SnowEx23 Mar23 IOP Computed Tomography Snow Microstructure, Version 1 Technical Reference

1 INTRODUCTION

1.1 Summary

This data set characterizes snow microstructure for 11 snow pits from the SnowEx 2023 NASA field campaign Intensive Observation Period (March 2023) using microcomputed tomography (micro-CT). Included with this data set are two- and three-dimensional microstructural analysis of snow samples, black and white binary images of each sub-sample scan, and raw instrument data. Containers of snow were collected at 6 snow pits in approximately 17 cm intervals. There were approximately 5-8 discrete containers per pit and each container had an ~1-2 cm overlap with the sample below. A 6-cm section of snow was dissected from each container of snow, which were analyzed in ~2 cm sub-sections. Each sub-section was scanned in three intervals using a micro-CT instrument. The three interval scans comprise multiple slices and were combined into the reconstructed final scan used for calculating the snow microstructural data.

1.2 Parameters

This data set presents snow microstructural data, which encompasses multiple variables. The following two-dimensional variables are available for each sample and subsample:

- the number of objects
- total region of interest (ROI)
- object area, percent object area
- total ROI perimeter
- object perimeter
- object perimeter/object area
- average object area
- average object area-equivalent circle diameter
- surface convexity index
- Euler number
- number of closed pores
- area of closed pore
- perimeter of closed pores
- closed porosity
- area of open space
- total area of pore space
- open porosity
- total porosity
- total orientation
- eccentricity
- structure thickness
- structure separation
- structure linear density
- fractal dimension
- intersection perimeter

The following three-dimensional (morphometry) variables are available for each snow pit:

- VOI volume
- object volume
- percent object volume
- VOI surface

- intersection surface
- object surface/volume ratio
- object surface density
- surface convexity index
- centroid(s)
- moments of inertia
- radii of gyration
- product(s) of inertia
- orientation
- structure model index
- structure thickness
- structure linear density
- structure separation
- fractal dimension
- number of objects
- number
- volume and surface of closed pores
- closed porosity
- volume of open pore space
- open porosity, total porosity
- Euler number, connectivity
- connectivity density
- degree of anisotropy
- Eigenvalue(s)
- specific surface area

1.3 File Information

1.3.1 Format and Naming Convention

The data are available in 11 multifile granules. The organization of each granule is described below and in Table 1.

Each multifile granule represents a single snow pit, which are named according to the following convention:

`SNEX23_MAR23_CTSM_[pitID]_20230307-20230316_v01.0`,

where `SNEX23_MAR23_CTSM` is the data set short name, [`pitID`] is the unique snow pit identifier, and `20230307-20230316` is the date range of the sampling period.

Each granule contains three `.tgz` files which follow the same naming convention as the granule, with the addition of a variable indicating the data parameter, as follows:

`SNEX23_MAR23_CTSM_[parameter]_ [pitID]_20230307-20230316_v01.0.tgz`,

where the available parameters include: `IMAGES`, `RAW`, and `CSV`.

The `IMAGES` .tgz files each contain subfolders with the processed images and header files for each sampling range. These subfolders are named as follows:

`SNEX23_MAR23_CTSM_ [pitID]_[D1_D2]_rec_voi_snow_v01.0`, where [D1_D2] represents the sampling range, expressed as a depth within the snow pit wall between D1 cm and D2 cm.

The CSV .tgz file contains the processed 2D and 3D data for each snow pit, available as four .csv files which are named as follows:

SNEX23_MAR23_CTSM_[datatype]_ [pitID]_v01.0.csv,

where [datatype] is 2DIA (2D analysis), SDSD (structure separation distribution), SDSM (3D scalar morphometry), and SDTD (3D structure thickness distribution).

The RAW .tgz file contains raw data analysis file for each sampling range, formatted as .txt files.

