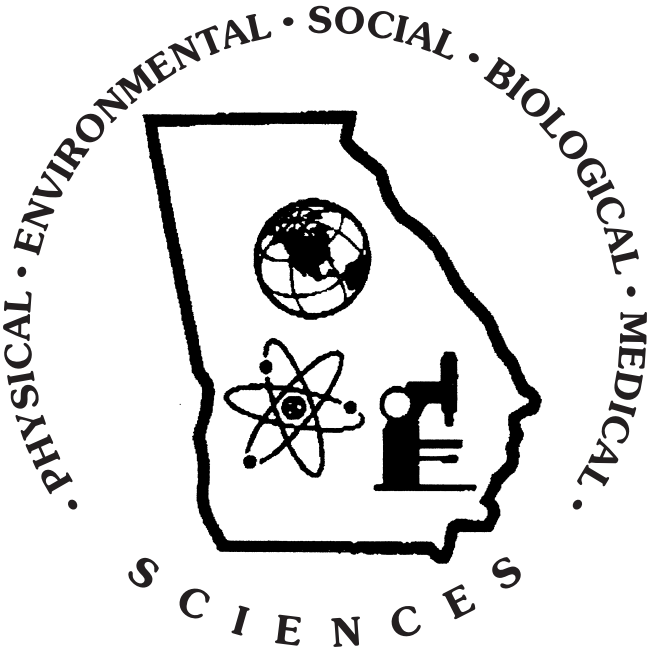


# GEORGIA JOURNAL OF SCIENCE

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## **GAS PRESIDENT'S COMMENTS AND REPORT FROM THE ACADEMY COUNCIL**

Colleagues,

Plans for our 87th Annual Conference on March 27 and 28, 2010 at Columbus State University are well under way. Bonita Fluornoy, the Georgia Academy of Science Local Arrangements Chair, and Dr. Timothy Mescon, President of Columbus State University have put together an informative and exciting format. Section papers will be presented on Friday March 27 starting 11:00 am and go until 4:00 pm. There will be a reception at the Coca Cola Space Science Center on Friday evening at 6:00 pm until 8:00 pm where attendees will go on a space mission in an IMAX theater presentation. On Saturday all section papers will be presented from 8:00 am until 12:00 pm. During that time there will be a chance for all sections to have a business meeting to elect their section officers and to finalize the judging of the presented papers. Following the paper presentations and section business meetings there will be a luncheon featuring Dr. Shawn Cruzen, Director of the Coca Cola Space Science Center as our guest speaker. Also featured at the banquet will be the section student presentation awards. Registration will begin at 8:00 am Friday and go until 4:00 pm. Saturday registration will go from 8:00 am until 11:00 am.

On Saturday there will be professional workshops for math and science teachers in middle and secondary schools. These workshops presented at our annual meeting are a good way for our organization to promote science education in our state. For annual meeting information, please see the Academy website at [www.gaacademy.org](http://www.gaacademy.org).

On another front, I would like to quote our University System of Georgia Chancellor Erroll B. Davis Jr.

“Georgia must respond to the increasing state and national crises in the education of mathematicians, scientists, technicians and engineers, and to the preparation of science and mathematics teachers. Addressing the need to increase the number of baccalaureate degrees in these fields is one of the highest priorities of the University System of Georgia. Accordingly, I have committed to the provision of funding to support the successful implementation of our MATH + SCIENCE = SUCCESS initiative over the next several years.”

The Board of Regents of the University System of Georgia has funded the STEM (Science, Technology, Engineering and Mathematics) University System Initiative. The charge of this initiative is to increase the number of K through 16 students interested in science, technology, engineering and

mathematics, the number of students in college who pursue the STEM disciplines and the number of teachers prepared to keep who are better able to keep K through 12 students in the STEM pipeline. To date six USG institutions have successfully developed and implemented these teaching service learning courses. On Friday February 19, 2010, Georgia Perimeter College and Georgia Tech are sponsoring a STEM Regional Institute. It will be held at the GTRI Conference Center, Room 119, 250 14th Street NW, Atlanta, Georgia. To register for this conference please go to <http://www.steminstitute.gatech.edu/register.php>. To get information on how your institution could participate in the STEM Initiative contact Ms. Judy Awong-Taylor, Director of the USG STEM Initiative, Board of Regents of the University System of Georgia at [Judy.Awong-Taylor@usg.edu](mailto:Judy.Awong-Taylor@usg.edu).

I hope all of you have had a good holiday break and will return refreshed to you institutional endeavors. Please communicate to me or any of our Academy officers your suggestions or concerns that will strengthen our efforts to promote science education and promote scientific research in the State of Georgia.

Respectfully submitted,

Bob McDonough  
President  
The Georgia Academy of Science

**VARIATION IN STEMMATAL MORPHOLOGY OF LARVAE  
OF *LIODESSUS NOVIAFFINIS* MILLER  
(DYTISCIDAE: HYDROPORINAE: BIDESSINI)**

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**ABSTRACT**

Second and third instars tentatively identified as *Liodessus noviaffinis* Miller have six dorsolateral stemmata near the origin of each antenna. However, each stemma lacks a corneal (cuticular) lens on the surface exterior to its internal sensory pigmented components.

**Key words:** Dytiscidae, *Liodessus*, larva, stemmata, corneal lenses.

Bidessine larvae collected on 26 October 2007 from a small drainage ditch in Bibb County, Georgia, USA (N32°52.813'; W083° 45.425') were identified tentatively as *Liodessus noviaffinis* Miller. The identification was based on distribution records (1, 2) and co-occurrence of adults identified as *L. noviaffinis*. The morphology of third instars in this cohort also corresponded, in general, to that attributed to *Liodessus* (3, 4) with the exception of the stemmata. Larvae of most dytiscid species have six stemmata located on and in the cranium posterior to the origin of each antenna (1). The cuticle above each stemma usually forms a biconvex corneal (cuticular) lens exterior to the crystalline cone and the various stemmatal sensory components of the cranial interior (5, 6). Although complete stemmata were expected based on previous descriptions (3, 4), there were no indications of corneal lenses on exuviae of second instars in this cohort.

Our analysis of intact second and third instars that had been preserved and stored in 70% glycerated alcohol revealed six moderately pigmented

dorsolateral stemmata defining stemmatal regions posterior to the origin of each antenna. However, corneal lenses were not observed (Meiji, ML2000; 400x) on the cranial exteriors although the pigmented interior stemmatal components tended to obscure our observations. The absence of a corneal lens on each stemma was readily apparent when non-sclerotized internal material was removed with 15% KOH. Thus, on these second and third instar bidessine larvae corneal lenses are absent, but the internal stemmatal sensory components appear to be present defining a rather typical stemmatal region.

Assessments of stemmatal morphology included in many descriptive studies of dytiscid larvae may provide useful information for systematic evaluations. Areas of corneal lenses, volumes of cellular sacs (7) and orientation of individual stemma (8) may vary within stemmatal regions of individual taxa. Some species of Dytiscinae have a seventh stemmatal-like pair of structures on larvae in addition to the usual six (1). Stemmata are reportedly absent on the mature larva of the subterranean hydroporine genus *Haideoporus* Young and Longley (9) and on first and second instars of *Hydrocolus* Roughley and Larson (10, as *Hydroporus paugus* Fall). The absence of corneal lenses on these bidessine larvae presents systematists with an additional source of stemmatal variation that may be evaluated objectively with no more difficulty than assessments of cranial sensilla. However, pigmented internal sensory components may obscure the absence of the corneal lenses and the absence of lenses does not necessarily mean that stemmata are absent.

