Shell Etching on Clams from Low-Alkalinity Ontario Lakes: A Physical or Chemical Process?

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Elliptio complanata (Unionidae: Bivalvia) were sampled from sites of low and high water turbulence in four Ontario lakes that varied in pH (6.0–7.5) and alkalinity (22–243 $\mu eq \cdot L^{-1}$). External shell etching on each clam was quantified using an image analysis digitizer system. Within-lake variation in shell etching was contrasted using a log–log analysis of covariance approach. Clams exposed to higher turbulence regimes (and large sediment particles) were significantly more etched than low-exposure clams ($P < 0.05$). Approximately 52% of the total shell etching variability resulted from within-lake differences between high- and low-exposure clams. The remaining variation was accounted for by differences among individual clams. Shell etching in these lakes appears to be primarily a physical process probably related to water turbulence. Etching was not related to variation in lake water chemistry and thus is likely not influenced by lake acidification.

On a prélevé des échantillons d'*Elliptio complanata* (bivalves, unionidés) dans des emplacements de faible et de haute turbulence dans quatre lacs ontariens dont les eaux étaient d'un pH et d'une alcalinité de valeurs différentes (pH de 6,0 à 7,5, alcalinité de 22 à 243 $\mu eq \cdot L^{-1}$). On a ensuite fait l'étude quantitative du relief externe de chaque coquillage au moyen d'un système d'analyse d'image par numérisation. On a étudié la variation du relief des coquilles des bivalves d'un même lac par analyse de covariance bilogarithmique. On a constaté que les bivalves exposés à des eaux turbulentes (et à l'action de grosses particules de sédiments) avaient un relief significativement plus marqué que ceux qui étaient moins exposés ($P < 0,05$). Approximativement 52 % de la variabilité totale du relief résulte de différences entre les bivalves très exposés et peu exposés d'un même lac. Le reste de la variation s'explique par des différences individuelles. Il semble que le relief des coquilles des bivalves des lacs étudiés soit principalement le résultat d'un processus physique qui est probablement lié à la turbulence des eaux. Selon les observations, le relief n'est pas lié à la variation de la chimie de l'eau et, dès lors, il n'est probablement pas influencé par l'acidification du lac.

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Freshwater unionid clams possess shells that are primarily composed of calcium carbonate (Wilbur 1964) and that can be important in a freshwater system's calcium budget. Green (1980) found that 50% of the calcium in a shield lake near Inuvik, Northwest Territories, was in shells of live *Anodonta grandis*. The majority of this calcium is not returned to the lake until death of the clam and the subsequent dissolution of the shell. However, unionids also lose calcium while they are alive.

The unionid shell is covered by a thin fibrous schleroproteinaceous layer called the periostracum, which provides the matrix for deposition of calcium carbonate (Saleuddin and Petit 1983). The resilience of the periostracum seems to decrease on older portions of the shell, as it is often missing from the umbonal region. Underlying shell layers, primarily calcium carbonate, are also often missing.

It has been suggested that external shell etching (the loss of periostracum and underlying shell layers) is a chemical process analogous to chemical weathering of calcareous rock by naturally occurring carbonic acids (Beauchamp 1886; Grier 1920; Coker et al. 1921). However, the phenomenon of shell etching has never been quantitatively evaluated. Hence, an alternative explanation for shell erosion in living clams is physical erosion, through contact with abrasive particles. Just as in geological weathering, an interaction may exist between physical and chemical processes.

An added component to the question of the physical versus chemical basis of shell etching is the effect of anthropogenic enhancement of the acidity of precipitation. If the chemical weathering scenario is correct, then increases in acid loading (and decreases in lake pH) should enhance rates of shell etching just as it enhances strictly geochemical weathering. Alternatively, if shell etching is a predominantly physical process, etching will be independent of lake pH. In this study we examined shell etching in freshwater unionid mussels (*Elliptio complanata*) collected from four lakes which vary in alkalinity and pH. Within each lake, clams were collected from an area of high exposure to potentially abrading particles (high water turbulence) and low exposure (low water turbulence) based on sediment characteristics. Within-lake variation in shell etching due to exposure differences was compared across the four lakes.

