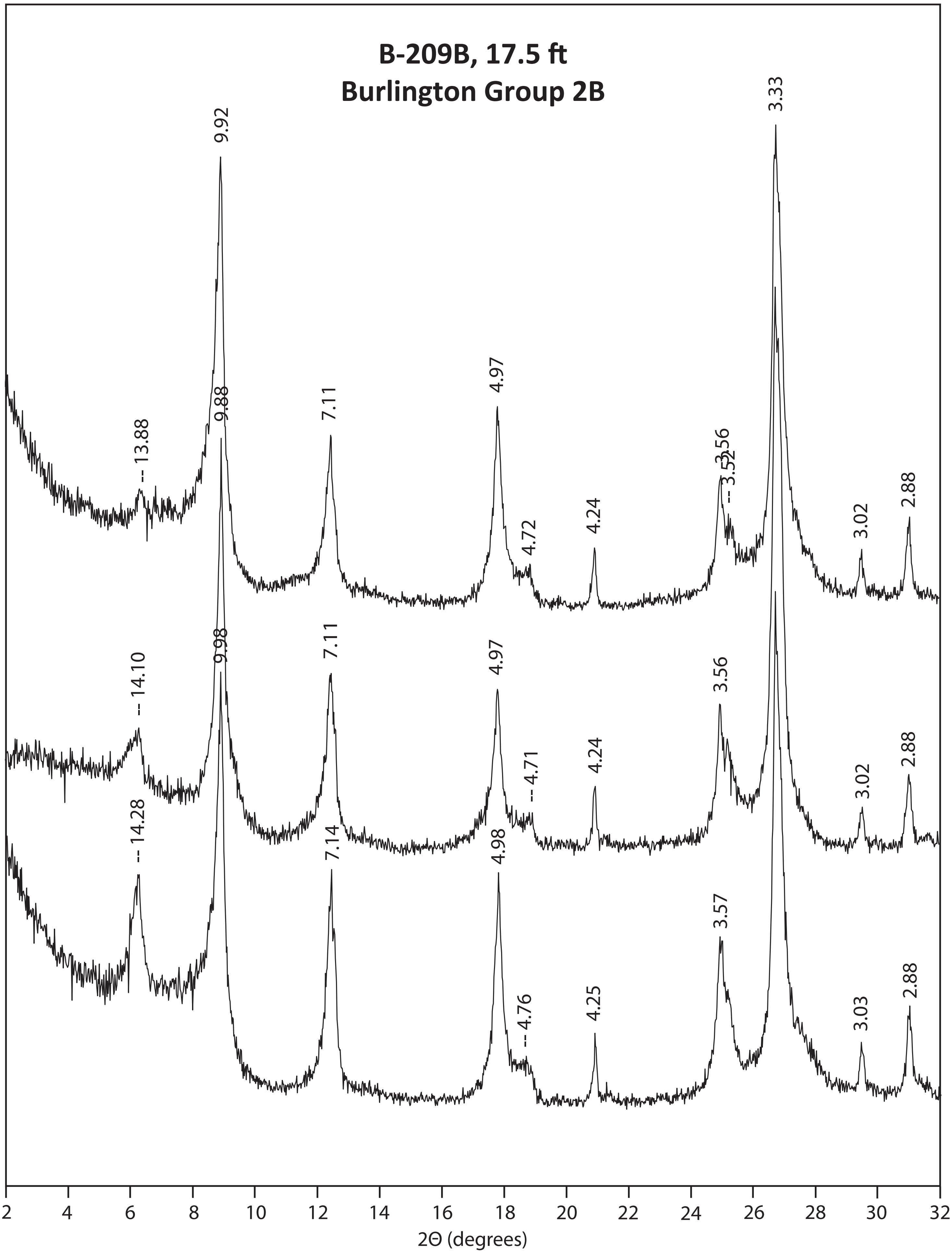


B-209B, 12.5 ft
Burlington Group 2B

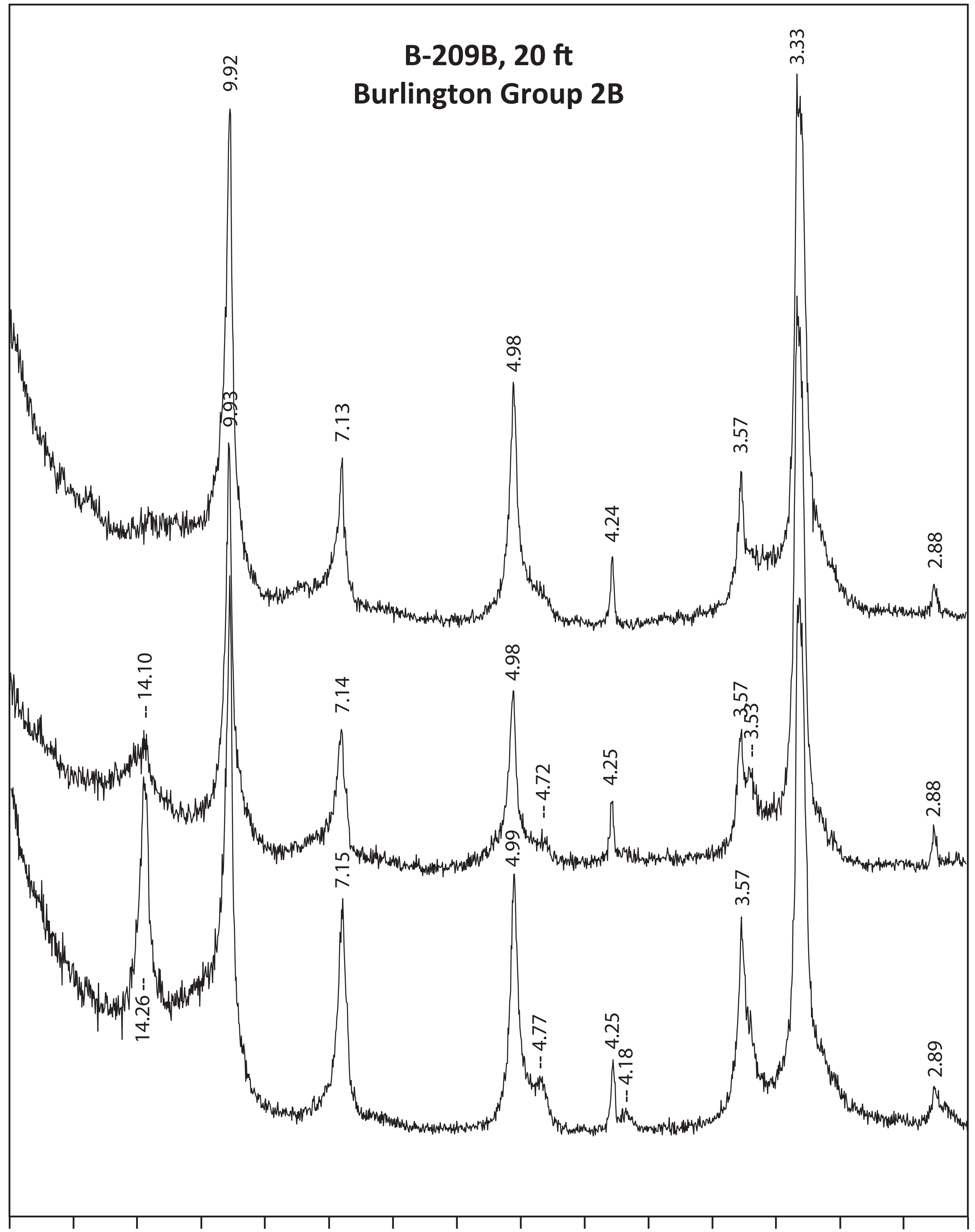


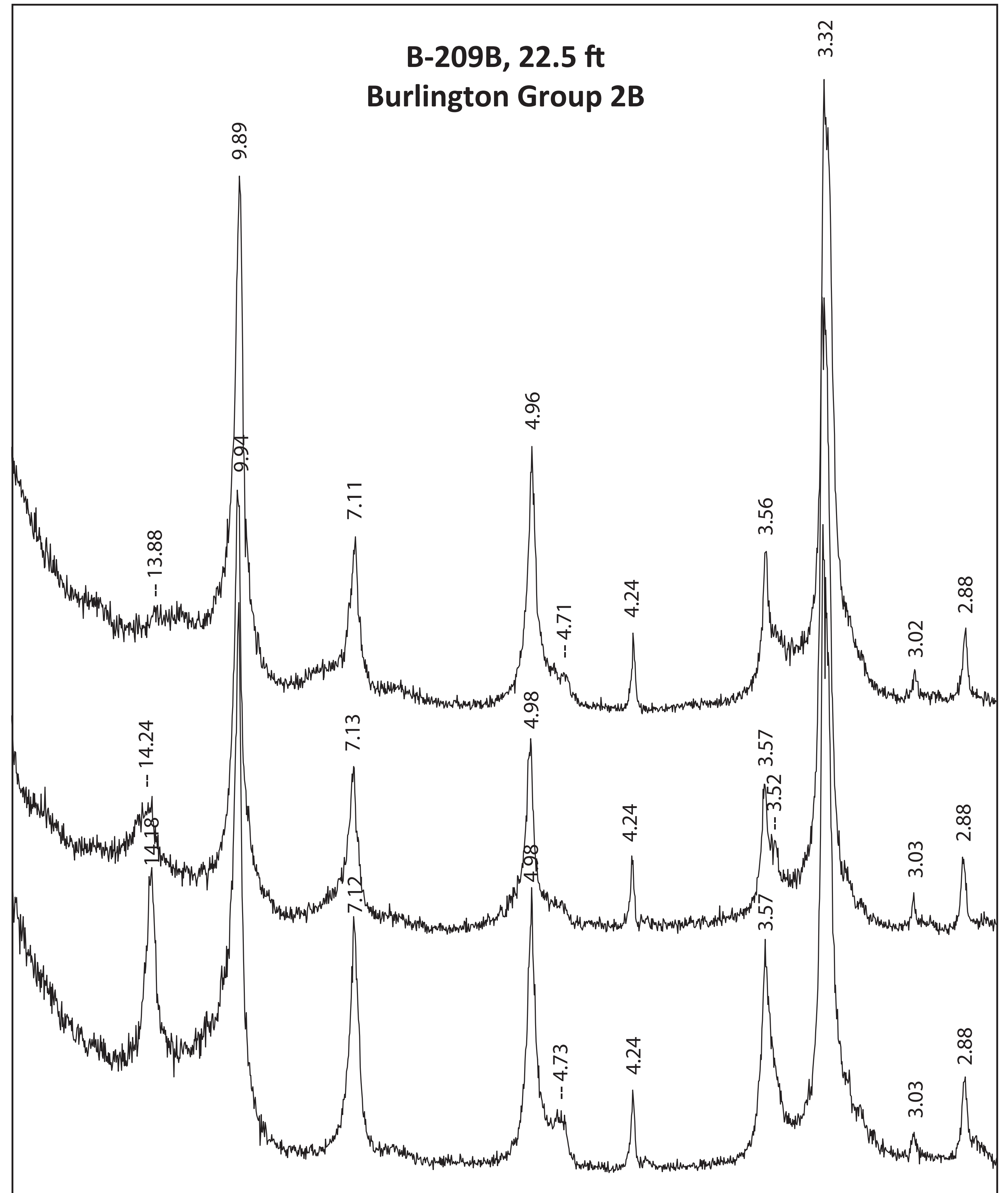
B-209B, 15 ft

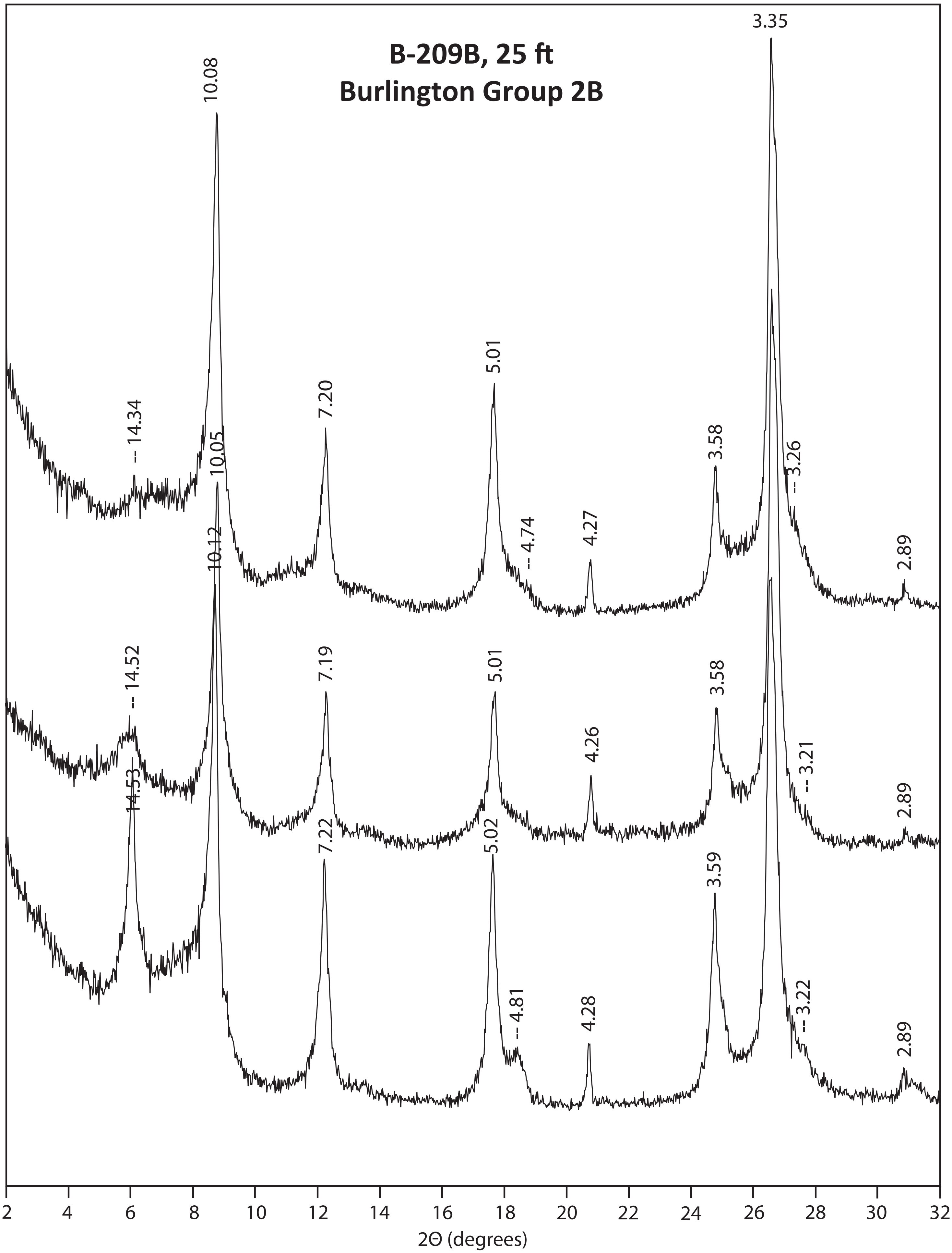
Burlington Group 2B

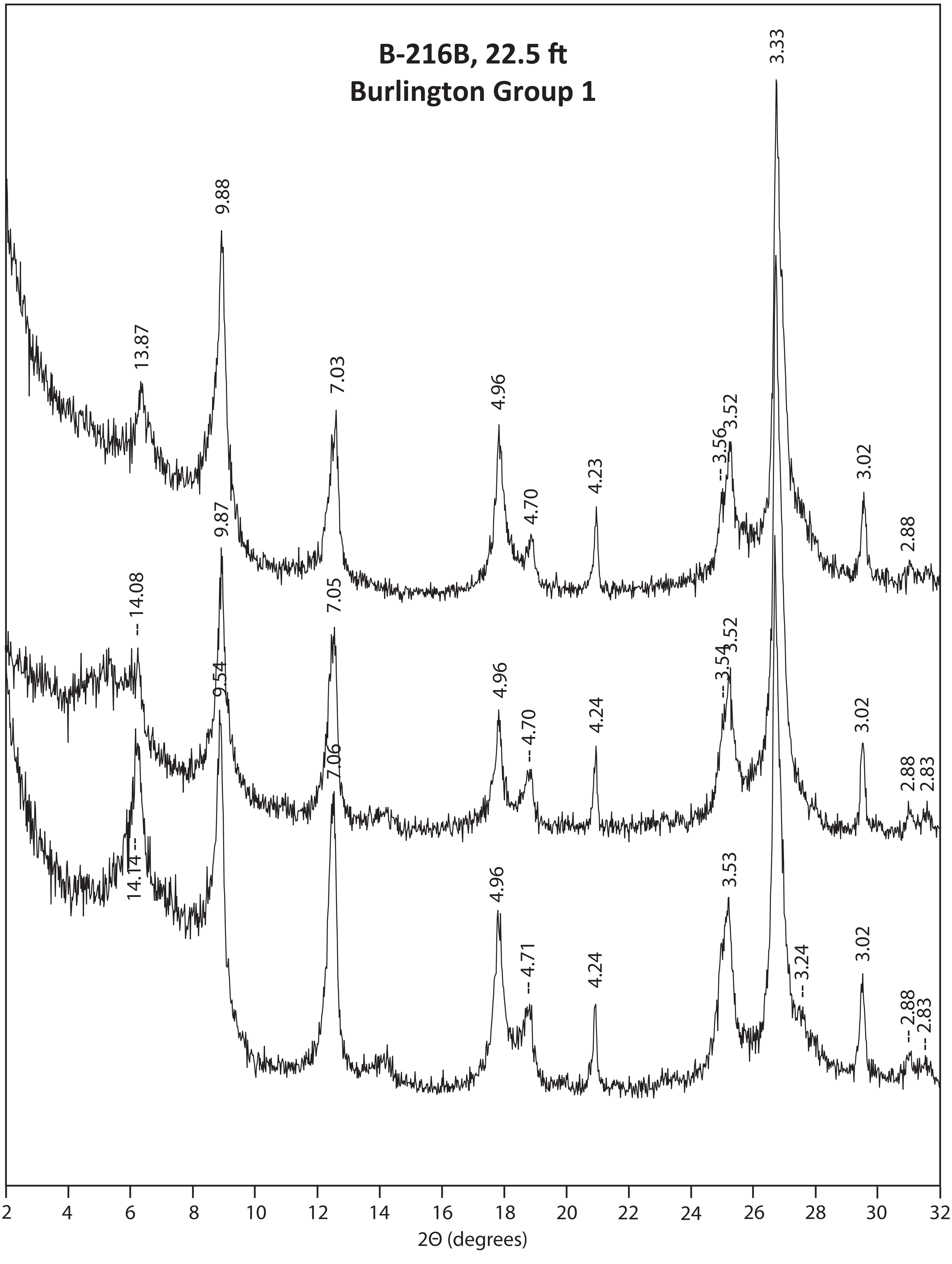


B-209B, 17.5 ft
Burlington Group 2B


B-209B, 20 ft
Burlington Group 2B
9.92
3.33
4.98
9.93
7.13
3.57
4.24
2.88
14.10
