PS Testing 3D Seismic Attribute Strategies for Subtle Fault Mapping*

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Abstract

Discovering and mapping fine-scale faults is a critical activity for carbon sequestration planning. Particularly important is assessing the risk of subtle faults or fractures that may continue from a potential sink upward through a potential seal. Further, if such faults or fractures can be shown to have propagated from seismogenic depths (e.g., from Precambrian 'basement'), then a risk of reactivation may exist. In order to assess the potential strengths and weaknesses of using geophysical data to study the problem of subtle faults, we use a publicly available 3D seismic reflection data set from the Illinois Basin where a deep Paleozoic interval for carbon sequestration has been identified. The Illinois Basin provides special challenges for carbon sequestration planning because geologic anomalies (e.g., faults) can be faint and easily missed using 2D seismic data or even 3D data if only conventional display strategies are used. Previous studies have suggested that many large-scale structures in the basin are facilitated by deep-seated faults, which have propagated up continuously from Precambrian rocks into the shallow Paleozoic section. However, the same cannot necessarily be said for small-scale faults in the basin. Using the 3D seismic data from the Illinois Basin, we employ a suite of seismic attributes to demonstrate how deep faults at the target sequestration interval may initially appear to propagate vertically through the Paleozoic (and uppermost Precambrian) section in conventional displays, but when mapped in detail are seen to be much more complex. We have computed attribute displays based on discontinuity, positive and negative curvature, amplitude change in X and Y directions, and seismic shaded relief. Our results show how sets of small-scale faults can apparently grow and die out in a vertical section, while skipping laterally up or down section, thus lacking significant vertical continuity. However, such faults can appear continuous when viewed without detailed analysis and without optimal display parameters and orientation. Our study provides a general strategy for assessing subtle fault continuity and a cautionary tale for concluding significant fault continuity where none may actually exist.

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Summary

Because the confinement of CO_2 in a storage reservoir depends on a stratigraphically continuous set of seals to isolate the fluid in the reservoir, the detection of structural anomalies is critical for guiding any assessment of a potential subsurface carbon storage site. Employing a suite of 3D seismic attribute analyses (as opposed to relying upon a single attribute) maximizes the chances of identifying geologic anomalies or discontinuities (e.g., faults) that may affect the integrity of a seal that will confine the stored CO_2 in the reservoir. The Illinois Basin, a major area for potential carbon storage, presents challenges for target assessment because geologic anomalies can be ambiguous and easily misinterpreted when using 2D seismic reflection data, or even 3D data, if only conventional display techniques are used. We have procured a small 3D seismic reflection data set in the central part of the basin (Stewardson oil field) in order to experiment with different strategies for enhancing the appearance of discontinuities by integrating 3D seismic attribute analyses with conventional visualizations. Focusing on zones above and below target interval of the Cambrian Mt. Simon Sandstone, we have computed attribute traveltime slices (combined with vertical views) based on discontinuity computations, cross-line-directed amplitude change, azimuth of the dip, shaded relief, and fault likelihood attributes. The results provide instructive examples of how discontinuities (e.g., sub-seismic scale faults) may be almost "invisible" on conventional displays, but become detectable and mappable using an appropriate integration of 3D attributes. Strong discontinuities in underlying Precambrian basement rocks do not necessarily propagate upward into the target carbon storage interval. The origin of these discontinuities is uncertain, but we explore a possible strike-slip role that also explains the localization of a structural embayment developed in lower Paleozoic strata above the discontinuities.

