Digital Publication 3

DIGITAL STRUCTURE MAP OF THE EAGLE FORMATION, CENTRAL AND EASTERN MONTANA

Jay A. Gunderson

Montana Bureau of Mines and Geology

Montana Bureau of Mines and Geology

INTRODUCTION

The Eagle Formation (Fm) in Montana is a Late Cretaceous sandstone, shaly sandstone, and sandy shale that can be an important groundwater aquifer or a source for petroleum, depending on location within the State. It comprises marginal marine sandstones along a north–south trend in central Montana, grading eastward into shale of the upper Gammon Fm. The Eagle and Gammon Formations are relatively flat-lying across central and eastern Montana, except near major structural uplifts that either originated, or were reactivated, during the Late Cretaceous and Early Tertiary (fig. 1).

Hand-contoured structure maps of the Eagle Fm were generated in the 1980s (e.g., Bergantino, 2012, 2019) and have been widely used by geologists, hydrogeologists, and water-well drillers. However, digital maps are much more flexible than paper maps; they can be easily manipulated, integrated with other data, and used in a variety of computer applications.

The purpose of this work is to create a digital structure map of the top of the Eagle Formation (and its stratigraphic equivalents) for central and eastern Montana, east of the Rocky Mountain Fold and Thrust Belt. The product is an ESRI map package containing the stratigraphic picks of the Eagle Fm from oil and gas wells, a raster surface (and XYZ grid) covering the eastern two-thirds of Montana, and a set of structure contour lines generated from the grid.

METHODS

The elevations of the top of the Eagle Formation (Gammon Fm in eastern Montana; Virgelle Member of the Eagle Fm west of the Sweetgrass Arch in northwestern Montana) were interpreted from geophysical logs for 6,042 petroleum wells in eastern and central Montana. Geophysical logs were obtained from MJ Systems of Calgary, Alberta and well header and location data were acquired from the Montana Board of Oil and Gas.

Well header data and formation top elevations were also obtained for 651 wells located in neighboring states and provinces from the North Dakota Industrial Commission Department of Mineral Resources, Wyoming Oil and Gas Conservation Commission, South Dakota Department of Environment and Natural Resources, Alberta Geological Society, and Saskatchewan Ministry of Energy and Resources. Elevations for the top of the Eagle Fm (or its stratigraphic equivalent formation) from these organizations were used “as is,” without further interpretation.

Well data were loaded into the IHS PETRA software. The Eagle Fm elevations interpreted from well log data were gridded using a 2,500 m square grid spacing and PETRA’s “Least Squares Method” interpolation algorithm. Descriptions of the gridding/interpolation options used are provided in appendix A; these descriptions were taken directly from PETRA’s online documentation.

In structurally complex areas and near Eagle outcrops where well control is sparse, “control points” and “overlay contours” (hand-drawn contour lines) were used to guide the interpolation. Elevation control points were generated along the Claggett/Eagle contact (Vuke and others, 2007) using ESRI’s ArcGIS and extracting elevations from the 10-m Digital Elevation Model. Hand-drawn overlay contours were based on well data, geologic maps, and existing structure maps (e.g., Dobbin and Erdmann, 1955; Bergantino, 2012, 2019).

Post processing of the grid in PETRA included:

1. Hand-editing individual grid node elevations to remove gridding artifacts such as small bullseyes and other features that were geologically unlikely. The result is a more realistic grid surface and set of contour lines.
2. Setting grid nodes to null values along Eagle outcrop edges, state boundaries, and some large structural uplifts where the Eagle Formation is absent, such as the Sweetgrass Arch and the Pryor Mountains (fig. 1). For smaller structures where the Eagle Formation is also absent (e.g., Porcupine Dome, Bears Paw

Mountains, Little Rocky Mountains, Black Hills Uplift, and several small dome structures within the Central Montana Uplift), grid nodes were not forced to null values because doing so produces holes in the grid with unrealistic "stair-step," or jagged, edges. A more continuous grid is also convenient for grid-to-grid operations.

The final, edited XYZ grid from PETRA was imported into ArcGIS and converted to an ESRI raster using a 2,500 m cell size. The set of contour lines generated in PETRA were imported directly into ArcGIS.

