Geomorphology 102 (2008) 615–623

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Post-glacial fluvial response and landform development in the upper Muskegon River valley in North-Central Lower Michigan, U.S.A.

Alan F. Arbogast [a,*], Juleigh R. Bookout [a], Bradley R. Schrotenboer [a], Amy Lansdale [b], Ginny L. Rust [c], Victorino A. Bato [d]

[a] Department of Geography, 123 Geography, Michigan State University, East Lansing, MI, 48824-1115, USA
[b] ENVIRON International Corp, 4350 North Fairfax Drive, Suite 300, Arlington, VA 22203, USA
[c] Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA
[d] National Mapping and Resource Information Authority of the Philippines, Makati City, Philippines

ARTICLE INFO

Article history:
Received 29 November 2007
Received in revised form 10 June 2008
Accepted 11 June 2008
Available online 20 June 2008

Keywords:
Muskegon River
Michigan
Stream terraces
Paleomeanders

ABSTRACT

This study focuses on the upper part of the Muskegon River system in north-central Lower Michigan and is the first to reconstruct the post-glacial history of fluvial landform development in the core of North America's Great Lakes region. Results indicate that the upper Muskegon River valley contains four alluvial terraces and numerous paleomeanders. Radiocarbon dating of peats within these old channels provides a good chronology for stream behavior and landform development. The T-4 terrace is a paired Pleistocene outwash/lacustrine surface that probably formed about 12,500 years ago. The T-3 terrace is a fill-strath surface that was cut between about 12,000 and perhaps 9500 years ago. The geometry of macromeanders on this surface suggests that stream discharge was ~8 times greater than during the Holocene.

The Pleistocene/Holocene transition is marked by a major period of downcutting that likely began as the climate warmed/dried and sediment yield diminished. This period of downcutting potentially lasted through the drier middle Holocene, creating a 6-m-high escarpment in the valley. The Muskegon River then began to aggrade when the climate became wetter. Subsequently the river again incised, creating the paired T-2 terrace, about 3400 years ago when the climate became still wetter. T-2 paleomeanders indicate that stream discharge at this time was consistent with the modern river. In the past 2500 years, the stream has constructed a poorly defined complex of T-1 terraces. These surfaces likely formed due to complex response associated with more variable climate. This study demonstrates that the upper Muskegon River has a similar post-glacial history as streams on deglacial and periglacial landscapes elsewhere in the world.

1. Introduction

The importance of fluvial landforms in Quaternary landscape studies has long been recognized (e.g., Davis, 1909; Penck and Bruckner, 1909; Fisk, 1944; Dury, 1970; Knox, 1975; Harvey et al., 1981; Ballantyne and Whittington, 1999; Howard et al., 2004). In the context of these investigations, internal adjustments and landform development have been linked to a number of variables, including base level change (e.g., Davis, 1909; Chorley, 1963; Bull, 1990), climate fluctuations (e.g., Knox, 1984; Van Nest and Bettis, 1990; Arbogast and Johnson, 1994; Hsieh and Knuepfer, 2001; Bridgland et al., 2004), and internal complex responses (e.g., Schumm and Parker, 1973; Womack and Schumm, 1977; Minako and Tetsuji, 2006). Taken together, these studies have demonstrated that stream systems are excellent indirect indicators of environmental change.

One particular focus of stream studies has been the response of fluvial systems in glaciated and periglacial areas at the end of the most recent ice age (marine Oxygen Isotope Stage 2) and the subsequent evolution of landforms during the Holocene. It is well documented, for example, that braided meltwater streams around the world developed meandering channels when sediment yield decreased as deglaciation progressed (Schumm and Brakenridge, 1987; Knox, 1995; Starkel, 1995; Blum and Törnqvist, 2000). Similar changes have been reported for streams in periglacial areas (e.g., Kozarski, 1991; Kasse et al., 1995; Straffin et al., 2000).

Other streams, such as some in the western Canadian prairies (e.g., Bryan et al., 1987) and Europe (Schumanski, 1983; Starkel et al., 1996; Sidorchuk et al., 2001), changed from systems with macromeanders during the late Pleistocene to those with much smaller Holocene meandering patterns. Another observation is that many streams began downcutting at the Pleistocene/Holocene transition because of reduced sediment load, resulting in distinct, paired terraces. This type of channel adjustment has been reported in Europe (Starkel, 1991; Walker, 1995; Tebbens et al., 1999; Howard et al., 2004), the western

* Corresponding author. Tel.: +1 517 355 5262; fax: +1 517 432 1671.
E-mail address: dunes@msu.edu (A.F. Arbogast).

0169-555X/$ – see front matter
doi:10.1016/j.geomorph.2008.06.008

Canadian prairies (Rains and Welch, 1988; Campbell and Campbell, 1997; Otelelaar, 2002), and the state of New York in the eastern U.S. (Scully and Arnold, 1981).

Following the adjustments at the Pleistocene/Holocene transition, many streams in formerly glaciated and periglacial areas subsequently underwent a series of changes in the Holocene that led to the creation of terraces. In northern Britain, for example, flights of terraces developed during the middle and late Holocene due to climate variation and human activity (Howard et al., 1999). Along the upper Susquehanna River in the state of New York, 2 terraces and the floodplain have formed since deglaciation due to climate changes. A series of alluvial terraces has also been recognized in Alberta, Canada that formed since the ice retreated (Otelelaar, 2002; Evans et al., 2004).

Although much is known about the post-glacial landform development of river systems in many deglacial and periglacial areas, little is known about such histories in the core of the Great Lakes region in North America. Abundant fluvial research has been conducted on streams in the state of Wisconsin, but has largely focused on Holocene alluviation processes (e.g., Knox, 1972), the Holocene flood history of the upper Mississippi valley (Knox, 1993, 2006), and terrace formation due to European settlement (Woltemade, 1994). A limited amount of fluvial research has also been conducted in Michigan, but has focused primarily on stream response near the Great Lake's coasts during the Nipissing transgression in the middle Holocene and subsequent cutting and filling cycles in the late Holocene (Monoghan and Lovis, 2005).

The primary goal of this study is to reconstruct the chronology of stream behavior and landform development in the Great Lakes region and relate it to patterns observed elsewhere in the world (e.g., Scully and Arnold, 1981; Schumanski, 1983; Bryan et al., 1987; Sidorchuk et al., 2001; Howard et al., 2004). It focuses on the upper Muskegon River valley in north-central Michigan where a variety of stream terraces and related landforms have been identified that spans the post-glacial history of the system.

2. Regional setting

The Muskegon River is a meandering stream that originates in north-central Lower Michigan at Houghton Lake (Fig. 1). From this locality, the river flows about 340 km before it enters Lake Michigan at the city of Muskegon. Over its course, the stream drops 189 m and drains about 6000 km^2 of area (O'Neal, 1997). The study area for this project focuses on the upper half of the Muskegon River, extending ~150 km from Reedsburg Dam near Houghton Lake southwest to the US-10 bridge in the town of Evart (Fig. 1). Along this length, the river descends 45 m, winding its way through numerous meanders, split channels, and oxbow lakes. The average gradient of the Muskegon River in this reach of the system is ~0.005. Mean discharge of the Muskegon River at Evart ranges from a low of about 14 m^3/s in late summer and early fall to a high of about 60 m^3/s at the height of the spring snow melt (USGS, 2004).

