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Bedload abrasion and the *in situ* fragmentation of bivalve shells

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ABSTRACT

The aim of this study was to determine how *Unio* bivalve shells fragment within the channel of the Sakmara River (southern Urals, Russia). The Sakmara River has an abundant bivalve population and a highly variable flow regime which, at low flow, allowed much of the channel bed to be examined. A large data set of 1013 shells (*Unio* sp.) was examined and these were shown to have consistent patterns of orientation, aspect, shell abrasion, perforation and fracture. The close spatial relationship between areas of shell abrasion, shell perforation and shell fracture showed that they form part of a continuum whereby areas of abrasion evolve into perforations and perforations coalesce and enlarge into fractures. The mechanism of shell damage proposed is one of abrasion in place, whereby the shell remains stationary on the surface of the point bar and is impacted by bedload. Underpinning this process are the hydrodynamic properties of the bivalve shell, with consistency in the orientation and aspect of the valve in a flowing current producing consistency in the distribution of damage on the shell surface. Valves preferentially lie in a convex-up position and orientate in the flow such that the umbo faces upstream. The elevated, upstream-facing umbo region is exposed to particle impact and is the first to be abraded and perforated. The vulnerability of the umbo to perforation is greatly increased by the thinness of the shell at the umbo cavity. The *in situ* abrasion process is enhanced by the development of an armoured gravel bed which restricts valve mobility and maintains shells within the abrasion zone at the sediment–water interface. The *in situ* abrasion process shows that broken shells are not a reliable indicator of long distance transport. The study also raises the issue that tumbling barrel experiments, which are generally used to simulate shell abrasion, will not replicate the type of directionally focused sand-blasting which appears to be the principal cause of shell fragmentation in the Sakmara River.

Keywords Abrasion, bivalve, fragmentation, point bar, river, Russia.

INTRODUCTION

Bivalves are key components of recent marine and freshwater ecosystems and have been for most of the Phanerozoic. In ancient sedimentary deposits, they can provide information on cryptic environment variables such as salinity and temperature (Hendry *et al.*, 2001; Good, 2004). In modern rivers, bivalve shell geochemistry increasingly is being used to provide otherwise inaccessible historical insights into the anthropogenic pollution of aquatic environments (Brown *et al.*, 2005). Fundamental to these applications is an understanding of how shells behave as sedi-

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mentary particles (Allen, 1984; Olivera & Wood, 1997; Dey, 2003) and how they are modified by physical, biological and chemical processes (Zuschin *et al.*, 2003). For example, a demonstrable link between transport and shell fragmentation would assist in identifying shells which may have been removed from their life environment.

The aim of this study was to determine the mechanism of unionid bivalve shell fragmentation in the channel of the Sakmara River in the southern Urals, Russia (Fig. 1). There have been few previous studies on the processes of shell fragmentation in a modern river channel. The Sakmara River had the advantage of an abundant unionid bivalve population and a highly variable flow regime which, at low flow, allowed much of the channel bed to be examined. Using a large data set of 1013 shells, the study produced the unexpected result that in-place abrasion was the principal cause of shell fragmentation. The results have implications on how the degree of fragmentation is used to determine the age and transport path of shells within modern and ancient high-energy, bedload-dominated environments; they also raise the issue of whether conventional methods of simulating shell abrasion using tumbling barrels are realistic.

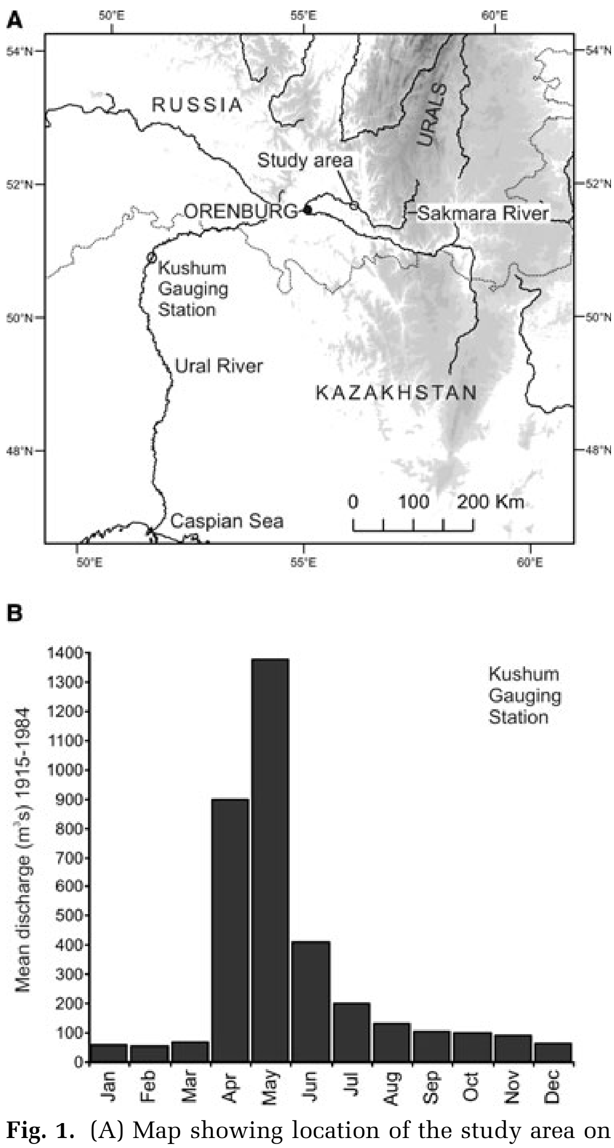

Fig. 1. (A) Map showing location of the study area on the Sakmara River. (B) Mean monthly discharge at the Kushum Gauging Station (Vörösmarty *et al.*, 1998).

