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Modeling the effect of convex upward sediment deformation and horizontal core sectioning on paleolimnological data

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Modeling the effect of convex upward sediment deformation and horizontal core sectioning on paleolimnological data

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Abstract

We analyzed photos of convex upward deformation in split sediment cores to obtain reasonable parameters with which to model the effect of convex upward deformation on paleolimnological data. Using a 3-dimensional raster model, we modeled the effect of this deformation on a hypothetical dataset. Model results indicated that convex upward sediment deformation integrates samples from an increasingly broader range of stratigraphic layers with an increasing degree of deformation. After applying deformation, extruded concentration profiles were nearly identical, despite varying the extrusion interval between 0.1 cm and 1 cm, suggesting there is a limit to the resolution that can be attained by horizontal sectioning if deformation occurred during sampling. Our data suggest that it is essential to determine the degree of sediment deformation caused by coring prior to conducting high-resolution analyses on horizontally sectioned samples.

Keywords: Sediment coring, Deformation, 3D Model, Extrusion, Stratigraphy

Introduction

Deformation of lake sediment during the coring process has long been recognized (Martin and Miller 1982; Wright 1993; Glew et al. 2001) and coring equipment has been designed in an attempt to minimize the conditions that promote deformation during coring (Martin and Miller 1982; Lane and Taffs 2002). Glew et al. (2001) provided a detailed examination of the forces that act on sediments as a result of coring, including displacement of sediment during core tube penetration that results in core shortening. Convex upward sediment deformation, although commonly observed (Wright 1993; Rosenbaum et al. 2010), is rarely discussed. Kegwin et al. (1998) noted a radial bias in paleomagnetic data from Ocean Drilling Program (ODP) piston cores and proposed a logarithmic function to model the observed deformation. Aubourg and Oufi (1999) noted development of a "conical fabric" as a consequence of "edge smearing" in soft sediments, also in relation to paleomagnetic data from ODP piston cores. Acton et al. (2002) revised the logarithmic function proposed by Kegwin et al. (1998) and created a model to correct paleomagnetic data for this bias. The logarithmic function proposed by Kegwin et al. (1998) is a function of radius (r), core barrel radius (R), and degree of deformation (b).

$$(1)\quad Z(r) = -b\left(ln(1-\frac{r}{R}) + \frac{r}{R}\right)$$

Acton et al. (2002) estimated the b parameter of the equation is generally less than 0.2, but can range up to 0.4 in ODP piston cores (Fig. 1).

When deformed sediment is sectioned horizontally, adjacent strata are incorporated into each sampled section (Fig. 2). Rosenbaum et al. (2010) noted that horizontal sectioning (extrusion) of deformed sediment is not ideal, however the degree to which this deformation occurs and the effect of deformation on paleolimnological data has not been investigated quantitatively. We suspect, given the large number of paleolimnological studies that use coring and extrusion to produce reproducible results, that deformation, or its effect on the data, is minimal. This paper attempts to quantify and constrain the degree to which convex upward deformation biases paleolimnological data from horizontally sectioned cores.

Materials and methods

We used R statistical software (R Core Team 2013) to model, manipulate, and visualize our data. Packages *dplyr* and *ggplot2* were used to manipulate and visualize data, respectively (Wickham et al. 2016; Wickham and Francois 2016).

Core photo analysis

To obtain reasonable parameters for b in our deformation function (Acton et al. 2002), we loaded 12 scale photos of deformed cores from six sources into image analysis software and digitized deformed strata (Table 1). We performed a regression on the digitized coordinates to estimate the degree of deformation (b) for each layer.

Deformation model

We modeled horizontal sections with height H and diameter D as a 3-dimensional raster grid with a cell size of 0.5 mm (Fig. 3). For each cell i, an original depth d_{0i} (i.e. depth prior to convex upward deformation) was calculated, with a reasonable range of b parameters obtained from digitized strata. Density histograms were then produced to estimate the contribution of adjacent strata (represented by the original depth d_0) to the slice. For each slice, d=0 refers to the middle of the slice. We produced these models for D=6.5 cm, as this represents the barrel width of our Glew (1989) gravity corer. More complex deformation was not modeled using this method, although the model could be modified to enable inclusion of more complex deformation.

Effect on paleolimnological data

To model the concentration (mass fraction) we would obtain by sectioning and homogenizing a sample with variable concentration and density, we needed to calculate the total mass of the target substance divided by the mass of the slice. With a 3-dimensional raster grid that uses n cells, this value can be written as a sum of the product of concentration (w), density (ρ), and volume (V) divided by the sum of the product of V and ρ (2).

$$(2) \quad w_{avg} = \frac{\sum_{i=1}^{n} w_i \rho_i V_i}{\sum_{i=1}^{n} \rho_i V_i}$$

We can remove V_i from the summation in both the numerator and denominator because the cell size is constant for each i, and write w and ρ as functions of d_{0i}.

$$(3) \quad w_{avg} = \frac{\sum_{i=1}^{n} w(d_{0i}) \rho(d_{0i})}{\sum_{i=1}^{n} \rho(d_{0i})}$$

Equation (3), in combination with our deformation model, enables modeling the effect of sectioning, homogenization, and deformation, given high-resolution, un-altered data. We used a generated dataset to test our deformation model, designed to resemble 1-mm-resolution XRF core scanner data (Guyard et al. 2007; Brunschön et al. 2010; Kylander et al. 2011), and a linear dry density gradient from 0.1 to 0.5 g/cm^3. Generated data were transformed, smoothed, random log-normal data, with a set seed for replicability purposes.

Results

Core photo analysis

We digitized 49 deformed layers from 12 scale photos of split cores. The logarithmic function modeled most layers well (median r^2 of 0.84), but some layers poorly. This suggests that deformation forces other than those modeled by the logarithmic function also act on sediments during coring, and that these forces may not be applied predictably. The b coefficient ranged from 0.15 to 5.24, with a median of 0.78 (Fig. 4). We chose 0, 0.5, 1, and 2 as coefficients for our model to produce a reasonable summary of the deformation that was observed (Fig. 5). Many analyzed photos of deformed cores were of cores collected by percussion coring, which can produce intense, convex upward deformation (Reasoner 1993), however photos of split gravity cores also contained observable deformation.

