River Warren boulders, Minnesota, USA: catastrophic paleoflow indicators in the southern spillway of glacial Lake Agassiz

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Boulders resting on meltwater-sculpted and striated-granite bedrock near the head of the southern outlet spillway of glacial Lake Agassiz are used to generate paleodischarge calculations. The rounded nature of many boulders suggests fluvial transport and a corestone origin. The distribution of boulders in clusters and linear trains records the interaction of clasts during transport and deposition. The geomorphology of the spillway with streamlined erosional remnant hills is characteristic of other large flood spillways. Using the Manning equation and a variety of empirical equations to determine paleovelocity, preferred discharges between 0.364 and 0.102 Sv are calculated. These discharges agree well with flood discharges using modeling methodologies, and most likely represent ephemeral and catastrophic flood events linked to either episodic incision at the outlet or the result of rapid inputs of meltwater to Lake Agassiz.

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Meltwater delivery from a glacial lake affects downstream valley development (e.g. Knox 1993; Marchitto & Wei 1995; Blum *et al.* 2000) and isotopic composition of ocean water (Broecker *et al.* 1989). With the recent interest in linkages between meltwater delivery and climate change (Licciardi *et al.* 1999; Clark *et al.* 2001; Fisher *et al.* 2002; Teller *et al.* 2002) that built upon earlier work (Rooth 1982; Broecker *et al.* 1988), the magnitude of a meltwater flood is of interest along with its timing. Glacial River Warren is the drainage through the Minnesota River valley when the southern outlet spillway of Lake Agassiz was active (Fig. 1). Presently, the Minnesota River is a tributary to the Mississippi River (Fig. 1A); it is incised into glacigenic sediment, shale and granite bedrock, and crosscuts the Big Stone Moraine (Fig. 1). Drainage along the spillway likely inherited older spillways or valleys associated with recession of the Des Moines Lobe and glacial Lake Benson (Johnson *et al.* 1998; Rittenour *et al.* 1998).

A variety of methods have been used to calculate discharge for River Warren, including empirical calculations (Matsch 1983; Becker 1995), drainage basin reconstructions (Teller 1990a, b; Mann *et al.* 1999; Leverington *et al.* 2000; Teller *et al.* 2002), and more sophisticated computer simulations of past climate with associated runoff (Liccardi *et al.* 1999). The goals of these projects were to determine water discharge from Lake Agassiz's various outlets to ocean basins because a freshwater influx of ~0.1 Sv may shut down or slow North Atlantic deep water formation, in turn affecting climate (Rahmstorf 2000, and references therein). The inherent difficulty in flow models that involve reconstructing spillway geometry has prompted the drainage basin and paleoclimate approach to flow reconstruction. The modern-day spillway geometry is usually only an approximation of the spillway geometry when it was active because of infilling, subsequent incision, isostatic tilting and/or incomplete exposure of its sedimentary deposits. The large boulders resting on sculpted bedrock in the southern outlet spillway of Lake Agassiz offer a reasonable approach to reconstruct paleodischarges. Such deposits may record the last stage in the history of the spillway; however, it will be demonstrated below that the boulders were likely not transported during the last flow event in the spillway, but instead in a previous large and likely catastrophic flood, instrumental to the development of the spillway.

In this article I briefly review the early stages of glacial Lake Agassiz and past paleohydraulic reconstructions for River Warren before presenting velocity and discharge estimates based on boulders in the southern outlet spillway. The purpose of the article is to determine velocity and associated discharge required to transport the boulders and to compare these results with other flow reconstructions of River Warren and other selected large floods. The term catastrophic flood is used here to describe high magnitude, ephemeral flows that result in often anastomosing channel segments, U-shaped spillways with streamlined residual remnant hills, scoured surfaces and large boulders (Fisher *et al.* 1995). Radiocarbon ages are presented in radiocarbon years before present (^{14}C BP), and calendar year equivalents are indicated in Fig. 2. Discharge is reported in Sverdrups (Sv), where 1 $\mathrm{Sv} = 1 \times 10^{6}\ \mathrm{m}^{3}\ \mathrm{s}^{-1}$, the unit preferred by modelers, particularly oceanographers.