Table 1. Multifile Granule Organization

<table>
<tr><th>Granule →</th><th>.tgz Files →</th><th colspan="2">Subfolders/Data files</th></tr>
<tr><td rowspan="3">11 multi-file granules, 1 granule per snow pit</td><td>IMAGES</td><td>Subfolders; 1 per sampling range</td><td>Processed .png image files for each sampling range, representing snow/no snow from each individual micro-CT x-ray imaging slice. Also included are header files containing the metadata used during image processing (.bmp and .txt).</td></tr>
<tr><td>CSV</td><td colspan="2">Processed data, available in 4 .csv files as follows:
• 2DIA: 2D analysis
• SDSD: 3D structure separation distribution
• SDSM: 3D scalar morphometry
• SDTD: 3D structure thickness distribution</td></tr>
<tr><td>RAW</td><td colspan="2">Raw analysis data for each sampling range, formatted as .txt files. These data were used to create the data files available in the CSV .tgz file</td></tr>
</table>

1.4 Spatial Information

1.4.1 Coverage

Northernmost Latitude: 70.08434° N

Southernmost Latitude: 64.69925° N

Easternmost Longitude: 147.48583° W

Westernmost Longitude: 149.59716° W

1.4.2 Geolocation

This data set conforms to the WGS 84 coordinate reference system (EPSG 4326).

1.5 Temporal Information

1.5.1 Coverage and Resolution

7 March 2023 to 16 March 2023

2 DATA ACQUISITION AND PROCESSING

2.1 Background

Quantitative snow microstructural data provides essential insight into the process of microwave radiation transfer within a snowpack, and is integral for interpreting data collected by remote sensing instruments, such as NASA's SWE Synthetic Aperture Radar and Radiometer (SWESARR). Microcomputed tomography (micro-CT) provides a non-destructive means of analyzing the two- and three-dimensional microstructure of snow samples. This data set presents microstructural data from snow samples extracted from eleven snow pits dug during the SnowEx 2023 Intensive Observation Period (IOP) between 7-16 March, 2023. More information about the SnowEx 2023 IOP, including study location details, snow pit sampling strategy, and other core observations can be found in the NASA SnowEX 2023 Experiment Plan.

2.2 Acquisition

Snow microstructure samples were collected from 11 sampling locations in Alaska; 7 snow pits were located in tundra environments in the North Slope region and 4 snow pits were located in boreal environments within the Bonanza Creek Experimental Forest, near Fairbanks, AK. Samples were collected along the full-depth profile of the snow pit wall, from the snow surface to the ground, using sample containers 18 cm in length with a 10 cm^2 horizontal cross-sectional area. Each sample was collected with a 1-2 cm overlap in depth with the sample immediately above to ensure full coverage and to account for edge effects caused by cutting and manipulating the snow samples. All samples were collected as pure snow and stored and shipped back to the US Army Corp of Engineers Cold Regions Research and Engineering Laboratory (CRREL) laboratory in Hanover, NH. Dry ice was used to maintain a cold temperature during transit.

At the lab, the snow samples were divided into sub-samples measuring 2 cm in length, with a horizontal cross-sectional area of 4 cm^2. Each sub-sample was scanned using a cold-hardened Skyscan1173 Bruker Micro-CT scanner at a resolution of 20 microns. The raw data output by the micro-CT scanner consists of a series of greyscale x-ray images of the snow sub-samples which can be reconstructed into a three-dimensional point cloud representing the snow phase and the corresponding air phase.

2.3 Processing

Following scanning, the output images are binarized using the segmentation methods outlined in Freitag et al. (2004), which uses a threshold value equal to the mean of the maxima in the bimodal grey-level histograms that represent the white (snow) and black (air) segments of each sample. For these samples, the threshold is based on an average of the histograms for the individual scan that is performed. This threshold value establishes a fixed range of grayscale values which represent snow; all values outside the threshold represent air. Despeckling is also performed on the binarized data, which removes clusters of pixels that are smaller than a specified area diameter. The thresholding values and despeckling parameters are available in the `RAW` data files for each sample.

The software package CT Analyzer (CTan, published by Bruker) is used to calculate the raw morphometric parameters in two and three dimensions. Two-dimensional parameters are calculated using cross-section images of each sample, both individually and integrated over a volume of interest (VOI). Three-dimensional parameters are calculated based on a volume model generated in the reconstruction phase. These parameters can also be found in the `RAW` data files for each sample.