Deformation model

Slice thicknesses of 0.1 cm, 0.5 cm, and 1 cm were modeled with a core-barrel diameter of 6.5 cm. When d=0, d_0 values ranged from 0 cm to -4 cm and were more negative with increasing deformation (Figs. 6 and 7). Slices represented a wider range of d_0 values with increasing deformation (Figs. 7 and 8), and when deformation was >0.5, slices smaller than 1 cm did not decrease the range of d_0 values. In the model, d_0 values of high magnitude were concentrated in the outer few millimeters of the section.

Effect on paleolimnological data

As expected, increasing the thickness of the extrusion interval decreased the detail visible in the data (Fig. 9). The original data include thin (<0.5 cm) layers of high concentration (>60 units), only some of which were resolvable at extrusion intervals greater than 1 mm. Peak values were lower with increasing extrusion interval size, reflecting the inclusion of less concentrated material within the interval. High values in the topmost sample are an artifact of the model; it is likely that the effect of deformation at the top of the core differs from the effect of deformation deeper in the section. Increasing the degree of deformation also decreased the ability to resolve high-concentration layers, decreased the peak concentration, and also resulted in increasing the depth at which peak values were observed. When deformation occurred, decreasing the extrusion interval size did not result in increasing the effective resolution of the data. In particular, extrusion intervals of 0.1 cm and 0.5 cm produced nearly identical results when any deformation was applied in our model.

Conclusions

The model indicates that even minimal convex upward deformation has an effect on paleolimnological data. Even when deformation was small, reducing the extrusion interval did not result in an appreciable difference in the paleolimnological data (Fig. 9) or decrease the range of depths represented by the slice (Fig. 8). Extrusion methods can produce sediment intervals of less than 0.1 cm (Cocquyt and Israël 2004). Our data, however, suggest that reducing the extrusion interval does not increase the effective resolution of the data if sediments were deformed by coring. The data also suggest that it is essential to check for deformation caused by coring before conducting high-resolution analyses of horizontally sectioned samples, and that eliminating the outer several millimeters of extruded core sections may mitigate the effects of deformation. We recognize the limits of applying a simple idealized model to cases where many deformation forces exist. We leave the modeling of more complex deformation to future investigators.

Acknowledgements

We acknowledge funding from the Natural Sciences and Engineering Research Council (NSERC) of Canada, the insightful comments on this manuscript from both anonymous reviewers, and Mark Brenner for editorial handling.

Tables

Table 1 Sources of core photos that contained digitized layers used in this study

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ds_unpubl2	2	Dunnington and Spooner (unpublished data)	Gravity
ds_unpubl3	1	Dunnington and Spooner (unpublished data)	Gravity
ds_unpubl4	1	Dunnington and Spooner (unpublished data)	Gravity
longlake_pc1	1	White (2012)	Percussion
suzielake_1	4	Spooner et al. (1997)	Percussion
suzielake_2	9	Spooner et al. (1997)	Percussion
whistler_gc4	1	Dunnington (2015)	Gravity
whistler_gc8	1	Dunnington (2015)	Gravity

Figures

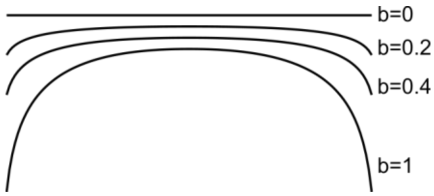
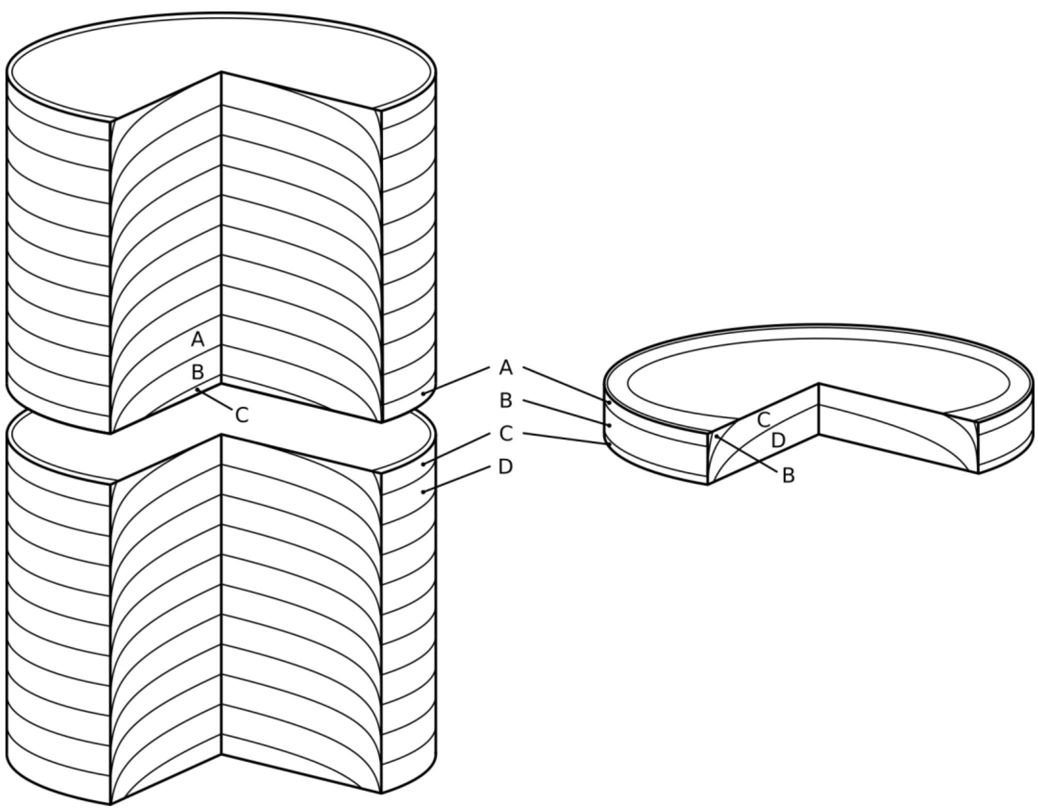