The extent of valid Eagle structure data for this project is bounded by the approximate Claggett/Eagle contact exposed at the surface (Vuke and others, 2007), the State boundary, the easternmost fault of the fold and thrust belt in northwest Montana, the top of the Groat sandstone bed (probably equivalent with part of the Eagle Fm) in southwest Montana, and an arbitrary line extending from the Crazy Mountain Basin to the Beartooth Mountain Front in south-central Montana, roughly coincident with the extent of valid well data. These were used to develop boundaries (polygons) to remove contour lines and mask the raster surface where the top of the Eagle Fm is absent.

OUTPUT FILES

The data and results from this project are contained in the ArcGIS map package Eagle_Structure_Map.mpk (v. 10.5, 10.6, 10.7) and illustrated in plate 1. The coordinate reference system for the map package is NAD83 State Plane Montana FIPS 2500 (meters).

The map package contains the following elements:

Eagle_tops_data—Shapefile containing well header information and elevations of the top of the Eagle Fm from 6,693 oil and gas wells.

Eagle_raster_grid—A raster surface representing the elevation of the top of the Eagle Fm.

Eagle_contours—Structure contour lines generated from the grid in PETRA. The contour interval is 100 ft except in some areas of steeply dipping beds where contour intervals were increased to 500 ft or 1,000 ft to reduce the number of contour lines.

Clipping_boundaries—Clipping boundaries for the raster grid and contour lines, derived from the Claggett/Eagle contact exposed at the surface (Vuke and others, 2007), the State boundary, and other boundaries.

Simplified Geology—Folds, faults, and Eagle Fm surface outcrops (modified from Vuke and others, 2007). Also, polygons for areas where the Eagle Fm is absent.

Base layers—Cities, 100k quadrangles, counties, State boundary.

For portability to other software applications, Excel data files are provided for the Eagle Fm tops interpreted from oil and gas wells (eagle_topsdata.xlsx) and for the Eagle Fm structure grid (eagle_grid.xlsx). The structure grid is in XYZ format, where X is longitude, Y is latitude, and Z is elevation of the top of the Eagle Fm in feet.

DISCUSSION OF RESULTS

- There is high confidence in the accuracy of the raster surface and contour lines in major sedimentary basins and in the plains that lie between the basins and areas of structural deformation (fig. 1). In these regions, the Eagle Fm is relatively flat lying or gently dipping, and there are sufficient well data to generate an accurate surface using a 2,500 m grid spacing. The accuracy is less certain along the structurally complex Central Montana Uplift and near some of the other major uplifts where well data are sparse and beds are steeply dipping. Figure 2 provides a qualitative indicator of grid confidence; it shows the difference between the Eagle Fm elevation interpolated from the grid in PETRA and the Eagle Fm elevation picked in the wells. These elevation differences are included in the Eagle_tops_data shapefile and in the eagle_topsdata.xlsx file.

- Some grid/contour artifacts are a consequence of data distribution, grid size, and data interpolation between grid nodes. For example, some small structural folds and domes, mappable at the surface, may not be fully resolved using the 2,500 m grid spacing; they occur partly or entirely between grid nodes and are not constrained by well data. Other, somewhat larger structures may resolve in odd shapes because of their size and position with respect to grid spacing and well distribution. Several interpolation artifacts were removed or modified by hand-editing individual grid nodes.

- The area surrounding the Bears Paw Uplift in north-central Montana is affected by gravity slide faulting (fig. 1). The Eagle Fm occurs above the main glide plane and is included in the horizontally transported fault blocks. Because the stratigraphic offset between wells in adjacent fault blocks ranges from 700 to 1,600 ft (Reeves, 1946), the raster surface and contour lines within the faulted area should be used with caution.

ACKNOWLEDGMENTS

The contributions of several MBMG colleagues were critical to the success of this project. Bob Bergantino provided valuable technical reviews. His critique of several interim grid surfaces helped improve the gridding methods to minimize computer-generated artifacts while preserving interpretation of the geologic structure reflected in the grid. Jeremy Crowley and Paul Thale provided their support, guidance, and ArcGIS expertise throughout the project – from conception to final product design.

REFERENCES

Bergantino, R.N., 2012, Forsyth—Top of the Eagle Formation/Gammon Shale: Montana Bureau of Mines and Geology Open-File Report 617-E, 1 sheet, scale 1:250,000.

Bergantino, R.N., 2019, Lewistown—Top of the Eagle Formation: Montana Bureau of Mines and Geology Open-File Report 708-D, 1 sheet, scale 1:250,000.