This raw CTAN data is then concatenated (by depth) into four .csv files for each snow pit: 1) the 2D analysis, 2) the 3D scalar morphometry results, 3) the 3D structure thickness distribution and 3D structure separation distribution. A full description of the 2D and 3D parameters are available in Table 3 and Table 4 in the Appendix.

2.4 Instrumentation

All analyses were performed using a Bruker Skyscan1173 Micro-CT instrument using the settings listed in Table 2 below:

Table 2. Instrumentation Settings

Scan resolution	20 μm
Scan duration	~ 12 minutes
Step rotation	0.6 degrees
Exposure	330 ms
Voltage	40 kV
Current	20 us
Filter	None

3 REFERENCES

Freitag J, Wilhelms F, Kipfstuhl S. 2004. Microstructure-dependent densification of polar firn derived from X-ray microtomography. Journal of Glaciology: 50(169):243-250. doi:10.3189/172756504781830123

4 APPENDIX

4.1 Raw Data Files

Each raw data file (`RAW`) begins with a header indicating the version of CT Analyser (CTAN) software used, name of the dataset, file type, image size (in pixels), total number of images making up the 3D data set, the range of the VOI vertical dimensions within scanned sample, number of images within the defined Volume of Interest (VOI), the number of images within the VOI, the vertical range of the images within the VOI, the spacing between images, and the pixel size (in microns, um The parameters of the data processing steps are listed, including thresholding values used to covert greyscale values to binary values and despeckling.

Also included in each raw file are details about the stereology results, 2D, and 3D analysis. The stereology analysis includes measurements of thickness, separation, and number/linear density based on the mean intercept length (MIL) analysis which represents an alternative basis for these architectural measurements.

The 2D analysis results begin with a header that lists the date and time the analysis was conducted and specifies “2D analysis”. The rest of the header includes the operator and computer name, the time to perform the calculation, the dataset folder, the pixel size (in microns, um), and the lower and upper grey scale thresholds. Data are listed per 2D horizontal slice as represented by one bitmap in the stack of images comprising the total VOI, with the vertical resolution between 2D slice equal to the pixel size. The number of slices is equal to the number of images within the volume of interest (VOI), given in the header. The 2D analysis header is followed by 28 columns of data. Column names are described in Table 3.

The 3D analysis data begins with a header with the first line containing the date and time of the data analysis, and the designation “3D analysis.” Following the first line, the header contains the date and time of the data analysis, the operator identity, the computer name, computation time for the 3D analysis, the data set name, and the location of the data set on the computer. The header also contains the description of the data set, including the number of layers, the lower vertical position of the VOI, the upper vertical position of the VOI, the pixel size, and the upper and lower greyscale thresholds. Column names are described in Table 4.

Table 3. 2D Data Parameters

Variable	Description	Units/Format
File name	Bitmap file name corresponding to one horizontal slice within the stack of images comprising one 3D micro-CT scan	Pit name_depth in pit_resolution_reconstruction_voi.bmp
Z position	Vertical position within stack of images/absolute position within sample	mm from bottom of sample
Number of objects	Total number of identified discrete objects in image (i.e., not connected to one another)	
Total ROI area	The area within the defined region of interest (ROI).	mm^2
Object area	The mean of the cross-sectional object for all slices in the selected range of the ROI.	mm^2
Percent object area	The proportion of the ROI occupied by binarized solid objects.	%
Total ROI perimeter	The 2D perimeter of the defined region of interest of each individual slice.	mm
Object perimeter	The mean of the cross-sectional object perimeter for all slices in the selected range of the VOI.	mm
Object perimeter/ area ratio	The mean of the cross-sectional object perimeter for all slices in the selected range of the VOI divided by the area of the ROI.	1/mm
Average object area	The mean area of discreet 2D objects in a single cross-sectional image slice. This parameter can be an indicator of structural connectivity – in interconnected structures high connectivity results in highly interconnected objects which are few in number in a single cross-section – by contrast fragmentation results in larger numbers of smaller objects.	mm
Average object area-equivalent circle diameter	The mean equivalent circle diameter of all discreet 2D objects in a single cross-sectional image slice, defined as the diameter of the equivalent circle having the same area as the measured object.	mm

