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**Chronology and Stratigraphy of the Imlay channel in Lapeer County,
Michigan, USA**

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ABSTRACT

The Imlay channel in Lapeer County, Michigan was one of two outlets for the glacial Lake Maumee phase of ancestral Lake Erie. Fifteen new radiocarbon and optical ages from within and adjacent to the Imlay channel constrain sedimentation rates within the channel and the timing of regional deglaciation. For nearly 50 years the deglaciation of this region of Michigan has been based on a single age from the Weaver Drain site located near the Imlay channel, and a new radiocarbon age of 16.7–17.0 cal ka BP from 3 km east of the Imlay channel supports this long-standing deglacial age. On average there is a 14 m thick sediment fill within the channel. Radiocarbon and OSL ages reveal that much of the alluvial fill was deposited by 14.9 ka, and alluvial fans building into the channel stabilized in the early Holocene. Cross-sections along and perpendicular to the Imlay channel, built from geotechnical borings and water-well records, reveal a current-day bedrock sill elevation at 235 masl that would have permitted drainage of all stages of glacial Lake Maumee in the past.

KEY WORDS

Lake Maumee, Imlay Channel, Ancestral Lake Erie, Great Lakes, Fort Wayne Outlet

35 Introduction

36 The chronology and history of the Imlay channel and its role in draining glacial Lake Maumee in
37 the Lake Erie and Lake Huron basins remains poorly known. Leverett and Taylor's (1915)
38 original work on the Imlay channel was updated by Burgis (1970), but beyond several reviews of
39 lake development controlled by ice-margin recession that include the Imlay channel as an outlet
40 for glacial Lake Maumee (Fullerton 1980; Calkin and Feenstra 1985; Barnett 1992; Lewis et al.
41 1994; Larson and Schaetzl 2001), we are unaware of any subsequent work in this region. The
42 relationship between the Fort Wayne (FWO) and the Imlay channel outlets remains unknown as
43 does the controlling sill elevation. Moreover, the most recent deglacial radiocarbon date for this
44 region, 16.1–17.3 cal ka BP, was published ~50 years ago (Buckley and Willis 1972) and
45 changes in radiocarbon dating technology now result in more precise ages. In this paper we
46 demonstrate that when the Imlay channel was deglacialated it could drain any level of glacial Lake
47 Maumee, that the controlling sill elevation was ~14 m below the modern drainage divide, and
48 with new radiocarbon dates, the minimum deglacial age is now 16.7–17.0 cal yr BP.

49 Deglaciation of the Thumb of Michigan (Fig. 1C) began after the Port Bruce stadial when
50 the Huron-Erie Lobe readvanced to the Union City moraine in northeast Indiana (Mickelson et
51 al. 1983; Barnett et al. 1991). The geometry of deglaciation across the Thumb was one of
52 unzipping the northern Saginaw Lobe from the eastern Huron Lobe as they receded
53 northeastwards across the high elevation Interlobate moraine (Fig. 1C). Water in contact with the
54 retreating Saginaw Lobe drained west into glacial Lake Chicago (Fig. 1B) and eventually ponded
55 to form glacial Lake Saginaw (Leverett and Taylor 1915; Eschman and Karrow 1985). East of

the Interlobate moraine (Fig. 1C), water of glacial Lake Maumee was in contact with the retreating Huron and Erie lobes and drained out the FWO (Fig. 1B). The Imlay channel formed when a low area on the Interlobate moraine was deglaciated, capturing drainage from glacial Lake Maumee (Leverett and Taylor 1915; Calkin and Feenstra 1985). Continued retreat of the Huron Erie Lobe eventually uncovered lower outlets across New York state (e.g., Calkin and Feenstra 1985) and water levels fell, ending the glacial Lake Maumee phase of ancestral Lake Erie (ALE). The subsequent Port Huron readvance of the Huron Erie Lobe culminated with deposition of the Port Huron moraines in Michigan (Fig. 1C), and water level in the Lake Erie and Lake Huron basins rose to form glacial Lake Whittlesey with the Uby channel draining the lake westwards (Fig. 1B).

A reexamination of the FWO by Bleuer and Moore (1971) determined that the controlling sill elevation is low enough to drain all stages of glacial Lake Maumee. For comparison, we want to know what the controlling sill elevation is for the Imlay channel. Leverett and Taylor (1915) suggest a controlling elevation of 244 m within the Imlay channel that was later updated to 250 masl based on Burgis' (1970) evaluation of topographic maps. The north-south drainage divide within the channel is at 250 masl. As with the FWO study (Bleuer and Moore 1971), a better understanding of the characteristics of fill within the Imlay channel will result in a more accurate understanding of the water levels in glacial Lake Maumee than relying on the surface elevation of the channel fill.

A single radiocarbon age of $13,770 \pm 210$ ^{14}C years BP (I-4899, 16.1–17.3 cal ka BP, Buckley and Willis 1972) from plant litter within interbedded layers of sand, silt, and clay was

collected in the 1960s by Burgis (1970) at the Weaver Drain site, ~8 km northeast of the Imlay channel (Fig. 1A). For nearly 50 years this single age has been used to constrain the deglacial history in southeastern Michigan, and the same age is found at several sites in south central Michigan (Fisher et al. 2020), including an OSL age of 16.8 ± 1.0 ka from a glacial Lake Maumee strandline in northwestern Ohio (Fisher et al. 2015). The age from the Weaver Drain site has also been used to date cessation of water flow through the Imlay channel (Burgis 1970; Buckley and Willis 1972; Fullerton 1980; Calkin and Feenstra 1985). The Weaver Drain site has been described as a glacial outwash channel (Buckley and Willis 1972) and a part of the Maumee lake plain (Eschman and Karrow 1985).

