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Catastrophic middle Pleistocene jökulhlaups in the upper Susquehanna River: Distinctive landforms from breakout floods in the central Appalachians

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ABSTRACT

Widespread till and moraines record excursions of middle-Pleistocene ice that flowed up-slope into several watersheds of the Valley and Ridge Province along the West Branch of the Susquehanna River. A unique landform assemblage was created by ice-damming and jökulhlaups emanating from high gradient mountain watersheds. This combination of topography formed by multiple eastward-plunging anticlinal ridges, and the upvalley advance of glaciers resulted in an ideal geomorphic condition for the formation of temporary ice-dammed lakes. Extensive low gradient (1°–2° slope) gravel surfaces dominate the mountain front geomorphology in this region and defy simple explanation. The geomorphic circumstances that occurred in tributaries to the West Branch Susquehanna River during middle Pleistocene glaciation are extremely rare and may be unique in the world. Failure of ice dams released sediment-rich water from lakes, entraining cobbles and boulders, and depositing them in elongated debris fans extending up to 9 km downstream from their mountain-front breakout points. Poorly developed imbrication is rare, but occasionally present in matrix-supported sediments resembling debris flow deposits. Clast weathering and soils are consistent with a middle Pleistocene age for the most recent flows, circa the 880-ka paleomagnetic date for glacial lake sediments north of the region on the West Branch Susquehanna River. Post-glacial stream incision has focused along the margins of fan surfaces, resulting in topographic inversion, leaving bouldery jökulhlaup surfaces up to 15 m above Holocene channels. Because of their coarse nature and high water tables, jökulhlaup surfaces are generally forested in contrast to agricultural land use in the valleys and, thus, are readily apparent from orbital imagery.

1. Introduction

A jökulhlaup is a glacier outburst flood that usually occurs when a glacially dammed lake drains catastrophically, or when there is a catastrophic release of water from a glacier. Jökulhlaups are common in Iceland, where subglacial volcanism triggers catastrophic episodic releases of meltwater (i.e., Costa, 1988a; Waitt, 2002; Carrivick et al., 2003; Carrivick, 2007). They also occur in nonvolcanic regions where they tend to occur from the temporary damming of unglaciated tributary valleys by glacial ice in the mainstream valley such as at Hidden Lake, Alaska (Anderson et al., 2003). In special cases, major ice lobes intersected mountain ranges to dam large rivers; a primary example being the Channeled Scabland Floods associated with the Glacial Lake Missoula jökulhlaups of the northwestern U.S.A. (Baker, 1973; Waitt, 1985). The geomorphic impact of jökulhlaups is typically huge as illustrated by the paleoflood landforms of the Channeled Scablands.

We report here on a geological setting and perhaps unique set of fluvioglacial conditions created by the movement of glacial lobes up tributary valleys to the West Branch Susquehanna River and by the distinctive structural geology of the region that provided conditions favorable for the formation of temporary ice-dammed lakes and subsequent jökulhlaups in central Pennsylvania (Kochel et al., 2003). Thin glacial lobes (~200 m thick) flowed upslope into the Buffalo Valley from the West Branch Susquehanna River and intersected a series of en-echelon sandstone ridges formed by eastward-plunging anticlines (Fig. 1). Headwater streams emerging from the mountains between the plunging folds were temporarily dammed by the ice. Jökulhlaups were released as these temporary ice dams failed resulting in a distinctive suite of landforms visible from orbital imagery (Fig. 1) and whose legacy remains significant in the geomorphic evolution and land use history of the region today.

Sediment-rich flows created from the jökulhlaups occurred because of the interaction of periglacial and glacial processes. These events created a series of elongated debris fans composed of matrix-supported gravel resembling debris flow deposits, but these deposits were emplaced on exceptionally shallow gradients that are well below the slopes required for normal debris flow transport (Fig. 2). Post-glacial fluvial incision resulted in topographic inversion of some of the jökulhlaup surfaces because their coarse sandstone fill armored them, causing streams to downcut in softer shales along their margins. The

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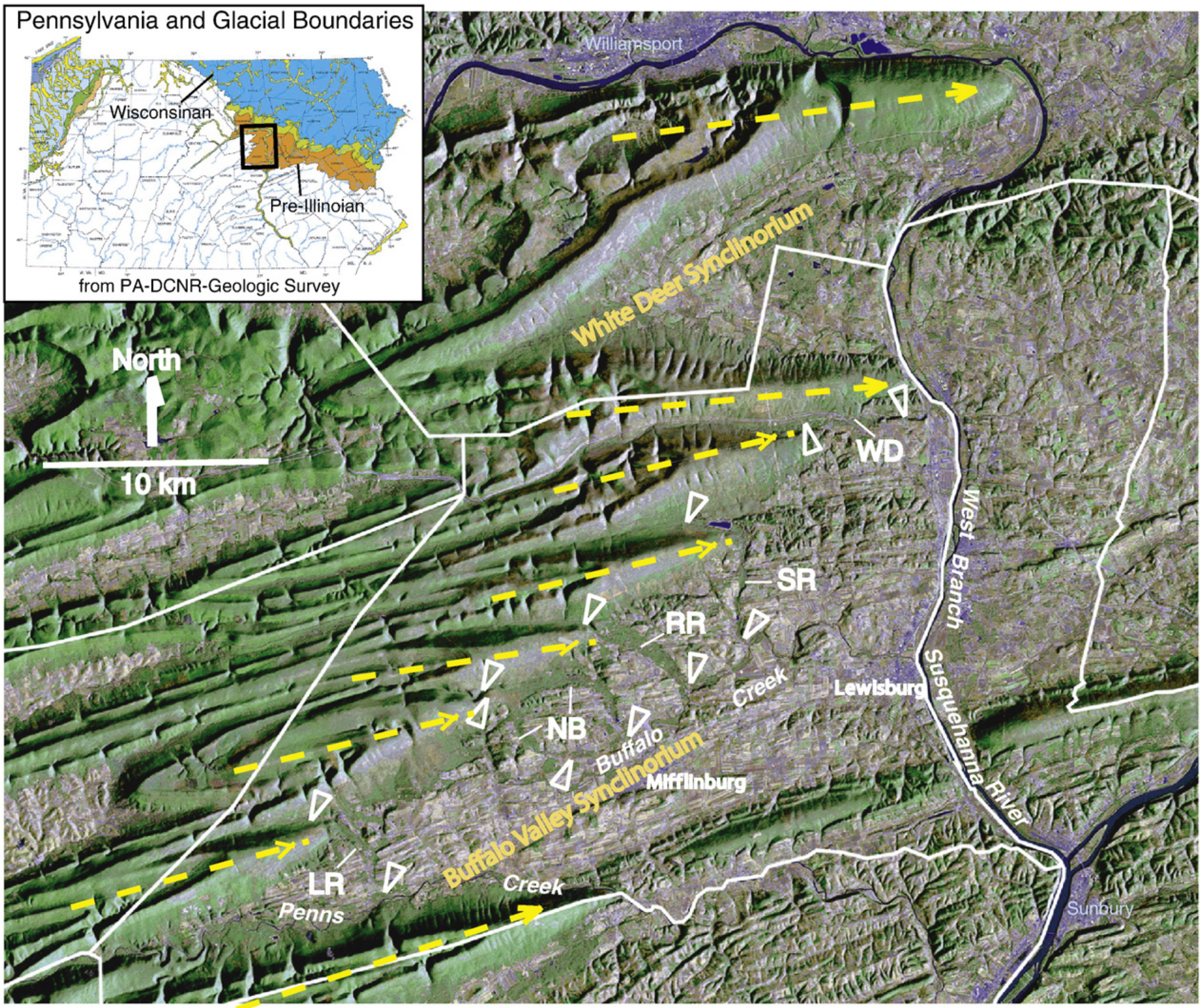

Fig. 1. Orbital image of north-central Pennsylvania showing the West Branch Susquehanna River. Note the series of eastward-plunging folds (dashed arrows) and the jökulhlaup surfaces discussed here (white triangles — WD = White Deer Creek, SP = Spruce Run, RR = Rapid Run, NB = North Branch Buffalo Creek, LR = Laurel Run). Landsat 7 image courtesy of NASA/PASDA (Pennsylvania State Digital Access). Solid white lines are county boundaries.

impact of the flows has been significant in the evolution of mountain-front geomorphology in this section of the Valley and Ridge. These catastrophic floods likely played a role in the evolution of macro-tubulent erosional development of the lower gorge of the Susquehanna River located more than 150 km downstream. The middle Pleistocene landforms produced by these floods still dominate the geomorphology of the region today and are readily visible from orbital imagery (Fig. 1).

2. Regional setting

2.1. Pleistocene geology of north-central Pennsylvania

2.1.1. Glaciation

The impact of Pleistocene climate changes have been significant in north-central Pennsylvania, including numerous episodes of glaciation and extensive periglacial activity on the ridges and hillslopes (Peltier, 1949; Denny, 1956; Braun, 1989; Marchand and Crowl, 1991). Late Pleistocene glaciers advanced over significant portions of the Appalachian Plateau north of Williamsport (Fig. 1), but failed to cover the ridges to the south in the Valley and Ridge. Middle Pleistocene glaciers were more extensive but also failed to cover the ridges south of Williamsport. Evidence of these earlier, more extensive ice advances is widespread in the form of extensively weathered till, subdued moraines, and glacial lake deposits in the West Branch Susquehanna River (Peltier, 1949; Bucek, 1976; Marchand and Crowl, 1991). Investigations of weathering and soil development on these sediments suggest a middle Pleistocene age for these deposits (Peltier, 1949, Marchand and Crowl, 1991). Intersection of these ice lobes with Bald Eagle Ridge (the northernmost of the large Ridge and Valley folds) temporarily dammed the West Branch Susquehanna River at Williamsport, resulting in an extensive lake, Glacial Lake Lesley (Bucek, 1976). Paleomagnetic evidence indicates this lake dates to ~880,000 BP (Ramage et al., 1998), supporting the pedogenic interpretations for a middle Pleistocene age for the till. More extensively weathered tills have been observed in some locations

Fig. 2. Quaternary deposits in Buffalo Valley, Union County, Pennsylvania; including jökulhlaups, ice dammed lakes, till, and terraces. Jökulhlaup surfaces (orange) extend downstream from the mountain-fronts of White Deer Creek (WD), Spruce Run (SR), Rapid Run (RR), North Branch Buffalo Creek (NB), and Laurel Run (LR). An extensive Late Pleistocene debris fan (brown) occurs near the head of Buffalo Creek and a smaller one on Stony Run. Significant middle Pleistocene till deposits are shown (pink), while scattered thin till occurs throughout the valley region. The approximate limit of the middle-Pleistocene ice (pink dashed line), which advanced from the ENE between the two branches of the Susquehanna River, is modified from Marchand and Crowl (1991). Alluvium (yellow) is undifferentiated middle Pleistocene to Holocene because of the map scale; however, our detailed mapping has identified several middle Pleistocene terraces and at least one post-jökulhlaup-age terrace along Penns Creek and Buffalo Creek.