Surface convexity index	The surface convexity index calculates an index of relative convexity or concavity of the total solid surface, on the principle that concavity indicates connectivity, and convexity indicates isolated disconnected structures. Where structural results in enclosed air spaces, then dilation of solid surfaces will contract the surface. By contrast, open ends will have their surface expanded by surface dilation. As a result, lower surface convexity index signifies better connected trabecular lattices while higher surface convexity index means a more disconnected solid structure. A prevalence of enclosed cavities and concave surfaces results in negative values. This parameter is best considered as a relative index for comparing different scanned objects; its absolute value does not have much meaning.	1/mm
Euler number	The Euler number is an indicator of connectedness of a complex object. The Euler number measures the degree to which parts of the object are multiply connected (Odgaard et al. 1993). It is a measure of how many connections in a structure can be severed before the structure falls into two separate pieces. The components of the Euler number are the three Betti numbers: $\beta 0$ is the number of objects, $\beta 1$ the connectivity, and $\beta 2$ the number of enclosed cavities. The Euler-Poincare formula for a 3D object X is given: $\chi(X) = \beta 0 - \beta 1 + \beta 2$. In calculating the Euler number of an individual object, $\beta 0$ will always be 1. The values of $\beta 1$ and β 2 will therefore determine the single object's Euler number.	
Number of closed pores	Count of all the individually closed pores.	
Area of closed pores	Total cross-sectional area of all closed pores within the 2D slice.	mm^2
Perimeter of closed pores	Sum of the perimeter of all identified closed pores.	mm

Closed porosity	Closed porosity is measured in the 2D slice-by-slice analysis. Binarized objects are identified containing fully enclosed spaces, and closed porosity is the area of those spaces as a percent of the total area of binarized objects. Note that the denominator of total object area includes the closed pores. Closed porosity measurement ignores space which is not fully surrounded by solid. Note – closed porosity in 2D is usually much larger than the equivalent parameter measured in 3D; a space region is more likely to be surrounded by solid in a single cross-sectional plane in 2D than in all directions in 3D	%
Area of open pore space	The total area of all open pores within the ROI. An open pore is defined as any space located within the 2D slice that has any connection in 2D to the space outside the ROI.	mm^2
Total area of pore space	The total area of all open and closed pores within the ROI combinws.	mm^2
Open porosity	Percent open porosity is the area of open pores (as defined above) as a percent of the total ROI.	%
Total porosity	The total combined open and closed porosity.	%
Total orientation	The orientation of the major axis of the object, in degrees. Orientation is defined in the upper hemisphere only, with values from 0-180 degrees.	degree
Eccentricity	Eccentricity is a 2D shape analysis of discreet binarized objects. Objects are approximated as ellipses, and eccentricity is an elliptic parameter indicating departure from circular shape by lengthening (a circle is an ellipse with an eccentricity of zero). An ellipse is defined as having two focal points (F1 and F2), a center (C) and major and minor axes. The major axis is defined as 2a where a is the “semi major axis”; likewise, 2b is the minor axis. Eccentricity e is a function of the (semi)major and minor axes such that: e = sqrt(1-b^2/a^2). Higher	

