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

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

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Keywords: Coring, Deformation, 3D Model, Extrusion, Stratigraphy

Abstract

We analyzed photos of convex upward deformation in split cores to obtain reasonable parameters with which to model the effect of convex upward deformation on paleolimnological data, and, using a 3-dimensional raster model, modeled the effect of this deformation on a hypothetical dataset. Results indicated that convex upward deformation integrates sample from an increasingly wider range of stratigraphic layers with 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 attainable by horizontal sectioning if deformation occurred during sampling. Collectively our data suggest that determining the degree of deformation due to coring is essential prior to conducting high-resolution analysis of horizontally sectioned samples.

Introduction

Deformation of lake sediment during coring has long been known (Martin and Miller 1982; Wright 1993; Glew et al. 2001), and coring equipment design has attempted to minimize the conditions that promote deformation during coring (Martin and Miller 1982; Lane and Taffs 2002). Glew et al. (2001) provide a detailed examination of the forces acting on sediments as a result of coring, including the displacement of sediment during core tube penetration resulting in core shortening, however convex upward deformation, while widely observed (Wright 1993; Rosenbaum et al. 2010), is infrequently 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 deformation observed. Aubourg and Oufi (1999) noted a "conical fabric" develop due to "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) $Z(r) = -b\left(ln(1-\frac{r}{R}) + \frac{r}{R}\right)$

Acton et al. (2002) estimate 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 horizontal sectioning of deformed sediment occurs, adjacent strata are incorporated into each section (Fig. 2). The idea that horizontal sectioning (extrusion) of deformed sediment is not ideal has been proposed (Rosenbaum et al.

2010), however the degree to which this deformation occurs and the effect that deformation has 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 either deformation or its effect on the data is minimal. This paper is our attempt to quantify and constrain the degree to which convex upward deformation adds bias to horizontally sectioned paleolimnological data.

Methods

We used R statistical software (R Core Team 2013) to model, manipulate, and visualize our data. Packages *dplyr* and *ggplot2* were used for manipulation and visualization of 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 modification of this model would make including more complex deformation possible.

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 need to calculate total mass of the target substance divided by the mass of the slice. With a 3-dimensional raster grid using 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 allows for 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 was transformed and 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 was able to model most layers well (median r^2 of 0.84), but modeled some layers poorly. This suggests that deformation forces other than those modeled by the logarithmic function are also acting 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 deformed core photos that were analyzed 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 (Fig. 6; Fig. 7). Slices represented a wider range of d_0 values with increasing deformation (Fig. 7; Fig. 8), and when deformation was >0.5, slice sizes smaller than 1 cm did not result in decreasing 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 that was 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 behavior of deformation differs at the top of the core compared to deformation below. 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, the extrusion interval of 0.1 cm and 0.5 cm produced nearly identical results when any deformation was applied in our model.

Conclusions

The data indicated that even minimal convex upward deformation has an effect on paleolimnological data. Even when deformation was small, decreasing the extrusion interval did not result in an appreciable difference in the paleolimnological data (Fig. 9) or in decreasing 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), however our data suggest that reducing the extrusion interval does not increase the effective resolution of the data if sediment has been deformed by coring. Our data suggest that checking for deformation due to coring is essential prior to conducting high-resolution analysis of horizontally sectioned samples, and that eliminating the outer several millimeters of extruded sections may mitigate the effects of possible deformation. We recognize the limits of an idealized model where many deformation forces exist, however we leave the modeling of more complex deformation using similar methods to future authors.

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_unpubl1	1	Dunnington and Spooner (unpublished data)	Gravity

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

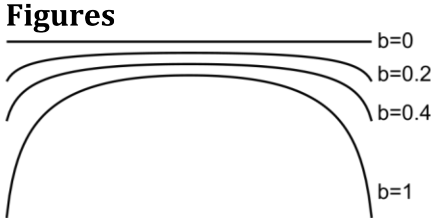

Fig. 1 Ideal patterns of deformation according to the logarithmic deformation function (Acton et al. 2002).

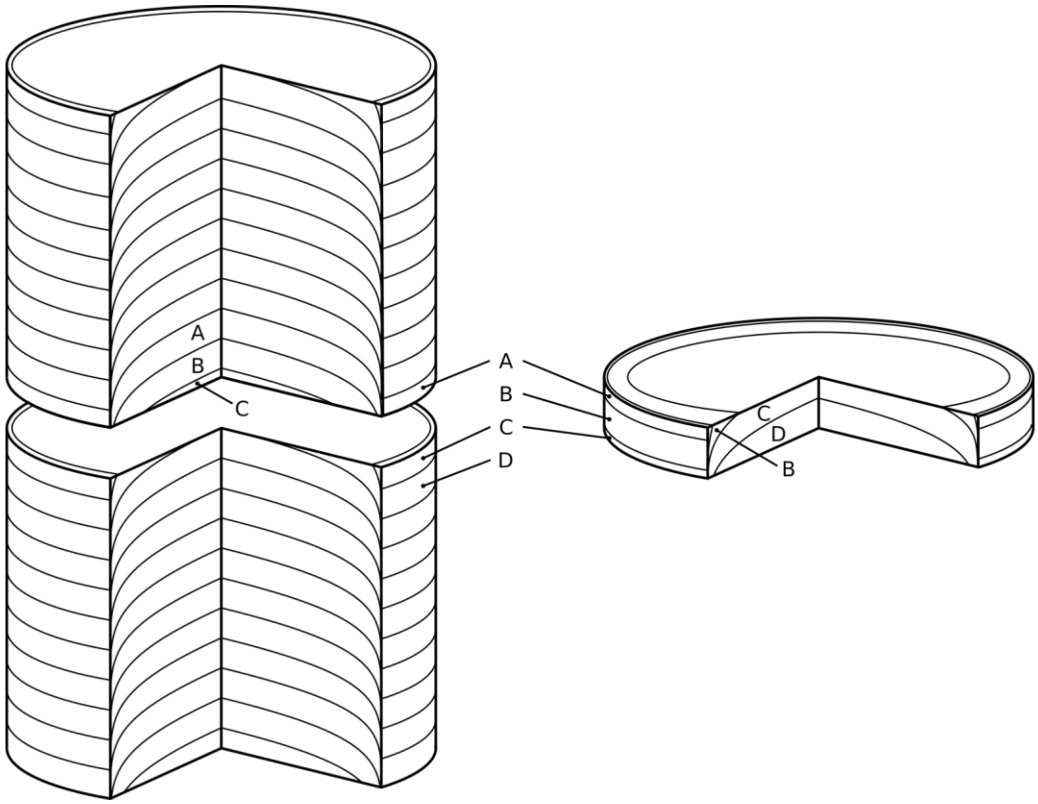

Fig. 2 Schematic of how adjacent deformed strata may become incorporated into a single horizontal section of a core.