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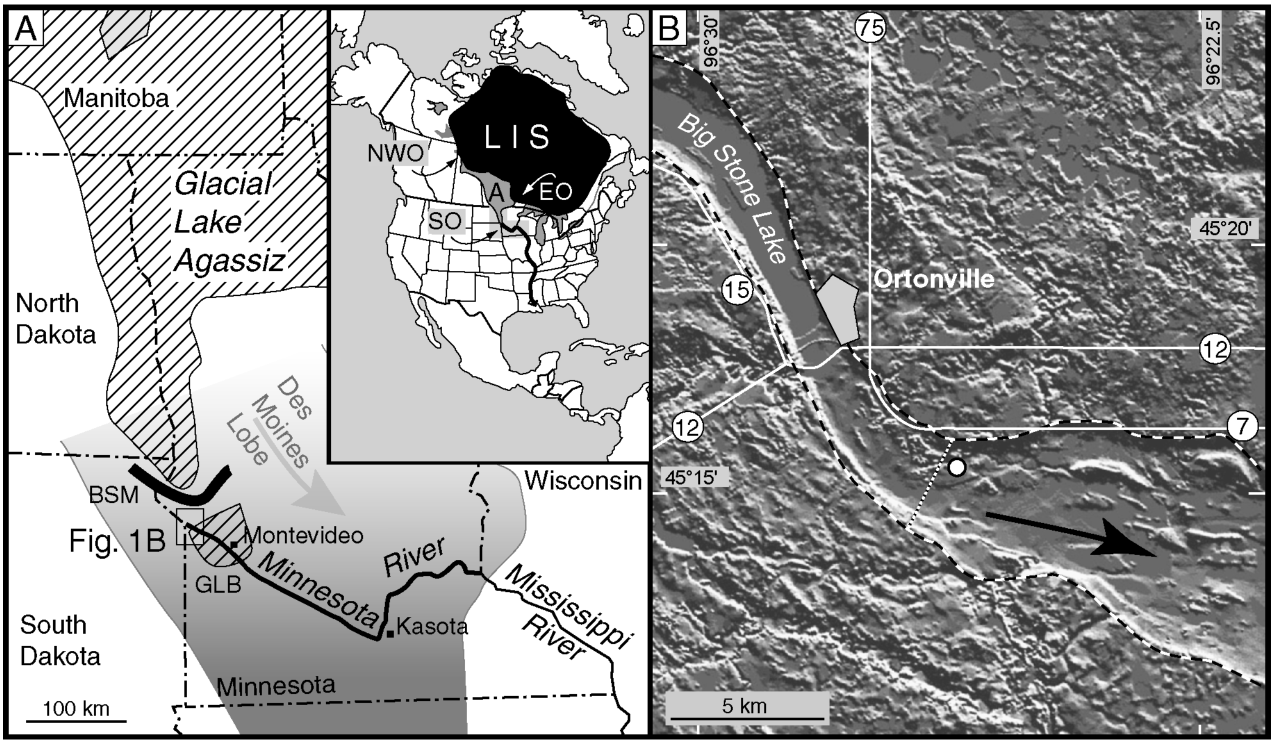

Fig. 1. A. The southern outlet is located at the southern end of Lake Agassiz (A on the North America inset map). The southern outlet (SO) is incised through the Big Stone Moraine (BSM) and widens out southeast of Ortonville (B). GLB refers to glacial Lake Benson, a precursor to glacial Lake Agassiz. LIS, NOW, and EO refer to the Laurentide Ice Sheet, northwestern and eastern outlets, respectively. Circled numbers are highway numbers. B. Spillway boundary is indicated by the black and white dashed line; cross-spillway dashed line is where spillway width was measured; and white circle is location of boulders in Fig. 4.

Glacial Lake Agassiz

Lake Agassiz formed when the Red River Lobe of the Laurentide Ice Sheet receded north of the drainage divide separating Hudson Bay from the Gulf of Mexico. Upham (1895) described a series of strandlines around the southern end of the lake basin linked to the southern outlet. From highest to lowest the strandlines are named the Herman (323 m a.s.l.), Norcross (317 m), Tintah (311 m), and upper Campbell (299 m) (H, N, T, UC in Fig. 2). Debate continues about the age of some of the strandlines (e.g. Teller *et al.* 2002; Fisher 2003), and when the outlet sill was lowered to these elevations. Radiocarbon ages on wood in flood gravel and overlying lacustrine sediment beneath Big Stone Lake, a spillway scour lake, indicate that the southern spillway had formed by 10 800 ^{14}C BP, with a brief reoccupation ending by 9400 ^{14}C BP (Fisher 2003). It is agreed that the lake began approximately 11 700 ^{14}C BP (Fenton *et al.* 1983) with the southern outlet opening at approximately that time (Fig. 2), with final abandonment of the southern outlet at 9400 ^{14}C BP (Fisher 2003). Between those times the eastern and/or northwestern outlets were activated in response to ice-margin fluctuations and isostatic adjustments, resulting in temporary abandonment of the southern outlet. The Lockhart Phase refers to the time when the southern outlet was first open, the Moorhead Phase when the lake was below the southern outlet draining eastwards and/or northwestwards, and the Emerson Phase is the time when the northwest outlet was active at 9900 ^{14}C BP and the southern outlet was briefly reoccupied (Fig. 2). For a brief period of time at the end of the Emerson Phase, the northwestern and southern outlets may have operated simultaneously (Fisher & Souch 1998; Teller 2001; Fisher 2003) before the eastern outlets west of Lake Nipigon opened.

