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

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# 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*).

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 *d0i* (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 *d0*) 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 (), density (), and volume (*V*) divided by the sum of the product of *V* and (2).

We can remove *Vi* from the summation in both the numerator and denominator because the cell size is constant for each *i*, and write and as functions of *d0i*.

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/cm3. 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 *r2* 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, *d0* 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 *d0* 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 *d0* values. In the model, *d0* 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

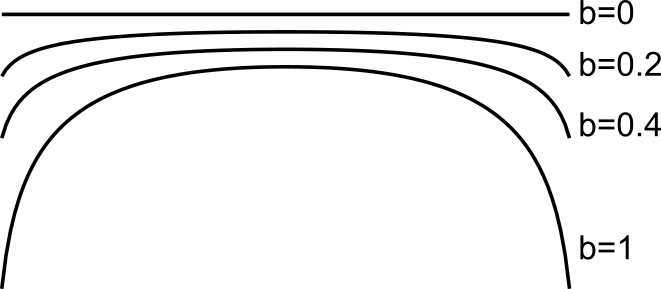
We acknowledge funding from the Natural Sciences and Engineering Research Council (NSERC) of Canada, the insightful comments on this manuscript from both anonymous reviewers, and Mark Brenner for editorial handling.

# Tables

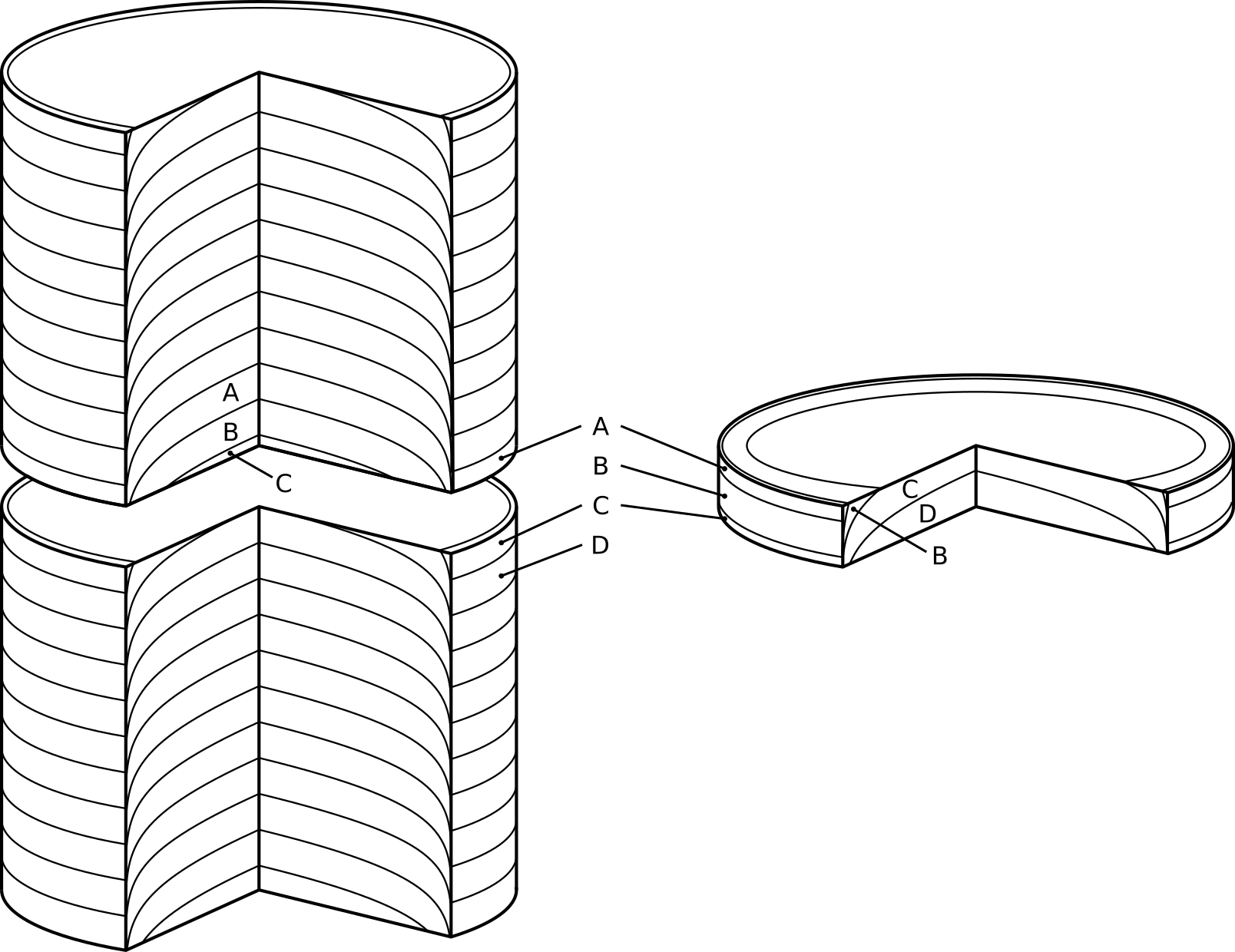
**Table 1** Sources of core photos that contained digitized layers used in this study.

