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Remote sensing and GIS investigation of glacial features in the region of Devil's Lake State Park, South-Central Wisconsin, USA

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ABSTRACT

This study utilizes Landsat TM, ASTER and Synthetic Aperture Radar (SAR)-derived DEMs in conjunction with Geographic Information Systems (GIS) in order to reevaluate previously-published interpretations of glacial landforms in and around Devil's Lake State Park, south-central Wisconsin, USA. Devil's Lake sits in a gorge carved into the southern flank of a doubly-plunging syncline known as the Baraboo Hills through which the Wisconsin or some other river flowed prior to the last ice age. During the last glacial maximum about 18,000 B.P., an outlet glacier of the Laurentide Ice Sheet called the Green Bay Lobe extended southward into south-central Wisconsin and left behind extensive glacial landforms such as moraines, drumlins and eskers. During advance of the Green Bay Lobe into the region, Devil's Lake Gorge was plugged at both ends by glacial deposits and resulted in formation of Devil's Lake. The Wisconsin River, if it originally flowed through Devil's Lake Gorge, found a new course to the east of the Baraboo Hills Syncline. This study utilizes the aforementioned remote sensing data to spatially image the following features: (1) Original extent of the Green Bay Lobe, (2) Moraines and streamlined glacial landforms as indicators of ice-flow directions, and (3) Former path of the old Wisconsin or some other river prior to being rerouted by the Green Bay Lobe. GIS analysis is also performed in order to test published interpretations of the regional glacial history. This study confirms that glacial features observed today are consistent with the former advance of the Green Bay Lobe into the area, formation of glacial Lake Wisconsin, plugging of Devil's Lake Gorge by a moraine to form Devil's Lake, and subsequent glacial retreat leading to the breaching of an ice dam and catastrophic flooding by ~14,000 years ago. The large aerial coverage of satellite imagery with resolutions up to 15 m are valuable for reevaluating regional interpretations previously based on local field mapping and aerial photography of limited extent.

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1. Introduction

Reconstructions of glacial landforms that in the past relied on contour maps and aerial photography are now increasingly performed using satellite imagery, digital elevation models (DEMs) and Geographic Information Systems (GIS) (Clark, 1997; Dunlop and Clark, 2006; Smith et al., 2006). Although field mapping, LIDAR, and aerial photography provide detailed visualization of landforms and are useful for fine-resolution mapping, the last two techniques having pixel resolutions approaching a few meters, these methods are relatively expensive and cover only limited areas (Smith et al., 2000; Smith et al., 2006). In contrast, low-cost multi-spectral satellite imagery such as Landsat TM and ASTER cover large areas of 100 × 100 km and greater at low to moderate resolutions of up to 15 m (Clark, 1997; Smith et al., 2006). The larger viewing area permitted by satellite imagery compared to aerial photographs led to the discovery of mega-lineaments that were unrecognized at smaller scales (Clark, 1993, 1997). In addition, near-global DEMs derived from Shuttle Radar Topography Mission (SRTM) data record absolute elevations and allow visualization of landscapes with spatial resolutions of 30 to 90 m (Smith et al., 2006, Jensen, 2007). GIS integrates a wide variety of information on glacial landforms, both spatially and temporally, in order to reconstruct ice dynamic scenarios (Clark, 1997) and test interpretations. This study utilizes Landsat TM, ASTER and Synthetic Aperture Radar (SAR)-derived DEMs in conjunction with Geographic Information Systems (GIS) to first study glacial landforms in south-central Wisconsin on a regional scale, and then focus on Devil's Lake. The larger coverage of satellite imagery, easier visualization of landforms compared to topographic maps, and modeling capabilities of GIS provide new perspectives and powerful tools in order to test previous interpretations that were based on localized field mapping and aerial photographs of limited extent.

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2. Regional geology

2.1. Older rocks

The Baraboo Hills (Fig. 1) is a doubly-plunging syncline comprised mostly of Precambrian quartzite (Defrates, 2007). The Baraboo and six correlative red quartzites are the remnants of a once vast clastic wedge that covered much of the southern margin of the Superior Province (Medaris et al., 2003). Detrital zircons obtained from the quartzite yield U/Pb ages that cluster around 1754, 1850 and 2550 Ma (Van Wyck and Norman, 2004). The quartzite was folded into a syncline at approximately 1650 Ma in the foreland of the Mazatzal Orogen (Defrates, 2007).

Overlying Cambrian rocks are largely sandstones and contain quartzite pebbles found locally in Cambrian basal conglomerate. The Cambrian sands lapped onto the flanks, and filled the center of the Baraboo Syncline (Black, 1974). Devil's Lake Gorge (Fig. 1) was originally cut into the southern flank of the Baraboo Syncline during Late Cambrian time or earlier by an ancient stream as evidenced by the presence of Cambrian sandstone at the southwest corner of Devil's Lake (Dalziel and Dott, 1970; Black, 1974; Clayton and Attig, 1989). Further erosion of the gorge was accomplished by subsequent streams. The occurrence of Paleozoic rocks high on the flanks of the Baraboo Hills indicate that the gorge was completely buried during Paleozoic time and subsequently exhumed in Cretaceous or Cenozoic time (Thwaites and Twenhofel, 1921, p. 296; Clayton and Attig, 1989). The Precambrian and Cambrian rocks are largely covered by Pleistocene glacial deposits and wind-blown silt in the area of Devil's Lake (Black, 1974).

2.2. Pleistocene glacial features

Twenty thousand years ago, the latest major glacial advance of the Pleistocene Epoch spread out from centers near Hudson Bay and buried all of eastern Canada, New England, and much of the Midwest under enormous sheets of ice that averaged more than 1.5 km in thickness (Imbrie and Imbrie, 1979). The Green Bay Lobe (Fig. 2), an outlet glacier of the Laurentide Ice Sheet, was as much as 1000 m thick over Green Bay, Wisconsin, during the last glacial maximum about 18,000 B.P. (Colgan, 1999). At its maximum, the Green Bay Lobe was 125 km wide and more than 200 km long (Colgan, 1999). The advancing ice lobes carved deep, smooth troughs into the terrain, carrying and pushing along boulders and huge volumes of finer sediment to form various glacial features such as moraines, drumlins and flutes (Colgan and Mickelson, 1997). Streams flowing in tunnels beneath the ice deposited long, sinuous ridges called eskers. Many of these glacial features are found today in formerly glaciated regions.

The ice sheets began to retreat ~14,000 years ago and within 7000 years had shrunk to the present limits (Imbrie and Imbrie, 1979). In south central Wisconsin, retreat of the Green Bay Lobe may have begun between 16,000 and 13,000 B.P., leaving a series of ice-margin positions as recorded by end moraines and contact fans (Colgan, 1999). The Green Bay Lobe surged repeatedly after 13,000 B.P., with minor advances or periods of stability as evidenced by small drumlins (<1 km long) and remolded drumlins, before finally retreating into southern Ontario after 9900 B.P. (Colgan, 1999).

Devil's Lake resides in a gorge carved into the quartzite ridge of the Baraboo Hills (Fig. 1), through which the Wisconsin or some other river might have flowed prior to the maximum advance of the Green Bay Lobe during the last ice age. During that age, known as the late Wisconsin stage of glaciation, the gorge was plugged on the northern and southern ends by glacial deposits of the Green Bay Lobe at 15,000–16,000 BP (Clayton and Attig, 1989) and resulted in formation of Devil's Lake (Figs. 1 and 2). The Wisconsin River, if it originally flowed through Devil's Lake Gorge, found a new course to the east of the Baraboo Hills Syncline (Fig. 1). Immediately west of the areas of Figs. 1 and 2 is a region called the Driftless Area of southwestern Wisconsin that lacks any evidence of ever being covered by ice sheets (Trowbridge, 1921; Imlay, 1973; Anderson, 1988; Hobbs, 1997, 1999).

3. Methodological approach and data sources

Remote sensing data and GIS are utilized in an attempt to image and model the following features: (1) The former extent of the Green Bay Lobe, (2) Glacial moraines and other landforms as relicts of the last ice age, (3) Distinguish glacial material from older bedrock and modern alluvium, (4) The former path of the Wisconsin or some other river prior to being rerouted by the Green Bay Lobe, and (5) Model and test published interpretations of the glacial history of the area.

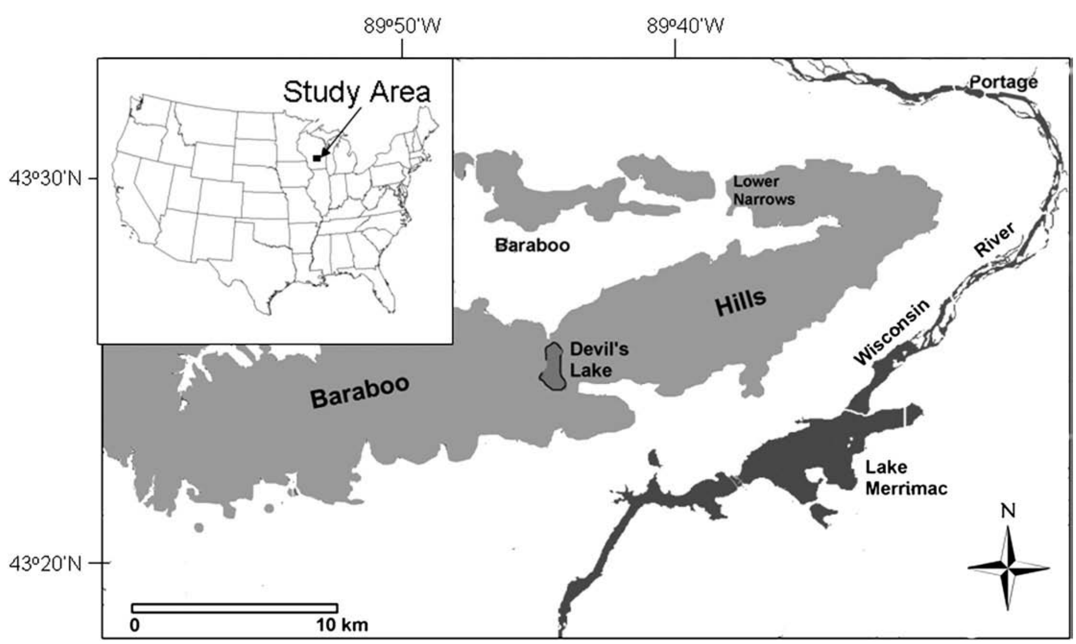

Fig. 1. Regional extent of the Baraboo Hills, a doubly-plunging syncline, in south-central Wisconsin. Devil's Lake is located within a gorge that cuts through the southern limb of the syncline. The Wisconsin River, which flows around the eastern nose of the syncline, is also depicted.