### ACKNOWLEDGEMENTS

We appreciate the assistance and comments generously provided by Dr. M.C. Michat of the University of Buenos Aires, Argentina and the identification of adult material by Dr. G. William Wolfe of this University. This project was supported in part by Faculty Research Grants awarded by the Office of Research Services, Georgia College & State University. Aquatic Coleoptera Laboratory Contribution Number 76.

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## SEXUAL DIMORPHISM WITHIN CANINE DIMENSIONS OF *DIDELPHIS VIRGINIANA*

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### ABSTRACT

Sexual dimorphism in canine size was analyzed from a sample of the Baldwin County, Georgia population of *Didelphis virginiana* (Virginia opossum). Where possible 6 measurements were obtained from 59 (47 males, 12 females) individuals collected as roadkill. Although range overlap exists for all measurements, males were found to be significantly larger for upper and lower canine length, width and height. The observed sexual dimorphism agrees with previously published analyses of cranial and post-cranial sexual dimorphism in this species and is likely related to intrasexual aggression between males during mating season.

**Key words:** Sexual dimorphism, *Didelphis virginiana*, canines, Virginia opossum

### INTRODUCTION

Sexual dimorphism within osteological dimensions is prominent throughout both extant and extinct populations. In most mammalian lineages, there appears to be some degree of sexual dimorphism (1), much of which is observable in cranial dimensions. Within human populations, skeletal variation has been studied extensively because of the importance of being able to determine the sex of archeological remains (2). This ability to determine sex is also of great importance in paleoecological studies of prehistoric taxa.

Intraspecific variation within osteological proportions can occur for a wide variety of reasons. In populations where “female-choice” is the primary mode of sexual selection, males typically exhibit larger dimensions as a result of competitive interactions with other males. Other groups show variation in relation to display behaviors. This concept has been known and comprehensively studied since its proposal by Darwin (3, 4). Males that possess a “better fit” adaptation in relation to mating will reproduce more frequently and supply the next generation with a greater proportion of their genotype. This practice is especially prominent in mammalian lineages, as in many species of ungulates. Loison *et al.* (5) found that sexual dimorphism is especially

pronounced within the Bovidae and Cervidae families, both of which exhibit male-male competitive interactions.

*Didelphis virginiana* (Virginia opossum) is a species found in large populations in the eastern and extreme western portions of the United States. With this prevalence, the species is readily available for scientific analyses; however, few studies have analyzed its osteological variation, and more specifically sexual dimorphism. Tague (6) determined that males were significantly larger for 14 of 16 pelvic and 8 non-pelvic dimensions. Patterson and Mead (7) found that males were significantly larger for 8 cranial and 5 post-cranial measurements. Coues (8) provided a detailed study of the osteology and myology of *Didelphis virginiana*, however, only noted that the male canines appeared to be much larger than those of females. Gardner (11) presented a detailed study of *Didelphis virginiana* and after analyzing 64 random museum specimens from across the country, suggested that sex could be determined with a high degree of certainty based upon canine dimensions and age class. However, in many paleontological and ecological instances, determination of age class is virtually impossible due to the isolated nature of the material. The present study analyzes the degree of sexual variation within the canine dimensions of *Didelphis virginiana* independent of adult age class, proposes a standardized measurement technique, and provides baseline data for the use in additional comparative studies.

## MATERIALS AND METHODS

During the winter months (January-March) of 2002 and 2004, 59 (47 males and 12 females) specimens of *Didelphis virginiana* were collected as road-kill in Baldwin County, Georgia. These individuals were sexed, weighed and tagged at the time of collection, and were later skeletonized by Dermestid beetles. All samples were determined to be of mature age (10+ months) based upon the parameters suggested by Gardner (9). All specimens are housed in the Georgia College and State University Recent Mammal Collection.

Where possible, length, width and height measurements were obtained for upper and lower canines of each specimen using Chicago Brand digital calipers accurate to within 0.01 millimeters. However, owing to the nature of death on roadways, many of the individuals had damaged dentition. The upper and lower left canines were measured when possible. In cases where left canines were broken or absent, those on the right side were measured. Upper and lower length (UL, LL) and width (UW, LW) were obtained at the bone level on either the maxilla or the dentary. Lengths were measured from the most anterior portion of the canine to the most posterior. Widths were obtained by measuring from the center of the lingual surface to the center of the labial surface. We measured upper and lower crown heights (UCH, LCH) from the labial margin of the canine alveolus to the apex of the crown. For each dimension, a sample mean, range, standard deviation, and standard error were calculated. Student's t-test was used to determine the significance

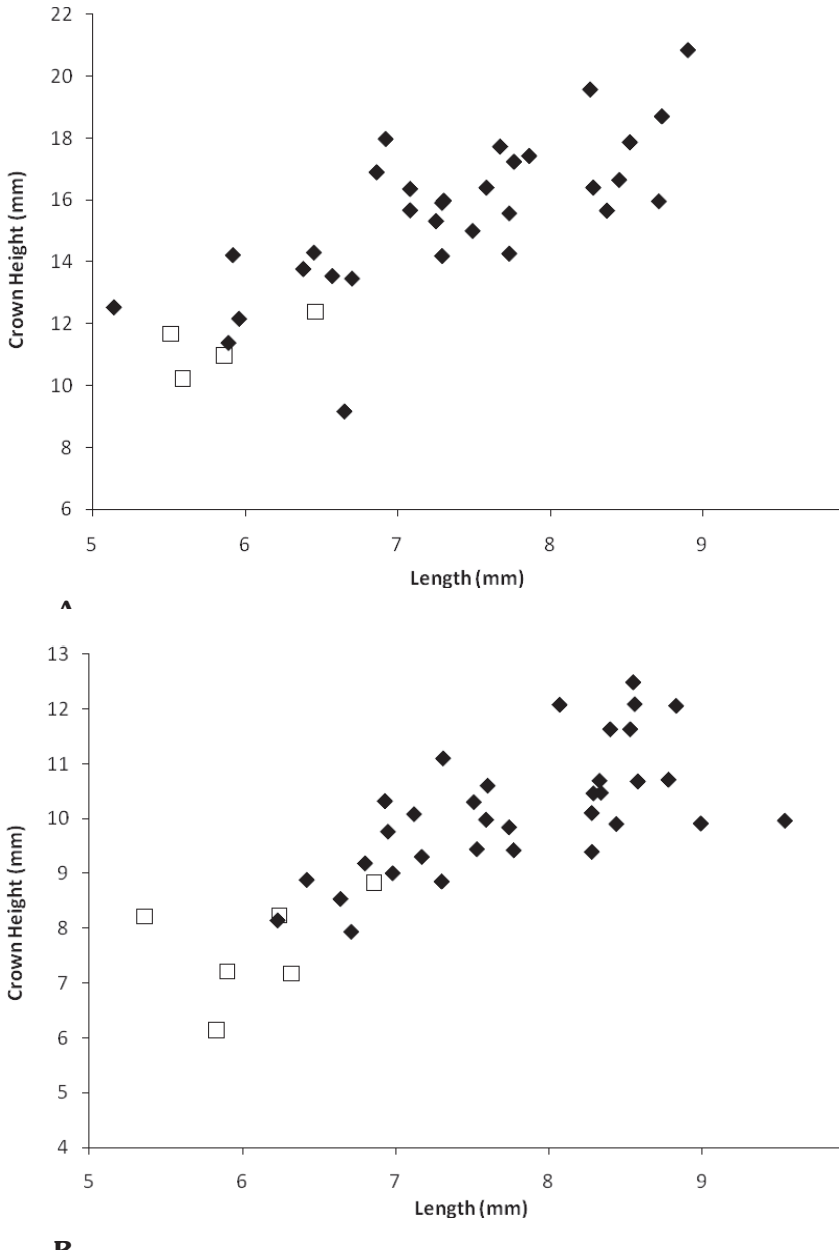
of the difference between male and female mean values. Crown height was plotted against length and width for both upper and lower canines.

