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A new approach for associating earthquakes with geological structures: Application to epicenters in southern Illinois and southeastern Missouri

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[1] A spatial statistical analysis method has been applied successfully on diffuse seismicity of southern Illinois and southeastern Missouri. The study area is a region of diffuse deformation and seismicity close to the New Madrid Seismic Zone. The New Madrid Earthquake Catalog is examined through the Blade Method applied on collapsed epicenters. This is a new approach since the Blade Method is applied on improved locations through the Best Estimate Method. The Blade Method performs tests on binomial distributions for the detection of significant seismic alignments within a sparse epicenter distribution. From the epicenters of the New Madrid Earthquake Catalog, using the Blade Method on collapsed epicenters, it is statistically valid to state that seismicity is associated with the New Madrid Seismic Zone and the Black, Ellington, Salem and Ste Genevieve faults. *INDEX TERMS:* 7205 Seismology: Continental crust (1242); 7223 Seismology: Seismic hazard assessment and prediction; 7230 Seismology: Seismicity and seismotectonics. **Citation:** Amorèse, D., A new approach for associating earthquakes with geological structures: Application to epicenters in southern Illinois and southeastern Missouri, *Geophys. Res. Lett.*, *30*(13), 1689, doi:10.1029/2003GL017247, 2003.

1. Introduction

[2] The New Madrid Seismic Zone (NMSZ), located in the central Mississippi River valley is one of the world's most intensively studied seismic zones. The NMSZ is clearly tracked by the epicenters of the seismic events (Figure 1). Farther North, in southern Illinois and southeastern Missouri, the NMSZ is thought to change from a single main zone of faulting in the south to an array of braided subsidiary faults [*McBride*, 1998]. This dispersive deformation pattern combined with a lack of accuracy in epicenter locations certainly explain the observed diffuse epicentral pattern (Figure 1). The present-day low seismic activity may not be characteristic of southern Illinois. Actually, the southern Illinois region has had larger twentieth-century earthquakes than the NMSZ [*Langer and Bollinger*, 1991]. The strongest paleoearthquakes in the region lay, north of the NMSZ, within Illinois and Indiana [*Obermeier et al.*, 1996].

[3] In southern Illinois and southeastern Missouri, due to the diffuse epicentral pattern, any attempt of visually associating epicenters with regional faults may be misleading. For the assessment of earthquake hazard, the ability to reliably associate faults and seismicity is of crucial interest in a region where major destructive earthquakes are likely to occur. The objective of this study is to examine statistically, using a new methodology, the correlation of the southern Illinois and southeastern Missouri epicenters with regional faults.

[4] It is widely accepted that zones of intraplate seismicity reactivate fundamental pre-existing "zones of weakness" [*Sykes*, 1978]. In southern Illinois and southeastern Missouri, these zones of weakness correspond to late Cenozoic NW-striking, N-striking or NE-striking faulting [*Nelson and Bauer*, 1987; *McBride*, 1998]. These faults have been argued to correlate with contemporary seismicity [*Harrison and Schultz*, 1994; *Sexton et al.*, 1996; *Langenheim and Hildenbrand*, 1997; *Nelson et al.*, 1997]. The clearest examples are the NE-striking Commerce fault zone (Commerce Geophysical Lineament) and an array of parallel NW-striking faults in southeastern Missouri. The Du Quoin and Salem-Louden west-dipping faults appear to be associated spatially with a localised zone of seismicity [*Mitchell et al.*, 1991]. The WNW-trending Cottage Grove fault system is another possible seismically active discontinuity (Figure 1) [*Mitchell et al.*, 1991]. *Hamburger and Rupp* [1988] have suggested that the June 10, 1987 seismic sequence, North of Wabash Valley, is associated with the NW trending La Salle belt, a possible fault cored anticline.

2. The Blade Method

[5] The Blade Method is a statistical procedure for the detection of significant seismic alignments within a sparse epicenter distribution. The Blade Method is fully described and tested by *Amorèse et al.* [1999]. We summarize it below. Each epicenter is the center of rotation of a blade (Figure 2). In order to investigate the whole circular area, the maximum rotation angular increment should be:

$$\Delta\alpha_{max} = 2\arctan\left(\frac{W}{\sqrt{4R^2 - W^2}}\right) \qquad (1)$$

where R and W label the blade radius and the blade width.