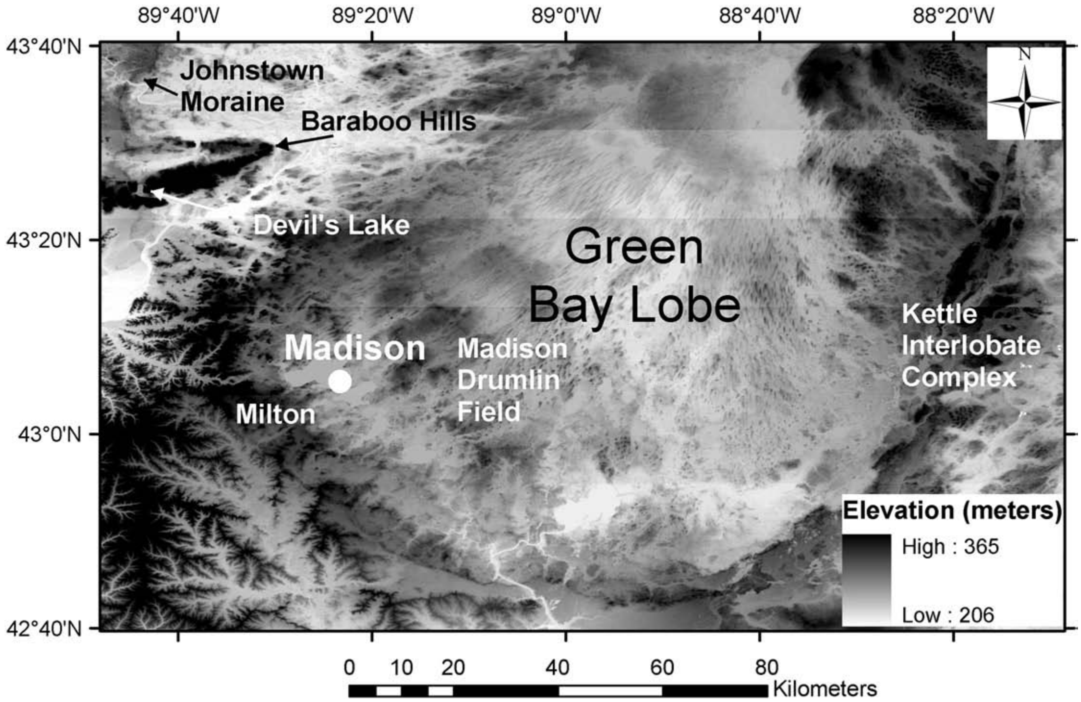

Fig. 2. A composite of several SAR-derived DEMs for south central Wisconsin indicating the region once covered by the Green Bay Lobe. The overall lobate form of the glacially-carved topography is easily seen with much of the terrain having been scoured by moving ice into the smooth surfaces of the Green Bay Lowland. The Madison Drumlin Field, Baraboo Hills, moraines and other features are labeled.

Synthetic Aperture Radar (SAR), Landsat TM, and ASTER remote sensing data are utilized in this study. These data sources were selected based on the following considerations: (1) Employed by other researchers in the study of glacial landforms, e.g. Clark (1997) Landsat TM, Brown et al. (1998) DEM, Dunlop and Clark (2006) ASTER, and Smith et al. (2006) Landsat TM and SAR; (2) Good spatial and spectral resolutions for determining large-scale landforms and trends; (3) Inexpensive; and (4) Multiple spectral bands (Landsat TM and ASTER). The SAR data were obtained during the Shuttle Radar Topography Mission (SRTM) in February, 2000, utilizing bands X (9.6 cm) and C (5.3 cm) with a resolution of 30 m (Jensen, 2007) and converted to DEMs. The DEM and the ASTER data were downloaded from the USGS website (http://www.lpdaac.usgs.gov/datapool/datapool.asp).

The multi-spectral data sets of the ASTER and Landsat TM (Table 1) have 15 and 30 m spatial resolutions, respectively, coupled with spectral resolutions of ~0.1 μm. The spatial resolutions do not permit identification of small features on the scale of a few meters, but should be useful for visual interpretations of large-scale landforms with dimensions exceeding tens to hundreds of meters. The principle lithologies in the area are sandstone and quartzite, which exhibit the greatest reflectance within the visible (~0.4–0.7 µm) range of the electromagnetic spectrum. Landsat TM and ASTER Bands 1 through 3 should therefore be useful in identifying old river channels and bedrock exposures. Bands within the near to middle infrared (0.7–2.4 µm) portion of the electromagnetic spectrum are useful for distinguishing different types of vegetation and their moisture characteristics (Jensen, 2007). Landsat TM Bands 4, 5 and 7 along with ASTER Bands 3 through 9 might therefore be useful in areas of vegetation cover where the latter varies as a function of lithology. The DEMs, in turn, should complement the spectral images in landform identification. Although digital image classification was not employed in this study due to the extensive vegetation cover, Brown et al. (1998) considered soil type and vegetation among the controls for differentiating glaciated landscapes in DEMs of Michigan using supervised classification techniques. Visual interpretation of the remote-sensing data therefore offers a new perspective of glacial landforms while GIS analyses allow us to test previous interpretations of the region's glacial history that were largely based on field mapping, contour maps, and aerial photographs of limited extent.

4. Data analysis and results

4.1. Regional glacial features

Fig. 2 is a composite of several SAR-derived DEMs of the region once covered by the Green Bay Lobe. Radar measures the visible surface, including vegetation canopy, so that DEMs may not represent true ground elevations (Smith et al., 2006). Even so, DEMs are useful for recognizing topographical features from which glacial landforms might be distinguished. The overall lobate form of the glacially-carved

Table 1
Summary of spectral bands for Landsat TM and ASTER data.

Landsat TM	ASTER
Band 1 (0.45 –0.515 µm)	Band 1 (0.52–0.60 µm)
Band 2 (0.525–0.605 µm)	Band 2 (0.63–0.69 µm)
Band 3 (0.63–0.690 µm)	Band 3 (0.76–0.86 µm)
	SWIR (6 bands)
Band 4 (0.75–0.90 µm)	Band 4 (1.60–1.70 µm)
Band 5 (1.55–1.75 µm)	Band 5 (2.145–2.185 µm)
	Band 6 (2.185–2.225 µm)
Band 7 (2.08–2.35 µm)	Band 7 (2.234–2.285 µm)
	Band 8 (2.295–2.365 µm)
	Band 9 (2.360–2.430 µm)
	TIR (5 bands)
	Band 10 (8.135–8.475 µm)
	Band 11 (8.475–8.825 µm)
	Band 12 (8.925–9.275 µm)
	Band 13 (10.25–10.95 µm)
	Band 14 (10.95–11.65 µm)
All bands have 30 m spatial resolution	Bands 1–3: 15 m spatial resolution
	SWIR Bands: 30 m spatial resolution
	TIR Bands: 90 m spatial resolution

topography is easily seen with much of the terrain having been scoured by moving ice into the smooth surfaces of the Green Bay Lowland. The rim of the large-scale, lobate structure is bordered by extensive ridges consisting of moraines and associated glaciofluvial sediment that was transported and piled up along the margins of the advancing ice sheet, or deposited by glacial meltwater. The Johnstown Moraine in the upper left hand corner of Fig. 2 marks the maximum extent of the Green Bay Lobe in the area and abuts against the Baraboo Hills synclinal structure. Other arcuate ridges inboard of the Johnstown Moraine include the Milton Moraine and associated glaciofluvial sediment that formed during retreat of the Green Bay Lobe following the Johnstown Phase (Colgan and Mickelson, 1997). The eastern margin of the Green Bay Lowland is defined by the Kettle Interlobate Complex. The Kettle Moraine is composed of ice-contact and glaciofluvial sediment that is bounded by an escarpment of Silurian dolomite, forming the boundary between the Green Bay Lobe and Lake Michigan Lobe to the east (Colgan and Mickelson, 1997; Colgan, 1999).

4.2. Madison drumlin field

Within the interior of the Green Bay Lowland are extensive fields of drumlins and other streamlined landforms, the largest being the Madison drumlin field (Figs. 2–4). The Madison drumlin field consists of over 5000 streamlined forms that include drumlins, flutes, and eskers (Colgan and Mickelson, 1997) that are excellent indicators of original ice-flow directions. Many of these streamlined landforms are easily distinguishable at 30 m resolution (Fig. 2). Colgan and Mickelson (1997) made distinctions among these various glacial forms. Flutes are parallel ridges and grooves commonly several hundred meters to several kilometers long, 20 to 200 m wide, but less than 3 m in height. Large drumlins are 1000 to 6000 m in length, while small drumlins are less than 1000 m in length (Colgan and Mickelson, 1997). These readily-identifiable landforms in Fig. 2 indicate that overall ice flow was away from the axis of the Green Bay Lobe, southwestward on the western side and southeastward on the eastern side.

Fig. 3A shows a portion of the composite DEM of Fig. 2 centered on the Madison drumlin field and outlined in the inset map (Fig. 3C) of Colgan and Mickelson (1997) for the Green Bay Lobe. The radar DEM at 30 m resolution (Fig. 3A) is compared with an ASTER image (Fig. 3B) at 15 m resolution and RGB 3 2 1 band combination for the same area. Although the ASTER data has higher resolution, the vegetation cover obscures easy identification of glacial features. The different shades, however, largely reflect variable vegetation and can be used to distinguish glacial landforms. Flutes and drumlins are more likely to be heavily-vegetated and wooded, and hence display darker shades in this band combination, because of the steep slopes and boulder-rich glacial material that discourages clearing and cultivation. Long, linear flutes and drumlins are visible in the ASTER images of Fig. 3B,D, indicating former ice movement towards the SSW. A close-up of the ASTER image highlights the 15,000 year old glacial lakes that

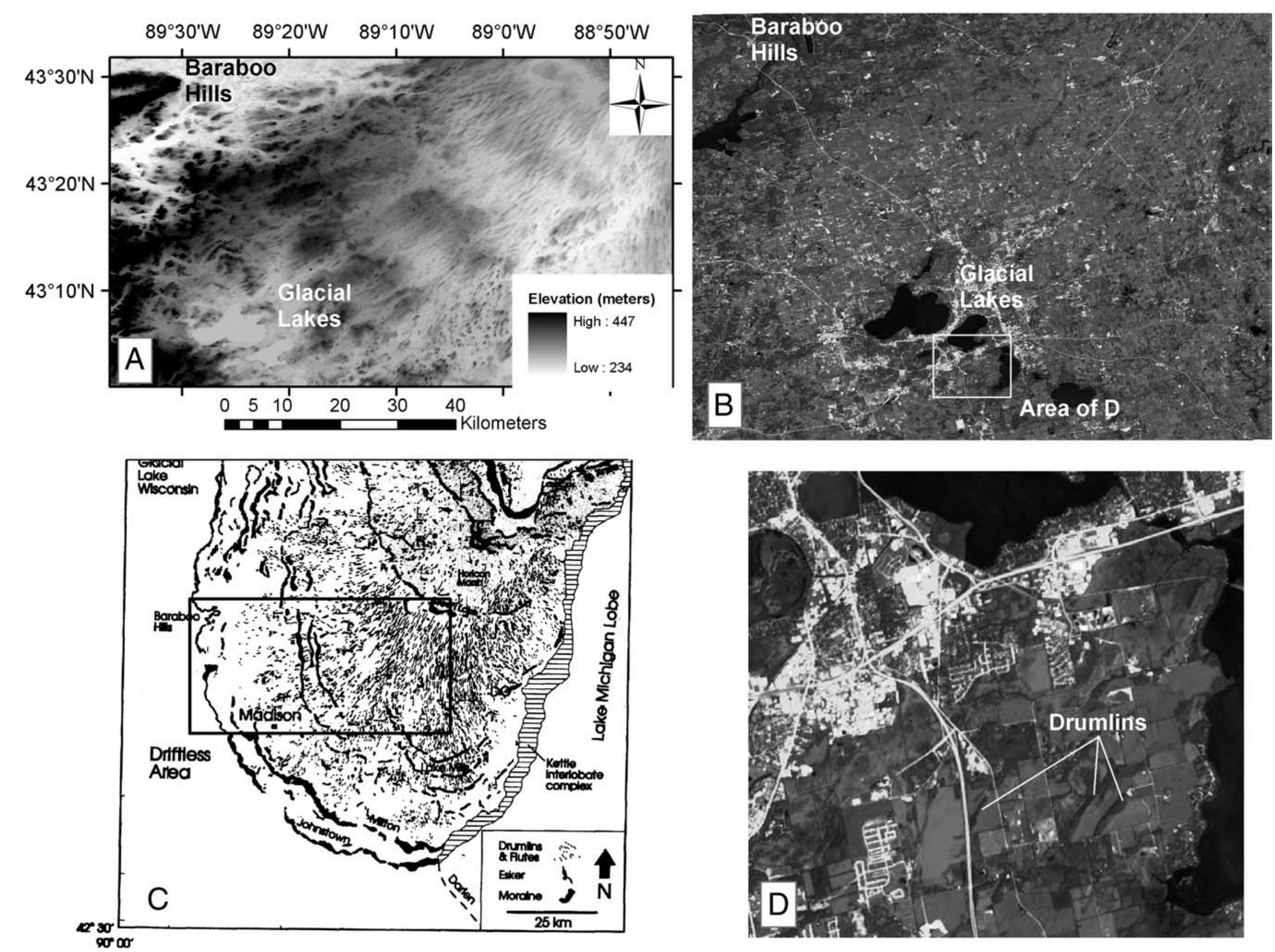

Fig. 3. Close-up images centered on the Madison Drumlin Field. A) Portion of the composite radar DEM shown in Fig. 2. B) ASTER image in RGB 3 2 1 band combinations for the area of (A) showing glacial lakes around Madison, Wisconsin. C) Map of the Green Bay Lobe (from Colgan and Mickelson, 1997). The rectangle outlines the areas of (A) and (B). D) Close-up of the area around Madison, Wisconsin, outlined in (B). The long, linear features are mostly drumlins and are good indicators of ice movement towards the SSW.

