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SHORT NOTE

Conditioning Geologic Models to Local Continuity Azimuth in Spectral Simulation

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The Problem

Spectral simulation has gained wider application in building geologic models because of the advantage of better honoring the spatial continuity of petrophysical properties, such as reservoir porosity and shale volume. A detailed review of the theoretical background of spectral simulation and how to condition the model to well data can be found in Yao (1998). Distinct from sequential simulation methods, spectral simulation is a global algorithm in the sense that a global density spectrum is calculated once and the inverse Fourier transform is performed on the Fourier coefficient also only once to generate a simulation realization. The generated realization honors the spatial continuity structure globally over the whole field instead of only within a search neighborhood, as with sequential simulation algorithms. However, the disadvantage of global spectral simulation is that it traditionally cannot account for local information such as the local continuity trend and local continuity azimuth, which are often observed in reservoirs and hence are important to be incorporated in geologic models. A recent paper by Yao et al. (2006) discussed a new method for accounting for local continuity trend, i.e., by gradually varying variogram range, in spectral simulation. Equally important local information in geologic modeling is the local direction of maximum continuity (or azimuth) of a petrophysical property. The orientation of the property may vary from one location to another, for example, to follow the curvilinear structure of meandering channels. In this short note, a new method of conditioning the geologic model to have locally varying azimuth is proposed, using a grid representing azimuths of maximum continuity.

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Methods for Accounting for Local Azimuth

Petrophysical-property continuity within a reservoir often shows anisotropy, i.e., continuity is greater in one direction than in another. In addition, the local direction of greatest continuity might change from one location to another within the reservoir. Consider sediments deposited in a river channel. Paleo-hydrodynamics often control the distribution of the lithological and petrophysical properties within the channel. It is well known that the continuity of these properties is anisotropic, typically greatest along channel and less continuous across channel. The meandering channel may also have a sinuosity that causes a local variation in direction; therefore, the petrophysical-property continuity will also locally vary in direction. This local continuity direction can be recorded as a grid of azimuths, which is often based on seismic interpretation.

Methods used to introduce variable directions in rock-property continuity or varying azimuths into the geologic model are generally based on the traditional pixel-based geostatistical method published by Xu (1996). Under the sequential simulation paradigm, the local kriging system is build from a variogram model with local azimuth. The shortcoming of this method is that the local azimuth values within the search neighborhood for building the kriging system are assumed to be the same as the azimuth value at the block being simulated. It also assumes that the continuity between two blocks within the search neighborhood follows that azimuth as a straight line and does not allow for any sinuosity between blocks, which is not true in reality.

In this proposed method, to condition to the locally varying continuity azimuth, we first identify the strings of connected nodes from the azimuth grids (Jones et al. 2003). See Fig. 1. Then we simulate each string to have maximum continuity along

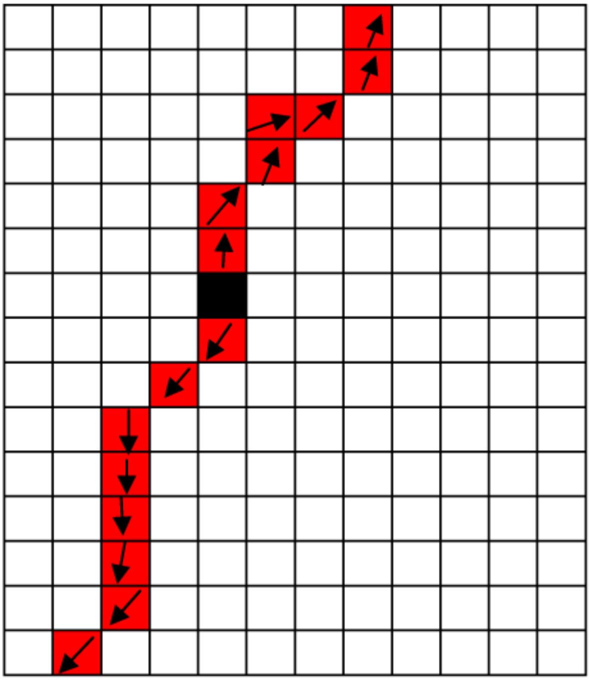

Fig. 1 An example of a string of connected nodes (indicated by *grey squares*). Nodes are at the center of each square (*block*). The starting node (*black block*) was selected randomly. Notice that the local azimuth values for a given node, both upstream and downstream from this starting block, are in the direction of the next block in the string