Conventional Time-slice 3D Views of Carbon Storage Target Stratigraphic Interval

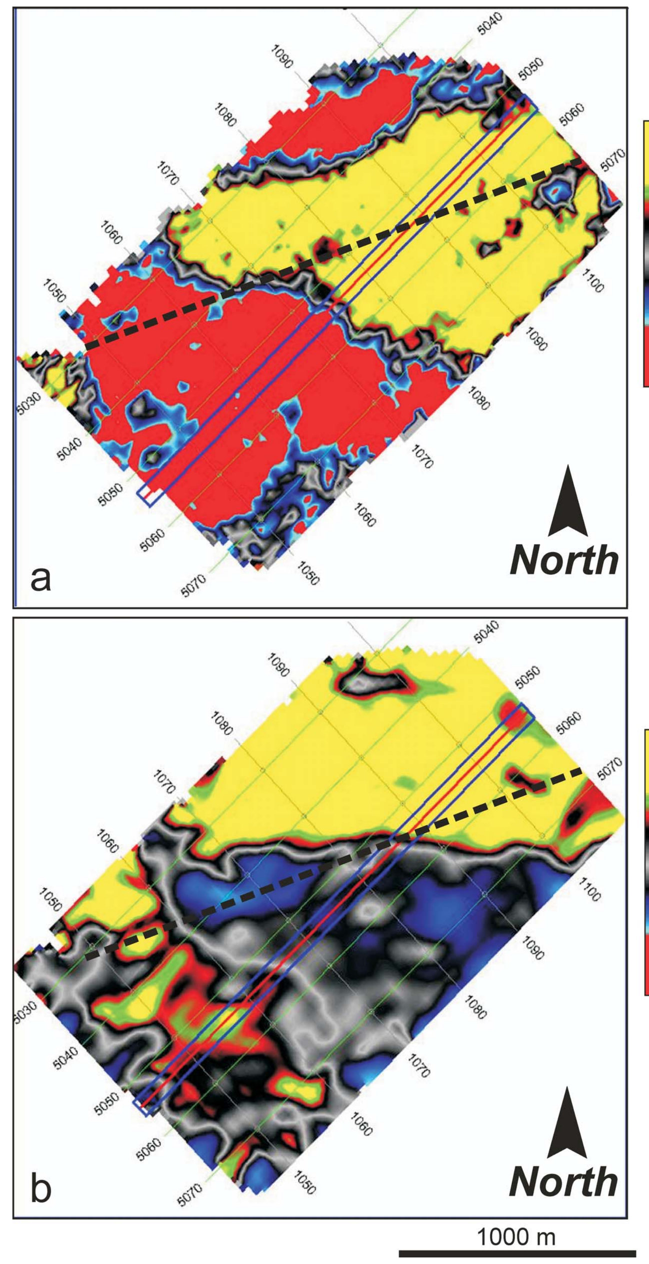

Figure 3. **(a)** Traditional time slice view at base of Knox level (1000 ms). **(b)** Same view, but the volume was processed as shaded relief attribute (135° azimuth). Line across volume shows location of profile in Figure 2 (bottom). Thick dashed line shows trend of deep discontinuity, for reference, mapped within Precambrian basement at 1378 ms (Figure 6).