|  |  |  |  |
| --- | --- | --- | --- |
| Photo ID | Layers Digitized | Reference | Coring Method |
| cheak1 | 8 | Menounos and Clague (2008) | Percussion or gravity |
| cheak2 | 8 | Menounos and Clague (2008) | Percussion or gravity |
| crevice\_lake | 12 | Rosenbaum et al. (2010) | Percussion piston |
| 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 |

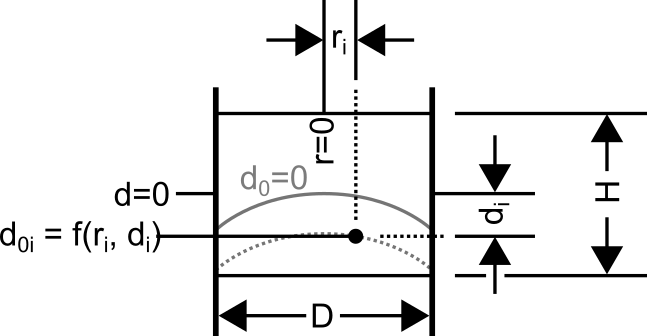
# Figures



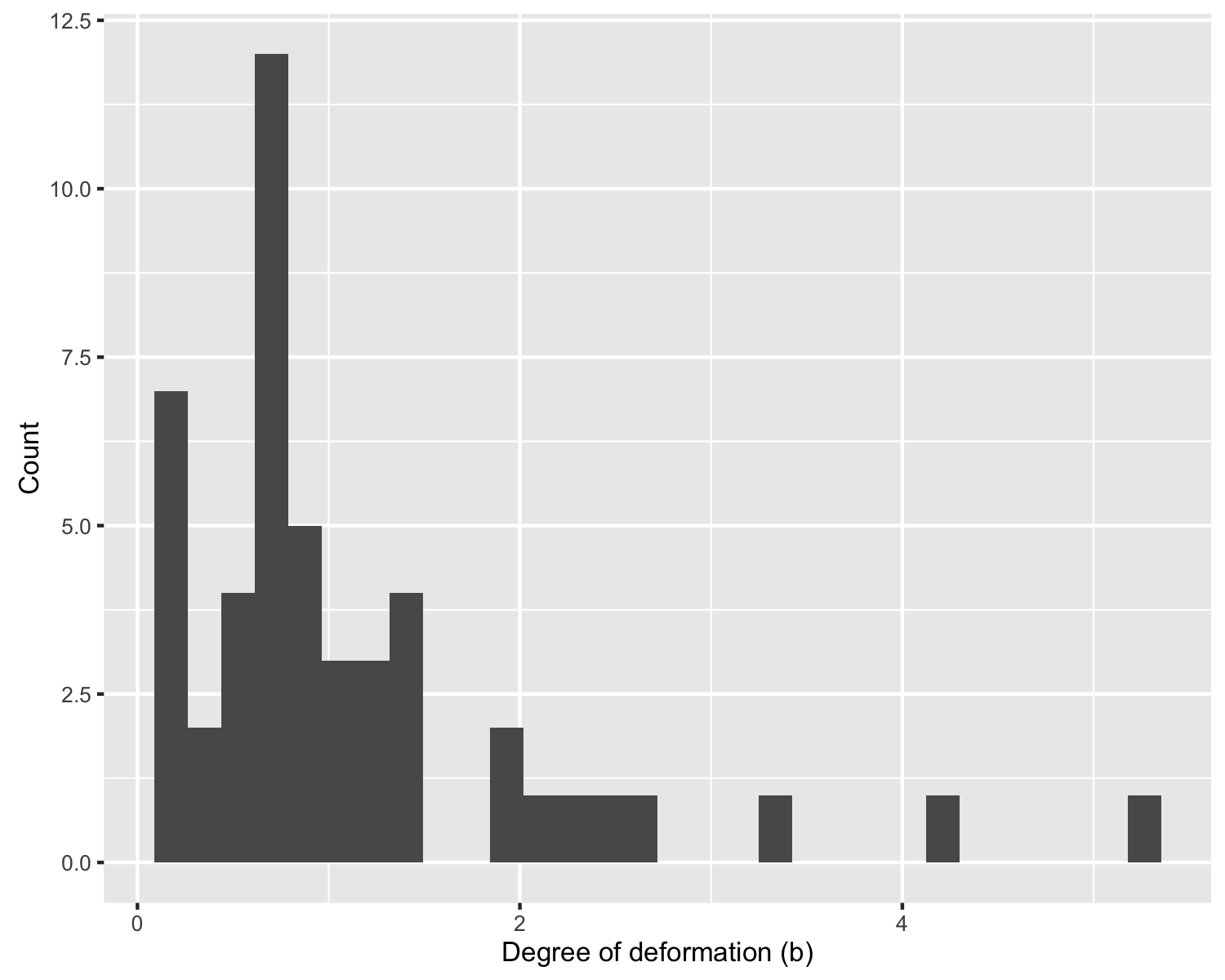
**Fig. 1** Ideal patterns of deformation according to the logarithmic deformation function (Acton et al. 2002).