The Imlay channel study area is in northeast Lapeer County, Michigan (Fig. 1A). The modern drainage divide of the Imlay channel is near the intersections of Clear Lake and Van Dyke roads (DD, Fig. 1A). The sedimentary bedrock underlying the study area includes three formations (Fm.) that are all Mississippian in age (Milstein 1987; Westjohn and Weaver 1996; Michigan Department of Environmental Quality 2018). The Coldwater Fm. (6% of area) is up to 390 m thick in the state of Michigan and is overlain by the Marshall Fm. (84%). The Coldwater Fm. is comprised of shale, siltstone, sandstone, and carbonates (Westjohn and Weaver 1996). The 60 m thick Marshall Fm. is a major regional aquifer comprised of shale, siltstone, sandstone, and carbonates (Westjohn and Weaver 1996). Overlying the Marshall Fm. is the Michigan Fm. (10%) (Fig. 2B), which is ~120 m thick and consists of shale, siltstone, sandstone, carbonates, and gypsum (Westjohn and Weaver 1996). The purpose of this study is to further investigate the

Imlay channel's role in draining the glacial Lake Maumee phase of ALE, its sedimentary fill, and to update the minimum limiting age for the channel.

Methods

Surficial mapping of the Burnside 7.5' Quadrangle, through which the Imlay channel passes, used a LiDAR derived digital elevation model (DEM, Figs 2, 3) base map with 1-m horizontal resolution (Luczak 2018). The DEM maps in Figure 1 were constructed from USGS NED elevation data with Natural Scene Designer ProTM software. All maps have a UTM 17N projection using the NAD 83 datum. Sedimentary data were collected from vibracoring (Fisher 2004, 2018), hydraulically assisted Livingstone coring, hand augers, hand-dug pits, and at outcrop exposures. Clear Lake (Fig. 1A) was cored from an anchored canoe-pontoon catamaran platform. Numerous days were spent trying to locate the stratigraphy described by Burgis (1970) along the Weaver Drain but were unsuccessful.

Geologic cross-sections from the surface topography to the bedrock surface are based on water-well data from Michigan's Wellogic Database (2018) and unpublished geotechnical borings provided by Genesee County, MI (PSI 2013). The cross-section approximately perpendicular to the Imlay channel along Clear Lake Road is ~650 m southeast of the modern topographic drainage divide, and the geotechnical logs are along it. The water-wells used are those that penetrate to bedrock and are within 150 m of the topographic profile. For the longitudinal cross-section, well logs chosen are within ~700 m of the center of the Imlay channel. The geotechnical logs use the Unified Soil Classification System (USCS), and without access to the sediment, sedimentary units were divided into three generalized units keyed to

positions on the landscape: diamicton, undifferentiated glaciofluvial/glaciolacustrine sediment, and post-glacial fill. The latter unit within the Imlay channel and Clear Lake valley includes peat, marl, sand and gravel, clay, sand, and silt. The simple sediment descriptions from water-well logs include, for example ‘red clay, blue clay, yellow sand’, and are more subjective than those from the geotechnical logs. Comparisons were made between the water-well log units and the adjacent geotechnical logs and sediment collected across the study area (Luczak 2018), resulting in water-well log sedimentary units of diamicton, clay, sand and silt, and sand and gravel.

The interpolated bedrock and drift thickness maps (Fig. 2) were created in ArcGIS by using 947 water-well records from Michigan’s Wellogic database (2018). The elevations in the bedrock topography map (Fig. 2B) were calculated by subtracting the depth of the first bedrock surface encountered in the water-well log from the surface elevation of the LiDAR DEM where the well is located. The surface was interpolated with ordinary kriging using ESRI’s ‘Geostatistical Wizard’ tool. The drift thickness map (Fig. 2C) was made in a manner similar to the bedrock topography map, except the thickness of unconsolidated sediments overlying the first bedrock surface encountered in the wells was used in the interpolation rather than the elevation of the first bedrock surface.

The Maumee and Whittlesey strandlines of ALE were traced using ArcGIS from a starting point near Bryan, Ohio (Fig. 1B), ~215 km southwest of the study area and ~65 km northeast of the FWO, where the three strandlines are found. Strandlines associated with highest glacial Lake Maumee (499 elevation points), lowest glacial Lake Maumee (556 elevation points), and Lake Whittlesey (787 elevation points) were traced to the northeast using 1/9 arcsecond

DEMs and following the methodology of Breckenridge (2013) and Dilworth (2017). Datasets for the three water levels of ALE were plotted against distance along the direction of maximum uplift (DMU of 18° NNE) where strandlines plot at higher elevations to the north because of greater glacioisostatic adjustment (GIA). The DMU was determined by finding the direction of a line in ArcMap drawn perpendicular to highest glacial Lake Maumee isobases, i.e. strandlines of equal elevation on opposite sides of the Huron-Erie basin. The DMU for this study is similar to the DMU of 23.1° NNE from Breckenridge's analysis (2013) of strandlines in the western Lake Superior basin and 23° NNE from a study of the ALE basin by Dilworth (2017; personal communication 2018).

Radiocarbon ages are from Woods Hole Oceanographic Institution and Beta Analytic are calibrated using Calib8.2 software (Stuiver et al. 2021) and the IntCal20 calibration curve (Reimer et al. 2020) and are reported with a two-sigma range (Table 1). Samples for optically stimulated luminescence (OSL) dating were collected in hand-dug pits and outcrops at least 1 m below the surface, and from the lowermost 30 cm of unopened sections of aluminum vibracore tubes, that ranged from 1.3–4.4 m in length. The Optical Dating and Dosimetry Lab at North Dakota State University was used for OSL analysis. The ages were determined from clean quartz sand extracts in the grain size range 150–250 µm using single aliquot regenerative dose (SAR) procedures (Murray and Wintle 2000; Wintle and Murray 2006). Sample preparation, instrument details, and data analysis methodology are described in more detail in the supplement to Lepper et al. (2007) as well as in Fisher et al. (2020). Dose rates were calculated following the methods presented in Aitken (1985, 1998) and Prescott and Hutton (1988, 1994) and presented in Tables 2 and 3.