SEDIMENTARY ENVIRONMENT

The Sakmara River drains some 30 000 km^2 in the southern Ural Mountains and is a major tributary of the Ural River which flows south into the Caspian Sea (Fig. 1A). The river has a highly variable flow regime with peak stream discharges generated by rapid snowmelt in April and May which are vastly in excess of normal base flow (Fig. 1B). This study was undertaken at low flow (in July) when much of the channel bed was exposed and available for study. The channel is meandering, with a maximum bankfull depth of 8 m and average width of 150 m. The river actively shifts across a 6 km wide floodplain, leaving numerous abandoned channels.

Channel macroforms in the Sakmara River are dominated by gravelly point bars located on the inner bank of meander bends. One point bar was mapped in detail for the purpose of this study (Fig. 2). The bar was located at 51 53′ 2″N, 56 9′ 4″E and had a maximum length of 340 m, a width of 150 m and an area of 51 000 m^2. The bar was composed largely of gravel and sandy gravel, fining in maximum clast size from cobble to pebble size in a downstream direction. Well-sorted sand was deposited on the downstream side of the bar below a system of sinuous slipfaces. Most of the bar surface was remarkably flat with few bedforms.

A characteristic feature of this point bar and others in the Sakmara River is the development of large chute channels between the gravelly point bar and the inner bank (Fig. 2). These natural flood-relief channels are active only during the high flow stage. Sediment in chute channels fines downstream from pebble-size gravel at the entrance, to sand at the exit, where chute bars are deposited (Fig. 2). Thin veneers of mud are locally deposited within chute channels from pools of standing water which are cut off during the falling stage. These muddy deposits become

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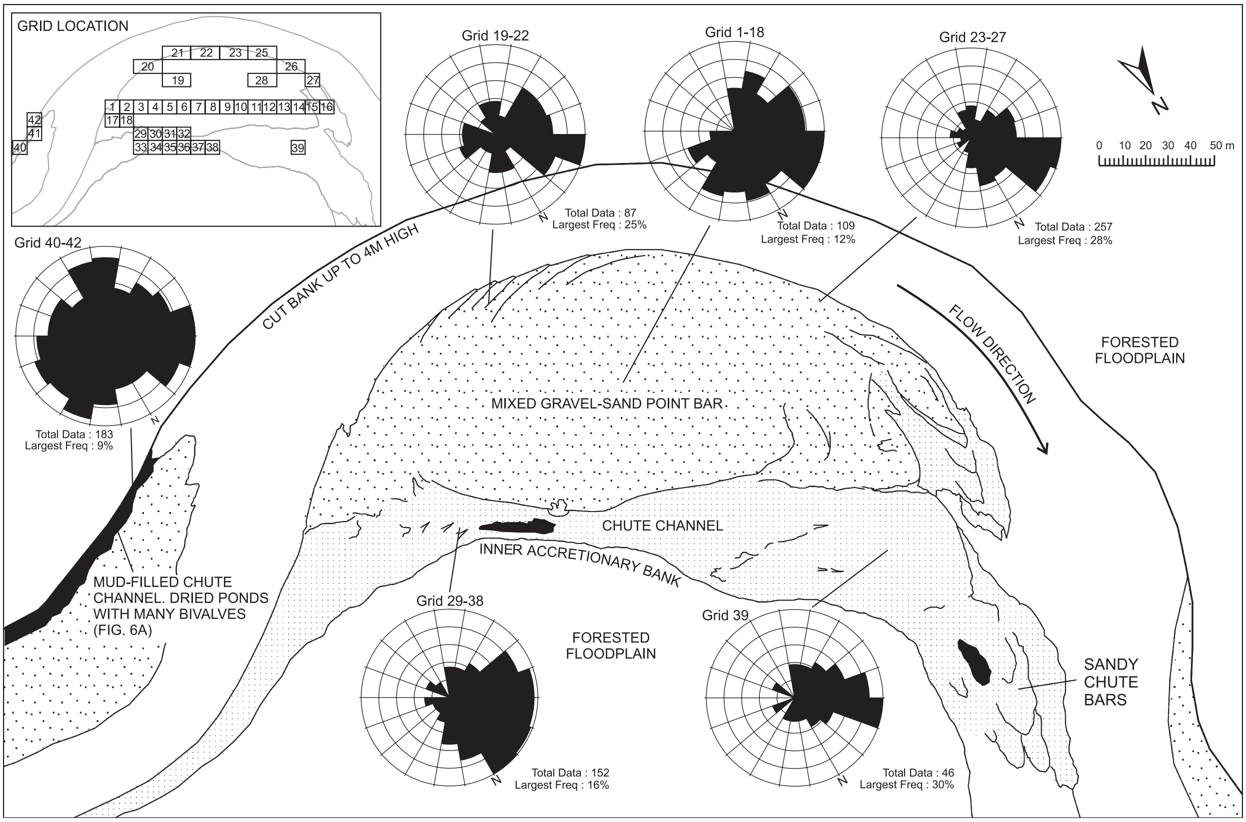

Fig. 2. Map of the studied point bar on the Sakmara River with rose diagrams showing the azimuth of the posterior end of bivalve measured along the hinge (Fig. 3). Inset map shows the location of sample grids.

much thicker in chute channels where the upstream entrance has become blocked. During rising flow stages, these closed channels receive water and fine sediment from its downstream junction with the main channel.