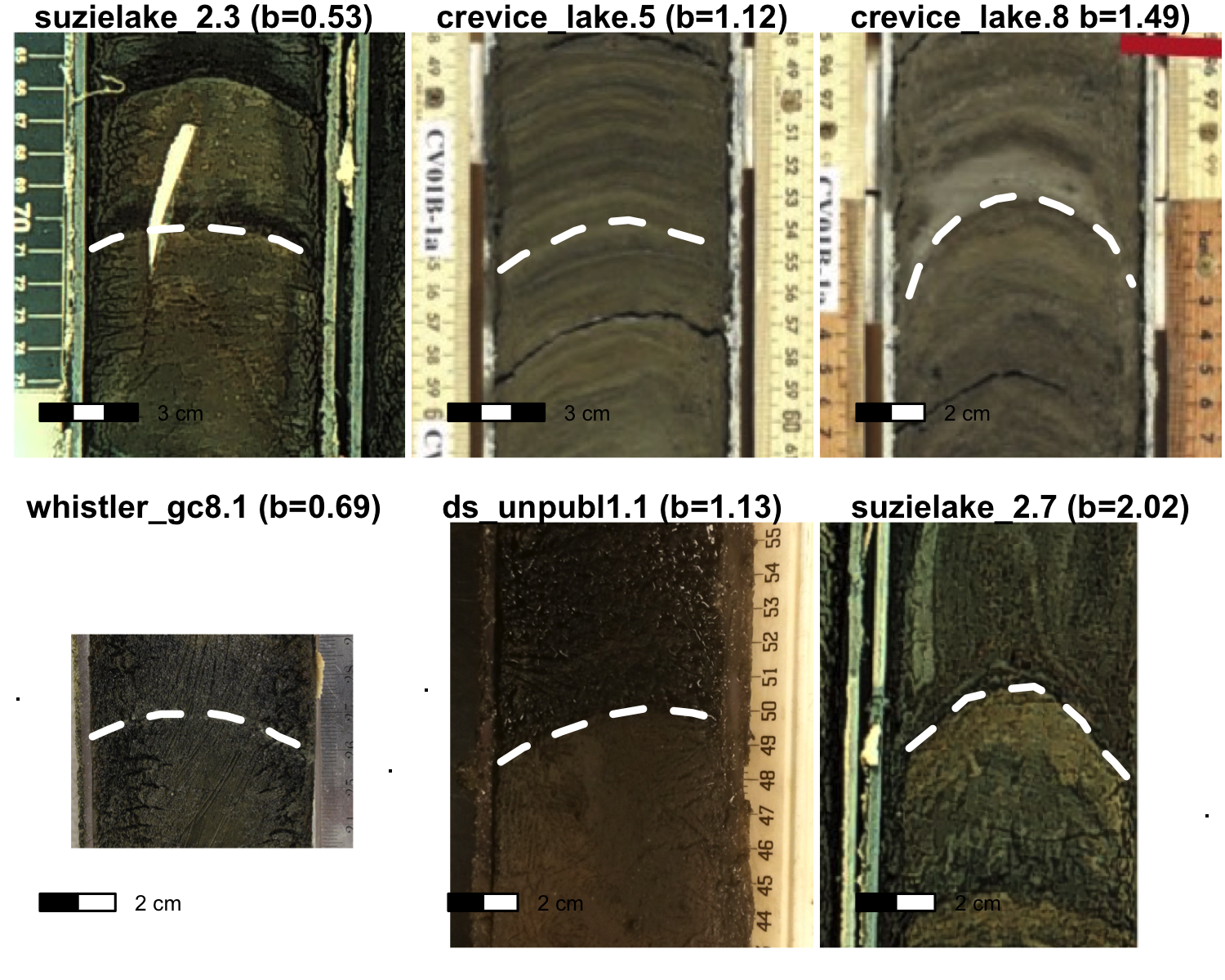
**Fig. 2** Schematic of how adjacent deformed strata may become incorporated into a single horizontal section of a core.