Carbon Storage/Structural Setting

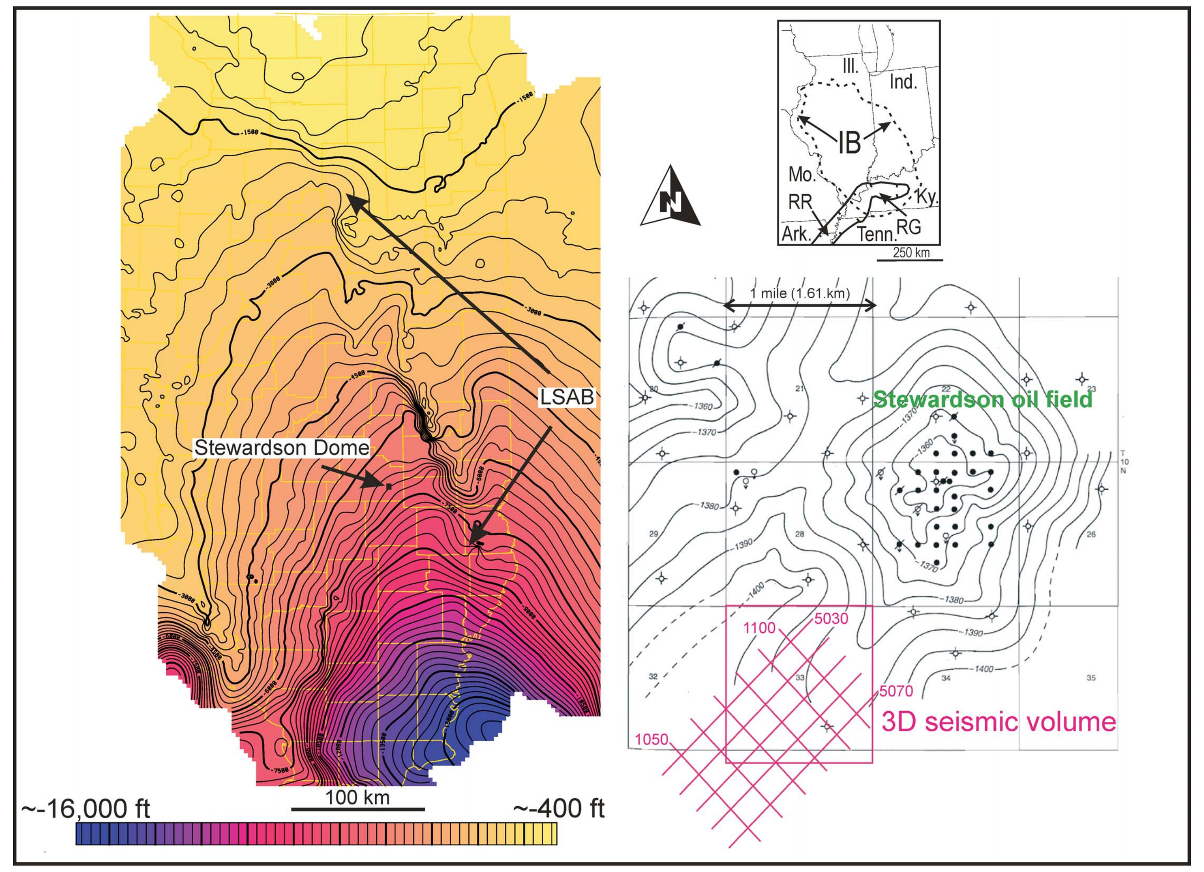

Figure 1. Structural contour map for the top of the Cambrian Mt. Simon Sandstone constructed from well data. The Mt. Simon ranges from -400 ft (122 m) to a projected -16,000 ft (4877 m) below sea level. Contour interval is 300 ft (91 m). Inset shows outline of the Illinois Basin (IB), the Rough Creek graben (RG), and the Reelfoot rift (RR). LSAB is La Salle anticlinal belt. Also shown is a structural contour map for the top of the Ste. Genevieve Formation (Mississippian), which defines the Stewardson oil field, from Rice et al. (1993). Contour interval is 5 ft (1.5 m). The outline of the 3D seismic volume is shown with in-lines (1000s) and cross-lines (5000s) labeled.