BIVALVES

Live freshwater bivalves and bivalve shells are abundant in the Sakmara River. In the studied reach *Unio* sp. and *Anodonta* sp. were present; this study focused only on *Unio* which formed the vast bulk of the shell assemblage. *Unio* consists of two externally symmetrical valves connected at their dorsal margins by a resilient ligament. The shells are elongate and elliptical with an expanded posterior and the umbo (the elevated portion of the dorsal margin) placed anteriorly (Fig. 3). The exterior surface is smooth with the exception of low ridges formed from the concentric growth rings. Unionid shells are composed of an outer organic membrane or periostracum and two internal layers of prismatic and nacreous calcium carbonate embedded within an

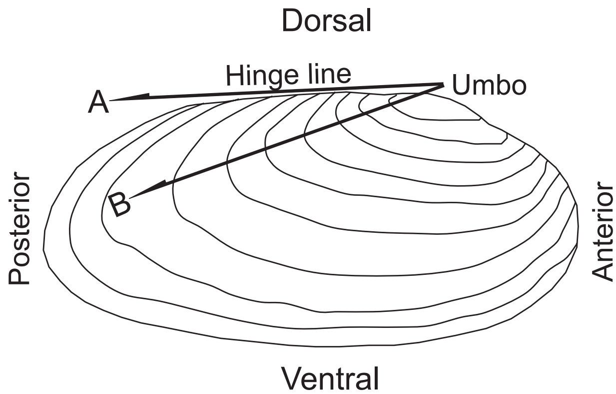

Fig. 3. General morphology of *Unio* valve. Concentric lines are growth rings. The azimuth of arrow A was measured for orientation analysis. Arrow B shows the usual orientation of the shell with respect to flow direction.

organic matrix (Checa & Rodríguez-Navarro, 2001). The composite structure of unionid shells imparts to them a high fracture strength and fracture toughness (Chen *et al.*, 2004).

Unionids are noted for their ecophenotypic plasticity (adaptation of shell form to habitat) and those in the Sakmara River show the characteris-

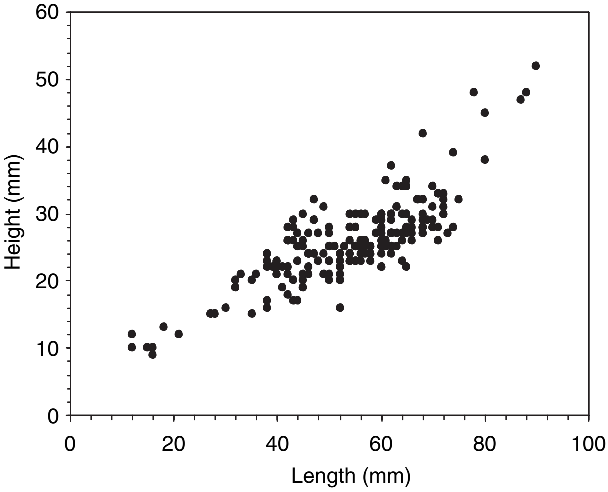

Fig. 4. Plot of length versus height for 718 intact *Unio* valves.

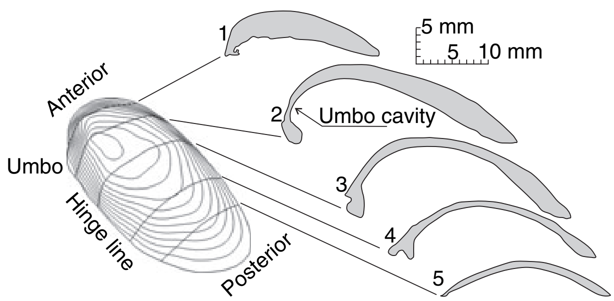

Fig. 5. Cross-sections through a *Unio* valve to show the variable thickness of the shell. Note the greatly thickened anterior in cross-section 1 and the thin shell at the umbo cavity in cross-section 2.

tic modifications for life in high flow velocities with a large shell length relative to height and a thickened shell (Eagar, 1978; Good, 2004). The typical dimensions of the *Unio* valves are 60 mm in anterior–posterior length, 30 mm in dorsal–ventral height (Fig. 4) and 10 mm in width measured from the commisure plane to the point of maximum projection (Fig. 5). The thickness of calcium carbonate for a typical 60 mm long *Unio* shell shows significant variation across a valve with up to 3·5 mm at the anterior and an average of 1 mm at the posterior (Fig. 5). The cavity on the inside of each valve leading into the umbo is a notable thin area (1 mm) in the otherwise thickened anterior part of the valve (Fig. 5). As discussed later, this area of thin shell at the umbo cavity is of significance regarding the mode of shell perforation and fracture.

Unionids require water that is shallow, perennial, well oxygenated and of low turbidity (Good, 2004). In the Sakmara River, live unionids were observed on the gravelly floor of the main channel, on fine-grained substrates on the downstream margin of point bars and in pools within chute channels which are isolated by falling water levels. Unionids frequently become trapped within the chute-channel pools because the river is subject to very rapid decreases in discharge and unionid locomotion is slow. As the pools evaporate, oxygen levels fall and eventual drying out produces spectacular mass-death assemblages with up to 100 shells per m^2 (Fig. 6A). This process has been described from comparable populations of unionids in channel habitats subject to rapid decreases in water level (Tudorancea, 1972). Flushing of these chute-channel pool assemblages during spring flooding probably contributes most of the shell material to the river system.