[6] For each blade position, the number of observed points within the blade is determined. The number of points within the circle is n. The number of points per blade is then considered as a process that consists of a sequence of n independant trials, where the outcome of each trial is either a success (the epicenter is inside the blade) or a failure (the epicenter is outside the blade). If that is the case and if the probability of success on any trial is p, the number of

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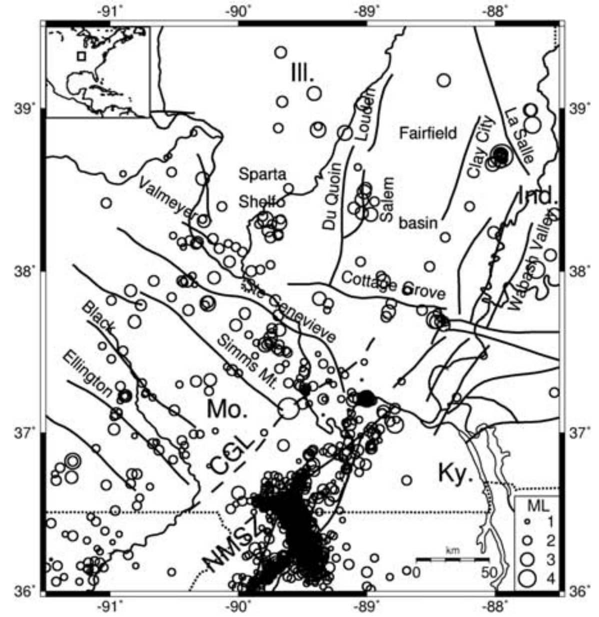

Figure 1. Map of the study area, showing the main regional faults (simplified from *McBride* [1998]) and the shallow (depths smaller than 5 km) seismicity (symbol sizes are proportional to magnitude values) from the New Madrid Earthquake Catalog for the 1974–2002 time period.

success x in n trials has the binomial distribution defined as follows:

$$P(X = x) = \frac{n!}{(n-x)!x!} p^x (1-p)^{(n-x)} \qquad x = 0, 1, \ldots, n. \tag{2}$$

[7] The value of p is simply the ratio of the blade area to the area of the circular zone investigated around each epicenter. This ratio is:

$$p = \frac{W}{2\pi R^2}\sqrt{4R^2 - W^2} + \frac{2\arcsin\left(\frac{W}{2R}\right)}{\pi} \tag{3}$$

[8] The algorithm is implemented as follows. Initially, the value of p is computed from equation (3), then for each blade, the quantity

$$\sum_{k=0}^{x-1} \frac{(n-1)!}{(n-1-k)!k} p^k (1-p)^{(n-1-k)} \tag{4}$$

is determined, where n is the number of epicenters found in the circular zone and x is the number of epicenters found in the blade. In equation (4), when compared to equation (2), $x - 1$ appears instead of x and $n - 1$ replaces n: because the binomial distribution assumes that the absence of point is possible within a blade, centers of circles are not counted when binomial distributions are evaluated.

[9] We reject the random origin of the line at the level of significance α if quantity (4) is larger than or equal to $(1 - \alpha)$. Practically, we use a 0.05 level of significance. This is a standard value usually used when statistical tests are performed.

[10] Additional tests considering the distribution of the epicenters inside each blade are also performed. A mean index (m.i.) and a dispersion index (d.i.) are defined:

$$m.i. = \frac{\frac{1}{x}\sum_{i=1}^{x} d_i}{2R} = \frac{\bar{d}}{2R} \tag{5}$$

$$d.i. = \frac{\sqrt{\frac{1}{x}\sum_{i=1}^{x} \left(d_i - \bar{d}\right)^2}}{2R} \tag{6}$$

where x is the number of points in the blade, $2R$ is the length of the blade, and d_i is the position (distance measured from one tip of the blade) of point i inside the blade. Mean index values vary between 0 (epicenters are located on one tip of the blade) and 1 (epicenters are located on the other tip of the blade) and quantify the symmetry of the point distributions inside blades. Dispersion index values vary between 0 and 0.5 and reflect the degree of clustering of the point distributions. Any blade showing an heterogeneous point distribution should be discarded. Actually, a heterogeneous point distribution may be a indication of an erroneous line detection. That may be the case when the blade is straddling two parallel or subparallel active faults: the areal density of points may be too large to be issued