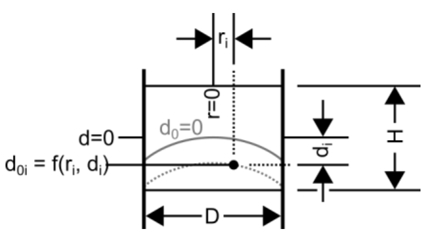

Fig. 3 Schematic of variables used in the deformation model. Models were produced for sections of diameter D and thickness H. Each point i in the section had a coordinate d_i and r_i, which were used to calculate the depth prior to convex upward deformation (d_{0i})

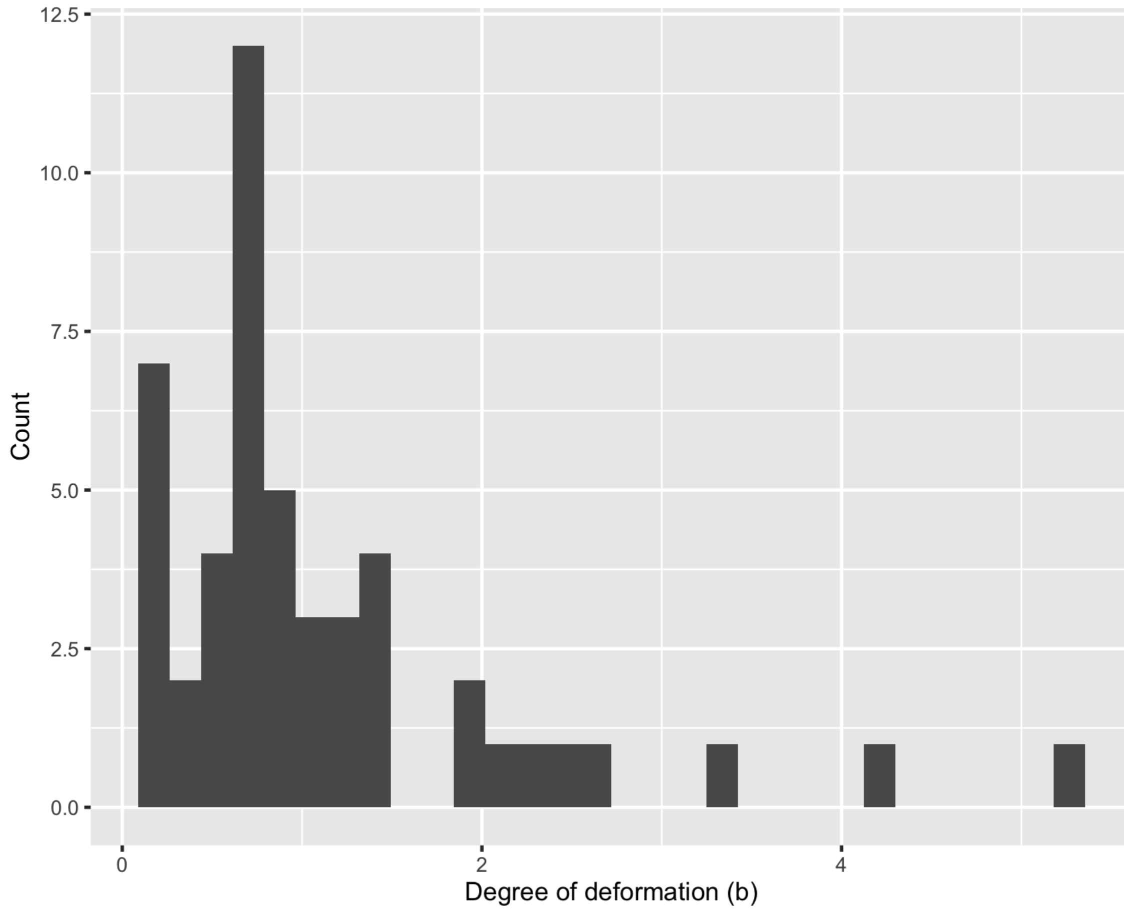

Fig. 4 Histogram of degrees of deformation (b) from digitized layers. Higher degrees of deformation corresponded to strata that were more deformed; lower degrees of deformation corresponded to strata that were less deformed.

