Cover Sheet

Title: Open-source tools for making geometrically-complex fault surfaces

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Open-source tools for making geometrically-complex fault surfaces

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Abstract

Three–dimensional fault geometries are critical for realistic analyses of crustal deformation, seismic hazard, and rupture dynamics, yet 3D fault datasets are sparse outside a few well–studied regions. We present a set of free and open-source QGIS plugins that enable users to construct accurate 3D fault surfaces from common types of geological and geophysical data. The workflow combines (1) CrossSectionDigitizer, for georeferencing and extracting fault geometries from map-referenced cross–sections; (2) Contours2Surface, for generating triangular meshes from manually drafted contours; and (3) a modified Qgis2threejs plugin for interactive 3D visualization. Together, these tools allow geoscientists to build complex, non-planar fault surfaces in a familiar GIS environment without specialized modeling software. The methods are illustrated with examples from the Yakima Folds Province.

Introduction

Faults are geometrically complex. Virtually all fault traces show clear deviations from planarity along strike, and subsurface data and inferences commonly indicate variable dip with depth. Splays, branches, and other complex features of fault networks are also ubiquitous. The accuracy of any analysis that incorporates fault geometry is dependent on the accuracy of that geometry. Therefore, creating realistic and accurate 3D fault geometries is a necessity for analysis of regions without existing high–quality 3D fault datasets; and this, in turn, requires the tools to build the fault geometries.

Creating 3D fault geometries from the typical surface and subsurface data (fault traces, balanced cross–sections, depth–migrated seismic lines, earthquake hypocenters) requires a suite of skills: geological reasoning, geospatial data manipulation and visualization, computational geometry and other numerical programming. Beyond the inherent challenges of structural

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interpretation, the individual tasks required to create 3D fault geometries are not especially complex. However, their combination is uncommon—these skills are rarely taught together in geoscience curricula, and are often distributed across different specialists within an organization.

In this report, we present a set of permissively licensed, open–source tools for creating accurate, realistic 3D fault surfaces in the context of the data used to constrain them (Figure 1). The tools are QGIS plugins (QGIS Development Team, 2009); there are two new plugins and a modification of an existing one. These tools support a contour-based workflow for constructing fault surfaces at depth, and then generating 3D triangular meshes from those contours. Drawing contours is a foundational skill for geoscientists, and is easily done in QGIS in the same manner as mapping or other linework. Below we describe the three QGIS plugins that together enable construction and visualization of realistic 3D fault surfaces from standard geologic data.

Software Overview

The first plugin in the workflow is the CrossSectionDigitizer (Styron and Bachelot, 2025b), which enables the user to take a geologic cross–section, depth–migrated seismic section, or other vertical image, and both *digitize* it (in the sense of familiar "plot digitizer" software), i.e. extracting the coordinates of faults, horizons, or other data from the cross–section image in the data's (distance, depth/elevation) coordinate system simply by clicking on the data in the image, and *georeferencing* the data and the image to a geographic (longitude, latitude, elevation) coordinate system.

The second plugin is the Contours2Surface (Bachelot and Styron, 2025) plugin. This enables the user to create 3D triangular meshes from contours and export the meshes to a vector GIS file, with facilities for sorting contours, and specifying mesh size.

The third plugin is a modified version of the Qgis2Threejs plugin (Akagi, 2024; Styron, 2025), which renders 3D data in a QGIS window or web browser with the Three.js Javascript library. Our modification allows for displaying 2D raster images in 3D geographic space, such as cross–sections georeferenced with the CrossSectionDigitizer plugin. This lets the user visualize the cross–sections, contours, 3D fault mesh, topography, and other data such as earthquake hypocenters, together in an interactive plot, while building the fault surfaces or doing subsequent interpretation.