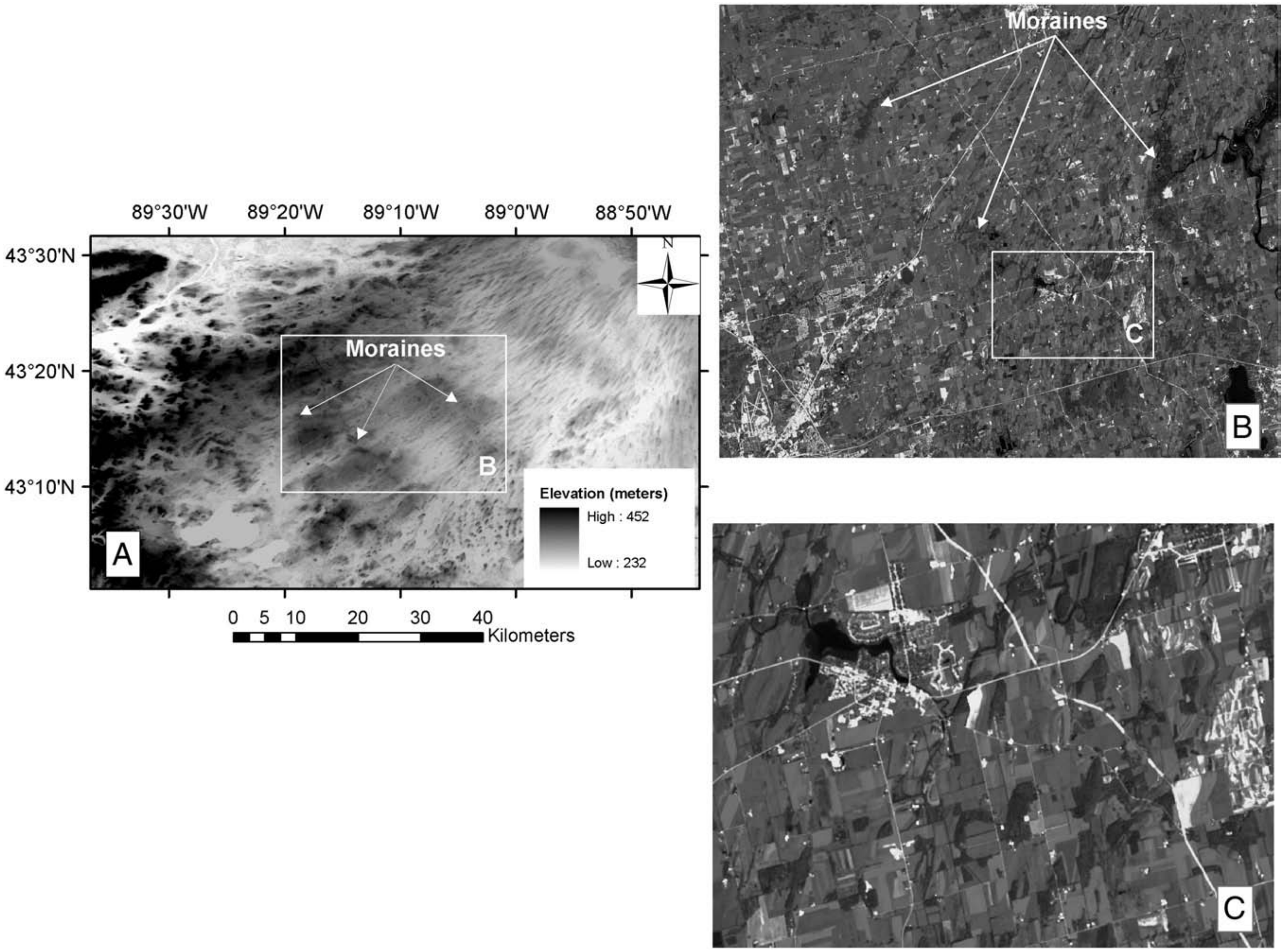

Fig. 4. More images of the Madison Drumlin Field. A) Radar DEM of the same area as Fig. 3A. Three moraines indicated within Rectangle (B) are described by Colgan and Mickelson (1997) as hummocky moraines of the Lake Mills phase that formed following glacial retreat after the Johnstown phase. B) ASTER image of Rectangle (B) in RGB 3 2 1 band combinations. C) Close-up of an area in Fig. (B) shows SSW-trending flutes and drumlins in ASTER RGB 3 2 1 band combinations.

occur in and around Madison, Wisconsin, immediately inboard of the Milton Moraine (Figs. 2 and 3).

In the radar DEM of Fig. 4A, the three moraines indicated in area 'B' are described by Colgan and Mickelson (1997) as hummocky moraines of the Lake Mills phase that formed following glacial retreat after the Johnstown phase. An ASTER image of Area 'B' is displayed in Fig. 4B in band combinations RGB 3 2 1. Fig. 4C shows SSW-trending flutes and drumlins in ASTER RGB 3 2 1 band combinations. The radar DEM and ASTER images of the Green Bay Lobe indicate different ice flow directions that trend southwest on the western side and south to southeast in the central and eastern parts of the lobe. These ice-flow directions are consistent with the trends determined by other investigators (e.g. Colgan, 1996) based on aerial photographs, topographic maps, and glacial geologic maps (Colgan, 1999). These overall trends indicate that the ice spread outward and away in different directions from the axis of the Green Bay Lobe.

4.3. Baraboo Hills and surrounding area

The SAR-derived DEM of Fig. 5 shows the track of the Johnstown Moraine within the vicinity of Baraboo Hills and Devil's Lake. The two moraine plugs, one on either side of Devil's Lake Gorge, are easily seen along with continuation of the moraine south of the Quartzite Ridge. Relict outwash plains of the Green Bay Lobe are also easily distinguished. Fig. 6 is a three-dimensional image of Devil's Lake Gorge derived from the SAR-derived DEM of Fig. 5 and displayed in Arc Scene. The Johnstown Moraine and plug are clearly visible.

Fig. 7 shows the results of aspect analysis of a DEM calculated from an ASTER image of the Baraboo Hills and surrounding area, revealing conspicuous trends within the landscape. The different slope directions of the DEM are shown in Fig. 7A. The long, sinuous ridges that trend N-S are probably moraines as evidenced by the parallelism with the inferred margins of the Green Bay Lobe in this area. Fig. 7B only highlights features that have slopes dipping to the northwest and southeast, revealing an overall fabric of the terrain that trend NE to SW and parallel to the inferred ice-flow directions in this area. The NE to SW fabric of Fig. 7B terminates at the moraine and provides further evidence that these features are glacial in origin.

Fig. 8 shows a close-up of the Devil's Lake area displayed as ASTER SWIR Bands RGB 4 5 6. The area is mostly covered by trees, grass, and other vegetation that obscures direct spectral identification of bedrock and sediment. However, geologic features can be indirectly discerned by the SWIR spectrum of the vegetation. The heavily-wooded Baraboo Quartzite (Q) in Fig. 8 is darker than the surroundings with its overall synclinal structure readily apparent. Lighter areas are mostly grassland and low vegetation over glacial sediment (G). Former glacial lakes, as outlined in Black (1974) (his Fig. 59), can be seen on the ASTER image as lighter areas within the heavily-wooded quartzite ridge east of Devil's Lake. These lake beds are relatively smooth compared to the surrounding quartzite ridges and consist of grassland and low vegetation underlain by silty sands, clay and gravel (Black, 1974). The two moraine plugs on either side of Devil's Lake can be easily distinguished as darker, heavily wooded ridges within the gorge. A light-colored trail north of Devil's Lake

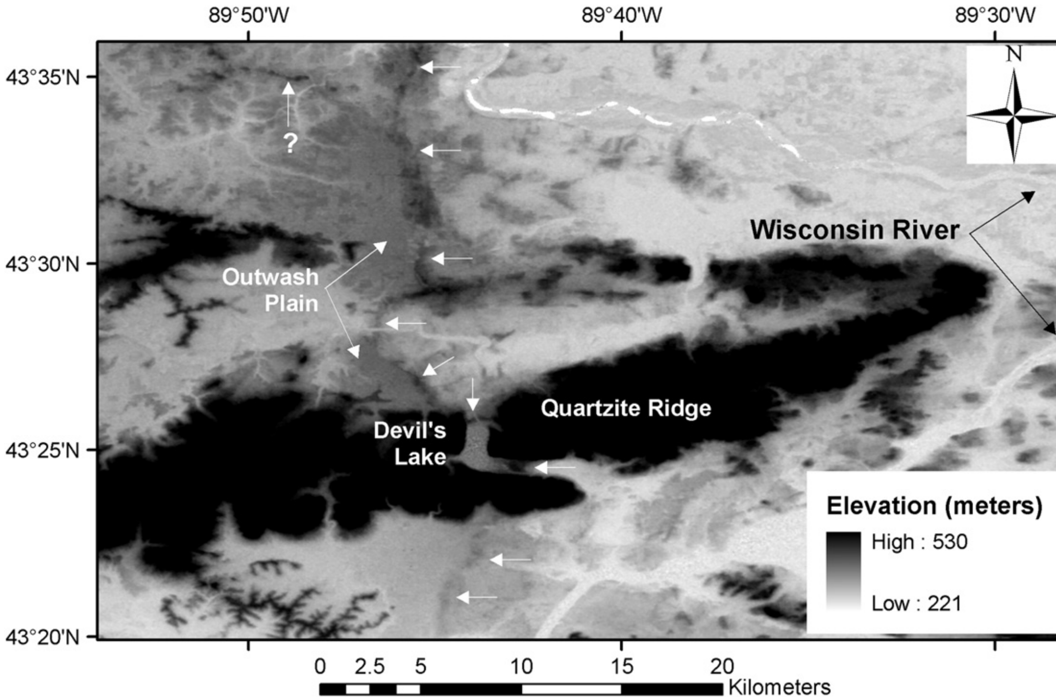

Fig. 5. SAR-derived DEM showing the Johnstown Moraine, as indicated by arrows, within the vicinity of Baraboo Hills and Devil's Lake. The moraine extends into the interior of the synclinal structure where the modern Baraboo River flows through a breach. The two moraine plugs on either side of Devil's Lake Gorge are easily seen along with continuation of the moraine south of the Quartzite Ridge. Relict outwash plains of the Green Bay Lobe are also easily distinguished.