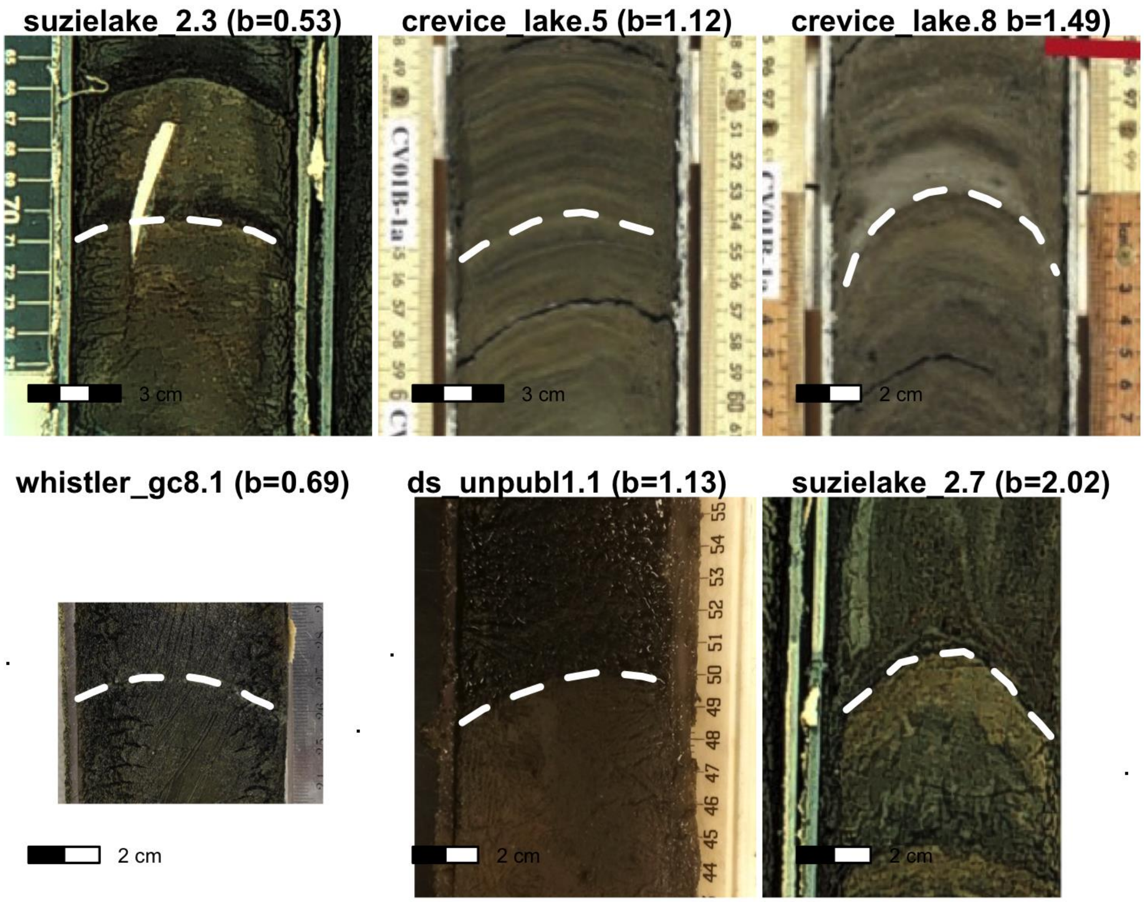

Fig. 5 Representative layers for selected degrees of deformation.

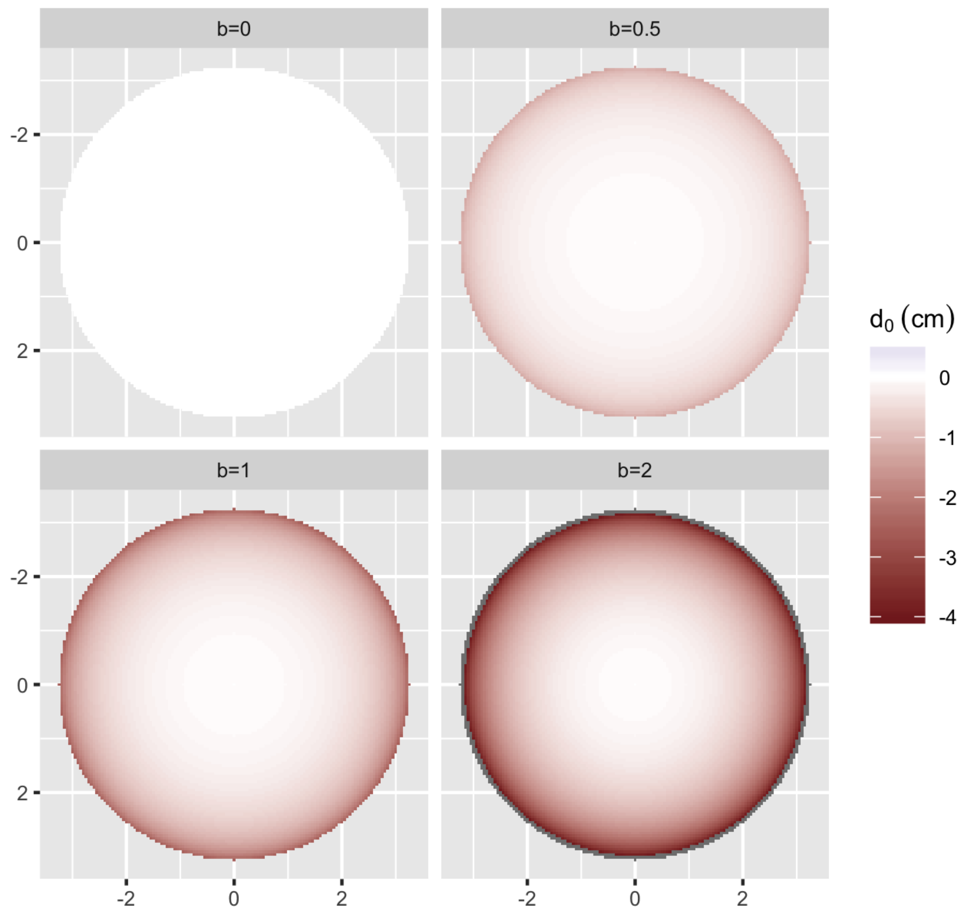

Fig. 6 Distribution of d_0 for d=0 by degree of deformation. Value b=0 indicates no deformation; b=2 indicates maximum deformation in the model. Coordinates are in centimeters.

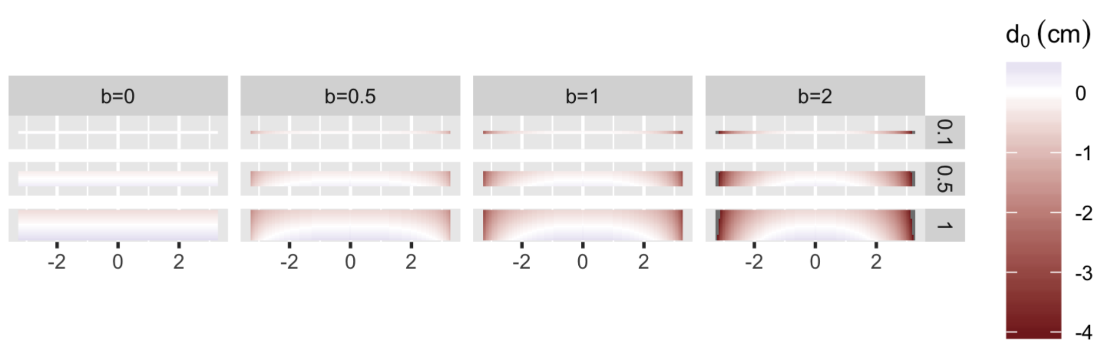

Fig. 7 Distribution of d_0 of a vertically sliced section for multiple degrees of deformation and slice sizes. Coordinates are in centimeters. Slice thickness is in centimetres and is indicated at right.