Dobbin, C.E., and Erdmann, C.E., 1955, Structure contour map of the Montana plains: United States Geological Survey USGS Oil and Gas Maps 178-B, 1 sheet, scale 1:1,000,000.

Reeves, Frank, 1946, Origin and mechanics of thrust faults adjacent to the Bearpaw Mountains, Montana: Geological Society of America Bulletin, v. 57, p. 1033–1048.

Vuke, S.M., Porter, K.W., Lonn, J.D., and Lopez, D.A., 2007, Geologic Map of Montana: Montana Bureau of Mines and Geology Geologic Map 62, 73 p., 2 sheets, scale 1:500,000.

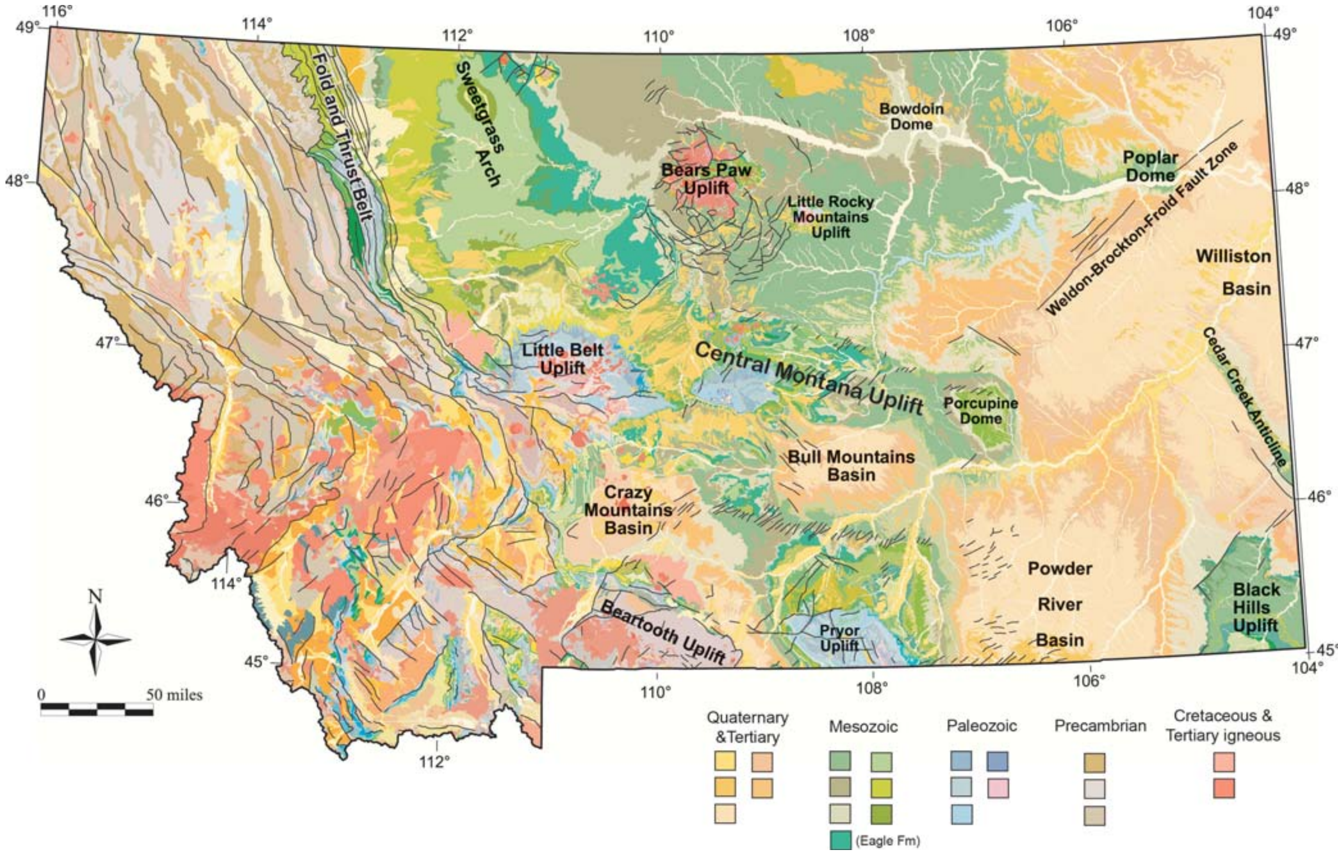


Figure 1. Tectonic map of Montana (modified from Vuke and others, 2007). Surface traces of faults shown as black lines.