Intended Use Cases

The tools presented here are designed to be used to create complex fault surfaces manually, one at a time. These fault surfaces, though created individually, may be part of an interconnected system. The primary use case is to create more accurate fault surfaces where subsurface information exists, for faults within a larger fault model with less well constrained geometries for other structures (e.g., Plesch et al., 2007; Basili et al., 2008; Seebeck et al., 2024), or for a standalone fault or fault system (e.g., Di Bucci et al., 2016). The plugins are not meant to be used to create simplified 3D fault surfaces, for example by projecting a

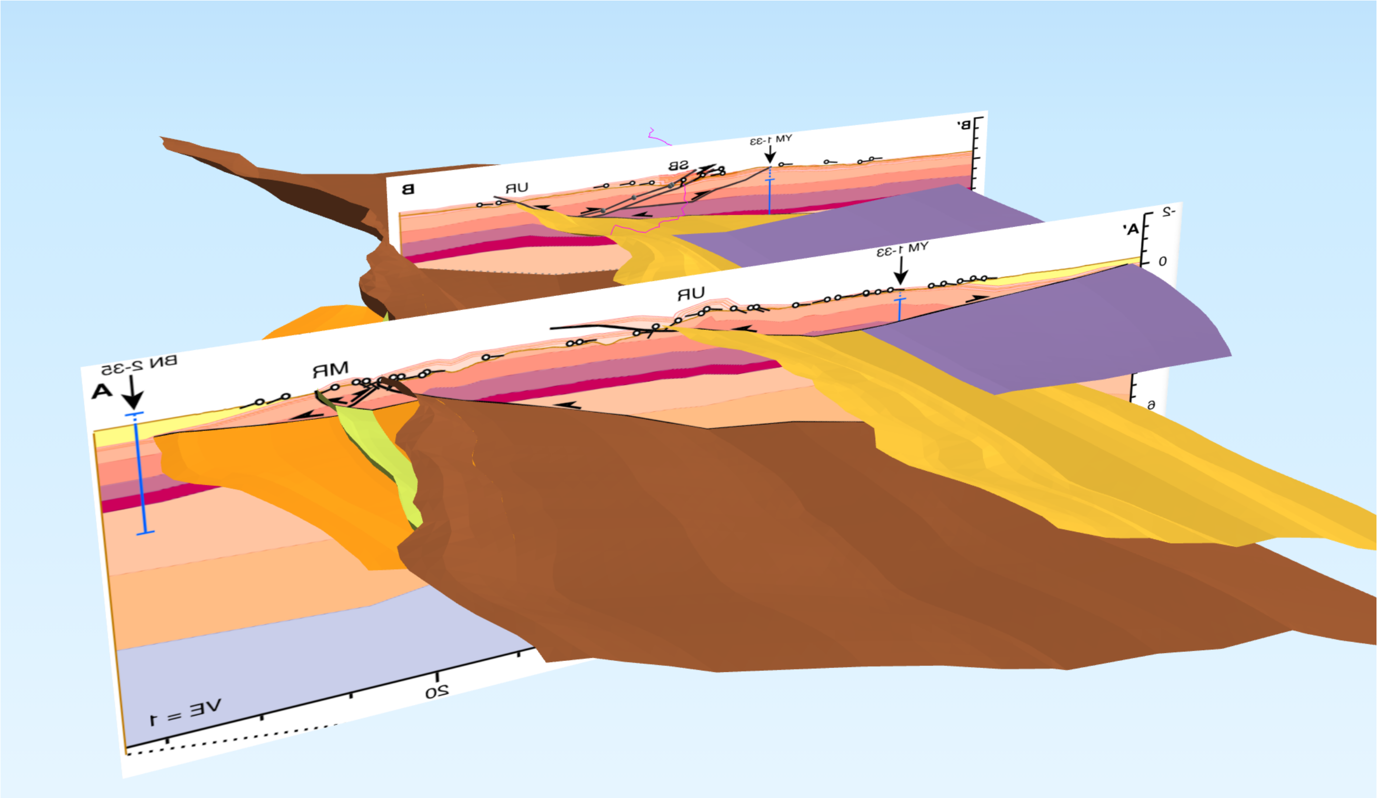

Figure 1: 3D fault model for the Umtanum and Manastash faults, Yakima Fold Province, with cross–sections from Staisch et al. (2018)
Alt-text: 3D fault surfaces for the Umtanum and Manastash faults, with the two balanced cross-sections placed in their georeferenced positions. The visualization shows how the digitized cross-section geometries and map-based traces combine into continuous, nonplanar fault meshes that branch and vary in dip along strike.

trace to depth at a constant dip, as the plugin–based approach is very inefficient for this task. However, as explained below, the code underlying the plugins may be used to script more automated creation as well.