Prior to the initial development of the Muskegon River, northern Michigan was covered by glacial ice for much of the Late Wisconsin glacial period (e.g., Eschman, 1985; Blewett and Winters, 1995; Schaetzl and Weisenborn, 2004). Final deglaciation of the study area occurred ~16 ka when ice retreated from southern Michigan north to the Straits of Mackinac and to the west and east toward the Lake Michigan and Lake Huron basins, respectively (e.g., Schaetzl and Weisenborn, 2004). Although details are vague, Tardy (2005) believes that a large outwash plain (known locally as the Saint Helen outwash plain) was constructed in the area where the Muskegon River now originates during this deglacial phase. Soil evidence (e.g., laminae, thick clay lenses) suggests that much of the outwash plain was

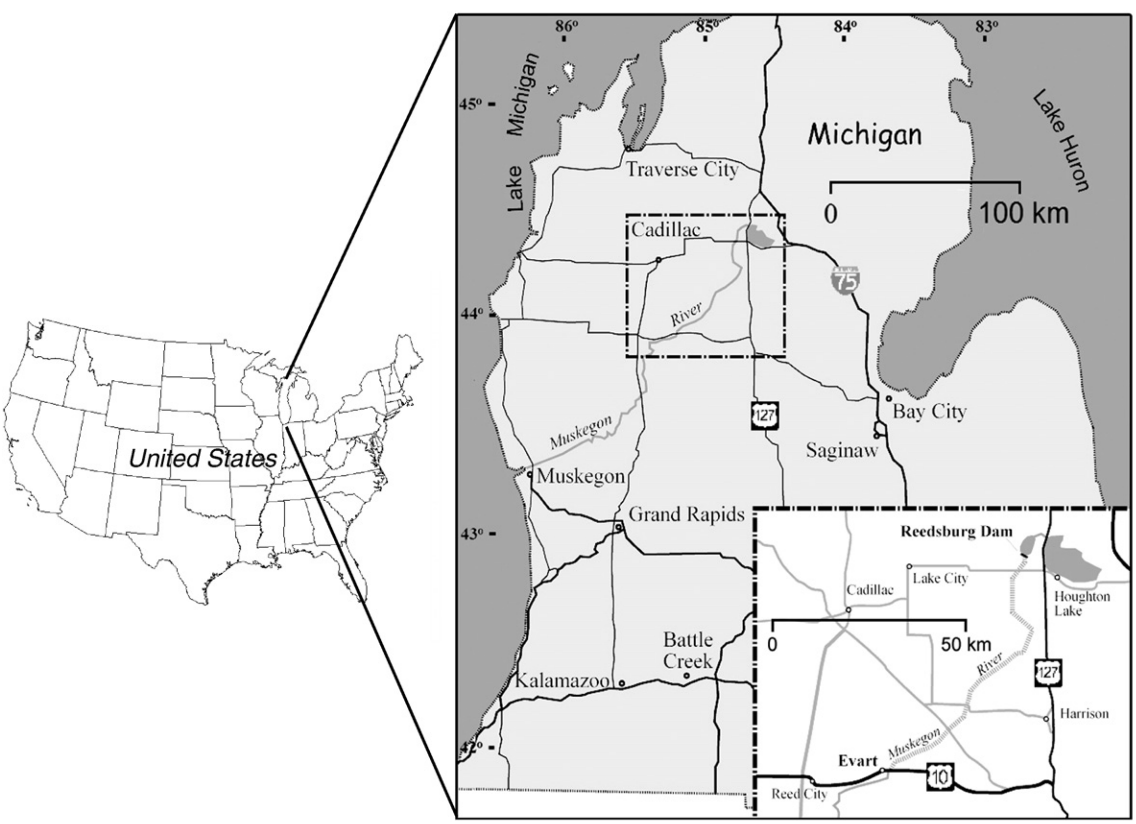

Fig. 1. The location of the Muskegon River in Lower Michigan. Inset maps show the position of Michigan in the U.S and the extent of the study area from Reedsburg Dam to Evart.

subsequently inundated by a meltwater lake or lakes (Tardy, 2005) as the ice receded further. Houghton Lake is probably a remnant of this late Pleistocene lake system.

In addition to the outwash and lacustrine sediments in the region, a portion of the study area consists of complex mix of swamps, bogs, and sand dunes. A large bog occurs, for example, northwest of the uppermost reaches of the Muskegon River west of Houghton Lake. An array of other bogs are scattered throughout the area. A small (~20 km^2) dune field occurs on the east side of the Muskegon River about 25 km south of Houghton Lake.

The climate of the Muskegon watershed is classified as humid continental, with cold winters and warm, humid summers. Most precipitation occurs during the late summer months as moisture from the Gulf of Mexico flows north into the area. Winter precipitation falls as snow, with the heaviest snowfalls brought in by fronts moving east across Lake Michigan. Some additional snowfall accumulates from lake-effect precipitation, especially to the southwest. Total precipitation generally increases from NE to SW across the watershed, ranging from an average of 71 cm near Houghton Lake to 94 cm around Newaygo (Eichenlaub et al., 1990). Vegetation within the study area is largely mixed conifer–hardwood forests composed of White pine (*Pinus strobes*), Trembling aspen (*Populus tremuloides*), oak (e.g., *Quercus rubra*), and Paper birch (*Betula papyrifera*). Maple (e.g., *Acer rubrum*), American beech (*Fagus grandifolia*), and Eastern hemlock (*Tsuga canadensis*) are also found in smaller numbers (Bernabo, 1981).

3. Materials and methods

The first step we took in this study was to analyze the study reach by investigating county soil surveys, aerial photographs, and 1:24,000-scale topographic maps. Through this analysis, we identified three prominent landforms: i) an irregular valley wall that essentially bounds the study area; ii) a broad, paired terrace; and iii) a considerable terrace escarpment on either side of the present river channel that confines the river to an “inner valley.” Within this inner valley, several poorly defined terraces appeared to be also present. In order to verify these observations, we entered the field with the intent to characterize and map all of the terraces along the river. However, poor road access and dense vegetation in most places precluded our ability to construct a detailed map and, therefore, we adjusted the scope of our project to instead focus on mapping the valley wall and prominent terrace escarpment near the stream. We also sought to characterize the valley in cross-section and determine the ages of the more well-defined terraces where we could distinguish between them.