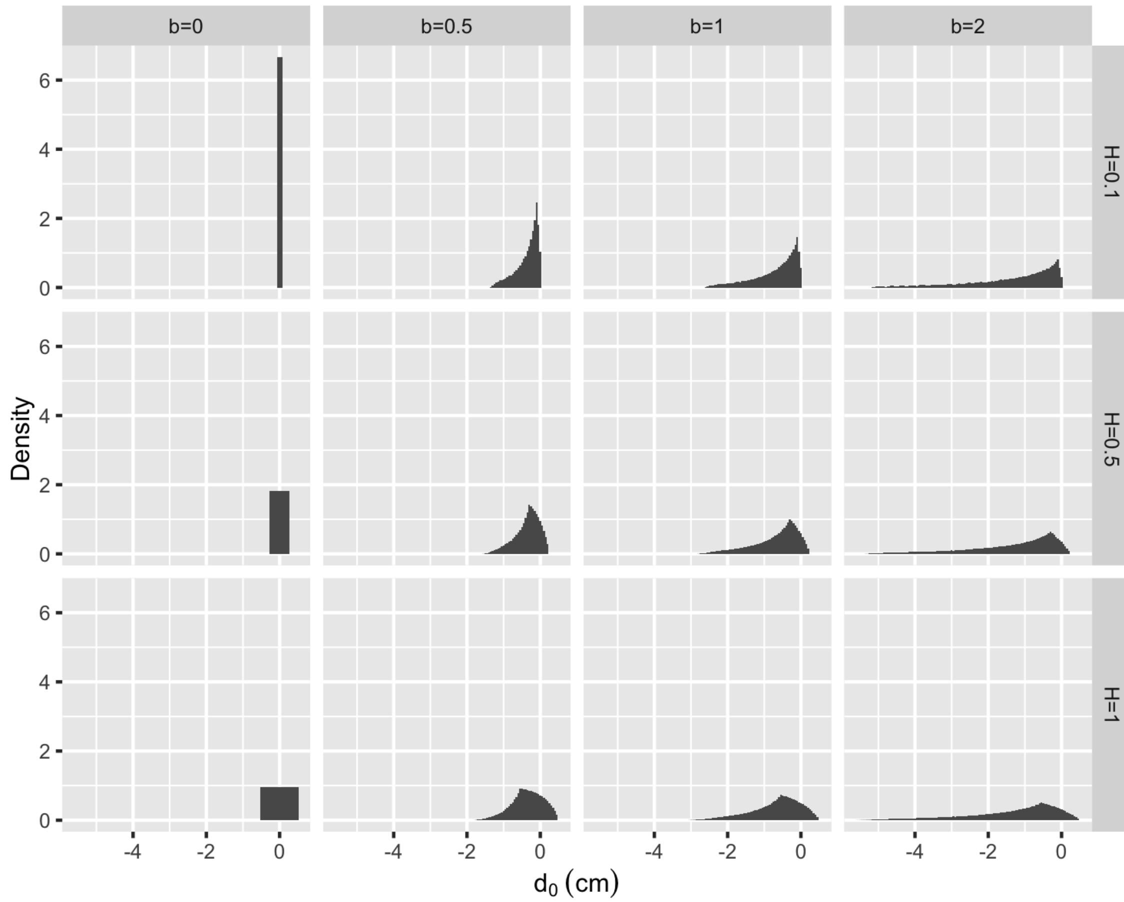

Fig. 8 Distribution of d_0 values modeled for multiple deformation coefficients and slice sizes. Wide distributions indicate that a wide range of original depths (d_0) contributed to that slice. Negative d_0 values in the distribution indicate the inclusion of strata from above the center depth of the slice.

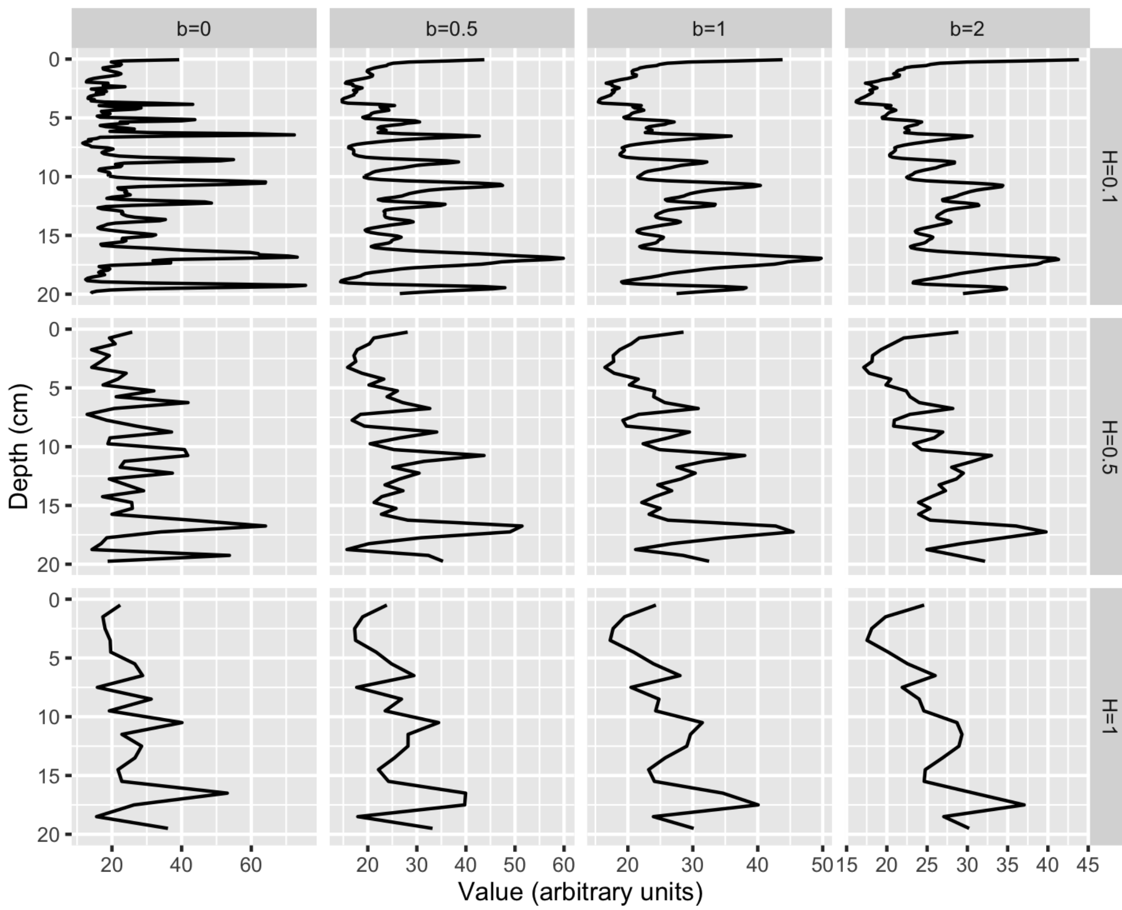

Fig. 9 Extrusion and deformation modeled for artificial 0.5 mm resolution concentration data. Original data is top left. Degree of deformation increases to the right; slice thickness increases toward the bottom.