Contiguous vertical views showing lateral variability in fault definition

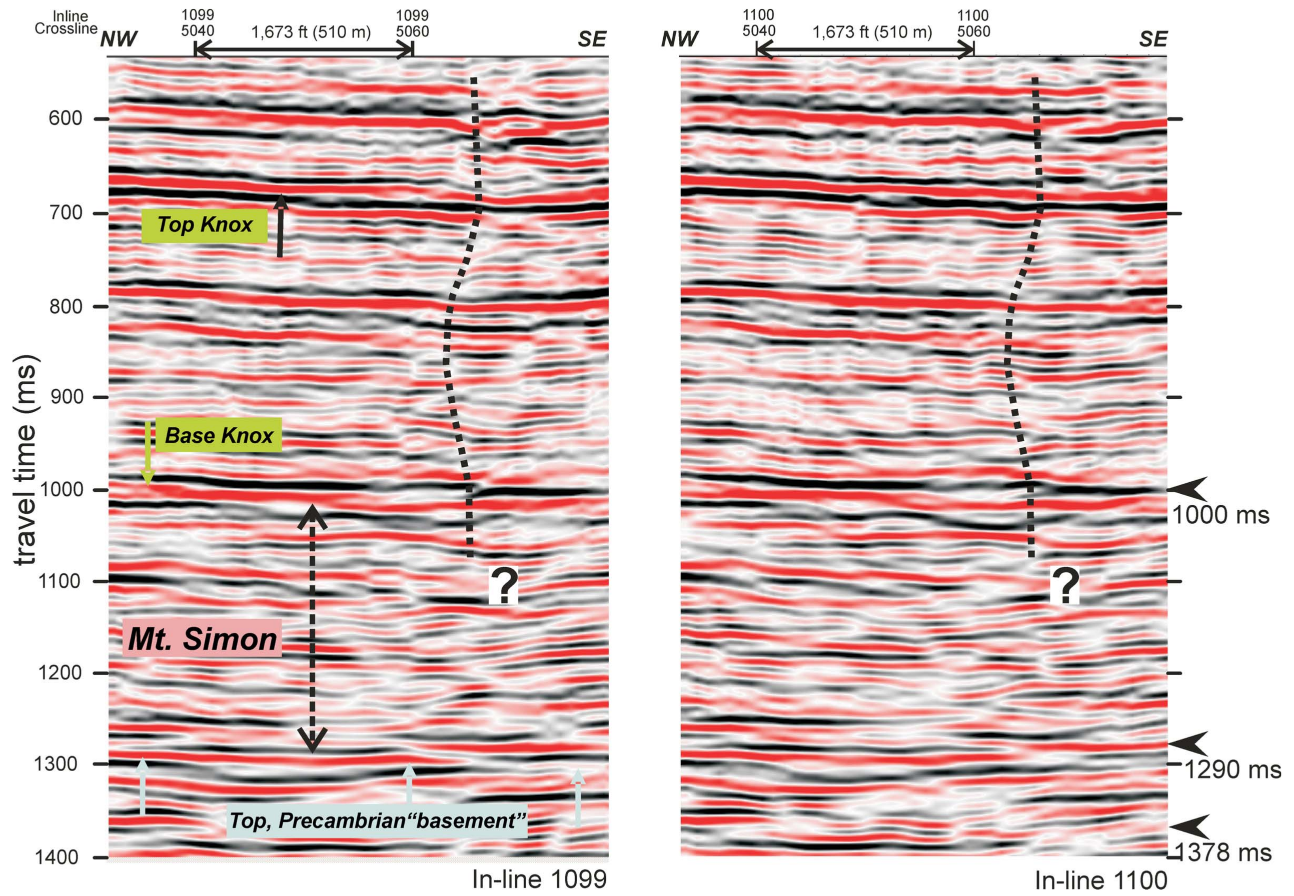

Figure 9. Two contiguous vertical views (in-line 1099 and 1100). In-line 1099 is optimally chosen to show offset reflectors (see dashed), which could be tentatively interpreted as a near-vertical fault propagating from the top of the Knox upward; however moving just one in-line to the northeast, only a distance of 110 ft (33.5 m), to in-line 1100 the upward continuation of the fault is much less viable (the fault interpreted from in-line 1099 is shown for reference). A similar result occurs moving the in-line in the opposite direction, to the southwest. This indicates the difficulty in mapping such subtle features from profiles alone. Arrows on right indicate the three levels analyzed with seismic attributes.