7.14
4.98
3.57
3.53
4.72
4.25
2.88
7.15
4.99
3.57
14.26
4.77
4.25
4.18
2.89
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)

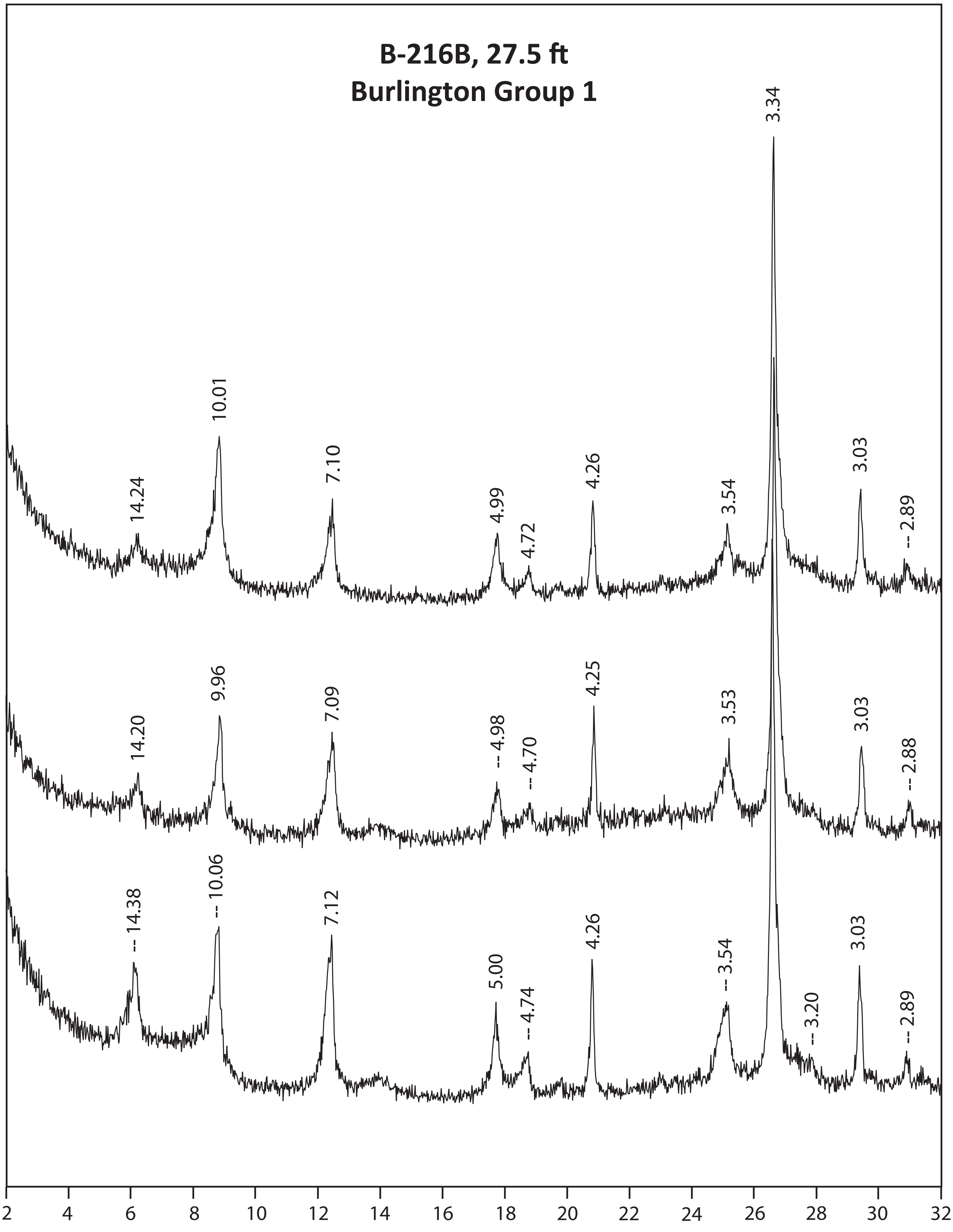

B-209B, 22.5 ft
Burlington Group 2B
9.89
3.32
4.96
9.94
7.11
13.88
3.56
4.71
4.24
2.88
3.02
14.24
7.13
4.98
3.57
3.52
4.24
2.88
3.03
14.18
4.98
7.12
3.57
4.73
4.24
2.88
3.03
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)