## RESULTS

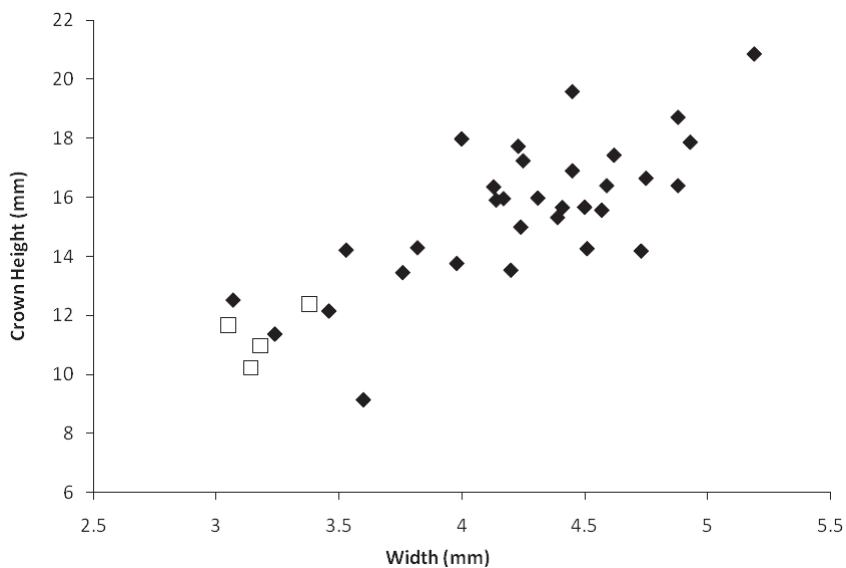
Summary statistics of the upper and lower canine dimensions (Table I) show range overlap; however, males are significantly larger ( $P < 0.001$ ) for each measurement. The mean values show the greatest difference between males and females for both the upper and lower crown heights. Upper and lower canine lengths in relation to crown heights are presented in Figures 1A and 1B. Upper and lower canine widths in relation to crown heights are presented in Figures 2A and 2B. In each figure, the overlap between large females and small males is clearly evident.

**Table I.** Upper and lower canine dimensions for the study sample of *Didelphis virginiana* from Baldwin County, Georgia. All measurements are in millimeters. UL = upper canine length, UW = upper canine width, UCH = upper canine crown height, LL = lower canine length, LW = lower canine width, LCH = lower canine crown height.

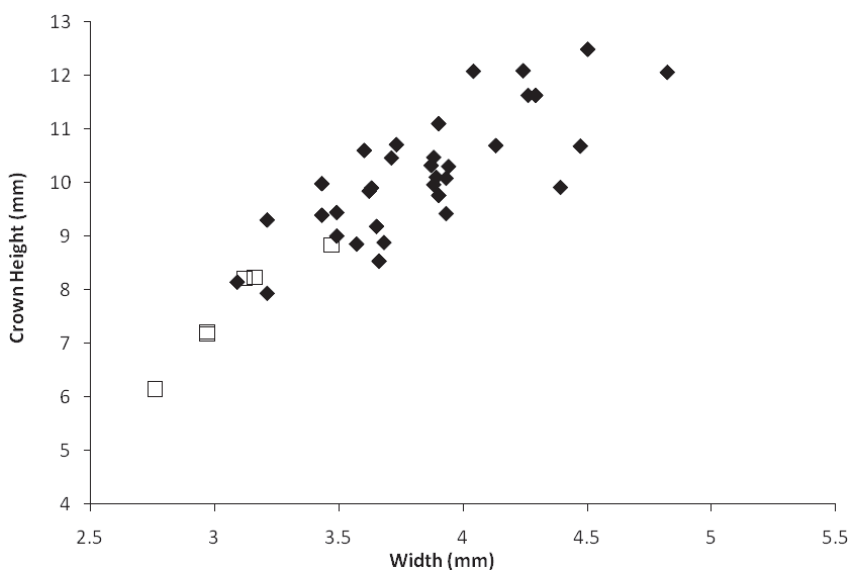
| Dimension | Sex | Mean  | N  | Range       | SD   | SE   | P      |
|-----------|-----|-------|----|-------------|------|------|--------|
| UL        | M   | 7.39  | 35 | 5.14-9.81   | 1.01 | 0.17 | <0.001 |
|           | F   | 5.85  | 6  | 5.51-6.46   | 0.37 | 0.15 |        |
| UW        | M   | 4.30  | 36 | 3.07-5.43   | 0.57 | 0.10 | <0.001 |
|           | F   | 3.20  | 6  | 3.05-3.38   | 0.13 | 0.05 |        |
| UCH       | M   | 15.57 | 32 | 9.16-20.85  | 2.41 | 0.43 | <0.001 |
|           | F   | 11.31 | 4  | 10.22-12.39 | 0.93 | 0.47 |        |
| LL        | M   | 7.72  | 40 | 6.23-9.54   | 0.83 | 0.13 | <0.001 |
|           | F   | 6/02  | 7  | 5.36-6.86   | 0.49 | 0.19 |        |
| LW        | M   | 3.83  | 39 | 3.09-4.82   | 0.37 | 0.06 | <0.001 |
|           | F   | 3.02  | 7  | 2.70-3.47   | 0.26 | 0.10 |        |
| LCH       | M   | 10.14 | 34 | 7.93-12.49  | 1.14 | 0.20 | <0.001 |
|           | F   | 7.63  | 6  | 6.14-8.83   | 0.97 | 0.40 |        |



**Figure 1.** Scatter-plots of A) upper canine lengths (UL) in relation to upper canine crown heights (UCH) and B) lower canine lengths (LL) in relation to lower crown heights (LCH) for the study sample of *Didelphis virginiana* from Baldwin County, Georgia. Males are represented with solid diamonds; females are represented with open squares.



**A**



**B**

**Figure 2.** Scatter-plots of A) upper canine widths (UW) in relation to upper crown heights (UCH) and B) lower canine widths (LW) in relation to lower crown heights (LCH) for the study sample of *Didelphis virginiana* from Baldwin County, Georgia. Males are represented with solid diamonds; females are represented with open squares.

## DISCUSSION

This analysis indicates that males within the Baldwin County population of *Didelphis virginiana* exhibit significantly ( $P < 0.001$ ) larger upper canine lengths, upper canine widths, upper canine crown heights, lower canine lengths, lower canine widths, and lower canine crown heights. Gardner (11) and McManus (12) reported that males engage in combative interactions, especially during mating season. This suggests that the sexually dimorphic nature of canines is likely the result of selection pressures associated with mate selection. Increased canine dimensions in relation to larger cranial proportions (7) would also amplify the likelihood of survival in aggressive interactions.

The Baldwin County sample of *Didelphis virginiana* is composed of 47 males and 12 females, suggesting that males are more highly active during the period of collection (January-March) (11, 13). Golley (14) found that mating season in Georgia peaked in February. Males range widely in search of mates, and thus increase their likelihood of being killed on roadways. This larger proportion of males would suggest a degree of sampling bias, however, the post cranial measurements for this sample (7) were consistent with those of Gardner's (9) much larger sample. The slight variation between the two populations could be accounted for by age class designation or museum sampling bias.