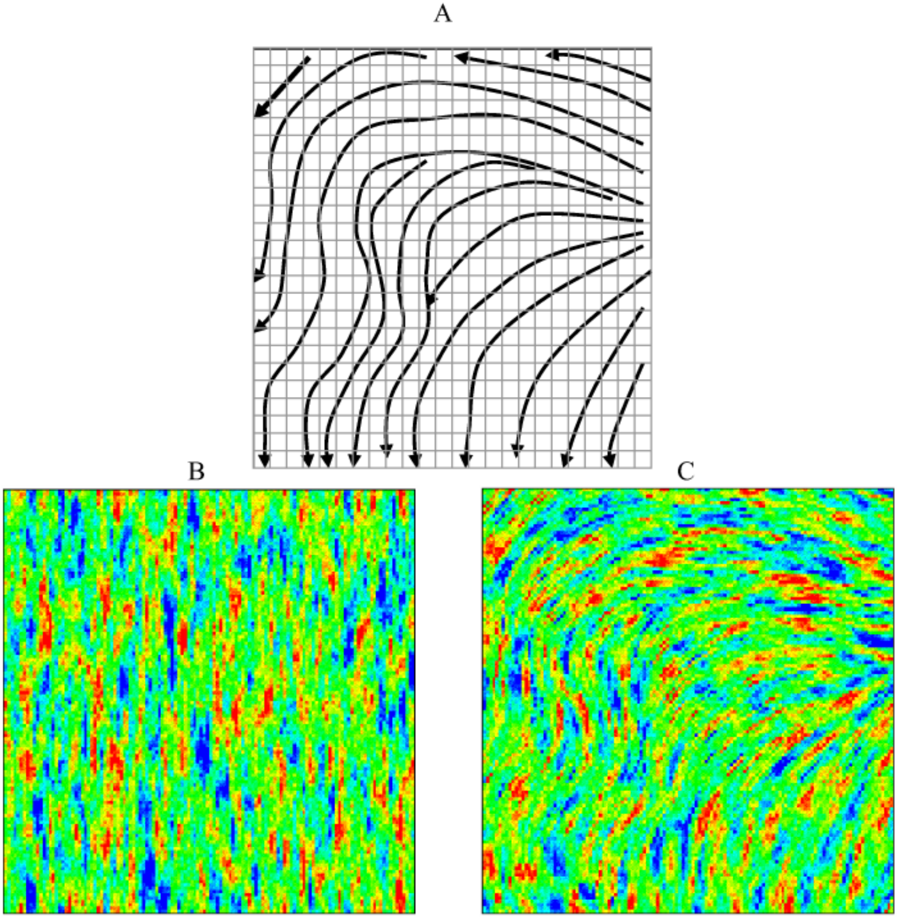

Fig. 2 **A** "Flowlines" drawn on grid indicate directions of greatest petrophysical-property continuity. These flowlines are used to assign an azimuth value to each grid node. **B** 2D Model built using traditional spectral-simulation method which can accommodate only a single direction of maximum continuity, in this case N-S. **C** Model of same area as Fig. 2B, though with local changes to the direction of greatest continuity according to the azimuth grid

that string, using 1D spectral simulation. Finally, we put the simulated values back to the original nodes along the string. Therefore, the continuity along a path that bends according to the azimuth data as desired is reproduced, whereas the current pixel-based geostatistical methods require that this path be represented locally by a straight line. If those segments are small (i.e., the range of continuity is short), the curved line can be approximated well with straight-line segments. However, if the segments are long (i.e., the range of continuity is long), the curved line can not be approximated with straight-line segments. This limitation practically manifests itself as a trade-off between honoring the azimuth data and the target variogram range. In this new method, it is proposed that continuous petrophysical properties are simulated along a bent path, therefore, it should produce better results in situations when long-range continuity is to be represented along a curved geologic feature (see Fig. 2).

Steps for Accounting for Local Azimuth

There are three broad steps in this proposed method for conditioning the model to local azimuth (see also Calvert et al. 2003), and are presented next.

Step One: Prepare a Tentative Geologic Model

1. Build a 3D geologic modeling framework in a stratigraphic system, so that the vertical continuity is orthogonal to the horizontal stratigraphic layers.
2. Calculate a 3D amplitude spectrum using a variogram model which has the same vertical continuity range as the target variogram model, but with isotropic horizontal continuity range identical to the shorter range of the target variogram model. For example, if the target variogram model is 1000 meters along the channel direction, 200 meters across the channel direction, and 10 meters in the vertical direction, a 3D spectrum with horizontal isotropic range of 200 meters and vertical range of 10 meters is calculated.
3. Generate a tentative geologic model using spectral simulation and the calculated 3D amplitude spectrum. The details of this process can be found in Yao (1998). The geologic model is tentative in the sense that the continuity is isotropic in the stratigraphic layers instead of honoring the anisotropy and local azimuth. However, it does ensure that the correlation in the direction perpendicular to the channel direction is reproduced through spectral simulation.