(Fig. 8) is spectrally similar to channel sands of the modern Wisconsin River and possibly reflects the course of an old, abandoned river channel. This channel-like feature can be traced north of Devil's Lake where it then bends westward into the town of Baraboo, beyond which the trail becomes obscured. Cambrian sandstone (SS) is the source of channel sands and should exhibit a similar spectral image.

4.4. Analyzing the course of the old Wisconsin River

The possible abandoned river channel identified in Fig. 8 is compared with a Landsat TM image displayed in RGB 4 5 6 band combinations in Fig. 9. Although fluvial sands, roads, parking lots, sandstone bedrock and various buildings are all in nearly the same color, the suspected channel (arrows) must have been extensive since it can easily be traced at 30 m pixel resolution. The appearance of this feature in the field immediately north of Devil's Lake Gorge is consistent with that of a dry river channel covered by soil, grass and small vegetation. The bedrock of the area is Cambrian sandstone, so any alluvium encountered at depth would likely be sand similar to that of the modern Wisconsin River. Further west, the tract is obscured (question mark of Fig. 9) by other materials of similar spectral signatures.

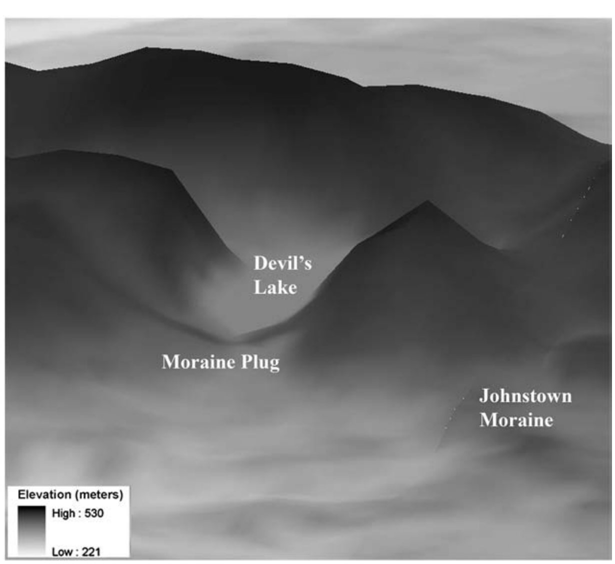

Fig. 6. Three-dimensional image of Devil's Lake Gorge derived from the SAR-derived DEM (Fig. 5) and displayed in Arc Scene. The view is looking south. The Johnstown Moraine and plug are easily discerned.

4.5. Hydrology and stream flow models

The Johnstown Moraine within the vicinity of the Baraboo Hills and Devil's Lake (Fig. 5) is an important consideration when modeling stream flows because it affects the local topography. The hydrology tools in ArcGIS were utilized to calculate stream flows. The DEM used for the stream flow models was constructed from an ASTER image.

The Flow Direction Tool in ArcGIS was applied to the DEM to create a raster of flow direction from each cell to its steepest down-slope neighbor. The Flow Accumulation Tool was then employed to create a flow accumulation raster from the flow direction grid by accumulating the weight for all cells that flow into each down-slope cell. The raster calculator was then used to generate a stream network raster to assign the number 1 to each cell that has a flow accumulation greater than a threshold value. The resulting stream network raster will, therefore, consist of cells with boolean values of zero or one. Finally, the Stream Link Tool was used to uniquely identify each stream segment (or link) from the stream network and flow direction grids.

Fig. 10 shows the calculated stream links for flow accumulation values greater than 3000, 10,000 and 15,000 superimposed on the ASTER DEM. The calculated stream networks decrease in number at higher values of flow accumulation. Flow accumulations greater than 3000 (Fig. 10A) and 10,000 (Fig. 10B) generate streams that flow north and northeastward from Devil's Lake Gorge out through Lower Narrows Outlet and into the modern Wisconsin River. Just north of Devil's Lake Gorge, the calculated stream also branches westward towards the Baraboo Outlet, but then abruptly terminates before

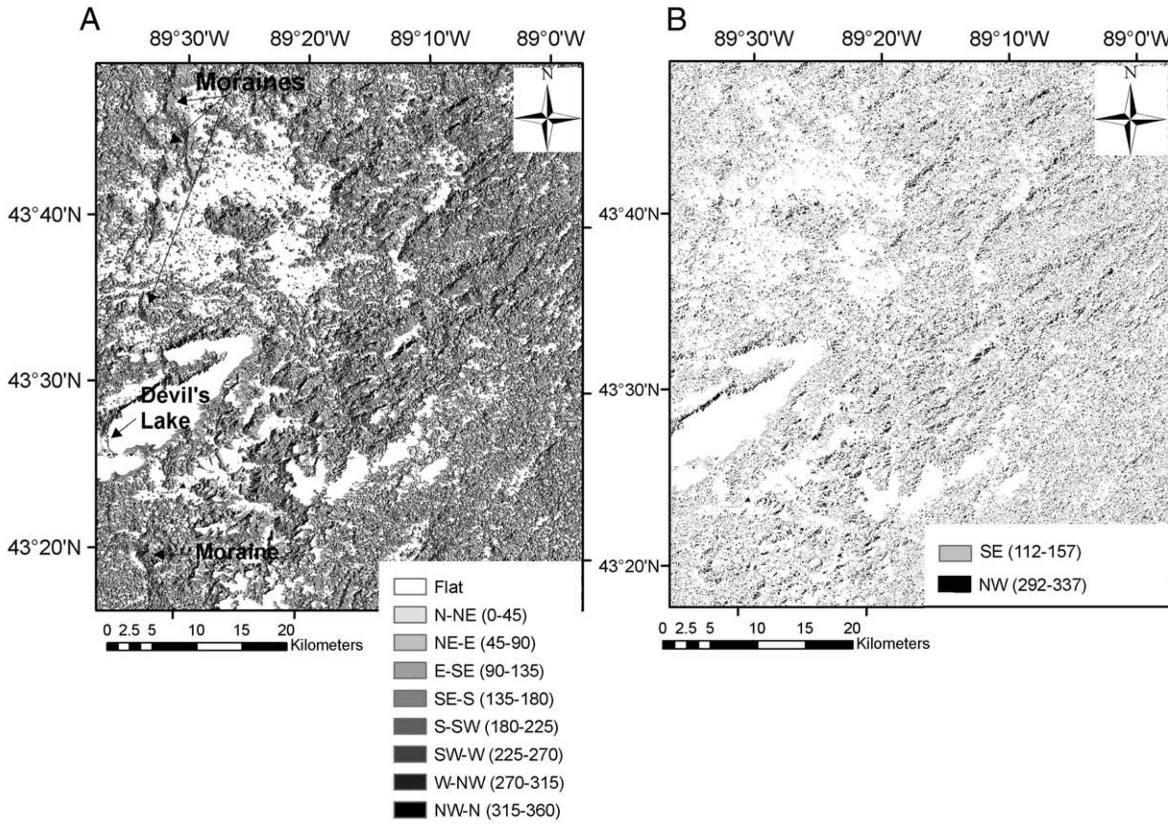

Fig. 7. Aspect analysis of a DEM calculated from an ASTER image of the Baraboo Hills and surrounding area. A) Slope directions. The long, sinuous ridges that trend N S are probably moraines. B) Highlight of slopes dipping to the northwest and southeast, revealing an overall fabric of the terrain that trend NE SW and parallel to the inferred ice-flow directions. The NE SW fabric terminates at the moraine.

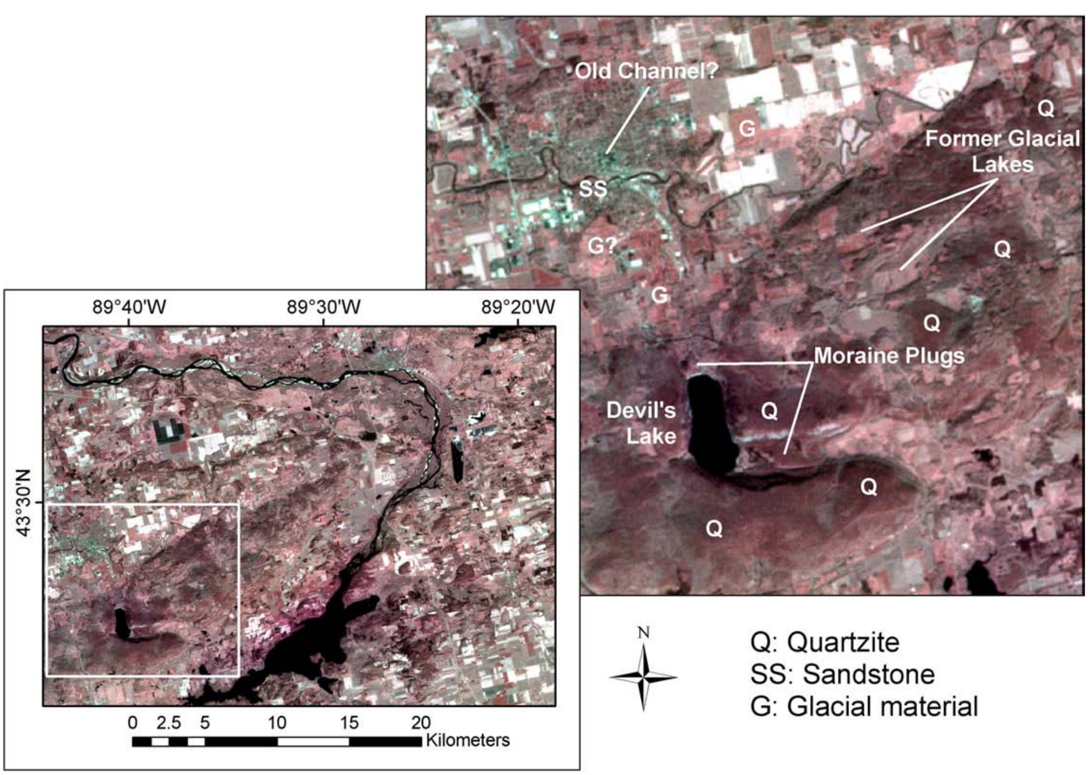

Fig. 8. Close-up of the Devil's Lake area displayed as ASTER SWIR Bands RGB 4 5 6. The heavily-wooded Baraboo Quartzite (Q) appears darker and the synclinal structure is readily apparent. The lighter material mostly consists of grass and low vegetation on glacial deposits (G) making former glacial lakes easily distinguishable east of Devil's Lake. The heavily-wooded moraine plugs on either end of Devil's Lake are also conspicuous. A light-colored trail north of Devil's Lake is spectrally similar to channel sands of the modern Wisconsin River and possibly reflects the course of an old, abandoned river channel that can be followed northwestward into the town of Baraboo. Cambrian sandstone (SS) is the source of channel sands and should exhibit a similar spectral image.