Carbon Storage/Seismic Stratigraphic Setting

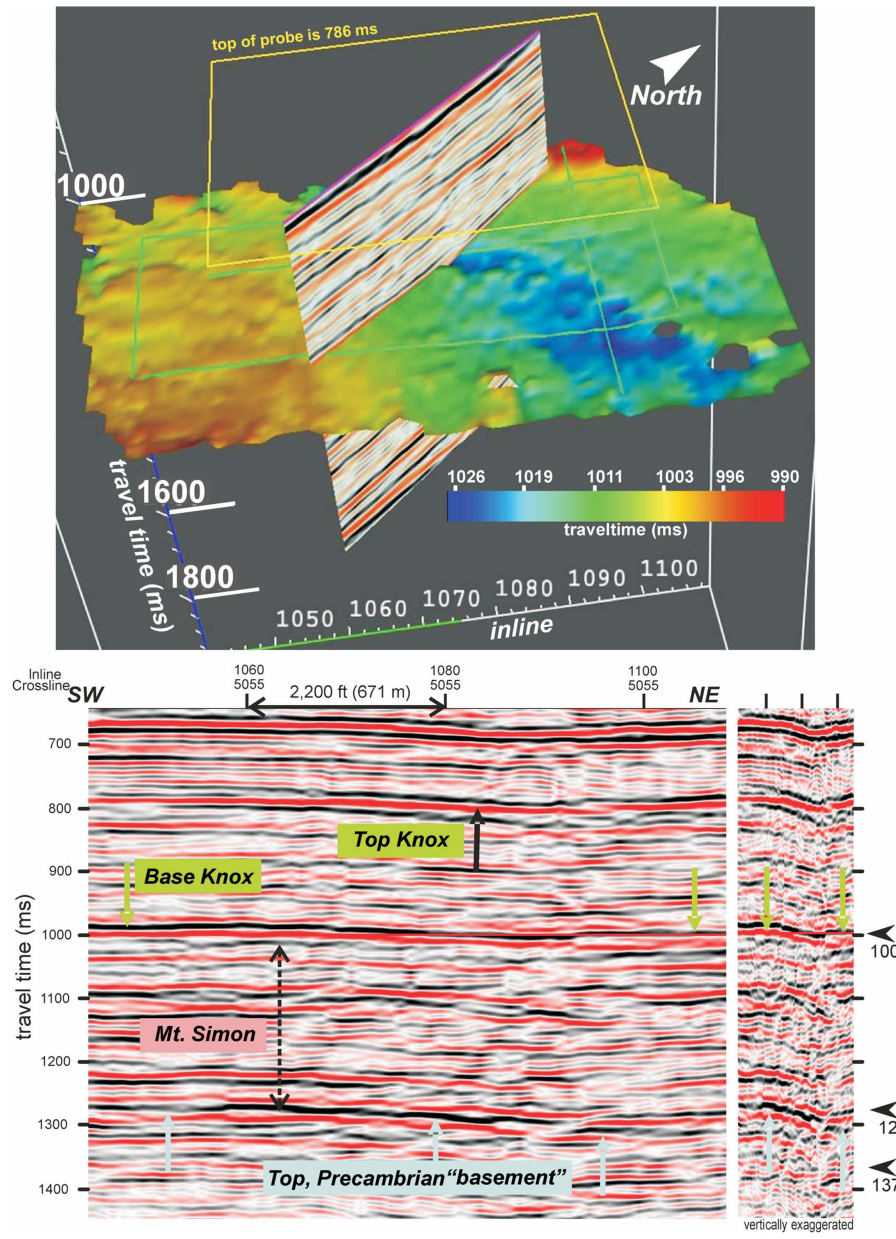

Figure 2. Top, perspective view of structure mapped on the base of the Knox Supergroup (~1000 ms) with a correlated vertical view. Bottom, excerpted vertical view for cross-line 5055 with Knox and Mt. Simon units identified. Although no direct well correlations are available, stratigraphic picks match regional interpretations (Heigold, 1991; McBride and Kolata, 1999). Arrows on right indicate the three levels extracted from volume seismic attributes. Note that Eau Claire Shale is not shown, but is located near the base of the Knox. Section on right is same, but with a very large vertical exaggeration.