Methods

The four study lakes are located in south-central Ontario on the Precambrian Shield (Fig. 1). Although morphologically

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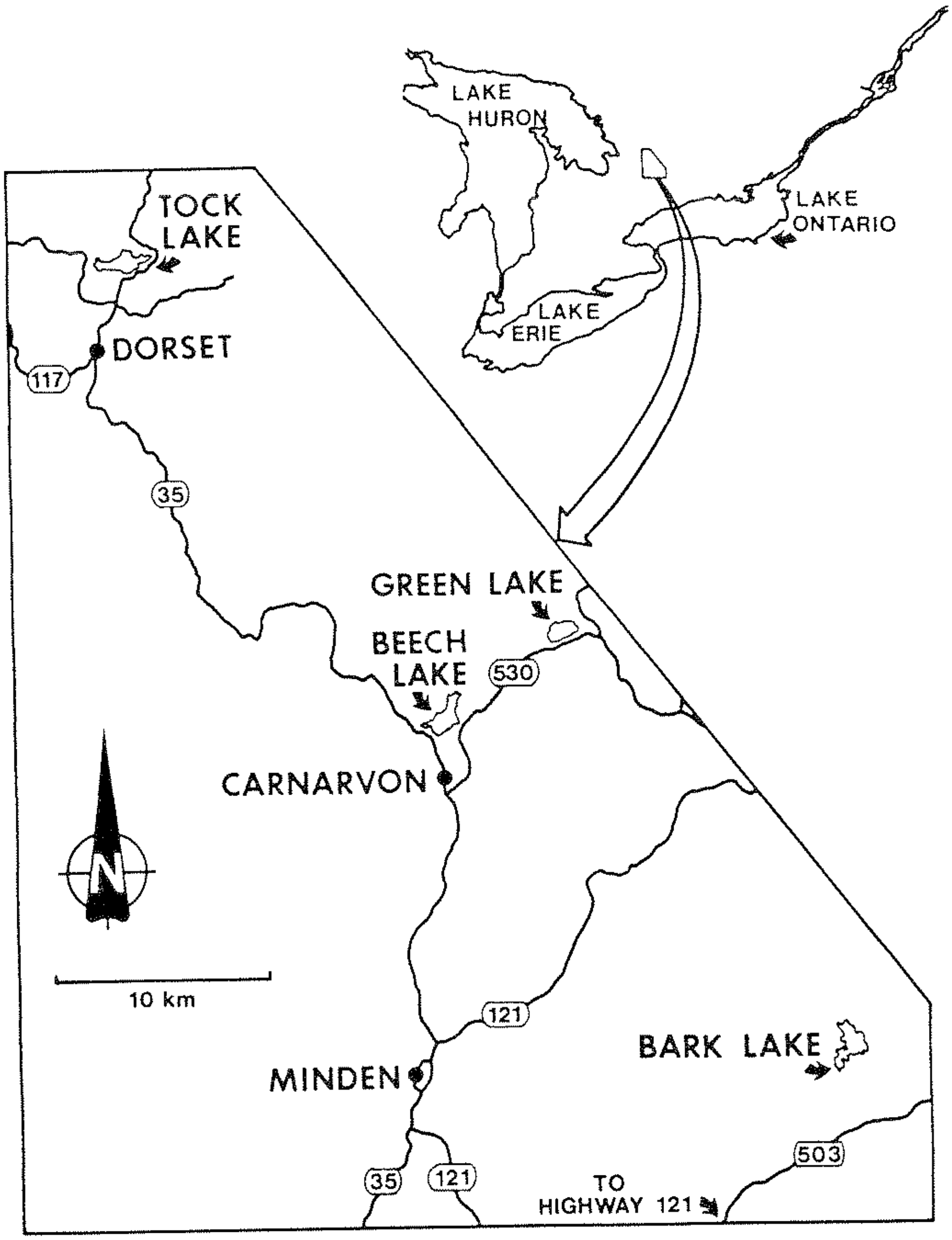