Although multiple studies (8, 10) have noted the sexually dimorphic nature of the canines within the Virginia opossum, none have analyzed them in a method independent of adult age class. Gardner (11) found little overlap in male and female dimensions of the same age class, and concluded that sex could be determined based upon length and width measurements. Within Gardner's age class 4, no overlap existed between male and female length dimensions, and within his age class 5 there was no height overlap. However, there was height overlap in age class 4 and length overlap in age class 5 making this sexing technique inaccurate without first knowing the age class.

As with most mammalian species, age determination in *Didelphis virginiana* is primarily based upon eruption and wear of the molars. In many biological circumstances, age class is nearly impossible to determine due to the fragmentary nature of the material, but the information provided by sex ratios is vital to understanding the dynamics of a population. This study supports Gardner's (11) findings, in that age class must be determined in order to positively identify the sex based on canine dimensions. However, with the information provided in this study, biologists can predict sex with a high probability of certainty in instances where age determination is not possible, but canine proportions are obtainable.

## ACKNOWLEDGMENTS

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provided by Kalina Manoylov, Heidi Mead and Dennis Parmley who read earlier drafts of this manuscript. In addition, this manuscript benefitted from the helpful suggestions of an anonymous reviewer.

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**AN ALLOMETRIC ANALYSIS OF ONTOGENETIC CHANGES  
(VARIATION) IN THE CRANIAL MORPHOLOGY OF LARVAE  
OF *HYDATICUS BIMARGINATUS* (SAY)  
(COLEOPTERA: DYTISCIDAE: DYTISCINAE)**

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**ABSTRACT**

Distortion coordinates (Cartesian Transformations) are used to compare the ontogenetic allometry in cranial morphology of first, second, and third instars of *Hydaticus bimarginatus* (Say). The most significant difference in the dorsoventral view is the expansion of the posterior lateral margins. Cranial expansion is likely due to an increase in the mass of the adductor muscles which are responsible for closing the mandibles. The ontogenetic shift in head orientation to a more subprognathic position evident in the analysis of lateral silhouettes indicates that second and third instars may be adapted to feeding on substrate associated prey. These differences are thought to reflect possible changes in prey regimes and habitat preference occurring during larval development.

**Key words:** *Hydaticus bimarginatus*; larva; crania; allometry; ontogeny, prey.

**INTRODUCTION**

Extra oral digestion (EOD) is a common feeding method employed by a variety of arthropod taxa (1), including a majority of dytiscid larvae (2). In this feeding method, the mandibles are utilized almost exclusively for prey capture, manipulation and consumption. This feeding strategy allows for the exploitation of larger prey than through "piece meal" consumption (1). Dytiscid larvae are obligatory and opportunistic predators, with prey selection limited principally by the size and shape of the prey (2; 3). This conclusion



has been reinforced by observations of larval predation *ex situ*, in which larvae can be propagated into adults by consuming prey that they may never encounter in nature. Although Tate and Hershey (4) attempted to mimic *in situ* prey regimes, their electrophoretic analysis of gut contents of various field caught dytiscid larvae never the less differed from those feeding exclusively in laboratory systems. Thus, prey consumed in laboratory environments may not accurately reflect prey exploited by larvae in natural systems.

Natural habitats of various dytiscid species may include prey components that are unique to their specific microhabitats and these differences in prey regimes are reflected in the variation in larval cranial morphology (5, 6). Due to the small, complex nature of dytiscid reproductive habitats and the small size of both the predator and prey, direct observations of predation in the field are difficult. However, based on the relative importance of mandibles in prey capture and manipulation, it is our belief that natural selection will shape cranial morphology and mandibular geometry to optimize the efficiency of the exploitation of food resources most often encountered and utilized in nature. Thus, observable differences in cranial morphology between species or instars may be interpreted as indications of differential exploitation of *in situ* prey regimes (5, 6).

Numerous descriptive studies have shown that significant inter- and intra-specific variation in cranial (7, 8, 9, 10) and mandibular (11) morphology is present in Dytiscidae. There have been comparatively few studies dealing with allometric change in larval insects and only one (6) was focused on a dytiscid species. In this study significant ontogenetic changes in dorsoventral cranial morphology were shown for larvae of *Agabus disintegratus* (Crotch) by using distortion grid transformation analysis. These variations were interpreted biomechanically as adaptations that would allow instars to exploit different prey regimes. However, this study focused exclusively on the dorsoventral morphological transformations. Few studies describing lateral head morphology in dytiscid larvae have been attempted (e.g., 12, 13) and none has compared shifts in lateral cranial architecture among instars.

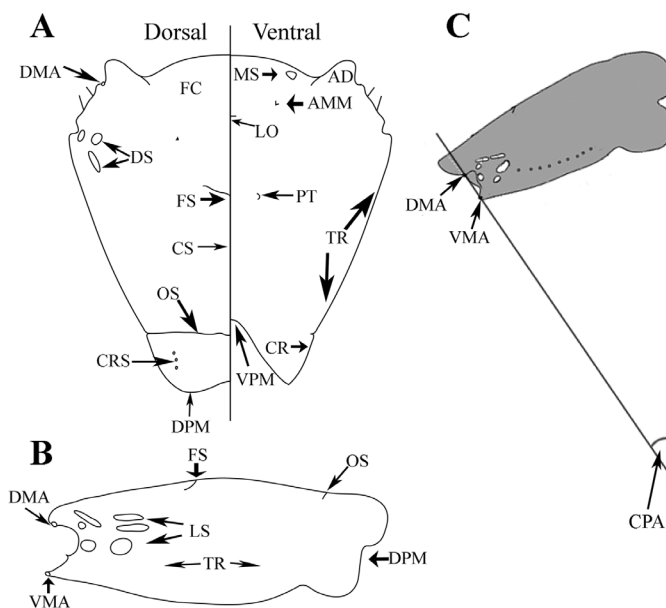
*Hydaticus bimarginatus* (Say) is determined to be more advanced phylogenetically (14) than *A. disintegratus* which was evaluated by Brannen *et al.* (6). Thus, the objectives of this study were to: (1) utilize distortion grid analysis to describe and compare dorsoventral and lateral ontogenetic cranial morphology of first, second and third instar larvae of *H. bimarginatus*; (2) evaluate the biomechanical implications of modifications in cranial architecture to infer differences in prey regime composition.

## MATERIALS AND METHODS

Morphological observations were performed on larvae collected between 30 June and 15 September 2004 from an ephemeral habitat in Bibb County (N 32° 52.033', W 83° 47.999'), Georgia, USA and identified as *H. bimarginatus* by culture into adults by Jackson *et al.* (15). First and second instars were identified by an association with these mature larvae.

Heads of first (n=6), second (n=10), and third (n=9) instars of *H. bimarginatus* were measured dorsally along the coronal suture from the posterior margin of the cranium to the distal margin of the frontoclypeus, excluding the frontoclypeal sensilla to determine lengths (HL). Head widths (HW) were measured dorsally at the widest point. The mandibular length was calculated by measuring ventrally from the center of the articulation to the mandibular apex (11). Head length ratios were determined by dividing head length (HL) by head width (HW). Gape was measured ventrally from the center of each mandibular ball that articulates with the cranium. Intermandibular ratios were as calculated by dividing intermandibular distances (ID) by head lengths (HL) and widths (HW). Brooks-Dyar indices (16) of dimensional change between first and second instars and second and third instars of *H. bimarginatus* were computed for cranial lengths, widths, and intermandibular distances.