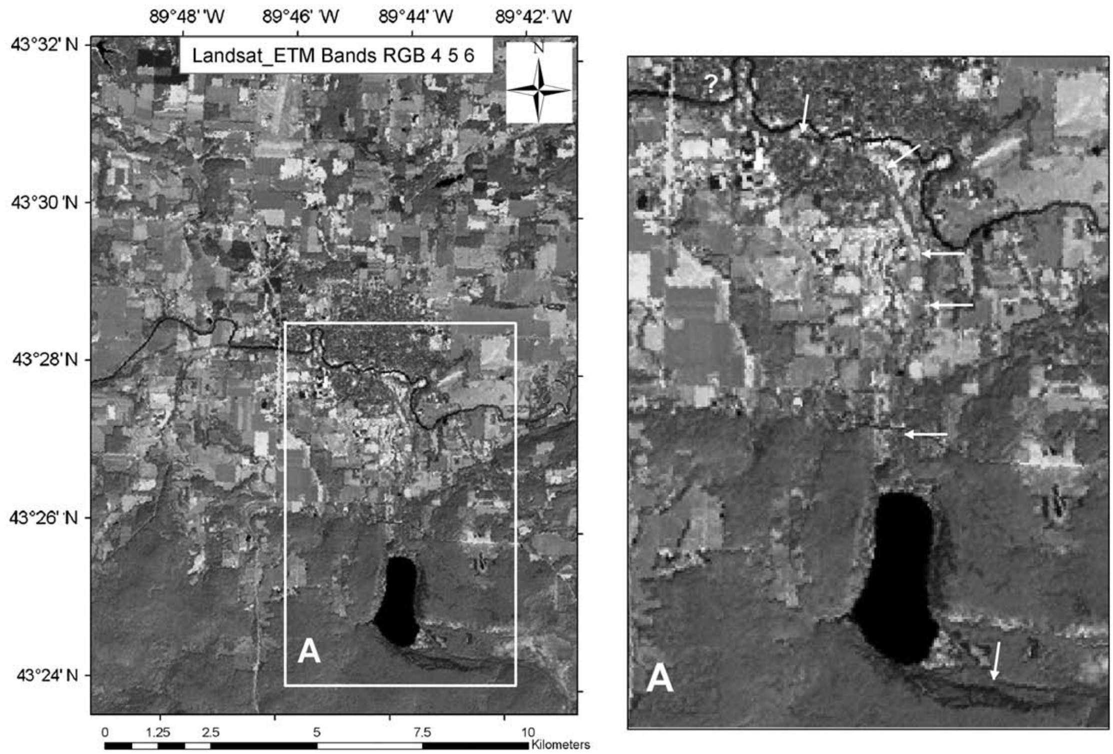

Fig. 9. Landsat TM image displayed in RGB 4 5 6 band combinations. Fluvial deposits, such as sand and gravel, appear aqua blue in this band combination. The possible course (arrows) of the old Wisconsin River appears as a band that can be traced north of Devil's Lake into the town of Baraboo, similar to the trend in Fig. 8.

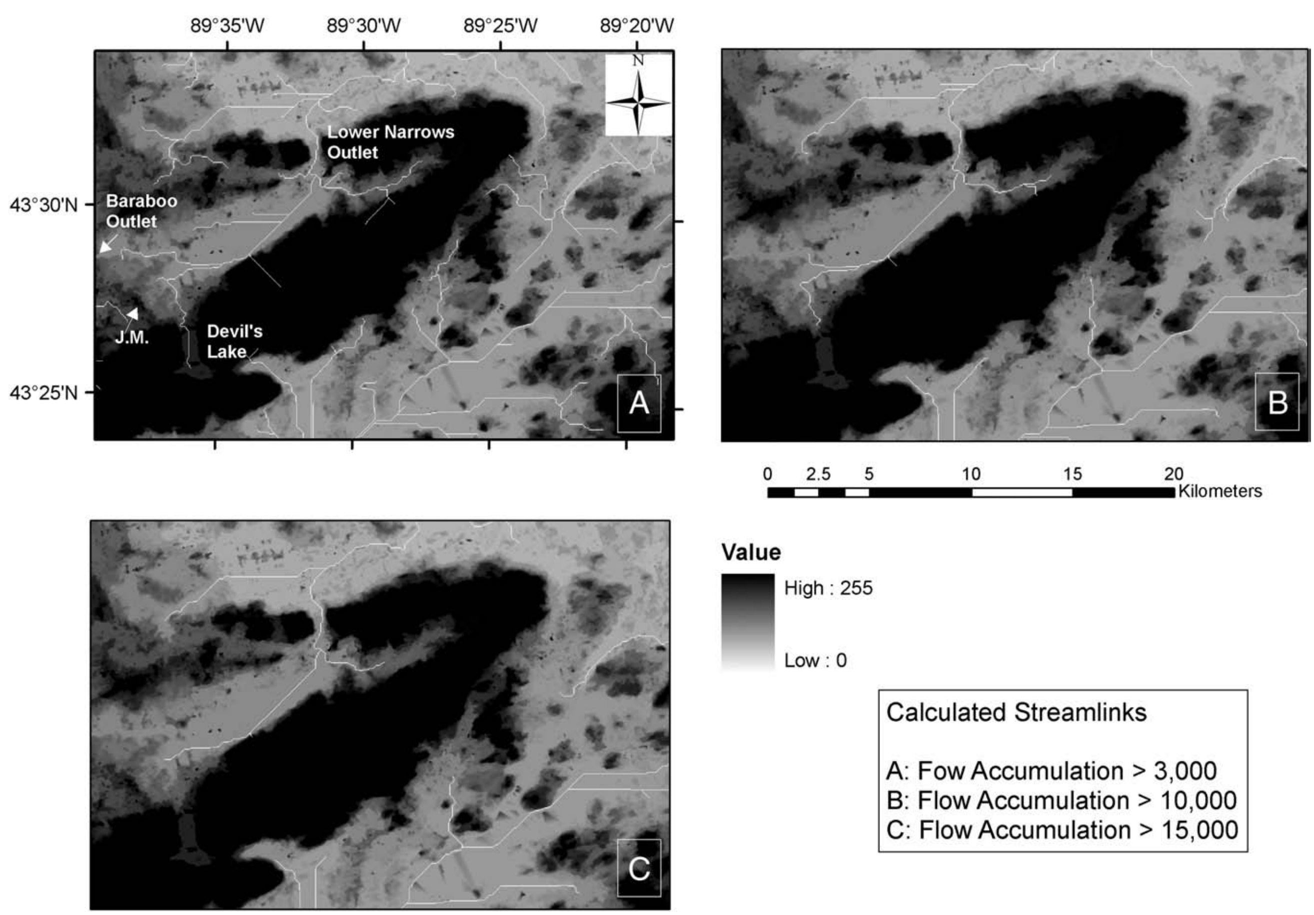

Fig. 10. Calculated stream links for flow accumulation values greater than (A) 3000, (B) 10,000 and (C) 15,000 superimposed on the ASTER DEM. See Section 4.5 for an explanation of the values. (A) and (B) generate streams that flow north and northeastward from the Devil's Lake Gorge out through the Lower Narrows Outlet and into the modern Wisconsin River. Just north of the Devil's Lake Gorge, the calculated stream also branches westward towards the Baraboo Outlet, but then abruptly terminates before reaching the latter.

reaching the latter. This truncation of the westward stream flow within the interior of the Baraboo Syncline is a result of blockage by the Johnstown Moraine (J.M. in Fig. 10A). If the old Wisconsin River originally flowed through Devil's Lake Gorge, then subsequent glaciation and formation of the Johnstown Moraine blocked and rerouted the river to a new location.

Fig. 11 compares the ASTER DEM (Fig. 11A) with the Aster Band 4/Band 5 image (Fig. 11B). The stream links for flow accumulations>3000 are also shown in both figures. The possible course of the old Wisconsin River is indicated by arrows. The old channel can be confidently traced northwestward of Devil's Lake only to the upper arrow at the tight bend in the present Baraboo River, beyond which the channel is probably buried by the younger Johnstown Moraine.

5. Discussion

5.1. Glacial history

Although the maximum and subsequent extents of the Green Bay Lobe are known from moraines, the exact timing of glacial advance, duration of ice stillstands, and retreat remain controversial (Winguth et al., 2004). The following ages and interpretations are based on available field evidence, scarce radiometric dating of associated materials, and glacier flow models.

The Green Bay Lobe reached the east end of Baraboo Hills ~19,000 years ago during the Wyeville Phase (Fig. 12A). During this phase, a large glacial lake called Lake Wisconsin was already in existence to the north and may have emptied southward through Devil's Lake Gorge into the Wisconsin River as shown in Fig. 12B (Clayton and Attig, 1989). The Green Bay Lobe advanced further westward such that Devil's Lake Gorge was plugged on both ends by ~15,000 years ago during the Johnstown Phase, blocking southward drainage of Lake Wisconsin (Figs. 13 and 14). The Green Bay Lobe began to recede eastward during the waning stages of the Wisconsin Glaciation. During the Elderon Phase ~14,000 years ago, a gap known as the Alloa Outlet opened between the eastern Baraboo Hills and retreating glacier (Fig. 15) and resulted in catastrophic drainage of Lake Wisconsin to the south (Clayton and Attig, 1989). It is within this context that the history of Devil's Lake and surrounding area is considered.

5.2. Moraines

The correct identification of glacial landform features from remote sensing imagery is largely dependent on pixel size (Clark, 1997; Smith et al., 2000). The area formerly covered by the Green Bay Lobe is characterized by narrow (<1 km) end moraines of moderate to high-relief in the ice margin zone while the ice margin zone behind the moraines is mainly rolling till plain (Colgan, 1999; Winguth et al., 2004). These features should tentatively be distinguishable at resolutions of 30 and 15 m on Landsat TM and ASTER data, respectively.

The Johnstown Moraine, which formed during maximum extent of the Green Bay Lobe ~15,000 years ago (Figs. 5, 13 and 14), today serves as a drainage divide between the Wisconsin River Valley to the west and the Fox River Valley to the east (Clayton and Attig, 1989). The moraine is not easily identified on the ASTER (Fig. 8) or Landsat TM (Fig. 9) spectral images, but stands out on the aspect analysis grid (Fig. 7A) and DEMs (Figs. 5 and 10). Smith et al. (2006) found that Landsat TM fared poorly in imaging glacial landforms in central Scotland, whereas Clark (1993) utilized Landsat TM in mapping complex ice flow patterns in Quebec, Canada. Factors such as the amount of cloud cover, apparent angle of the sun (ideally <20°) and vegetative cover affect the quality of Landsat TM data (Clark, 1997; Smith et al., 2006). Dunlop and Clark (2006) utilized ASTER data to study the distribution of ribbed moraine ridges that ranged from 17 to 1,110 m wide, 45 to 16,000 m long, and 1 to 64 m high in central Quebec, Canada.