FIG. 1. Location of study areas in Haliburton Co., south-central Ontario.

similar (Hinch and Bailey 1988), the lakes were chosen because of differences in alkalinity and pH (see Fig. 2). Mean wind direction for the ice-free season is from the west-southwest, based on Environment Canada wind summary data from 1983 and 1984. Therefore, high-exposure habitats will exist primarily on the northeast shores of these lakes whereas low-exposure habitats will primarily be found on the southwest shores. In August 1985, 25 clams were collected using SCUBA from a low (southwest) and a high (northeast) exposure site in each lake (Fig. 2). Stretches of shoreline near inflows and outflows were not sampled. Sediments at the low-exposure sites appeared to be relatively fine whereas those at the high-exposure sites were primarily composed of sand and small gravel. These differences were quantitatively verified by randomly taking three sediment core samples at each site following the methodology of Allison and Harvey (1981) (Table 1). Clams occurred at water depths of 1.5–2.5 m. To reduce the effects of age structure as a confounding factor, only old individuals (greater than 8 yr of age based on annual rings) were collected. These clams tend to be the largest in the populations and are very near their population asymptotic sizes (S. G. Hinch, unpubl. data).

The meat was removed from each clam and the shells allowed to dry. Shell etching was quantified using an image analysis process run on a microcomputer-based digitizer system. Detailed descriptions of the design, construction, specifications, and software of the system can be obtained through correspondence with Dr. Lewis Brown (Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401, USA, unpubl. data). Shell etching was defined as any area on the shell which was missing periostracum and underlying shell layers (Fig. 3). In preparation for the digitizing process, all etched areas were painted white. This procedure provided a sharp contrast with

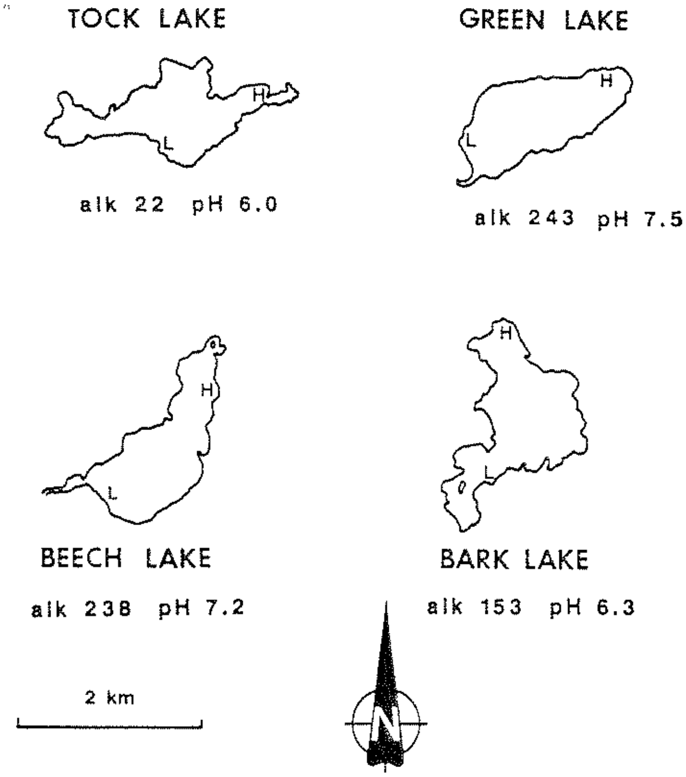

FIG. 2. Low-exposure (L) and high-exposure (H) sites in the four study lakes. Alkalinity ($\mu eq \cdot L^{-1}$) and pH values based on acidic precipitation in Ontario study (OME 1981–83).