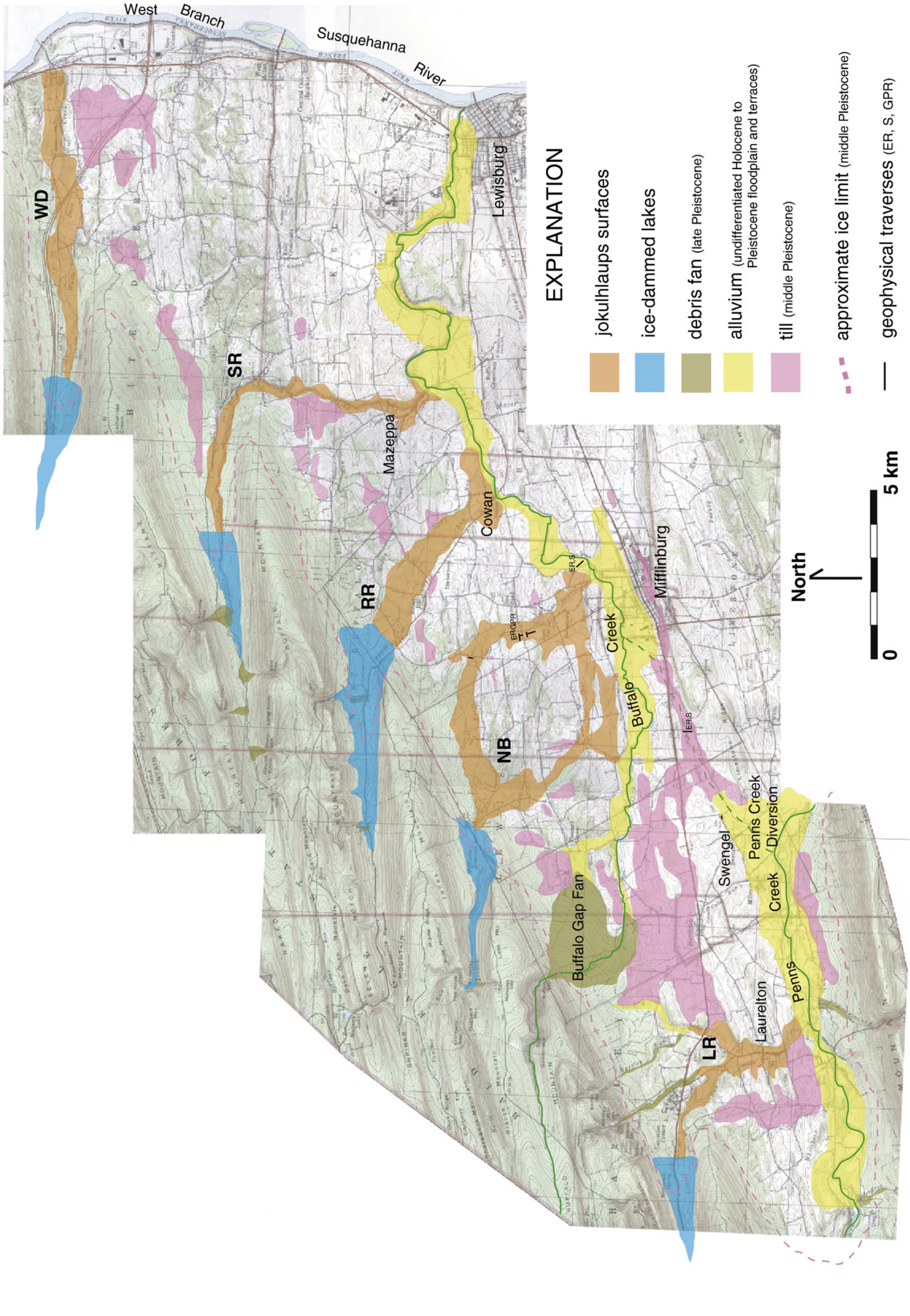
West Branch Susquehanna River
Lewisburg
WD
SR
Mazeppa
Cowan
RR
Mifflinburg
Buffalo Creek
NB
Buffalo Gap Fan
Swengel
Penns Creek Diversion
Penns Creek
Laurelton
LR
ER,S
ERGPR
EXPLANATION
jokulhlaups surfaces
ice-dammed lakes
debris fan (late Pleistocene)
alluvium (undifferentiated Holocene to Pleistocene floodplain and terraces)
till (middle Pleistocene)
approximate ice limit (middle Pleistocene)
geophysical traverses (ER, S, GPR)
North
0
5 km

Fig. 3. Middle Pleistocene terminal moraines in western Buffalo and Penns Creek. (A) View northeastward from Swengel of the short outwash plain and terminal moraine in the distance was formed during the diversion of Penns Creek to the south. (B) Hummocky surface of boulder-rich terminal moraine west of Laurelton. (C) View of the orange soil and till in the terminal moraines west of Laurelton (view is along the road shown in Fig. 3D). (D) Hummocky surface of terminal moraine complex west of Laurelton.

(Peltier, 1949; Marchand and Crowl, 1991) indicating there may have been several middle to early Pleistocene ice advances down the West Branch of the Susquehanna River.

Although these middle Pleistocene glaciers did not cover the ridges south of Williamsport, they did extend several tens of kilometers southward into the Valley and Ridge as relatively thin glacial lobes along the West Branch Susquehanna River (Fig. 2). Extensive weathered moraines occur in the valleys of Buffalo Creek and Penns Creek, marking the upvalley extent of these ice lobes that were sourced by the glacier moving south along the West Branch Susquehanna River (Fig. 3). Middle Pleistocene till has been reported at least 10 km south of the confluence of the branches of the Susquehanna River at Sunbury (Peltier, 1949; Marchand and Crowl, 1991; Sevon and Braun, 1997). Widespread till and glacial landforms in tributary valleys to the Susquehanna (such as White Deer Creek, Buffalo Creek, and Penns Creek) show that portions of the Susquehanna glacial lobe moved significant distances up these tributary valleys (Fig. 2). These ice lobes resulted in significant drainage adjustments and valley alteration in some locations. For example, a lobe of the ice dammed the former channel of Penns Creek, depositing a moraine just SW of the village of Mifflinburg (Fig. 2). Prior to this, Penns Creek joined Buffalo Creek at the western edge of Mifflinburg. The till now buries the former channel of Penns Creek, which was detected in geophysical surveys (Fig. 4), and diverted Penns Creek southward across a low divide into a new valley near Swengel. Four major terraces occur along Penns Creek upstream of Swengel. The two older terraces do not make the turn southward at Swengel but continue eastward until they are lost in the outwash and moraines deposited by the ice lobe that deflected Penns Creek. The two younger terraces follow Penns Creek southward toward Selinsgrove and the Susquehanna River, having formed later in the Pleistocene following the drainage diversion. Studies of soil chronosequences (Malonee, 2001) are consistent with a middle Pleistocene age for the upper terraces and a Late Pleistocene age for the lower ones.

Eventually, the upvalley-moving ice intersected the plunging folds and headwater streams emanating from the ridges, where they formed temporary ice dams and lakes at the mountain front (Figs. 1 and 2). Structural features lead to the unique presence of headwater lakes dammed against middle Pleistocene glacial lobes. In this region the north limb of the major Buffalo Valley synclinorium, trending N. 60° E., is the physiographic expression of the resistant Tuscarora Sandstone, dipping SE into the valley containing less-resistant shales, sandstones, and limestones of Silurian and Devonian age. On this SE-dipping limb there are five en-echelon minor anticlines with crest-to-crest wavelengths of 3 km that plunge toward N. 70° E. The eroded synclinal valleys in this system contain small NE-flowing streams of varying discharge, some of which spawned significant lakes against the glacial ice dams. Other SE-dipping limbs of major synclinoria in the region do not contain the array of minor folds that have been so important in creating the fluvial environment for the different-sized