The highest moraine elevations are assumed to reflect ice surface elevations at the time of moraine formation, with lines of equal elevation perpendicular to flowlines (Winguth et al., 2004). The highest moraine elevation was approximately that of the highest

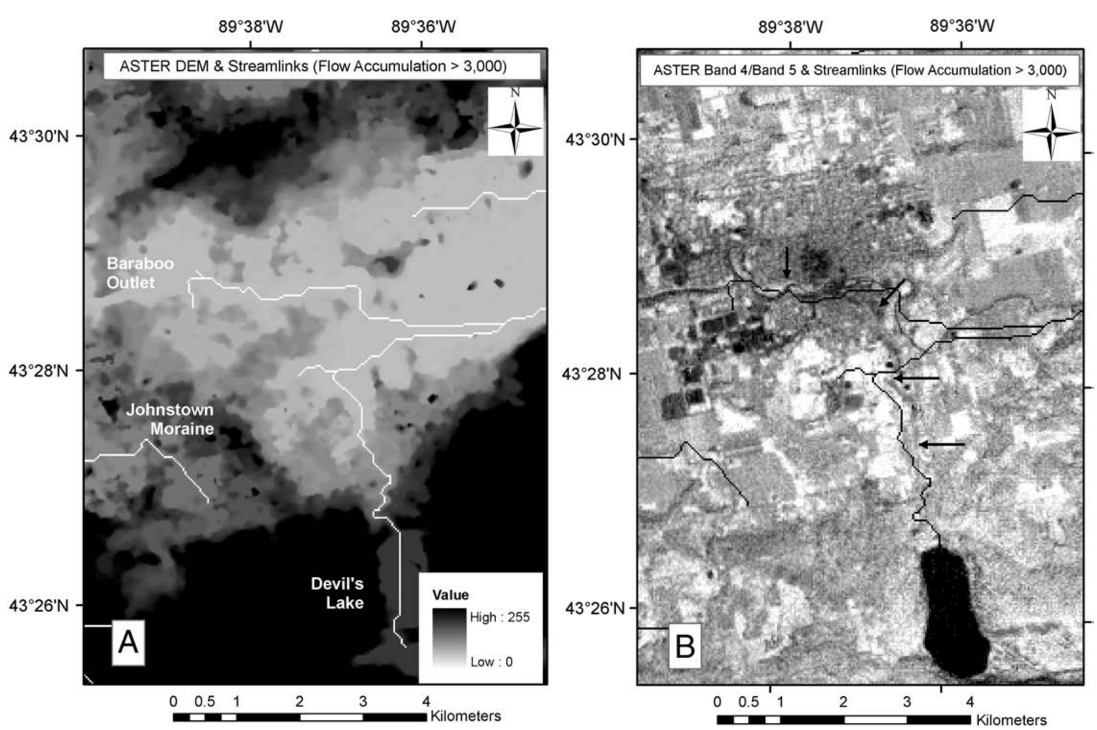

Fig. 11. Comparison of (A) the ASTER DEM with (B) the Aster Band 4/5 image. The stream links for flow accumulation values>3,000 are also shown in both images. The possible course of the old Wisconsin River is indicated by arrows in (B). The old channel can be confidently traced northwestward of Devil's Lake only to the upper arrow near the tight bend in the present Baraboo River, beyond which the channel is probably buried by the younger Johnstown Moraine.

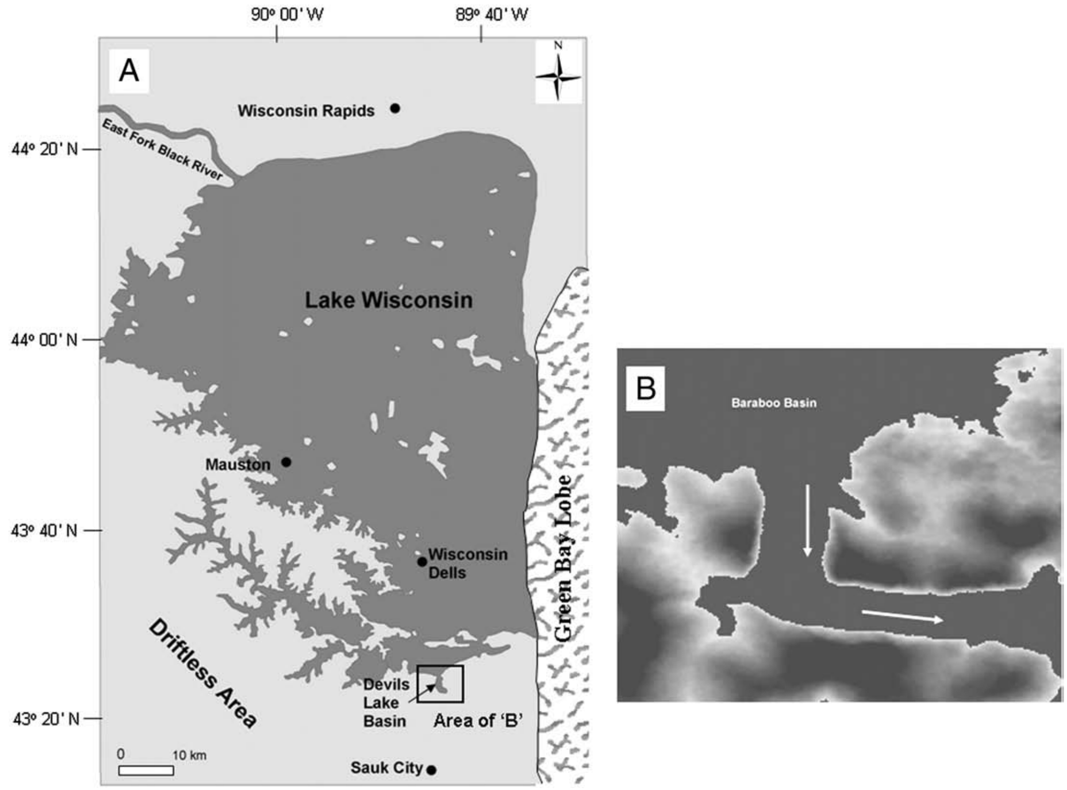

Fig. 12. The Green Bay Lobe reached the east end of the Baraboo Hills ~19,000 years ago during the Wyeville Phase. During this phase, a large glacial lake called Lake Wisconsin (A) was already in existence to the north and may have emptied southward through the Devil's Lake Gorge (B) into the Wisconsin River. Modified after Clayton and Attig (1989, their Figs. 19 and 31).

elevation in the Baraboo Hills, which is Sauk Point at 486 m (Colgan, 1999). Fig. 13A shows the possible extent of the Green Bay Lobe on the SAR-derived DEM during the Johnstown Phase, assuming that elevations of up to 380 m were glaciated. The western boundary of the lobe extends to the Johnstown Moraine as determined from the DEM. Fig. 13B shows the ice surface contours of Colgan (1999) based on the elevations of moraines, with the assumption that ice flow in this area was convergent and that the ice-surface topography focused water towards the Baraboo Hills. In both models, only the southern limb of the Baraboo Hills is exposed within the ice field.

During stable ice phases, sliding at the ice base is not an important process within a zone of at least 100 km behind the ice margin (Winguth et al., 2004). Glacial retreat, however, could form a new series of features. Aspect analysis of the ASTER-derived DEM in Fig. 7A,

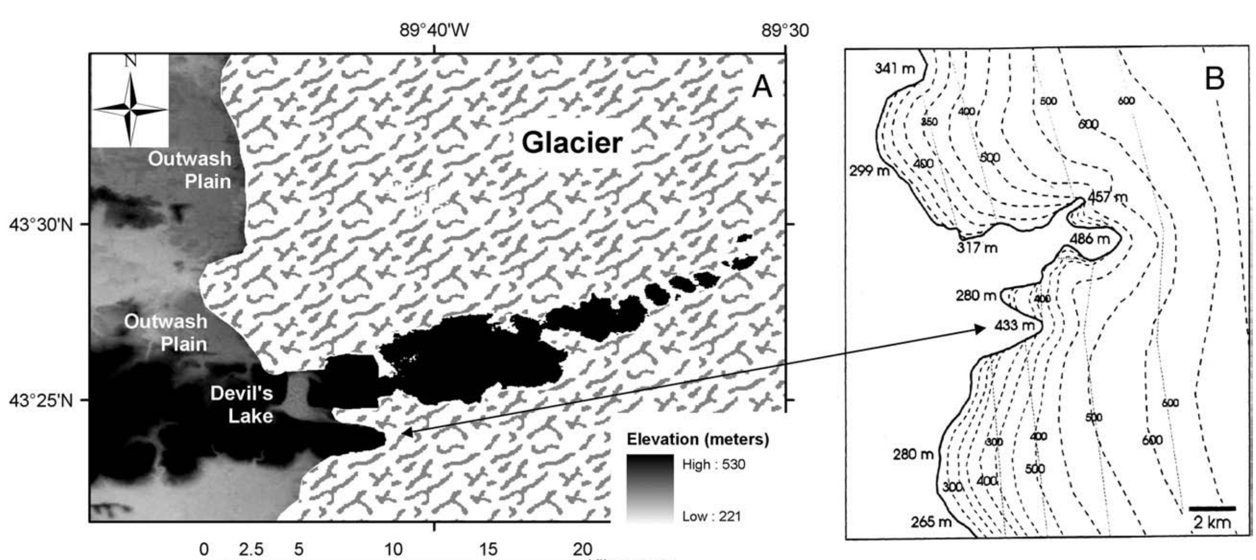

Fig. 13. Possible extent of the Green Bay Lobe during the Johnstown Phase ~15,000 years ago. A) SAR-derived DEM with an assumption that elevations of up to 380 m were glaciated. The western boundary of the lobe extends to the Johnstown Moraine as determined from the DEM. B) Ice surface contours of Colgan (1999) based on the elevations of moraines.

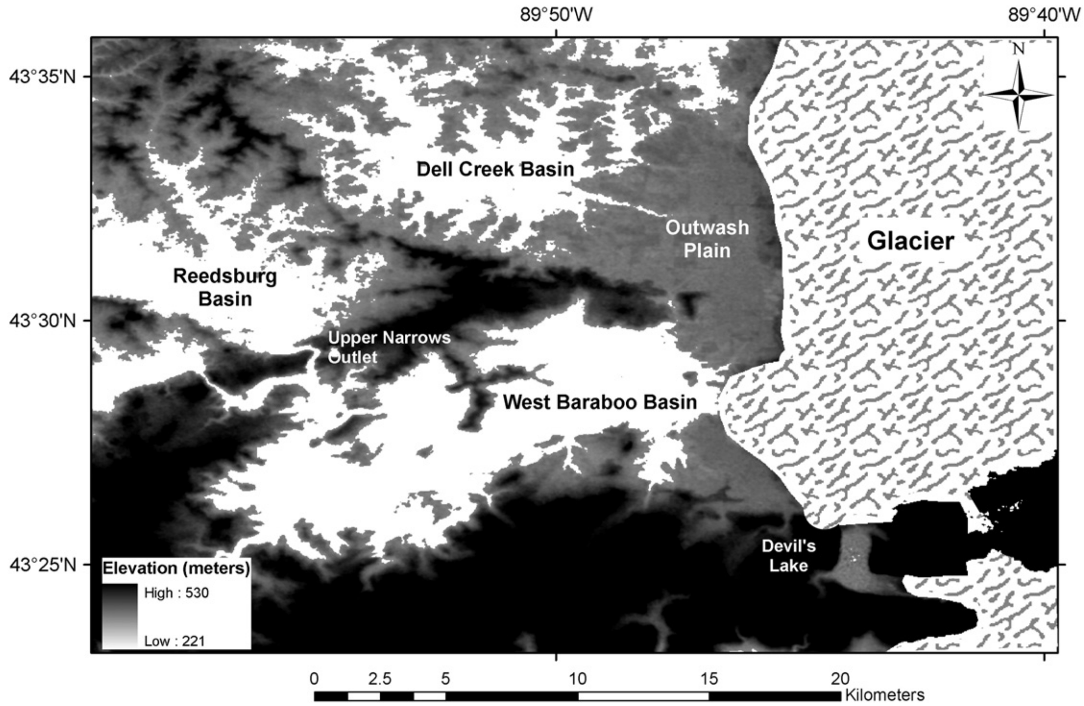

Fig. 14. Basin-fill model of the SAR-derived DEM for the southern basins of Lake Wisconsin showing possible water levels in the Dell Creek, Reedsburg, and West Baraboo basins during the Johnstown phase. The water surface of 280 m above modern sea level is taken from the contours of Clayton and Attig (1989, their Fig. 29). The glacial extent of the Green Bay Lobe terminates at the Johnstown Moraine and assumes that elevations up to 380 m were glaciated.