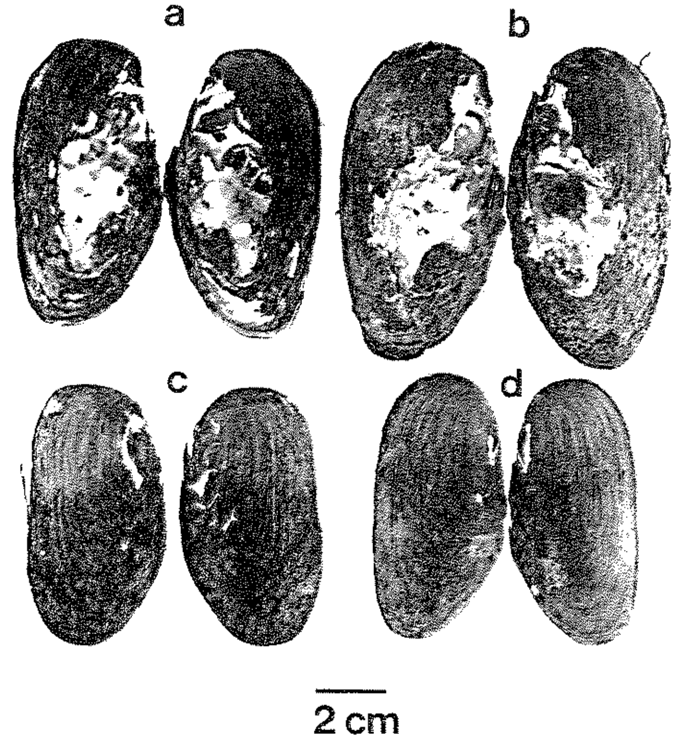

FIG. 3. *Elliptio complanata* shells from the (a and c) low-exposure and (b and d) high-exposure sites in Beech Lake demonstrating (a and b) maximum and (c and d) minimum amounts of shell etching.

TABLE 1. Mean (SE) percentage of sediment, by weight, that passed through a 0.5-mm sieve from each of the two exposure sites within the four lakes. At each site, $n = 3$.

Site	Mean (SE)
Green high	68.70 (5.25)
Green low	97.16 (1.01)
Beech high	66.27 (4.14)
Beech low	99.75 (0.16)
Bark high	55.00 (6.26)
Bark low	82.20 (2.66)
Tock high	50.58 (11.14)
Tock low	97.90 (0.31)

TABLE 2. Probability levels for main and interaction effects from the ANCOVAs contrasting low- and high-exposure sites within the four lakes. For an experiment-wise error rate of $\alpha = 0.05$, the appropriate α for each test is 0.013 based on Bonferroni's inequality. Asterisks denote values that are not associated with null hypotheses of interest.

	Beech Lake	Green Lake	Bark Lake	Tock Lake
LNEA	*	*	*	*
SIDE	<0.001	<0.001	0.009	<0.001
LNEA × SIDE	0.024	0.267	0.008	0.022

the dark brown nonetched areas. Nonetched shell areas were first determined. Both valves of a given shell were placed under the video camera with the outer shell surface up. The dark area was digitized and its area determined. The digitizing process only determines area (i.e. two dimensions). However, *E. complanata* have a thin profile (valve thickness ranging from 7 to 9 mm. Hinch and Bailey 1988), and we believe distortion caused by shell width was minimal. Total shell area was then determined by painting the shell's entire external surface black and repeating the digitizing process. Etched area was equal to the total shell area minus the nonetched shell area.

To account for population-dependent differences in clam sizes for a given age (Hinch and Bailey 1988), some form of standardization was required. To avoid the statistical problems inherent with ratios (Green 1979), we decided to use a regression of log of etched area (LEA) against the log of nonetched area (LNEA) rather than the superficially more simple percentage of shell etched. The advantage of a regression-derived estimate is that proportions can be compared without resorting to ratio-based variables (Green 1987). We then used analysis of covariance (ANCOVA) to compare the regression relationships from the high- and low-exposure sites within a given lake. Nested random effects ANCOVA was used to estimate the proportion of the total variance in shell etching attributable to variation among the four lakes, between exposure level sites within the lakes, and among individual clams within the sites. Maximum experimental error was controlled by adjusting the significance levels for independent, simultaneous comparisons using Bonferroni's inequality (Snedecor and Cochran 1980).