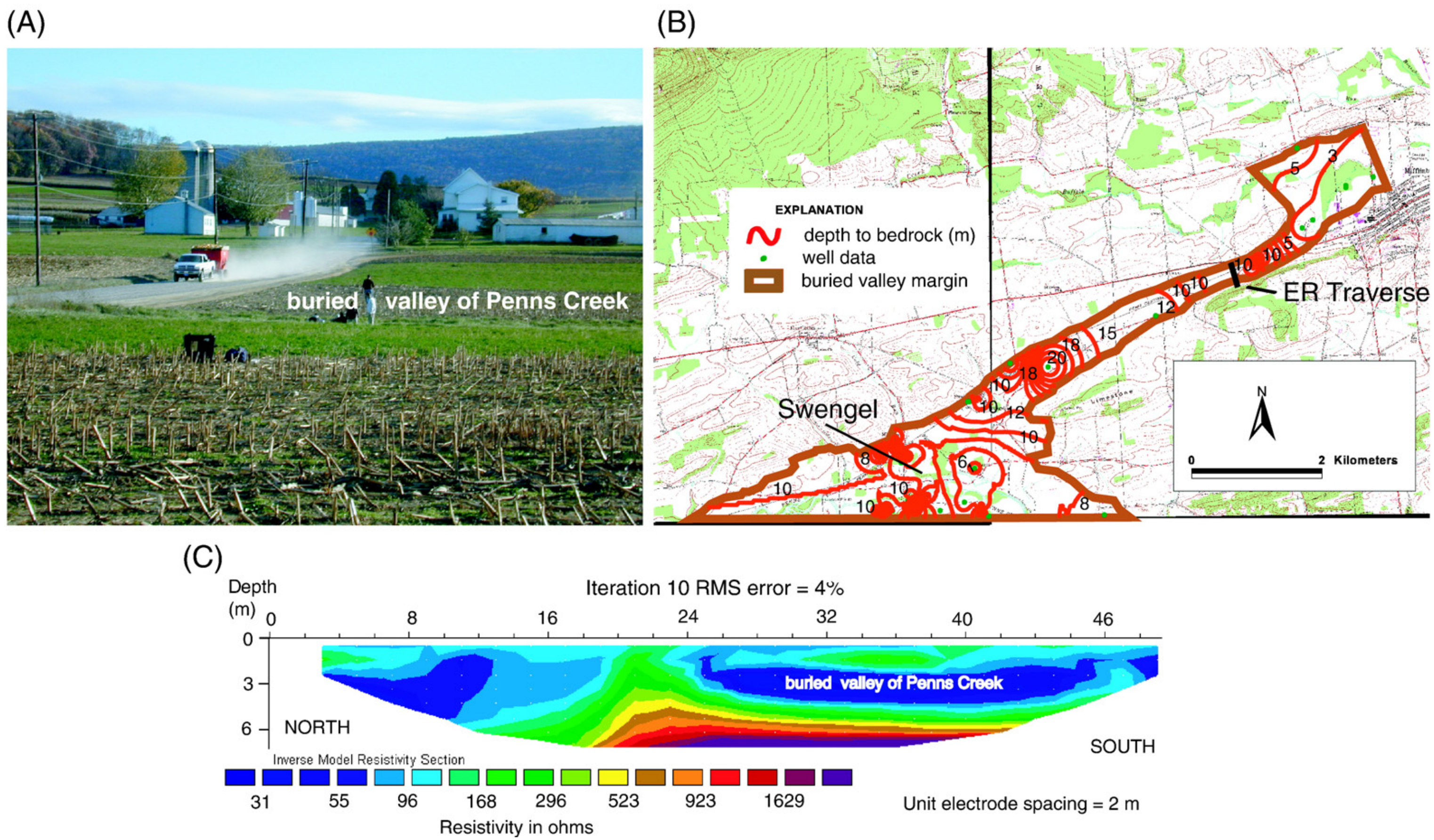

Fig. 4. Buried paleochannel of Penns Creek. The middle Pleistocene ice lobe, advancing upvalley from the east, blocked the former channel of Penns Creek NE of Swengel (moraine), diverting it southeastward from Swengel over a low divide, and burying the former course of Penns Creek through this valley toward Buffalo Creek at Mifflinburg. (A) Seismic and electrical resistivity survey across the former valley of Penns Creek. View is to the south along the N to S ER Traverse line in Fig. 4B. The former course of Penns Creek is in the swale near the center of the photo. (B) Map of the buried valley formerly occupied by Penns Creek. The two oldest (of four) terraces of Penns Creek stop abruptly as they head northeastward into this valley from Swengel (Malonee, 2001), erased by the till deposited in the moraine and subsequent outwash. Two younger terraces along Penns Creek follow its current course to the south. Note the wide expanse of alluvium near Swengel where this diversion took place. (C) Electrical resistivity survey running north-south across the buried valley of Penns Creek. The buried valley appears as the dark oval between 2 and 5 m depth and is buried by ~2 m of till and outwash sediment.

ice-dammed lakes. Specifically, the next synclinorium to the north, the White Deer synclinorium (which was also occupied by a glacial lobe) did not have any small en-echelon folds that would have served as a focus for ice-dammed lakes. We have found no evidence that jökulhlaups were generated along the SE-dipping limb of the White Deer synclinorium. Apparently, the ice was unable to completely dam the stream emanating from this large synclinal valley. The glacial lobes that flowed toward the SW upgradient into both the Buffalo valley and the White Deer synclinorium valley were unable to surmount the ridges to the west and north that stood over 300 m above the valley floor. The elevations of the till observed in Buffalo, White Deer, and Penns Creek valleys indicate that ice thickness in these Susquehanna tributaries was ~200–250 m.

Temporary ice-dammed lakes formed where the major tributaries to Penns Creek and Buffalo Creek emerge from the mountain front in this region. Significant are the lakes at the emergence of West Branch Buffalo Creek, Rapid Run, Laurel Run, and Spruce Run (Fig. 2). Some ice damming also occurred where White Deer Creek exits the mountain front 10 km NE of Spruce Run. The ice dam at White Deer Creek, however, does not appear to have fully blocked the stream. Thus, its lake and subsequent jökulhlaups are not as extensive as they are for some of the tributaries to the west in Buffalo Creek. It is unclear why damming of White Deer Creek was less extensive, but may have been related to the flow vector of the glacial ice toward the SW, slightly bypassing this valley because of deflection toward the south around the easternmost anticlinal ridge just to the north of White Deer. The jökulhlaup events deposited extensive elongate debris fans along the piedmont zones of these headwater streams, creating the bouldery surfaces that are the subject of this paper.

2.1.2. Periglacial activity

Throughout the Pleistocene glacial intervals, extensive periglacial activity affected the ridgetops and hillslopes of the Valley and Ridge south of Williamsport (Peltier, 1950; Marsh, 1987; Braun, 1989, 1994; Bunting, 2005). Extensive blockfields, stone stripes, and thermokarst features are widespread across hillslopes in this region (Fig. 5). Gelifluction and thermokarst decay processes were probably extensive during these periglacial climates, delivering large volumes of sediment to headwater tributary streams. Relict gelifluction lobes are common as undulatory benches throughout the region. Debris fans at the mouths of small headwater streams unaffected by direct ice contact show significant terracing, likely the result of the influence of gelifluction activity. Pleistocene debris fans are common throughout central Pennsylvania (Berntsen, 1993). Terracing is particularly well developed on debris fans with south-facing aspects throughout the region.

3. Jökulhlaups

3.1. Jökulhlaup surfaces and landform geometry

Deposits from the jökulhlaups appear as smooth elongated, low-gradient, bouldery, fan-like surfaces (linear forested zones in Figs. 1, 2, 6, 7 and 8) extending away from the mountain-front locations of

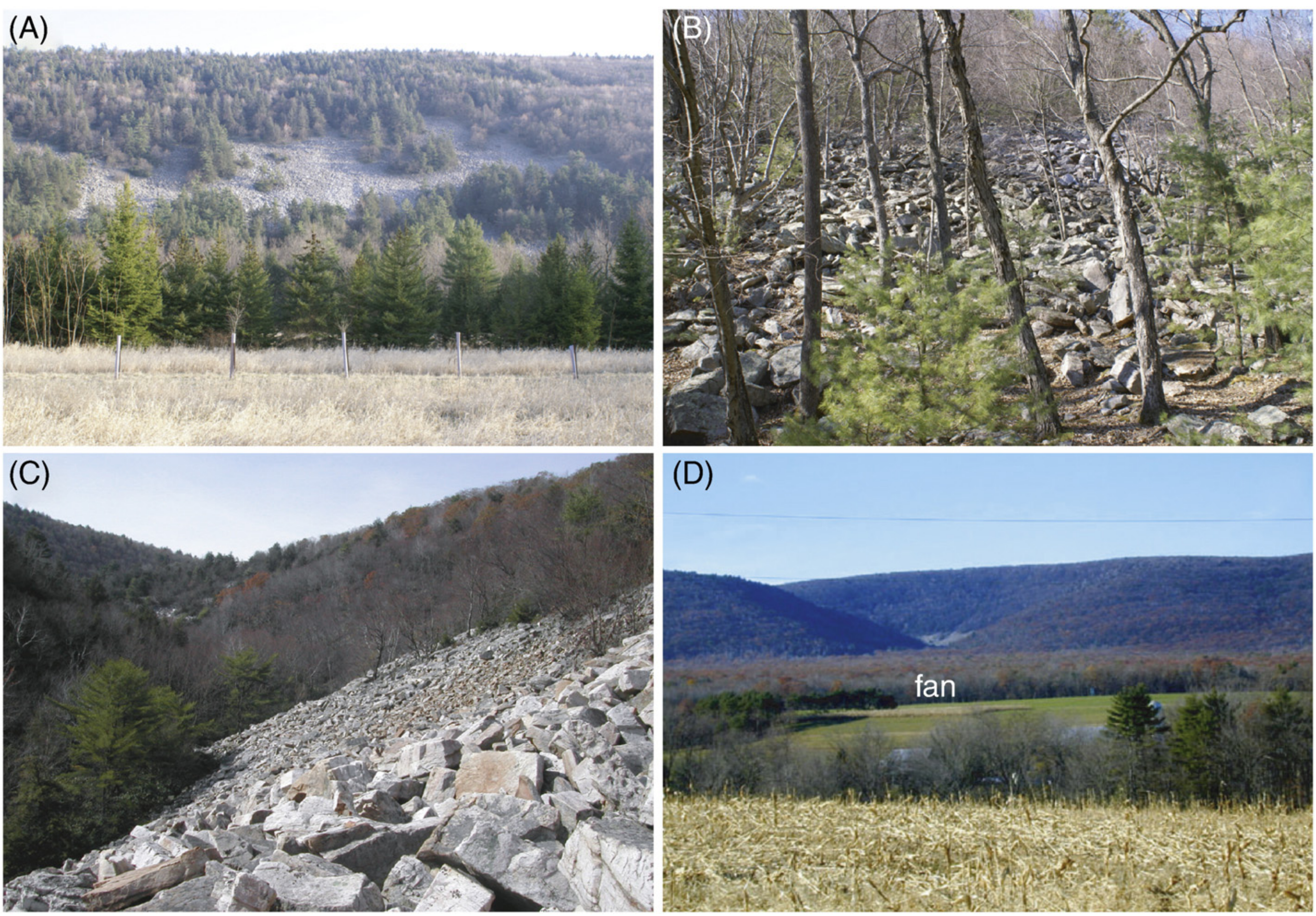

Fig. 5. Examples of periglacial features in the region. (A) Large blockfield on north-facing slope along Penns Creek west of Weikert. (B) Stone stripes along the upper slopes of Stony Run watershed near Laurelton. (C) Blockfield on south-facing slope (north-facing slope also has a major blockfield) in Buffalo Gap. (D) Large late Pleistocene debris fan emanating from Buffalo Gap, where the headwaters of Buffalo Creek exit the mountain front north of Hartleton. These slopes show the widespread abundance of periglacial colluvium typical of the areas upstream of the ice-dammed lakes that likely contributed much sediment to the sediment-rich jökulhlaups.