The D_e distributions for all samples in this study were symmetric, having population mean to median ratios (M/m) less than 1.05. The M/m ratio is a gauge of distribution symmetry/asymmetry of the D_e data set and is used as a gauge of the degree of solar resetting along with consideration of dispersion. Dispersion (v_t) is a gauge of the relative variability of the data set. Additional discussion can be found in the supplement to Lepper et al. (2007). Because the data sets in this study were symmetric and most had moderate dispersion values, interpreted as adequate resetting prior to deposition, the mean and standard error of each equivalent dose distribution was used as the basis for age calculations. Ages, errors, and uncertainties are presented using the convention proposed in Lepper et al. (2011).

Results

The modern surface expression of the Imlay channel is flat-bottomed and contains numerous alluvial fans fed by tributary streams, especially near its present-day topographic divide where it is flanked by highlands of the interlobate area to the west and the Deanville Mountain kame to the east (Figs. 1, 3). The Imlay channel extends for about 30 km southeast to northwest and then turns sharply to the west near the top of Figure 1A. At the current topographic (drainage) divide the channel is ~900 m wide at an elevation of 250 masl (DD on Figs. 1, 3). The upstream end of the channel is near the southernmost section of the Imlay moraine where the northern extent of the Maumee strandlines end (Fig. 1A). Bedrock is not exposed in the channel, and water-well data suggest an irregular bedrock surface underlies the channel fill (Fig. 2).

Cross-sections

The 10.5-km long Clear Lake Road cross-section (CLRCS) perpendicular to the Imlay channel (Fig. 4A) is based on the interpretation of 50 previously collected geotechnical borings and 18 Wellogic water-wells that penetrate to bedrock. The 22-km long longitudinal cross-section (LCS) along the Imlay channel (Fig. 4B) is based on 14 water-well logs that penetrate to bedrock. Units within the geotechnical logs described as clay, sandy clay, clayey sand and gravel, and silty clay

with gravel are most likely till, taking into account their position on the landscape, and compared with surficial geology mapping in the area (Burgis 1970; Luczak 2018). Small stream valleys incised into the diamicton are filled with sand, silt, clay (i.e. alluvium and glaciolacustrine), and gravel interpreted to be undifferentiated glaciofluvial or glaciolacustrine fill, likely capped with more recent alluvial sediment. The Clear Lake valley and Imlay channel are shown on the cross-section as post-glacial valley fill. Geotechnical logs from the Imlay channel are from borings 6–12 m long, and descriptions include sand and gravel, sand, clay, silt, silty sand, and laminations of silty clay. Similar length borings from the Clear Lake valley contain post-glacial alluvium consisting of sand and gravel, and organic silt and marl as far as 10 m below the surface.

Bedrock along the CLRCS is generally shale or sandstone and likely represents the Marshall Fm. (Westjohn and Weaver 1996) based on data from the interpolated bedrock map (Fig. 2B).

Bedrock elevations from water-well logs range from 207 masl near the valley leading to Clear Lake, to 244 masl just west of the Imlay channel's eastern boundary (Fig. 4A). The available water-well records indicate the lowest bedrock surface elevation beneath the Imlay channel along the CLRCS is at 235 masl, with ~14 m of fill above it. The bedrock surface is deeper within the Clear Lake valley, and it is floored with diamicton and glaciofluvial or glaciolacustrine sediment.

Only three general sedimentary units are used in the LCS because of the simpler nature of the available water-well descriptions (Fig. 4B). Diamicton (assumed to be till) is found in bedrock lows, overlain by sand and gravel, and finer-grained fill. Finer-grained fill consisting of clay, silt and sand is found at the top of most wells. Diamicton is observed at two wells south of the CLRCS, one in and another along the southern edge of a deep depression. North of the CLRCS more diamicton is recorded in the wells, but Wells 4 and 5 containing diamicton are along the channel edge, and Wells 1–3 near the center of the channel and further north are without diamicton, suggesting that the depth to diamicton in the center of the channel between Well 3 and the CLRCS is likely deeper (Fig. 4B). The lower elevation of the sand and gravel and the bedrock surface can be used as a measure of incision depth for the base of the Imlay channel (Fig. 4B). Depth to the bedrock surface elevations from water-well data range from 197 masl at Well 6 to 235 masl at Well 9, where the LCS intersects the CLRCS (Fig. 4B). Thus, the lowest bedrock surface beneath the Imlay channel along the CLRCS at 235 masl corresponds with the highest bedrock surface beneath the channel along the LCS. And other than the

uncertainty of the diamicton surface elevation in Wells 4–6, the lower depth of sand and gravel fill in the LCS is lower than the bedrock sill.

Water planes

The results of mapping strandlines from near the FWO to the Imlay channel are shown on Figure 5. The strandlines of highest glacial Lake Maumee, lowest glacial Lake Maumee, and Lake Whittlesey all increase in elevation along the DMU (Fig. 5). The highest Maumee strandline extends to the head of the Imlay channel (Fig. 1A) and plots ~18 m above the present-day elevation of the topographic drainage divide. The lowest Maumee strandline ends 40 km south of the Imlay channel, near Almont, Michigan, and plots ~3 m below the modern topographic drainage divide. The Whittlesey strandline extends into the map area shown in Figure 1A, and its distribution is continuous at an elevation below the head of the Imlay channel.

Sedimentary sequences

Sedimentary data from several cores and a hand-dug pit (Fig. 3) from within the Imlay channel, Clear Lake, and a meltwater channel on the east side of Deanville Mountain offer greater detail into chronology (Tables 1,3), sedimentation rates, and the paleoenvironments than do the water-well and geotechnical logs. Sedimentary data from Cores 1–3 on either side of the drainage divide reveal that peat up to 1 m thick overlies gravelly sand. The structure of the fine to very-coarse grained gravelly sand alternates between massive to weakly bedded with silty sand, and abrupt, sometimes erosional, lower contacts. The gravel is pebble-sized, very-fine to fine grained, and subangular to subrounded. The sand matrix is comprised of quartz grains, crystalline lithics, and plates of mica. The upper mud in Core 3 contains gravel and is fossiliferous. The gravelly sand units represent an environment of moderate energy with deposition as fluvial and alluvial sediment in the channel bottom and where entering a shallow lake or pond (Miall 1977; Rust and Koster 1984; Nanson and Croke 1992). Shallow lakes and/or ponds could form in abandoned fluvial channels or in depressions between alluvial fans

intermittently damming drainage along the floor of the Imlay channel. The water table was ~0.30 m below the upper surface of the peat at coring sites within the Imlay channel, and we suspect that the many drainage ditches across the Imlay channel have lowered regional water tables since European settlement. A similar depositional sequence of gravel, sand and organic sediment is described from spillway channels elsewhere (e.g., Bleuer and Moore 1971; Kehew and Boettger 1986).