In an effort to identify the sequence of terraces in the valley, we established six cross-sectional transects that were surveyed with a Trimble Geo Explorer III GPS unit. These transects were evenly distributed across space between the headwaters and Evart and extended between the uplands on either side of the valley. Points were collected at 50-m intervals on horizontal surfaces and at targeted locations such as the top and base of escarpments. The data were

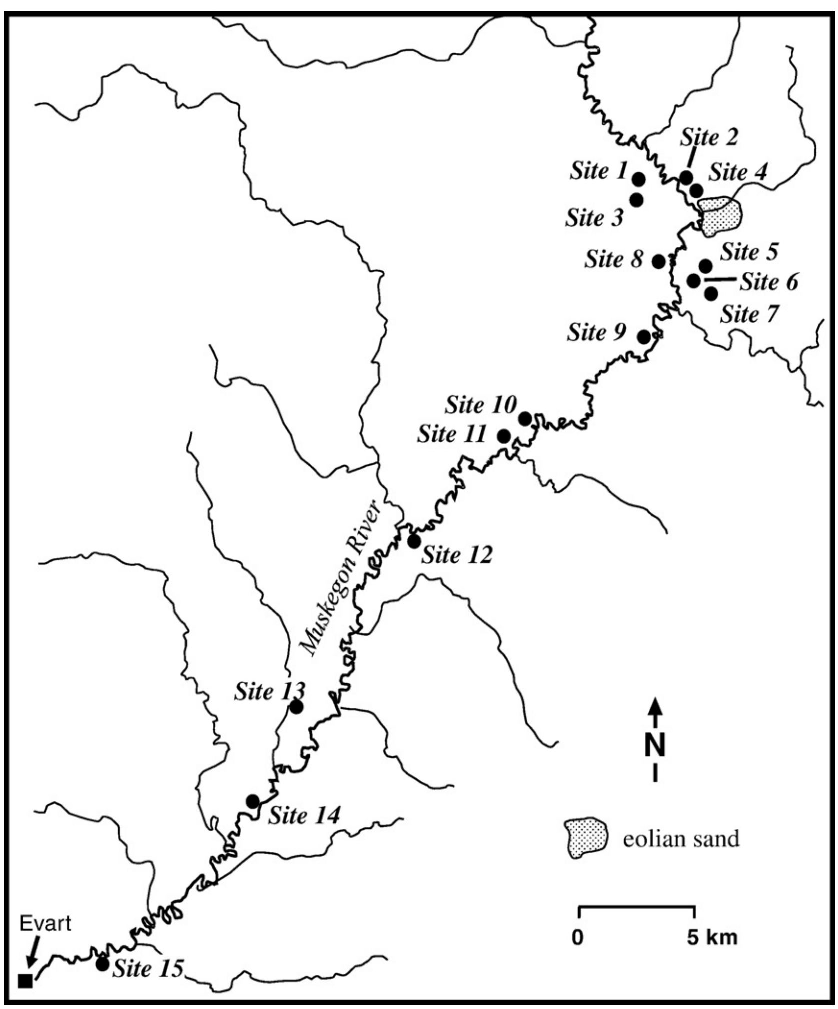

Fig. 2. Map of study sites in the upper part of the Muskegon River valley.

Table 1
Radiocarbon ages presented in this study. All ages are derived from basal peats in paleomeanders

Site	Terrace	Depth (m)	Lab #	Conventional age (2σ)	Calibrated age[a] (2σ)	^{13}C[b]
1	T-1	.75	Curl-5510	2150±80	2335–1986	−25.5
2	T-3	1.5	Curl-5511	8700±100	10,148–9500	−26.5
3	T-3	.88	Curl-5512	3590±80	4091–3688	−25.1
4	T-1	1.52	Beta-161766	1800±80	1830–1610	−25.9
5	T-3	1.50	Curl-5514	9540±110	11,169–10,575	−26.0
5	T-3	1.45	Beta-172561	9890±80	11,300–11,200	−27.8
5	T-3	1.61	Beta-172560	9930±80	11,530–11,220	−27.3
6	T-2	0.15	Beta-161771	Modern	Modern	−26.6
6	T-2	0.22	Beta-161770	3790±80	4280–4010	−27.1
6	T-2	0.60	Beta-161769	1210±80	1250–1050	−26.9
7	T-3	1.8	Beta-179270	9080±100	10,260–10,180	−27.6
8	T-2	1.52	Beta-161772	3350±80	3680–3470	−25.1
9	T-1	0.46	Beta-161768	1190±80	1230–990	−28.3
10	T-2	1.1	Beta-179269	4160±60	4830–4570	−24.5
11	T-2	1.1	Beta-198066	5500±80	6330–6210	−28.0
12	T-1	0.91	Beta-198065	520±80	630–510	−25.5
13	T-3	2.45	Beta-198064	10320±140	12360–11,640	−31.1
14	T-2	2.45	Beta-198063	3590±100	4060–3720	−27.3
15	T-1	0.75	Beta-198062	1200±80	1240–1000	−24.5

[a] Calibrated from conventional $\delta^{13}C$-corrected radiocarbon age to calendar years using a tree-ring curve. All calibrations reported here were based upon the 20-yr atmospheric curve (e.g., Linick et al., 1985; Stuiver et al., 1986). Program used is discussed in Stuiver et al. (1998).
[b] For a discussion of the $\delta^{13}C$-correction procedure, see Stuiver and Polach (1977) and Taylor (1987).

differentially corrected, resulting in horizontal and vertical accuracies of ~.6 m and 1.5 m, respectively. The overall goal in this phase of the project was to learn enough about the valley to create a representative cross-section that illustrates the various terraces.

In addition to mapping and characterizing cross-sections of the river valley, another goal of the project was to determine the age of the terraces. Although no dateable material was present in any of the cutbanks investigated in the area, we discovered that several prominent meander scars contained thick (>1 m) deposits of peat. Assuming that peat accumulation began shortly after oxbow formation, the age of basal organics in meander scars represents a reasonable minimum-limiting estimate for the associated stream terrace. This sampling method has been successfully used to estimate the minimum-limiting age of beach ridges immediately lakeward of peat-filled swales along the Great Lakes (Thompson, 1992; Thompson and Baedke, 1997; Baedke and Thompson, 2000). Leigh (2006) used a similar strategy to date paleomeanders in streams on the Atlantic Coastal Plain in the southeastern U.S.

We sampled the peat at 15 sites (Fig. 2) by hand-augering to a depth a few centimeters below the contact with underlying sands. The resultant core at the peat–sediment interface was then split open and an organic sample was collected immediately above the contact with the underlying sand from the interior of the core to avoid contamination. The samples were then wrapped in aluminum foil and frozen until they were shipped for age determination via AMS dating. Fifteen samples were processed at Beta Analytic in Miami, FL, and four were analyzed at the INSTAAR Laboratory in Boulder, CO. In order to correct for long-term variations in the radiocarbon timescale, all dates were calibrated to the tree-ring curve established by Stuiver et al. (1998), allowing radiocarbon dates to be adjusted to calendar years before present (i.e., cal. YBP).

4. Results

4.1. Stream terraces and radiocarbon dates

Results from this study indicate that four stream terraces are present in the upper Muskegon River valley. Radiocarbon dates from these surfaces range in age from the late Pleistocene to the late Holocene (Table 1). The geomorphic relationship of these surfaces can be seen in the schematic transect presented in Fig. 3. In addition, the stratigraphy of sites and related terraces is presented in Fig. 4.