Simplified structural elements for Illinois Basin and study area

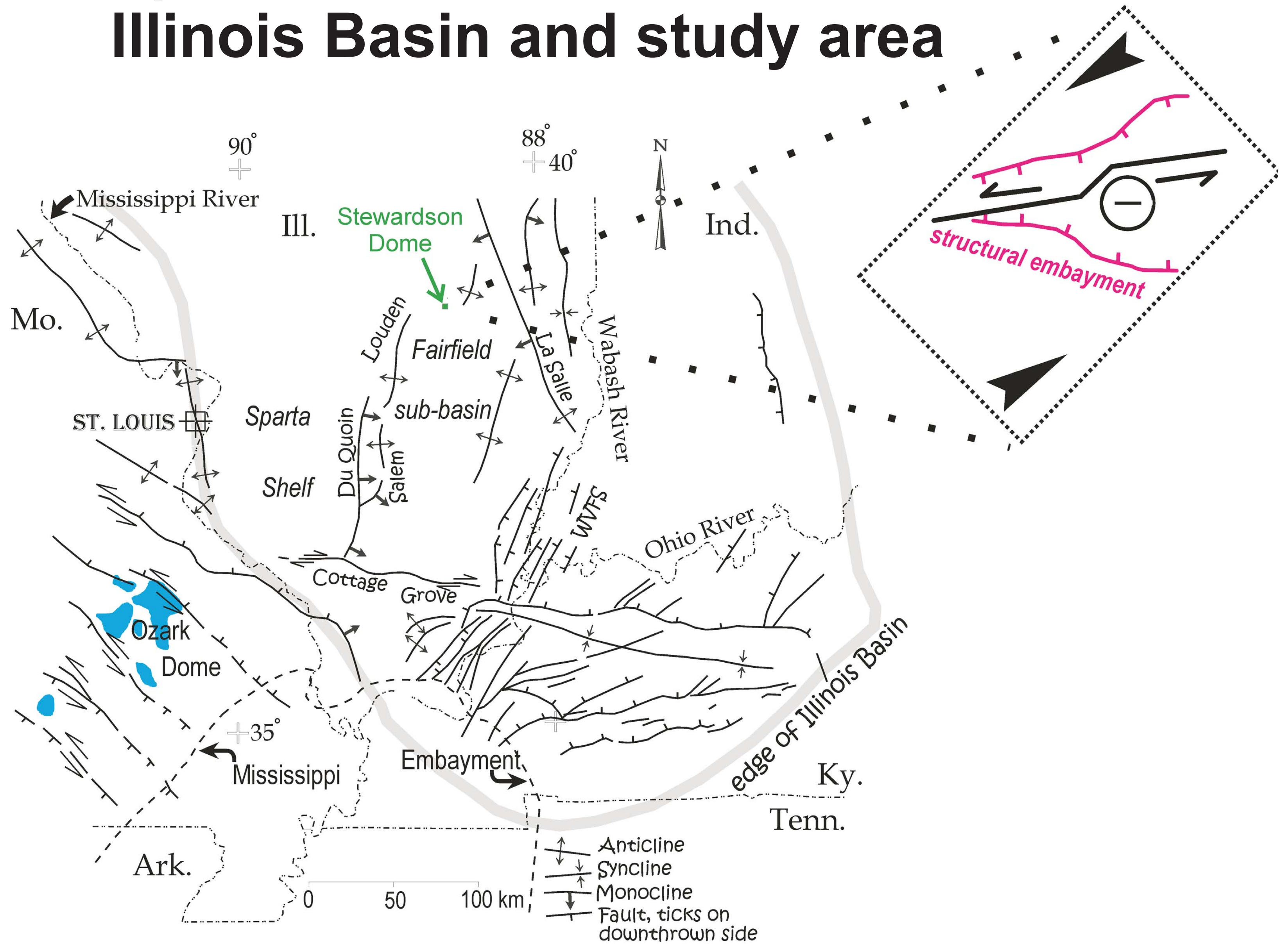

Figure 11. Much simplified structural elements map for the Illinois Basin and vicinity with the location of the Stewardson Dome noted. WVFS is Wabash Valley fault system. The reader is referred to Nelson (1995) and McBride and Nelson (1999) for more explanation for regional structural features in this region. Rectangular inset shows orientation of the discontinuity at the base of the Cambro-Ordovician Knox reflector with hypothetical strike-slip deformation that could be caused by the stresses that formed the surrounding folds and faults (especially the LaSalle anticlinal belt) as shown by large arrows. The circle indicates where a depression associated with a left-lateral strike-slip step-over would develop.