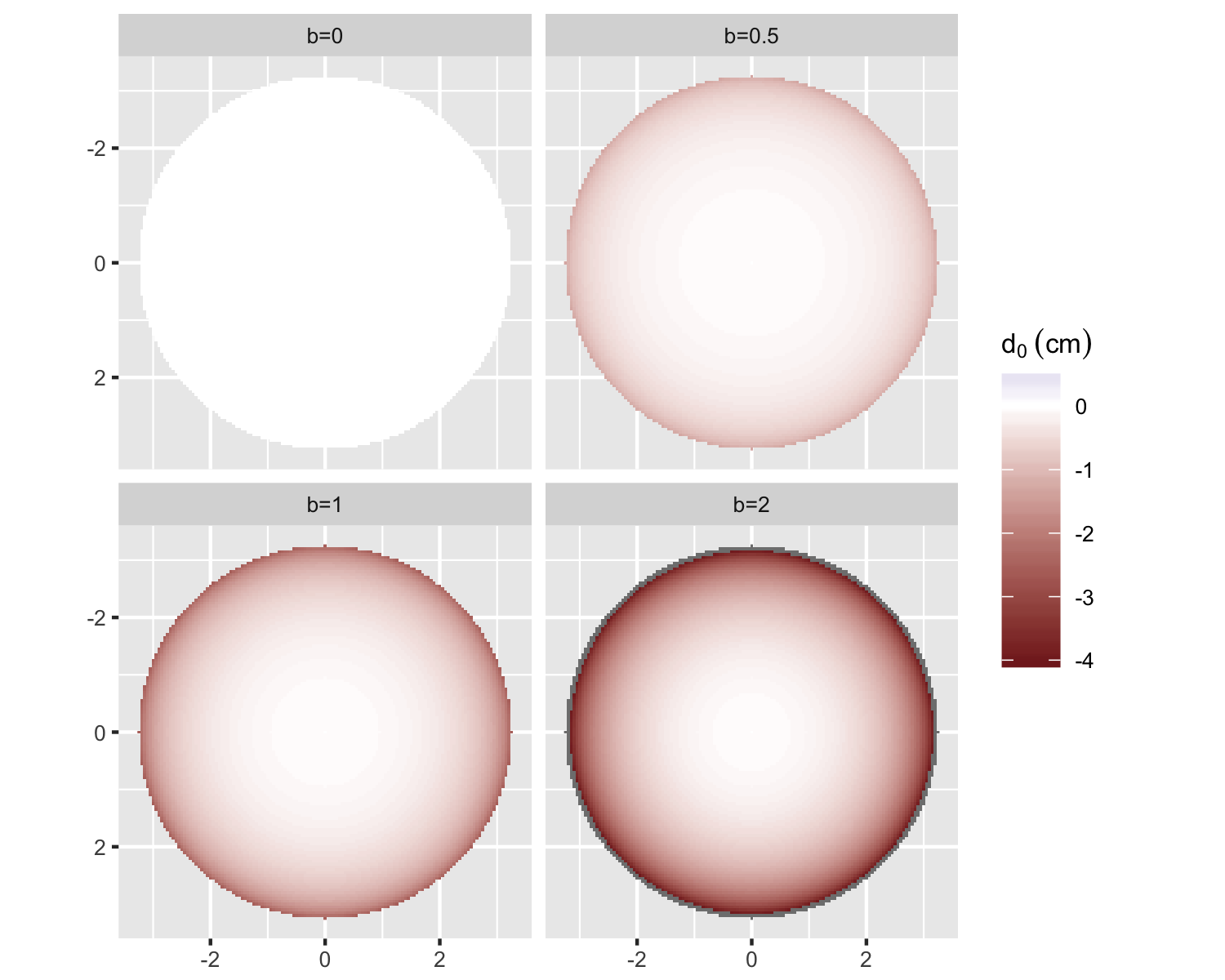
**Fig. 3** Schematic of variables used in the deformation model. Models were produced for sections of diameter D and thickness H. Each point i in the section had a coordinate di and ri, which were used to calculate the depth prior to convex upward deformation (d0i)