The T-4 and T-3 terraces collectively form the dominant alluvial surfaces in the valley and are mapped as part of the local outwash plain by Tardy (2005). Field examination of the underlying fill of cutbank exposures of the T-4 and T-3 terraces supports this hypothesis as it consists largely of sand with lenses of gravel. The T-4 surface is the most extensive of these landforms, extending to the east for more than

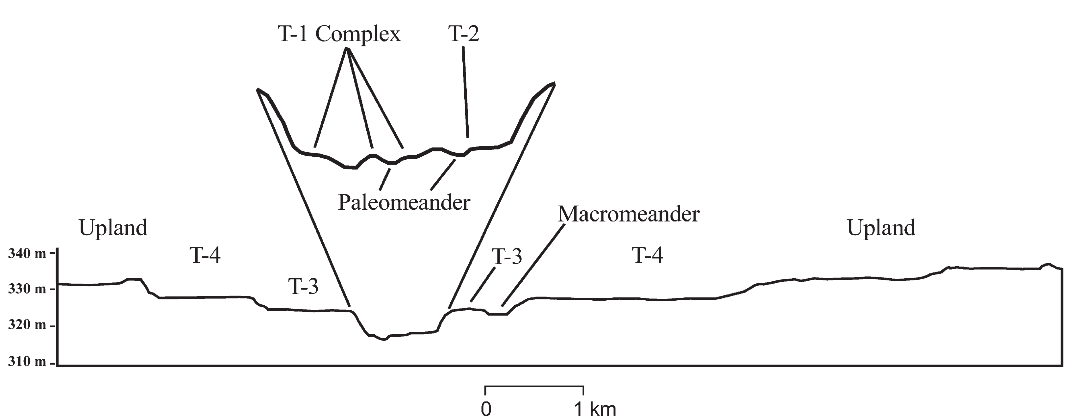

Fig. 3. Schematic cross-section of landforms in the upper part of the Muskegon River valley. The larger-scale map showing detail of the inner valley is magnified 3×.

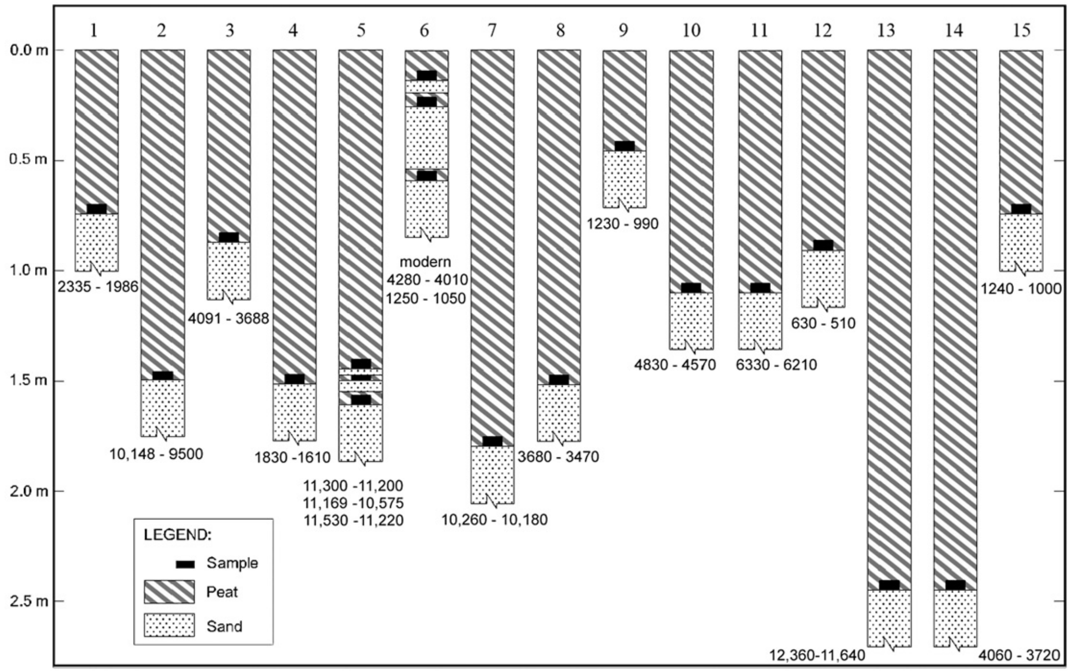

Fig. 4. Stratigraphy and radiocarbon dates from sites investigated in this study.

1 km in places and up to 0.5 km on the west side of the stream. The T-3 terrace lies between ~1.5 and 2.0 m below the T-4 surface and is less-extensive, ranging from about 100 to 500 m wide.

Evidence indicates that the T-3 surface was created by a meandering ancestral Muskegon River that planed off the upper portion of T-4 fill, making the T-3 a fill-strath terrace. This evidence can be seen in Fig. 5 in the form of 3 large paleomeanders in the upper part of the study area. Each of these channels is ~90 m wide and has a radius of curvature of ~325 m. The meander wavelength is ~800 m. Peat thickness in these macromeanders ranges from ~2.5 m at sites 5, 13, and 14 to 0.9 m at site 3 (Fig. 4).

Calibrated radiocarbon dates from basal peat in the macromeanders provide minimum-limiting estimates for the T-3 terrace. Of the six age estimates derived from this surface, 5 of them range from 12,360 to 9500 cal. YBP. At Site 5 two lenses of sand were observed with interbedded peats (Fig. 4). Ages derived from these peats all fell between about 11,500 and 10,500 cal. YBP. At another site (Site 3) an age of 4091–3688 cal. YBP was derived from basal peat on the T-3 terrace. Overall, the older dates from the T-3 terrace indicate that the ancestral Muskegon River occupied this surface in the latest Pleistocene. The younger date is a bit problematic and could be explained by the following: i) the sample was contaminated with younger organic material, resulting in anonymously younger ages; ii) peat did not begin to form in the paleomeander for thousands of years after they were abandoned; and iii) the Muskegon occupied the T-3 surface from the late Pleistocene into the middle Holocene. This latter hypothesis is rejected for reasons outlined below.

Although the precise chronology of T-3 surface occupation by the Muskegon River is unknown, it clearly became a terrace following a major period of downcutting in the valley. This period of entrenchment produced a distinct but narrow inner valley throughout the study area that is bordered on both sides of the river by a ~6-m-high escarpment that separates the T-3 terrace from younger surfaces (Fig. 3). Two terraces were identified in this inner valley, a T-2 that lies directly below the T-3, and a T-1. The escarpment between the T-2 and T-1 is ~1 m high and is clearly visible only in scattered forest clearings and along the river where both surfaces are present. The T-1 terrace actually appears to be a complex of poorly defined terraces that differ slightly in elevation on a local level.

One of the most notable features of the T-2 and T-1 surfaces is that they both contain numerous paleomeanders and oxbow lakes (e.g., Fig. 5). In contrast to the macromeanders on the T-3 terrace, the abandoned channels on the lower surfaces are substantially smaller. The width of these old channels is ~30 m, the radius of curvature ranges from ~50 to 75 m, and the meander wavelength is from ~200 to 350 m. These geometric aspects are very consistent with the modern river.