with a resolution of 15 m, reveals a series of distinct N S oriented moraines north of the Baraboo Hills. These recessional moraines, also clearly seen on the SAR-derived DEM, probably formed as the western margin of the Green Bay Lobe receded (Attig, 2007). Glacial retreat from the Johnstown Moraine may have occurred at a rate of 50 m yr^{-1} during the early stage (Colgan, 1999) and later quite rapidly at rates of

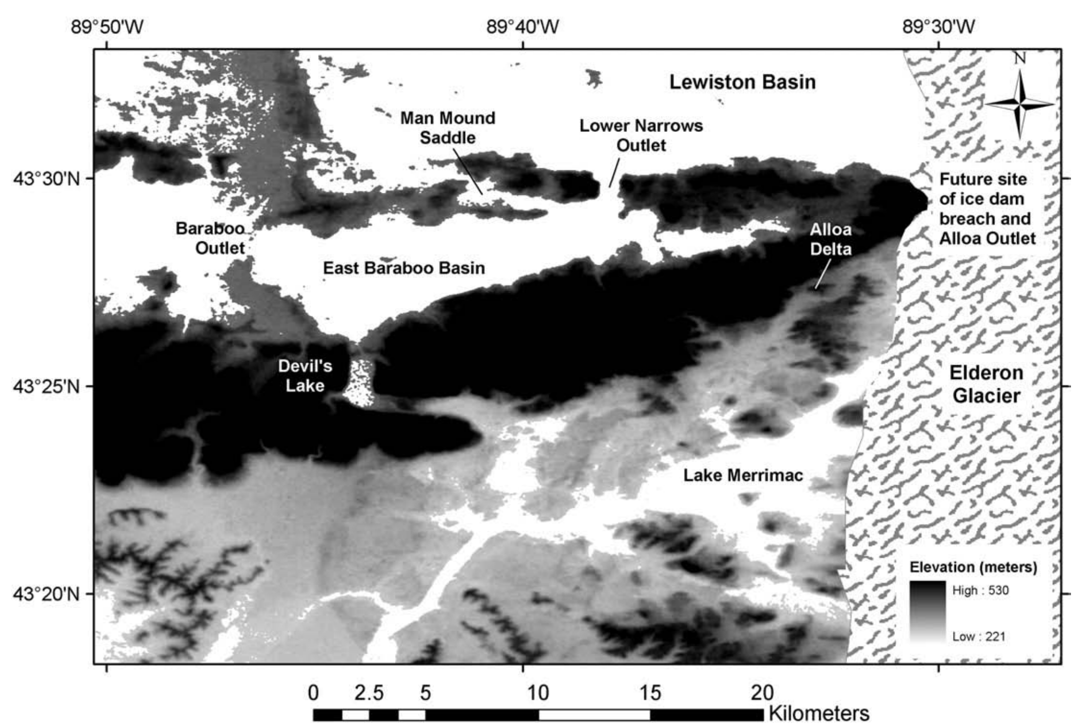

Fig. 15. SAR-derived DEM showing the possible extent of the Elderon glacier ~14,000 years ago, prior to breaching of the ice dam near the eastern bend of the Baraboo Syncline and opening of the Alloa Outlet. The postulated position of the Elderon glacier is taken after Clayton and Attig (1989, their Fig. 4). The Lewiston and East Baraboo basins are filled to 293 m above sea level, while the water level in Lake Merrimac to the south is only 245 m. This figure shows that the Baraboo Hills and moraine plugs on either side of Devil's Lake Gorge were sufficient to hold back Lake Wisconsin until the ice dam was breached at the Alloa Outlet.

300 to 900 m yr^{-1} (Maher and Mickelson, 1996; Winguth et al., 2004).

5.3. Other glacial features

It is possible to map individual drumlins, eskers, outwash deltas, and meltwater channels using Landsat TM data with a pixel size of 30 m (Clark, 1997), so that identification of these features with ASTER data at 15 m resolution should be straightforward. The streamlined landforms, such as drumlins and flutes, are easily identified (Figs. 2–4). These features are interpreted to generally parallel the direction of ice flow and therefore are good indicators of ancient ice-flow directions during the advance and retreat of glaciers. The duration of an ice stillstand and prevailing ice-flow conditions are important factors for drumlin formation. During the Johnstown phase, the ice was probably between 200 and 600 m thick over the Madison Drumlin Field. Large drumlins (Figs. 2-4) probably formed during that time since they are associated with steep ice margins and thick ice (Colgan and Mickelson, 1997). Large drumlin formation is likely associated with ice stillstand of at least 1000 years in combination with extensive frozen-bed conditions and subsequent thawing, along with ice flow velocities of 50 to 150 m yr^{-1} and high basal shear stress (Winguth et al., 2004).

During glacial retreat, sliding at the ice base is also important in the formation of drumlins (Winguth et al., 2004). Flutes and small drumlins are generally associated with thinner ice than are large drumlins. In the Madison drumlin field, small drumlins are found superimposed on large drumlins (Colgan and Mickelson, 1997). Small drumlins and remolded drumlins are evidence of minor advances or periods of stability during overall retreat of the Green Bay Lobe after 16,000 to 13,000 B.P. (Colgan, 1999). The overall streamlining of drumlins probably also occurred during deglaciation and ice retreat when basal meltwater and sliding became more important at the ice base. Most eskers in the Madison Drumlin Field also formed during glacial retreat and are good evidence for warming of the glacier (Colgan and Mickelson, 1997; Winguth et al., 2004).

Deglaciation modeling of the Green Bay Lobe by Winguth et al. (2004) suggests that the area exposed after glacial retreat was characterized by permafrost until at least ca. 14 ka B.P. Permafrost and a frozen bed near the glacial margin are important factors for shaping the glacial landscape, especially during ice retreat. Glacial landforms associated with cold ice conditions and permafrost includes tunnel channels, polygons (Clayton and Attig, 1989), and drumlins (Mickelson et al., 1983). Meltwater probably discharged through a series of tunnel channels during glacial advance of the Johnstown phase, but switched to an esker system during glacial retreat (Colgan, 1999). Drumlins, flutes, striations, and eskers suggest that the base of the Green Bay Lobe was not frozen during retreat, even though permafrost was present ahead of the glacier (Colgan, 1999).

5.4. Lake Wisconsin

During the last part of Wisconsin glaciation, central Wisconsin was occupied by a large proglacial lake known as Lake Wisconsin (Fig. 12A) that existed from approximately 19,000 to 14,000 years ago. Lake Wisconsin probably came into existence when the Green Bay Lobe reached the Baraboo Hills approximately 19,000 years ago during the Wyeville Phase, blocking the south-flowing Wisconsin River and causing water to back up and form the large proglacial lake (Clayton and Attig, 1989; Hooyer et al., 2004; Attig, 2007; Clayton and Knox, 2008). During its existence, Lake Wisconsin occupied several interconnected basins (Figs. 12 and 14) that included the main basin and several smaller basins to the south. During most of its history, Lake Wisconsin drained to the northwest via the Black River (Fig. 12A), a tributary of the Mississippi River. During the Wyeville Phase ~19,000 years ago, Lake Wisconsin may have also drained southward through Devil's Lake Gorge (Fig. 12B) before the latter was plugged by the Johnstown Moraine (Clayton and Attig, 1989).

5.5. The Alloa flood

When the glacier receded past its interface with the Baraboo Hills during the Elderon Phase ~14,000 years ago (Fig. 15), the ice dam was breached and resulted in catastrophic drainage of Lake Wisconsin into Lake Merrimac (Clayton and Attig, 1989; Hooyer et al., 2004; Attig, 2007; Clayton and Knox, 2008). When water first flowed through the Alloa Outlet (Fig. 15) following this breach, the west bank was mostly erosional-resistant Baraboo quartzite while the east bank was an easily-eroded glacier. Final drainage through the Alloa Outlet was probably catastrophic and caused the water level in the Lewiston Basin to drop tens of meters in only a few days (Clayton and Attig, 1989; Attig, 2007). The abrupt drop in the water level of the Lewiston Basin, in turn, caused water from the main and southern basins to flood into the Lewiston Basin through a breach in the Johnstown Moraine, cutting the sandstone gorges of the Wisconsin Dells (Clayton and Attig, 1989; Hooyer et al., 2004).

When Lake Wisconsin began flowing into Lake Merrimac (Fig. 15), the water level in the Lewiston Basin might have dropped over 30 m in only a few days (Clayton and Attig, 1989). Clayton and Knox (2008) estimate that the breach and resulting catastrophic flood may have drained Lake Wisconsin in about a week. The initial flood down the Wisconsin River involved a catastrophic discharge from the Lewiston basin that was manifested further downstream, as evidenced by large boulders of Baraboo quartzite downstream near Sauk City, the scouring of loess deposits, and intense erosion of terrace deposits (Clayton and Attig, 1989; Hooyer et al., 2004). Clayton and Knox (2008) attribute the stair-step terraces in the lower Wisconsin River valley, downstream from Lake Merrimac, to episodic downcutting associated with the initial flood of Lake Wisconsin and subsequent smaller events from the same or nearby proglacial lakes.

The Alloa delta, located near the eastern bend of the Baraboo Syncline (Fig. 15), records the catastrophic flood that resulted from the sudden drainage of Lake Wisconsin into Lake Merrimac. Sediment of the Alloa delta, as observed by Bretz (1950) in a gravel pit, display “foresets of extraordinary open-work coarse gravel” that dip southward and contains boulders as large as 1.5 m in diameter (Clayton and Attig, 1989; Clayton and Knox, 2008).

5.6. The Baraboo Hills and Devil's Lake

Precambrian and Cambrian rocks within and surrounding Devil's Lake State Park are mostly covered by glacial deposits and Recent wind-blown silt (Black, 1974). Glacial till in the area comprises the Horicon Formation and consists of sandy diamicton containing boulders and a matrix composition of sand, silt and clay (Colgan and Mickelson, 1997). Most of the Horicon Formation was probably deposited sometime between 21,000 and 14,000 B.P. (Maher and Mickelson, 1996; Colgan and Mickelson, 1997).

The most conspicuous glacial feature in the area is the end moraine of Cary age (late Woodfordian) that forms the plugs on either end of Devil's Lake (Fig. 8). The moraine is probably only 13,000–16,000 years old and is part of the Johnstown Moraine (Black, 1974 and references within). Within Devil's Lake State Park, the end moraine is generally 4.5 to 6 m high. The two plugs that contain Devil's Lake, however, rise 27 to 40 m above the lake (Black, 1974). The outwash plains that occur ahead of the former glacial fronts in and around the state park can be readily seen in Fig. 5. Former proglacial lakes, characterized by basins containing distinctive lake deposits such as silty sands, clay and gravel (Black, 1974), are readily distinguished in Fig. 8.

Devil's Lake Gorge today is 1 km wide, 5 km long, and 140 m deep (Clayton and Attig, 1989). At least part of the gorge is Precambrian in age judging from the presence of Cambrian sandstone. The valley under Devil's Lake is filled with at least 100 m of glacial sediment since the deepest well in the gorge, ~117 m, did not reach bedrock (Black, 1974; Clayton and Attig, 1989). It is possible that an Early-Pleistocene glacier invaded the gorge long before formation of the Late Pleistocene moraine plugs (Black, 1974). Just before the maximum expansion of the Green Bay Lobe during the Johnstown Phase approximately 15,000 years ago, Lake Wisconsin may have emptied southwards through Devil's Lake gorge (Fig. 12B) into the Wisconsin River (Clayton and Attig, 1989). This could also account for much of the Pleistocene material in Devil's Lake basin.