Figure Legends

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References

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Figure 1

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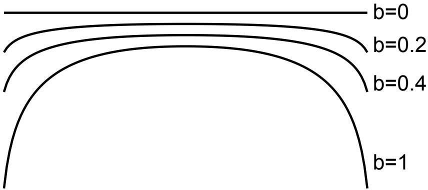

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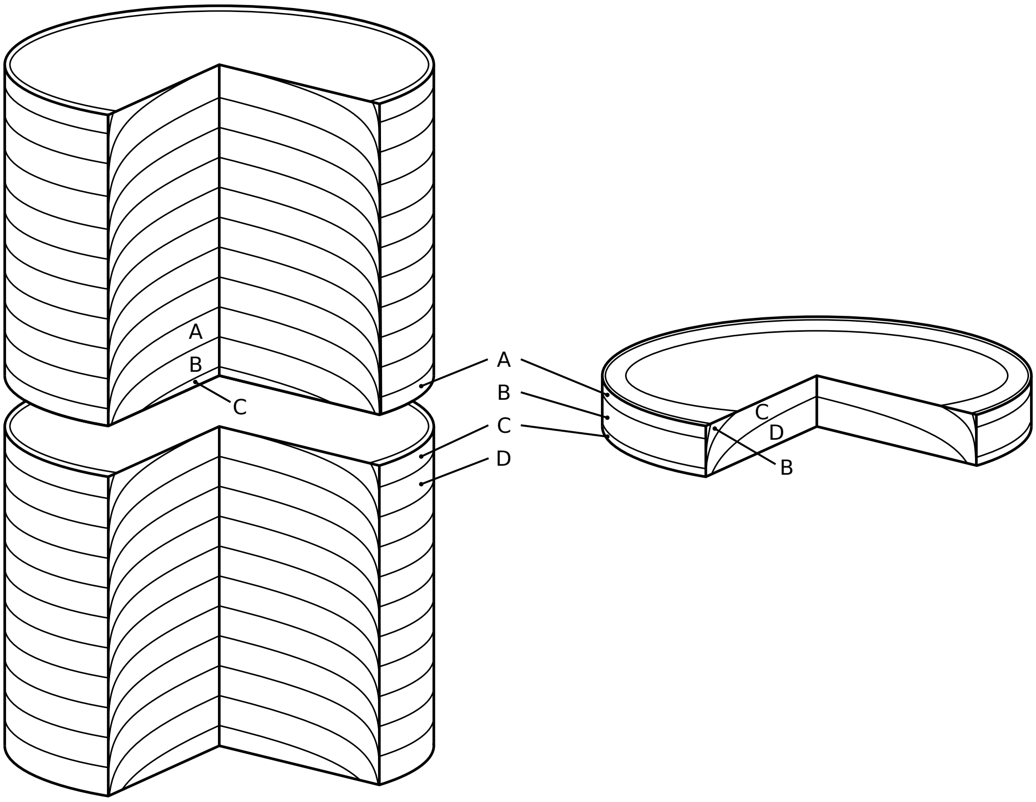

Figure 3

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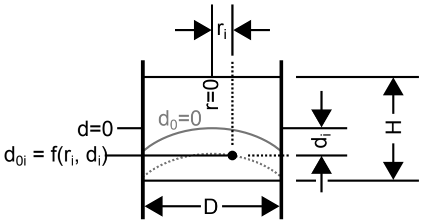

Figure 4

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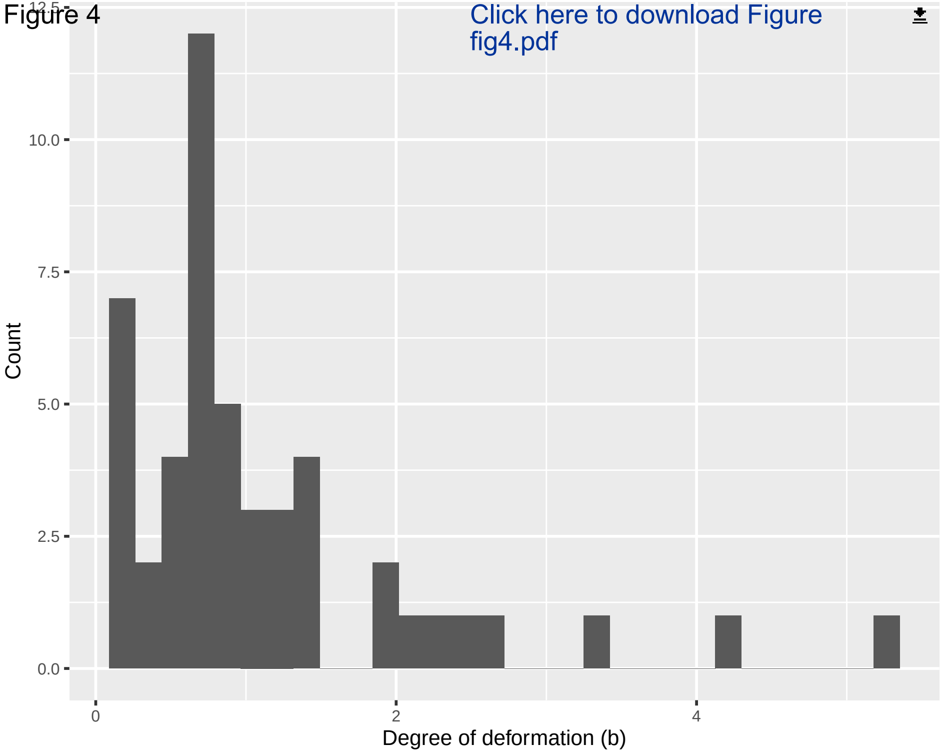