Demonstration of Workflow

The functionality of each of the plugins is demonstrated by presenting an overview of building a set of complex, branching faults from a geologic map and two balanced cross–sections. The overview presented here is illustrative rather than instructional, but a detailed tutorial is available at `https://cascadiaquakes.github.io/fault-geometry-building-tutorial/QGIS_plugin.html` (Styron and Bachelot, 2025c). The example data are from the Yakima Folds Province of Washington State, USA (Staisch et al., 2018).

Map and Cross–Section Georeferencing

The first step in the process is gathering and georeferencing the map and cross–sections. In this case, as is common, the map and cross–sections are taken from figures in a publication, simply by taking screengrabs of the PDF. Once the screengrabs have been cropped, the map is georeferenced using the Georeferencer plugin included in QGIS. Then, georeferencing the cross–sections can begin. The CrossSectionDigitizer plugin is opened, and the first section is loaded (Figure 2). Next, the user clicks three control points (an (X_0, Z_0) point, an (X_1) point, and a (Z_1) point), and enters their coordinates in the cross–section's (X, Z) distance–elevation coordinate system. The plugin records the control points' (x, y) coordinates in the images' pixel coordinate system. The correspondence between the two sets of coordinates creates a linear map that transforms arbitrary pixel coordinates to cross–section coordinates.

Subsequently, another linear map has to be made to transform cross–section (X, Z) coordinates to geographic (longitude, latitude, elevation) coordinates. The user clicks on two more control points of known geographic location on the cross–section, and either types their geographic coordinates or clicks on their locations on the geologic map (the cross–section endpoints are particularly helpful here). Now, the cross–section is georeferenced, and the two coordinate transformations may be combined to transform any (x, y) pixel coordinates to (longitude, latitude, elevation), so that digitization of the data in the cross–section can be performed. The user may now press the 'georeference' button, which will produce a 3D polygon representing the extent of the cross–section image in the QGIS main window, a precondition for displaying the cross–section in 3D with the Qgis2threejs plugin, as well as any data points that have been digitized.

The user also may wish to save their work. An 'export project' button writes the control points, coordinate transformations, cross–section file paths, and any digitized data to a JSON (structured and labeled plain text) file, which can be loaded in a later session.

Displaying the Cross–Section in 3D

Once the cross–section has been loaded, it can be visualized in 3D with the modified Qgis2threejs plugin. The geologic map, DEM, and 3D polygon created during georeferencing can be loaded in the Qgis2threejs window. Then, the cross–section image can be displayed in the extent of the 3D polygon (Figure 3). This step both verifies that the georeferencing is correct and places the cross–section in its proper spatial context, which will aid in drawing the contours to create faults as well as other interpretation.

Data Digitization

Now the user can begin to digitize the fault data using the 'digitize fault data' tab. For each dataset (i.e., each fault or other feature), the user can make a new data series. Then, the user simply clicks on the cross–section in the CrossSectionDigitizer window. Each click registers a point in the image (x, y) and cross–section (X, Z) coordinates coordinates. For faults from balanced cross–sections, it may be sufficient to only digitize the hinge points and any branch points, as the faults are often drawn as straight lines in between the hinges. For faults from seismic sections, more dense digitization may be desirable to represent the fault geometry precisely. Each data series may be saved as a CSV. When the user is finished with the digitization of one or more series, they may be georeferenced by clicking that button; each series will appear in the QGIS main window as a `MultiPointZ` vector dataset, and can be saved to file.