	eccentricity means generally elongated objects, while decreased values means an approach toward circular shape.	
Structure thickness	Calculation – or estimation – of structure thickness from 2D measurements requires an assumption about the nature of the structure (a “structural model”). Three simple structure models, the parallel plate, the cylinder rod and the sphere model, provide the range of values within which a hypothetical “true” thickness will be located. Thickness defined by these models (Parfitt et al. 1987) is given by the relation the surface to volume ratio (S/V) in mm^{-1}: Parallel plate model: 2/(S/V); Cylinder rod model: 4/(S/V); Sphere model: 6/(s/V). Note that for the above equations, if the surface measurements are made from one or a few 2D cross-sectional slices, then the numerator (2, 4 or 6) should be divided by a correction factor of 1.199 to approximate a correction from 2D to 3D. The plate model is used in these calculations.	mm
Structure separation	Structure separation is essentially the thickness of the spaces as defined by binarization within the VOI. It can also be calculated from 2D images with model assumptions. Structure separation can be defined by the parallel plate model (=(1/structure linear density)-structure thickness) and the cylinder/rod model: structure diameter x sqrt(pi/4 x total volume/solid volume)-1. The plate model is used in these calculations.	mm
Structure linear density	Structure linear density implies the number of traversals across a solid structure made per unit length by a random linear path through the volume of interest (VOI). Plate and rod model 2D-based definitions of structure linear density again take the corresponding structure thickness values. Plate model is used for these calculations.	1/mm

Fractal dimension	Fractal dimension is an indicator of surface complexity of an object, which quantifies how that object's surface fills space. Fractal dimension is calculated using the Kolmogorov or "box counting" method. For 2D calculation of FD, the crossection image is divided into an array of equal squares, and the number of squares containing part of the object surface is counted. This is repeated over a range of square sizes such as 2-100 pixels. The number of squares containing surface is plotted against square length in a log-log plot, and the fractal dimension is obtained from the slope of the log-log regression.	
Intersection Perimeter	Intersection perimeter is the perimeter of the ROI intersected by solid binarized objects, that is, the part of the ROI boundary surface that runs through solid objects. The intersection perimeter is calculated for each separate cross-section level, but is also integrated over all VOI levels in the data summary at the head of the 2D analysis report. Note that the intersection perimeter calculated in 2D does not include vertical (between-cross-section) surfaces, only perimeters of objects within cross-sections.	mm

Table 4. 3D Data Parameters

Variable	**Description**	**Units/Format**
Total volume of interest volume	Total volume of the volume-of-interest (VOI). The 3D volume measurement is based on the marching cubes volume model of the VOI.	mm^3
Object volume	Total volume of binarized objects within the VOI. The 3D volume measurement is based on the marching cubes volume model of the binarized objects within the VOI.	mm^3

Percent object volume	The proportion of the VOI occupied by binarized solid objects. This parameter is only relevant if the studied volume is fully contained within a well-defined biphasic region of solid and space, and does not for example extend into or beyond the boundary of the object. The meaningfulness of measured percent volume depends on the criteria applied in selecting the volume of interest. Where the ROI / VOI boundaries are loosely drawn in the surrounding space around an object for instance, then % object volume has no meaning.	%
Total VOI surface	The surface area of the volume of interest, measured in 3D (Marching cubes method).	mm^2
Object surface	The surface area of all the solid objects within the VOI, measured in 3D (Marching cubes method).	mm^2
Intersection surface	Intersection surface is the surface of the VOI intersected by solid binarized objects, or the part of the VOI boundary surface that runs through solid objects.	mm^2
Object surface / volume ratio	The ratio of solid surface to volume measured in 3D within the VOI. Surface to volume ratio or “specific surface” is a useful basic parameter for characterizing the thickness and complexity of structures.	1/mm
Object surface density	The ratio of surface area to total volume measured as described above in 3D, within the VOI.	1/mm

Surface convexity index	The surface convexity index calculates an index of relative convexity or concavity of the total solid surface, on the principle that concavity indicates connectivity, and convexity indicates isolated disconnected structures. Where structural results in enclosed air spaces, then dilation of solid surfaces will contract the surface. By contrast, open ends will have their surface expanded by surface dilation. As a result, lower surface convexity index signifies better connected trabecular lattices while higher surface convexity index means a more disconnected solid structure. A prevalence of enclosed cavities and concave surfaces results in negative values. This parameter is best considered as a relative index for comparing different scanned objects; its absolute value does not have much meaning.	1/mm
Centroids x, y, z	The centroid is the 3D XYZ coordinate of the average Cartesian vectorial position of all voxels within the VOI.	mm
Moments of inertia x, y, z	The moment of inertia is a basic strength index and indicates the resistance to rotation of a cross-section about a chosen axis (assuming uniform material stress-strain strength properties). Moment of inertia is the rotational analogue of mass for linear motion and must be specified with respect to a chosen axis of rotation. For a point mass (represented by an image pixel) the moment of inertia (I) is simply the mass (m) times the square of perpendicular distance (r) to the rotation axis, $I = mr^2$.	mm^5