Several OSL samples from the Imlay channel sediment (Fig. 3) indicate that gravelly sand continued to be deposited at 14.9 ± 1.4 and 14.1 ± 1.4 ka ago. Younger radiocarbon ages from the edge of an alluvial fan in core 3 from the top of the gravelly mud and the base of the peat indicate that the depositional environment transitioned from alluvial to paludal between 13 (12.7–13.1 cal ka BP) and 11.9 cal ka BP (11.8–12.4 cal ka BP). From a nearby alluvial fan a few meters higher on the landscape (site 4 pit, Fig. 3) an OSL age of 10.2 ± 0.9 ka indicates that alluvial fan deposition continued into the early Holocene.

Core 5 is from the west end of Clear Lake with a fossiliferous, fining upwards, basal gravelly sand overlain by sapropel and marl lacustrine sediment (Fig. 3). The gravelly sand is very similar to that previously described from Cores 1–3 suggesting that it could be an alluvial fan deposit submerged by a deepening Clear Lake. Alternatively, the gravelly sand may be a littoral deposit drowned when water tables rose to deepen Clear Lake. The two black dashed lines in the CLRCS (Fig. 4A) show the elevation of the gravelly sand (upper line) and bottom of the lake assuming a similar fill thickness (lower line). These depths indicate that the Clear Lake valley is cut well below the Imlay channel. Radiocarbon dates from the basal gravelly sand (13.8–14.1 cal ka BP) and overlying sapropel (14.1–14.8 cal ka BP) are out of stratigraphic order. Using the median ages (Table 1), the average of the youngest date (13.9 cal ka BP) from gravelly sand and the oldest date (14.2 cal ka BP) from sapropel suggests Clear Lake deepening at about 14.1 cal ka BP.

Core 6 is within a meltwater channel ~1.4 km southeast of the channel's northernmost end (Fig. 3). Core penetration stopped within the basal fossiliferous diamicton unit. The bluish gray (2GLEY 5/5B) matrix of the diamicton supports very-fine to coarse pebbles. The diamicton

is interpreted to be colluvial in origin, likely debris flow material due to its position at the base of a channel immediately adjacent to the steep, gullied eastern edge of Deanville Mountain (Fig. 3). The silt interbedded between the diamicton units suggests two episodes of colluvial activity into a ponded environment. The oldest radiocarbon date (16.9 cal ka BP; 16.7–17.0 cal ka BP) is a few thousand years older than three other wood fragments from the diamicton that are similar in age to those from sediment collected from the floor of the Imlay channel and the base of Clear Lake. (Fig. 3).

Two OSL ages are from the Deanville Mountain, a large kame with many abandoned and active gravel pits on it (Figs. 3, 6). The kame rises 50 m above the till plain to the northeast, and the active pit visited in this study had high walls of 12 m (Fig. 6A). Sheets of westward, gently dipping planar beds of gravel have normal and reverse faults, and in places involuted sediment recording melting of buried ice blocks in which overlying gravel becomes progressively less deformed upwards (Fig. 6B). OSL sample 7 (Figs. 6F, G) is from the proximal end of the kame on an upper bench exposing a minimum 0.4-m thick laminated sand overlain by 1.3 m of clast-supported sand and gravel with an erosional lower contact. A ~30 cm thick soil is developed into the top of the gravel. The sampled laminated sand is very-fine to very-coarse grained, subangular to rounded consisting of quartz and crystalline lithologies. The OSL age of sample 7 is 70.3 ± 6.9 ka. (Fig. 6F; Table 2).

OSL sample 8 (Figs. 6C and E) is from a more distal position than sample 7 (~0.5 km west). The sample is from the middle of a ~0.90 m thick sequence of clean, horizontally bedded laminated sand (Figs. 6C, E), with characteristics the same as from sample site 7. The sampled sand is underlain by ~1 m of exposed cross-bedded sand and gravel, and overlain by about 9.7 m of sand and gravel estimated from photos and the DEM. The OSL age of sample 8 is 60.6 ± 6.0 ka (Fig. 6E; Table 2).

Discussion

Deglaciation age and occupancy of the Imlay channel

Deglaciation across the Thumb of Michigan and the limiting chronology for deglaciation of the Saginaw Lobe since the 1970s has depended upon the single radiocarbon age from the Weaver Drain site of 16.1–17.3 cal ka BP (Burgis 1970; Buckley and Willis 1972). The oldest wood fragment of 16.7–17.0 cal ka BP from the Deanville Mountain meltwater channel overlaps

with the Weaver drain age. With this new higher precision radiocarbon date, the minimum limiting age for deglaciation for this region is now 16.7–17.0 cal ka BP, which is earlier than deglaciation between ~16.8–16.1 ka calibrated BP shown on the isochrone deglaciation maps of Dalton et al. (2020). The oldest radiocarbon date represents colonization of the area by plants followed by mass movement activity during paraglacial time. Earlier workers (Leverett and Taylor 1915) had noted that the North Branch and Elm Creek channels downstream of the Weaver Drain (Fig. 1A) may have acted as outlets for glacial Lake Maumee once ice had retreated from that area, but the timing of those channels compared with abandonment of the Deanville Mountain meltwater channel and opening the Imlay channel remains unknown.