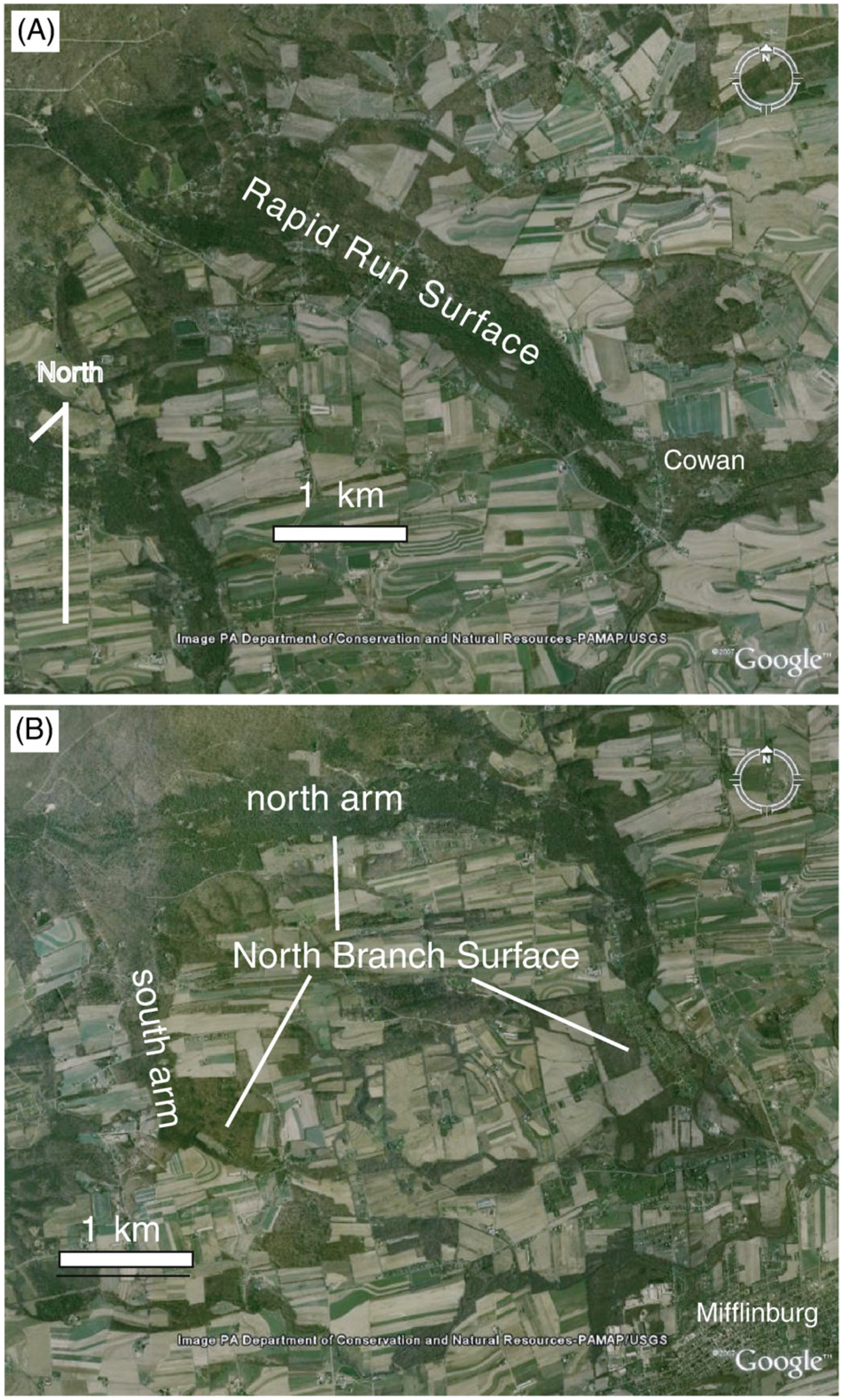

Fig. 6. Jökulhlaup surfaces viewed from the air in vertical air photos. Flow of both jökulhlaups was from NW to SE. (A) Rapid Run surface. (B) North Branch surfaces (2006 photos courtesy PA-DCNR).

major tributaries to Buffalo Creek and Penns Creek in Union County. It is important to note that although the jökulhlaup deposits now occur in both watersheds they were within a single watershed prior to the middle Pleistocene glaciation that produced them. At that time, Penns Creek joined Buffalo Creek along the western margin of Mifflinburg (Figs. 1 and 2).

The elongate jökulhlaup surfaces extend between 5 and 9 km from their mountain-front source and are up to 1 km in width (Fig. 6). In most cases, the deposits fill the valley from one wall to the other and are singular. However, the deposit from North Branch Buffalo Creek is more complex and branches into two surfaces separated by up to 3 km. Post-depositional modifications and stream captures have masked some of the original extent of the North Branch surface that appears to have at been formed by at least two phases of activity. Observations of weathering indices do not reveal significant differences, suggesting that the ages of the two arms of the North Branch surface are not

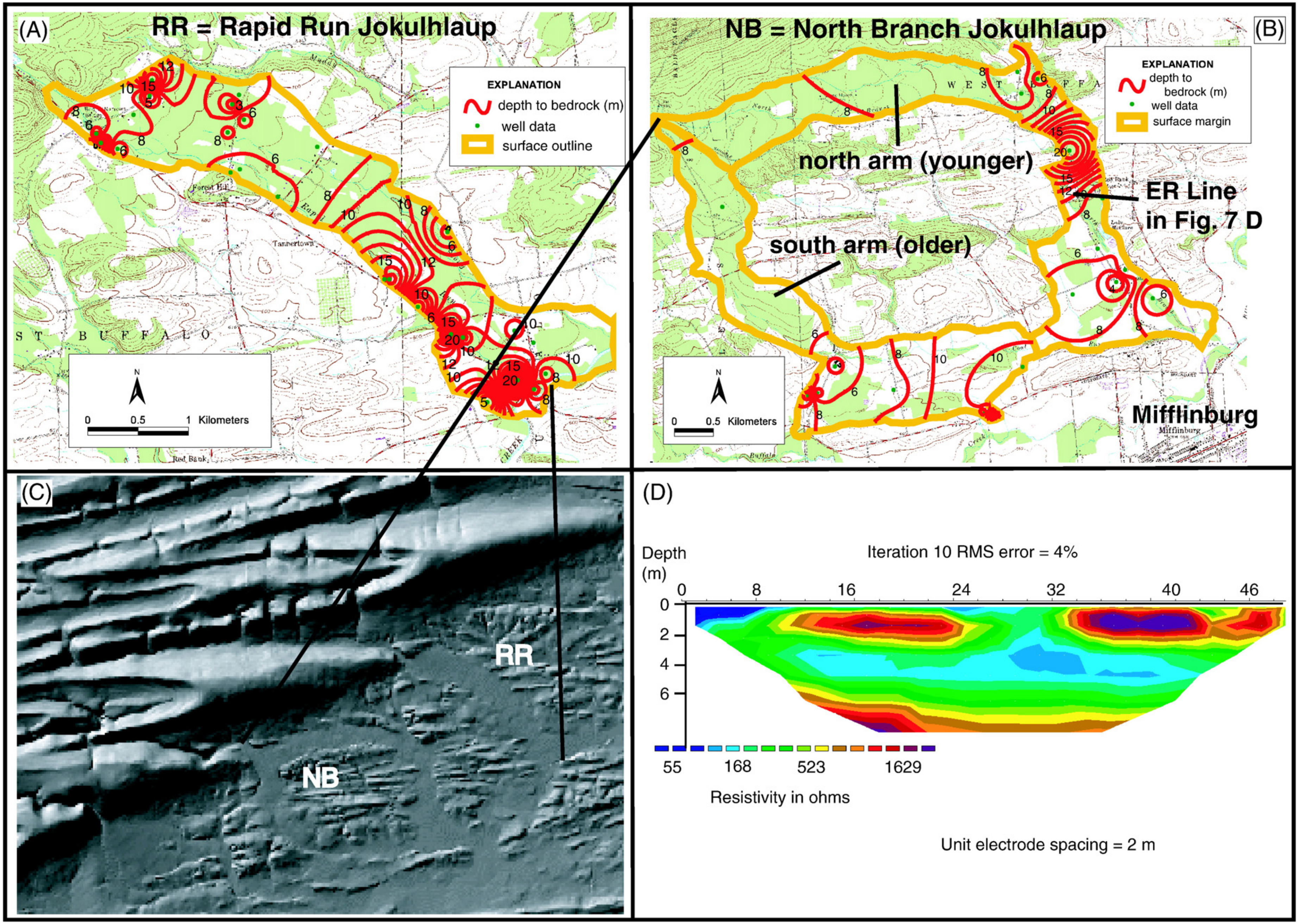

Fig. 7. Isopach maps of typical jökulhlaup surface thicknesses based on water well data. Well logs and electrical resistivity surveys indicate that average thickness of the deposits is ~10 m. (A) Rapid Run surface. (B) North Branch Buffalo Creek surfaces. (C) DEM hillshade view of Rapid Run (RR) and the bifurcated North Branch (NB) jökulhlaup surfaces. (D) Model of the electrical resistivity survey across North Branch surface (line shown in Fig. 7B and photo 8B).