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Testing 3D Seismic Attribute Strategies for Subtle Fault Mapping

Comparisons of Different Attributes for Target Storage Interval (top)

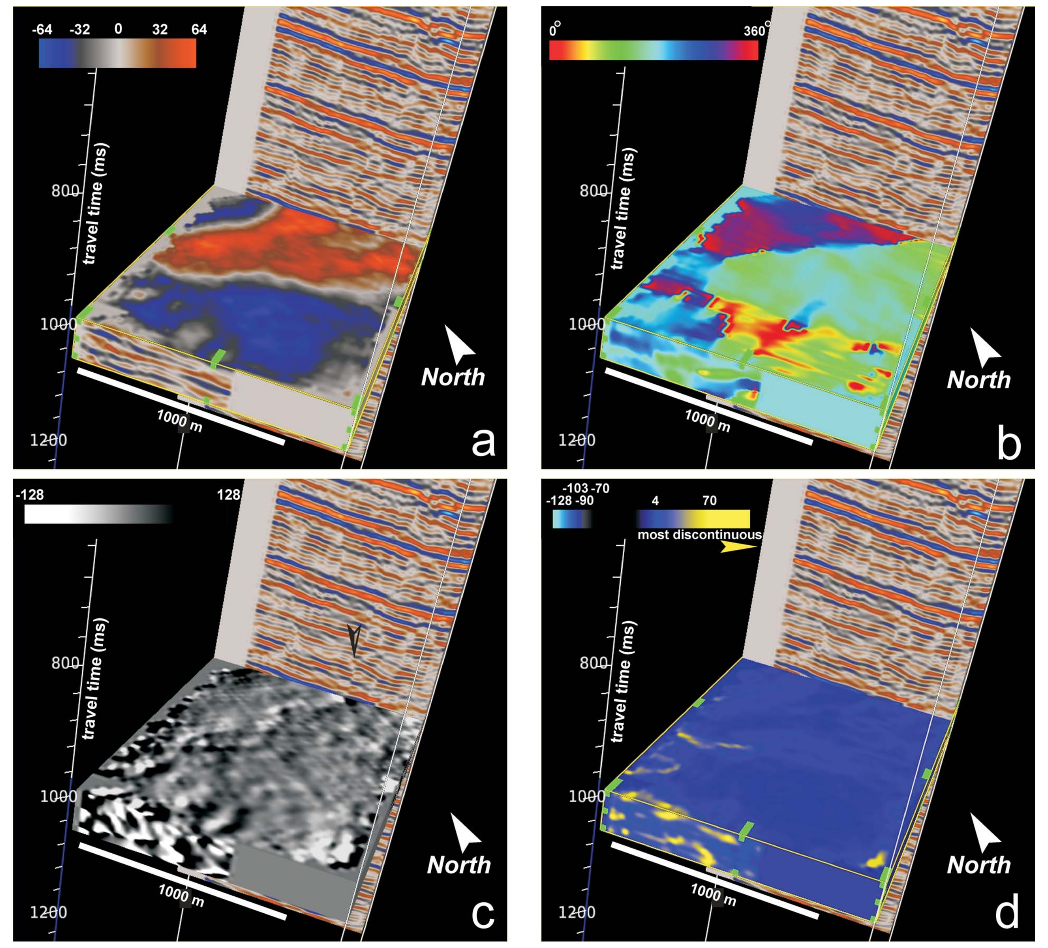

Figure 5. **(a)** Perspective view of seismic volume (vertical view is in-line 1099) with probe shown for travel time at 1000 ms (near base of the Knox) showing amplitude. **(b)** Same as in (a), but showing azimuth of the dip. Red indicates north azimuth, blue is south, green is west, purple is east. **(c)** Same as in (a), but showing cross-line-directed amplitude change. The gray levels are treated as illumination from a distant light source, proceeding from white to black as if observed on ridges oriented normal to the light source (i.e., black is most relative positive gradient of change in the cross-line direction, and white is most relative negative gradient of change). Vertical arrow shows offset reflector zone for reference. **(d)** Same as in (a), but showing discontinuity. Yellow indicates discontinuity.