Polar moment of inertia	The polar moment of inertia is a basic strength index in polar coordinates and indicates the resistance to rotation of a cross-section about a chosen axis (assuming uniform material stress-strain strength properties). Moment of inertia is the rotational analogue of mass for linear motion and must be specified with respect to a chosen axis of rotation. For a point mass (represented by an image pixel) the moment of inertia (I) is simply the mass (m) times the square of perpendicular distance (r) to the rotation axis, $I = mr^2$.	mm^5
Radius of gyration (x, y, z)	The radius of gyration is defined as the radial distance to a point which would have a moment of inertia the same as the body's actual distribution of mass, if the total mass of the body were concentrated there.	mm
Polar radius of gyration	The radius of gyration in polar coordinates is defined as the radial distance to a point which would have a moment of inertia the same as the body's actual distribution of mass, if the total mass of the body were concentrated there.	mm
Product of inertia (xy, xz, yz)	The products of inertia are the sums of the products formed by multiplying the mass (m) of each point of the body or system by the product of two of the coordinates x_k, y_k, z_k of the point.	mm^5
Total orientation (theta, phi)	The orientation of the major axis of the object, in degrees. Orientation is defined in the upper hemisphere only, with values from 0-180 degrees.	°
Structure model index	Structure model index indicates the relative prevalence of rods and plates in a 3D structure. SMI involves a measurement of surface convexity. An ideal plate, cylinder and sphere have SMI values of 0, 3 and 4 respectively. The calculation of SMI is based on dilation of the 3D voxel model, i.e., artificially adding one voxel thickness to all binarized object surfaces (Hildebrand et al. 1997b).	

Structure thickness	With 3D image analysis by micro-CT a true 3D thickness can be measured which is model-independent. Local thickness for a point in solid is defined by Hildebrand and Ruegsegger (1997a) as the diameter of the largest sphere which fulfils two conditions: the sphere encloses the point (but the point is not necessarily the center of the sphere); the sphere is entirely bounded within the solid surfaces.	mm
Structure linear density	Structure linear density implies the number of traversals across a solid structure made per unit length on a random linear path through the VOI. This parameter is measured in CT-analyser in 3D by application of the equation for the parallel plate model (fractional volume/thickness), but using a direct 3D measurement of thickness. Note that the optional stereology analysis (not included in this report) includes measurements of thickness, separation and number/linear density based on the mean intercept length (MIL) analysis which represents an alternative basis for these architectural measurements.	1/mm
Structure separation	Structure separation is essentially the thickness of the spaces as defined by binarization within the VOI. It is measured directly and model-independently in 3D by the same method used to measure structure thickness (see above), just applied to the space rather than the solid voxels.	mm
Fractal dimension	Fractal dimension is calculated using the Kolmogorov or “box counting” method. It is calculated in both 2D and 3D in CTan. For the 3D calculation of the fractal dimension, the volume is divided into an array of equal cubes, and the number of cubes containing part of the object surface is counted. This is repeated over a range of cube sizes such as 2-100 pixels. The number of cubes containing surface is plotted against cube length in a log-log plot, and the fractal dimension is obtained from the slope of the log-log regression.	