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Figure 5

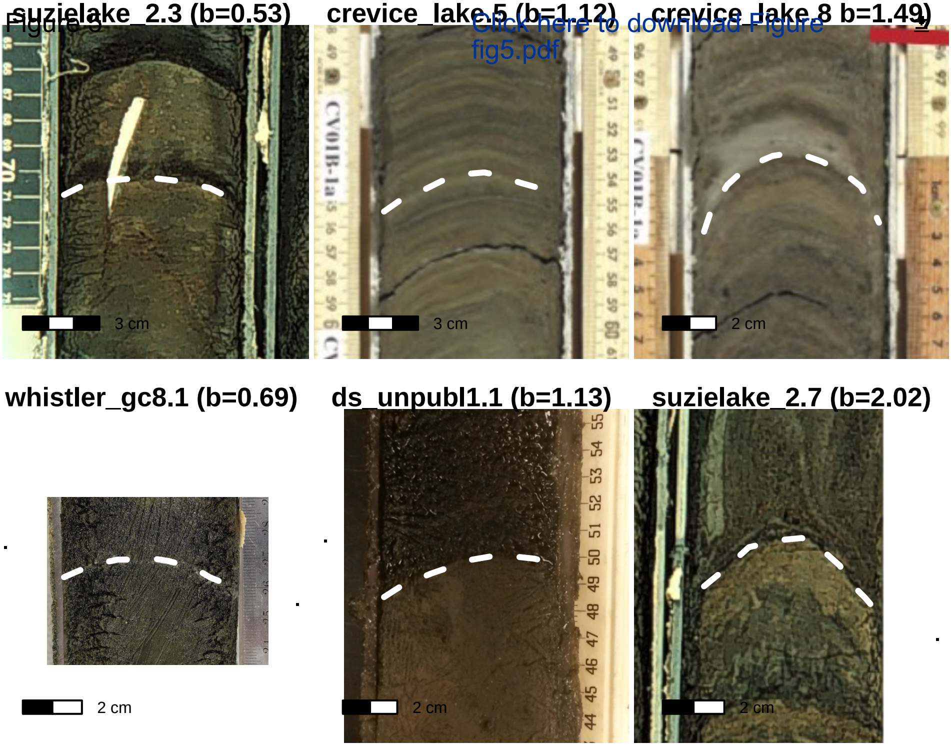

Figure 6

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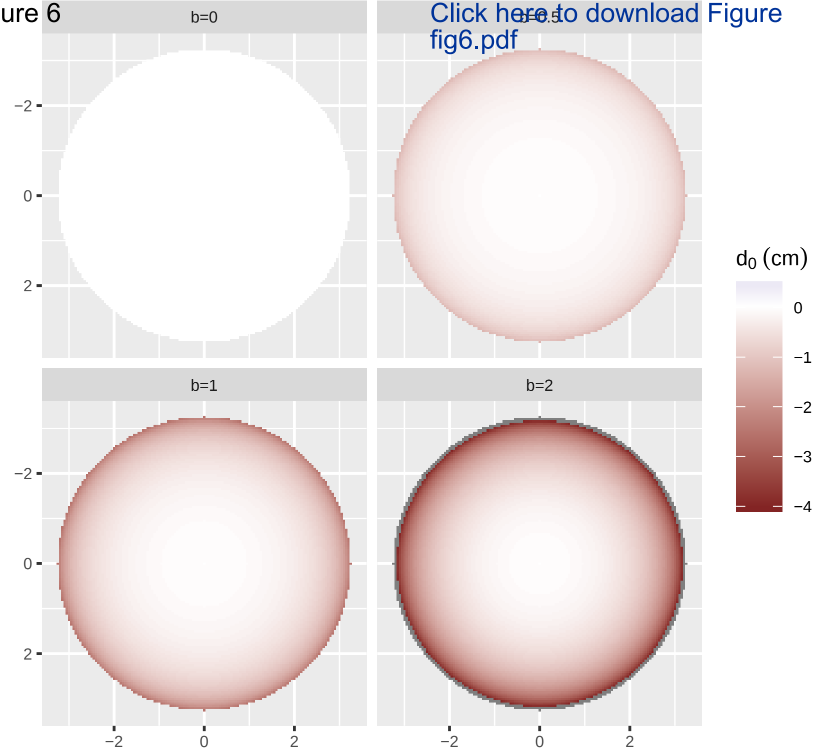

Figure 7

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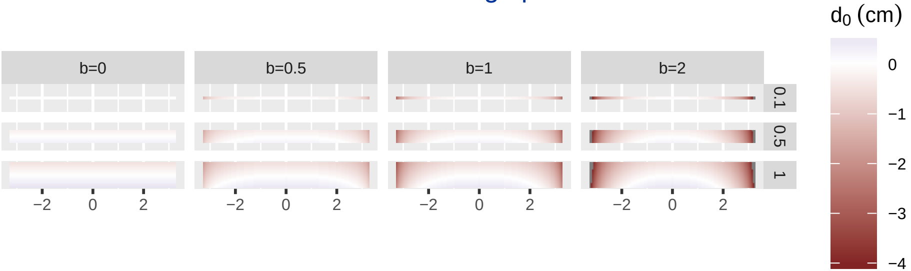

Figure 8

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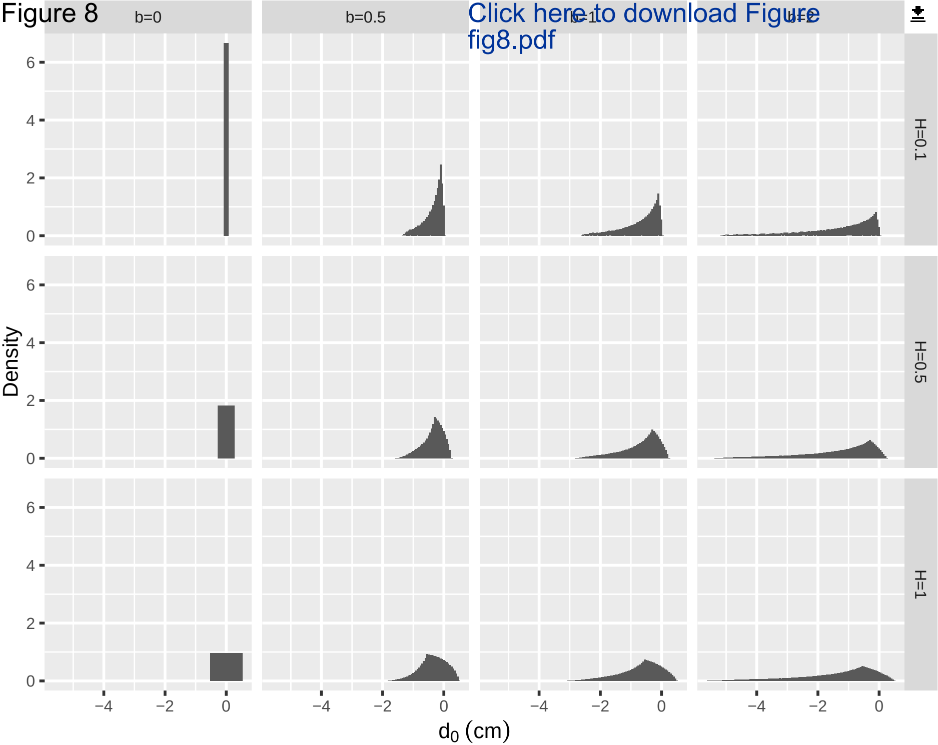