A major goal of the study was to estimate when the extensive period of channel entrenchment occurred that created the T-3 terrace and to determine the age of the T-2 and T-1 surfaces. In that context, 12 radiocarbon ages were obtained from peats in paleomeanders within the inner valley, with seven obtained from the T-2 and five from the T-1. The ages from the T-2 surface range from 6330 to 3720 cal. YBP, with two ages falling between 4830 and 4010 cal. YBP (Table 1; Fig. 4). Ages derived from the T-2 at site 6 were stratigraphically inverted. The basal sample (0.60 cm deep) at this

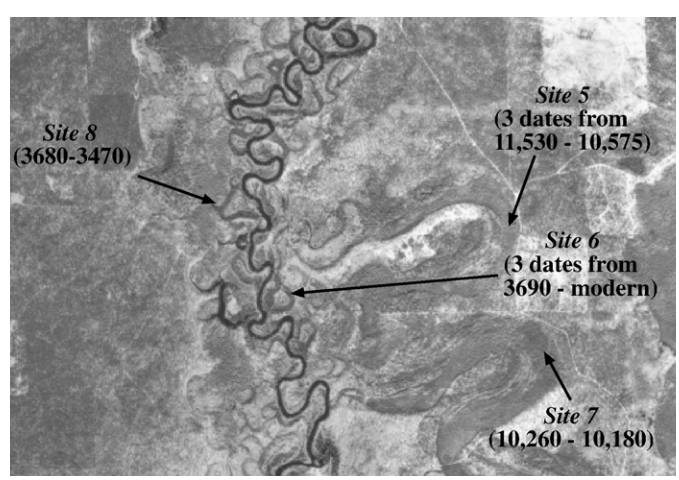

Fig. 5. Aerial photograph showing the nature and ages of late Pleistocene and Holocene paleomeanders in the upper part of the Muskegon River valley. Note the difference in size between the paleomeanders of differing ages.

site provided an age of 1250–1050, whereas a sample from 0.22 cm yielded an estimate of 4280–4010. We conclude that the peat at this site was somehow disturbed, perhaps by tree throw or burrowing animals. Ages obtained from the T-1 terrace range from 2335 to about 500 cal. YBP. Of the five ages derived from this surface, four occur within a range that extends from 1830 to 1000 cal. YBP.

5. Discussion

This study reconstructed the chronology of post-glacial stream processes and associated landform development in the upper part of Michigan's Muskegon River system. Results indicate that four stream terraces occur along this reach. The development of these surfaces appears to be related to distinct periods of environmental change and associated stream responses (Table 2). The initial history of the system is uncertain and is probably related to the deglaciation of the area. The earliest ancestral Muskegon River may have been associated with the braided stream system that formed the extensive Saint Helen outwash plain when ice retreated from the area around 16 ka. Alternatively, the stream originated, or was somehow modified, when the meltwater lake(s) that apparently existed in the area (Tardy, 2005) for an unknown period of time began to drain.

Although the earliest history of the Muskegon River is not presently known, evidence indicates that by the latest Pleistocene the stream had downcut ~2 m to form the T-4 terrace. This surface is a paired terrace that is underlain by the uppermost outwash/lacustrine sediments. During this time the ancestral Muskegon River had a large meandering channel that cut an erosional surface into outwash and lacustrine sediments where they are present. This cut surface ultimately became the T-3 terrace following a subsequent period of downcutting.

The oldest radiocarbon date obtained from peat contained within a macromeander on the T-3 terrace is 12,360–11,640 cal. YBP. This date provides a minimum-limiting estimate for the Muskegon's initial downcutting event and suggests that the river had developed into a meandering stream by perhaps 13–12.5 ka. This period of time marks the initial expansion of spruce into the region (Webb et al., 1983), which may have stabilized channel banks and reduced the yield of sandy bank material such that a change in channel form from braided to meandering occurred (e.g., Carson, 1984; Bridge, 2003; Leigh, 2006). It is also possible that the change occurred in part because sediment supply from periglacial sources to the north diminished.

Table 2
Chronology of stream behavior and environmental change in upper Muskegin River valley

Years ago	Stream response	Environment
0		
1000	Aggradation/incision; complex response	More variable climate; Northern
2000		hardwood forest
3000	Incision	Cooler/more moist;
4000		pine-dominated forest
5000	Aggradation; river is meandering	Cool/moist; pine-dominated forest
6000		
7000		
8000	Incision	Warmer/drier, oak forest
9000		
10,000		
11,000	Macromeanders; Q=~8×Holocene;	Cool/moist; Spruce forest
12,000	Planing of T-3 terrace	
13,000		
14,000	Uncertain; draining of lake? Slight	Cool/dry; Spruce-sedge parkland
15,000	incision	
16,000	Deglaciation	Cold/dry; Tundra

Dashed lines between stages reflect dating uncertainties.

This kind of relationship as has been reported for streams in Europe (Kozarski, 1991; Kasse et al., 1995; Straffin et al., 2000).

Although the reason for the change in channel pattern is unknown with certainty, it is clear from the size of the macromeanders on the T-3 terrace that the ancestral Muskegon River had a much greater discharge than the stream had during the Holocene or today. These macromeanders are generally consistent in size and form with those reported along the glacial margin in Europe (Schumanski, 1983; Starkel et al., 1996; Sidorchuk et al., 2001) and Alberta, Canada (Bryan et al., 1987). Macromeanders of very similar size (i.e., channel width, meander wavelength, radius of curvature) as those observed in this study have also been reported along several streams on the Atlantic Coastal Plain in the southeastern U.S. Leigh and Feeney (1995) estimated that mean annual bankfull discharge in these ancient streams was between ~400 and 500 m^3/s, whereas modern average bankfull discharge is between ~60 and 85 m^3/s. According to Leigh and Feeney (1995), this higher discharge occurred because the climate between ~31–28 ka and ~8.5–4.5 ka (when the meanders formed) was about 10%–30% wetter than the current one.

Given the general geometric consistency of macromeanders reported in this study with those in the southeastern U.S. (Leigh and Feeney, 1995), we believe that mean annual bankfull discharge of the ancestral Muskegon River during the late Pleistocene was at least ~400 m^3/s. This amount of flow is ~8 times greater than average modern spring discharge in the river and probably occurred because i) the meltwater lake(s) in the area (Tardy, 2005) were draining significantly, ii) the regional water table was very high due to the recently melted glacier in the area (e.g., Webb et al., 2004), or iii) a combination of the two.

Radiocarbon dates from macromeanders on the T-3 terrace suggest that the ancestral Muskegon River maintained this high discharge for the last ~2500 to 2000 years of the Pleistocene and perhaps into the very early Holocene. This conclusion is based on the fact that the majority of minimum-limiting age estimates from the macromeanders range from between ~12,360 and 9500 cal. YBP. This period of time nicely correlates to the interval during which spruce forests dominated similar low-lying and moist outwash areas in the upper Midwest (e.g., Pregitzer et al., 2000). The Muskegon River was apparently in static equilibrium (Bull, 1991) during this phase of its history as it migrated laterally and planed the fill-strath surface that became the T-3 terrace.

This period of equilibrium ended when a major period of incision began in the upper Muskegon valley, one that elevated the T-3 terrace relative to the active flood plain and created a 6-m-high escarpment. Circumstantial evidence suggests that this period of downcutting occurred at the Pleistocene/Holocene transition when the climate began to warm and stream discharge decreased. This form of channel response at the Pleistocene/Holocene transition has been documented in the glacial and periglacial parts of Europe (e.g., Starkel, 1991; Walker, 1995; Tebbens et al., 1999; Howard et al., 2004), along the Bow River in Alberta, Canada (Otelelaar, 2002), and along the upper Susquehanna River in New York (Scully and Arnold, 1981). A variety of evidence (e.g., Webb et al., 1983; Krishnamurthy et al., 1995; Bartlein et al., 1998; Kutzbach et al., 1998; Davis et al., 2000; Booth et al., 2002) indicate that this climate transition occurred at about 10 ka in the Great Lakes region. In Lower Michigan, this environmental transition resulted in spruce forests being replaced by oak-dominated forests (Manny et al., 1978).