Geomorphological and paleohydrological studies of the southern outlet began with Upham (1895), then Matsch & Wright (1967), Matsch (1983), and is briefly reviewed by Johnson *et al.* (1998). Using the Manning equation, Matsch (1983) outlined a variety of flow parameters to calculate discharges that ranged from 0.017 to 0.13 Sv in different areas along the spillway with 1 Sv not being unreasonable (Table 1). Rare discharges of 0.3 Sv every few hundred years were suggested by Wiele & Mooers (1989), and they augmented their meltwater production rate of 0.05 Sv by catastrophic drainages into Lake Agassiz from other lakes and possible surging of the ice sheet displacing water from the lake basin to generate the 0.3 Sv discharge (Mooers & Wiele 1989). Becker (1995) used HEC-2 model simulations for peak outflow when the

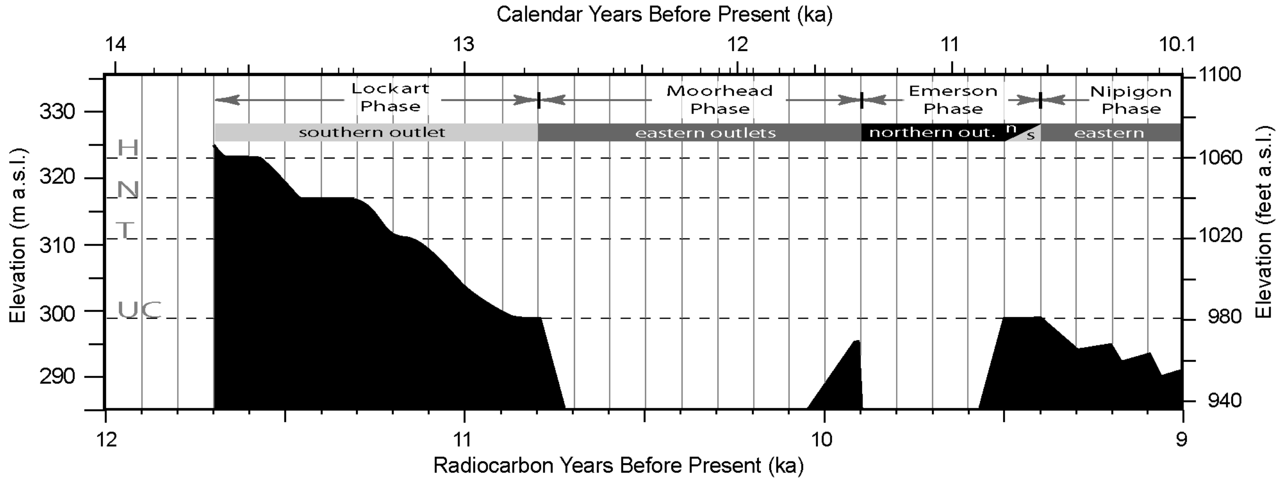

Fig. 2. Lake-phase diagram for the southern outlet of Lake Agassiz. Strandline elevations are for the head of the spillway, and H–Herman, N–Norcross, T–Tintah, UC–Upper Campbell refer to specific strandlines. Lake level change is only an estimate as the strandlines above the Campbell are not dated. Incision to the Campbell level, and subsequent abandonment and reoccupation of the southern outlet, is based on core data from within the spillway (Fisher 2003). Other southern outlet occupations and abandonment episodes as suggested by Teller (2001) are possible, but at present are not substantiated by stratigraphic evidence.

lake was at the Campbell (0.014 Sv) and Tintah (0.027 Sv) stages, resulting in values less than those calculated by Matsch (1983), and concluded that average discharge at the Campbell stage was probably less than 0.005 Sv. Importantly, Teller *et al.* (2002) differentiate between flood flow and baseline flow for their paleodischarge calculations at different stages of the lake. Their flood fluxes (floods caused by reoccupation of outlets and subsequent rapid sill lowering) vary between 0.12 and 0.3 Sv, with baseline values of either 0.034 Sv at the Campbell and Tintah stages or 0.047 Sv for the Norcross and Herman stages. Licciardi *et al.* (1999), building on earlier work by Teller (1990a, b), calculated total precipitation, ice melt, and runoff values for various time slices and drainage basins. During the Lockhart Phase (Fig. 2), discharge to the Mississippi

Table 1. Discharge (Q) and hydraulic variables from River Warren and other floods.

Flood Q Sv	Baseline Q Sv	Hydraulic variables	References
River Warren (southern outlet)			
0.13–0.073	0.04	n, 0.01–0.03; V, 0.33–0.39, ms^{-1}	Matsch (1983)
0.3	~0.05		Wiele & Moores (1989)
0.3–0.12	0.034–0.047	n, 0.03–0.05	Teller *et al.* (2002)
	0.0915–0.0519		Licciardi *et al.* (1999)
0.29	0.014–0.024	S, 0.0002; n, 0.035	Becker (1995)
0.64	0.022	V, 7.48–0.82 ms^{-1}	Holland (2001)
0.29		w, 2.8 km; d, 12.2 m; S, 0.001; n, 0.02	This study, Manning eq.
0.147–0.102		V$_{ml}$, 4.3^{a}, 3.0 ms^{-1b}	This study, Williams (1983)
0.170–0.129		V, 4.97^{a}, 3.77 ms^{-1b}	This study, Koster (1978)
0.364–0.257		V$_{x}$, 10.67^{a}, 7.51 ms^{-1b}	This study, Costa (1983)
1.038–0.725		V$_{mu}$, 30.4^{a}, 21.21 ms^{-1b}	This study, Williams (1983)
Eastern Outlets			
0.2–0.1		n, 0.03–0.05	Teller & Thorleifson (1983)
Northwestern Outlet			
1.2–7.38		V, 6.3–39 ms^{-1}; area, 189250 m^{2}	Fisher (1993)
2.16	0.042	V, 12 ms^{-1}; w, 1800 m; d, 100 m	Fisher *et al.* (2002)
Other large catastrophic floods (max. discharge)			
0.82–0.06	Souris flood		Lord & Kehew (1987)
1	Lake Bonneville		O'Connor (1993)
17 ± 3	Missoula floods		O'Connor & Baker (1992)
18	Altai floods		Baker *et al.* (1993)

[a] Based on 5 largest clasts.
[b] Based on 5 largest clasts for clast b-axis $\leq$3000 mm.