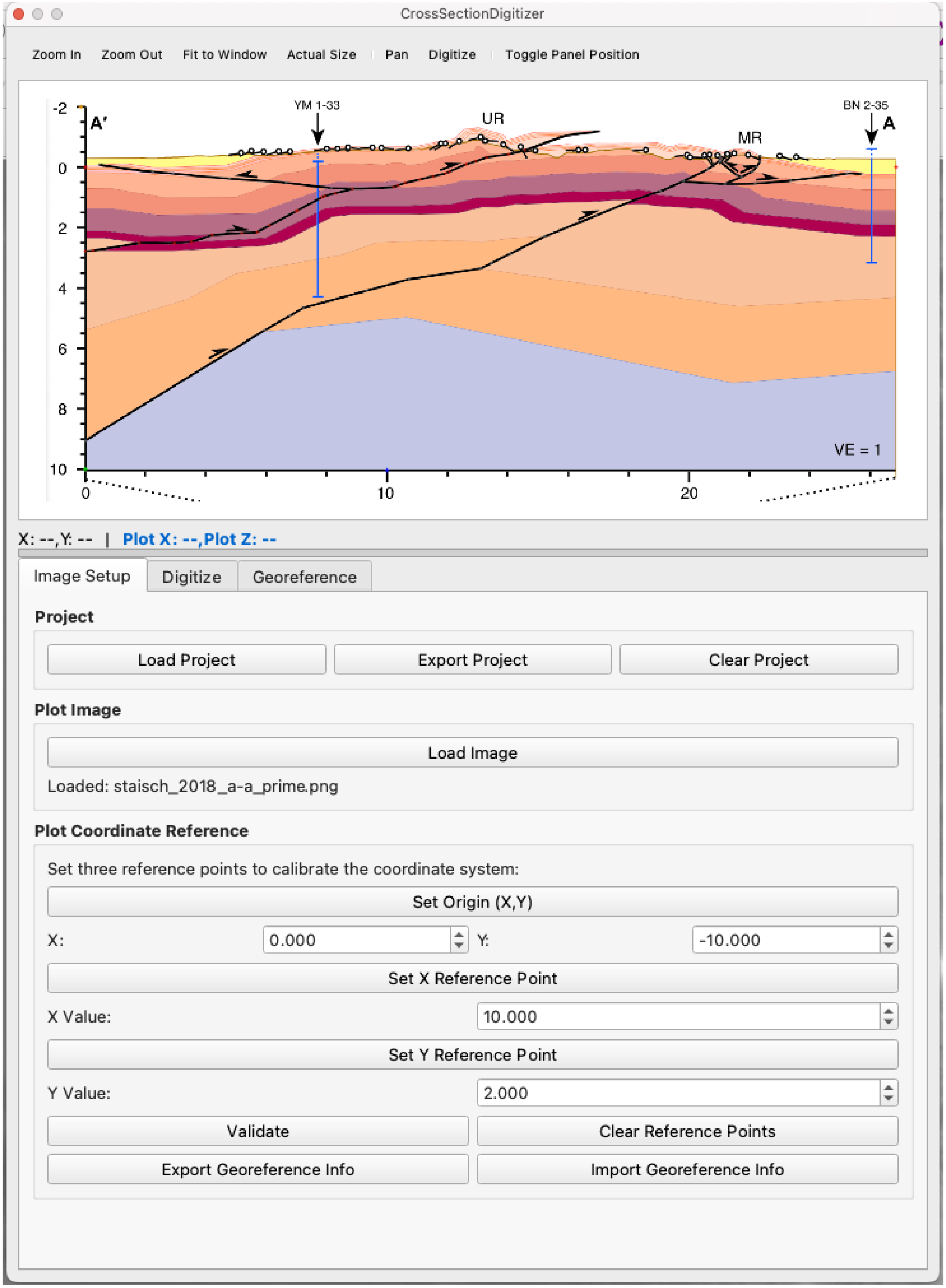

Figure 2: Cross–Section Digitzer plugin

Alt-text: User interface of the CrossSectionDigitizer shown with a geologic cross-section loaded. The display highlights how control points, reference coordinates, and digitized points are recorded, enabling transformation from pixel coordinates to section coordinates and then to geographic coordinates for use in 3D fault construction.