SHELL FRAGMENTATION ANALYSIS: METHOD

Sedimentary structures within the exposed areas of the studied channel reach were mapped at a scale of 1:1000 using a system of 20 m × 20 m grids. A selection of the grids was then used to systematically sample and locate shells (Fig. 2). In total, 1013 *Unio* shells were examined. Where possible, data on each shell were collected regarding:

1 Dimensions (length and height).

2 Articulation, classified into: (i) single valves; (ii) detached valves but in close proximity and from the same individual; and (iii) paired valves with intact ligament.

3 Attitude classified into convex up or convex down.

4 Orientation measured as the azimuth of the valve posterior taken along the hinge line (Fig. 3).

5 Degree of shell damage classified as: (i) undamaged; (ii) minor chipping of the margins; (iii) abrasion of the periostracum and surface layers of shell carbonate; (iv) perforation of the shell; and (v) fractured. A sketch of each shell was produced to show the location of perforations and fractures.

SHELL FRAGMENTATION ANALYSIS: RESULTS

Articulation

The two valves of a living unionid shell are attached at the hinge by an elastic ligament.

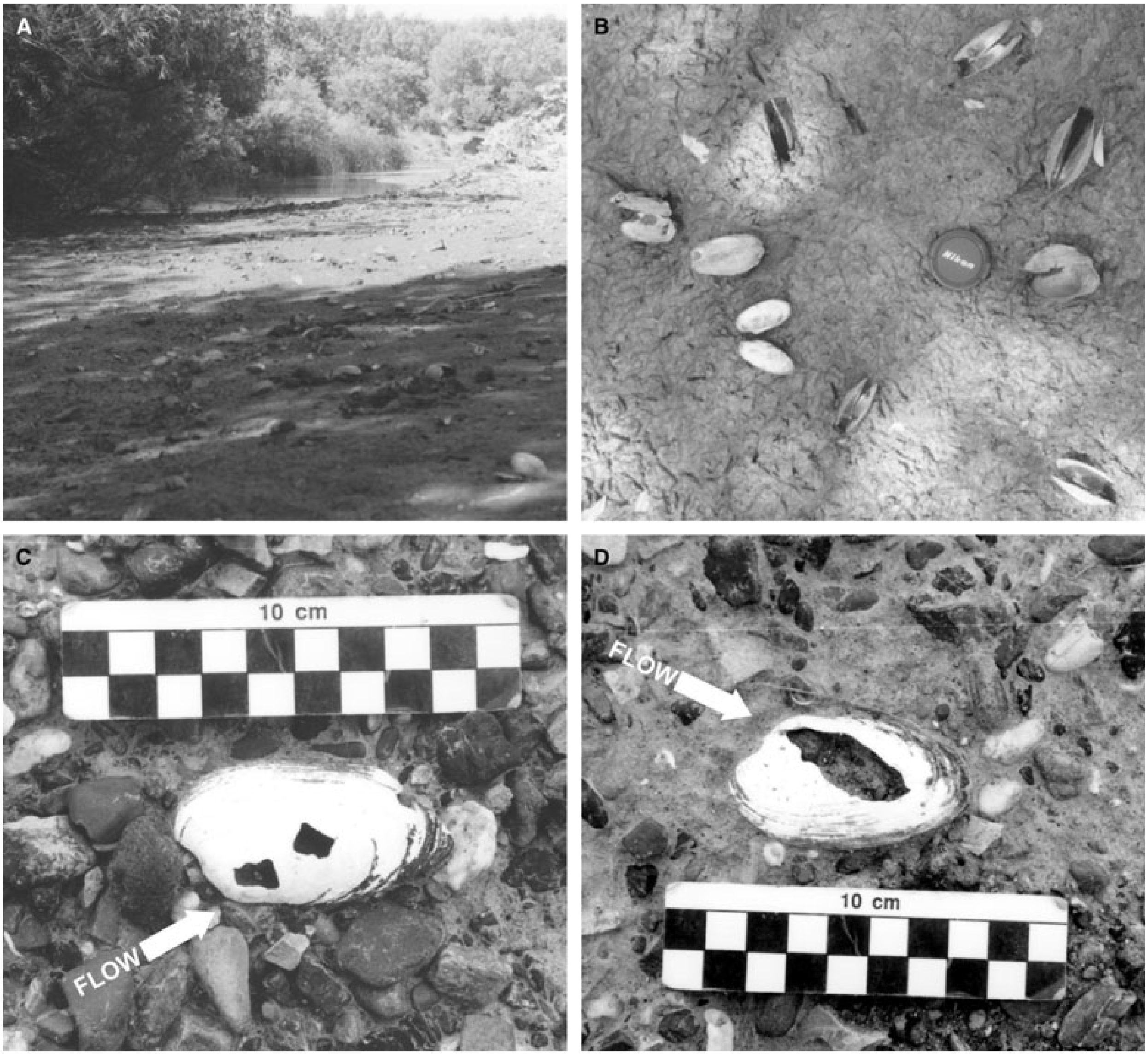

Fig. 6. (A) Mass death assemblage of bivalves in dried-out ponds at the downstream end of a chute channel (located on Fig. 2). (B) Partially open, articulated bivalves in dried-out ponds of chute channel. (C) *Unio* showing abrasion, two perforations and a posterior notch. Arrow shows flow direction. (D) *Unio* showing elongate perforation and partial covering of fine sediment.