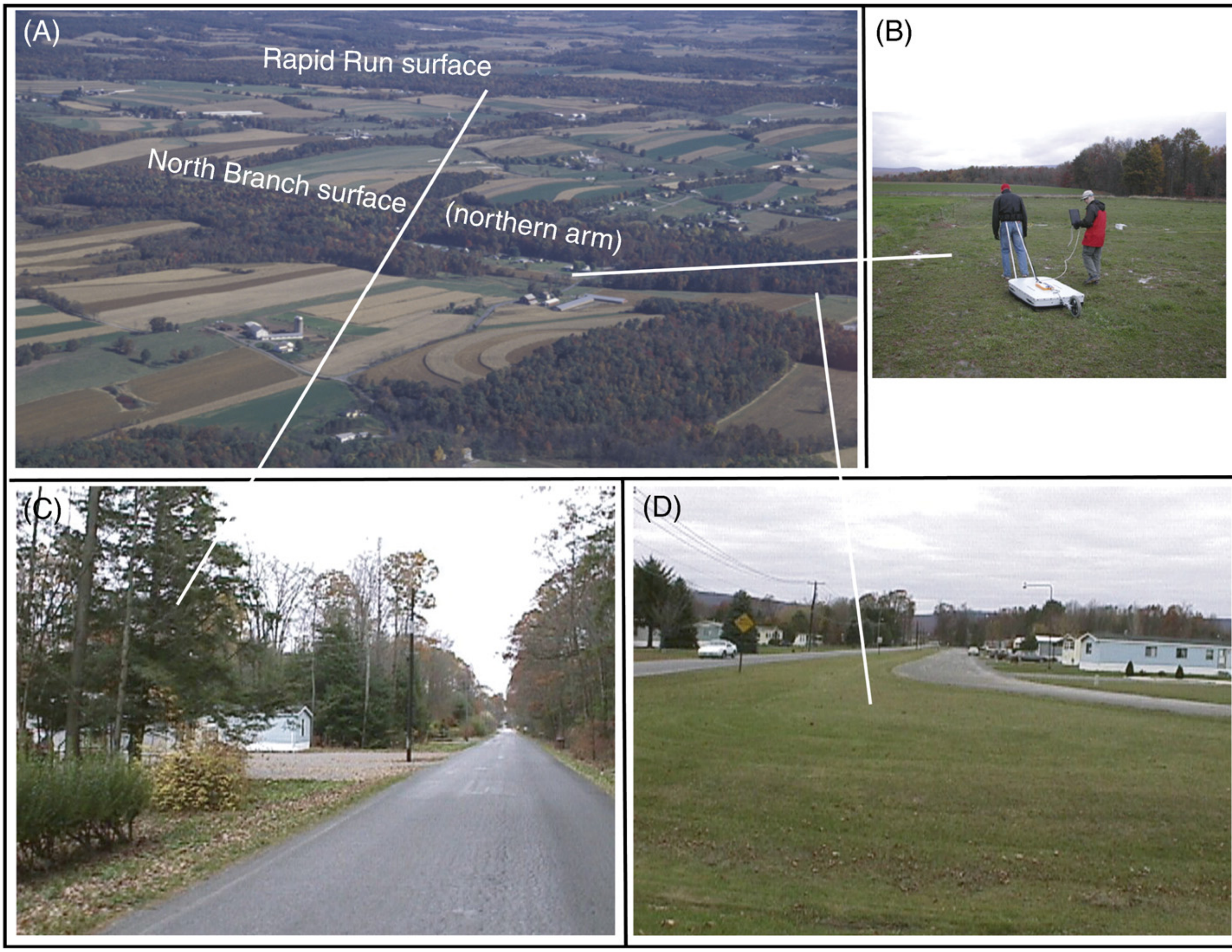

Fig. 8. Jökulhlaup surface morphology. (A) Oblique aerial view of part of the northern segment of the North Branch surface (foreground) and Rapid Run surface (background). (B) Electrical resistivity survey across North Branch surface at the location shown in Figs. 7B and 8A. (C) View across the Rapid Run surface near Forest Hill. Here, the surface is 1.2 km wide. (D) View upslope of the North Branch surface just north of Mifflinburg near Johnstown.

greatly different. Many of the jökulhlaup surfaces are quite distinctive in aerial and orbital imagery because they are continuous forested regions extending from the mountains through an otherwise agricultural area (Figs. 1 and 6). Their coarse nature (locals refer to these surfaces as stone runs) and high water tables have rendered them difficult-at-best for farming and residential uses. Note the wide spacing of the contours in Fig. 2 on the jökulhlaup surfaces. The axial gradient of these jökulhlaup surfaces averages 1–2°, making them very distinctive in an otherwise hilly topography (Fig. 8). This low gradient will be addressed later in discussions related to emplacement processes.

3.2. Volumes of ice-dammed lakes and jökulhlaups

A combination of selected geophysical surveys, excavations, and household well records shows that the jökulhlaup deposits average about 7 to 10 m in thickness, with isolated pockets up to 20 m thick (Fig. 7). Fig. 7D shows an electrical resistivity survey along the northern segment of the North Branch Buffalo Creek deposit, which is fairly typical of several such surveys that have been made in the region. Because of the abundance of a fine-grained matrix in these sediments, ground penetrating radar surveys proved relatively uninformative. Table 1 provides estimates of the aerial extent and volume of these ice-dammed lakes, peak discharge, and volume or the associated jökulhlaup sediments. The lake on Rapid Run was the largest, having a volume of nearly 1 km^3. Lake depths averaged between 70 and 80 m, with depths at the ice dams averaging between 120 and 140 m. Estimates of peak discharge are rough at best, based on comparisons to historical observations of jökulhlaups. The duration for emptying the lakes is thought to have been rapid. Eskilsson et al. (2002) showed that the large jökulhlaup in 1996 at Skeiarsandur, Iceland drained in less than 48 h. Peak discharge was estimated assuming most of the flow was discharged in 48 h, following a hydrograph similar in shape to the one observed by Eskilsson et al. (2002). Discharge estimates are in the

Table 1
Estimated dimensions of the ice-dammed lakes and associated jökuhlaups.

Fan	Approx. lake volume (km^3)	Approx. lake depth (m)	Approx. lake area (km^2)	Peak discharge (cms)*	Mean sediment size (mm)	Fan slope	Fan sediment volume (km^3)
Rapid Run	0.973	90	6.61	16,500	210	0.0129	0.07
North Branch	0.215	60	3.56	4800	200	0.0135	0.09
Spruce Run	0.27	70	3.41	3000	230	0.0075	0.03
Laurel Run	0.73	80	6.43	11,500	180	0.0148	0.03
Stony Run	0.09	50	1.71	2100	190	0.042	0.008

*Peak discharge estimated based on assumption of draining the lakes in 24 h, using the jökuhlaup breakout model summarized in Costa (1988a) and following a hydrograph similar to that observed for the 1996 jökuhlaup in Iceland by Eskilsson et al. (2002).

range expected using jökulhlaup breakout models based on the relationship between lake volume and dam height shown as a compilation of studies by Costa (1988a). The ice-dammed lakes were not large, nor were their paleoflood discharges exceptional, but, the volume of coarse sediment deposited and its influence on the geomorphology of the region was significant. The summation of peak flows from the jökulhlaups described here exceeds that of the largest historical flow recorded ~150 km downstream on the Susquehanna River (at Holtwood) in 1972 from Hurricane Agnes.

3.3. Rapid Run surface

The largest and best preserved of the jökulhlaup surfaces is the one in Rapid Run (Figs. 1, 2 and 6). Most of this surface is forested with spotty low-density home development. The Rapid Run surface extends for more than 6 km until it merges with the upper of two terraces of Buffalo Creek at the village of Cowan (Figs. 2 and 6). There, sediment influx appears to have caused significant aggradation of Buffalo Creek, as evidenced by a notable flattening of its gradient for several kilometers upstream (Fig. 9A). The volume of coarse gravel input from Rapid Run appears to have played a major role in the creation of a thin fill terrace downstream for at least 4 km along Buffalo Creek. The Rapid Run deposit is widest (1.2 km) near its upstream emergence from the mountains, where it attains full width abruptly, and narrows to 0.8 km just before it merges with Buffalo Creek. The Rapid Run surface is strewn with sandstone boulders and is

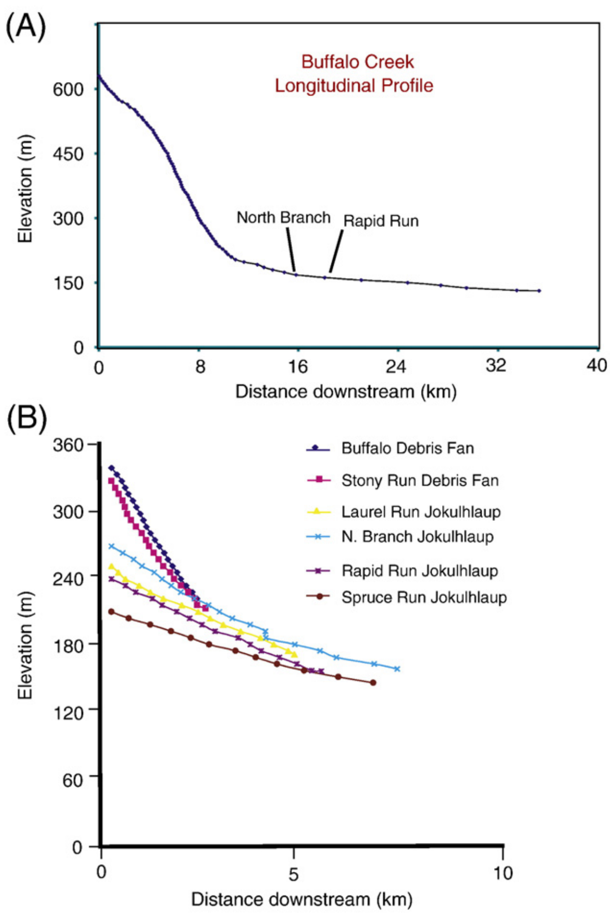

Fig. 9. (A) Longitudinal profile of Buffalo Creek. The moderately-sloping segment is the large debris fan where the creek exits the mountain-front. Note the slight shallowing of gradient between North Branch and Rapid Run, and the slight steepening downstream. (B) Longitudinal profiles of tributaries, and related features. Quaternary debris fans are common in the region, normally having slopes between 6 and 12° (Berntsen, 1993), while jökulhlaup surfaces average 1–2°.

exceptionally smooth (Fig. 8C). Rapid Run and a series of small, subparallel tributaries have barely incised into its surface. Intense rainfalls typically result in the inundation of much of the surface as these channels rapidly flow over their low banks of <1 m.