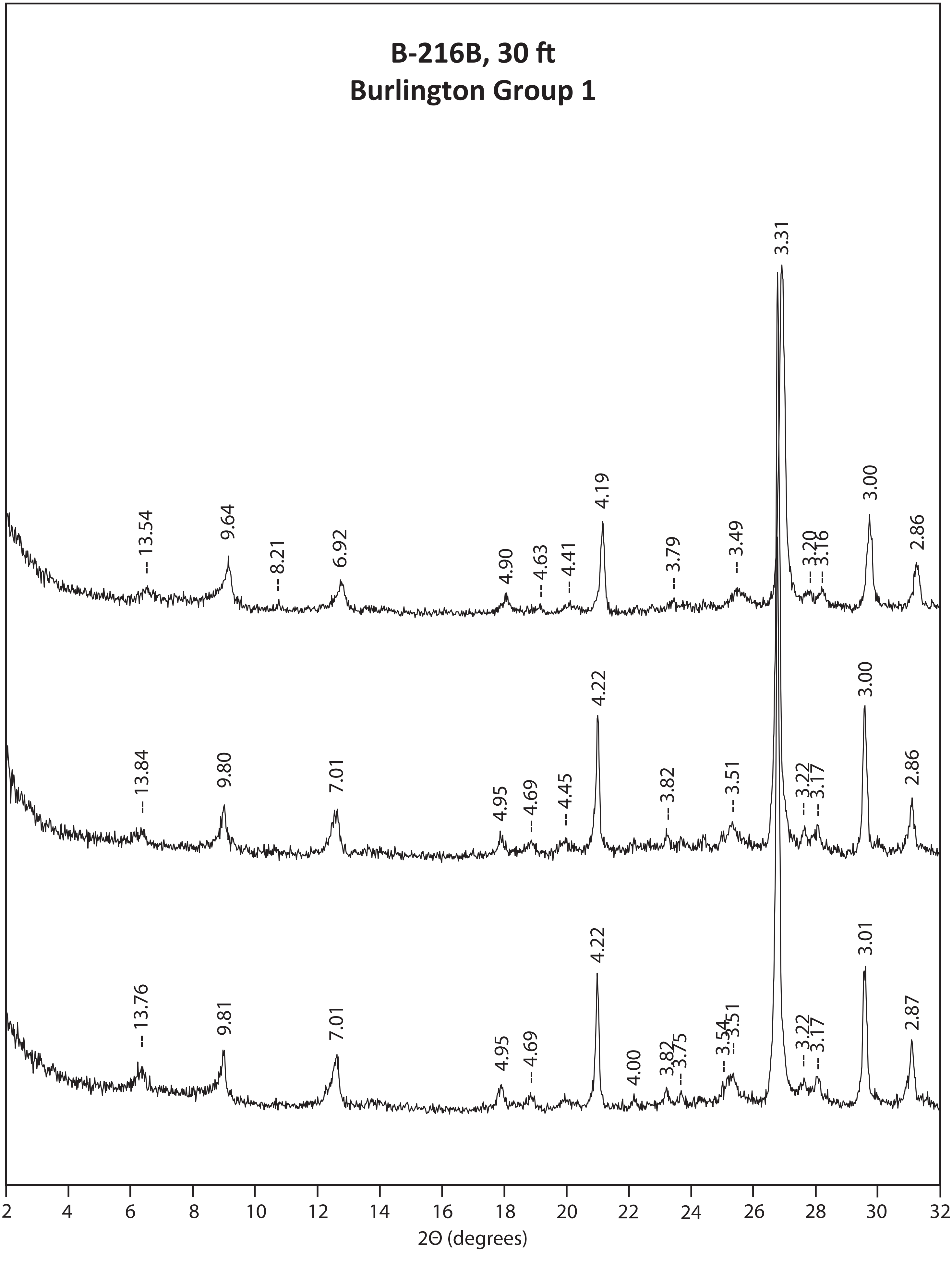

B-209B, 25 ft
Burlington Group 2B
3.35
10.08
-- 14.34
7.20
5.01
10.05
-- 4.74
4.27
3.58
-- 3.26
2.89
10.12
-- 14.52
7.19
5.01
4.26
3.58
-- 3.21
2.89
14.53
7.22
5.02
-- 4.81
4.28
3.59
-- 3.22
2.89
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)