Leverett and Taylor (1915) suggested that oscillatory ice-margins in the study area resulted in cyclic glacial Lake Maumee water-level fluctuations in the ALE basin, and the cross-cutting of moraines evident in Figure 1A (e.g., Goodland moraine truncating the Imlay moraine) do indicate at least one readvance was possible, but the extent of the preceding retreat is unknown. Reanalysis of some “washed” moraines—which Leverett and Taylor (1915) used as evidence of transgressive-regressive events in the ALE basin may instead be interpreted by a simpler regressive water-level history (Totten 1985; Fisher et al. 2015) with lake stages controlled by episodic incision of the outlet(s) during the glacial Lake Maumee phase of ALE. There is a possibility that no significant readvance occurred closing a lower outlet, and that the Imlay, Goodland, and Deanville moraines (Fig. 1A) are simply recessional in nature.

Two possibilities exist for the OSL ages (60 to 70 ka) of kame deposits on Deanville Mountain (Fig. 6). The first is that the kames were deposited during an earlier glacial period associated with marine isotope stage 4, i.e., ~70 ka (Eyles and Westgate 1987; Mickelson and Colgan 2003; Dyke 2004). Another possibility is that the kame deposits are late Wisconsinan in age, which would require that the luminescence of the sand was only partially reset prior to deposition, possibly due to the turbidity of proglacial meltwater in close proximity to the ice-margin (e.g., Rittenour, 2008). Partial resetting is more likely for the two older samples discussed here (UT1703JL, UT1707JL [Table 2]). Even though they have symmetric D_e distributions, they also have high dispersion, which has been previously observed for partially reset samples over 50 ka in age (Banerjee et al. 2002; Lepper unpublished data). This second possibility is consistent with the preservation of the feature. Presumably, if the kame was deposited 60,000–70,000 years ago it would have been overrun by an unknown number of

glacial advances and readvances, making its preservation tenuous. Thus, a geomorphic argument supports a younger (late Wisconsinan) age requiring that the sand was only partially reset. Large kames are common within interlobate areas during the last deglaciation (e.g., Carlson et al. 2004), as are thick sedimentary sequences elsewhere in Michigan (Rieck 1979; Rieck and Winters 1993).

Water drainage through the Imlay channel

The water-well logs and geotechnical borings used to construct the geologic cross-sections (Fig. 4) reveal that fluvial scour was to bedrock at nearly all sites upstream (south) of the bedrock high in the CLRCS. The data is not as clear downstream of the CLRCS where Wells 4–6 include diamicton over bedrock. From these data, the low point on the bedrock beneath the CLRCS would be the controlling sill in the Imlay channel at 235 masl (Fig. 4). The elevations of the various glacial Lake Maumee strandline elevations all plot a minimum of 12 m above the bedrock sill (Figs. 4A, B), implying that once deglaciated, the Imlay channel was an outlet for any stage of glacial Lake Maumee. Strandlines associated with the lowest level of glacial Lake Maumee are not found within ~40 km of the channel mouth (Fig. 5), and their absence may be explained by burial from peat or colluvial deposits. Strandlines are not expected in the mouth of the spillway because as the channel deepens and widens any initial strandlines near the channel mouth would be eroded.

Glacial isostatic adjustment (GIA) curves relative to distance for the highest and lowest levels of glacial Lake Maumee have similar slopes (Fig. 5), suggesting that these lake stages formed under similar GIA conditions at roughly the same time, similar to other studies of glacial lakes (e.g., Breckenridge, 2013). From Ohio, an OSL age for the middle Maumee strandline of 16.7 ± 0.8 ka (Fisher et al. 2015), overlaps with the deglaciation age for the Imlay channel. The shallower slope of the Whittlesey strandline (Fig. 5) indicates that it was not affected by GIA over as long a period of time as the Maumee strandlines. The age of the Whittlesey strandline is considered to be 15.4–15.8 cal ka BP (Calkin and Feenstra 1985), about 1,000 years younger than the youngest Maumee strandlines. The result of the Whittlesey level plotting below the elevation of the bedrock sill in the Imlay channel supports the strandline mapping lower than the mouth of the Imlay channel (Fig. 1A) at 229 masl. Early workers (Leverett and Taylor 1915) suggested Lake Whittlesey's outlet was the Uby channel 65 km northwest of the Imlay channel

(Fig. 1C). Barnett (1978) describes the Lake Whittlesey strandlines near Richmond, Michigan, located ~260 km NE of the FWO (Fig. 5) at an elevation of 229 masl, like those in this study.

The most recent work on the FWO in Indiana by Bleuer and Moore (1971) found that the sill is made of hard loamy and clay till, and that it could accommodate the drainage of all stages of glacial Lake Maumee. Because the highest glacial Lake Maumee shorelines trace to the Imlay channel outlet, outlet incision to a lower lake level had not occurred until after the Imlay channel opened. Therefore, it is likely that opening the Imlay channel lowered glacial Lake Maumee to the middle and perhaps eventually to the lowest Maumee level. With the Clear Lake valley incised at least 15 m lower than the Imlay channel only a few km to the north, a steep gradient likely drove rapid incision of the channel by headward erosion into till until bedrock was encountered. The weakly developed middle Maumee strandline (e.g., Fisher et al. 2015) suggests a brief pause in channel incision to provide time for it to form. Drainage interactions between the Imlay channel on a faster rebounding isobase than the FWO suggests that once the bedrock sill was reached in the Imlay channel discharge out the FWO would increase through time. Results from this study (Figs. 4, 5) suggest that like the FWO, all levels of glacial Lake Maumee could have drained through the Imlay channel, but interactions between the two outlets remains speculative. A lake with two active outlets, while uncommon, is not unprecedented. Thompson et al. (2011; 2014) discuss three contemporaneous outlets for mid-Holocene aged Nipissing phase in the upper Great Lakes basin.

