To: Appalachian Basin GPFA

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Subject: Conversion of Seismic Risk Data to Risk Maps

Applicability: This memo describes detailed methodology used to convert the seismic risk data (i.e. distance to nearest earthquake, and angle to critical stress) into a two seismic risk maps.

Earthquake Based Risk Map

The distance from the grid cell centers on the standardized project raster grid (points file: *Fishnet2_label.shp*) to the nearest earthquake was determined. First, Voronoi tessellation of the epicenters from the earthquake database was performed, such that each earthquake was located in only one polygon. The earthquake nearest to any grid point within a polygon is the earthquake within the polygon. Following the tessellation, the earthquake information was joined to the attribute table of each polygon.

Then, the earthquake information in the polygons was spatially joined to the attribute tables of the grid points. This resulted in an attribute table containing the location of the grid points, and the location of the earthquake nearest to all grid points. The distance from a grid point to the nearest earthquake was determined in a Postgres query. This grid of points was converted into a raster representing the distance to the nearest earthquake for all points on the grid.

The distance to earthquake information is combined with the information obtained from the gravity and magnetic potential field analyses to create the earthquake-based seismic risk factor map. First, the gravity and magnetic potential field edge points (“worm” points) that were within 20 km of an earthquake epicenter were selected and buffered by 2 km. The buffers for gravity and magnetic worms were dissolved independently, resulting in polygons for the gravity and magnetic buffered worms. A buffer around worm points is used because of potential hydrologic connectivity of the subsurface that may allow for fluid migration to the worm point within some distance of the point. The use of 2 km as a buffer is arbitrary. More detailed knowledge about the subsurface hydrology could better inform the buffer that would be most beneficial to limit the migration of fluids to activate faults at the location of the worm point.

Following the buffering, the raster of distance to the nearest earthquake was clipped to the buffered worm polygons, resulting in two clipped rasters (one for gravity and one for magnetic worms). These rasters represent the distance to the nearest earthquake for all grid points within 2 km of a worm point that is within 20 km from an earthquake. The ArcGIS Extract Multi Values to Points tool was used to add this information back to the grid points, with new fields for GravDist and MagDist representing the distance to the nearest earthquake for gravity points and magnetic points, respectively.

The GravDist and MagDist fields cannot be used directly to determine the most risky value (smallest distance to an earthquake) for each grid point. This is because the gravity and magnetic worm points did not cover the same areas, so some gravity and magnetic points were co-located (within the same 1 km^2 pixel) and others were not co-located. Points that were co-located had the same value for GravDist and MagDist, so the distance value is the risk value, called the RiskDist. In areas without co-located points, the value of one of GravDist or MagDist will be the distance to the earthquake, and the value of the other one would be the value assigned to a grid point with no information within the buffered state boundaries (see Processing Notes section below). This value was greater than the distance to any earthquake, and so the minimum distance to an earthquake for each grid cell was determined using a query for the minimum of GravDist and MagDist fields. The result was written to the RiskDist field. The standard deviation (see uncertainty section below) corresponding to the minimum distance (GravVar or MagVar) was placed in a new field called RiskVar. Finally, the RiskDist and RiskVar grid points were converted into a raster (Point to Raster tool in ArcGIS) to create the seismic risk factor map and uncertainty map based on the distance to the nearest earthquake.

Uncertainty

Simply put, the uncertainty in the distance to the nearest earthquake is the sum of the uncertainty in the earthquake location and the potential field point location (one of magnetic or gravity). Uncertainties in this case are taken as standard deviations of distance, so the combined uncertainty of earthquake and worm point positioning error is