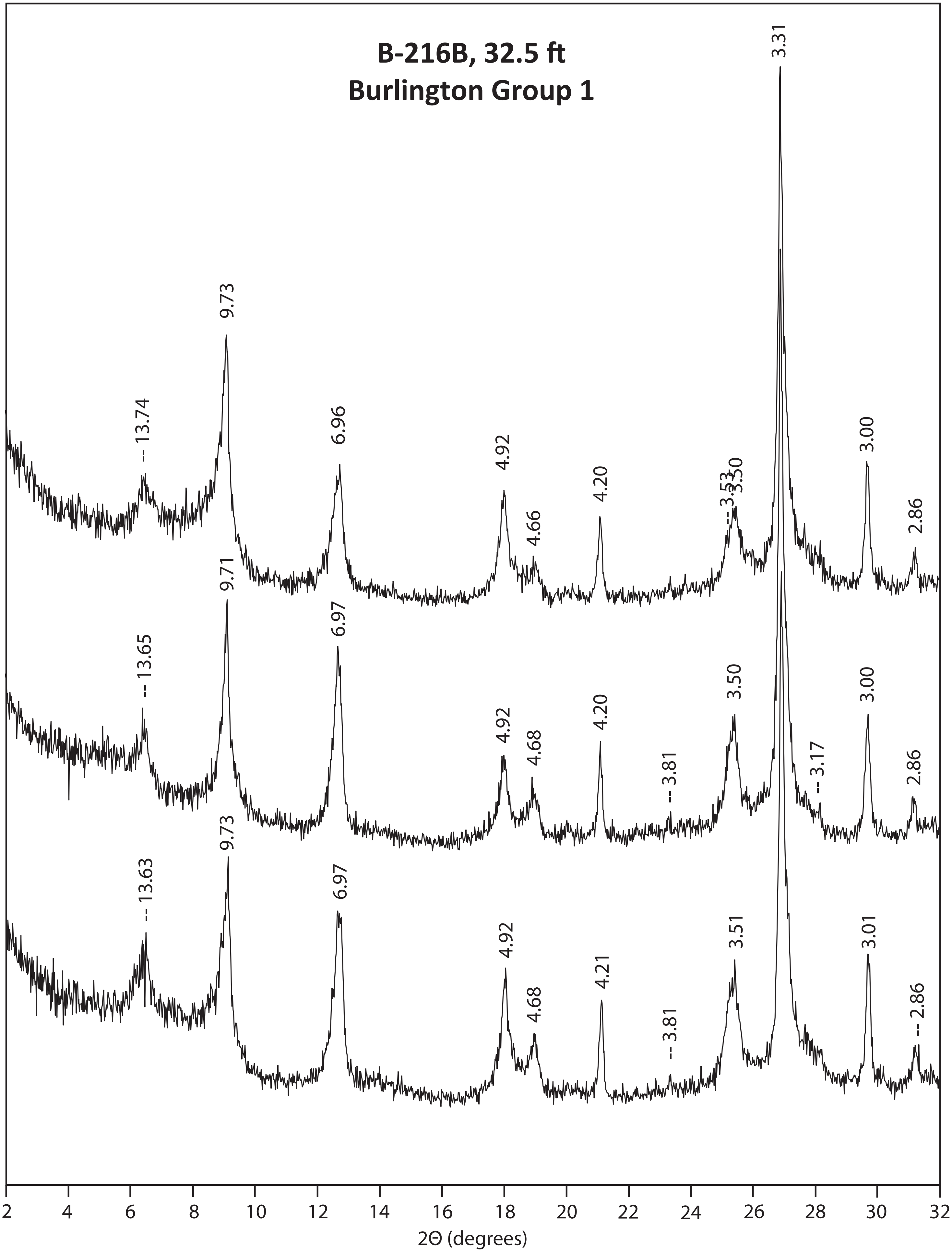
B-216B, 22.5 ft
Burlington Group 1

B-216B, 27.5 ft
Burlington Group 1

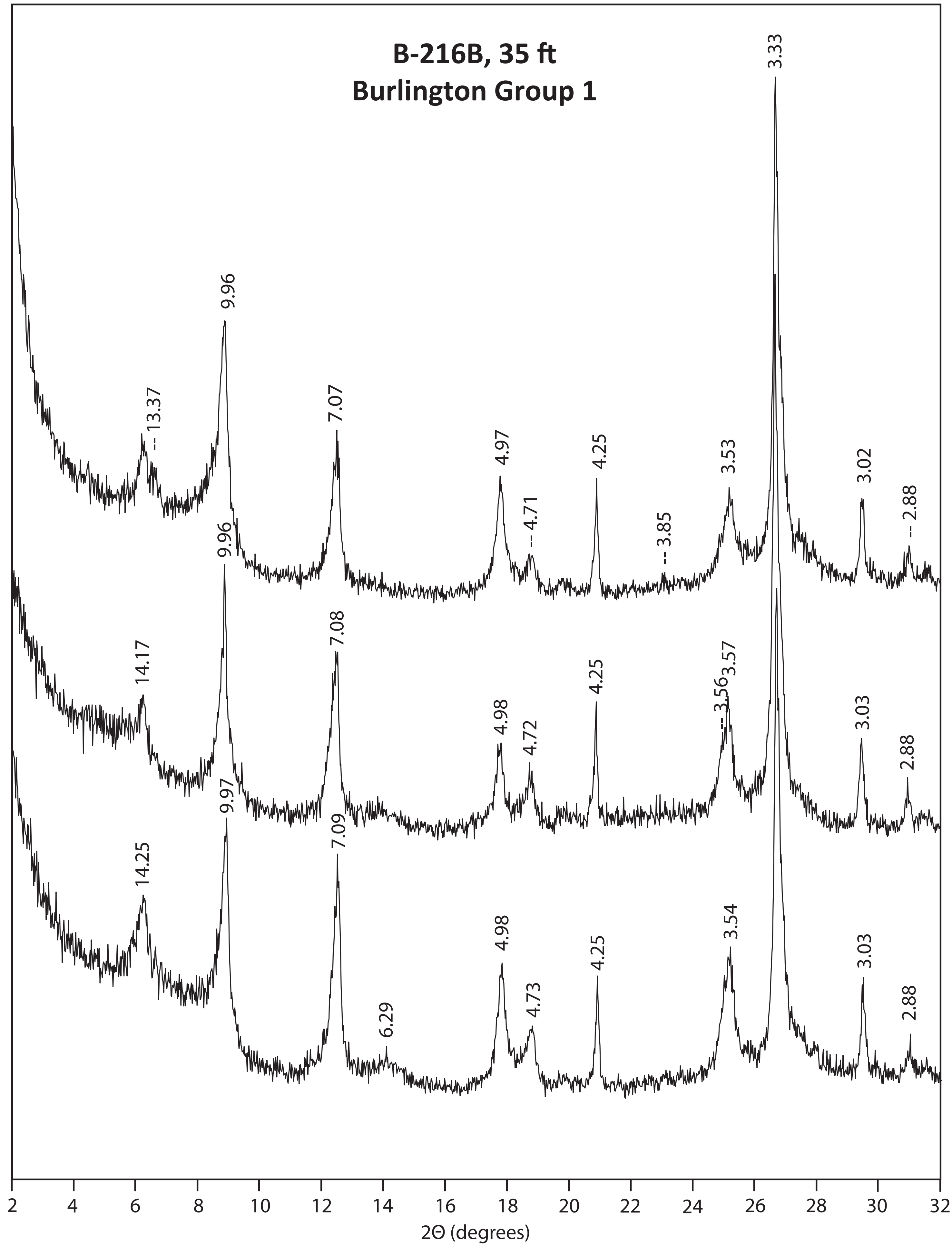




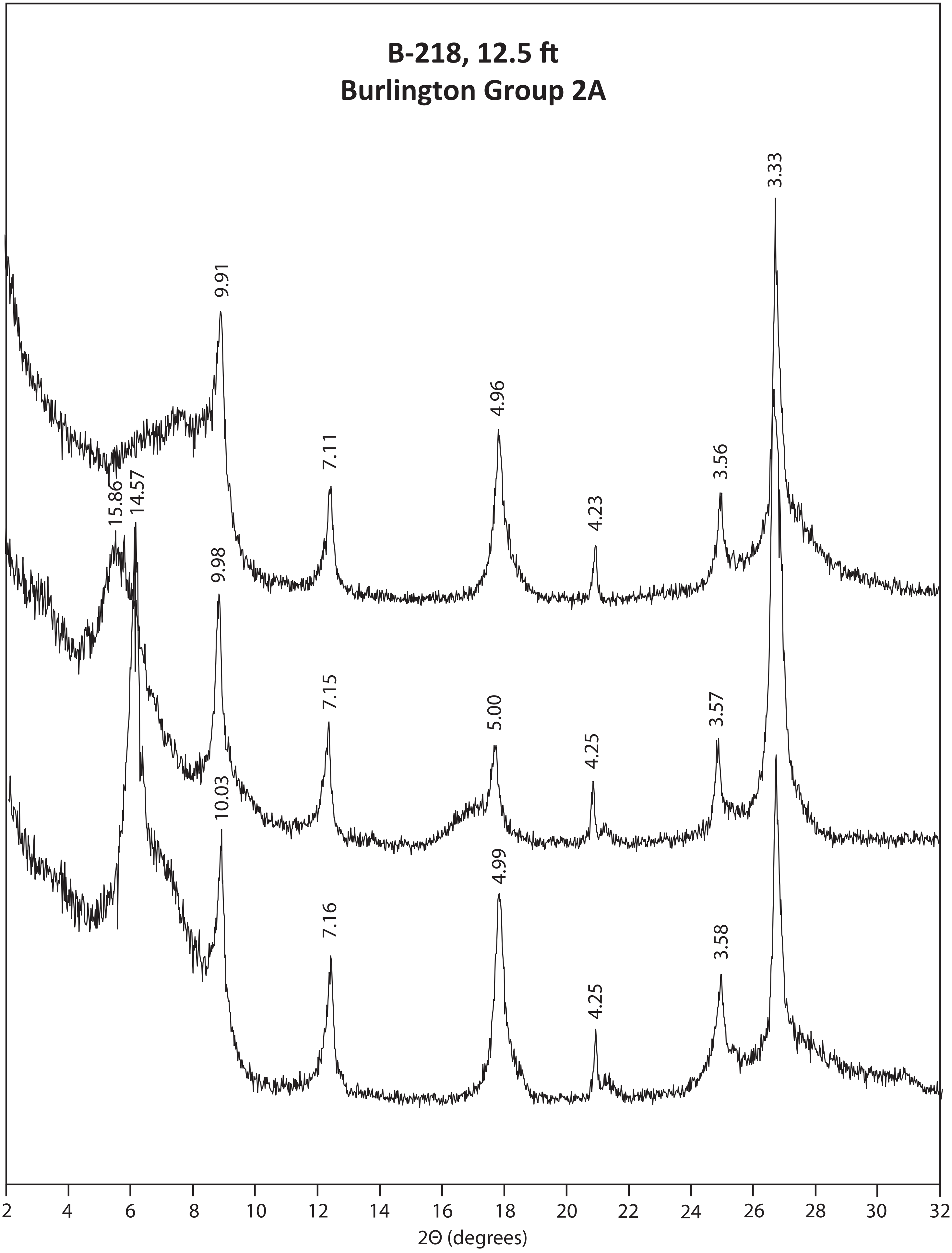
B-216B, 30 ft
Burlington Group 1

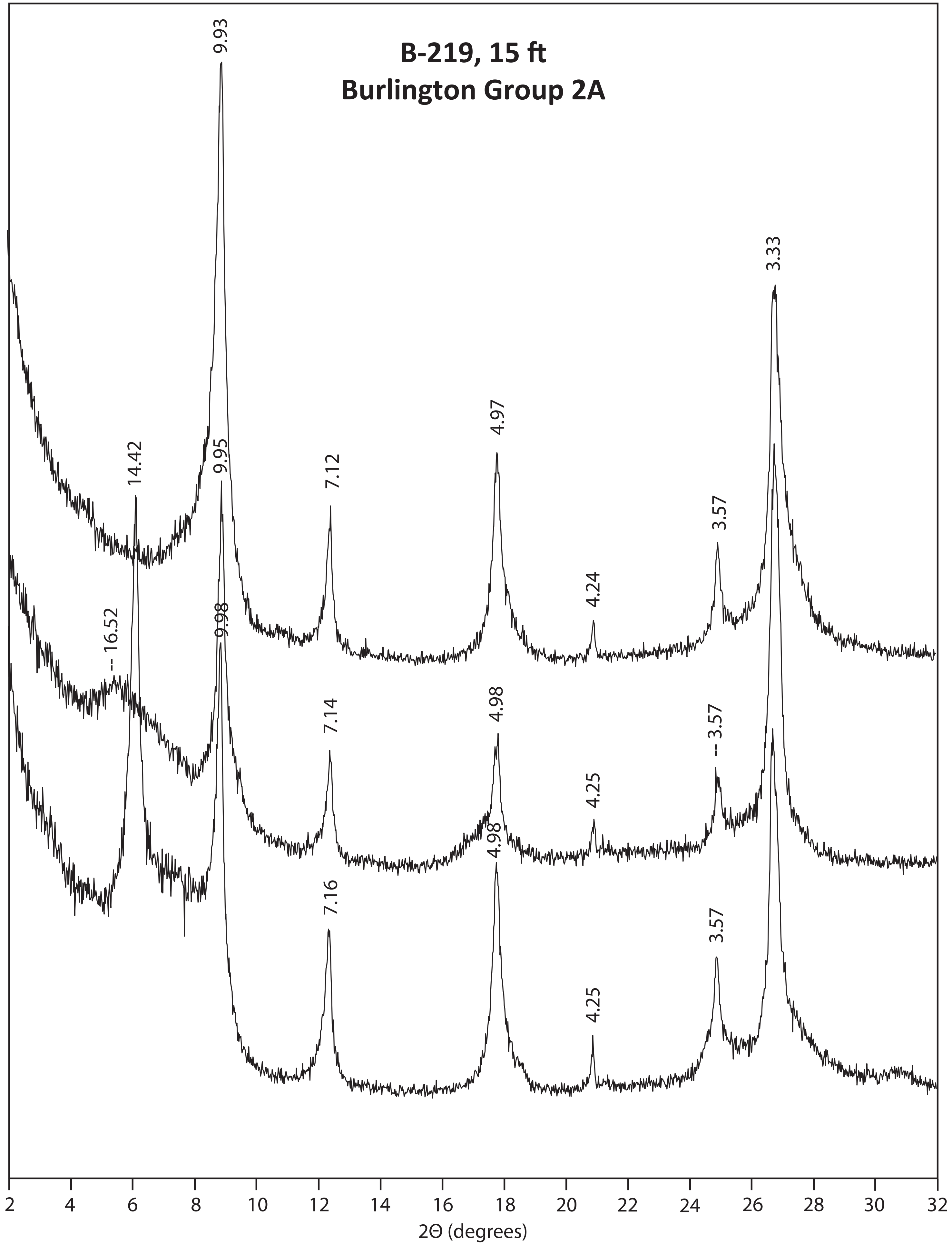


B-216B, 32.5 ft
Burlington Group 1

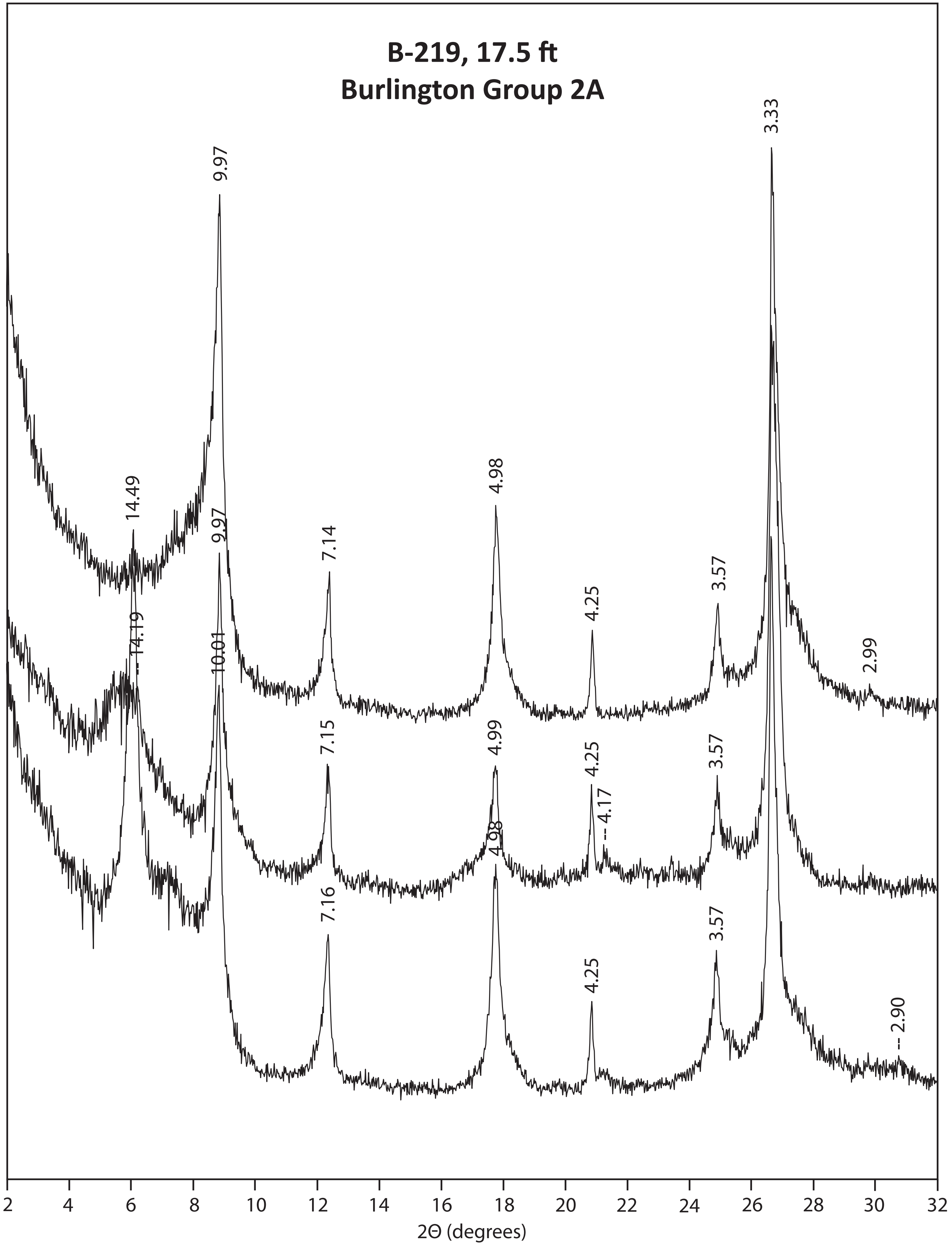


B-218, 12.5 ft