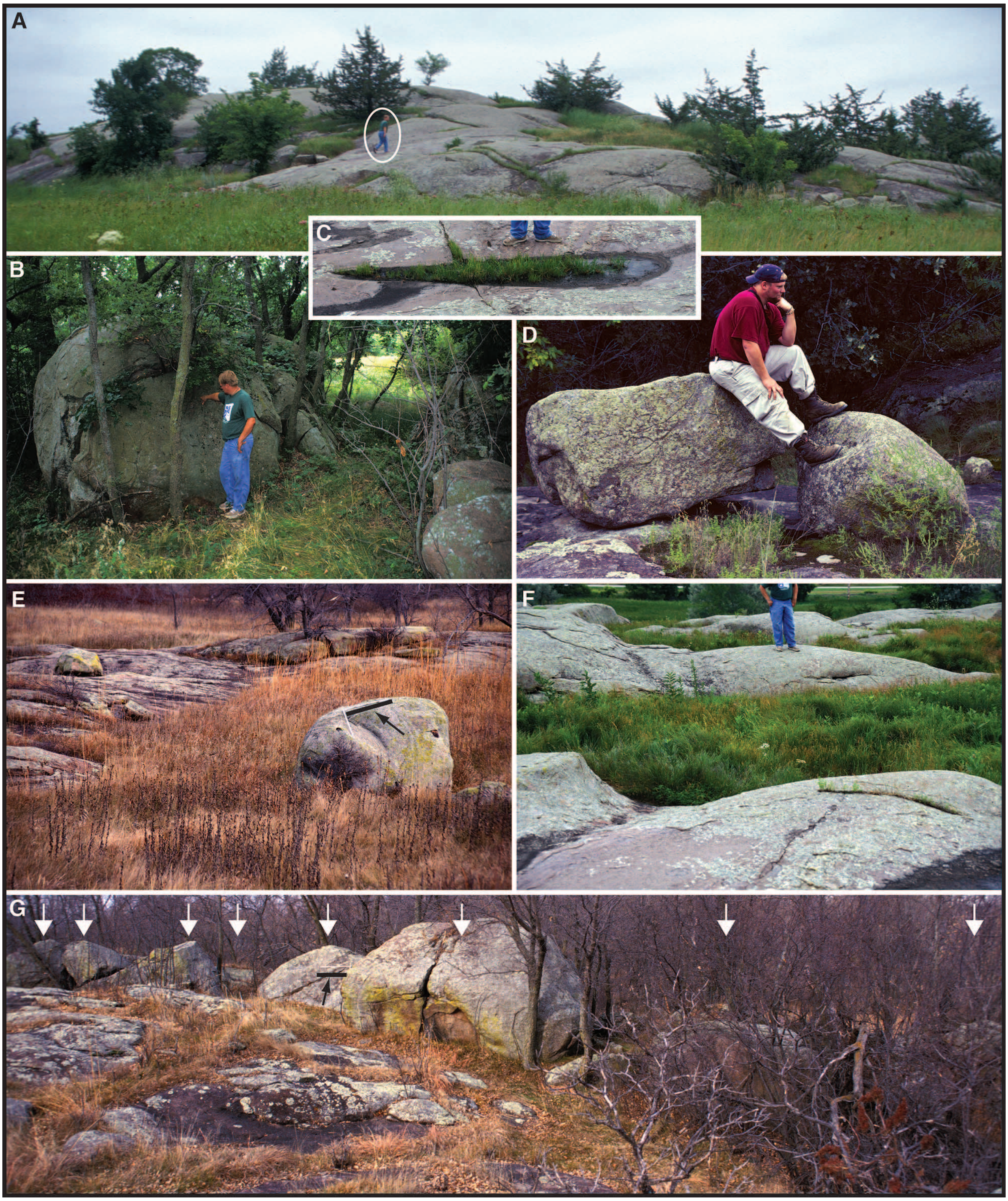

Fig. 3. Boulders and areas of exposed granite bedrock in Big Stone National Wildlife Refuge located with white circle in Fig. 1B. A. Outcrop of granite bedrock south of Ortonville, with sculpted whale-back forms. Flow was from right-to-left, and note circled 2-m-tall man for scale. B. One of the large boulders mapped in Fig. 4.C. 2.5-m-long flute incised into granite. D. Boulders perched high up on granite outcrop. E. Granite boulders resting on bedrock with Holocene sheeting of the bedrock surface evident in the background. Black scale bar resting on the foreground boulder is 0.6 m long. F. Foreground groove cut into granite and a sharp rimmed edge extending to the left of the man. Flow was from left to right. G. Linear arrangement of boulders with flow from left-to-right. White arrows indicate separate boulders and black scale bar is 0.6 m wide.