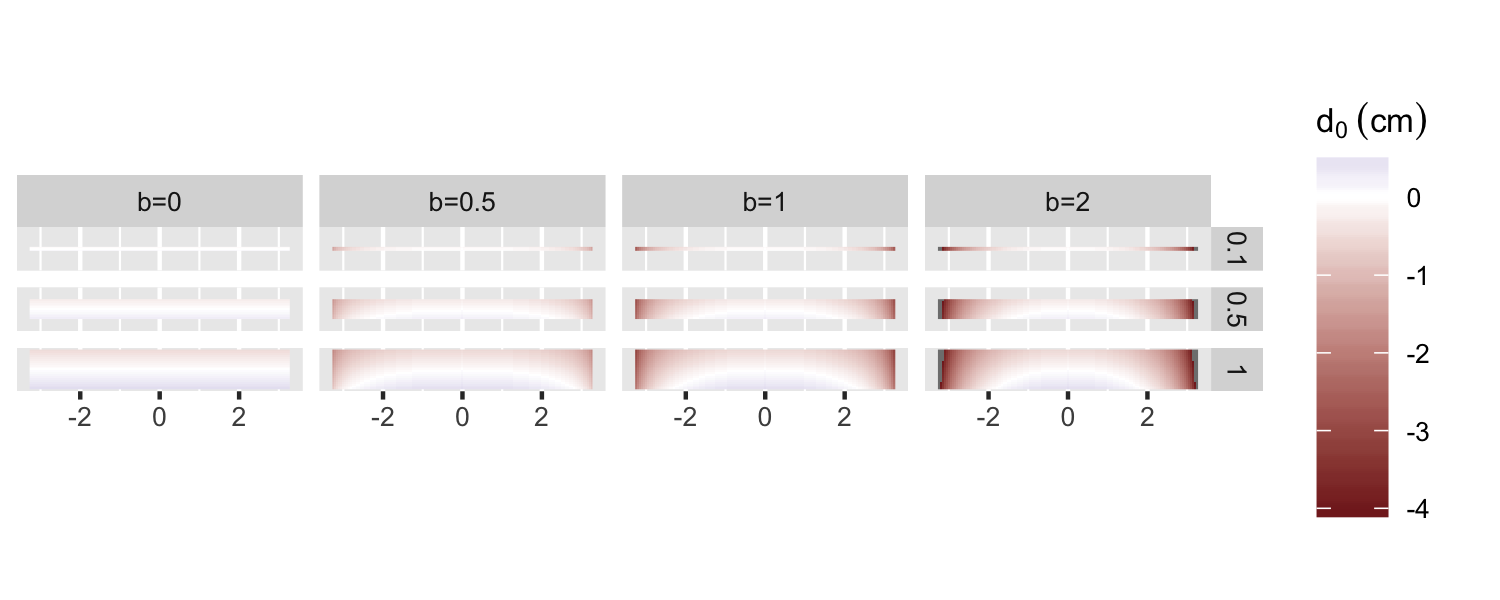
**Fig. 4** Histogram of degrees of deformation (b) from digitized layers. Higher degrees of deformation corresponded to strata that were more deformed; lower degrees of deformation corresponded to strata that were less deformed.