With the advance of the Johnstown Moraine ~15,000 years ago, Devil's Lake outlet was dammed by glacial material on either end (Figs. 13 and 14). Devil's Lake, therefore, became an independent proglacial lake poised 40 m above Lake Wisconsin. Fig. 14 shows the southern basins of Lake Wisconsin that included the Dell Creek, Reedsburg, and West Baraboo basins. The water surface of 280 m above modern sea level is taken from the contours of Clayton and Attig (1989). Water flowed from the Reedsburg Basin through the Upper Narrows Outlet and into West Baraboo Basin (Clayton and Attig, 1989).

The Green Bay Lobe receded eastward during the subsequent Elderon Phase, eventually exposing the East Baraboo Basin. The East Baraboo Basin therefore became part of Lake Wisconsin via its connection with the West Baraboo Basin through the Baraboo Outlet, and Lewiston Basin via the Lower Narrows Outlet (Clayton and Attig, 1989) assuming water levels 293 m above modern sea level (Fig. 15). Although dates from organic sediment obtained from Devil's Lake suggest that the Green Bay Lobe was near its maximum as late as 13,000 to 14,000 B.P. (Maher, 1982), these younger dates may simply reflect the time of degradation of permafrost and the arrival of spruce (Clayton et al., 1992; Colgan, 1999) following earlier retreat of the lobe.

Within the East Baraboo Basin, the Man Mound Saddle and Lower Narrows Outlet are two gaps within the north limb of the Baraboo Syncline (Fig. 15). Today the Baraboo River flows from the West Baraboo to the East Baraboo Basin via the Baraboo Outlet and then northward through the Lower Narrows Outlet, a narrow gorge about 0.5 km in width and 1 km long, before emptying into the modern Wisconsin River (Clayton and Attig, 1989). The Lower Narrows Outlet was probably cut by a preglacial river prior to the existence of Lake Wisconsin (Clayton and Attig, 1989). When Lake Wisconsin came into existence ~19,000 years ago, the water might have drained from the lake southward into the East Baraboo Basin via the Lower Narrows Outlet before exiting through Devil's Lake Gorge (Clayton and Attig, 1989). The advancing Green Bay Lobe buried the East Baraboo Basin during the Johnstown Phase (Figs. 13 and 14). Following retreat of the Green Bay Lobe during the Elderon Phase, the Lower Narrows Outlet carried water from the East Baraboo to Lewiston basins (Clayton and Attig, 1989). The Man Mound Saddle is possibly a predecessor of the Lower Narrows Outlet (Clayton and Attig, 1989). The Man Mound Saddle, which today lies between 287 and 293 m above sea level, may have been near the level of Lake Wisconsin prior to opening of the Alloa Outlet during the Elderon Phase (Clayton and Attig, 1989) as shown in Fig. 15.

Fig. 15 models the possible extent of the Elderon glacier prior to breaching of the ice dam. The maximum water level for Lake Wisconsin is 293 m, the height assumed by Clayton and Attig (1989) for the Elderon Phase based on scarce terrace elevations and other ancient shoreline features. At this lake level, the Man Mound Saddle is flooded and a continuous connection occurs from the Lewiston, through the East Baraboo and into the West Baraboo basins. The Alloa Delta is a conspicuous feature exposed above water. The Lewiston and East Baraboo basins are filled to 293 m above sea level, while the water level in Lake Merrimac to the south is only 245 m. Fig. 15 shows that the Baraboo Hills and moraine plugs on either side of the Devil's Lake Gorge were sufficient to hold back Lake Wisconsin until the ice dam was breached at the Alloa Outlet along the eastern nose of the Baraboo Syncline. The resulting torrent of water through Lake Merrimac and the lower Wisconsin River would have indeed been catastrophic. Following the final drainage of Lake Wisconsin 14,000 years ago, Devil's Lake took on its present character as an isolated water body dammed on both ends by glacial moraine.

5.7. Did the Wisconsin River flow through the Devil's Lake Gorge?

Early workers (i.e. Chamberlin, 1883; Alden, 1918) thought that the preglacial Wisconsin River flowed through the Devil's Lake Gorge prior to the latter being blocked on both ends by the Johnstown Moraine. Although the gorge was already partly exhumed by preglacial streams and mass-wasting processes after deposition of Paleozoic rocks but prior to Wisconsin glaciation, other workers claim that the Wisconsin River already flowed around the eastern edge of the Baraboo Hills before advancement of the Green Bay Lobe ~19,000 years ago (Clayton and Attig, 1989; Clayton and Knox, 2008).

The above interpretation, however, does not explain the dry river bed that presently extends north and westward from Devil's Lake into the town of Baraboo as revealed in the ASTER and Landsat TM images (Figs. 8 and 9). Unfortunately, any continuation of the river bed further to the north was subsequently buried by the Johnstown Moraine (Fig. 11A).

Fig. 16 postulates one possible route for the Old Wisconsin River. Following the general trend interpreted from Figs. 8 and 9, the river may have flowed west of its present course where it entered the northern limb of the Baraboo Syncline via the Hogback Outlet, flowed southeastward through the interior of the syncline and exited the southern limb through the Devil's Lake Gorge. Alternatively, the old river channel could have been further east where it entered the northern limb through an outlet between the Hogback Outlet and the Man Mound Saddle that is now buried beneath the Johnstown Moraine and an outwash plain, while the southern outlet would have remained the Devil's Lake Gorge. As the Green Bay Lobe advanced, the formation of the Johnstown Moraine by ~15,000 years ago buried much of the former river valley with glacial debris and outwash sediment (Fig. 16). Following retreat of the Green Bay Lobe and final drainage of Lake Wisconsin ~14,000 years ago, the Wisconsin River established a new course east of the Johnstown Moraine and around the eastern nose of the Baraboo Syncline.

6. Conclusions

Remote sensing and GIS provide new perspectives and tools for observing, analyzing and modeling glacial features in south-central Wisconsin. Although aerial photographs, topographic maps, and field mapping are important for identifying smaller features at resolutions of a few meters, remote sensing data can associate these features with larger-scale landforms and regional trends not readily recognized on a local scale. The SAR-derived DEM and ASTER data, although not capable of imaging landforms less than 15 or 30 m in size, clearly reveal larger-scale glacial moraines and streamlined features such as flutes, drumlins and eskers over extensive regions of the Green Bay Lobe. This regional perspective compliments earlier studies and shows that ice flowed radially away from the axis of the Green Bay Lobe with flow directions to the southwest on the western side and south to southeast in the central and eastern parts of the lobe.

The Landsat TM and ASTER multi-spectral data allows visualization at different wavelengths and band combinations in order to identify features not readily apparent on aerial photographs and topographic maps. Areas of glacial material, quartzite, sandstone, and recent alluvium can be distinguished using ASTER SWIR RGB band combinations that are sensitive to variations in vegetation. ASTER and Landsat TM band combinations identify an abandoned river

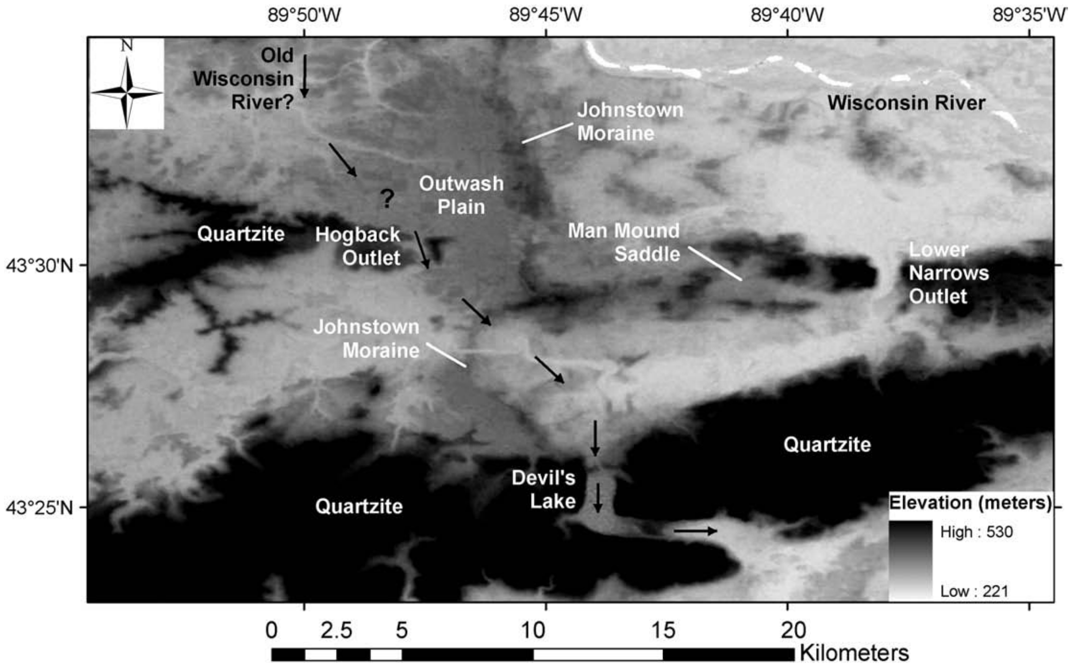

Fig. 16. SAR-derived DEM showing one possible route for the Old Wisconsin River as indicated by the arrows. The river may have flowed west of its present course where it entered the northern limb of the Baraboo Syncline via the Hogback Outlet, flowed southeastward through the interior of the syncline and exited the southern limb through the Devil's Lake Gorge. Alternatively, the old river channel could have been further east where it entered the northern limb through an outlet between the Hogback Outlet and Man Mound Saddle that is now buried beneath the Johnstown Moraine and outwash plain, while the southern outlet would have remained the Devil's Lake Gorge.

channel, possibly the old course of the Wisconsin River, which can be traced north and northwest of Devil's Lake into the town of Baraboo. DEMs generated from remote sensing data improve visualization of glacial and other landforms compared to topographic maps and cover larger areas than aerial photographs. A composite image of SAR-derived DEMs readily reveals the extent of the Green Bay Lobe along with moraines, streamlined glacial landforms (Fig. 2) and the doubly-plunging synclinal structure of the Baraboo Hills (Fig. 5).

The digital remote sensing data can be imported into a GIS in order to test interpretations of the glacial history of Devil's Lake and surrounding area. Aspect analyses of an ASTER-generated DEM (Fig. 7) reveals an NE SW trending glacial fabric that terminates at the Johnstown Moraine, in addition to several N S trending moraines north of the Baraboo Hills that possibly formed during eastward retreat of the Green Bay Lobe following the Johnstown Phase. Although the moraines are also visible on other DEMs, the aspect analysis highlights slope directions for easier identification. The possible abandoned river channel imaged by ASTER and Landsat TM band combinations can be tested in GIS. Stream-flow models created in GIS generate stream directions that roughly follow the river bed from Devil's Lake northwestward into the town of Baraboo, but are abruptly truncated by the Johnstown Moraine. The Johnstown Moraine likely buried any pre-existing river channel northwest of Baraboo. The maximum extent of the Green Bay Lobe was modeled by assuming that elevations $\leq$380 m were glaciated and the western termination of the Green Bay Lobe coincided with the Johnstown Moraine (Fig. 13A). This glacial episode formed the moraine plugs on both ends of Devil's Lake Gorge. Another DEM fill model uses easily discernable color combinations to display former glacial lakes and glacial cover (Fig. 14) in greater detail than could be visualized simply by viewing contour maps and aerial photographs. Fill models determined in GIS demonstrate that the Baraboo Hills and moraine plugs of Devil's Lake gorge were high enough to hold back Lake Wisconsin from draining into Lake Merrimac (Fig. 15) until the Alloa Ice Dam was breached ~14,000 years ago. Finally, a SAR-generated DEM was used to propose two possible courses for the old Wisconsin River (Fig. 16) prior to the advance of the Green Bay Lobe.

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