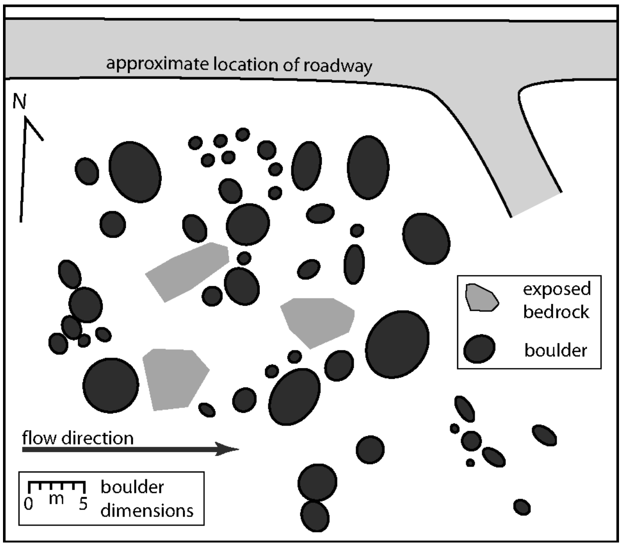

Fig. 4. Boulder cluster distribution in the Big Stone National Wildlife Refuge. Such a concentration of boulders was not observed elsewhere. Note small clusters of boulders, some with a linear alignment.

was 0.092 Sv when Lake Agassiz was above the Campbell stage, and 0.052 Sv when the outlet was last reoccupied during the Emerson Phase. A baseline value at this time is indicated as 0.01 Sv.

River Warren boulders and sculpted bedrock

An interesting aspect of the southern outlet spillway, or River Warren, is the large boulders scattered along it (Fig. 3). Southeast of Ortonville, MN (Fig. 1B) the Minnesota River meanders across the spillway floor through wetlands and between granite outcrops with scattered boulders. North of Ortonville, the spillway is narrow and deep, but widens and shallows dramatically immediately southeast of Ortonville (Fig. 1B), likely in response to the change from shale to granite bedrock. The boulders are subangular to subrounded in shape (Fig. 3), and range in size from less than 1 m in each dimension to as large as 5.8 × 4.3 m and 3.1 m high and are scattered on the surface of sculpted granite bedrock (Fig. 3B, D, E). In one area, the boulder distribution was mapped (Fig. 4) about 200 m southeast of the interpretive center in the Big Stone National Wildlife Refuge (white circle in south central Fig. 1B).

Granite outcrops in the floor of the spillway are responsible for most of the valley bottom topography. Most of the granite outcrops are streamlined parallel with the spillway (Figs 1B, 3A). The surface of the granite is jointed, and rock slabs have developed from sheeting processes (Fig. 3E). Smaller-scale forms (2–20 m) on the surface of the outcrops resemble whale-backs (Fig. 3A), while elsewhere the surface is ornamented with flutes (Fig. 3C), grooves and rimmed depressions (Fig. 3F), and undulating surfaces (Fig. 3A, E, F), all of which are parallel with the valley.

Boulder origins

Many of the spheroidal granite boulders resting on the sculpted bedrock could be corestones, as suggested by Patterson & Boerboom (1999), who similarly described these surfaces and boulders near Ortonville, and further

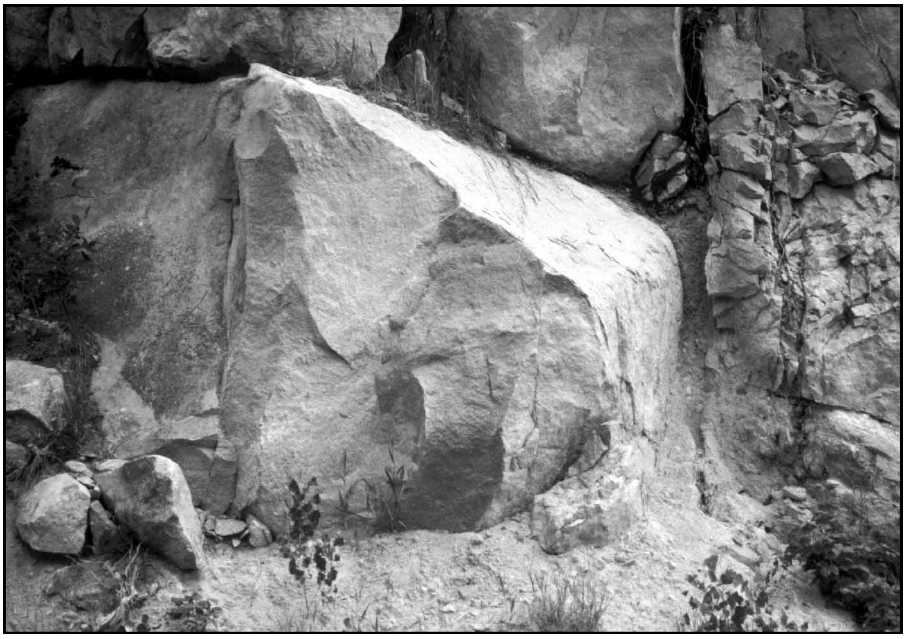

Fig. 5. Saprolite with boulder corestones exposed in a roadcut near Montevideo, MN (Fig. 1A). Boulder is *c.* 2 m across. See also Fig. 10 in Patterson & Boerboom (1999).