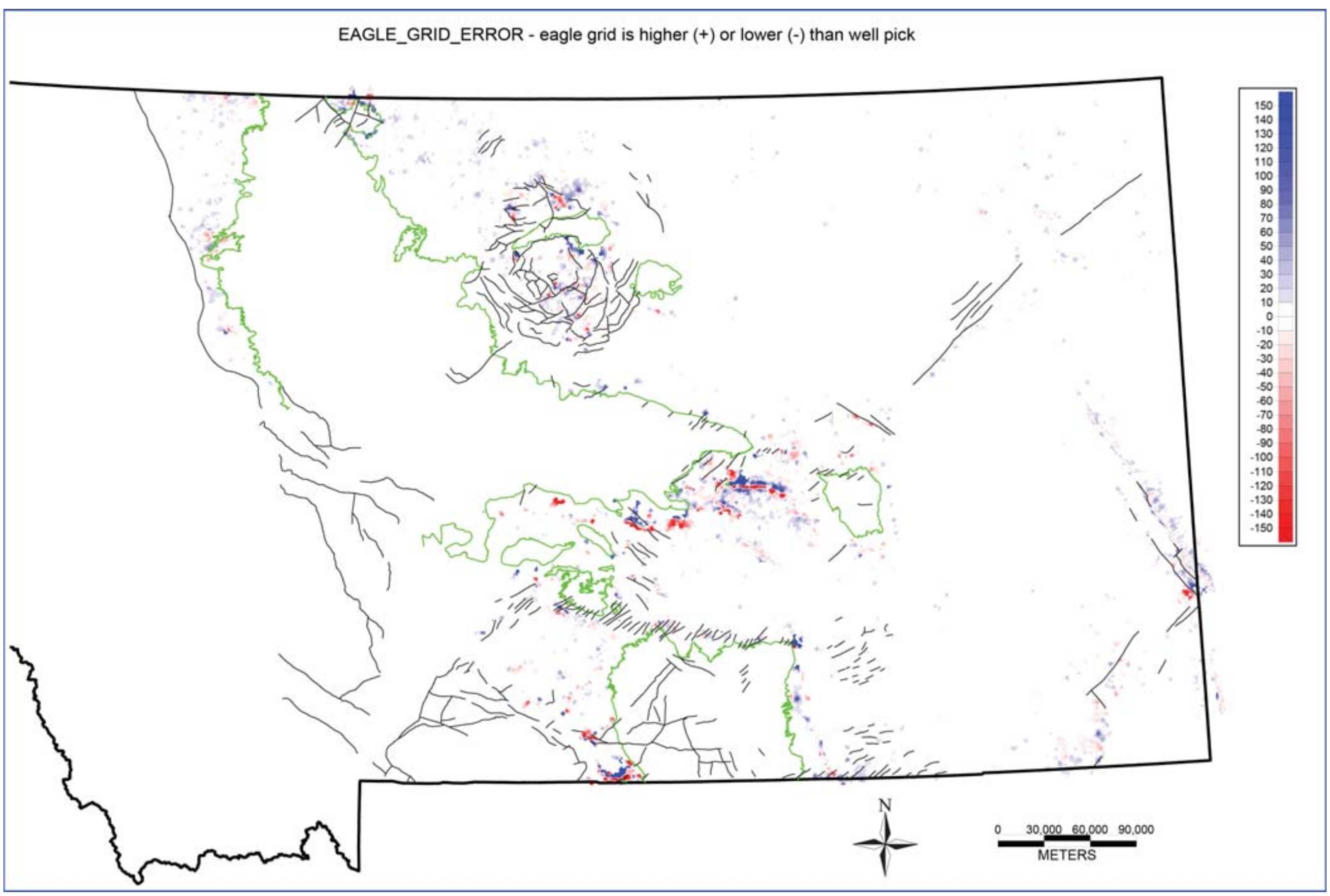


Figure 2. Elevation difference (in feet) between the top of the Eagle Fm interpolated from the PETRA grid and the top of the Eagle Fm picked in wells (positive where gridded surface is higher than the well pick). Stronger colors indicate areas where the gridded surface does a poorer job matching the well data. Surface traces of faults are shown as black lines for reference. The green line represents the Claggett/Eagle contact at the surface.