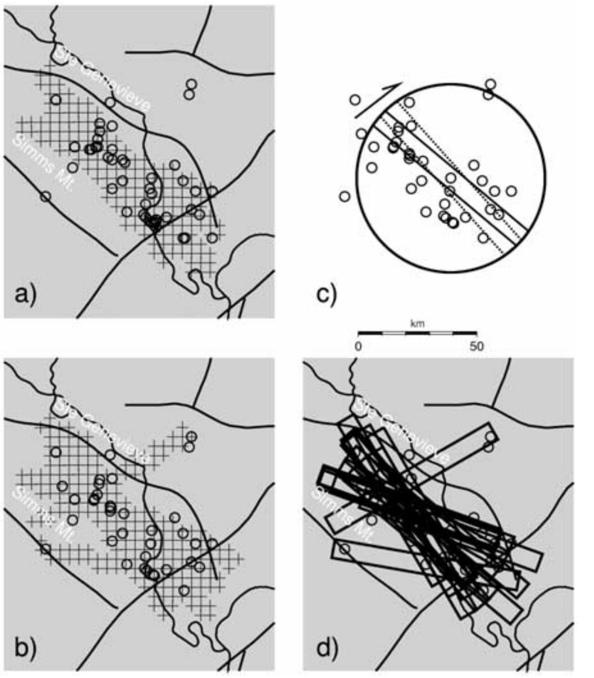

Figure 2. Application of the method to a specific group of epicenters. Results from the Blade Method without applying the Best Estimate Method (a). When the Best Estimate Method is applied (b), seismicity loses diffusivity and linear patterns are enhanced. In the Blade Method (c), each epicenter becomes the axis of rotation of a blade. The length and the width of the blade are kept constant. The rotation is incremental. Finally, a circular zone is investigated around the point. Each blade is a zone inside which points are counted. Blades are rectangular zones investigating the study area (d).

from a random process (i.e., a line is detected when testing quantity (4)), nevertheless real alignments are more or less perpendicular to the suspected line. Therefore, suspected lines are adopted only when *m.i.* is ranging from 0.4 to 0.6 (that means, within each blade, the distribution of epicenters is quite symmetrical) and *d.i.* is ranging from 0.2 to 0.3 (i. e. epicenters are not much too clustered within each blade).

[11] The Blade Method is used to study earthquake epicenter distributions. One should bear in mind that epicenter locations are determined inside location error ellipses. This situation is used to filter the data set prior any computation. In this study, the Best Estimate Method [*Bossu*, 2000] is used to symplify the image of the seismicity. The Best Estimate Method reduces the effect of random location uncertainties. This method is implemented in two steps [*Bossu*, 2000]: a) for each event *i*, the list of earthquakes whose initial locations fall within its location uncertainty is determined; b) the new pseudo-location for *i* is then given by the centroid of all these earthquakes. The process is repeated for all hypocentres. In the present study, uncertainty ellipses of all events are assumed to be the same, thus the Bossu's BEM present version can be used without modification. Otherwise, an improvment should be made: Bossu "merges" the locations of earthquakes i and j when the location of j falls within the location uncertainty domain of i. In fact, if the converse condition (the location of i should fall within the location uncertainty domain of j) is not required, misleading pseudo-locations can be computed (1) if earthquake i is a very badly located event (with a very large uncertainty ellipse), (2) earthquake j is a well located event (with a small uncertainty ellipse), (3) the uncertainty ellipse of i includes j and (4) the uncertainty ellipse of j does not include i.

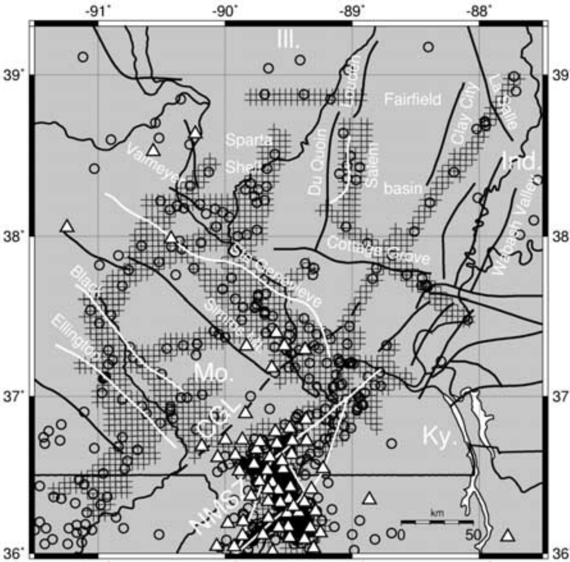

Figure 3. Map showing the results of the Blade Method applied to the seismicity of southern Illinois and southeastern Missouri. Areas where lines are detected (crosses), main regional faults (simplified from *McBride* [1998]) and 1067 centroid ("collapsed") epicenters (circles) used for the computation are displayed. White solid lines represent main regional faults correlated with seismicity by the Blade Method. White triangles are seismic stations.