Fig. 1



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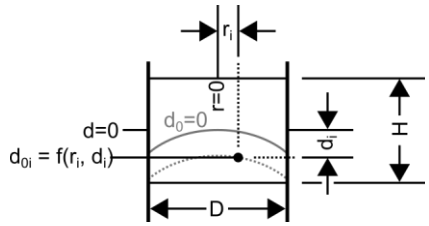

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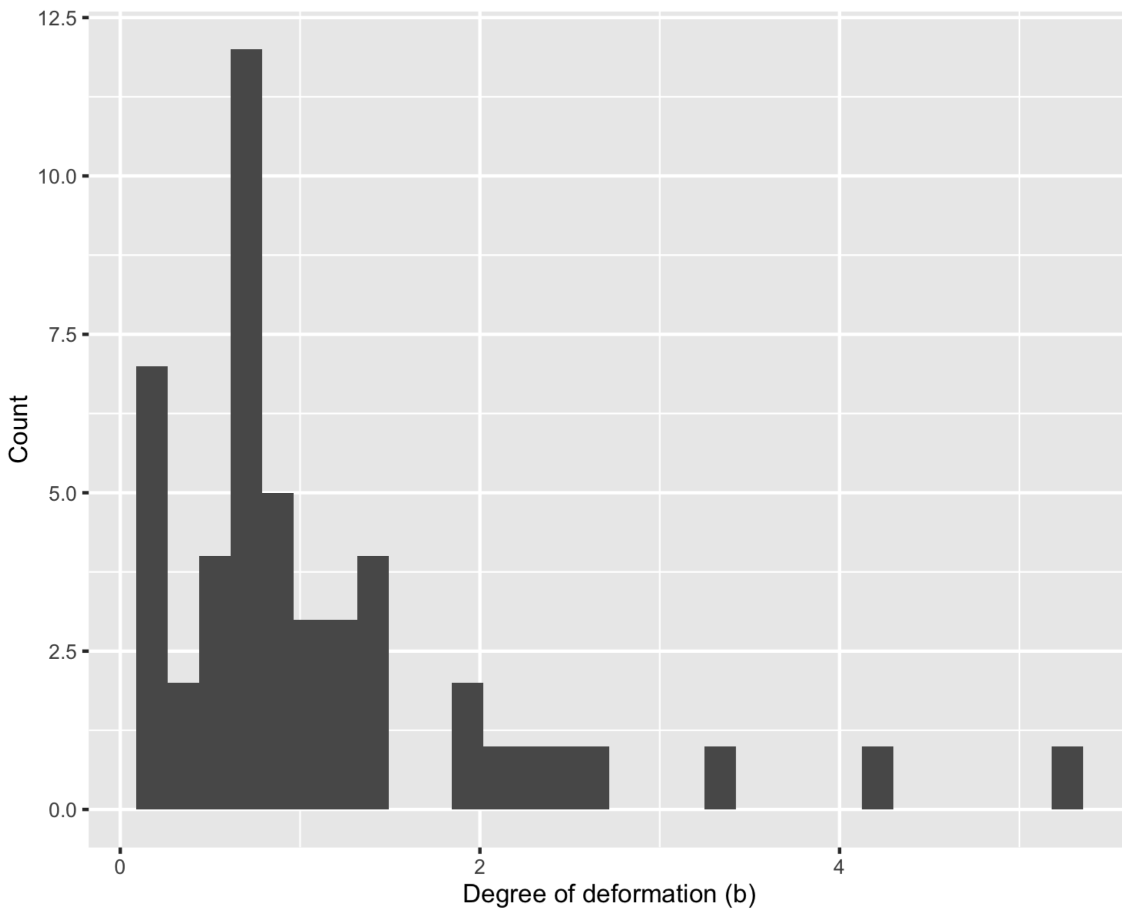
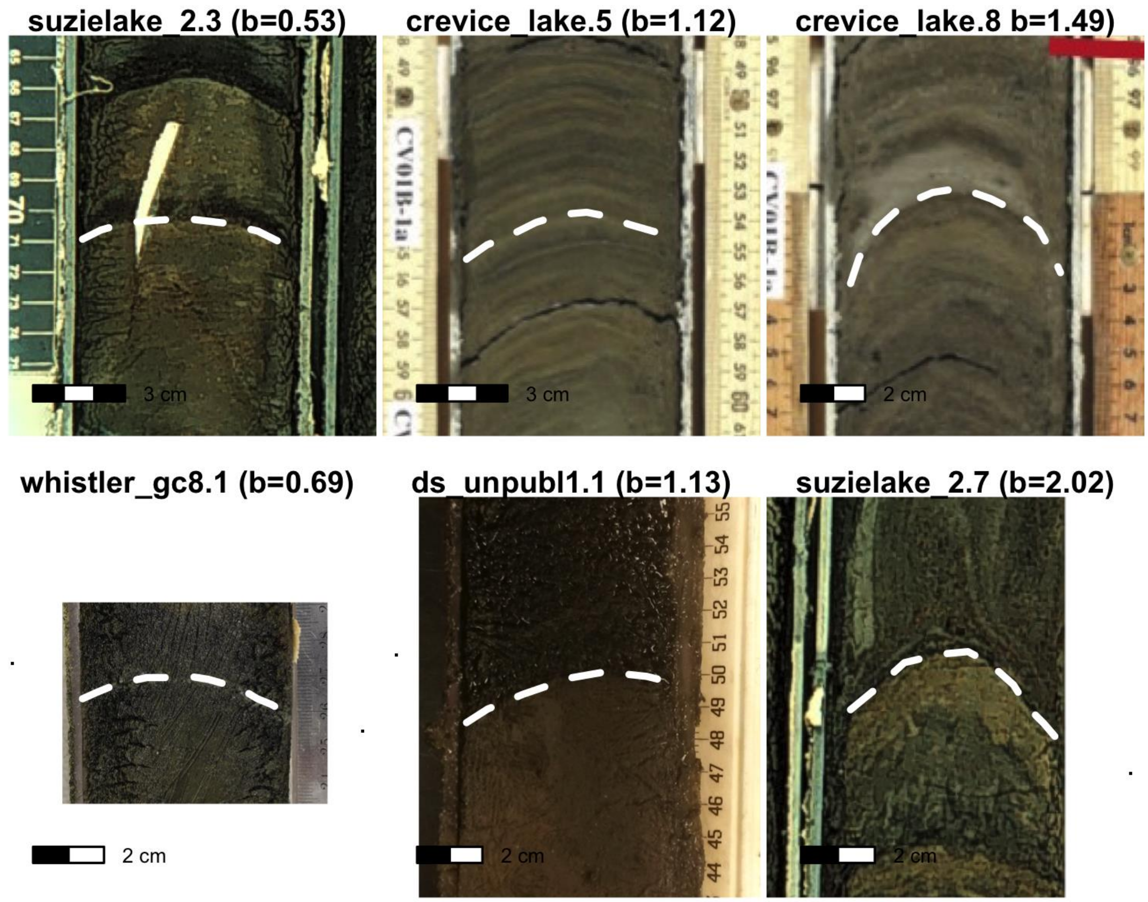
d=0
d_0=0
d_0i = f(r_i, d_i)
d_i
H
D