Burlington Group 2A

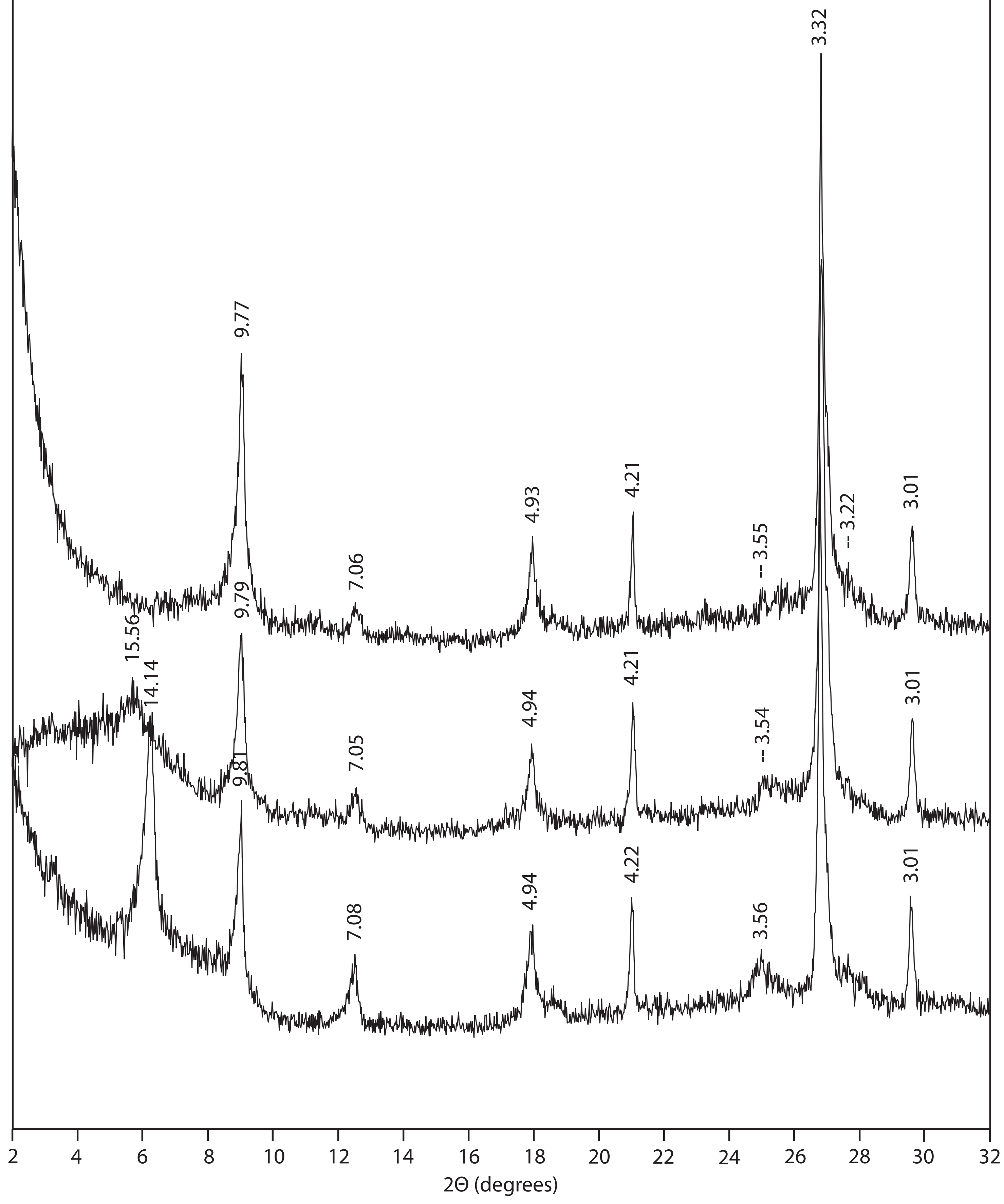


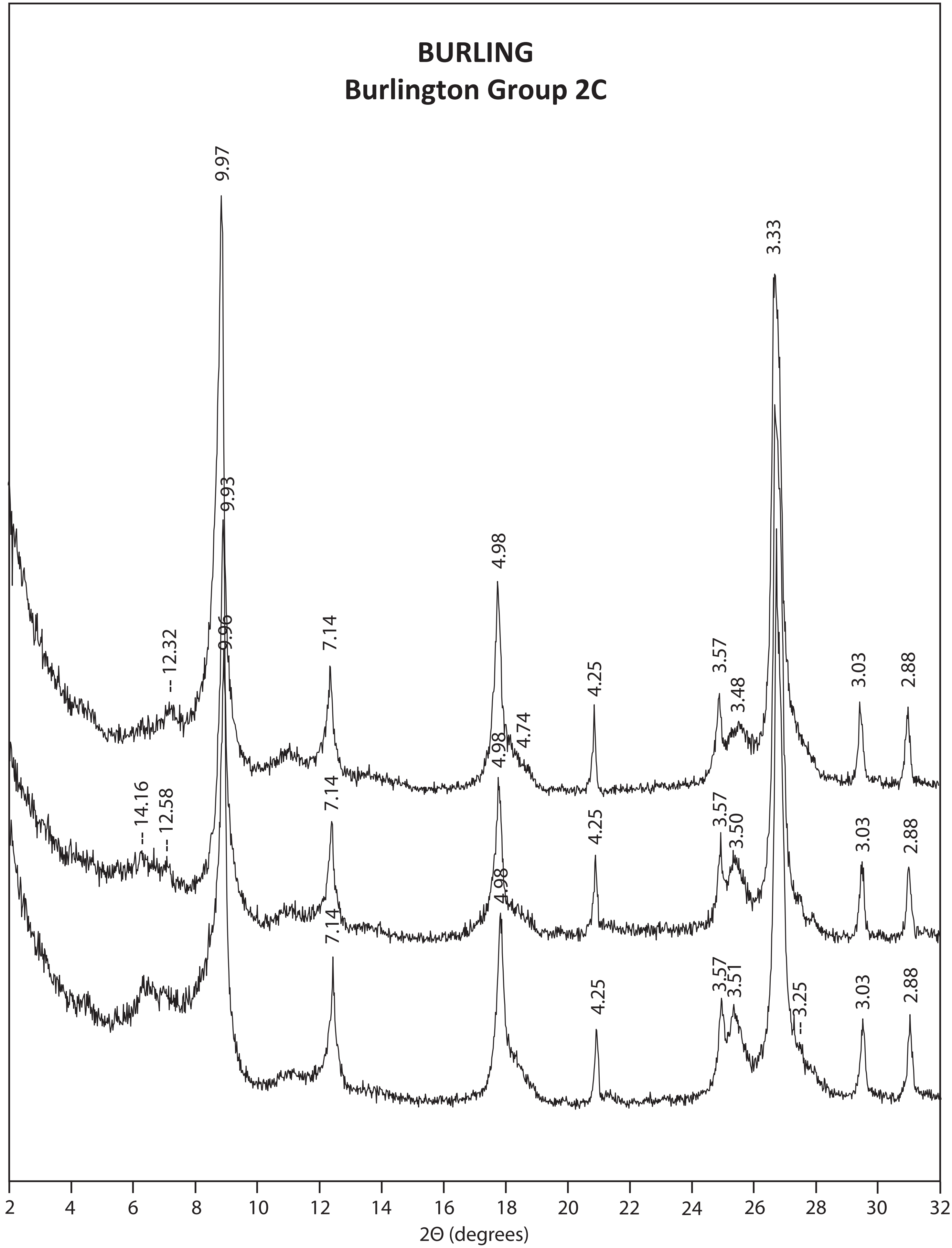


B-219, 15 ft
Burlington Group 2A

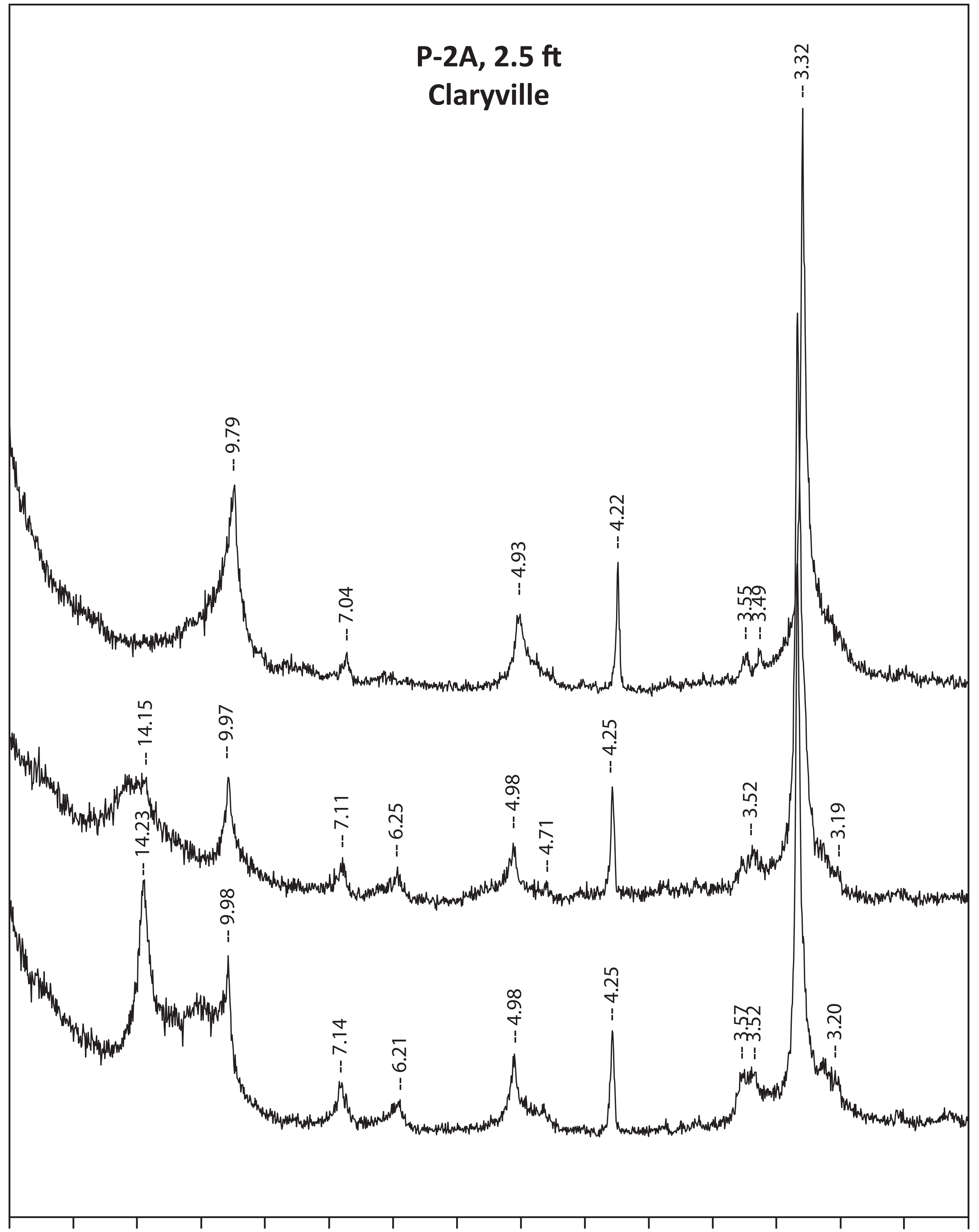

B-219, 17.5 ft
Burlington Group 2A
3.33
9.97
14.49
9.97
7.14
4.98
4.25
3.57
2.99
14.19
10.01
7.15
4.99
4.25
4.17
3.57
4.98
7.16
4.25
3.57
2.90
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)