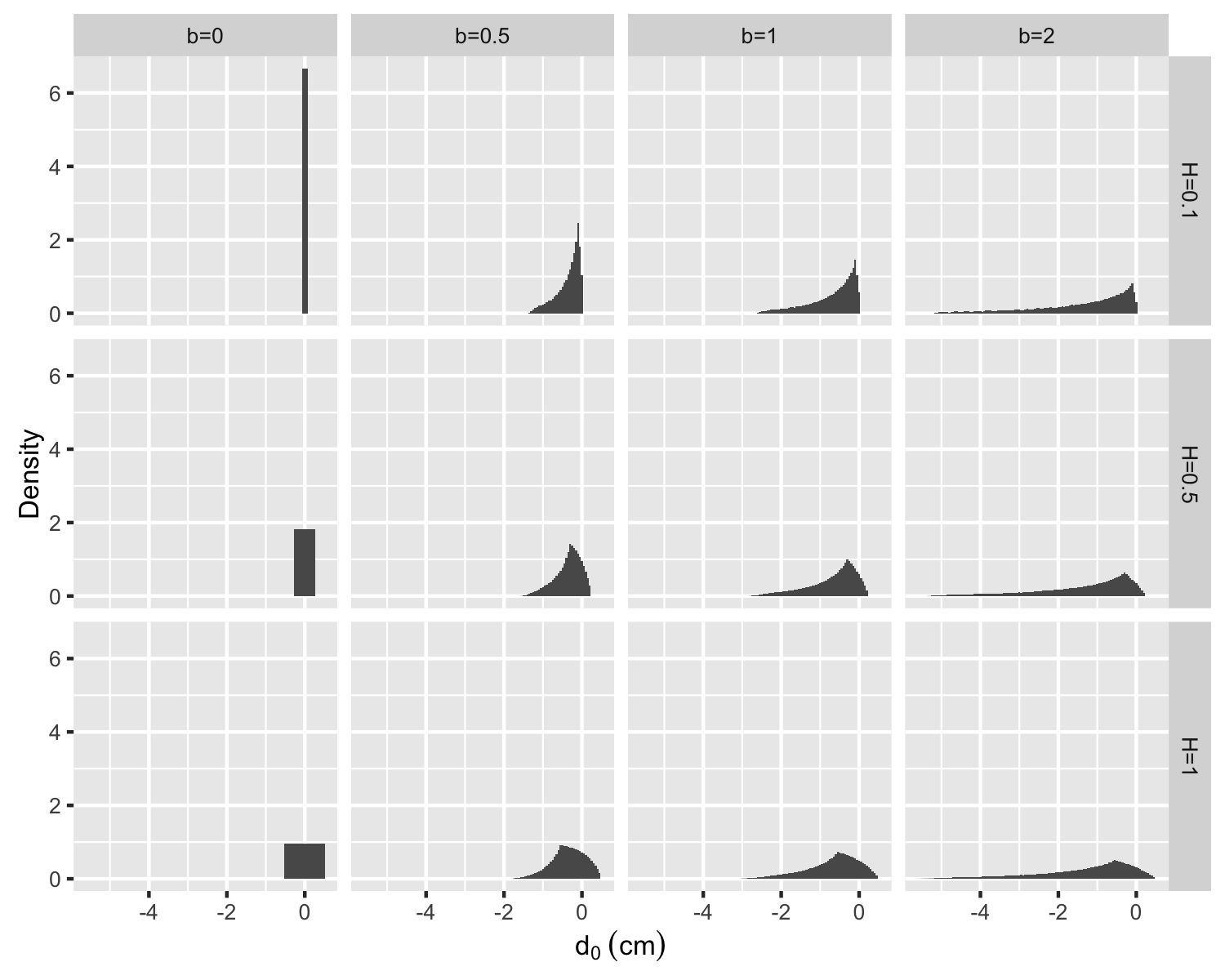
**Fig. 5** Representative layers for selected degrees of deformation.