southeast down the Minnesota River valley. They make the important point that many of the granite outcrops could reflect the base of a pre-Cretaceous weathering front or saprolite subsequently removed during Pleistocene glaciations. Granite corestones with diameters of many meters are exposed (Fig. 5) in quarries and roadcuts where the saprolite is often preserved in the downstream side of bedrock knobs or adjacent to the spillway. Many of the rounded granite boulders on the floor of the spillway are likely corestones. An important question arises: what is the source of the granite corestones southeast of Ortonville where the granite in the spillway bottom has no saprolite remnants, and the surface on which the boulders rest is striated in places?

Drilling records from the South Dakota and Minnesota Geological Surveys record the presence of saprolites between 3 m and 25 m thickness on either side of the spillway. The source of the boulders on the spillway floor was presumably the granite saprolite underlying Cretaceous shale beneath the Big Stone Lake basin or from within the glacial sediment itself (Matsch & Wright 1967). The elevation of the upper surface of the saprolites adjacent to the spillway at the south end of Big Stone Lake is more than 10 m lower than the granite spillway bottom without a saprolite; indicating that locally the spillway is over a bedrock high. Patterson & Boerboom (1999) make reference to a few small patches of striations on the bedrock in this area indicating that much, or all, of the saprolite located in the spillway downstream from Big Stone Lake was removed before the southern outlet spillway formed. These relationships indicate that, assuming they are corestones, the boulders were transported up to 10′s of kilometers before coming to rest in the spillway floor at the Big Stone National Wildlife Refuge. If some of the boulders are not corestones, then they were likely redeposited from glacigenic sediment and their transport distances may range from 10's of meters to 100 km, the length of the spillway upstream.

Paleohydrologic calculations

Paleohydrologic calculations for the south outlet spillway are based on boulders deposited in the spillway southeast of Ortonville in the Big Stone National Wildlife Refuge. Boulder dimensions were determined by tape measure and stadia rod. Discharge was determined using the continuity equations $Q = A \times V$, where Q = discharge, A = cross-sectional area (width[w] × depth[d]) and V = velocity (ms^{-1}), whereby the velocity was solved using the Manning equation: $R^{2/3} \times S^{0.5}/n$; where R = hydraulic radius ($wd/w{+}2\,d$), S = slope, and n = Manning roughness coefficient. Channel geometry was determined at the cross-section located in Fig. 1B. The depth of 12.2 m was determined from the height of the lowest terrace, and the value of 0.001 for slope was taken from Matsch (1983). A roughness coefficient of 0.02 is used because it represents minimal resistance in a broad, deep channel that corresponds with straight unlined earth canals in good condition (Chow 1964). An *n* value of 0.025 was used by Church & Gilbert (1975) for a mobile bed where sediment provides an apparently smooth water-sediment zone near the bed, and a value of 0.022 was used by Kehew (1982) and Kehew & Clayton (1983) for the similarly sized Souris River floods. Slightly larger *n* values were used for flood spillways carved into bedrock (O'Conner & Baker 1992; Teller & Thorleifson 1983). Solving the equations results in a velocity of 8.4 ms^{-1} and a discharge of 0.29 Sv.

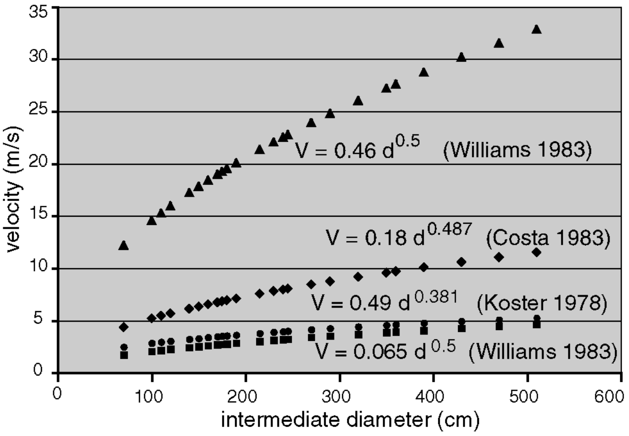

Fig. 6. Paleovelocity estimates determined from boulders deposited by River Warren in the southern outlet spillway of glacial Lake Agassiz.

Velocity estimates are also determined from various empirical equations with the results plotted in Fig. 6. The average velocity (V_x) of clasts between 0.005 m and 3.2 m in diameter can be calculated using the equation $V_x = 0.18d^{0.487}$ (Costa 1983), where d is the intermediate diameter in millimeters. Koster (1978) used the formula $V = 0.49d^{0.381}$ for clasts with intermediate diameters up to 0.3 m in gravel bedforms. Williams (1983) presented two equations for calculating mean velocity (V_m) based upon published data. The equation $V_{ml} = 0.065d^{0.5}$ gives a lower limit, or transition from no clast movement to potential movement for clasts with diameters, between 10 mm and 1500 mm. The equation $V_{mu} = 0.46d^{0.5}$ gives an upper limit, or transition from potential clast movement to movement for clasts, between 15 mm and 500 mm in diameter. The average velocities for the 35 boulders using the four equations are 7.57, 3.78, 3.02, and 21.39 ms^{-1}, respectively. If we assume that boulders larger than 3 m (b-axis) are corestones that were not moved any significant distance by the flood, the average velocities using the four equations are 6.43, 3.34, 2.56, and 18.08 ms^{-1}, respectively. Because averaging of boulder diameters to determine velocity would underestimate the velocity, the five largest clasts transported by the flood were used

Fig. 7. Linear arrangement of basalt boulders in a scoured zone of the Lake Bonneville flood, Massacre Rock State Park, Idaho USA (cf. O'Connor 1993).