Channel fill and chronology

The Weaver Drain radiocarbon date has been used to date abandonment of the Imlay channel at the end of the Maumee phase of ALE (Calkin and Feenstra 1985), and this event can now be updated to 16.7–17.9 cal ka BP. While speculative, it is assumed that sand and gravel was deposited under waning flow conditions as the outlet was being abandoned, similar to waning flow sedimentation in outlets from other glacial lakes such as glacial Lake Agassiz (Fisher 2003; Kelly et al. 2016; Fisher 2020). Thus, some of the basal sand and gravel in both cross-sections (Fig. 4) and shown in a depositional model for the Imlay channel (Fig. 7) may date to this time. Once the channel was abandoned, the geomorphic evidence of streams and gullies from the surrounding highlands terminating at alluvial fans lining both sides of the Imlay channel suggest that much of the channel fill originated from these highlands (Figs. 1, 3). At the CLRCS there is

~14 m of sediment over bedrock. The deepest core in the Imlay channel collected from this study penetrated only a little over 4 m. Thus, based on the OSL date from core 2 and assuming channel abandonment was close to the deglaciation age from the Deanville Mountain meltwater channel, ~10 m of sediment was deposited over a ~2000-year window. From core 3, and except for some alluvial fan activity, much of the Imlay channel fill was deposited by 13.0 ka when sedimentation transitioned to within a paludal environment (Fig. 7).

The lithology of sediment within the Imlay channel (Fig. 7) is similar to that of infilled spillway channels in other studies, i.e., clay, silt, sand, and gravel associated with alluvial fans, wetlands, and underfit streams (Bleuer and Moore 1971; Kehew and Boettger 1986). Alluvial fan construction likely generated ephemeral lakes in which sand and some mud could accumulate, and the gravelly sand recovered in Cores 1–3 are consistent with sedimentation in such an environment. The depression now occupied by Clear Lake (Figs. 1, 2) and the short valley connecting it to the Imlay channel likely acted as a backwater to the Imlay channel when the latter was active. Presumably then, Clear Lake valley predates the Imlay channel, having formed earlier during deglaciation. The age of the basal gravelly sand in the Clear Lake core 5 is similar to the ages of sediment fill within the Imlay channel. Thus, much of the alluvial fan growth and channel aggradation in the Clear Lake valley and Imlay channel was before ~14.9 ka.

Studies in paraglacial environments suggest that alluvial fans in alpine valleys (Lian and Hickin 1996) and the moderate relief of northern Lower Peninsula of Michigan (Schaetzl 2001) continued to be deposited and did not fully stabilize for thousands of years following local deglaciation. The timing of sedimentation within the Imlay channel may have also been prolonged due to the effects of permafrost on the landscape. Estimates of ~4,000 years have been made for the thawing of late Pleistocene permafrost following the deglaciation of southern Wisconsin after the last glacial maximum (Clayton et al. 2001). The uppermost sediment from alluvial fans on the present-day topographic floor of the Imlay channel (Fig. 3) appears to be ~1,800 years younger than the uppermost channel fill. Ballantyne (2002) noted that initial sedimentation within paraglacial environments is very rapid at the onset and slows toward the end as vegetation becomes established. Similarly, a study in Wisconsin (Mason 2015) also suggested that accelerated rates of hillslope erosion increased in periglacial environments there. Based on a single age, the youngest alluvial fans, dated at 10.2 ± 0.9 (Fig. 3, Table 2), were

stabilized by the start of the Holocene. Since then, and until European colonization, the floor of the Imlay channel has been a herbaceous wetland marsh.

Summary

The Imlay channel has been studied sporadically over the last 100 years, and this study has improved the understanding of the stratigraphy and paraglacial sedimentation within the Imlay channel and its role in the drainage of glacial Lake Maumee. The subsurface data from this study suggests that the sill of the Imlay channel is controlled by bedrock at an elevation of ~235 masl and is buried by at least 14 m of post-glacial, channel-fill sediment just south of the present-day drainage divide. Once deglaciated, all stages of glacial Lake Maumee, i.e., highest, middle (Fisher et. al. 2015), and lowest, could have drained through the Imlay channel. A plot of outlet sills and strandlines showing the effects of glacial isostatic adjustment indicates that both the Imlay channel and Fort Wayne outlet drained glacial Lake Maumee.

Cores taken within the Imlay channel for this study validate the upper stratigraphy of the previously collected geotechnical borings and water-well records. Together, the core and well-log data suggest that the Imlay channel sediment fill of sand, silt, clay and gravel was deposited between ~16.8 to 13 ka. During this time, the depositional environment within the channel was dynamic and fluctuated between fluvial and lacustrine. At about ~13 ka the depositional environment changed to a wetland marsh environment in which peat accumulated. The deposition of alluvial fans continued into the early Holocene.

The oldest radiocarbon date from this study overlaps in time and general location with the long-standing single date from the Weaver Drain site (Burgis 1970; Buckley and Willis 1972). The two-sigma minimum age for deglaciation at the study site is 16.7–17.0 cal ka BP, which comes from a wood fragment within colluvium in a meltwater channel from the base of Deanville Mountain. The new radiocarbon date offers a higher precision age control, but uncertainty remains how it extrapolates to opening or closing of the Imlay channel.

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626 **Table 1.** Radiocarbon dates.