Fig. 3



12.5
10.0
7.5
5.0
2.5
0.0
Count
0
2
4
Degree of deformation (b)

Fig. 4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crevice_lake.5 (b=1.12)
crevice_lake.8 b=1.49)
3 cm
3 cm
2 cm
whistler_gc8.1 (b=0.69)
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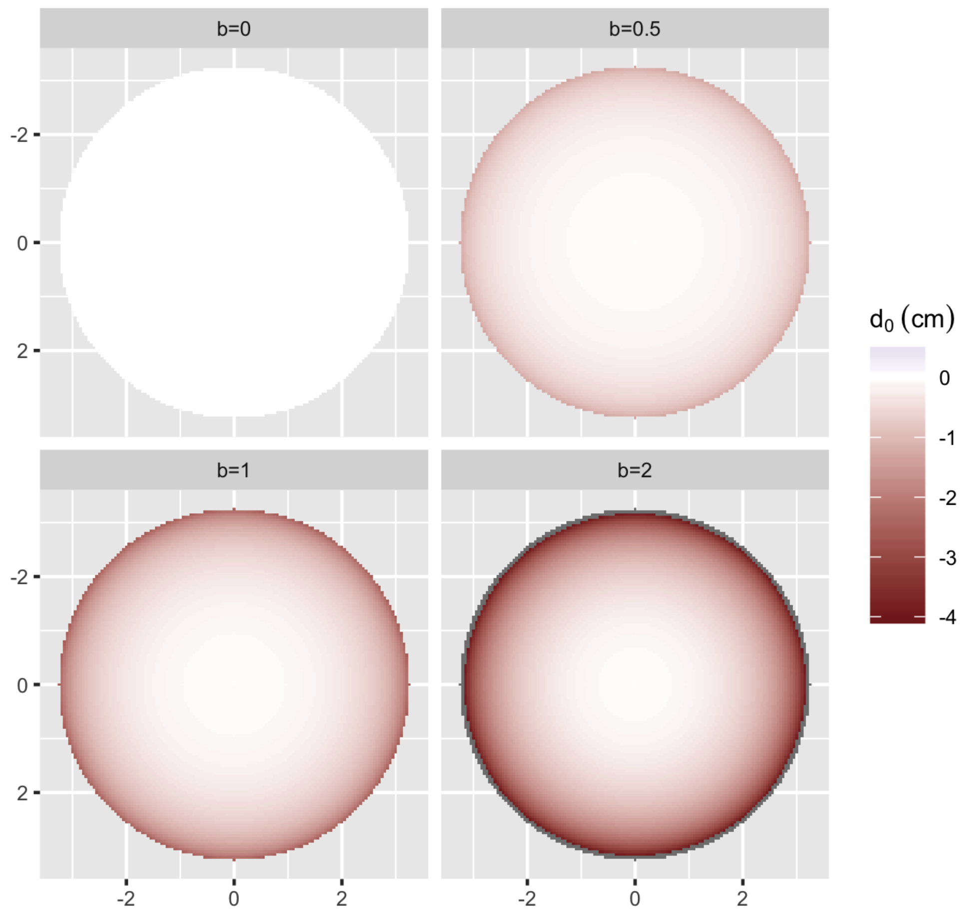
2 cm
2 cm
2 cm

Fig. 5



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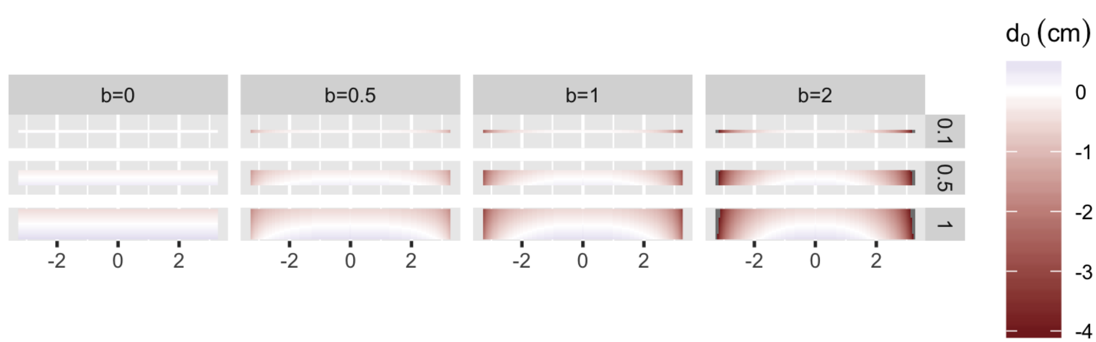