(cf. Costa 1983). Using this procedure and the four equations, the calculated velocities are 10.67, 4.97, 4.3, and 30.4 ms^{-1}, respectively, and the discharges are 0.364, 0.17, 0.147, and 1.038 Sv, respectively. If the 5 largest clasts with b-axis less than 3 m are used, the calculated velocities are 7.51, 3.77, 3.0, and 21.21 ms^{-1}, and the discharges are 0.257, 0.129, 0.102, and 0.725 Sv, respectively.

Discussion

The studied boulders in the southern outlet spillway were fluvially transported and deposited by River Warren. The best evidence for fluvial transport is the presence of sculpted bedrock beneath boulders (Fig. 3D), and the non-random distribution of boulders (Figs 3G, 4). Interestingly, only large boulders are found on the sculpted bedrock outcrops, smaller caliber sediment is not present unless beneath the wetlands. The mapped boulders in Fig. 4 represent the highest density of boulders in the surrounding area. Within the mapped area are smaller clusters of boulders, some of which have a linear arrangement. A more developed linear train of boulders (Fig. 3G) is just south of the area shown in Fig. 4. The density of boulders in the mapped area is the highest observed in this area of the spillway, which is suggestive of clast interaction during transport and deposition in shadow zones, or lee-side eddies of larger clasts. Actual transport distance is difficult to ascertain because if the boulder's origin is a corestone then its initial shape was spheroidal. However, the subangular clast morphology of some boulders, with some of the rounding likely a result of chemical weathering since emplacement, suggests that transport distance was likely quite short. The distribution of boulders, some of which are in linear trains or clusters, is best explained as sedimentary bedforms, or clast clusters (cf. Brayshaw 1984) similar to linear trains of large boulders within the Bonneville flood pathway in southern Idaho (Fig. 7). The possibility that a few of the largest boulders are *in situ* corestones with their associated saprolite stripped away cannot be discounted at present (cf. Patterson & Boerboom 1999).

One of the characteristics of spillway channels in the Interior Plains of North America is the lack of deposits within them (cf. Kehew & Lord 1986). At the head of River Warren the only sedimentary deposits described are boulder gravel lags and scattered boulders within the spillway. Patterson *et al.* (1999) mapped a few gravel bars within the spillway explaining them as older reworked alluvium. Holland (2001) briefly describes cobble gravel 70 km downstream of Ortonville near Montevideo, MN, and Johnson *et al.* (1998) mapped and described strath and fill terraces along the spillway near Kasota (Fig. 1A). Johnson *et al.* (1998) explain terrace sediment as a result of episodic cut and fill events, some of which could be outwash associated with the earlier recession of the Des Moines Lobe. At their Kasota site, cross-bedded gravel sets with foresets greater than 15 m thick suggest catastrophic flows either associated with River Warren or jökulhlaups from the Des Moines Lobe. The Kasota site is 250 km downstream of Ortonville, at which point River Warren would be expected to have had a considerable bedload component.

It is unclear if the mapped streamlined bars of gravels within the valley bottom east of Ortonville are constructional in origin, or if they are erosional remnants of pre-existing gravels. Matsch (1983) and Patterson *et al.* (1999) described gravel in the lee of bedrock knobs within the spillway (pendant bars of Baker 1973), but again it was not determined whether the bars are streamlined remnants of more extensive gravel laid down under a different flow regime. Erosional remnant bars in spillways are very common (Baker 1973; Kehew & Lord 1986; Elfstrom & Rossbacker 1985; O'Connor 1993; Fisher *et al.* 1995) and are commonly cited as evidence for catastrophic floods. Without further sedimentological information, and in conjunction with the boulder evidence, the streamline bars are interpreted as erosional remnants.

Further upstream beneath Big Stone Lake, Fisher (2003) described 4 m of pebbly gravel, with primarily a shale lithology, and in the Browns Valley Fan core at the upvalley end of Big Stone Lake, a 2-m-thick granite boulder overlain by 2 thin (<1 m) granite-rich gravel units. These sediment units generally fine upwards and represent waning flow upon spillway abandonment. If the spillway geometry is a function of the large flows (catastrophic?) initiated by either knickpoint migration upstream to the sill (Chamberlin – in Upham 1895; Matsch & Wright 1967), or outlet reoccupation (Teller 2001), then the final, smaller baseline flows did not significantly modify the spillway. Presumably, the larger boulders were deposited during the peak discharge events with the finer material kept in suspension. Johnson *et al.* (1998) concluded that the main incision events at their study site were catastrophic, followed by rapid valley infilling. After this event, they reconstruct lower and less variable discharge from Lake Agassiz to explain braided stream deposits. A second, and also undated, incision event at the Kasota site was interpreted to be a later, large discharge from Lake Agassiz. This relative chronology and episode history is in good agreement with Fisher's (2003), who concluded that the southern outlet spillway was fully developed by the end of the Lockhart Phase. This implies that the last large (likely catastrophic) flow was $>10\,800$ ^{14}C BP in age. A reoccupation of the outlet at about 9500 ^{14}C BP, near the close of the Emerson Phase, would not have affected the spillway incised into granite near Ortonville, but further downstream this discharge may have been responsible for the second incision event into valley fill (Johnson *et al.* 1998).