However, on the point bar 83% of transported shells are disarticulated (and disassociated) single valves (Fig. 7A). It is probable that minimal transport is required to separate the valves. In chute-channel pools most untransported shells are still in articulation. The articulated valves are open and diverge at angles up to 40° as a result of desiccation and contraction of the ligament following the decay of the adductor muscles (Fig. 6B). Field tests show that once contracted and desiccated the ligament becomes extremely brittle, requiring only slight finger pressure to cause failure. The predominance of single valves on the point bar probably results from valve separation during transport when the shell assemblages are flushed from chute channels during the flood stage. Where articulated valves are found on the point bar, most valves are still closed or show only minor displacement. These closed, articulated bivalve shells were probably transported and deposited while alive with functional adductor muscles. Transport while living is a recognized hazard for riverine bivalves (Eagar, 1978). With emergence of the point bar, valves can be prevented from opening by either partial burial or by the infilling of the shell with fine sediment which acts as a cement.

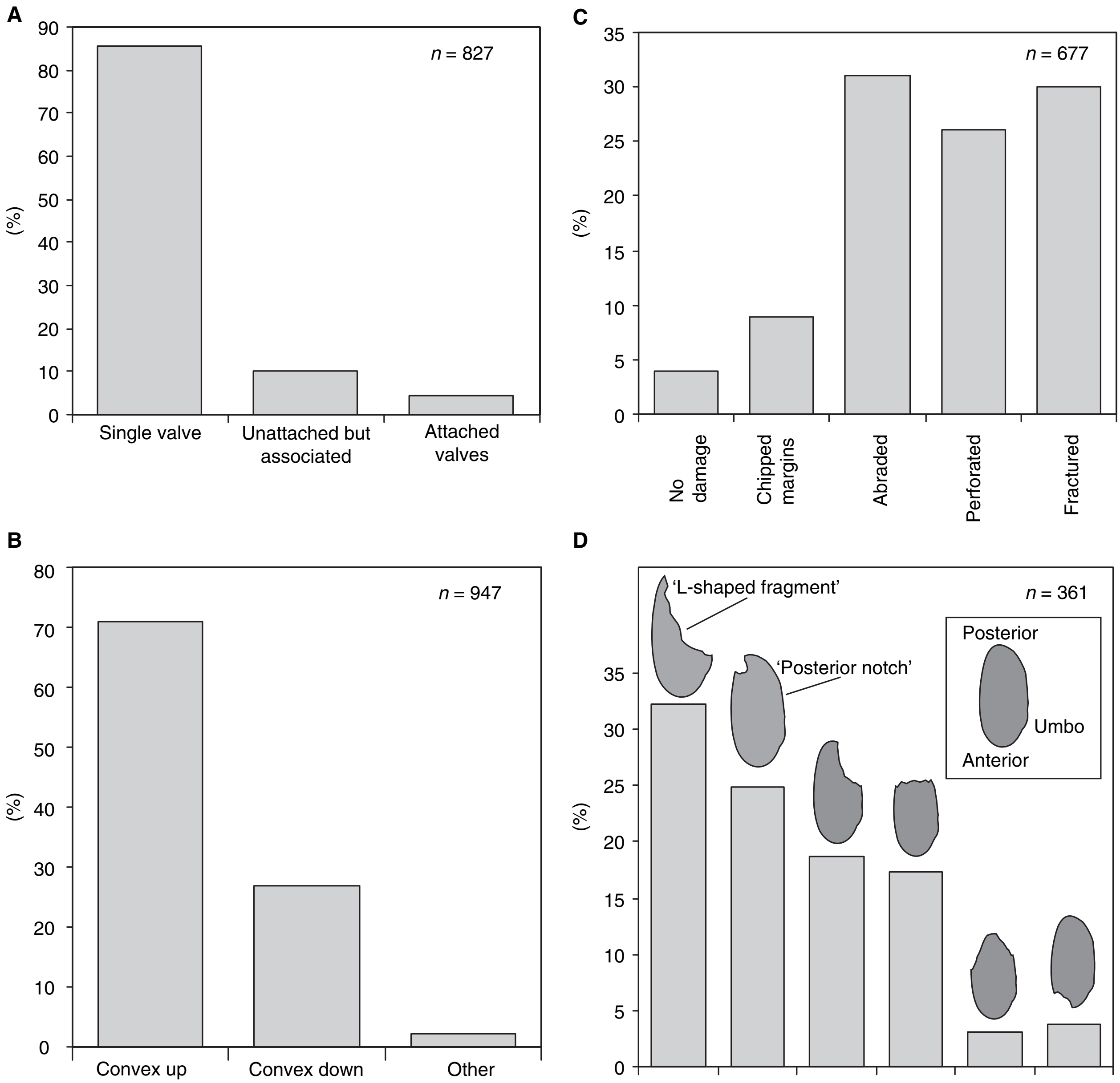

Fig. 7. Bar charts showing characteristics of the *Unio* assemblage, results exclude mass-death chute-channel pond assemblages (grids 40–42 of Fig. 2). (A) Valve articulation; (B) attitude; (C) degree of damage; (D) fracture style.