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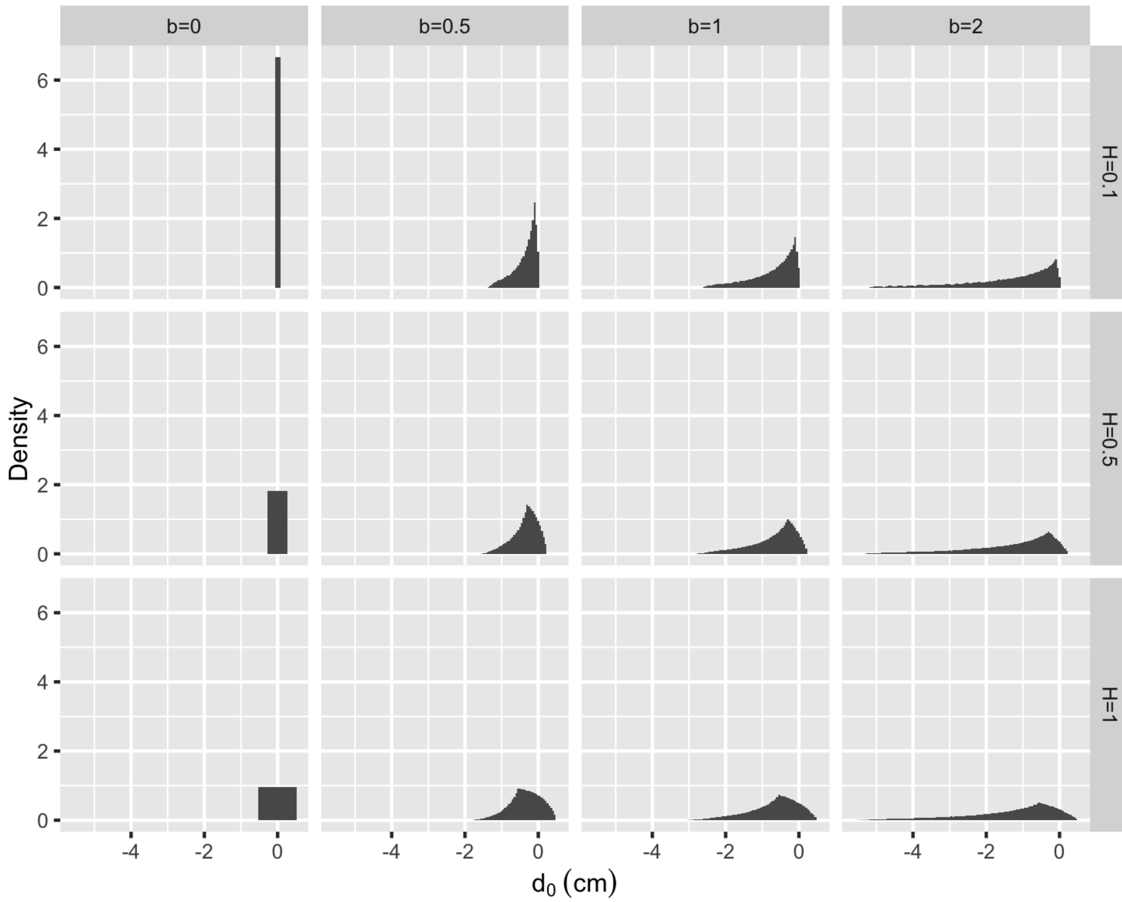

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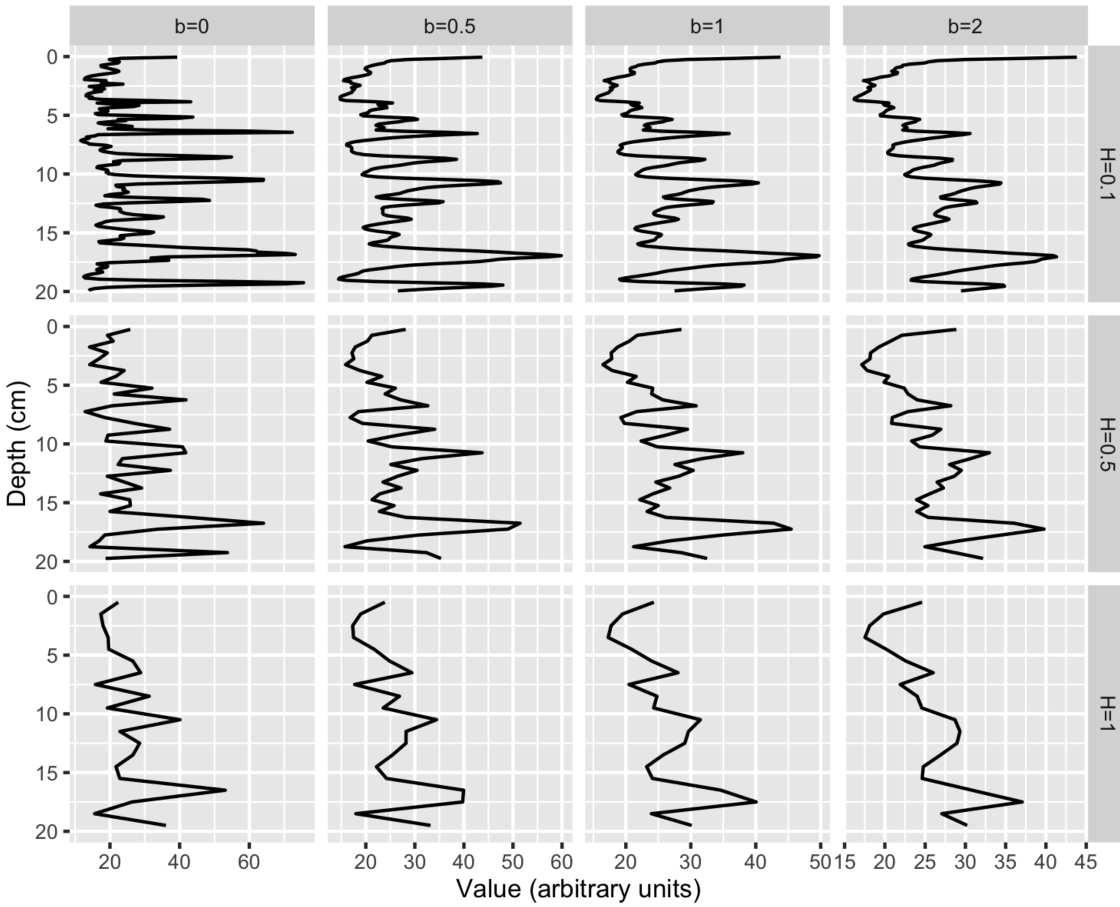