3. Application to Seismicity in Southern Illinois and Southeastern Missouri

[12] The area of investigation ranges from 36.0°N to 39.5°N and from 91.5°W to 87.5°W. The input data are 1828 event locations extracted from the New Madrid Earthquake Catalog for the time interval 1974–2002. This catalogue is provided by the Center for Earthquake Research and Information (CERI) of the University of Memphis. As the blade method needs to correlate seismic alignments with identified faults and as the faults in the study area are identified mainly from seismic profiles mostly shallower than 5 km [*McBride*, 1998], the 1828 processed events are events shallower than 5 km. About this selection based on depths, one should bear in mind the usual low reliability of focal depths: in common location methods, focal depths can be traded for origin time [*Nordquist*, 1962] unless the studied earthquake occurs close to one of the stations. The rule is that any focal depth less than the nearest station epicentral distance will be inaccurate. Therefore, considering the sparsity of the seismic network (Figure 3) in most of the study region, any hypocenter selection based on depth is certainly imperfect. Nevertheless, despite the lack of accurate depth values, the selection is performed, assuming that some events are really in the uppermost 5 km. In this study, as the Blade Method is only considering epicenters, the modified Best Estimate Method is not applied on hypocenters but only on epicentral locations. The association of seismicity with known faults in map view is usually an improper method. However, none of the regional faults described by *McBride* [1998, Figure 12c] is a gentle dipping fault. Moreover, concerning this issue, the possible shift due to focal depths is partly considered, since the Blade Method is detecting lines through blades that are wide enough (here, W = 8 km). Thus, in this study, the risk of misassociation is low. Error ellipse parameters are not provided in the catalogue, but in the most active part of the New Madrid Seismic Zone, horizontal location errors are estimated to be smaller than 2 km [Withers, pers. commun.]. In this paper, the choice of 4 km horizontal location errors is subjectively made since 2 km is certainly too small to account for location errors in all of the study area. Therefore, for the sake of this study, each event location is assigned a 4 km long radius circle, as a fictitious error ellipse. From the 1828 events, our modified version of the Best Estimate Method determines 1067 pseudo-locations (Figure 3). The Blade Method is applied using (1) a 0.05 significance level, (2) a 80 km long diameter for each circular zone (this value is in tune with the detection of the regional faults presented in Figure 1), (3) 8 km wide blades (this value corresponds to about twice the assumed maximum location uncertainties of the initial epicenters) and (4), in accordance with equation (1), a 10° wide rotation angular increment.

4. Results

[13] Although there are serious concerns about the reliability of regional earthquake locations, the results of this study can provide preliminary information to identify potential targets for future exploration of regional active faults and their relationship to earthquake hazard assessment in the southern Illinois and southeastern Missouri region.

The Blade Method appears to detect several previously documented faults. The branchs of the NMSZ and the Black, Ellington, Salem and Ste Genevieve faults are obviously detected by the Blade Method (Figure 3). A possible clustering induced by proximity to recording seismic stations does not seem to influence the results: there is no obvious spatial correlation between station locations and detected lines (Figure 3). When using the Blade Method, the Commerce Geophysical Lineament does not seem to be significantly seismic. Several ‘‘extra’’ faults (lines that are not supposed to correspond to geological structures) are highlighted, in the central part of Sparta Shelf, in the Clay City region or at the North-East ending of the Commerce Geophysical Lineament (Figure 3). We note that, if an array of faults exists, several epicenters may draw lines that are perpendicular to it and that have no geological origins. When examining the results of the Blade Method, one should bear in mind that a comparison of the inferred lines to the previously described fault traces or other structural markers is necessary to discard artificial seismic lineaments (‘‘mathematical’’ lineaments that are expected purely due to chance). Additionnal investigations (field experiments) are essential to possibly confirm if the ‘‘extra’’ lines are associated with real faults.

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