Although we do not know with certainty, it appears that early Holocene entrenchment extended through the middle Holocene dry period (a.k.a. Hypsithermal/Altithermal) that is well documented in the region (Webb et al., 1983; Krishnamurthy et al., 1995; Bartlein et al., 1998; Kutzbach et al., 1998; Davis et al., 2000; Booth et al., 2002, 2004). According to Davis et al. (2000), for example, the middle Holocene climate in northern Michigan was about 9% drier than the modern one. Knox (1972) argued that the overall more arid middle Holocene climate in the upper Midwest paradoxically resulted in more intense storms and flooding on a periodic basis. In the central U.S., this instability is linked to valley alluviation due to reduced vegetation on hillslopes and higher yield of fine-grained sediment (Knox, 1972; May, 1989; Martin, 1992; Van Nest and Bettis, 1990; Arbogast and Johnson, 1994; Baker et al., 2000). Such a reduction in vegetation cover likely did not happen in central Lower Michigan, however, as the late Pleistocene spruce forest merely changed to one dominated by pine and oak (Webb et al., 1983). As a result, the Muskegon River may have continued downcutting when periodic high discharges swept through the system in the middle Holocene.

Following the period of channel entrenchment that created the high escarpment below the T-3 terrace, the Muskegon River switched to an aggradational system. During this period of alluviation, the river deposited fine-textured sediment that partially filled the inner valley bordered by the high escarpment. This fill now underlies the T-2 terrace, which is preserved as a paired surface in the study area. Numerous paleomeanders occur on this surface, indicating that the Muskegon was a stream in dynamic equilibrium with a low flow velocity (Knighton, 1984). The oldest radiocarbon date obtained on basal peats from a T-2 paleomeander was 6330–6210 cal. yrs B.P., indicating that post-entrenchment alluviation began sometime before that time. According to several studies (e.g., Davis et al., 2000; Jackson and Booth, 2002; Booth et al., 2004), the climate of northern Michigan became more mesic about 6 ka. Given the constraints associated with assigning precise time periods through radiocarbon dating, we propose that alluviation within the Muskegon River system is generally associated with the return to a more humid climate between about 7 and 6 ka and the related delivery of more sediment consistently to the stream channel.

Following the period of alluviation that partially filled the inner Muskegon valley, the river apparently occupied the T-2 surface for a distinct period of time. Supporting evidence for this conclusion is that numerous paleomeanders occur on the T-2 terrace. These paleomeanders are significantly smaller with respect to their width, radius of curvature, and meander wavelength than the macromeanders on the T-3 terrace. Instead, they are consistent in size with the modern stream, suggesting that the average Holocene stream discharge was approximately 30–40 m^3/s. This kind of change to smaller Holocene channel geometry has been reported in Europe (Schumanski, 1983; Starkel et al., 1996; Sidorchuk et al., 2001), the western Canadian prairies (Bryan et al., 1987) and the Atlantic Coastal Plain in the southeastern U.S. (Leigh, 2006). Radiocarbon ages from basal peats in several of the paleomeanders along the upper Muskegon River range from 6330 to 3720 cal. YBP, suggesting that the stream flowed on this surface for ~2500 years.

Paleoclimate evidence from Michigan indicate that ~3200 cal. YBP the climate of the area became cooler and more moist (Bernabo, 1981; Jackson and Booth, 2002; Booth et al., 2004), with pine forest dominating the landscape. In the upper Muskegon River valley, this climate shift appears to be associated with a period of minor downcutting that formed the T-2 terrace. According to Bull (1991), this kind of stream degradation can be attributed to an increase in the total annual stream power, which would have resulted from a wetter climate. This type of climate shift/response has been linked with an episode of downcutting in the western Canadian prairies (Campbell and Campbell, 1997). The length of this period of limited entrenchment along the upper Muskegon River is uncertain, but may have been for several hundred years.

Following this latter period of downcutting, the Muskegon River began to respond in a complex manner that formed a series of ill-defined and unpaired surfaces close to the modern flood plain that are lumped into the T-1 terrace complex. The stream continued to meander during this phase, resulting in numerous paleochannels and oxbow lakes, The first stage of this chronology began with a period of valley filling that again deposited fine-grained sediment to a point about 1 m below the T-2 terrace. A radiocarbon date of 2335–1986 cal. yrs B.P. was obtained from a paleochannel at this elevation, suggesting that valley filling may have began approximately 2500 years ago. Since that time, the stream has undergone a series of subtle cutting and filling cycles, resulting in the T-1 terrace complex. Radiocarbon ages from paleomeanders in this complex of minor terraces range from ~2300 cal. YBP. to the present.

The apparent onset of the more complex late Holocene stream history correlates reasonably well with the paleoclimate record from northern Michigan. According to several studies (Jackson and Booth, 2002; Booth et al., 2004; Webb et al., 2004), the late Holocene climate of the region has fluctuated more than earlier periods, with alternating wet and dry intervals. Vegetation during this period of time has consisted of northern hardwoods. We propose that this more variable climate has provoked a complex response (Schumm and Parker, 1973; Womack and Schumm, 1977; Bull, 1991) in the system for the past 2500 years.

6. Conclusion

This study reconstructed the post-glacial chronology of stream behavior and landform development along the upper Muskegon River in north-central Lower Michigan. As a result, it is the first investigation to compare the history of a stream in the core of the Great Lakes region in North America with other streams around the world in deglacial and periglacial areas. This chronology is based on radiocarbon dates obtained from basal peats in paleomeanders on stream terraces.

Results indicate that the upper valley contains four alluvial terraces and that stream discharge varied significantly between the late Pleistocene and Holocene. The T-4 terrace is a Pleistocene outwash/lacustrine surface that probably formed during a period of downcutting about 12,500 years ago. The T-3 terrace is a fill-strath surface that was cut between about 12,000 and perhaps 9500 years ago. During this time the discharge of the river was perhaps 8 times greater than the modern stream, resulting in the formation of macromeanders consistent in size and form with late Pleistocene rivers in glacial and periglacial areas elsewhere in the world.

Following this period of dynamic equilibrium, a major period of downcutting likely began at the Pleistocene/Holocene climate transition, one that also occurred in streams on similar landscapes elsewhere in the world. In north-central Lower Michigan, this period of downcutting was likely triggered because stream discharge decreased as the climate became warmer and drier. We believe that this period of downcutting lasted through the drier part of the middle Holocene, creating a 6-m-high escarpment along both sides of the valley.

Following the period of middle Holocene entrenchment, the Muskegon River began to aggrade at the onset of a wetter climate period. This period of aggradation may have lasted about 2500 years. The size of paleomeanders from this time period indicates that the river was similar in size with the modern river and that discharge had decreased significantly from the late Pleistocene. Subsequently, the stream apparently incised again about 3400 years ago when the climate became still wetter. This period of incision created the paired T-2 terrace. In the past 2500 years, the stream has constructed a poorly defined complex of T-1 terraces. These surfaces may have evolved because the regional climate in the late Holocene has been more variable than at other times.

Acknowledgements

We would like to acknowledge Cathryn Dowd for her early work with this project. In addition, we would like to thank Eric Manschott for his assistance in the field. Lastly, this project was supported in large part by NSF grant #BCS-0117612. Comments from two anonymous reviewers substantially improved the manuscript and are much appreciated.

References

Arbogast, A.F., Johnson, W.C., 1994. Climatic implications of the late Quaternary alluvial record of a small drainage basin in the central Great Plains. Quat. Res. 41, 298–305.