Aspect

Seventy-one per cent of single valves were found resting on the point bar surface in a convex-up position (Fig. 7B). These data concur with much experimental evidence which shows that the convex-up position is more stable in traction–transport depositional settings (Allen, 1984). Concave-up shells have greater drag coefficients than those orientated convex up and are often flipped in unidirectional flows (Savarese, 1994). Concave-up orientations usually predominate where valves settle (usually convex-side down) through a sediment-laden water column and once on the bed there is insufficient horizontal tractional flow to flip them into the stable position. Allen (1984) demonstrated that during the settling process turbulent eddies can cause sediment to infill the descending concave-up valve and this additional mass may increase stability. This experimental result is supported by the observation that many of the concave-up valves on the point-bar surface had an infill of clay, silt and fine sand.

Orientation

Valve orientation was measured along a line parallel to the hinge, with the recorded data showing the azimuth of the posterior end. Figure 2 shows the results plotted as rose diagrams for different areas of the point bar. Given the development of complex flow patterns around a point bar, the interaction of shells with other sedimentary particles and the potential for reorientation during falling stage, the shells show a strong preferred orientation with the elongate posterior end of the valve pointing in a downcurrent direction. In detail, comparison of shell orientation with other flow direction indicators (imbrication, ripples and sand shadows around obstacles on the point bar surface) shows that valves normally orientate with their hinge slightly oblique to the flow direction and with the umbo and heavier anterior end in an upstream direction (Fig. 3A). This finding was confirmed by some simple flow experiments on single *Unio* valves in the Sakmara River and is in agreement with flume studies on elongate shells with anterior–posterior asymmetry (Allen, 1984)

Shell damage

Ninety-four per cent of *Unio* shells on the point bar showed some form of damage, most of which could be readily classified into: (i) minor chipping of the margins; (ii) abrasion of the periostracum and surface layers of shell carbonate; (iii) perforation of the shell; and (iv) fractured. Shells could show only one or all four of these damage types. These classes refer to modification of the valve exterior; even where abrasion to the outer surface is extensive, the interior nacreous layer of the shell generally remains pristine. Abraded, perforated and fractured shells were found in approximately equal proportions (Fig. 7C).

Abrasion was the most common form of shell damage. Where the total area of abrasion was small it was invariably located on the umbo region of the valve (Fig. 9). Shell carbonate could be exposed in this area, while around the valve margins the periostracum remained intact. As the area of abrasion expanded, it generally formed a diagonal strip running along the plunging ridge between the umbo and the posterior ventral margin (Fig. 9). Abrasion to the shell exterior was a ubiquitous feature of abraded, perforated and fractured shells.

Shell perforations ranged from small angular to sub-rounded holes, a few millimetres in diameter (Fig. 6C) to larger elongate holes several centimetres in length (Fig. 6D). Figure 8 shows the location of centre-points of shell perforations. Most are located on the umbo and along the plunging ridge between the umbo and the posterior ventral margin (Fig. 9). Single perforations on relatively undamaged shells were invariably located on the umbo.

Figure 7D shows the six shell fracture types that were developed and their relative abundance. The most common (33%) was an irregular curved fracture extending from the umbo to the posterior ventral margin resulting in an 'L-shaped fragment' (Fig. 9). A small fracture to the posterior ventral margin (24%) was also common, generating a 'posterior notch'.

MECHANISM OF SHELL FRACTURE

The close spatial relationship between areas of shell abrasion, shell perforation and shell fracture strongly suggests that they form part of a con-

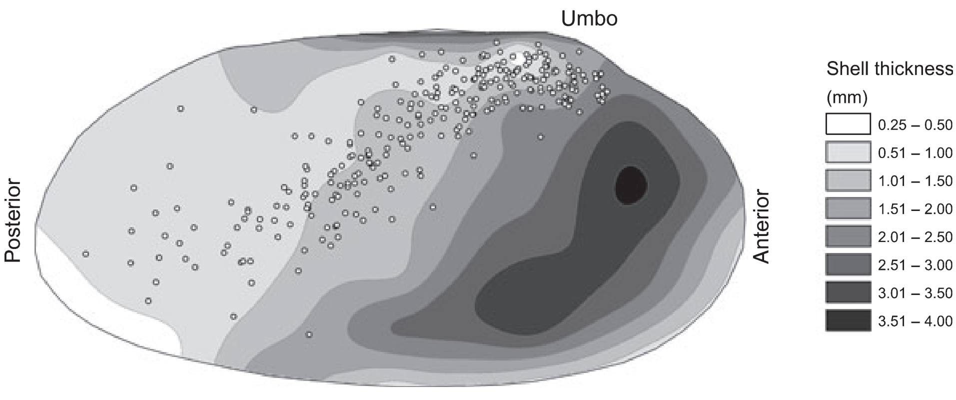

Fig. 8. Map showing the approximate centre-points of perforations found on 152 *Unio* shells, plotted against a contour map of shell thickness (contoured from mean thickness values from six 60 mm long *Unio* shells).