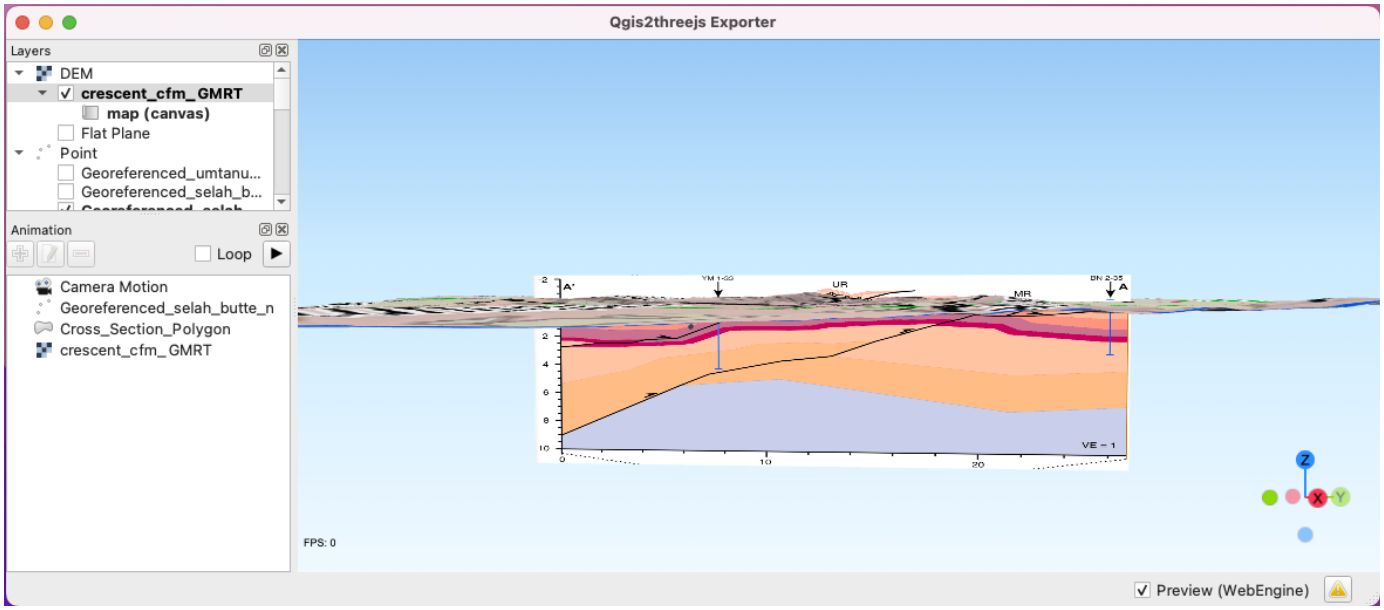

Figure 3: 3D view of the georeferenced cross–section and topography
Alt-text: Georeferenced cross-section displayed in a 3D scene with topography. The cross-section image is positioned at its correct spatial location and orientation, demonstrating alignment of elevation, distance, and geographic coordinates before contour drafting and mesh construction.

In some cases, such as when two cross–sections are intersecting, the same structures are used, it can be helpful to have points at the same elevation in each section to facilitate drawing contours. After digitizing each structure, the user can note which elevations are in each series, and then click on those points in the other section, by noting the *Z* coordinate of the mouse cursor (which updates with mouse movement and is displayed below the cross–section image).

Drafting contours

The workflow described here relies on contours lines to create surfaces. The digitized data series from the CrossSectionDigitizer serve as guides for the contours, as does the fault trace, but drawing the contours also requires some amount of geologic interpretation.

In our example, there are two cross–sections, each showing some faults that are present in both, and some that are unique to each. Initially, we build the lowermost thrust, the Manastash fault. First, we create a new, empty `LineStringZ` layer in QGIS. Then, we create a new feature for the trace (which functions as a contour, though each point may have a different elevation) by digitizing the trace from the geologic map (or by interpreting other data). Then, the elevations for each point are extracted from the DEM using QGIS's native Drape function. Finally, contours are drawn for each of the points in the fault data, and their elevations are added using another QGIS function.

The horizontal spacing in the down-dip direction between the fault data points is in places quite different between the two sections, indicating that the ramps and flats present in each do not project directly along strike, but instead require some lateral accommodations. The geometry of these transitions is not well constrained by the data, but require interpretation, which

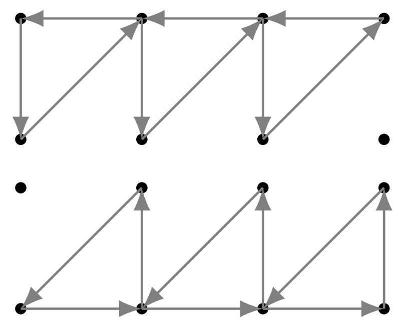

Figure 4: Algorithm to create triangles from point sets from resampled contours. In **A**, the upper triangles are created from the point set. In **B**, the lower triangles are created from the same point set.
Alt-text: Schematic illustration of the triangularization algorithm used to mesh resampled contours. The diagrams show how adjacent rows of equally sampled points are connected to form upper and lower triangles, producing a structured grid of triangular elements across the fault surface.

manifests in how the user draw the contours describing the transition: whether the transition is quite smooth, indicating a broad lateral ramp, or whether it is abrupt, indicating a narrow lateral structure.