Baedke, S.J., Thompson, T.A., 2000. A 4,700-year record of lake level and isostasy for Lake Michigan. J. Great Lakes Res. 26, 416–426.

Baker, R.G., Bettis III, E.A., Fredlund, G.G., Mandel, R.D., 2000. Holocene environments of the central Great Plains: multi-proxy evidence from alluvial sequences, southeastern Nebraska. Quat. Int. 67, 75–88.

Ballantyne, C.K., Whittington, G., 1999. Late Holocene floodplain incision and alluvial fan formation in the central Grampian Highlands, Scotland: chronology, environment, and implications. J. Quat. Sci. 14, 651–671.

Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb, R.S., Webb III, T., Whitlock, C., 1998. Paleoclimate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quat. Sci. Rev. 17, 549–585.

Bernabo, J.C., 1981. Quantitative estimates of temperature changes over the last 2,700 years in Michigan based on pollen data. Quat. Res. 15, 143–159.

Blewett, W.L., Winters, H.A., 1995. The importance of glaciofluvial features within Michigan's Port Huron moraine. Ann. Assoc. Am. Geogr. 85, 306–319.

Blum, M.D., Törnqvist, T.E., 2000. Fluvial responses to climate and sea-level change: a review and look forward. Sedimentology 47, 2–48.

Booth, R.K., Jackson, S.T., Thompson, T.A., 2002. Paleoecology of a northern Michigan lake and the relationship among climate, vegetation, and Great Lakes water levels. Quat. Res. 57, 120–130.

Booth, R.K., Jackson, S.T., Gray, C.E.D., 2004. Paleoecology and high-resolution paleohydrology of a kettle peatland in upper Michigan. Quat. Res. 61, 1–13.

Bridge, J.S., 2003. Rivers and Floodplains. Blackwell, Oxford.

Bridgland, D., Maddy, D., Bates, M., 2004. River terrace sequences: templates for Quaternary geochronology and marine-terrestrial correlation. J. Quat. Sci. 19, 203–218.

Bryan, R.B., Campbell, I.A., Fair, A., 1987. Postglacial geomorphic development of the Dinosaur Provincial Park Badlands, Alberta. Can. J. Earth Sci. 24, 135–146.

Bull, W.B., 1990. Stream-terrace genesis: implications for soil development. Geomorphology 3, 351–367.

Bull, W.B., 1991. Geomorphic Responses to Climate Change. Oxford University Press, New York.

Carson, M.A., 1984. The meandering-braided river threshold; a reappraisal. J. Hydrol. 73, 315–334.

Campbell, C., Campbell, I.A., 1997. Calibration, review, and geomorphic implications of postglacial radiocarbon ages in southeastern Alberta, Canada. Quat. Res. 47, 37–44.

Chorley, R.J., 1963. Diastrophic background to twentieth-century geomorphological thought. Geol. Soc. Amer. Bull. 74, 953–970.

Davis, W.M., 1909. Geographical Essays. Ginn and Company, Boston.

Davis, M., Winkler, M.G., Flakne, R., Douglas, C., Calcote, R., Cole, K.L., 2000. Holocene climate in the western Great Lakes National Parks and Lakeshores: implications for future climate change. Conserv. Biol. 14, 968–983.

Dury, G.H., 1970. Rivers and River Terraces. MacMillan, London.

Eichenlaub, V.L., Harman, J.R., Nurnberger, F.V., Stolle, H., 1990. The Climatic Atlas of Michigan. University of Notre Dame Press, Notre Dame, IN.

Eschman, D.F., 1985. Summary of the Quaternary history of Michigan, Ohio, and Indiana. J. Geol. Educ. 33, 167.

Evans, D.J.A., Campbell, I.A., Lemmen, D.S., 2004. Holocene alluvial chronology of One Tree Creek, southern Alberta, Canada. Geogr. Ann. 86, 117–130.

Fisk, H.N., 1944. Geological Investigation of the Alluvial Valley of the Lower Mississippi River. U.S. Army Corps of Engineers, Vicksburg. MS.

Harvey, A.M., Oldfield, F., Baron, A.F., Pearson, G.W., 1981. Dating of post-glacial landforms in the central Howgills. Earth Surf. Processes Landf. 6, 401–412.

Howard, A.J., Macklin, M.G., Black, S., Hudson-Edward, K.A., 1999. Holocene river development and environmental change in Upper Wharfdale, Yorkshire Dales, England. J. Quat. Sci. 15, 239–252.

Howard, A.J., Macklin, M.G., Bailey, D.W., Mills, S., Andreescu, R., 2004. Late-glacial and Holocene river development in the Teleorman Valley on the southern Romanian Plain. J. Quat. Sci. 19, 271–280.

Hsieh, M.L., Knuepfer, P.L.K., 2001. Middle-late Holocene river terraces in the Erhjen river Basin, southwestern Taiwan — implications of river response to climate change and active tectonic uplift. Geomorphology 38, 337–372.

Jackson, S.T., Booth, R.K., 2002. The role of late Holocene climate variability in the expansion of yellow birch in the western Great Lakes region. Divers. Distrib. 8, 275–284.

Kasse, K., Vandenberghe, J., Bohncke, S., 1995. Climatic change and fluvial dynamics of the Maas during the late Weishselian and early Holocene. Palaoklimaforschung 14, 123–150.

Knighton, D., 1984. Fluvial Forms and Processes. Edward Arnold, New York.

Knox, J.C., 1972. Valley alleviation in southwestern Wisconsin. Ann. Assoc. Am. Geogr. 62, 401–410.

Knox, J.C., 1975. Concept of the graded stream. In: Melhorn, W.N., Flemal, R.C. (Eds.), Theories of Landform Development. Publications in Geomorphology, State University of New York, Binghamton, pp. 169–198.

Knox, J.C., 1984. Fluvial response to small scale climate changes. In: Costa, J.E., Fleisher, P.J. (Eds.), Developments and Applications of Geomorphology. Springer, Berlin, pp. 318–342.

Knox, J.C., 1993. Large increases in flood magnitude in response to modest changes in climate. Nature 361, 430–432.

Knox, J.C., 1995. Fluvial systems since 20,000 years BP. In: Gregory, K.J., Starkel, L., Baker, V.R. (Eds.), Global Continental Palaeohydrology. John Wiley and Sons, Chichester, pp. 87–108.

Knox, J., 2006. Floodplain sedimentation in the Upper Mississippi Valley: natural versus human accelerated. Geomorphology 79, 286–310.

Kozarski, S., 1991. Warta — a case study of a lowland river. In: Starkel, L., Gregory, K.J., Thornes, J.B. (Eds.), Temperate Palaeohydrology: Fluvial Processes in the Temperate Zone During the Last 15,000 Years. John Wiley and Sons, Chichester, UK, pp. 189–215.

Krishnamurthy, R.V., Syrup, K.A., Baskaran, M., Long, A., 1995. Late glacial climate record of the Midwestern United States from the hydrogen isotope ratio of lake organic matter. Science 269, 1565–1567.

Kutzbach, J., Gallimore, R., Harrison, S.P., Behling, P., Selin, R., Larrif, F., 1998. Climate and biome simulations for the past 21,000 years. Quat. Sci. Rev. 17, 473–506.