Estimates of paleovelocity and discharge from boulders are variable (Table 1). Discharge estimates range from 1.038 to 0.102 Sv, with the upper estimate determined using a velocity (V_{ml}), which should be considered a maximum value because the formula is based upon a curve extrapolated beyond clast sizes of 500 mm (Williams 1983). Velocity and discharge estimates using William's lower velocity limit (V_{ml}) and Kosters (1978) V are similar, represent a critical velocity to initiate movement, and should be considered minimum values. The 0.29 Sv discharge calculated using the Manning equation is similar to the values calculated using the V_x equation of Costa (1983). Because the other three empirical formulae did not include boulders sizes as large as those from River Warren, the Costa equation, which is based on boulders up 3.2 m, is preferred. Also, the results are between the minimum and maximum estimates of the other methods and similar to other flood discharges from River Warren (Table 1).

The Manning equation assumes steady and uniform flow across cross-sections. These conditions were likely never satisfied in River Warren; nevertheless, it permits relative comparisons between workers and sites. Alternatively, the HEC-2 water profile modeling program accounts for steady and gradually varied flows to create discharge-rating curves. However, similar to using the Manning equation, the HEC-2 procedure also requires estimates of channel cross-sections and slope. For example, Becker (1995) calculated the discharge along a 50-km section at the head of the southern outlet spillway using the HEC-2 method and concluded that Matsch (1983) overestimated the discharges. However, Becker's channel bottom elevations obtained from Swain (1992) underestimate the thickness of lake sediment in Big Stone Lake by about 13 m based on the Browns Valley Fan core (Fisher 2003). In effect, this doubles the depth of Becker's (1995) southernmost cross-section and his calculated maximum discharge should be higher and more in line with other baseline flow estimates in Table 1.

Outflow from glacial Lake Agassiz, and concomitant River Warren discharges, must have varied considerably over time. Large inputs of water to the lake (e.g. Moore & Weile 1989; Sharpe & Cowan 1990; Kehew 1982), seasonal fluctuations in meltwater supply, storms, sieches, and sill erosion could result in catastrophic floods. Sediments associated with such flows may be in the pendant bars described by Matsch (1983; see also Kehew & Lord 1986: fig. 24) and Patterson *et al.* (1999) or part of the braided-river style outwash or cobble gravel further downstream (Johnson *et al.* 1998; Holland 2001). It is important to differentiate between these high magnitude, low frequency events and baseline flow. Such baseline flows are indicated in Table 1 and range between 0.022 and 0.09 Sv. The rarer flood(s) was (were) likely catastrophic flows (Table 1) that ranged between 0.073 and 0.64 Sv, ignoring the unsubstantiated estimate of 1 Sv by Matsch (1983), with a preferred discharge of 0.364 Sv using Costa's (1983) formula for paleovelocity. The boulder dimensions, velocities, and discharges for glacial River Warren are similar to other described spillway systems (e.g. the Souris and Bonneville floods) and outlets of Lake Agassiz, but are modest compared with the Missoula and Altai floods (Table 1). Close to the head of the spillway, the resultant geomorphology is one of erosional remnants, scoured bedrock, and scattered boulders. It is assumed that the spillway formed in response to at least one large flood of ~0.36 Sv, which occurred sometime before 10 800 ^{14}C BP, associated with the Lockhart Phase of Lake Agassiz.

Conclusions

The origins of many of the boulders in the spillway were likely corestones and boulders liberated from glacial sediment with poorly constrained transport distances. The position of the large granite boulders overtop sculpted and striated granite bedrock indicates that the boulders were mobile and not an erosional lag, and that deposition was in places influenced by clast-to-clast interactions. The catastrophic flood(s) that emplaced the boulders was (were) likely short-lived and are assumed to be correlated with episodic sill-incision events of Lake Agassiz, which may have coincided with large meltwater inputs into the lake. Paleodepth at the boulder site was 12.2 m, and velocities ranged from 3 to 30.4 ms^{-1}. A paleovelocity of 10.67 ms^{-1} was chosen for discharge calculations using the continuity equation, as this is similar to the results using the Manning equation. Reasonable discharge estimates calculated for boulders larger than 3 m in diameter range between 0.364 and 0.147 Sv and correspond well with discharges estimated for the eastern outlets of Lake Agassiz and modeling efforts of Teller *et al.* (2002), but are significantly larger than Becker's (1995) results and some of the estimates of Matsch (1983) for the same outlet.

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