Additionally, short-wavelength variations in fault geometry are evident at the trace, and it is straightforward to continue these at shallow depth, but without data–based guidance at greater depths, one tends to draw the contours more smoothly. Carrying this practice further, some workers (e.g. Plesch et al., 2007) intentionally smooth the geometries of faults at depth, as a means of representing increased uncertainty in the geometry.

After drawing at least two contours, a fault mesh can be created. This can be done iteratively during drafting of contours as a way of quality–checking the results, adjusting the contours as necessary, or at the end of drafting a fault.

Making a Mesh from Contours

The Contours2Surface plugin is used to create the triangular mesh representing the fault surface from the contours.

Mesh Generation Algorithm

The plugin works by resampling the uppermost contour (often the trace) with regularly–spaced points as close to a user–specified interpoint distance as possible while maintaining the start and endpoints, then resampling the other contours with the same number of points. Then intermediate contours are linearly interpolated from the resampled contours, so that the down–dip distance is the same as the horizontal interpoint distance. Then, a triangular mesh is created by connecting points on each contour and adjacent contours, through a simple and fast algorithm.

The triangular generation first creates an $M \times N$ array of points, where M is the number of rows (contours), and N is the number of points in each row. Then, the algorithm iterates over the rows, then the points. At each, the algorithm makes two triangles; the upper has two points on the current row and one point on the next row, and the lower has one point on the current row and two on the next row (Figure 4). In pseudocode, the algorithm looks like this:

```
tris = []

for pt i in row j:
    upper_tri = [(j[i],     j+1[i]),
                 (j+i[i],   j[i+1]),
                 (j[i+1],   j[i])]

    lower_tri = [(j[i+1],   j+1[i]),
                 (j+1[i],   j+1[i+1]),
                 (j+1[i+1], j[i+1])]

    tris.append(upper_tri)
    tris.append(lower_tri)
```

For a perfectly straight fault with a length and width that are integer multiples of the sampling distance, this produces perfect 45°-45°-90°triangles. With real data, the triangles may be more irregular, especially with large point distances. If this is problematic, it can be mitigated by decreasing the point distance.

Plugin Usage

To produce these surfaces, the user selects a contour layer, and opens the plugin (Figure 5). A list appears with all of the visible contours in that layer. The list is automatically sorted by the elevation of the contours, which may be manually reordered if necessary (for example if the fault or other feature is domed in part). Then, the user specifies the sampling distance and, optionally, the output file path. The surface is built with the click of a button and the resulting layer will be loaded in the QGIS main window.

The mesh is built as a `MultiPolygonZ` vector GIS layer. Each triangle is one polygon, and a single file can hold many faults as features (each composed of many polygons). This is an efficient and widely compatible file format, but suffers from the affliction that each feature (i.e., each fault) can have independent attributes (e.g., the fault's name, slip rate, or citation), though each polygon (triangle) cannot. Therefore, if the user requires specific attributes for each triangle, such as its strike, dip, or area, the layer must be converted to a `PolygonZ` type. When this is done, each triangle is a separate feature, but within a file or layer, triangles cannot be grouped by fault; separate files must be used for each fault.