Fig. 9

Figure Legends

Fig. 1 Ideal patterns of deformation according to the logarithmic deformation function (Acton et al. 2002)

Fig. 2 Schematic of how adjacent deformed strata may become incorporated into a single horizontal section of a core

Fig. 3 Schematic of variables used in the deformation model. Models were produced for sections of diameter D and thickness H. Each point i in the section had a coordinate d_i and r_i, which were used to calculate the depth prior to convex upward deformation (d_{0i})

Fig. 4 Histogram of degrees of deformation (b) from digitized layers. Higher degrees of deformation corresponded to strata that were more deformed; lower degrees of deformation corresponded to strata that were less deformed

Fig. 5 Representative layers for selected degrees of deformation

Fig. 6 Distribution of d_0 for d=0 by degree of deformation. Value b=0 indicates no deformation; b=2 indicates maximum deformation in the model. Coordinates are in centimeters

Fig. 7 Distribution of d_0 of a vertically sliced section for multiple degrees of deformation and slice sizes. Coordinates are in centimeters. Slice thickness is in centimeters and is indicated at right

Fig. 8 Distribution of d_0 values modeled for multiple deformation coefficients and slice sizes. Wide distributions indicate that a wide range of original depths (d_0)

contributed to that slice. Negative d_0 values in the distribution indicate the inclusion of strata from above the center depth of the slice

Fig. 9 Extrusion and deformation modeled for artificial 0.5-mm-resolution concentration data. Original data are at top left. Degree of deformation increases to the right; slice thickness increases toward the bottom

Table Headers

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Figure 1

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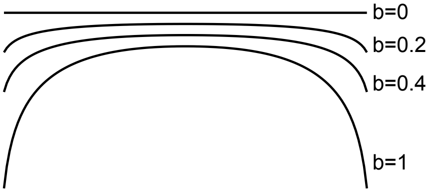

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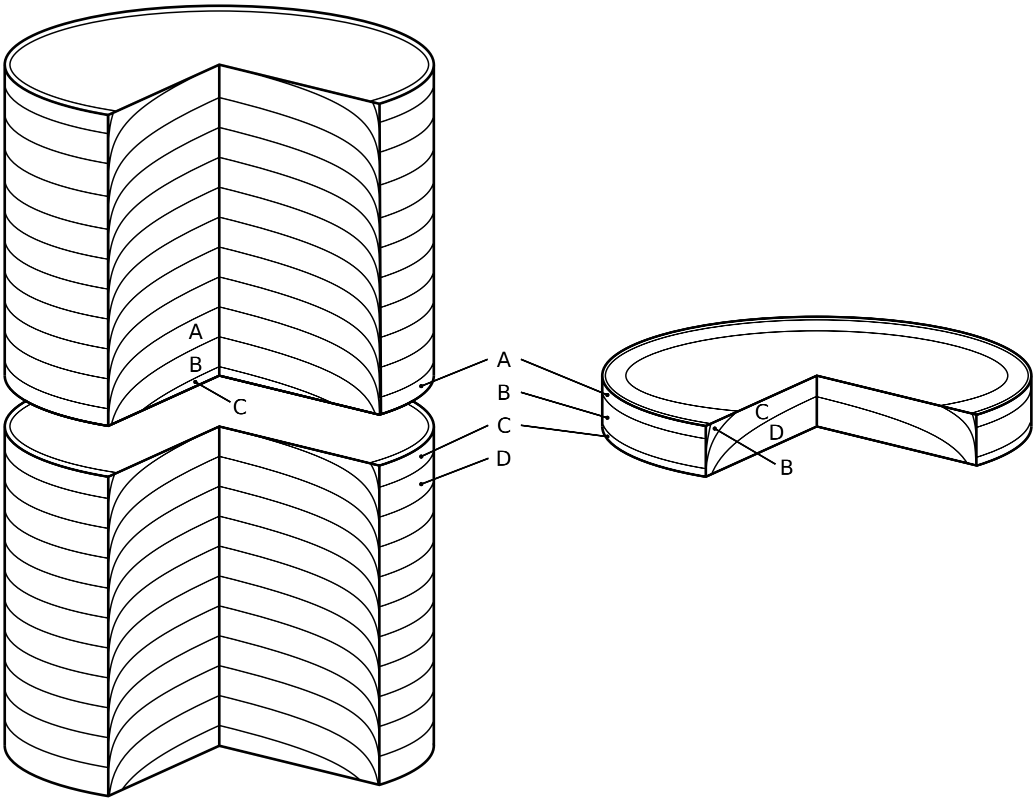

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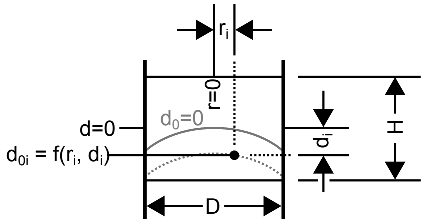