Figure 9

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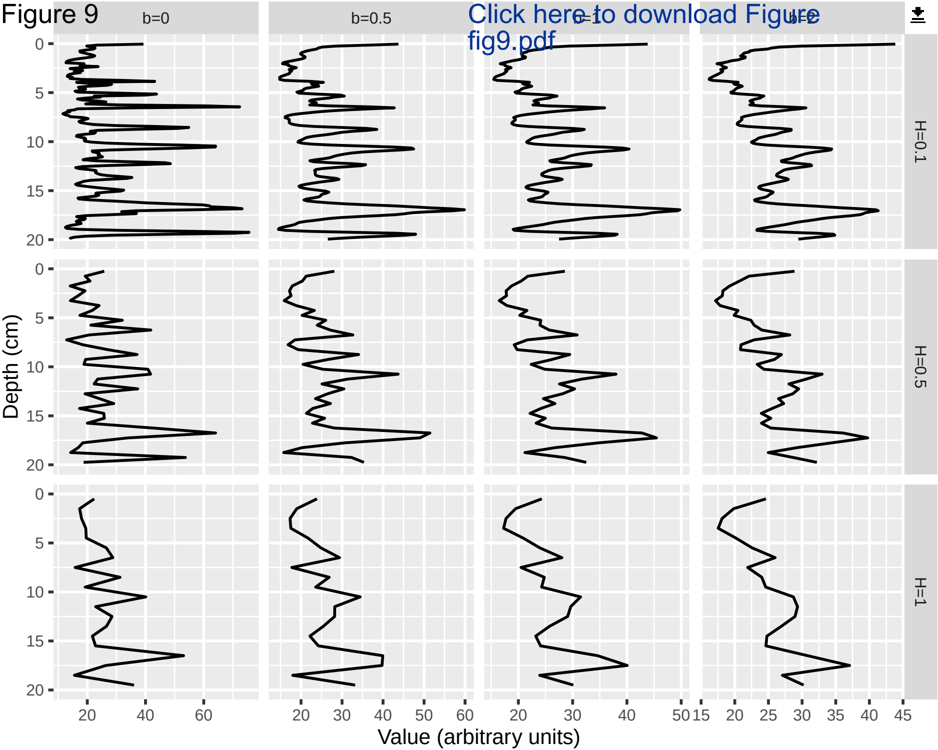

 Click here to download Table Table1.docx

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suzielake_1	4	Spooner et al. (1997)	Percussion
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whistler_gc4	1	Dunnington (2015)	Gravity
whistler_gc8	1	Dunnington (2015)	Gravity

Dear Dewey,

We have received the reports from our advisors on your manuscript, "Modeling the effect of convex upward deformation and horizontal sectioning on paleolimnological data", submitted to Journal of Paleolimnology.

Based on the advice received, we have decided that your manuscript can be accepted for publication after you have carried out the corrections as suggested by the reviewer(s). You will find the comments of Reviewer #1 below and those of Reviewer #2 attached here in the Editorial Manager System. As you revise, please follow JOPL style closely, i.e. no periods at the end of Table headers or figure legends. And use journal abbreviations throughout in the References. Please also put figure legends on a page separate from the figures.

Figure and table legends were added on a separate page; journal abbreviations were used instead of full journal names; periods were removed from the end of table and figure legends.

One additional thing. I recall that Glew et al. (2001) addressed sediment "compression" during coring. As I remember, the point was that sediment, with fluid-filled pore spaces, cannot be "compressed," so if you drive 1 meter, and collect only 90 cm, for example, it is because not all sediment was collected. This was attributed to a "wave front" that pushed sediment aside, ahead of the core barrel. Anyway, I believe they recommend using "core shortening." OK, we look forward to receiving the revised version.

Incorrect references to “compression” were removed or clarified.

Attached, please find the reviewers' comments for your perusal.

You are asked to carefully consider the reviewers' comments which are attached, and submit a list of responses to the comments. We do not necessarily expect that you will agree with all the comments, but we would like to receive justifications for any comments you decide should not be incorporated.

"Please submit your revision as an editable Word file. Please do not include active links to your references in the text of the revision".

Please also submit your response to the reviewers' comments online as submission item.

We are looking forward to receiving your revised manuscript
within 120 days.

With kind regards,

Mark Brenner, Ph.D.

COMMENTS TO THE AUTHOR:

Reviewer #1: A short paper that provides a mathematical model for evaluating convex-up deformation in sediment cores. While the paper adequately models the deformation I felt that some more practical advise might be reasonable to expect. For example, based on the deformation, once a horizontal slice of sediment has been collected how much of the periphery (outer diameter) could be removed from the slice to minimize the contamination of the sample caused by deformation? Is there other advise/guidance the authors provide?

We added the suggestion that the outer few millimeters of sediment be discarded in the conclusion, and the observation that the areas that contain the highest amount of deformation are in the outer few millimeters of the section in the model. It may be possible to quantify how much is enough, but we feel that since our model is an approximation, this measurement would change our suggestion of 'a few millimeters' little.

Minor points

Consider reversing order of 2nd and 3rd sentence in the abstract to have the methods come before the results.

We choose not to revise this, as our 3rd sentence contains more results, and reversing the sentences would not achieve the desired result. We feel our methods are adequately summarized in the first sentence, but would be happy to revise should a more specific revision be suggested.

Intro, ln 2, Glew et al. 2001 is a good reference here. They also discuss sediment bypassing which sometimes is assumed to be compression.

The Glew et al. 2001 reference was added at line 2. We corrected the statement about sediment bypassing which we had previously referred to as compression.

" ln 27, spelling of function.

The spelling of 'function' was corrected

" ln 37, whose function is proposed, yours or Kegwin et al's?

Kegwin et al. (1998) proposed the function. This was clarified in our revised manuscript.

" ln 57, avoid first person, instead "It is suspected . . ." also line 4, next page.

In this paper we have chosen to primarily use the first person active voice. Changing these two instances would lead to an inconsistent tone of the paper. We would be happy to remove all of our

first person references if requested, however we feel strongly that the manuscript is more compelling with first person reference left intact.