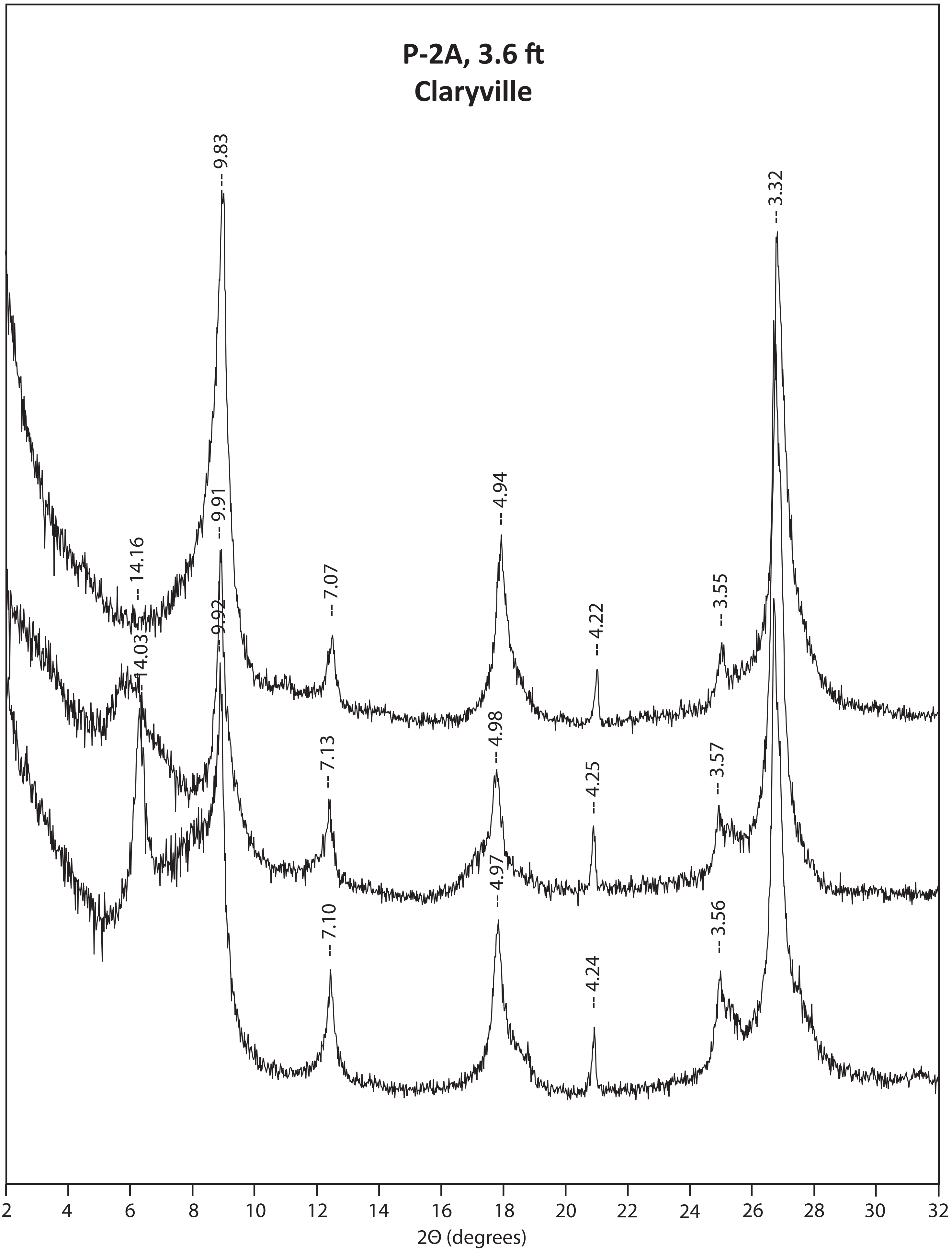
B-222, 60 ft
Burlington Group 5

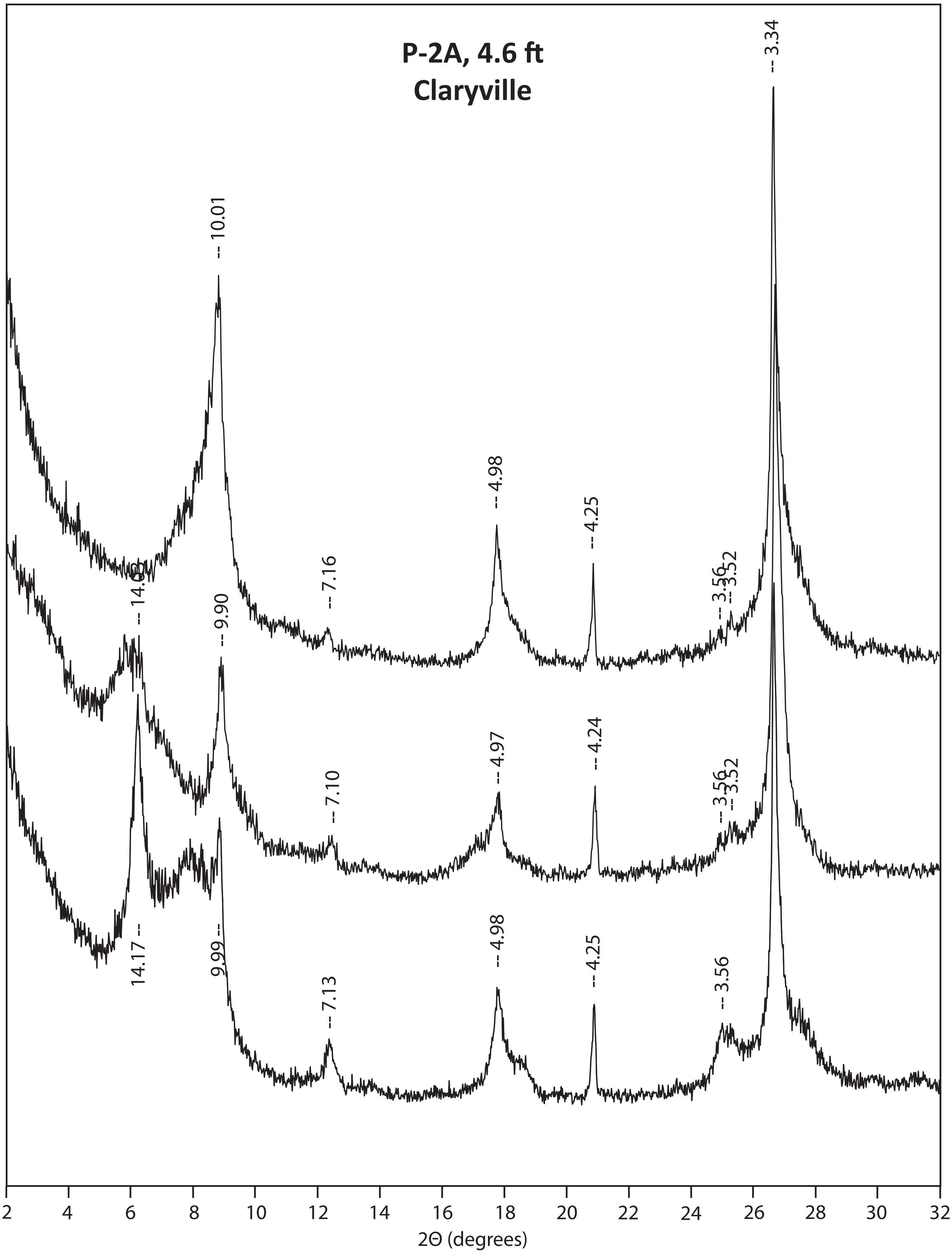


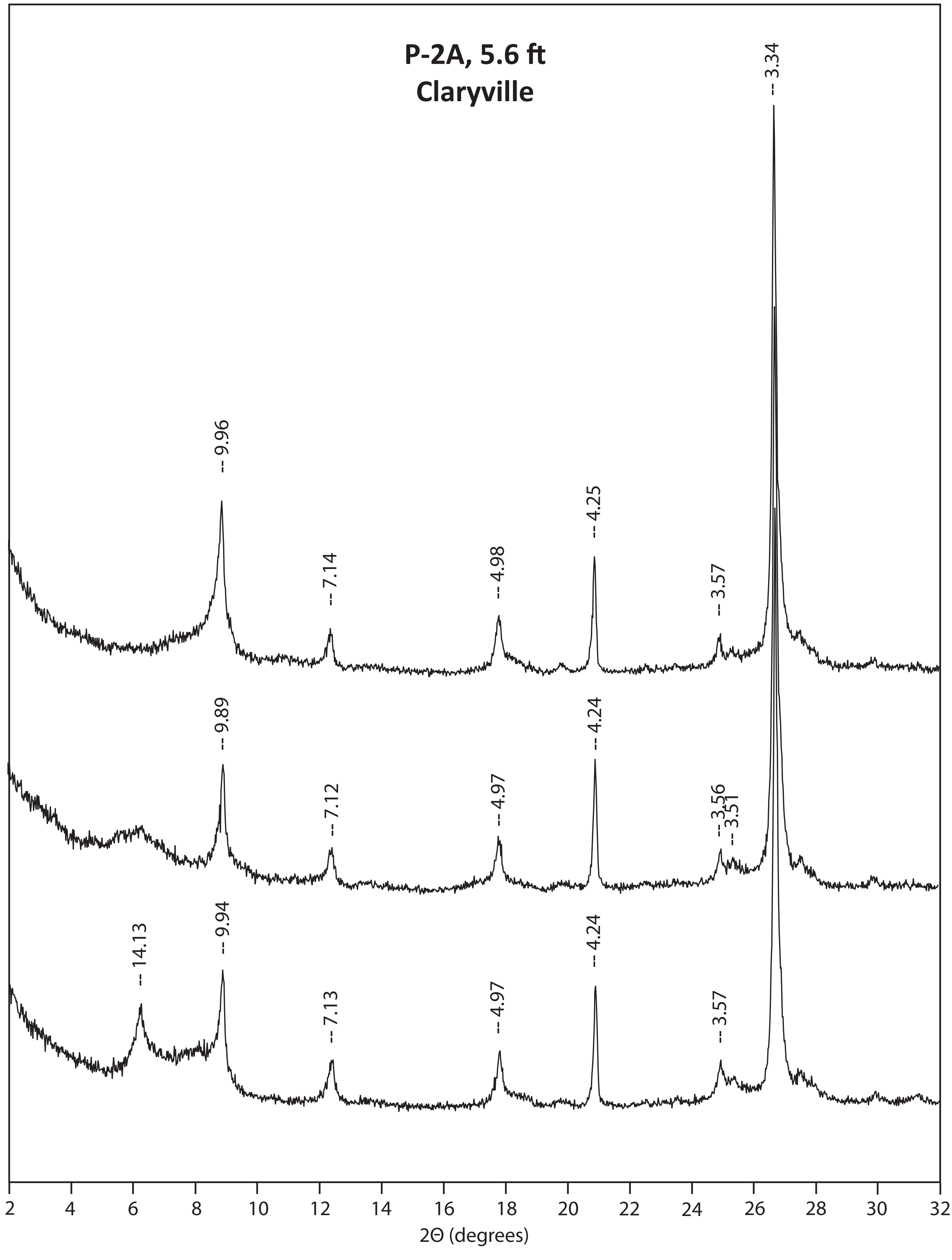


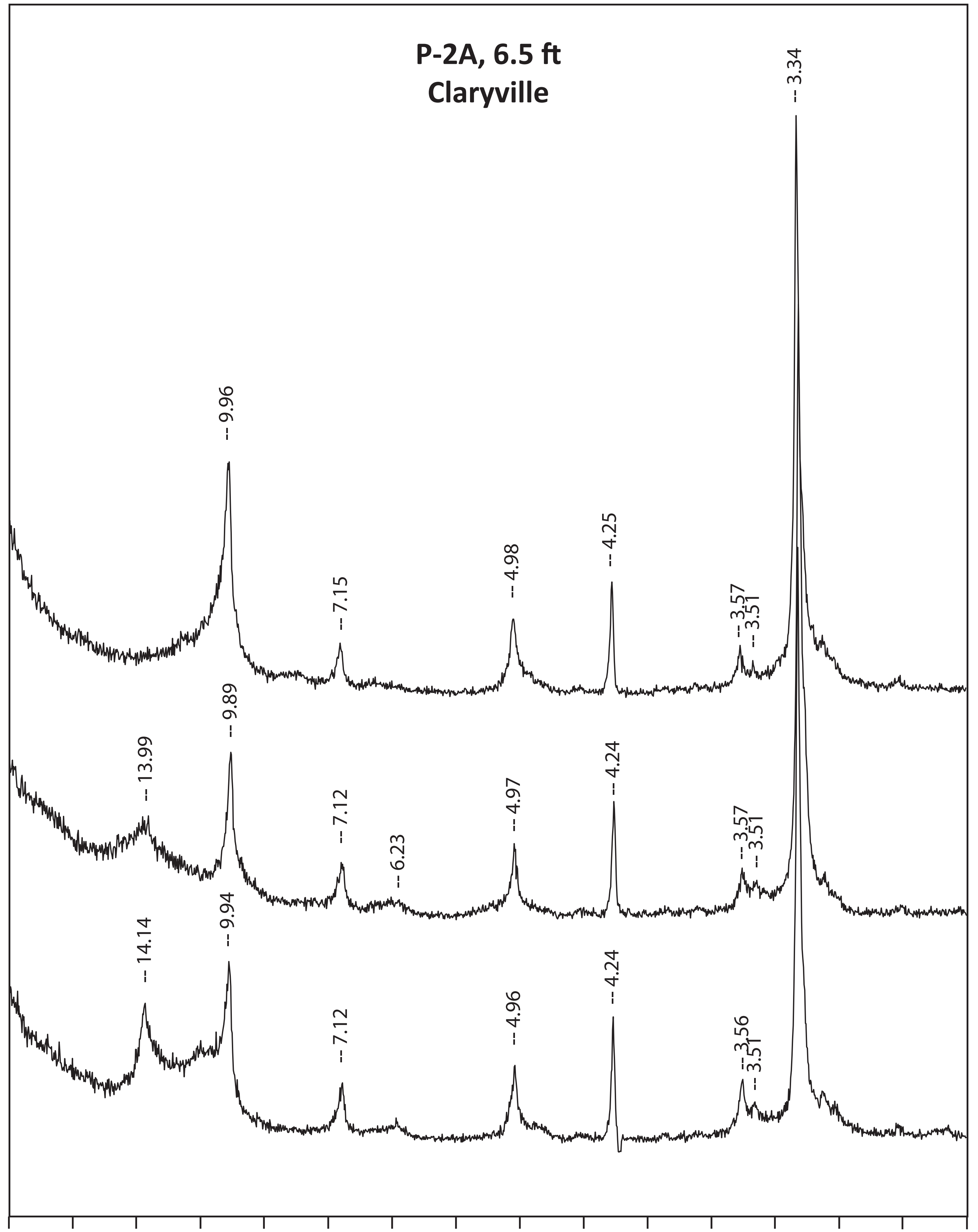
BURLING
Burlington Group 2C


P-2A, 2.5 ft
Claryville
3.32
9.79
7.04
4.93
4.22
3.55
3.49
14.15
9.97
7.11
6.25
4.98
4.71
4.25
3.52
3.19
14.23
9.98
7.14
6.21
4.98
4.25
3.57
3.52
3.20
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)

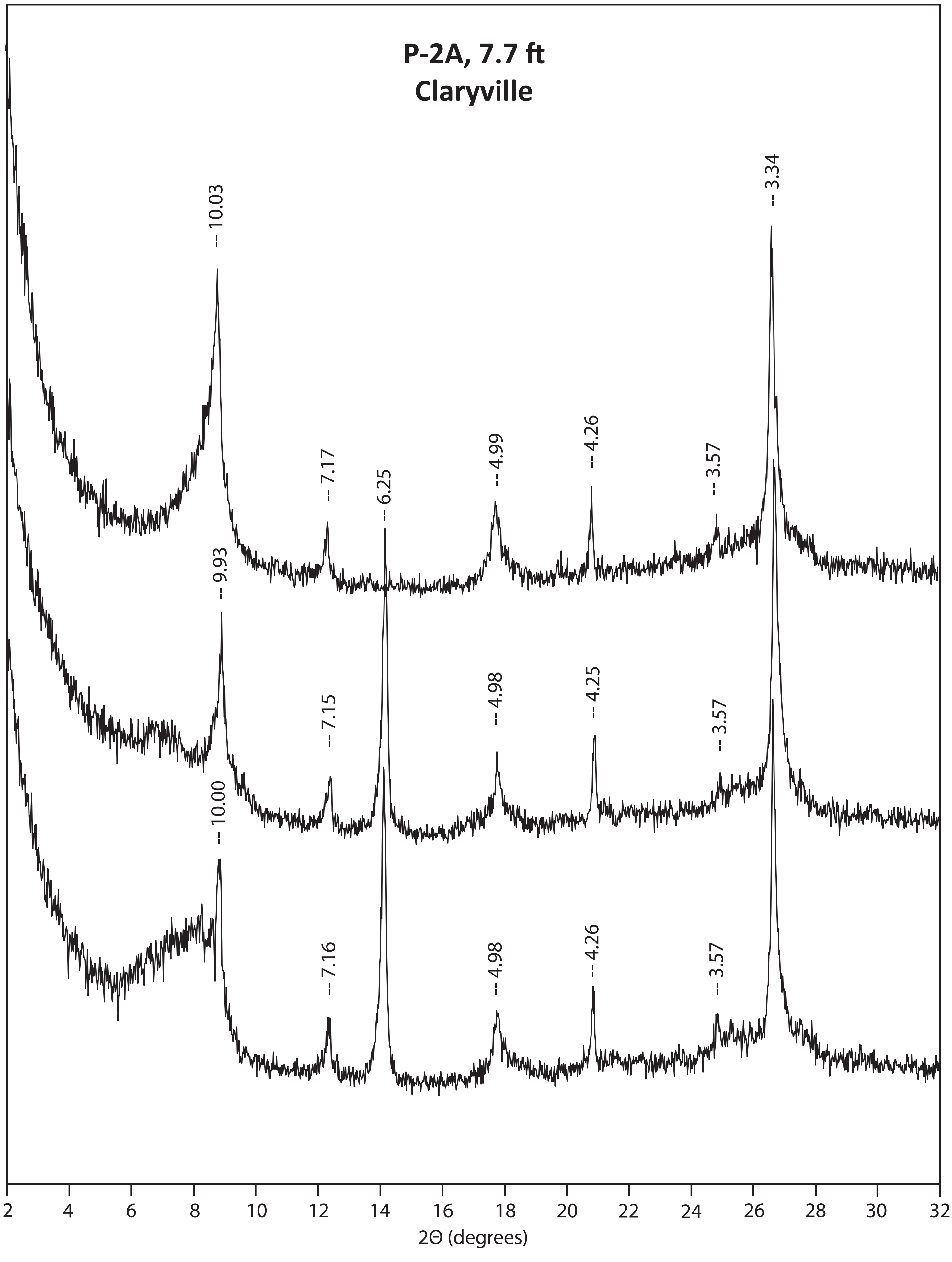

P-2A, 3.6 ft
Claryville
9.83
3.32
4.94
14.16
9.91
7.07
4.22
3.55
14.03
9.92
7.13
4.98
4.25
3.57
4.97
7.10
3.56
4.24
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)


P-2A, 4.6 ft
Claryville
3.34
10.01
4.98
4.25
7.16
3.56
3.52
14.0
9.90
4.97
4.24
7.10
3.56
3.52
14.17
9.99
4.98
4.25
7.13
3.56
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)


P-2A, 5.6 ft
Claryville
3.34
9.96
7.14
4.98
4.25
3.57
9.89
7.12
4.97
4.24
3.56
3.51
14.13
9.94
7.13
4.97
4.24
3.57
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)