APPENDIX A. PETRA parameters used for gridding; descriptions were taken verbatim from PETRA's online "HELP" documentation.

Method: Highly Connected Features

This option determines the shape and characteristics of the grid surface by applying different mathematical functions to the original data. Surface styles interpolate the data between data points on both rectangular and triangular grids.

The "Highly Connected Features" method uses a least squares gridding algorithm that works well for most data, particularly structure maps and gently changing petrophysical data. Also works well with faulted reservoirs. This surface style tends to not do well with rapidly changing or large contrasts between data points such as production in a closely-drilled field.

This method tends to avoid geologically unrealistic contours (or "artifacts") on the edges of the grid, though contours can to be somewhat jagged and uneven with small grid sizes. The application of surface flexing ("Smooth Contours Using Grid Flexing" immediately below the Surface Style drop down menu) works well with this surface style, as it tends to smooth and even out the spacing between contour lines.

Max Pts Per Octant = 2

Petra interpolates the value of each grid node from surrounding data points. This option sets the maximum number of data points in each octant used for each grid node, and can be anywhere from 1 to 8. For example, with a value of 2 the gridding process will use a maximum of 16 data points (2 for each octant) distributed around the grid node.

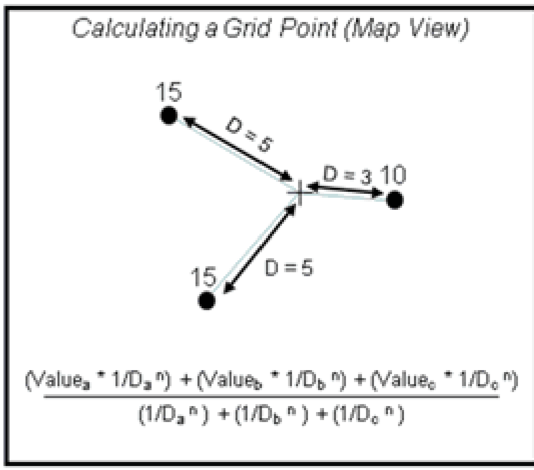
When determining which data points will be used for each grid node, Petra first divides the area around the grid node into eight wedges, or "octants." Petra then uses the closest data points (up to the maximum set by this option) in each octant for calculating an individual grid node's value. Dividing the surrounding data into octants helps avoid grid nodes that are too heavily biased by data points in one direction.

Distance Weighting Damping Factor = 2

Both the "Sample Weighing With Slopes" and "Sample Weighing Without Slopes" surface styles depend on "weighted averages", in which nearby data points contribute more to an individual grid point's average than distant data points. This parameter determines the relative contribution of close data points versus more distant data points to the final data grid value. Petra can use any value from 1 to 8, with a recommended default setting of 2. With a small factor, more distant data points have more influence on an individual data point which tends to average the grid node; this usually results in a smoother grid. With a larger factor, close data points influence the individual grid much more than more distant data points. The recommended value for this factor is 2.

Mathematically, when either of the sample weighing surface styles calculates an individual grid node, Petra uses the adjacent data points and multiplies them by an inverse of the distance to the grid node ($1/D^n$). Multiplying by the inverse of the distance minimizes the contribution of more distant data points (with a larger D) relative to more proximal ones (with a smaller D). The Distance Weighing Damping Factor, *n,* is the power of the distance in the inverse, which magnifies or minimizes the inverse's effect on distant data points.

The example below walks through a single grid node (the + in the center) calculated from three surrounding points. The map view on the left shows that two data points have values of 15 and are 10 units away from the grid node, while one data point has a value of 10 and is 3 units away from the grid node. The formula for calculating the grid node is below the map view. Filling in the values on the left side of the figure, it is a little easier to see how the Distance Weighting Damping Factor, *n*, affects the formula. Larger values of *n* decrease the relative contribution of the more distant wells with a value of 15, which drops the averaged grid node value.