3.4. North Branch Buffalo Creek surface

The surfaces formed by the jökulhlaups from North Branch Buffalo Creek are volumetrically the largest of the deposits described here (Fig. 7B and C). However, because of their complex history and post-depositional evolution, they are more discontinuous than the Rapid Run surface. The North Branch surface appears to have had at least two major episodes of formation, resulting in a northern and southern arm, separated by a broad area (several kilometers) of exposed bedrock with minor post-glacial drainage development and scattered till (Figs. 2, 6B, 7B, C). The northern segment is the most distinct and continuous, extending in a 9-km E–SE arc from the mountain front to its confluence with Buffalo Creek just north of Mifflinburg. Like its counterpart on Rapid Run, the North Branch surface is quite bouldery, of low gradient, and supports a system of shallowly incised braided channels during high flow. The northern segment is mostly forested, has a few low-density home developments, and is drained by the braided North Branch Buffalo Creek channels which have barely incised into its surface. The southern segment of the North Branch surface is less well defined and flows south and then SE until it joins the upper terrace of Buffalo Creek a few kilometers west of Mifflinburg (Figs. 2 and 7B, C). Because of the middle Pleistocene age of both segments, it is difficult to discern differences in the weathering of clasts or soil development between the northern and southern flows. The southern segment appears to be the oldest, supported by its position 2–3 m above the northern segment at its origin and its more dissected nature related to post-glacial stream piracy and erosion. Most of the southern segment is also forested, but lacks a well-defined stream like the other jökulhlaup surfaces. This segment was probably the path of an earlier North Branch jökulhlaup, which later shifted eastward to form the northern segment. Sediments from the southern segment can be traced eastward across a paleochannel of Buffalo Creek where it rejoins the northern segment at the village of Johnstown (Figs. 2, 7 and 8), 1.5 km upstream from its confluence with Buffalo Creek. Some of the sediment from the southern segment also flowed directly into Buffalo Creek west of Mifflinburg. This region has been extensively modified by post-glacial erosion and drainage development since the middle Pleistocene. As a result, the original bed of the southern jökulhlaup now occupies minor divides in the region in some of its downstream reaches. Evidence of the former valley floor are the deposits of rounded Tuscarora Sandstone boulders as thin terraces on these low divides. Post-glacial streams have incised along the margins of the bouldery fill, finding it easier to erode the soft shales of the valley floor bedrock.

3.5. Other jökulhlaup surfaces

Although less extensive, similar elongate bouldery jökulhlaup surfaces occur downstream from the mountain fronts along White Deer Creek, Spruce Run, and Laurel Run (Figs. 1 and 2). The White Deer jökulhlaup surface is relatively narrow, extending along the lower 6 km of the stream. No till or other direct evidence of the middle Plesitocene ice has been observed at elevations close to those where tills are found in tributaries to the west. Therefore, even though the White Deer watershed is larger than Spruce Run, Rapid Run, and North Branch Buffalo Creek watersheds, its jökulhlaup surface is relatively small. Apparently, the ice was unable to form a significant or long-enough-lasting dam to create a large lake here. There is, however, evidence of two jökulhlaup events in White Deer Creek. A small remnant of an older surface occurs near the upstream edge of the deposit along the north side of the creek. The older deposit is about 4 m above the more extensive younger jökulhlaup surface.

The Spruce Run surface (Figs. 1 and 2) is significantly narrower than the Rapid Run or North Branch surface because it occurs along a reach incised into more resistant sandstone bedrock along the plunge-out of one of the anticlines. Upstream of the sharp bend in the surface, the deposit appears to be between 0.5 and 1 km wide, but much of it is masked by a large reservoir. The lower kilometer of the Spruce Run surface widens again to more than 0.5 km before it merges with the upper terrace of Buffalo Creek at the village of Mazeppa.

The jökulhlaup surfaces along Laurel Run near the western margin of the study area (Figs. 1 and 2) are much smaller and are tributary to the now separate Penns Creek watershed. These surfaces are typically <0.25 km wide, but extend several kilometers downstream to Penns Creek. The smaller size of these surfaces reflects the significantly smaller drainage basin areas of these tributaries located along the terminal morainal belt from the glacial lobe.

The surface in Stony Run (Fig. 2) has a slightly higher gradient ranging from 4 to 6° (Fig. 9B) and may have formed as a simple debris fan fed by gelifluction sediments, without having an ice-dammed lake and jökulhlaup. The lower 2 km of the Stony Run surface abruptly levels to 1–2°, and appears similar to other jökulhlaup surfaces in the region before it grades into the Laurel Run jökulhlaup surface at the north edge of the village of Laurelton.

3.6. Sedimentology

Information on the sedimentology of the jökulhlaups deposits comes from a variety of sources, including observations of terrace and bank exposures; shallow excavations for homes, highway drainage ditches and pipelines; water well records; and isolated geophysical surveys, including electrical resistivity, ground penetrating radar, and seismic refraction. The jökulhlaup deposits are generally matrix-supported bouldery gravels with indistinct stratification (Fig. 10). Rare, poorly developed imbrication was noted in some exposures, but overall no fabric developed in these sediments. Similar matrix-supported sediments occur in jökulhlaups deposits formed on a 2–3° gradient along the southern coast of Iceland (Fig. 10D). Recent studies

Fig. 10. Sediments in the jökulhlaup deposits. (A) Bouldery surface of the Rapid Run jökulhlaup upstream of Cowan. (B) Trench excavated in the North Branch Buffalo Creek surface north of Mifflinburg. Note the poor sorting and matrix support. (C) Sediment piled from a home foundation excavated in North Branch Buffalo Creek surface north of Mifflinburg. (D) Similar matrix-supported sediment from the 1996 jökulhlaup deposits of Skeidarsandur, Iceland.

in Iceland have discussed the occurrence of matrix-supported gravels formed by fluidized flows similar to those described here (Kudsen and Russell, 2002; Marren, 2002; Rushmer, 2006; Carrivick, 2007) Clasts are composed primarily of rounded to subrounded very resistant Tuscarora Sandstone with minor amounts of Bald Eagle Sandstone. Clast size varies, but most average 15 to 25 cm in intermediate axis diameter. Larger clasts with intermediate diameters between 35 and 40 cm are not uncommon. Matrix sediment is a mix of sand and clay. Much of the clay appears to be pedogenic, giving the deposits (as well the till of similar age) a distinctive orange color with B horizon color in the 5 YR to 2.5 YR hue range. Clast size is somewhat greater for the most of the upstream deposits to the west (Laurel Run and Stony Run). Although no stratification has been recognized in any of the excavations, some foundation trenches reveal two distinctive deposits of similar nature separated by a moderately well-developed paleosol. No fine-grained units have been observed in any of the excavations, some of which penetrated 3 m into the gravels, suggesting that the jökulhlaup sediments were deposited by single, rapid sedimentation events.

3.7. Transport flow mechanics/emplacement processes

Deposition of the sediments in these surfaces appears to be from breakout floods, or jökulhlaups, related to catastrophic failure of small mountain-front lakes dammed by ice from the glacial lobe that was advancing westward up Buffalo Creek valley. The exact nature of the flow mechanics and emplacement of the sediment is less certain. The sedimentology of the jökulhlaup deposits is consistent with that of debris flow, probably at the water-rich end of the spectrum approaching that of sediment-rich hyperconcentrated flow (Costa, 1988b). The difficulty with a debris flow emplacement process is the low gradient present on these landforms. Debris flow runout generally ceases at slopes of 7–8° because of the deformation dynamics of these Bingham flows (Johnson, 1970; Costa, 1988b; Ritter et al., 2006). The steepest of the surfaces attains a gradient of about 4°, but the larger surfaces have slopes $<2°$.

Clearly the jökulhlaups were highly sediment-charged. The abundance of landforms reflecting active periglacial processes on hillslopes in the area (blockfields, stone stripes, gelifluction lobes, and thermokarst features) is strongly suggestive that large volumes of ice-rich sediment were delivered to the temporary ice-dammed lakes prior to their breakout floods. It is less clear whether catastrophic breakout floods could have transported the sediment with the rhealogy of a debris flow on the low valley gradients. Discussions with Richard Iverson (U. S. Geological Survey, personal communication, 2003) confirmed that it may have been possible to develop high basal pore-water pressures downstream of the ice dams because of permafrost during the glacial advance. This situation, combined with a likely high volume of ice in both the lake water and ice incorporated along the flow route from the catastrophically disintegrating glacial dam, may have provided a mechanism for rapid emplacement of these sediment-charged, slushy flows on these low gradients. It is also possible that warming during the glacial disintegration may have triggered widespread hillslope water and sediment additions to the lakes in the form of flows similar to the slush avalanches described in high latitude periglacial regions (Rapp and Nyberg, 1981; Nyberg, 1989). In any case, the jökulhlaup flows appear to have been similar to viscous debris flows but moving on an extraordinarily low gradient. Although subaqueous debris flows (density currents) can also occur on similar low gradients, this process is unlikely here as an emplacement process given the topographic setting because these surfaces are downstream of the lakes.

Another emplacement process that could explain transport of coarse-grained matrix-rich sediment on such gentle gradients is related to the occurrence of a major flood wave as the ice-dam abruptly collapsed. Significant flood waves have been described during ice-dam breakouts around the world (Costa, 1988a) and in accounts of major dam breaks with direct witnesses, such as the Johnstown, PA flood of 1889. Elevated energy gradients associated with significant flood waves can readily transport large volumes of coarse-grained sediment on relatively gentle gradients. Given that the ice-dammed lakes described here had depths ranging from 100 to 150 m at the ice-dams, it is quite likely that sudden collapse of the ice dam would have resulted in flood wave heights >10 m, capable of transporting the sediment-rich flows on low-gradient surfaces.

4. Downstream impacts

4.1. Interaction with mainstem streams

The volume of sediment contributed to the mainstem Buffalo Creek and Penns Creek during these jökulhlaup events was enormous. The largest, and highest, terraces along Buffalo Creek grade downstream from the jökulhlaup surfaces. This sediment appears to have remained as a lag following the breakout flows, forming a thin fill terrace. Major terraces along both streams can be tied directly to gravels sourced from the jökulhlaups. The channels of Buffalo and Penns Creeks are dominated by the sandstone gravel supplied from these events today, even though the downstream two-thirds of their watersheds are underlain by shale and limestone bedrock. Competence studies and point bar observations show that most of the gravel is entrained during bankfull to slightly overbank flows (Forsburg and Kochel, 2007). The longitudinal profile (Fig. 9A) of Buffalo Creek reflects some of the impact of the gravel contributed by North Branch and Rapid Run. The reach between these two tributaries is notably flatter than upstream and downstream segments, probably from aggradation and partial damming by the jökulhlaup sediment inputs to the mainstream. Aggradation at the mouth of Rapid Run may have partially dammed Buffalo Creek, resulting in up to 30 m of fill. Sediment poured into Buffalo and Penns Creeks, triggering significant aggradation and a minor decline of their axial gradients. Evidence for temporary ponding of Buffalo Creek upstream of the tributaries affected by jökulhlaups includes its exceptionally wide valley floor, as compared to the upstream and downstream reaches. Additionally, in the reach between Rapid Run and North Branch Buffalo Creek, the bedload in the main channel appears finer than upstream and downstream (Fig. 9A). This section of the reach is where gradient is slightly lower, suggesting that there *may have been* some partial damming by the sediment from Rapid Run causing enhanced mainstream aggradation. Buffalo Creek appears underfit along most of its course through its broad valley along this reach. Note in Fig. 9B the low gradient characteristic of the jökulhlaup surfaces (North Branch, Rapid Run, Spruce Run, and Laurel Run) compared to steeper profiles for debris fans (Buffalo Creek at Buffalo Gap and Stony Run fans). These debris fans, with gradients between 5° and 8° appear to have formed by normal hyperconcentrated flow and debris flow processes unrelated to ice-dammed lakes and jökulhlaups. Soils on the Stony Run surface are similar in age to the middle Pleistocene till and jökulhlaups. The very large fan emanating from Buffalo Gap (where Buffalo Creek emerges from the mountain front) appears to have formed subsequent to these events, in the Late Pleistocene, based on soil and weathering observations. The large debris fan at Buffalo Gap (Figs. 2 and 5D) appears to have prograded over the middle Pleistocene till.