Step Two: Prepare a Grid of Azimuths and Identify Strings of Connected Nodes

4. Using any practical means, generate a grid of azimuths that represent local variations in continuity direction within the stratigraphic layers in the geologic model. A single grid could be used to represent all layers in the geologic model, or just one or several layers. For geologic modeling, this grid could be generated using local continuity interpretations from seismic or well data. The angle simulation method described by Xu (1996) is one example, and generation of vector fields from flowpaths (Jones et al. 2003) is a second example.
5. Using the grid of azimuths generated in step (4), identify strings of nodes that are connected (see Fig. 1). The detail of this approach is described below.
   (a) Randomly select a node; call it P1. Each node has an azimuth assigned to it indicating the direction of maximum spatial continuity at that node. Call this direction “upstream”. The “downstream” direction is this azimuth plus 180 degrees.
   (b) In the upstream direction, using the azimuth, α, at P1, calculate a distance, d, that approximately spans a grid block in that direction

$$d = |1/\sin\alpha|, \quad 45^\circ < \alpha \le 135^\circ;\ 225^\circ < \alpha \le 315^\circ$$
$$d = |1/\cos\alpha|, \quad \text{otherwise}$$

   Calculate the coordinates of the point, P2, which is d distance and direction α from P1; P2 is not necessarily on a node of the grid.

(c) Find the node nearby to the point P2 identified in Step (b) and obtain its azimuth. This usually would be from the nearest node, but the azimuths of several nearby nodes could be combined to provide the next direction α. Using this azimuth, repeat step (b) to calculate the location of an additional point P3 that is at this calculated distance and azimuth from P2.
(d) Repeat step (c) to identify additional nodes until either the edge of the model or another boundary (e.g., facies boundary) is reached; or, until the current string intersects a node already belonging to a previously defined string; or, until the next node has an assigned azimuth that is very different from that of the previous block (greater than a threshold angle, e.g., $>5°$). This latter condition prevents sharp bends in the string, but has the intent of preventing discontinuous geologic features from being combined.
(e) Repeat steps (b)–(d) in the downstream direction.
(f) Place the identifiers of all nodes in this string into a 1D array, in the order of furthest block upstream to furthest block downstream. These nodes cannot be assigned to any other string.
(g) Repeat steps (a)–(f) for the next string, until every node is assigned to one string.

Note that if the azimuth is a 2D map, we will need to identify the connected strings only once and apply 1D spectral simulation along the same strings on different stratigraphic layers. Otherwise, if the azimuth is a 3D grid, we will need to identify the connected strings on each stratigraphic layer. Then, apply 1D spectral simulation along different connected strings on different stratigraphic layers.

Step Three: Perform 1D Spectral Simulation along the String Nodes

7. Map values from the tentative geologic model from step (3) to the 1D array of nodes along the strings identified from step (6), generate a 1D array of the tentative geologic model petrophysical-property values for each string of nodes. The nodes in each string should be in the order of furthest block upstream to furthest block downstream.
8. For each of the 1D arrays, perform a 1D spectral simulation of the petrophysical property. The amplitude spectrum used for this simulation should represent the maximum-desired spatial continuity for this property within the string of nodes; i.e., continuity in the orientation represented by the assigned azimuths.
9. Substitute the values simulated in Step (8) for the values in those corresponding nodes in the tentative geologic model from Step (3), resulting in a new geologic model having anisotropic spatial continuity that changes in direction according to the input azimuths.

An example of 2D application of this method is shown in Figs. 2A–2C. Figure 2A shows how the interpreted direction of maximum continuity (azimuth angle) locally changes across the grid (stratigraphic layer). In building the model, accurately representing this spatial continuity would be desirable, i.e., we would like to account for this local change in continuity direction. However, a traditional, 2D spectral-simulation method can represent maximum continuity in only one direction (i.e.

north-south in Fig. 2B). Figure 2C shows results using this method and the varying azimuth information depicted as flowlines in Fig. 2A. Notice the dramatic differences between Figs. 2B and 2C—the continuity in Fig. 2C mimics the directional trends shown in Fig. 2A.

Conclusion

A new method for accounting for the locally varying azimuth using spectral simulation for geologic modeling is proposed in this short note. Through 1D spectral simulation along the continuous strings identified from the azimuth grid, this new method reproduces the desired continuity along a path that bends according to the azimuth data. This is better than the traditional pixel-based method, where the continuous path is locally represented to be a straight line within the search neighborhood of kriging system. The detailed steps for this new method are discussed and illustrated by a 2D example. In 3D, to apply this method, it is important to start with a stratigraphic framework so that vertical continuity is orthogonal to the horizontal stratigraphic layers and the imposed change of continuity along the flow path will not alter the continuity in the vertical direction.

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