In second methods, of the photos used, were all cores collected using the same technique?

The coring method for each photo was added to Table 1.

Methods ln 32, when a number is <10, spell it out.

This was fixed in the methods section.

Bottom of page 3 sediment bypassing as well as compression, and delete last phrase in this sentence.

"Compression" was changed to "more complex deformation", as this more generically fits our intent.

5th line from bottom of page 4: 'inspired' is an odd choice of word.

We changed "inspired by" to "designed to resemble", as this more accurately describes our intent.

For results, start second paragraph with "Slice thicknesses of 0.1 . . . "

This was updated in the revised manuscript.

The conclusions introduce new information about a specific type of corer, which should be mentioned earlier and then is not needed in the conclusions.

This statement was moved to the results section.

Acknowledgments: Did the entire department offer comments> Instead, perhaps there are a few individuals who should be mentioned.

We updated this section to remove the awkward phrasing and acknowledge the reviewers' contributions.

The Menounos et al. 2005 reference was not cited.

The reference was removed

Reviewer #2: see attached comments

~~rocky point Cen BC~~

~~Elevation on section~~

JOPL Ms. No. JOPL - D - 16 - 00088

Modeling the effect of con...... Dunnington Spooner

This paper addresses the problem of orthogonal sectioning of sediment cores comprising of deformed strata. And evaluates the degree of integration of adjacent strata using a model. Considering the potential problems arising from this condition has come up repeatedly in paleolimnology. For this reason it is important to frame the problem as accurately as possible. the 3-D raster model used to describe and classify the degree of deformity is not something I am familiar with although if I understand it correctly it assumes some degree of symmetrical form to the convexity that occures as the cored material reacts to the downward motion of the core tube, while I realize that the model must simplify this I would like to see included in the paper some discusion of the problems that are present in doing this. A diagram similar to the one I include here may clarify this, I have drawn it because I cannot really find exisiting in the literature.

Many years ago I carried out some experiments in which lake sediemnts ~~and some~~ and some lab. created sediments were extruded through tubelar and rectangular sections of reduced dimensions 5 to 15 % of the core diameter the transition length being 3 times the core diameter. Although the experiment sought to examine the nature of the distortion to see if thin strata could be thickened (to magnify for subsampling). The conclusions drawn from this work were that distortion was very unpredictable, probably the most noticable aspect of the experiments was the increase and variability of pressure required to extrude them. Such pressures are similar to those present when a core is driven and results in a pressure zone being created directly below the advancing core tube.The result of this pressure (sometimes called a pressure bulb) results in thinning the strata that the core tube encounters. The net result is often refered to as core shortening, (note that in the introducion of this paper this is referred to incorrectly as core compression) this is not a volume reduction but rather a radial displacement of sediment horizontally from the vertical axis of the core tube above it. for a diagram of this see Glew Smol and Last 2001 Pigot 1941. Core shortening is not usually considered distortion because thinning occurs in the plane of the strata. I think the inclusion of some aspects of this would help put the material in this paper into context.

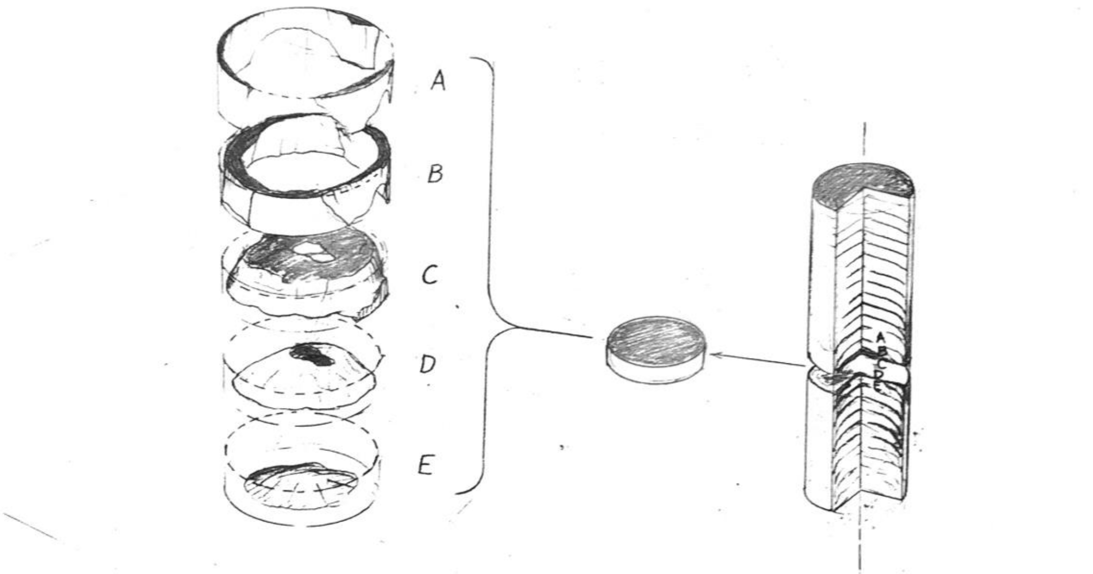
We thank the reviewer for his detailed artwork and careful consideration of the manuscript. As a result of these comments, we have incorporated the following changes into the manuscript:

- **Corrected the statement which incorrectly referred to core shortening as compression and referred readers to Glew et al. (2001) for a discussion of forces acting on sediments during coring.**
- **Added the reveiwer's language of "integration of adjascent strata" to the methods section to more clearly describe our model.**
- **Added a statement in the conclusion recognizing the limitations of an idealized model applied to a complex deformation environment, and a statement in the results recognizing the complex nature of deformed sediment.**

- **Generated a new figure attempting to replicate the reviewer's schematic of how multiple layers may become incorporated into a single horizontal section.**

- **Added a statement at the beginning of the second introduction paragraph referencing this figure.**

The reviewer's figure is far more detailed than the one we were able to construct, but the supplied figure is not quite up to publication standard and we do not feel comfortable asking a volunteer anonymous reviewer to put more time into a very elaborate figure. We are unsure of how to properly credit the reviewer for his contribution but would be happy to do so based on a suggestion by the reviewer/editor.



REPRESENTION OF FIVE DISTORTED
STRATA IN A VERTICAL CORE
CONTAINED IN A HORIZONTAL
SUBSAMPLE, TYPICAL USING
AN EXTRUDING TRAY.

JRG 2016.