Core ID	Depth (m)	Lab ID	Material	Age		$\delta^{13}\text{C}$ (‰)	2 Sigma	Median
				^{14}C Age (yr BP)	Error (yr)		Calib. Age (cal ka BP)	prob. Age ¹ (cal ka BP)
3	~0.8	OS-135589	wood frag.	10,250	± 35	-24.8	11.82–12.42	11.9
3	~0.9	OS-135590	wood frag.	11,050	± 35	-25.63	12.85–13.09	13.0
5	5.8 ²	OS-137075	wood frag.	10,850	± 55	NP ³	12.73–12.89	12.8
5	~6.5 ²	Beta-491847	wood frag.	12,250	± 40	-25.8	14.06–14.76	14.2
5	~6.8 ²	OS-137076	wood frag.	12,400	± 65	NP ³	14.18–14.91	14.5
5	~7.3 ²	Beta-491846	wood frag.	12,090	± 40	-26.2	13.81–14.1	13.9
6	2.41	Beta-496778	wood frag.	11,420	± 40	-24.3	13.18–13.41	13.3
6	2.48	Beta-496779	wood frag.	12,420	± 40	-24.3	14.28–14.88	14.5
6	2.52	OS-139410	wood frag.	12,300	± 55	NP ³	14.07–14.81	14.3
6	2.52	Beta-492602	wood frag.	13,870	± 40	-25.1	16.66–17.02	16.9

627 ¹Rounded to nearest hundred years628 ²Depths from below lake bottom with a water depth of 8 m.629 ³NP = not provided

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633 **Table 2.** Dosimetrically relevant data. Elemental concentrations from instrumental neutron activation
634 analysis (INAA).

Field Sample ID	Lab ID	Depth (m)	H ₂ O (%)	Potassium (ppm)	Rubidium (ppm)	Thorium (ppm)	Uranium (ppm)
BSG A1	UT1703JL	1.86	10 ± 3	7866 ± 800	24.71 ± 3.38	2.255 ± 0.210	0.553 ± 0.053

JTEA	UT1704JL	1.05	10 ± 3	12390 ± 1179	45.40 ± 4.62	2.442 ± 0.226	0.928 ± 0.078
ICC 1	UT1705JL	2.95	30 ± 3	11082 ± 1075	33.86 ± 2.58	1.700 ± 0.155	0.741 ± 0.054
ICB 1B	UT1706JL	4.00	30 ± 3	11052 ± 1003	34.04 ± 3.96	2.486 ± 0.229	0.561 ± 0.055
BSG B1	UT1707JL	10.20	12 ± 3	7713 ± 752	27.39 ± 3.88	1.526 ± 0.143	0.627 ± 0.053

Table 3. Optically stimulated luminescence ages and equivalent dose distribution data.

Sample ID ¹	Lab ID	N ²	M/m ³	υ ⁴	δD _c ⁵	Equivalent Dose ⁶ (Gy)	Dose Rate ⁷ (Gy/ka)	Age (ka)	Age Error ⁸ (ka)	Age Uncert. ⁹ (ka)
1	UT1705JL	94/96	1.00	0.362	3.4%	0.580	0.099	14.1	0.5	1.4
2	UT1706JL	93/96	1.00	0.380	0.7%	0.642	0.094	14.9	0.6	1.4
4	UT1704JL	92/95	1.04	0.258	3.3%	0.443	0.138	10.2	0.3	0.9
7	UT1703JL	84/96	1.01	0.347	1.2%	2.879	0.098	70.3	2.7	6.9
8	UT1707JL	91/94	1.04	0.443	2.3%	2.607	.081	60.6	2.8	6.0

¹See Core Label Conversion in Figure 3.

²No. of aliquots used for OSL D_e calculation / no. of aliquots from which OSL data was collected (filtering criteria given in Lepper et al. 2003).

³Mean/median ratio: a measure of dose distribution symmetry/asymmetry (see supplement to Lepper et al. 2007).

⁴Total dose distribution data dispersion (Std. dev./Mean).

⁵Dose recovery fidelity (refer to "check dose" in Lepper et al. 2000 and supplement to Lepper et al. 2007).

⁶Equivalent doses are based on the mean and std. err. of the OSL D_e distribution.

⁷Dose rates calculated following the methods described in Aitken (1985; 1998) and Prescott and Hutton (1988; 1994).

⁸Age error based on the std. err. of the OSL D_e distribution (Lepper et al. 2011).

647 ⁹Fully-propagated age uncertainty (Aitken 1985).

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Figure Captions

Figure 1. The Imlay channel is located across the Thumb of Michigan and was an outlet for glacial Lake Maumee in the Lake Huron and Lake Erie basins (B). A) DEM showing location of the study area (Fig. 3 black square outline), Imlay channel, ice-margins, strandlines, and flow direction into and through the Imlay channel (white arrows). The Imlay channel was abandoned once water level dropped below the lowest Maumee level. DD–drainage divide within the Imlay channel. DM–Deanville Mountain kame. WD–approximate location of Weaver Drain stratigraphic site of Burgis (1970). B) Southern Great Lakes region showing water draining from glacial Lake Maumee through an older outlet at Fort Wayne, IN and later through the Imlay channel outlet. Water may have passed through glacial Lake Saginaw on its way through the Grand River into glacial Lake Chicago, and then through the Chicago outlet to the Illinois River, tributary to the Mississippi River. The gray line is the Port Huron moraine (PHM) (e.g., Fig. 1C) (Larson and Schaetzl 2001) and the black line is the ~16.8 ka cal BP ice-margin of Dalton et al. (2020) shown in a more northerly position to permit opening the Imlay channel by then. C) DEM of the Thumb of Michigan showing Interlobate moraine, white arrows signifying deglaciation (unzipping) of the Saginaw and Huron-Erie lobes, and PHM. Elevation decreases from white to black. [Colour online.]

Figure 2. Relationship of A) surface topography with B) bedrock surface topography resulting in C) a sediment thickness map. Imlay Channel is evident in panel (A) along the longitudinal cross-section. The channel crosses over two bedrock highs in the subsurface. Bedrock contacts in 2B are from Milstein (1987). [Colour online.]

Figure 3. Location map of core and pit sites, lithostratigraphic logs, and dating sample sites. The drainage divide across Imlay channel is along black line labelled DD.

Figure 4. Geologic cross sections of surficial sediment overlying bedrock. A) Clear Lake road cross-section. B) Longitudinal cross-section along the Imlay Channel, numbers above wells refer to well sites located on the DEM in panel C. Note bedrock high in cross-section B–B' closely aligns with the position of the surface drainage divide immediately north of the Clear Lake Road

cross-section. The lowest elevation bedrock surface beneath the Imlay Channel at 235 m on cross-section A–A' corresponds with the highest bedrock elevation bedrock surface on cross-section B–B', suggesting that channel incision was stopped by bedrock at this sill location, and all stages of glacial Lake Maumee could have drained through the channel. Question marks refer to expected deeper depth of the diamicton surface in the center of the channel. C) Location of numbered water-wells in panel B. [Colour online.]