Calculating a Grid Point

$$\frac{(15 * 1/5^n) + (15 * 1/5^n) + (10 * 1/3^n)}{(1/5^n) + (1/5^n) + (1/3^n)}$$

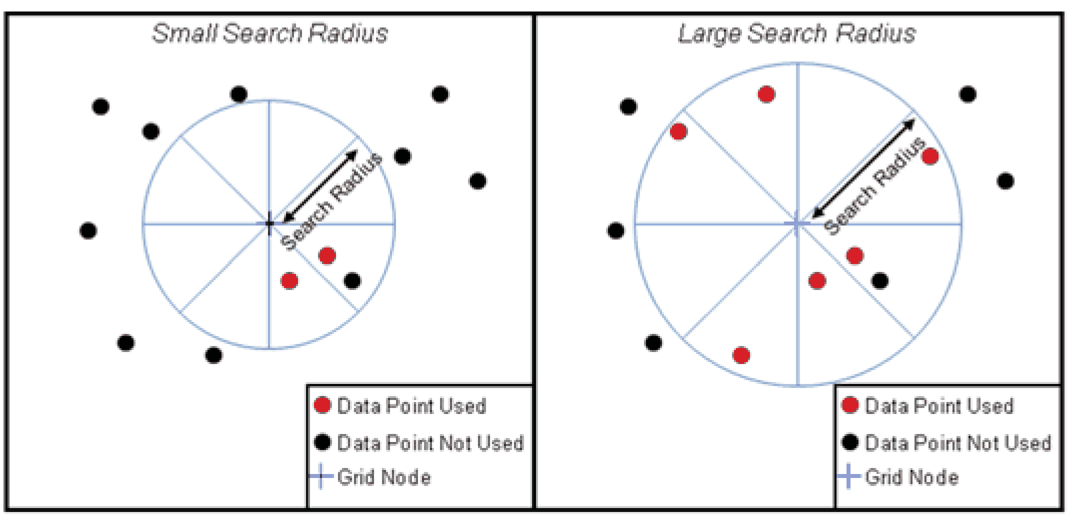
Distance Weighting Damping Factor	Grid Value
1	12.78
2	12.22
3	11.73
4	11.35
5	11.10
6	10.96
7	10.90
8	10.90

Using a damping factor to prioritize close data points at the expense of more distant data points

Search Radius = 0

To calculate a single grid node, Petra interpolates values from surrounding data points. Most rectangular gridding uses an "octant" search, where Petra uses only the nearest data points (set by the "Max Pts Per Octant" setting) from each of the eight pie-shaped wedges, or "octants." This option sets the radius of this search in XY units. The default, set with a zero value, is a fairly large search radius of half the diagonal of the gridded area.

Dividing the surrounding data into octants helps avoid grid nodes that are too heavily biased by data points in one direction. If the specified search limit is too small, the grid may contain null values in areas of sparse data control.



A small search radius only uses close data points (left) while a larger search radius can use use more points (right)

Smooth Contours Using Grid Flexing (Flex Grid Factor = 4)

This option adds an additional step after gridding to generate smoother, more even contour lines. When this option is selected, Petra first uses the selected surface style to interpolate between the data points to create grid nodes. Next, Petra applies the minimum curvature surface style to both the original data points and to a decimated sample of the newly-interpolated grid values.

The relative strength of the grid flexing option is set by the "Flex Grid Factor" on the Advanced Tab. This option can be set anywhere between 0 and 12. Setting a low grid factor will keep a relatively strong primary surface style, while a high grid factor will increase the relative strength of the minimum curvature surface style.

Grid flexing is also influenced by the "Min Curvature Tension" option on the Advanced Tab. Practically, high tension grids – particularly above 5 - have smoother and more even contours but may not honor the original data as well as lower tension grids.

Flex Grid Factor = 4

This option changes the relative strength of the "Smooth Contours using Grid Flexing" option. Low Grid Flex Factors create final grids that look like the original surface style, while higher Grid Flex Factors will create a grid that looks more like a Minimum Curvature grid.

When the "Smooth Contours using Grid Flexing" option is selected (on the Method Tab), Petra first interpolates the data points with the selected surface style, then adds an additional step to interpolate both the original data points and the newly created grid values with the minimum curvature gridding algorithm.

Mathematically, this option controls the decimation of the initial grid, and can be set from 2 to 12. When this option is set to 2, every other original grid point will be used in the Minimum Curvature step. In this case, a large number of initial grid points remain, which constrains much further interpolation from the second minimum curvature interpolation. When this option is set to 12, only every 12th original grid point will remain. The relative low number of initial grid points allows for more interpolation from the Minimum Curvature step. In short, the lower the Grid Flex Factor, the more the final grid will look like the original surface style. Higher Grid Flex Factors will create a grid that looks more like a Minimum Curvature grid.