4.2. Lower Susquehanna River gorge

The lower 40 km of the lower Susquehanna River in the Pennsylvania Piedmont Province is deeply incised through a narrow bedrock gorge cut into resistant metamorphic rocks of Pre-Cambrian age. The bedrock canyons, known locally as the Susquehanna Deeps (Matthews, 1917; Thompson and Sevon, 1999) of the Lower Susquehanna gorge were scoured below sea level by catastrophic macroturbulent flood flows in the Pleistocene (Kochel and Parris, 2000; Reusser et al., 2004). Evidence of these megafloods in the lower gorge includes large potholes, longitudinal grooves, hydraulically trapped erratic boulders from sources 100 km upstream, and multiple bedrock strath terraces (Fig. 11). It is likely that the upstream jökulhlaups, and much larger breakout flows associated with the draining of Glacial Lake Lesley above Williamsport(the volume of Lake Lesley was ~10 to 15 times larger than these lakes combined), contributed significantly to the catastrophic paleofloods that were integral in scouring the bedrock channels of the lower gorge. Although the bedrock straths have been cosmogenically dated as Late Pleistocene (Ruesser et al., 2004), it is possible that the major bedrock erosion features within the lower gorge were cut earlier and then modified by Late Pleistocene flows. Step-backwater modeling based on erratics and high-level slackwater sediments in the lower gorge (Kochel and Parris, 2000; Hubacz, 2009) documented paleoflood flows up to ~142,000 m^3/s (5,000,000 ft^3/s); five times the largest historical flow observed from Tropical Storm Agnes in 1972 (Moss and Kochel, 1978).

5. Post-glacial landform evolution and topographic inversion

The most prominent impact of the jökulhlaups on post-glacial landscape evolution of the region has been the armoring of the valley floors with the resistant bouldery sandstone gravel. Post-glacial hydrologic regimes have been largely unable to mobilize the jökulhlaup sediments and unable to significantly incise these flow surfaces. The primary channels of the tributaries to jökulhlaup surfaces have been able to incise their channels <1 m. As a result, these surfaces have relatively high water tables and contain wetlands and wet forest ecosystems. Although the Pleistocene sediment is no longer mobilized by modern floods, high magnitude events readily inundate the jökulhlaup surfaces. Post-glacial incision has occurred in areas between the tributaries and along their margins, resulting in the inversion of topography of some of the major jökulhlaup surfaces. The most prominent of these is along the upper half of the Rapid Run surface near the village of Forest Hill (Fig. 12). There, post-glacial incision by Muddy Creek into the softer shales and thin sandstones of the Bloomsburg Formation has resulted in perching of the Rapid Run jökulhlaup surface about 15 m above the floor of Muddy Creek. Post-glacial streams have found it easier to downcut into the softer bedrock, having been unable to entrain the resistant Tuscarora sandstone boulders of the jökulhlaup surfaces. This amount of downcutting is consistent with studies of regional denudation rates for the upper Susquehanna River region. Erosion rates have been estimated at about 2 cm/1000 y using modern suspended sediment data (Judson and Ritter, 1964) as well as long-term stratigraphic evidence from the Cenozoic sedimentary record (Sevon, 1999). Incision by post-glacial drainage has been slightly less than the 18 m expected, but certainly within the general range.

Inversion of topography along piedmont areas from armoring by glacial outwash composed of resistant clasts has been well documented along the Beartooth Front in Montana (Ritter, 1967). Ritter (1967) illustrated the importance of this process in the evolution of mountain-front geomorphology where Pleistocene outwash terraces along Rock Creek and other streams emanating from the Beartooth Mountains decrease in age as they step down, with the oldest terrace

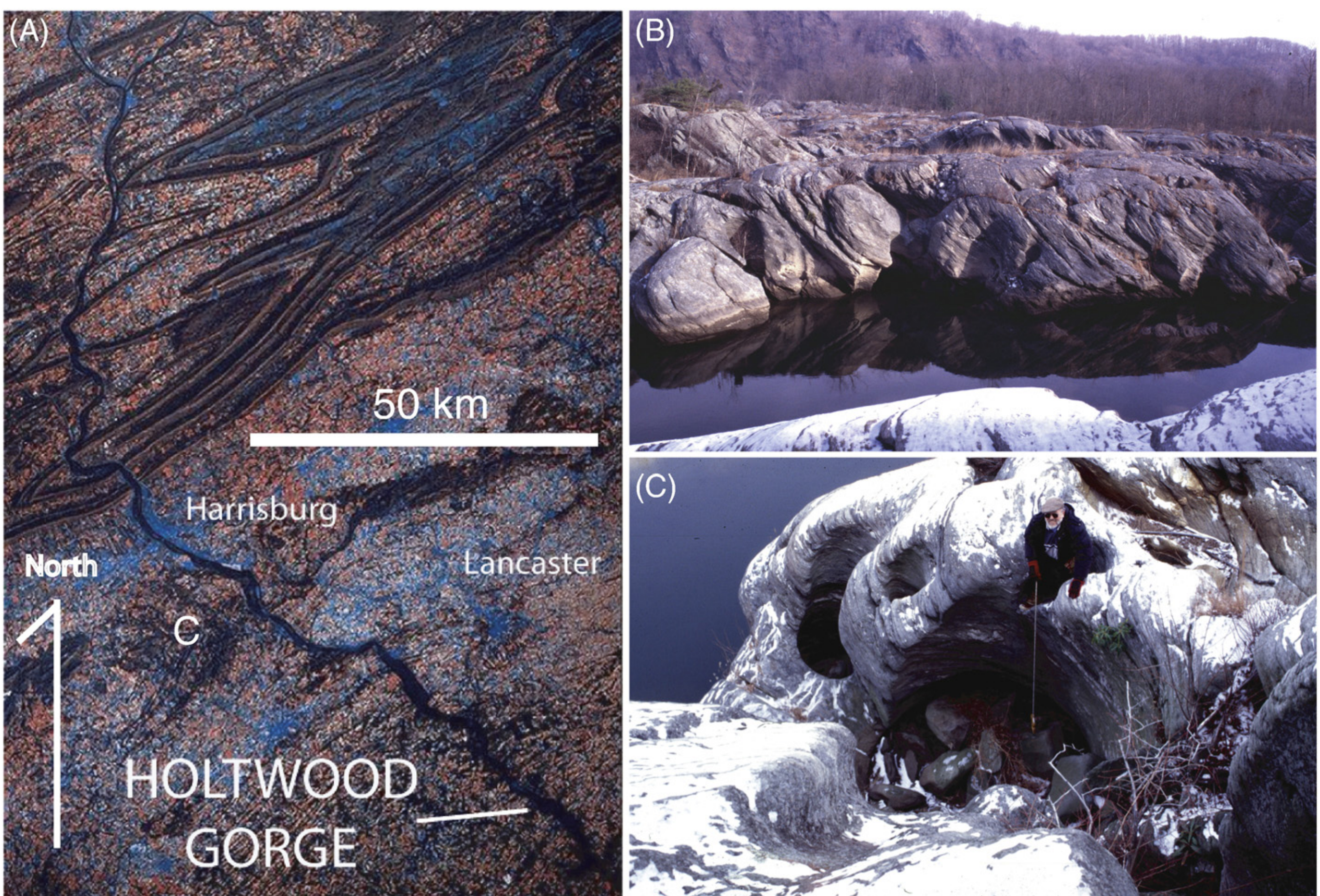

Fig. 11. Pleistocene paleoflood features in the lower gorge of the Susquehanna River near Holtwood. (A) Orbital view of the central and lower Susquehanna Valley and the Holtwood Gorge (courtesy, NASA). (B) Large potholes and bedrock straths cut in resistant pre-Cambrian schist by macroturbulence during the paleofloods. (C) Large pothole with boulder erratics trapped inside. Some of the erratics (like diabase) were sourced near Harrisburg, while some of the conglomerates originated from up to 50 km farther upstream.