Results and Discussion

The effect of exposure (SIDE) was significant in the four analyses, indicating that exposure influences the percentage of shell that is etched (Table 2). The high-exposure clams were proportionately more etched than the low-exposure clams in each lake (Table 3). Comparisons of the interaction term (LNEA × SIDE) from the four analyses (using Bonferroni's inequality) showed that only Bark Lake was even marginally significant (Table 2). This result indicates that as clam size increases, the amount of etching does not proportionately

TABLE 3. Mean (SE) shell etched area (mm^2) from each of the two exposure sites within the four lakes. At each site, $n = 25$.

Site	Mean (SE)
Green high	638.03 (77.47)
Green low	277.74 (34.95)
Beech high	1216.83 (98.43)
Beech low	429.08 (76.65)
Bark high	475.84 (45.55)
Bark low	368.86 (26.05)
Tock high	801.77 (57.95)
Tock low	300.33 (29.33)

change between the two sides in Beech, Green, or Tock Lake. Only in Bark Lake is there evidence that exposure may influence the relationship between clam size and percentage of shell that is etched.

Components of variance computed from the nested ANCOVA indicate that 52.3% of the total shell etching variability resulted from differences between exposures (within-lake). Lakes did not differ significantly in degree of shell etching. The remaining 47.7% was accounted for by differences among individual clams within sites.

Shell etching does not appear to be related to differences in lake water chemistry (i.e. alkalinity and pH as others have proposed (Grier 1920; Coker et al. 1921; Tevesz and Carter 1980). Among-lake differences in shell etching variability were trivial. If water chemistry were important in influencing shell etching, one would expect etching to be "ordered" along a water chemistry gradient, with clams from Tock Lake the most etched and those from Beech and Green lakes the least. This ordering did not occur; in fact, clams from Beech Lake were the most etched. The majority of the variability in etching was explained by within-lake exposure differences. Therefore, we suggest that shell etching is mostly a physical process related to water turbulence.

The mechanism of physical shell etching is probably a "sandblasting" effect, as abrasive sediment particles move past shells or dislodged shells are scoured as they contact the substrate. The magnitude of shell etching should be greater on clams from exposed habitats because more sediment particles would be suspended in wave-washed, turbulent habitats. Also, shell dislodgement and subsequent scouring would also be expected to occur more frequently in more turbulent habitats. Etching is most commonly observed in the umbo (hinge) region of the shell. This pattern is not surprising because the umbo is the oldest and presumably weakest portion of the periostracum. It is also the shell portion most exposed to water movement, since younger portions of the shell are normally buried in the sediment.

Within each lake, percent shell etching remains the same as clams size increases for both high- and low-exposure clams despite the fact that high-exposure clams from each lake have a much faster growth rate than the corresponding low-exposure clams (Hinch and Bailey 1988). The exception to this was Bark Lake clams. Upon further investigation it was determined that as high-exposure Bark Lake clams grew in size, the absolute area of shell that was etched decreased. Although unionids can superficially reseal holes in their shells and can reinforce etched areas using adventitious conchiolin (Tevesz and Carter 1980), it is unlikely that they can replace nacreous shell layers and periostracum on their umbo. We remain unable to explain this etching pattern. Nonetheless, the overwhelming factor influencing shell etching in Bark Lake clams is exposure.

We have determined that shell etching on clams from four Ontario lakes, differing in pH and alkalinity, is a physical process related to substrate type and water turbulence. Laboratory studies using unetched clams, standard size sediment particles, and controlled water turbulence are needed to better assess the manner in which shell layers are physically removed.

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