Dorsoventral (Fig. 1A) and lateral silhouettes (Fig. 1B) were drawn for crania of first, second, and third instars of *H. bimarginatus* using images from a WILD M5A dissecting microscope equipped with a Camera Lucida and digital images were taken with a Canon D60 digital camera attached to a Meiji RZ trinocular scope. For placement of dorsal and ventral landmarks, specimens were observed in depression slides up to 400X magnification. Lateral measurements and landmarks were determined by placing specimens in a depression slide cradled in a wax channel for increased stability and to control precision of positioning. In addition to the cranial outlines, dorsoventral landmarks included: cervical sensilla, origin of the coronal suture, egg bursters, dorsal mandibular articulations, origin of occipital suture, corneal lenses (17) one, two and three (18), anteromaxillary margins, cervical notches, and tentorial pits on the venter. The lateral landmarks included: origin of occipital suture, mandibular articulations, temporal spines, and corneal lenses (18). Dorsal and ventral cranial structures were combined in each dorsoventral silhouette. The cranial positional angle (CPA) of all three instars was calculated from lateral silhouettes. Independent line segments were drawn through the mandibular articulations and tangent to the cervical region. The angle where these two segments intersected was measured (Fig. 1C).



**Figure 1.** Dorsoventral (A) and lateral (B) views of a *Hydaticus bimarginatus* Say first instar showing internal landmarks used in distortion grid analyses. Legend: AD, adnasale; AMM, anterior maxillary margin; CS, coronal suture; CRS, cervical sensilla; CR, cervical region; DMA, dorsal mandibular articulation; DPM, dorsum of posterior margin; DS, dorsal corneal lenses; FS, origin of frontoclypeal suture; LO, labial margin origin; LS, lateral corneal lenses; MS, mandibular scar; OS, occipital suture; PT, posterior tentorial pit; TR, temporal region; VMA, ventral mandibular articulation; and VPM, ventral posterior margin. Technique (C) for computation of cranial positional angle (CPA, see materials and methods).

Thompson (19, first published in 1917) established the distortion grid method used for this study. This procedure employs a grid system over-laying either the assumed basal taxon (evolutionary allometry) or a preceding instar of the same species (ontogenetic allometry). A grid with lines of constant length and distance in both vertical and horizontal planes was superimposed over the dorsal and lateral illustration of the first instar head using Adobe Illustrator 10. Positioning of a grid over cranial illustrations of subsequent instars required distortion of the lines in order to maintain their relative position with respect to specific morphological landmarks present in the previous instar. Interpretation of these distortion grids was used to assess ontogenetic changes in cranial architecture occurring during larval development.

## RESULTS

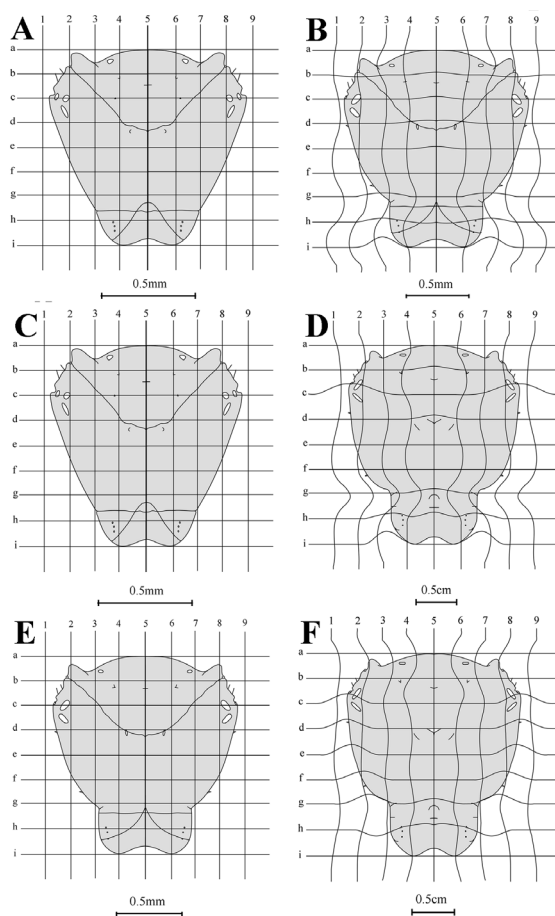
There were no significant differences between head length-width ratios (HL/HW) of first ( $\bar{x} = 1.10 \pm 0.05$ ) and second ( $\bar{x} = 1.12 \pm 0.02$ ) or third instars ( $\bar{x} = 1.13 \pm 0.03$ ) of *H. bimarginatus* ( $p > 0.05$ ). HL/HW ratios between the second and third also showed no significant differences ( $p > 0.05$ ). Both proportional intermandibular distances computed against head width (ID/HW) and head length (ID/HL) appear to decline during the transition between the first and second stadia (Table I). However, these differences were not significant ( $p > 0.05$ ). Brooks-Dyar indices (Table I) computed for increases in intermandibular distance ( $ID_1/ID_2$  and  $ID_2/ID_3$ ) were 0.65 from the first to the second and 0.69 from the second to the third. Comparable to indices computed for width ( $HW_1 \rightarrow HW_2 = 0.65$ ;  $HW_2 \rightarrow HW_3 = 0.69$ ) but not for length, which showed a small decrease in length ( $HL_1 \rightarrow HL_2 = 0.70$ ;  $HL_2 \rightarrow HL_3 = 0.69$ ).

**Table I.** Selected dorsoventral cranial dimensions (in mm) and proportions for first, second and third instars of *Hydaticus bimarginatus* (Say).

| Instar | Head Length (HL) | Head Width (HW) | Mandible Length (ML) | HL/HW       | Gape (GA)   | ID/HL       | ID/HW       |
|--------|------------------|-----------------|----------------------|-------------|-------------|-------------|-------------|
| First  | 1.23 ± 0.03      | 1.03 ± 0.02     | 0.63 ± 0.02          | 1.10 ± 0.05 | 0.83 ± 0.03 | 0.73 ± 0.03 | 0.81 ± 0.01 |
| Second | 1.77 ± 0.05      | 1.58 ± 0.05     | 0.95 ± 0.03          | 1.12 ± 0.02 | 1.27 ± 0.06 | 0.71 ± 0.03 | 0.80 ± 0.03 |
| Third  | 2.58 ± 0.09      | 2.28 ± 0.08     | 1.33 ± 0.07          | 1.13 ± 0.03 | 1.83 ± 0.08 | 0.71 ± 0.03 | 0.80 ± 0.01 |

The dorsoventral cranial architecture of each of the three instars of *H. bimarginatus* varied with the most pronounced differences occurring in the posterior regions. The silhouette of the first instar is trapezoidal in shape with its maximum width between line segments b and d (Fig. 2A). A cervical region is present, delimited by a weakly developed constriction near line segment h. Corneal lens three is fully visible on the dorsum. The silhouette of the second instar differs significantly from the first (Fig. 2A & B) in that the posterior-lateral margin between segment d and f is expanded and curved. The cervical region is compressed laterally between segments f and h. There is expansion laterally along the midline (segment 5) and laterally in the frontoclypeal region. Corneal lens three has a more lateral position. The third instar cranium of *H. bimarginatus* continues the trends observed when comparing the first to the third (Fig. 2C & D). However, the posterior-lateral margin expansion and constriction of the cervical region is more extensive. When comparing