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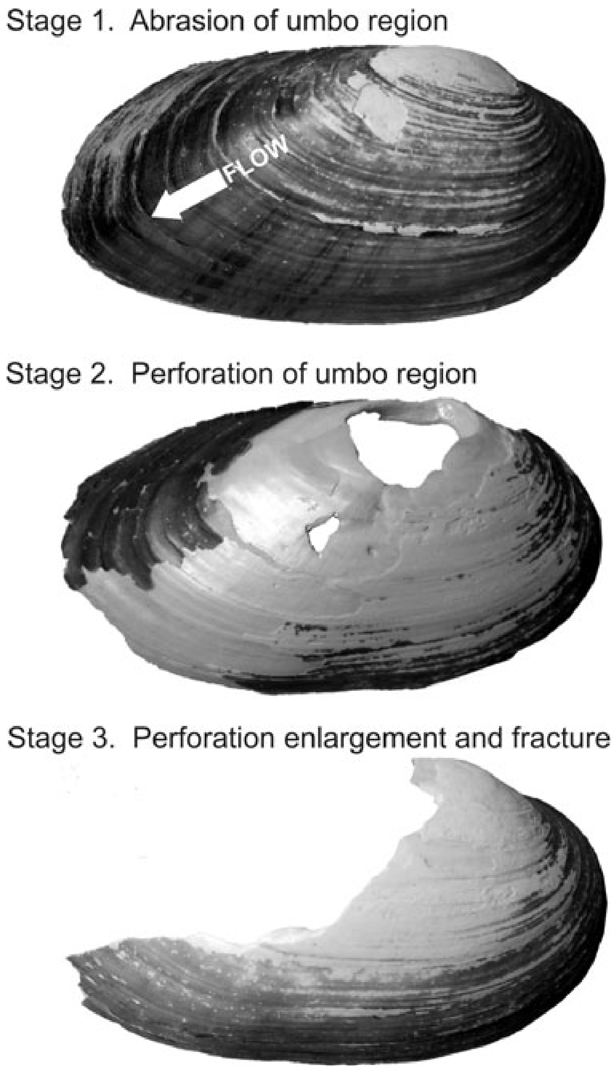

Fig. 9. The three stages in the *in situ* fragmentation of a *Unio* shell: (1) surface abrasion focused on the upstream-orientated umbo; (2) shell perforation at the umbo; and (3) multiple perforation and perforation enlargement leading to fracture. The three stages are part of a continuum from surface abrasion at the umbo to fracture.

tinuum, whereby areas of abrasion evolve into perforations and perforations coalesce and enlarge into fractures (Fig. 9). The detailed morphology of the features also supports this continuum with, for example, perforations having an irregular outline and terraced margins, which indicates that they result from the progressive abrasion of layers of periostracum and carbonate.

'Particle abrasion' in river channels is a summary term covering a range of mechanical processes such as chipping, crushing and grinding. Abrasion can operate in two forms:

1 'Abrasion in place', where a particle is either vibrating within the bed or is stationary and being abraded by sediment impacting upon it (Pearce, 1971; Schumm & Stevens, 1973).

2 'Progressive abrasion', where a particle is being abraded by its own downstream movement (Brewer & Lewin, 1993).

While progressive abrasion may make some contribution towards shell damage, the chief mechanism is considered here to be abrasion in place, where the shell remains stationary on the bed and is impacted by sediment. The critical evidence for this lies in those bivalves which have been transported and deposited on the point bar in a closed, articulated state. Closed, articulated shells often show abrasion, perforation or even fracture on the exposed convex-up valve, while the valve which is face-down and protected on the bed is undamaged. Damage to both valves would be expected if the bivalve was tumbling and saltating within the bedload during transport. A higher frequency of damage to the thin shell margins might also be expected if the observed damage was occurring by downstream movement (Zuschin *et al.*, 2003).

Underpinning the process of *in situ* abrasion and fracture are the hydrodynamic properties of the bivalve shell, with consistency in the orientation and aspect of the valve in a flowing current producing consistency in the distribution of damage on the shell surface. Valves preferentially lie in a convex-up position and rotate in the flow such that the umbo and the heavy anterior end face in an upstream direction. The elevated, upstream-facing umbo region is thus exposed to direct particle impact and is the first area of the shell to be abraded and perforated (Fig. 9). The vulnerability of this region to perforation is greatly increased because the shell can be <1 mm thick at the umbo cavity (Figs 5 and 8). This compares with up to 5 mm of shell at the valve anterior. Perforations developed in the umbo area can then propagate and merge in a downcurrent direction towards the posterior ventral margin through a relatively thin area of shell (Fig. 8). Linkage of the downward-propagating perforation and the 'posterior notch' fracture (Fig. 7D) leads to fracture and the development of the characteristic 'L-shaped' fragment.

The effectiveness of the *in situ* abrasion process is dependent on the stability of the shell such that the abrasive sediment can remain in traction while the shell remains fixed on the channel floor. Hydrodynamic studies (e.g. Allen, 1984; Olivera & Wood, 1997; Dey, 2003) have shown that bivalve shell entrainment typically requires flow velocities in the range 0·2–0·6 m sec^{-1}, with convexity or sphericity, roughness, and density or mass per unit projected area being the main morphological factors creating variation in the threshold velocity (Olivera & Wood, 1997). Hjulström's (1935) diagram showing the flow velocity required to transport siliciclastic grains of various sizes suggests that, at flow velocities less than that required for bivalve entrainment (0·2 m sec^{-1}), sand to granule-size particles remain in transport and may act as the abrasive agent. However, these general figures may be modified substantially because of the mixed sand and gravel bed of the Sakmara River. The removal of fines from a bed of mixed grainsize tends to produce a gravel armour of interlocking and immovable pebbles (Wilcock & Southard, 1989) which may stabilize the shells.