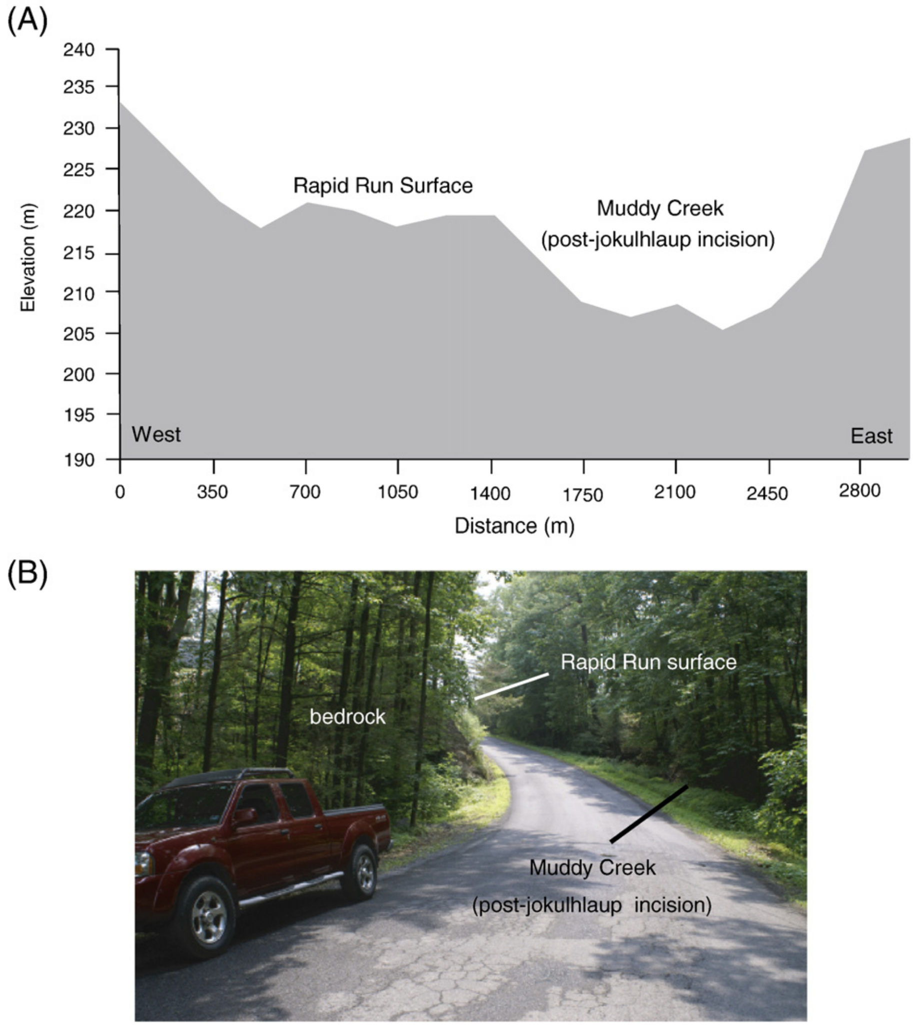

Fig. 12. Inversion of topography of the Rapid Run surface near Forest Hill, north of Mifflinburg. (A) Northeast to southwest topographic profile from the post-glacial Muddy Creek Valley (incised into relatively soft shale and sandstone bedrock) across the more resistant, boulder-strewn Rapid Run jökulhlaup surface. Rapid Run has been unable to incise into the bouldery deposits. Formerly the valley floor, this surface now forms a modest divide between Rapid Run and Muddy Creek. Sediments in Muddy Creek are local sandstone and shale and are much more angular than the rounded Tuscarora Sandstone boulders in the jökulhlaup. (B) View of the change in elevation along the northeastern margin of the surface. The floor of the photo (near the truck) is the floodplain of post-glacial Muddy Creek. Bedrock can be seen along the left side of the road, bordering the edge of the elevated jökulhlaup surface.

now forming major watershed divides as topography has been inverted (Fig. 13). Similar to the case in Pennsylvania, post-glacial streams were unable to downcut through the armored gravel surfaces of the outwash but were able to more readily incise through softer bedrock in the Bighorn Basin. In Pennsylvania, with time, this process will continue to elevate the former valley floors covered by jökulhlaup sediment, increasing the prominence of their legacy on landform evolution in the Buffalo Creek watershed.

6. Conclusions

The very unique interaction of an upvalley-flowing, thin glacial lobe with high gradient mountain streams along eroded plunging anticlines of the Appalachian Valley and Ridge resulted in a series of sediment-rich jökulhlaups, normally reserved to high latitude mountainous streams and alpine glaciers. The geomorphic circumstances that occurred in tributaries to the West Branch Susquehanna River during early to middle Pleistocene glaciation is extremely rare and may be unique in the world. Small lakes formed upstream from the mountain-front ice dams and likely filled with water and sediment from active periglacial denudational processes upstream in their watersheds. Failure of the ice dams resulted in catastrophic breakout floods as the ice advance waned. The jökulhlaups produced major piedmont landforms that extend as elongated fan-like surfaces composed of poorly sorted, matrix-supported gravel that are sedimentologically similar to debris flow sediments. However, the gradient of these surfaces generally ranges from 1 to 2°, far too low for normal debris flow processes. Enhanced basal pore-water pressures may have developed from the interaction of glacial meltwater and permafrost. This, in combination with catastrophic release of ice-dammed lakes as large flood waves, produced a special set of hydrogeomorphic conditions that facilitated the emplacement of these sediment-rich jökulhlaups along mountain-front tributaries to Buffalo and Penns Creeks in a series of catastrophic flow events.

Valley fills from these jökulhlaups averaged 7 to 10 m, producing gently-sloping, wide, smooth surfaces between 6 and 9 km in length and averaging 0.5 to 1 km in width. These landforms are prominent today, nearly a million years after their formation, and are readily visible from orbital imagery because of their forest cover. The surfaces remain forested chiefly because of their bouldery nature, and a high water table occurs because of poor drainage and limited incision by surface streams. Although most of the Pleistocene sediment is no longer mobilized by modern floods, high magnitude events readily inundate the jökulhlaup surfaces.

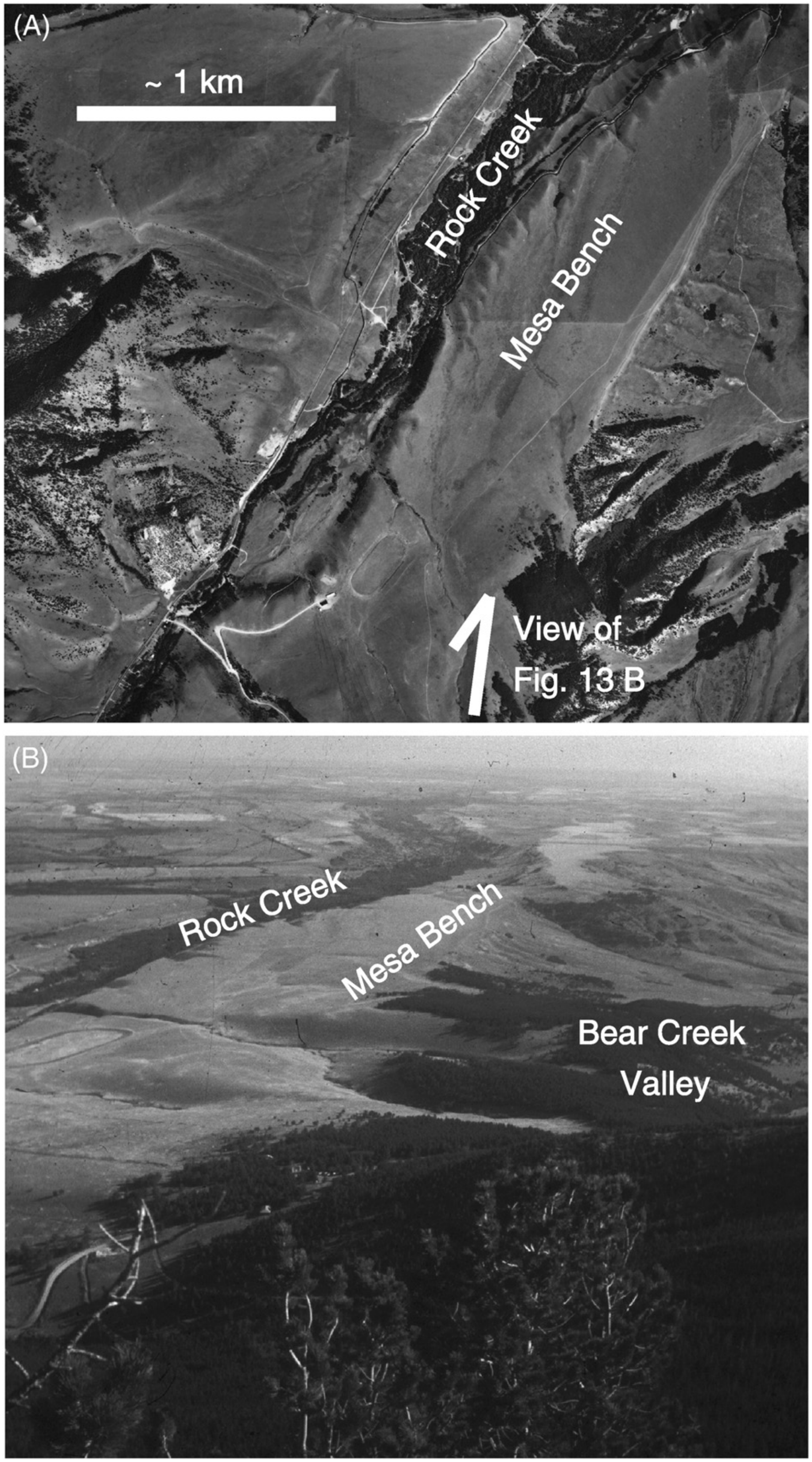

Fig. 13. Inverted topography of older terraces along Rock Creek near Red Lodge, Montana along the front of the Beartooth Mountains mapped by Ritter (1967). (A) Air photo showing Rock Creek and Mesa Bench. Mesa bench currently forms a major divide between Rock Creek and Bear Creek, but was formerly the middle Pleistocene valley floor of Rock Creek. (B) Oblique view looking north along the direction of the arrow in Fig. 13 A, showing the inverted topography of Mesa Bench.

The legacy of the jökulhlaups has considerably impacted the nature of the evolution of the piedmont region by post-glacial drainage in a manner similar to that described by Ritter (1967) along the Beartooth Front in Montana. Post-glacial streams have not had the competence to mobilize the jökulhlaup sediment. Thus, the tributaries have incised only negligibly into the bouldery fill. Post-glacial streams whose headwaters are valleyward of the ridges have been able to downcut into softer valley bedrock (thin, less competent sandstones and shales), leaving the jökulhlaups surfaces higher and developing an inversion of topography.

A paleosol seen in some deeper excavations suggests that jökulhlaups may have occurred episodically throughout the early and middle Pleistocene. This interpretation is consistent with the work of Peltier (1949) on Susquehanna River terrace chronosequences, description of multiple Pre-Wisconsin tills by Marchand and Crowl (1991), and the occurrence of remnants of higher jökulhlaup surfaces along the southern branch of the deposits from North Branch Buffalo Creek. It is unclear whether Penns Creek itself was dammed by ice to create a major lake in the canyon to the west of the study area, but the presence of high terraces with early-to-middle Pleistocene soils and similar sedimentology suggests that that may have occurred in a similar fashion. These catastrophic breakout flood events undoubtedly contributed to the rapid evolution and down-cutting of the lower gorge of the Susquehanna River, some 150 km downstream.

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This paper is dedicated to the memory and legacy of the late Louis C. Peltier who pioneered glacial and periglacial geomorphic research along the Susquehanna River. His insights were exceedingly progressive and his attention to detail was amazing. We had the fortune of benefiting from his visit to the field during the early stages of this work and numerous insightful discussions in subsequent years.

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