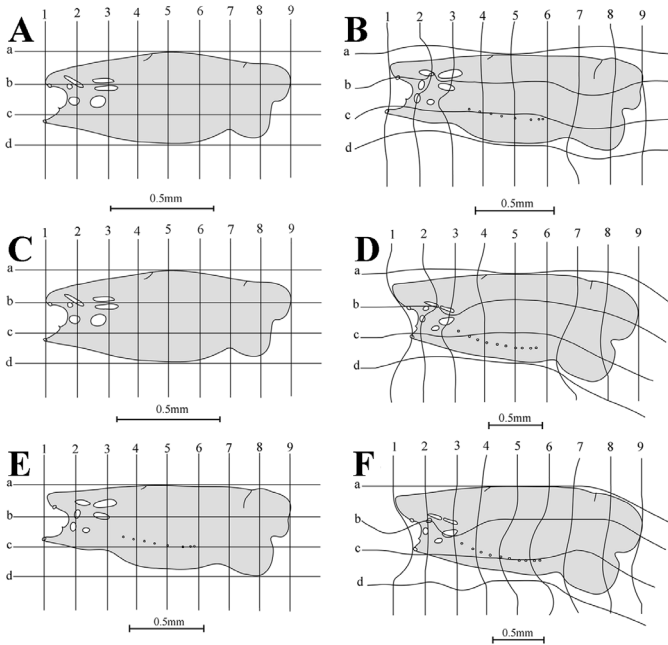
the second to the third instar, the horizontal variation between instars is less significant (Fig. 2 E & F). However, there is considerable vertical expansion of the lateral margin between segments c and g.



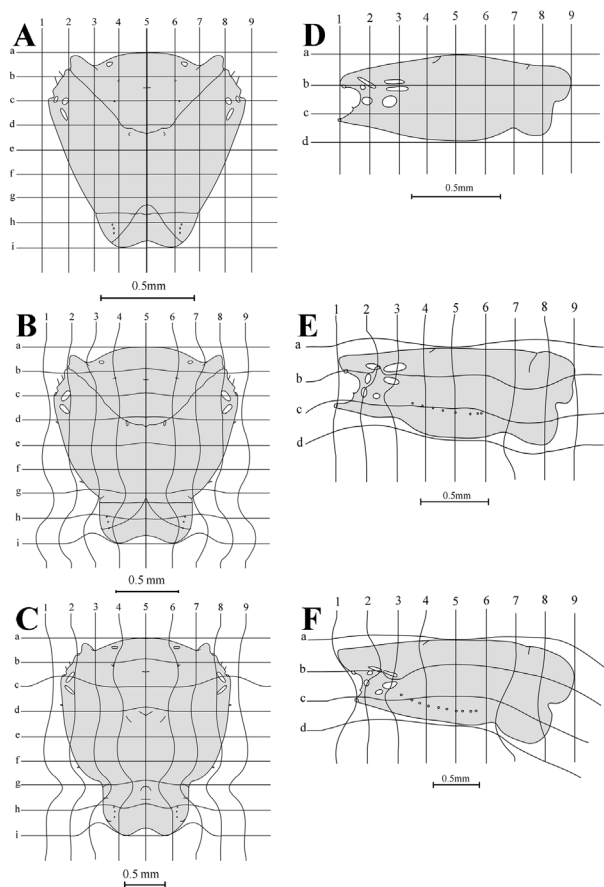
**Figure 2.** Distortion grids comparing dorsoventral silhouettes of *Hydaticus bimarginatus* (Say) first (A) and second instars (B); first (C) and third instars (D); and second (E) and third instars (F).

The lateral silhouettes (Fig. 3) also indicate significant changes in cranial architecture during development. The maximum depth of the first instar is located near the center of the cranium, at line segment 5. In the second and third instars the maximum depth has shifted posteriorly so that it is between segments 5 and 6. There has also been an increase in the depth of and changes in the orientation of the cervical region (Fig. 3; posterior to coordinates 7-a to 7-d). The ventral mandibular articulations are located slightly

anterior to the dorsal articulation on both the first and second instars. However, the ventral articulations of the third instar have moved posteriorly; almost in vertical alignment with the dorsal articulation (Fig. 3). Cranial positional angles (CPA) computed (Fig. 1C) for first and second instars were  $19^\circ$  and  $12^\circ$  respectively far smaller than the  $37^\circ$  estimate for the mature larva. As with the dorsoventral analyses, when comparing the lateral view of second and third instars we do not see as significant a change as when comparing the first to second or first to third (Fig. 4).



**Figure 3.** Distortion grids comparing lateral silhouettes of *Hydaticus bimarginatus* (Say) first (A) and second (B) instars; first (C) and third instars (D); and second (E) and third instars (F).



**Figure 4.** Distortion grids comparing dorsoventral (A-C) and lateral (D-F) silhouettes of *Hydaticus bimarginatus* (Say). Comparisons are first to second (AB; DE) and first to third (AC; DF).

## DISCUSSION

The analysis demonstrates that significant changes in cranial architecture are occurring during larval development of *H. bimarginatus* (Fig. 4). The successive dorsoventral transformation of *H. bimarginatus* is similar to that of *A. disintegratus* (6). Changes in the posterior and temporal cranial regions appear to be responses to accommodate subsequent and disproportional increases in the mass and volume of the mandibular adductor muscles, which serve to close the mandibles. The adductor muscles originate on large areas of the posterodorsal, posteroventral, and lateral interior walls of the head (20, 21, 22). The adductor muscles occupy a considerable portion of the cranial cavity, where the most significant dorsoventral ontogenetic changes

occur (6). An increase in the adductor muscle size would serve to increase the out force applied at the mandible tip. Conversely, smaller adductor muscles would signify that the larvae would have a lesser out force at the mandible tip. The trapezoid shape of the head of the first instar is due to the smaller size of the adductor muscle mass indicating this larval stage is adapted for feeding on delicate prey. The expansion of the posterior lateral margin of the second and third instar is most likely due to an increase in the adductor muscles, allowing the larvae to consume more robust prey. Thus, the prey regime composition of the first stadium may be significantly different from that of the second and third stadia. These results also suggest that while size may be an important factor in prey selection by dytiscid larvae, prey resistance to capture may be a significant factor as well.

Changes in the lateral morphology of *H. bimarginatus* also suggest a shift in the prey regime during larval development. The change from the almost classical prognathous cranium (20) of the first and second instars to a cranial orientation that is almost intermediate between prognathic and hypognathic conditions (subprognathic, 5) in the mature larva is notable. The pronounced subprognathic orientation of the third instar cranium may be an adaptation to feeding on organisms most often found on a habitat substrate (e.g., leaves or sediments) below the long axis of the *H. bimarginatus* body. An apparent shift in the position of the fourth corneal lens to a more ventral position also supports this hypothesis. A subprognathic declination angle was described for the mature larvae of *Coptotomus lenticus*, which were collected at or near the bottom of its habitat (23). This subprognathy would potentially allow mature larvae to locate and exploit substrate surface dwelling prey more effectively. In contrast to this subprognathic species, *Thermonectus basillaris* (Harris) is somewhat hyperprognathous (5) with the first and third corneal lenses greatly enlarged and dorsally orientated, suggesting that this taxon is more suited for feeding in the open water column or at or near the water's surface (24).

Dorsoventral ontogenetic development in the anterior regions of crania of *H. bimarginatus* is nearly isometric, including intermandibular distances (Table I). Intermandibular distance (ID) is interpreted as an approximation of gape, the maximum distance between the mandibular apices when larvae are poised to strike. This is an important factor in dytiscid larval feeding because an increase in gape would allow the larvae to consume larger prey. The ontogenetic increase in gape suggests that the prey consumed is also increasing in size. However, noticeable variation in the cranial architecture of *H. bimarginatus*, specifically positive allometric growth in the posterior and temporal regions, is present. These accommodations are thought to be a response to an increase in the adductor muscles, which close the mandibles.