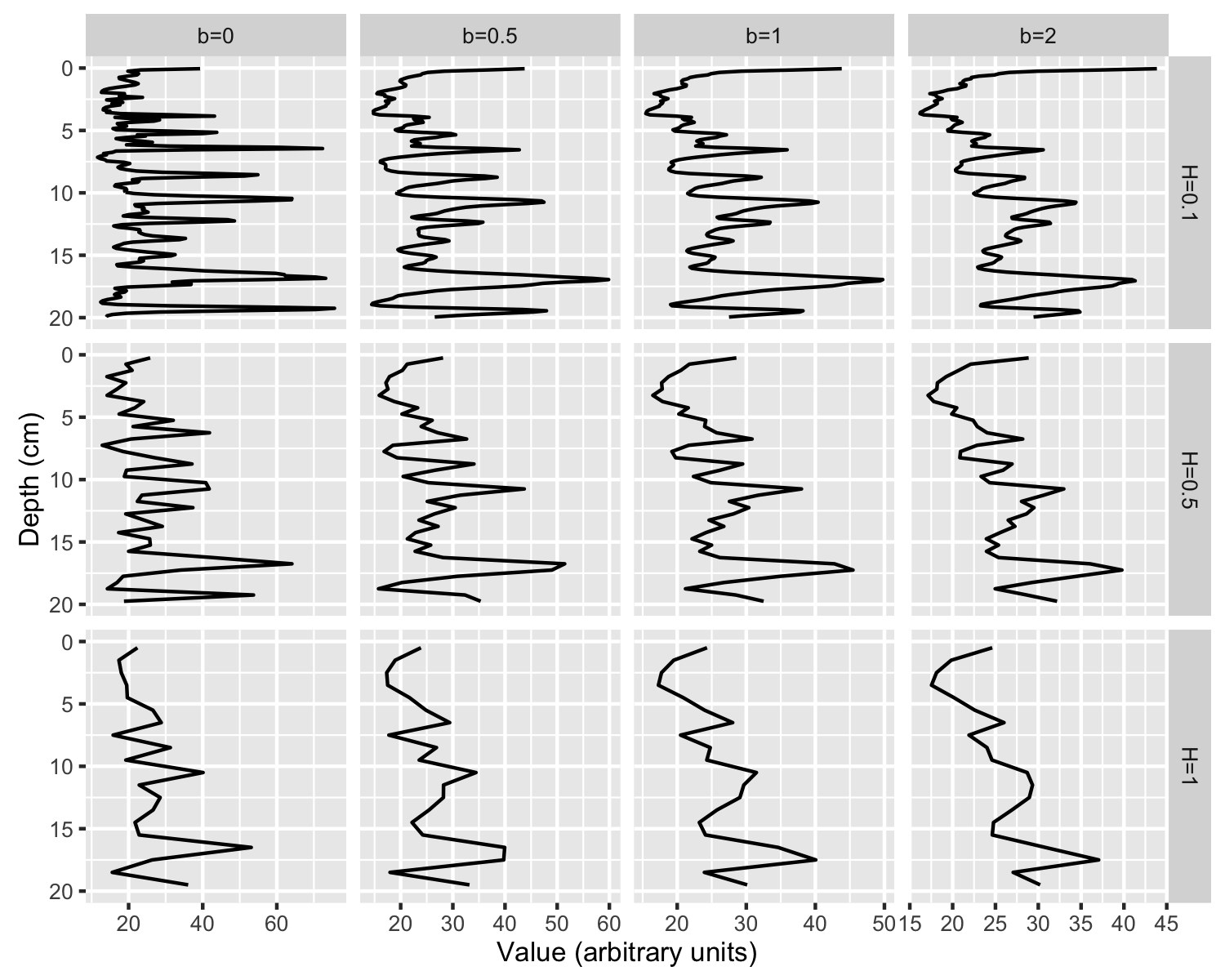
**Fig. 6** Distribution of d0 for d=0 by degree of deformation. Value b=0 indicates no deformation; b=2 indicates maximum deformation in the model. Coordinates are in centimeters.



**Fig. 7** Distribution of d0 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 d0 values modeled for multiple deformation coefficients and slice sizes. Wide distributions indicate that a wide range of original depths (d0) contributed to that slice. Negative d0 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

**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 di and ri, which were used to calculate the depth prior to convex upward deformation (d0i)

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