Figure 4

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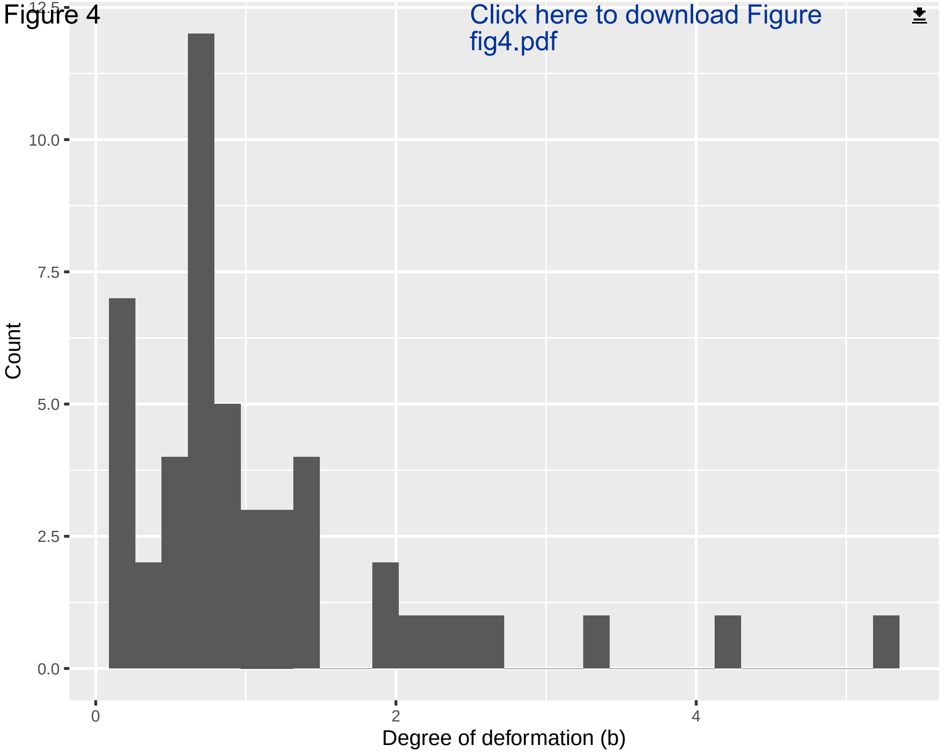

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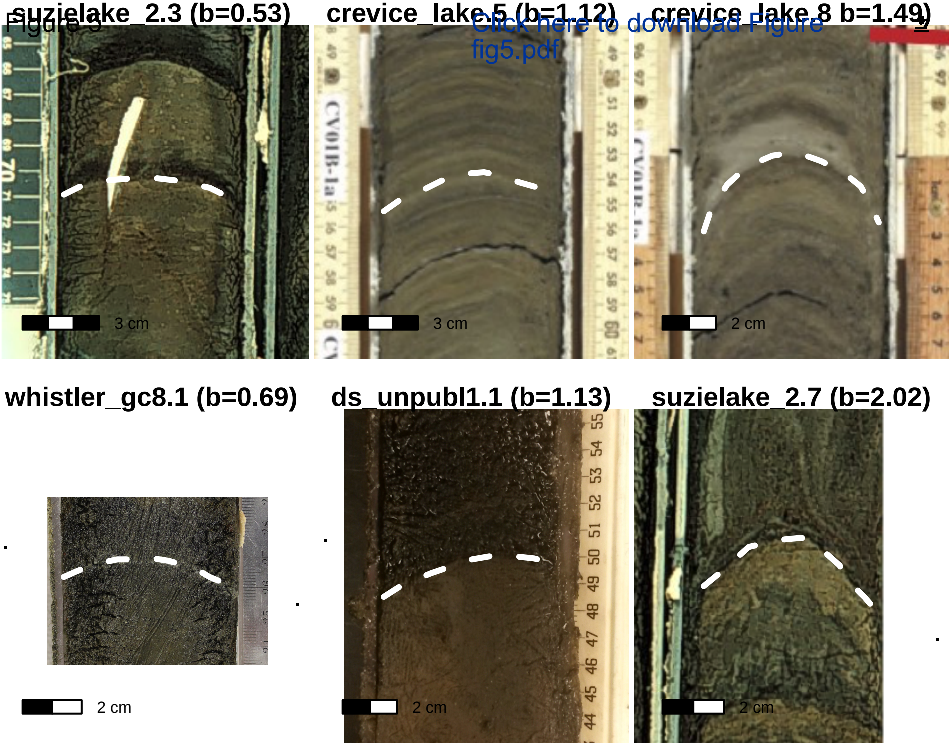
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2 cm
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2 cm

Figure 6

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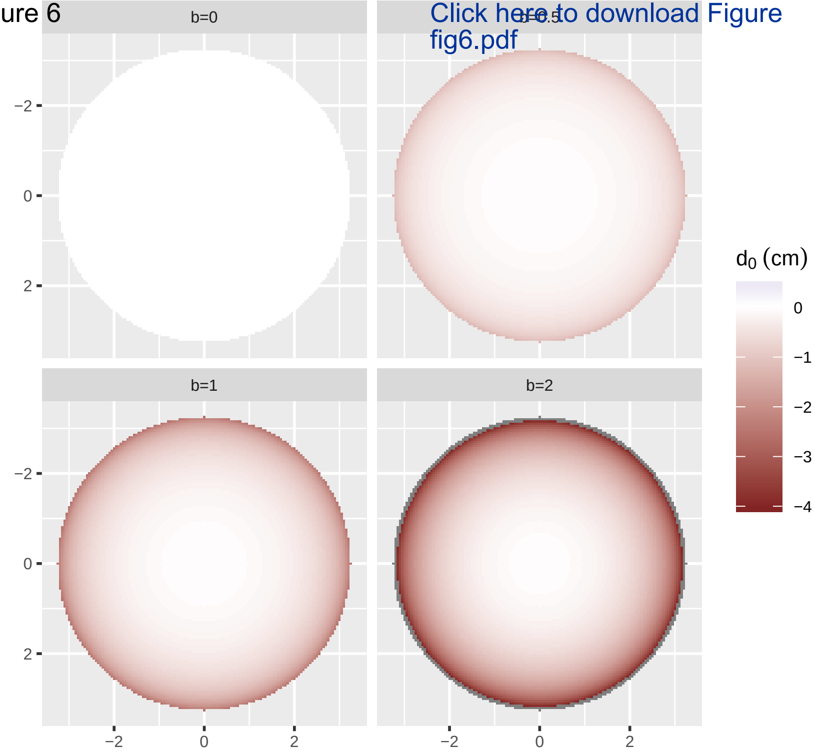