In summary, if previous studies are correct in assuming that dytiscid larvae are generalist and opportunistic predators and that competition is minimal, then there should be little variation in profiles of dytiscid cranium. However, this study shows that significant ontogenetic change in cranial architecture



occurs during larval development of *H. bimarginatus* in both dorsoventral and lateral profiles. The biomechanical interpretation of these changes suggests that the degree of resistance offered by prey to capture and feeding by larvae of *H. bimarginatus* may be an important selective force in determining cranial architecture. Changes observed also indicate that second and third instars may occupy different microhabitats than do first instars. Thus, the prey regime encountered by later instars would be significantly different than those exploited by first instars. Although this morphological variation does not permit identification of specific prey, it does suggest that larval prey regimes are far more complex than previously thought. Habitat preference studies and analysis of ontogenetic mandibular variation among instars are needed in order to fully understand the degree to which these instars partition their food resources.

### ACKNOWLEDGEMENTS

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## EFFECT OF FORMATION HYDRODYNAMICS ON MECHANICAL PROPERTIES OF CONTAINER MATERIALS

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### ABSTRACT

The objectives of this study were to compare the mechanical and physical properties of the sheets made using the Vortigen technology (a non-conventional technique that creates very high number vortices in a fluid flow mixture of water, fibers, and chemical additives) with those produced from a conventional method of papermaking and to provide insight into the impact of formation hydrodynamics on sheet properties. The results of formation, ultrasonic stiffness, and creep/accelerated creep measurements of the Vortigen sheets as compared with the standard sheets are presented. Samples of Vortigen (V) and standard (S) sheets (4 samples from each group) were obtained from papers produced on a pilot machine. Formation measurements (that provides a measure of density distribution in a sheet) were performed using a formation tester which is based on beta particle absorption. Measurements of creep and accelerated creep were made at a constant relative humidity (RH) of 80% and a cyclic RH between 30% and 80% for strips cut along the machine direction (MD) and cross machine direction (CD, which is perpendicular to MD) directions.

There was a significant difference between the distributions of basis weights for the two types of papers. The mean coefficient of variation in grammage for the V samples was 8.97 while that for the S samples was 12.60. The mean MD/CD stiffness ratios for the V and S samples were 1.1 and 1.6, respectively. The mean Z-direction longitudinal specific stiffness corresponding to the V samples were 18% greater than the corresponding value for the S samples. The MD strips from the S samples exhibited the smallest creep while the CD strips from the S samples exhibited the largest creep. Creep values corresponding to the Vortigen sheets were between the extreme values of the standard samples. The results of this study indicated that because of the influence of formation hydrodynamics on fiber orientation and formation, in general, the stiffness properties (and specifically the CD stiffness) of the Vortigen samples were greater than those of the standard samples.

**Key words:** physical properties, paper physics, creep, stiffness measurements, image analysis, ultrasonic techniques.

## INTRODUCTION

Vortigen technology focuses on improvement of formation in paper products, specifically in high basis-weight (mass per unit area) papers used for paperboard making. The mechanism of formation improvement using the Vortigen technology is described elsewhere [1], and is based on modification of the conventional head-box tubes by replacing them with a specific tube design that produces multidirectional flow of fiber suspension due to the effect of turbulent forces which have components in all three directions (MD, CD, and ZD being along out of plane direction). This technique results in a relatively uniform orientation distribution of fibers, thus, an isotropic sheet [2]. It has been reported that as a result of this improvement, many of the physical and mechanical properties of a sheet are improved. If this is the case, a significant economic advantage (e.g., saving in product cost per unit of strength) in paperboard products is anticipated. The head-box of a conventional paper machine is composed of straight tubes that produce a unidirectional stock flow (mixture of water, fibers, and chemical additives) pattern and result in a preferential orientation of fibers along the machine direction (MD). Aidun [1] has demonstrated that streaks on the forming table in a conventional paper machine which are caused by nonuniform secondary flows in the head-box as well as fluid dynamics of the free surface flow on the forming table are responsible for development of certain type of small-scale non-uniformities in basis weight, moisture, and stiffness properties. This study was conducted to characterize mechanical and physical properties of the sheets made by the Vortigen technology and compare them with those made by the conventional methods of papermaking (using a conventional head-box).

## MATERIALS AND METHODS

Fully restrained dried samples were obtained from Vortigen and Standard sheets produced on a pilot machine operating at a speed of 573 m/min. After conditioning, physical and mechanical properties corresponding to four samples (two circular and two rectangular sheets) from each paper type were measured and analyzed. The mean basis weight and mean density for Vortigen and standard samples were 107 g/m<sup>2</sup> and 109 g/m<sup>2</sup>; and 0.83 g/cm<sup>3</sup> and 0.79 g/cm<sup>3</sup>, respectively. The following equations were used to calculate the distribution of basis weight using a formation tester based on beta particle counts:

$$w = w_{avg} \frac{\ln (\beta_i / \beta_{air})}{\text{avg}[\ln (\beta_i / \beta_{air})]} \quad (1)$$

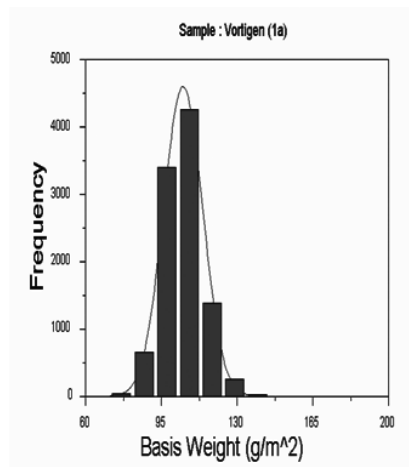
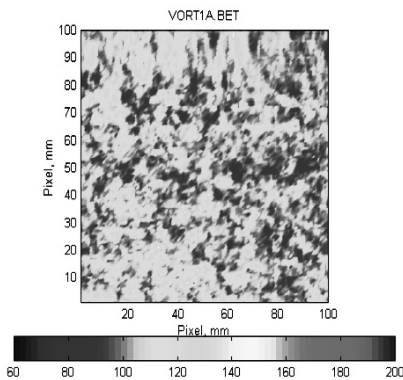
where

$$\text{avg}[\ln (\beta_i / \beta_{air})] = \frac{\sum_{i=1}^n [\ln (\beta_i / \beta_{air})]}{n} \quad (2)$$

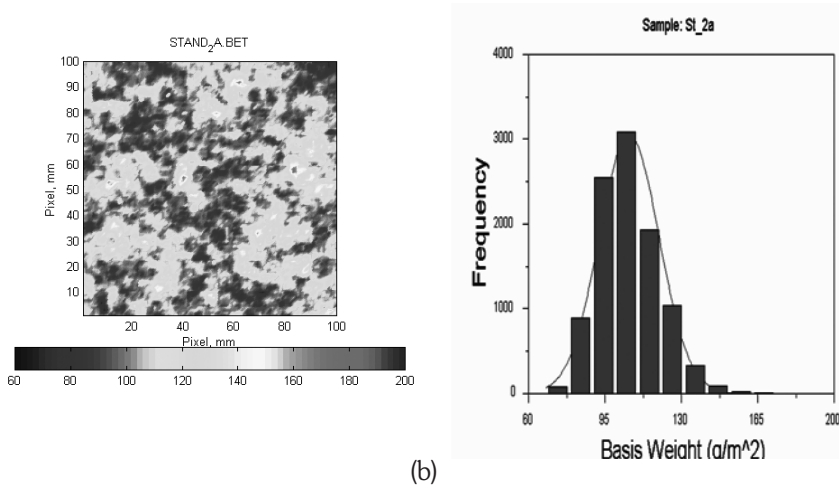
In the above equations  $w_{avg}$  is the average basis weight,  $\beta_i$  and  $\beta_{air}$  are beta counts at a point on a paper sample and that corresponding to air respectively,  $n$  is number of points on the sample at which beta counts were obtained. A computer program in MATLAB was developed that reads the matrix of beta counts created by the formation tester and applies equation (1) to generate a two-dimensional color image and a histogram corresponding to the distribution of basis weight. Stiffness properties were measured using ultrasonic technique. Creep and accelerated creep were determined at a constant relative humidity (RH) of 80% and a cyclic RH between 30% and 80% for strips cut along the MD and CD directions of each sheet according to methods described in previous studies [3-6].