Use of code in scripts

The code to build the faults from the contours is a separate Python library (Styron and Bachelot, 2025a). It can be easily incorporated into Python scripts or applications to support more automated or otherwise distinctive workflows for building

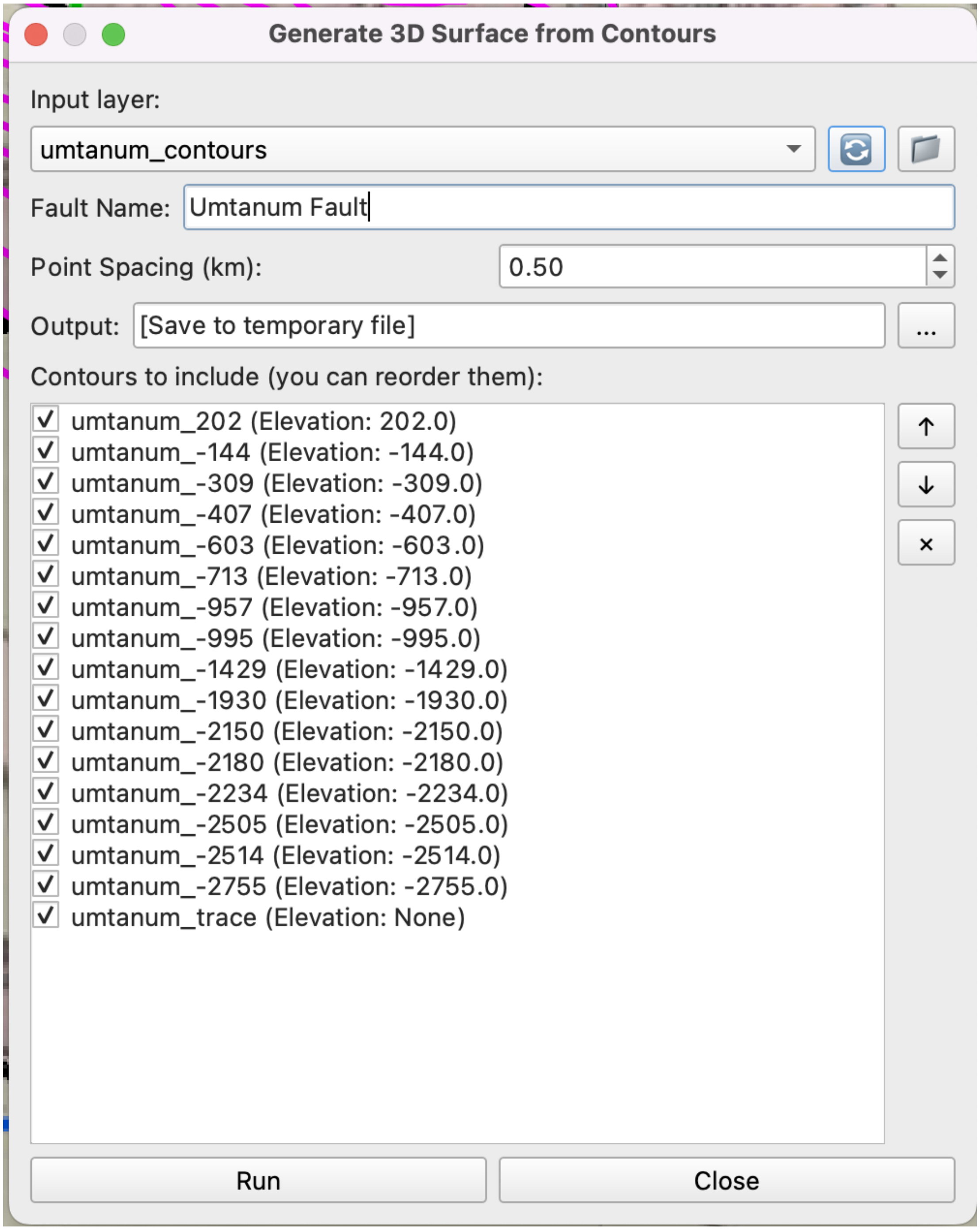

Figure 5: *Contours2Mesh* plugin menu.
Alt-text: Contours2Surface plugin interface showing a list of elevation-sorted contours, user-defined point spacing, and naming options. This interface controls resampling of contours, ordering adjustments, and generation of the resulting 3D triangular mesh representing a fault surface.

faults from contours. For example, the 3D representations of crustal faults in the Crescent Community Fault Model are built with this library within a Python script that creates contours at depth by projecting the fault trace at a constant dip and specified vertical spacing; pre–drawn contours of the Cascadia subduction zone from research by McCrory et al. (2012) are meshed with this library as well (Styron et al., 2025).

Data and Resources

All data used in this paper came from published sources listed in the references.

Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

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