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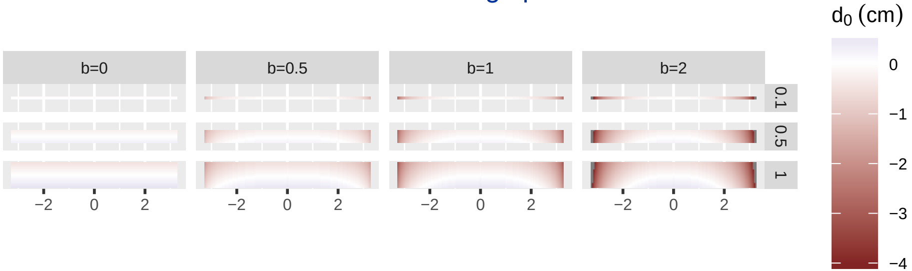

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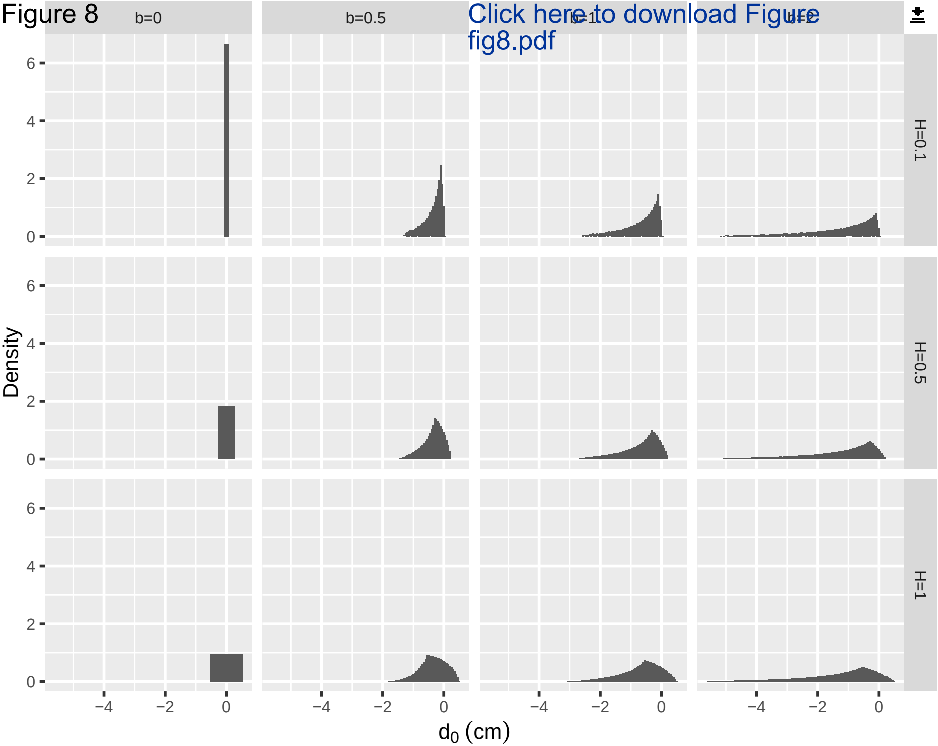

Figure 9

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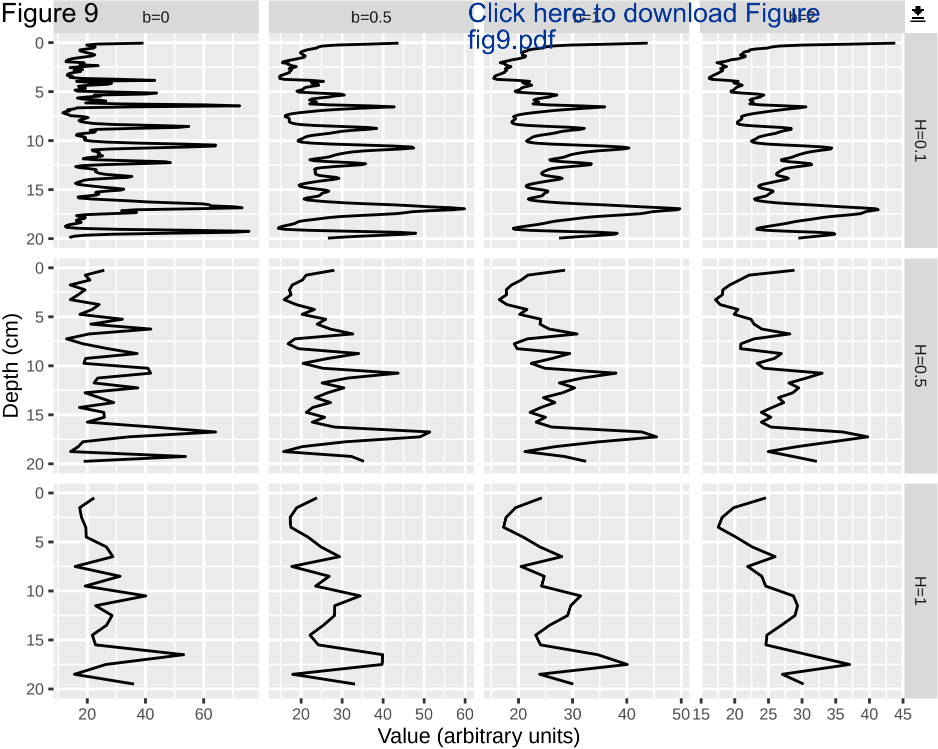

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whistler_gc8	1	Dunnington (2015)	Gravity