## RESULTS

Shown in Figure 1 are the results of formation measurement performed using a beta particle absorption technique (distribution of  $w$  in equation 1) for a sheet of paperboard made by the Vortigen technology and a standard sheet with approximately the same value of average basis weight.

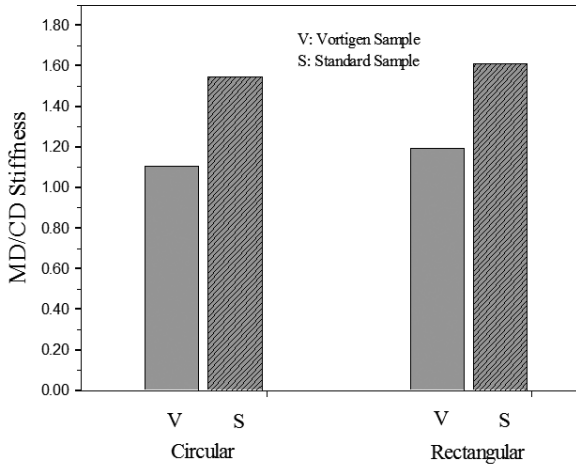


(a)

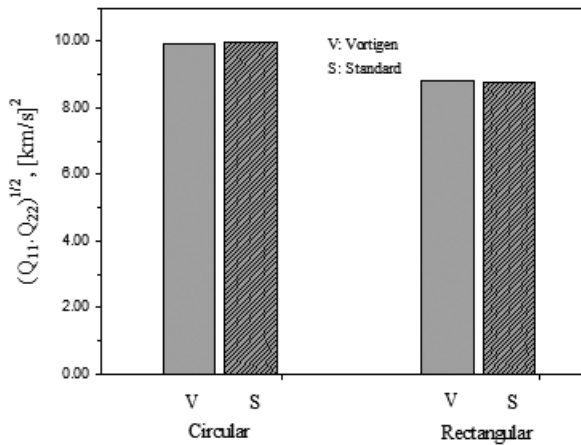


**Figure 1.** Comparison between images obtained from mass formation measurement for a Vortigen sheet (a) and a standard sample (b).

Note that the Vortigen sheet has a narrower band than the standard sheet. The mean coefficient of variation in basis weight for all Vortigen samples was 8.97 while that for the standard samples was 12.60. Shown in Figures 2 and 3 are the mean values of elastic stiffness ratio and geometric mean of in-plane elastic stiffness for Vortigen and standard sheets, respectively. Figure 2 shows that the Vortigen samples had similar elastic stiffness along the in-plane directions.



**Figure 2.** Mean stiffness ratio for circular and rectangular sheets corresponding to the Vortigen and standard samples.

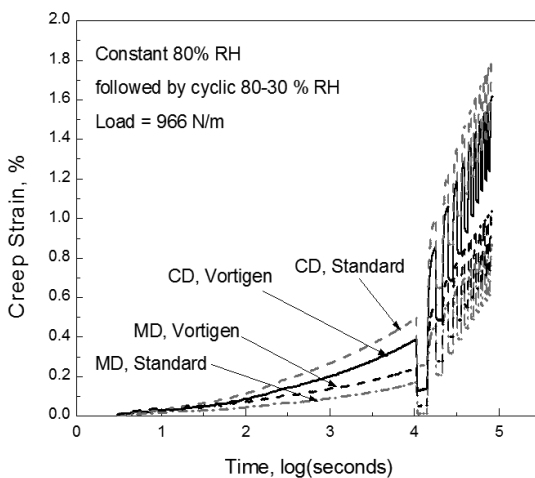


**Figure 3.** Geometric mean of in-plane elastic stiffness for circular and rectangular sheets corresponding to Vortigen and standard samples.

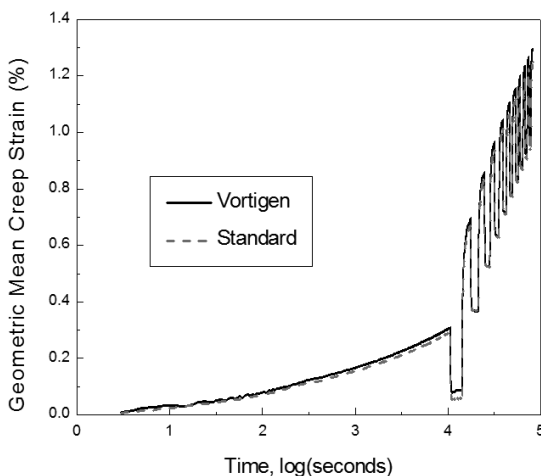
A tensile creep test was conducted for MD and CD samples for both sheets subjected to a constant relative humidity (RH) of 80% then followed by a cyclic RH between 80 and 30% RH. All tests were carried out at the same load level. The results, shown in Figure 4 indicates that the smallest and the largest creep values corresponds to the MD standard and the CD standard, respectively. The creep values of Vortigen sheets measured along



the CD and MD directions were between the two extreme values corresponding to the standard samples. Interestingly, the geometric mean creep response (Figure 5) for both sample types are the same in both the constant and cyclic regimes.



**Figure 4.** MD and CD creep curves for Vortigen and standard sheets.



**Figure 5.** Geometric Mean Creep response for Vortigen and standard sheets.

## **CONCLUDING REMARKS**

1. In paper making process using a conventional head-box, the hydrodynamic forces involved in the forming process tend to orient the fibers along the machine direction (MD). In a head-box retrofitted with the Vortigen system, the flow characteristics in the forming process are modified to create shear in the mean flow and turbulent fluctuations along the cross machine (CD) and out of plane (ZD) directions to improve fiber dispersion and to control fiber orientation. This creates a sheet with more isotropic fiber orientation, superior formation, and consequently higher strength properties along in-plane cross-machine direction.

2. The results show that compared to a standard forming system, a sheet with the same basis weight produced with the Vortigen system has a higher number of fibers orientated along the CD direction resulting in both higher CD elastic stiffness and CD creep stiffness. Since the geometric mean stiffness and the geometric mean creep response were equivalent for both sheet types, it appears that the increase in strength along the CD in a Vortigen sheet is obtained by transferring part of the strength from the machine direction to the cross machine direction. However, since paper generally fails at its weakest link, making the sheet more uniform and isotropic would be very beneficial; specifically in linerboards in which a great portion of functional loads are generally exerted along the cross machine (CD) direction.

## **ACKNOWLEDGEMENTS**

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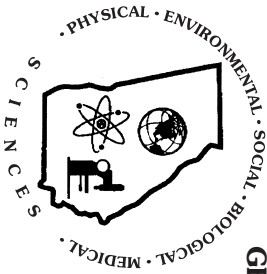
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