A second important feature of armoured beds is that they inhibit the development of bedforms (Leeder, 1999). Bedform migration can quickly bury shells under a protective layer of sediment (Allen, 1984), removing them from sandblasting at the sediment–water interface. Additionally, shells placed on a movable sand bed will tend to self-bury because of scouring around the shell (Allen, 1984). The stabilized gravel bed of the Sakmara River may thus promote abrasion and fragmentation by prolonging shell exposure to particle impacts.

Biological processes such as predatory breakage, boring and bioerosion and chemical corrosion need to be eliminated as these have been shown to be a major source of shell damage and fragmentation (Cadée, 1994; Zuschin *et al.*, 2003). In the Saint John River, Canada, comparable loss of umbonal shell material in unionid bivalves has been interpreted as largely a consequence of chemical dissolution from the oldest part of the shell, possibly accelerated by gastropod-induced boring or decay mediated by chlorophyta, cyanophyta or fungi (Lawfield & Pickerill, 2006). However, in the Saint John River, umbonal shell damage was present on all observed unionid shells both living and dead. In the Sakmara River, damage to living bivalve shells and those in the chute-channel mass-death assemblages (Fig. 6A) was extremely rare. If predatory boring, breakage and chemical corrosion were important processes, shell damage should be observed in both the untransported chute-channel assemblages and the transported bar-top assemblages. However, only the transported, bar-top assemblages showed extensive shell damage suggesting that physical and not biological/chemical processes are the major factor in shell fragmentation in the Sakmara River. This observation may reflect the relatively short 2-month period during the spring snowmelt when shells deposited on point-bar tops are immersed in water.

Comparison with marine environments and experimental results

In marine environments the importance of physical fragmentation is generally poorly quantified because of the difficulty in distinguishing physical fractures from those produced by biological activity such as crushing predation (Zuschin *et al.*, 2003). While predation has been shown to be a major source of shell breakage, fragmentation caused by abrasion has been described only for limpets (Seilacher, 1973; Cadée, 1999) and bivalve shells on surf-washed beaches (Driscoll, 1967). Driscoll's (1967) field experiments on shell abrasion in the surf zone make an interesting parallel to this study. Driscoll placed loosely tethered strings of single bivalve shells within moderate surf on a gravelly sand beach for 18 h and on a sand beach for 100 h. On the sandy beach, the valves of *Mercenaria mercenaria* became preferentially orientated convex up and with the umbonal region pointing towards the shore. This mode of orientation is very similar to that seen on the Sakmara point bar; however, on the surf-washed sandy beach it generated a contrasting damage pattern. Maximum abrasion was found around the margins of the valve immediately in contact with the sand bottom, whereas the elevated central portion of the valve was relatively undamaged. Only when the valve became partially buried, protecting the valve margins, did the raised central portion of the convex-up valve become abraded by sandblasting. This situation appears comparable with the point bar where the valves often rest convex-up with the margins protected below the level of the gravel pavement (Fig. 6C). Driscoll also found that the heavier and more stationary valves of *M. mercenaria* were much more prone to abrasive sandblasting than light shells such as *Mya arenaria* which were lifted and moved with each advancing and retreating wave. The absence of any significant breakage or abrasion in the mobile light valves of *M. arenaria* indicates cushioning of impact during transport within turbulent flow. Driscoll's (1967) observations regarding the importance of shell weight (the primary factor that increases entrainment velocity) and the lack of damage to valves during transport provides supporting evidence that abrasion and fragmentation of unionid shells in the Sakmara River is largely an *in situ* process. Driscoll also undertook experiments within the surf zone of a beach composed of gravelly sand. The most significant differences in the abrasion process between this beach and the one composed of fine sand are that abrasion took place at least five times faster and produced a rougher and more irregular surface on the shells. This is similar to the mixed grain-size of the Sakmara River where the abrasive process appears to be rapid. The presence of abraded and fractured articulated bivalves with soft tissue within the shell interior would suggest that the complete process from abrasion to fragmentation (Fig. 9) can occur within a 2-month flood cycle.

Tumbling barrels commonly have been used to simulate the process of shell abrasion (e.g. Driscoll & Weltin, 1973; Oji *et al.*, 2003). No studies have been undertaken with unionid bivalves; however, it seems unlikely that tumbling barrels could replicate realistically the sort of directionally focused sandblasting of flow-orientated shells described here. In tumbling barrels, shells are continually turned over, whereas on the point bar, valves maintain a definite aspect and orientation under a unidirectional stream. If the stream changes its direction, the shell changes its orientation accordingly, keeping the relative orientation with respect to the stream direction the same (Dey, 2003) and focusing the abrasion process on particular areas of the shell.

CONCLUSIONS

Evidence from the Sakmara River shows that bivalve shells can be fragmented without extensive transport by a process of *in situ* abrasion leading to perforation and fracture. Broken shells are thus not a reliable indicator of long-distance transport. The fracture process relies on the hydrodynamic properties of the shell which adopts a preferred orientation in a unidirectional flow focusing abrasion on the elevated portion of the valve from the umbo to the posterior ventral margin. Factors enhancing the *in situ* abrasion and fragmentation process include: (i) the variable distribution of shell thickness, with an area of reduced thickness in the upstream-facing umbo; (ii) the weight of the unionid bivalves which raises the entrainment velocity; (iii) the mixed grain-size of the abrasive bedload; and (iv) the armoured properties of the channel bed which stabilize the shell and prevent downward removal from the sediment–water interface. In the geological record, elongate bivalve shells showing evidence of abrasive fragmentation (e.g. distinctive L-shaped fragmentation) may be indicative of stabilized substrates and high rates of bedload transport.

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