Leigh, D.S., 2006. Terminal Pleistocene braided to meandering transition in rivers of the southeastern USA. Catena 66, 155–160.

Leigh, D.S., Feeney, T.P., 1995. Paleochannels indicating wet climate and lack of response to lower sea level, southeast Georgia. Geology 23, 687–690.

Linick, T.W., Suess, H.E., Becker, B., 1985. La Jolla measurements of radiocarbon in south German oak tree-ring chronologies. Radiocarbon 27, 20–32.

Manny, B.A., Wetzel, R.G., Bailey, R.B., 1978. Paleolimnological sedimentation of organic carbon, nitrogen, phosphorus, fossil pigments, pollen and diatoms in a hypereutrophic, hardwater lake: a case history of europhication. Pol. Arch. Hydrobiol. 25, 243–267.

Martin, C.W., 1992. The response of fluvial systems to climate change: an example from the central Great Plains. Phys. Geogr. 13, 101–104.

May, D.W., 1989. Holocene alluvial fills in the South Loop valley, Nebraska. Quat. Res. 32, 117–120.

Minako, A., Tetsuji, M., 2006. The origin of stream terraces in the alluvial lower reaches of rivers: an experimental examination of the complex response model. J. Geol. Soc. Jpn. 112, 315–330.

Monoghan, G.W., Lovis, W.A., 2005. Modeling archaeological site burial in southern Michigan: a geoarchaeological synthesis. Environmental Research Series No. 1. Michigan Department of Transportation. Michigan State University Press, East Lansing.

O'Neal, R.P., 1997. In: Division, F. (Ed.), Muskegon River watershed assessment. Michigan Department of Natural Resources, Lansing.

Otelelaar, G.A., 2002. River of change: a model for the development of terraces along the Bow River, Alberta. Geogr. Phys. Quat. 56, 155–169.

Penck, A., Bruckner, A.E., 1909. Die Alpen im Eiszeitalter. Tachnitz, Leipzig.

Pregitzer, K.S., Reed, D.D., Bornhorst, T.J., Foster, D.R., Mroz, G.D., McLachlan, J.S., Laks, P.E., Stokke, D.D., Martin, P.E., Brown, S.E., 2000. A buried spruce forest provides evidence at the stand and landscape scale for the effects of environment on vegetation at the Pleistocene/Holocene boundary. J. Ecol. 88, 45–53.

Rains, R.B., Welch, J., 1988. Out-of-phase Holocene terraces in part of the North Saskatchewan River basin, Alberta. Canad. J. Earth Sci. 25, 454–464.

Schaetzl, R.J., Weisenborn, B., 2004. The Grayling Fingers region of Michigan: Sedimentology, stratigraphy, and geomorphic development. Geomorphology 61, 251–274.

Schumanski, A., 1983. Palaeochannel of large meanders in the river valleys of the Polish Lowland. Quat. Stud. Pol. 4, 207–216.

Schumm, S.A., Parker, R.S., 1973. Implications of complex response of drainage systems for Quaternary alluvial stratigraphy. Nature 243, 99–100.

Schumm, S.A., Brakenridge, G.R., 1987. Stream responses. In: Ruddiman, W.F., Wright, H.E. (Eds.), North America and Adjacent Oceans During the Last Deglaciation. The Geological Society of America, Boulder, CO, pp. 221–240.

Scully, R.W., Arnold, R.W., 1981. Holocene alluvial stratigraphy in the upper Susquehanna River basin, New York. Quat. Res. 15, 327–344.

Sidorchuk, A., Borisova, O., Panin, A., 2001. Fluvial response to the Late Valdai/Holocene environmental change on the East European Plain. Glob. Planet. Change 28, 303–318.

Starkel, L., 1991. Long distance correlation of fluvial events in the temperate zone. In: Starkel, L., Gregory, K.J., Thornes, J.B. (Eds.), Temperate Palaeohydrology: Fluvial Processes in the Temperate Zone during the Last 15000 Years. Wiley, Chichester, UK, pp. 473–495.

Starkel, L., 1995. Palaeohydrology of the temperate zone. In: Gregory, K.J., Starkel, L., Baker, V.R. (Eds.), Global Continental Palaeohydrology. Wiley, Chichester, UK, pp. 233–258.

Starkel, L., Kalicki, T., Krapiec, M., Soja, R., Gebica, P., Czyzowska, E., 1996. Hydrological changes of valley floors in upper Vistula basin during late Vistulian and Holocene. In: Starkel, L. (Ed.), Evolution of the Vistula River Valley during the last 15000 years. Geographic Studies, Special Issue 9, 7–128.

Straffin, E.C., Blum, M.D., Colls, A., Stokes, S., 2000. Alluvial stratigraphy of the Loire and Arroux Rivers, Burgandy, France. Quaternaire 10, 271–282.

Stuiver, M., Polach, H.A., 1977. Discussion: reporting of ^{14}C data. Radiocarbon 19, 355–363.

Stuiver, M., Pearson, G.W., Braziunas, T.F., 1986. Radiocarbon age calibration of marine samples back to 9000 cal yr BP. Radiocarbon 28, 980–1021.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., Van der Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24000–0 cal. B.P. Radiocarbon 40, 1041–1083.

Tardy, S.W., 2005. Soil Survey of Roscommon County, Michigan. U.S. Department of Agriculture. Natural Resources Conservation Service, Washington, DC.

Taylor, R.E., 1987. Radiocarbon Dating: An Archaeological Perspective. Academic Press, Orlando, FL.

Tebbens, I.A., Veldkamp, A., Westerhoff, W., Kroonenberg, S.B., 1999. Fluvial incision and channel downcutting as a response to Late-glacial and Early Holocene climate

change: the lower reach of the River Meuse (Maas), the Netherlands. J. Quat. Sci. 14, 59–75.
Thompson, T.A., 1992. Beach-ridge development and lake-level variation in southern Lake Michigan. Sediment. Geol. 80, 305–318.
Thompson, T.A., Baedke, S.J., 1997. Strand-plain evidence for late Holocene lake-level variations in Lake Michigan. Geol. Soc. Amer. Bull. 109, 666–682.
U.S. Geological Survey, 2004. Daily Water Data for Michigan. Retrieved January 31, 2004.
Van Nest, J., Bettis III, E.A., 1990. Postglacial response of a stream in central Iowa to changes in climate and drainage basin factors. Quat. Res. 33, 73–85.
Walker, M.J.C., 1995. Climatic changes in Europe during the last glacial–interglacial transition. Quat. Int. 28, 63–76.
Webb, I.T., Cushing, E.J., Wright, H.E., 1983. Holocene changes in the vegetation of the Midwest. In: Wright, H.E. (Ed.), Late Quaternary Environments of the United States. University of Minnesota, Minneapolis, MN, pp. 142–165.
Webb, I.T., Shuman, B., Williams, J.W., 2004. Climatically forced vegetation dynamics in eastern North American during the Late Quaternary Period. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), The Quaternary Period in the United States. Elsevier, Amsterdam, pp. 459–478.
Woltemade, C.J., 1994. Form and process: fluvial geomorphology and flood-flow interaction, Grant River, Wisconsin. Ann. Assoc. Am. Geogr. 84, 462–479.
Womack, W.R., Schumm, S.A., 1977. Terraces of Douglas Creek, Northwestern Colorado: an example of episodic erosion. Geology 5, 72–76.