Figure 5. Strandline data of three water planes from ancestral Lake Erie plotted against distance perpendicular to direction of maximum uplift (N 18° E). Left side of plot is the outlet at Fort Wayne, IN (Fig. 1) and shorelines extend along the northwest side of the lake basin starting at Bryan, OH to the Imlay channel (Fig. 1). When ice-free any stage of glacial Lake Maumee used both the Fort Wayne and Imlay channels (Fig. 1B). Lower slope of Whittlesey strandline corresponds to its younger age and is too low to have intersected the Imlay outlet.

Figure 6. Stratigraphy of Deanville Mountain, a large kame, where two OSL samples were collected. A) View of the high wall along the east side of the pit. B) Exposure of interbedded sand and gravel with collapse structures from melted ice. Note how the deformed bedding, traced as white dashed lines, decreases towards the surface indicating continued sedimentation while an ice block was melting. Shovel and soil probe 1 m tall is circled. C) Site 8 stratigraphy for OSL sample 8. D) DEM of the gravel pit with sites 7 and 8 located, location of DEM shown in Figure 3. E) Site 8 stratigraphy for OSL sample 8. F, G) Site 7 stratigraphy for OSL sample 7.

Figure 7. Schematic depositional model of the sedimentary fill within the Imlay channel. The basal gravel and sand from waning flow in spillway was not observed but is expected. Scale is for channel cross-sectional area only. Styled after Kehew and Boettger (1986).

Figure 1. The Imlay channel is located across the Thumb of Michigan and was an outlet for glacial Lake Maumee in the Lake Huron and Lake Erie basins (B). A) DEM showing location of the study area (Fig. 3 black square outline), Imlay channel, ice-margins, strandlines, and flow direction into and through the Imlay channel (white arrows). The Imlay channel was abandoned once water level dropped below the lowest Maumee level. DD—drainage divide within the Imlay channel. DM—Deanville Mountain kame. WD—approximate location of Weaver Drain stratigraphic site of Burgis (1970). B) Southern Great Lakes region showing water draining from glacial Lake Maumee through an older outlet at Fort Wayne, IN and later through the Imlay channel outlet. Water may have passed through glacial Lake Saginaw on its way through the Grand River into glacial Lake Chicago, and then through the Chicago outlet to the Illinois River, tributary to the Mississippi River. The gray line is the Port Huron moraine (PHM) (e.g., Fig. 1C) (Larson and Schaetzl 2001) and the black line is the ~16.8 ka cal BP ice-margin of Dalton et al. (2020) shown in a more northerly position to permit opening the Imlay channel by then. C) DEM of the Thumb of Michigan showing Interlobate moraine, white arrows signifying deglaciation (unzipping) of the Saginaw and Huron-Erie lobes, and PHM. Elevation decreases from white to black.

177x213mm (300 x 300 DPI)

Figure 2. Relationship of A) surface topography with B) bedrock surface topography resulting in C) a sediment thickness map. Imlay Channel is evident in panel (A) along the longitudinal cross-section. The channel crosses over two bedrock highs in the subsurface. Bedrock contacts in 2B are from Milstein (1987).

153x244mm (300 x 300 DPI)

Figure 3. Location map of core and pit sites, lithostratigraphic logs, and dating sample sites. The drainage divide across Imlay channel is along black line labelled DD.

171x227mm (300 x 300 DPI)

Figure 4. Geologic cross sections of surficial sediment overlying bedrock. A) Clear Lake road cross-section. B) Longitudinal cross-section along the Imlay Channel, numbers above wells refer to well sites located on the DEM in panel C. Note bedrock high in cross-section B-B' closely aligns with the position of the surface drainage divide immediately north of the Clear Lake Road cross-section. The lowest elevation bedrock surface beneath the Imlay Channel at 235 m on cross-section A-A' corresponds with the highest bedrock elevation bedrock surface on cross-section B-B', suggesting that channel incision was stopped by bedrock at this sill location, and all stages of glacial Lake Maumee could have drained through the channel. Question marks refer to expected deeper depth of the diamicton surface in the center of the channel. C) Location of numbered water-wells in panel B.

231x178mm (300 x 300 DPI)

Figure 5. Strandline data from of three water planes from ancestral Lake Erie plotted against distance perpendicular to direction of maximum uplift (N 18° E). Left side of plot is the outlet at Fort Wayne, IN (Fig. 1) and shorelines extend along the northwest side of the lake basin starting at Bryan, OH to the Imlay channel (Fig. 1). When ice-free any stage of glacial Lake Maumee used both the Fort Wayne and Imlay channels (Fig. 1B). Lower slope of Whittlesey strandline corresponds to its younger age and is too low to have used the Imlay outlet.

172x98mm (300 x 300 DPI)

Figure 6. Stratigraphy of Deanville Mountain, a large kame, where two OSL samples were collected. A) View of high wall along the east side of the pit. B) Exposure of interbedded sand and gravel with collapse structures from melted ice. Note how the deformed bedding, traced as white dashed lines, decreases towards the surface indicating continued sedimentation while an ice block was melting. Shovel and soil probe 1 m tall is circled. C) Site 8 stratigraphy for OSL sample 8. D) DEM of the gravel pit with sites 7 and 8 located, location of DEM shown in Figure 3. E) Site 8 stratigraphy for OSL sample 8. F, G) Site 7 stratigraphy for OSL sample 7.

178x140mm (300 x 300 DPI)

Figure 7. Schematic depositional model of the sedimentary fill within the Imlay channel. The basal gravel and sand from waning flow in spillway was not observed but is expected. Scale is for channel cross-sectional area only. Styled after Kehew and Boettger (1986).

118x82mm (300 x 300 DPI)