$$RiskVar = \sqrt{s_{EQ}^2 + (GravVar^2 \text{ OR } MagVar^2)}$$

where s_{EQ}^2 is the standard deviation of the earthquake position, $GravVar$ is the standard deviation of the gravity worm position, and $MagVar$ is the standard deviation of the magnetic worm position. The uncertainty in earthquake locations is available for some, but not all, earthquakes in the database. As a result, a conservative estimate of the uncertainty is selected as 2.5 km in any direction, regardless of the magnitude of the earthquake (e.g. greater magnitudes likely have smaller uncertainty in location). The uncertainty in the potential field point locations is difficult to pin down as a result of the many processing steps involved. Lacking the time to quantify the uncertainty in the potential field points via a Monte Carlo analysis, 20% of the distance between potential field points is used as the uncertainty for all points. Gravity points have an uncertainty of 500 m (2500 m spacing between points), and magnetic points have an uncertainty of 250 m (1250 m between points). The uncertainty in earthquake location and worm point locations is treated as a standard deviation. Therefore, the total RiskDist uncertainty under these assumptions is 2550 m for gravity points and 2515 m for magnetic points. For both, this corresponds to 3 pixels at the resolution of the risk factor maps.

Stress Field Based Risk Map

First, new fields called GravAng and MagAng were added to the gravity and magnetic potential field points that contained information about the angle normal to the principal stress (values ranging from 0° to 180°), and the uncertainty (standard deviation) in that angle. The GravAng and MagAng fields represent the minimum of the absolute value of the angle needed to arrive at each of the critical angles, in degrees. The minimum is selected because this represents the greatest risk (closer to one of the critical angles). These fields were used as the continuous risk metric, where 0° is the greatest risk. Note that the following equation is only valid if the normal angle ranges from 0° to 180°. If the normal angle ranges from 0° to 360°, one must take the modulus of the normal angle minus the critical angles (65.2° and 114.8° in this case.

$$GravAng = \min\left(\mathrm{abs}(normal\_angle - 65.2°), \quad \mathrm{abs}(normal\_angle - 114.8°)\right)$$

Next, the potential field points (gravity and magnetic) were buffered by 2 km, for the same reason as described above. These buffers were dissolved independently, and converted into 4 total rasters: angle for gravity (GravAng), uncertainty for gravity (GravVar), angle for magnetic (MagAng), and uncertainty for magnetic (MagVar). The values in each of these rasters were added to the standardized grid cell centers using Extract Multi Values to Points tool in ArcGIS.

Then, the minimum of the GravAng and MagAng was selected as the RiskAng for each grid point. The uncertainty (standard deviation) of each grid point was the uncertainty corresponding to the minimum of GravAng and MagAng (either GravVar or MagVar) and was called the RiskVar. Note that the RiskVar in this case assumes that errors in the positioning of the worm points are captured in the error of the angle, because the same positioning error is assumed for all points along a worm segment. Therefore, positioning errors in the worms are assumed to be implicitly captured. A Monte Carlo analysis that includes positioning errors would be needed to verify this assumption.

A plotting priority field called Weight was added to the worm data, which was equal to 65.2° – RiskAng, where 65.2° is the maximum number of degrees that an angle could be from one of the critical angles (from 0° to 180°). This field is used to determine plotting preference when converting this data into a raster dataset – higher values have higher preference. This ensures that a RiskAng value of 0° has the highest plotting preference, and therefore will be selected as the raster value.

Finally, the stress field based seismic risk factor maps were created by converting the RiskAng and RiskVar points into rasters using Point to Raster conversion in ArcGIS.

Processing Notes:

Before running the conversions, information about whether or not a standardized grid point was located within the 50 km buffered states region was added to the point features (binary variable, in or out of the states). After processing, the grid points without state data are assigned a value of -9999 to indicate that these areas were not assessed for seismic risk. The grid points within the state buffer that did not intersect buffered worm points are assigned a value of 100 for stress-based maps and a value of 1,234,567 for earthquake-based maps because these areas have low seismic risk. These values were selected because they are numbers greater than the maximum RiskAng and RiskDist, and are easily identified by data processing programs. For example, 1,000,000 was not used because this value is converted to 1E+6 in some programs, which is converted to text in some programs. Text fields are not numbers, and cannot be displayed on rasters.