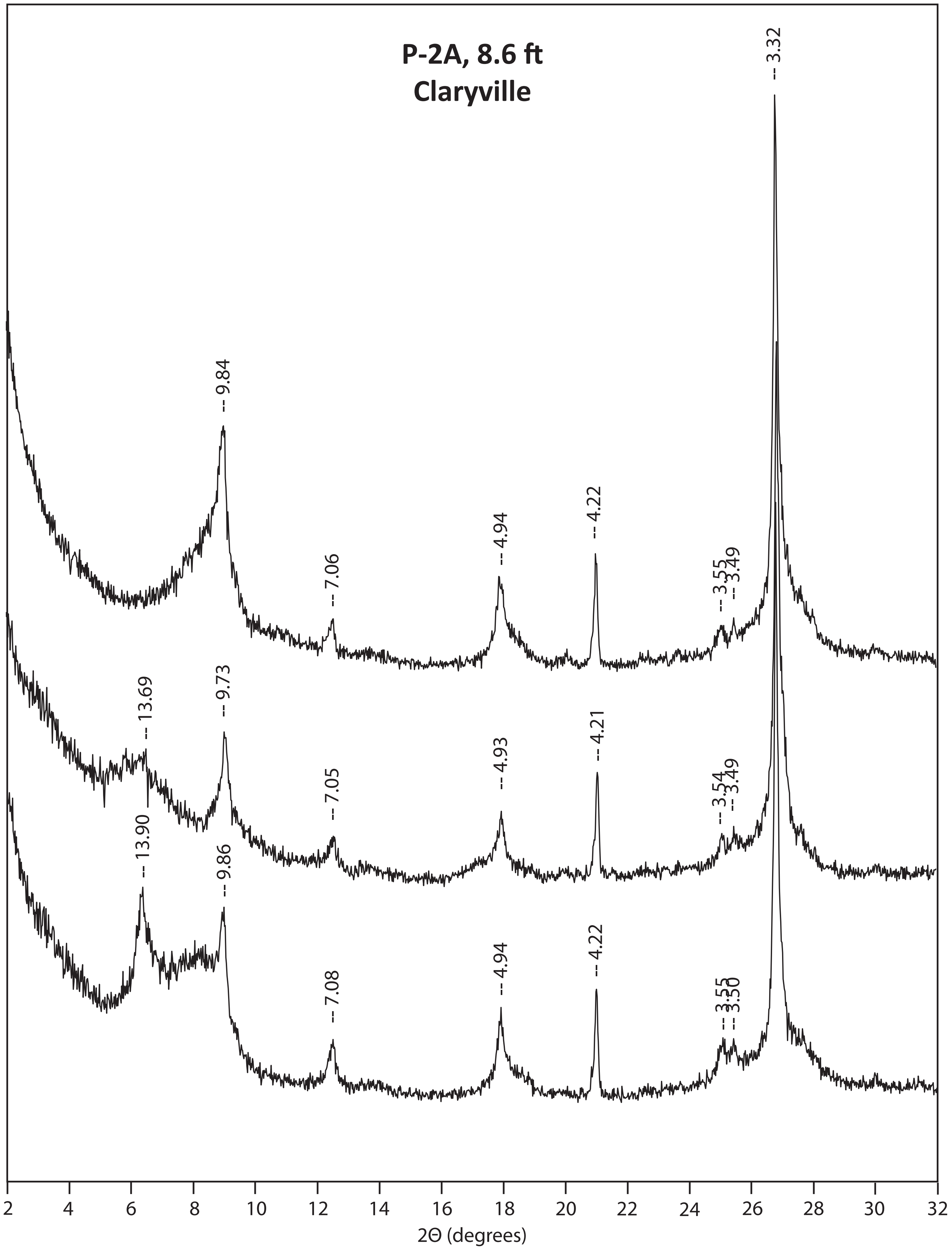


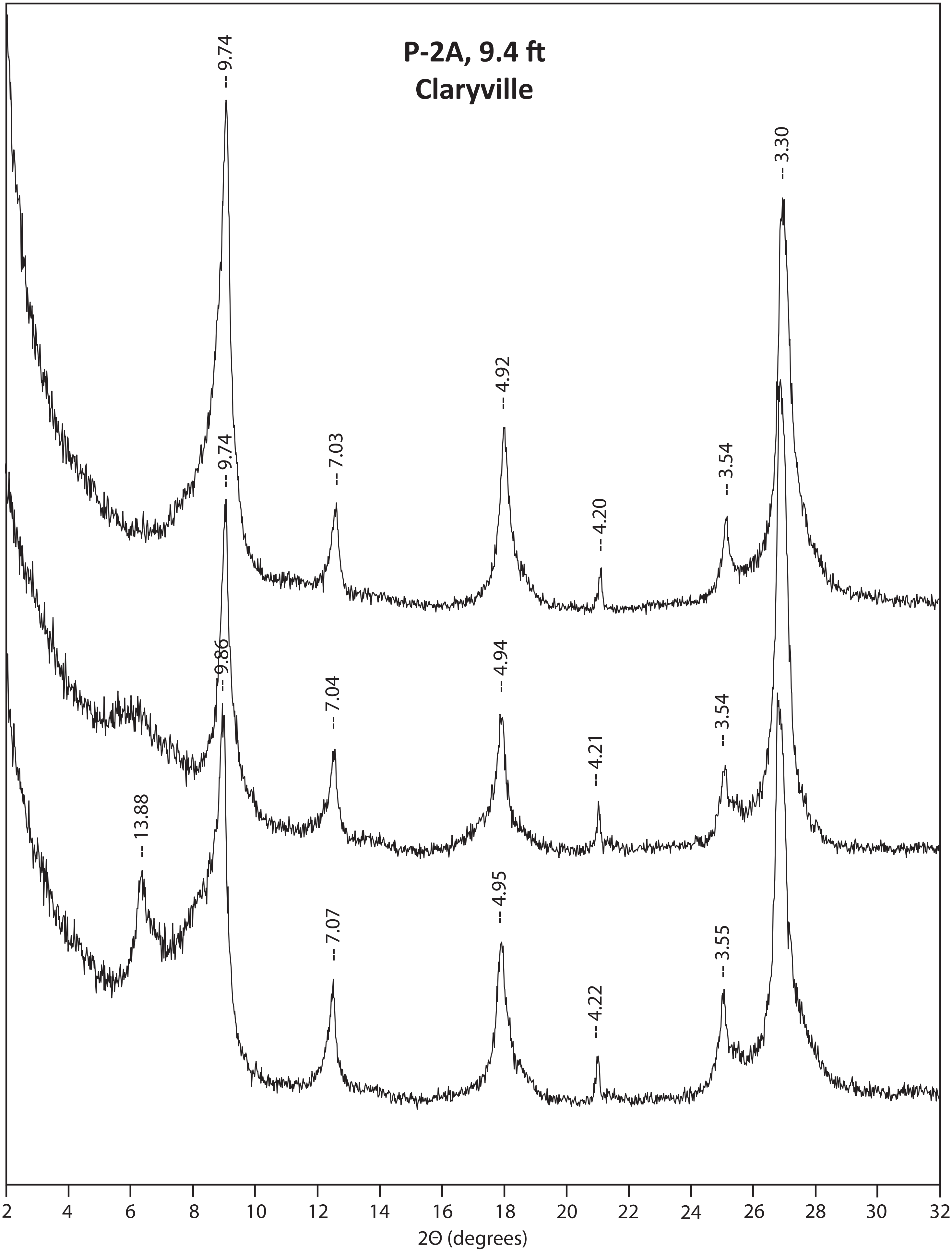
P-2A, 6.5 ft
Claryville

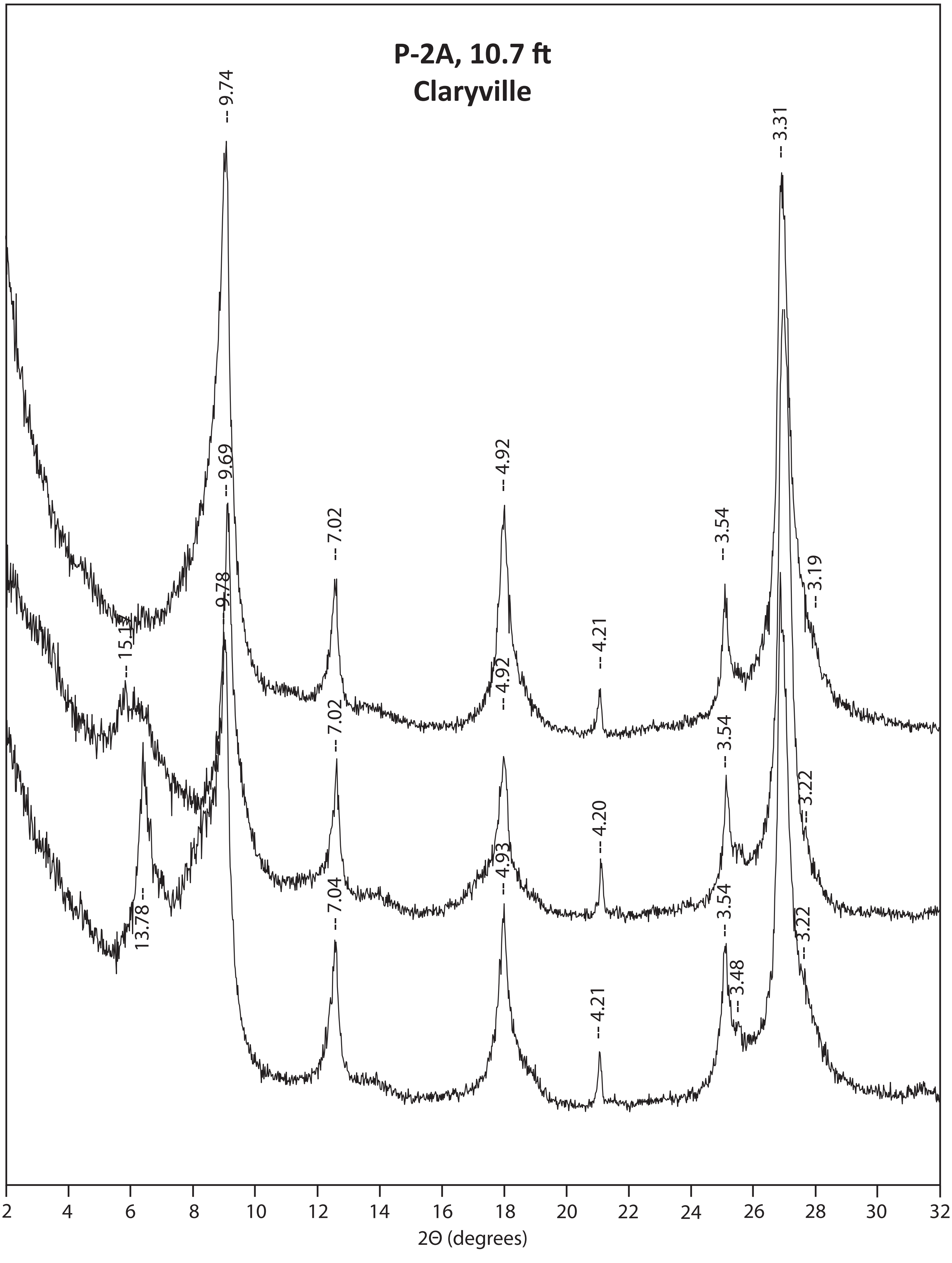


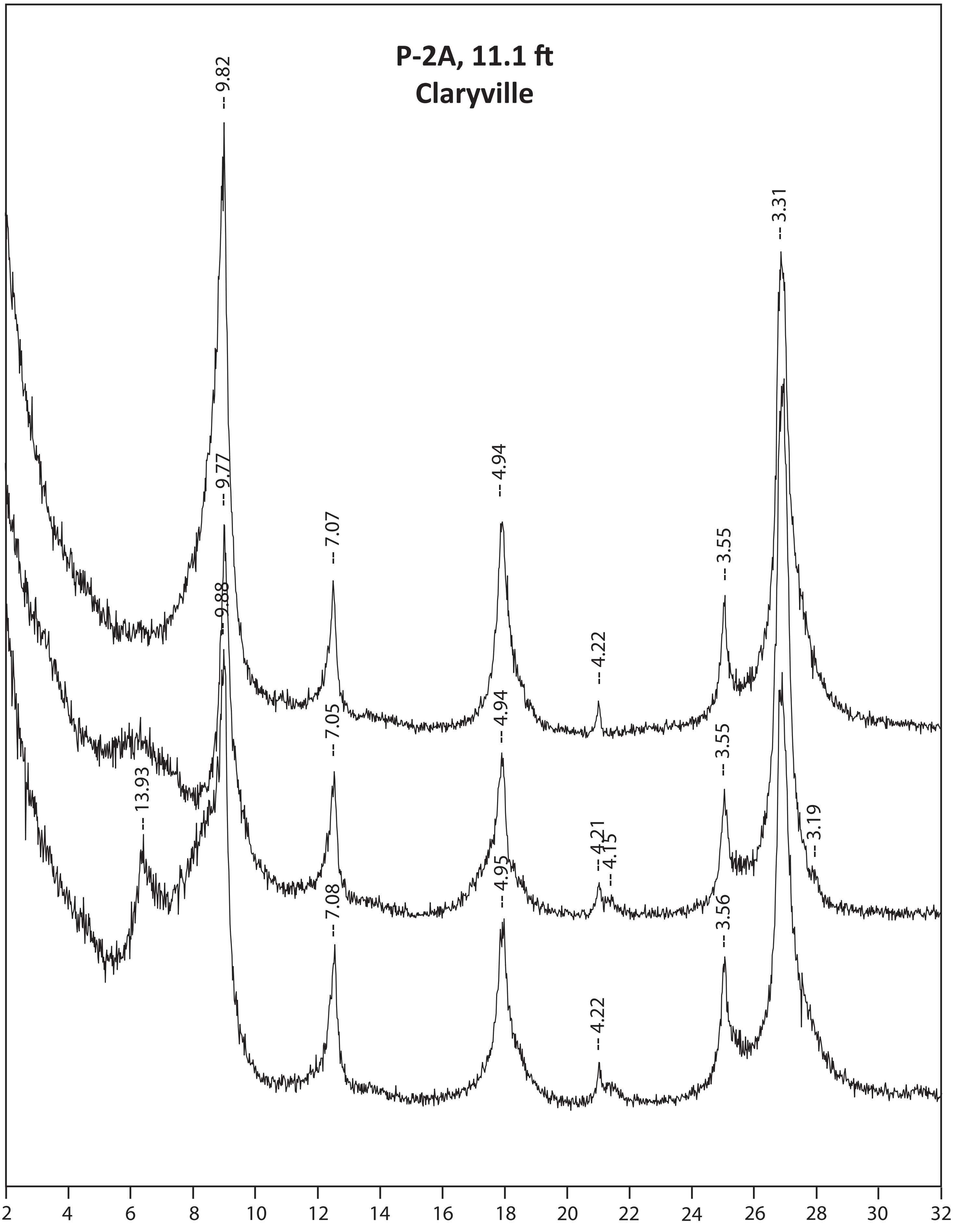
P-2A, 7.7 ft

Claryville


P-2A, 8.6 ft
Claryville
3.32
9.84
7.06
4.94
4.22
3.55
3.49
13.69
9.73
7.05
4.93
4.21
3.54
3.49
13.90
9.86
7.08
4.94
4.22
3.55
3.50
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)


P-2A, 9.4 ft
Claryville
9.74
3.30
4.92
7.03
3.54
4.20
9.74
9.86
4.94
7.04
3.54
4.21
13.88
4.95
7.07
3.55
4.22
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)


P-2A, 10.7 ft
Claryville
9.74
3.31
9.69
4.92
7.02
3.54
3.19
9.78
15.1
4.21
4.92
7.02
3.54
3.22
4.20
13.78
4.93
7.04
3.54
3.22
3.48
4.21
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)


P-2A, 11.1 ft
Claryville
9.82
3.31
4.94
9.77
7.07
3.55
9.88
4.22
7.05
4.94
3.55
13.93
4.21
4.15
3.19
4.95
7.08
3.56
4.22
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
2Θ (degrees)