Number of objects	The total number of discreet binarized objects within the VOI is reported. A discreet 3D object is a connected assemblage of solid (white) voxels fully surrounded on all sides in 3D by space (black) voxels.	
Number of closed pores	The total number of discreet binarized closed pores within the VOI is reported. A closed pore in 3D is a connected assemblage of space (black) voxels that is fully surrounded on all sides in 3D by solid (white) voxels.	
Volume of Closed Pores	The total volume of all closed pores within the VOI, as defined above (under “number of closed pores”).	mm^3
Surface of Closed Pores	The total surface area of all closed pores within the VOI, as defined above (under “number of closed pores”).	mm^2
Closed Porosity	Percent closed porosity is the volume of closed pores (as defined above) as a percent of the total of solid plus closed pore volume, within the VOI.	%
Volume of Open Pore Space	The total volume of all open pores within the VOI, is reported. An open pore is defined as any space located within a solid object or between solid objects, which has any connection in 3D to the space outside the object or objects.	mm^3
Open Porosity	Percent open porosity is the volume of open pores (as defined above) as a percent of the total VOI volume.	%
Total Volume of Pore Space	The total volume of all open and closed pores within the VOI.	mm^3
Total Porosity	Total porosity is the volume of all open plus closed pores (as defined above) as a percent of the total VOI volume.	%

Euler number	The calculation of Euler number in 3D uses the Conneulor method from Aarhus University, Denmark (Dr. Anders Odgaard; see Gunderson et. al. 1993). The Euler number is an indicator of connectedness of a 3D complex structure. The Euler number is characteristic of a three-dimensional structure which is topologically invariant (it is unchanged by inflation or compression or distortion of the structure). It measures the degree to which parts of the object are multiply connected (Odgaard et al. 1993). It is a measure of how many connections in a structure can be severed before the structure falls into two separate pieces. The components of the Euler number are the three Betti numbers: β_0 is the number of objects, β_1 the connectivity, and β_2 the number of enclosed cavities. The Euler-Poincare formula for a 3D object X is given: $\chi(X) = \beta_0 - \beta_1 + \beta_2$. Euler analysis provides a measure of connectivity density, indicating the number of redundant connections between structures per unit volume.	
Connectivity	Calculated using the Conneulor method of Gunderson HJG et al. (1993).	
Connectivity density	The connectivity density indicates the number of redundant connections between solid structures per unit volume.	$1/mm^3$

Degree of anisotropy (DA)	Isotropy is a measure of 3D symmetry or the presence or absence of preferential alignment of structures along a particular directional axis. Apart from percent volume, DA and the general stereology parameters of trabecular bone are probably the most important determinants of mechanical strength (Odgaard 1997). Mean intercept length (MIL) and Eigen analysis are used to calculate DA. Consider a region or volume containing two phases (solid and space), both having complex architecture. If the volume is isotropic, then a line passing through the volume at any 3D orientation will make a similar number of intercepts through the solid phase. Mean intercept length (MIL) analysis measures isotropy (it is usual to talk of measurement of the negative quantity anisotropy). Mean intercept length is found by sending a line through a 3D image volume containing binarized objects, and dividing the length of the test line through the analyzed volume by the number of times that the line passes through or intercepts part of the solid phase. Note that in this MIL calculation the intercept length may correlate with object thickness in a given orientation but does not measure it directly. Therefore it will give an accurate result if analyzing a volume containing a sufficiently large number of objects, but is not suitable for analysis of single or small numbers of objects. For the MIL analysis, a grid of test lines is sent through the volume over a large number of 3D angles. The MIL for each angle is calculated as the average for all the lines of the grid.	Degree of anisotropy (DA)
Eigenvalue (1, 2, 3)	The three eigenvalues are each an index of the relative MIL values in each of the three axes described by the eigenvectors. These three directions are also expressed as the eigenvectors, and are orthogonal to each other.	

Structure thickness distribution	The structure thickness distribution is a list of the distribution of structure thickness values list of ranges, the midrange of the bins, the volume represented by the bin, and the percent volume within the range of structure thickness values.	mm
Standard deviation of structure thickness	Standard deviation of structure thickness	mm
Structure separation distribution	The structure separation distribution is a list of the distribution of structure separation values list of ranges, the midrange of the bins, the volume represented by the bin, and the percent volume within the range of structure separation values.	mm
Standard deviation of structure separation	Standard deviation of structure separation	mm