Comparisons of Different Attributes for Target Storage Interval (bottom)

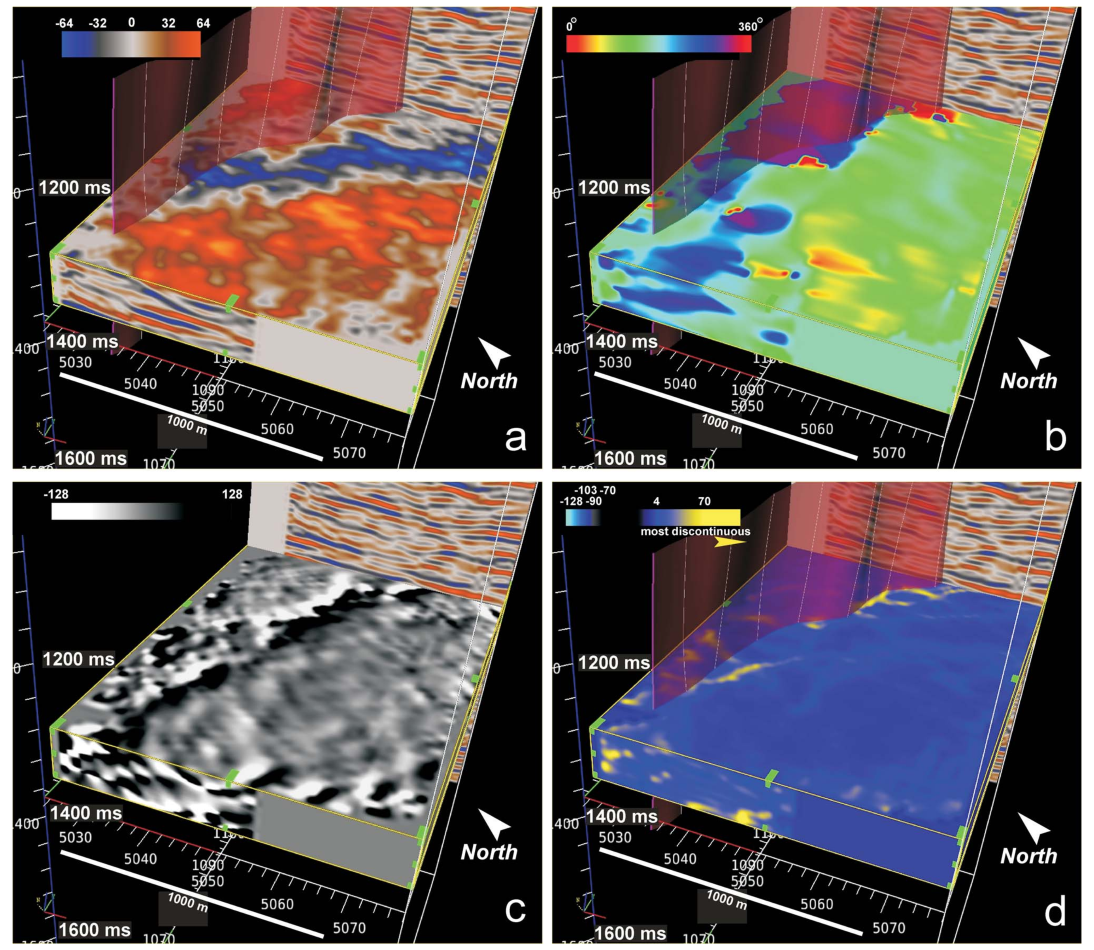

Figure 8. **(a)** Perspective view of seismic volume (vertical view is in-line 1099) with probe shown for travel time at 1290 ms (top of Precambrian basement/base of Cambrian Mt. Simon) showing amplitude. **(b)** Same as in (a), but showing azimuth of the dip. Colors as in Figure 5b. **(c)** Same as in (a), but showing cross-line-directed amplitude change (like shown in Figure 5c). Vertical arrow shows offset reflector zone for reference. **(d)** Same as in (a), but showing discontinuity. Colors as in Figure 5d. Interpreted fault surface, projected upward, is shown in parts a, c, and d.

Comparisons of Different Attributes for Deep Precambrian Basement

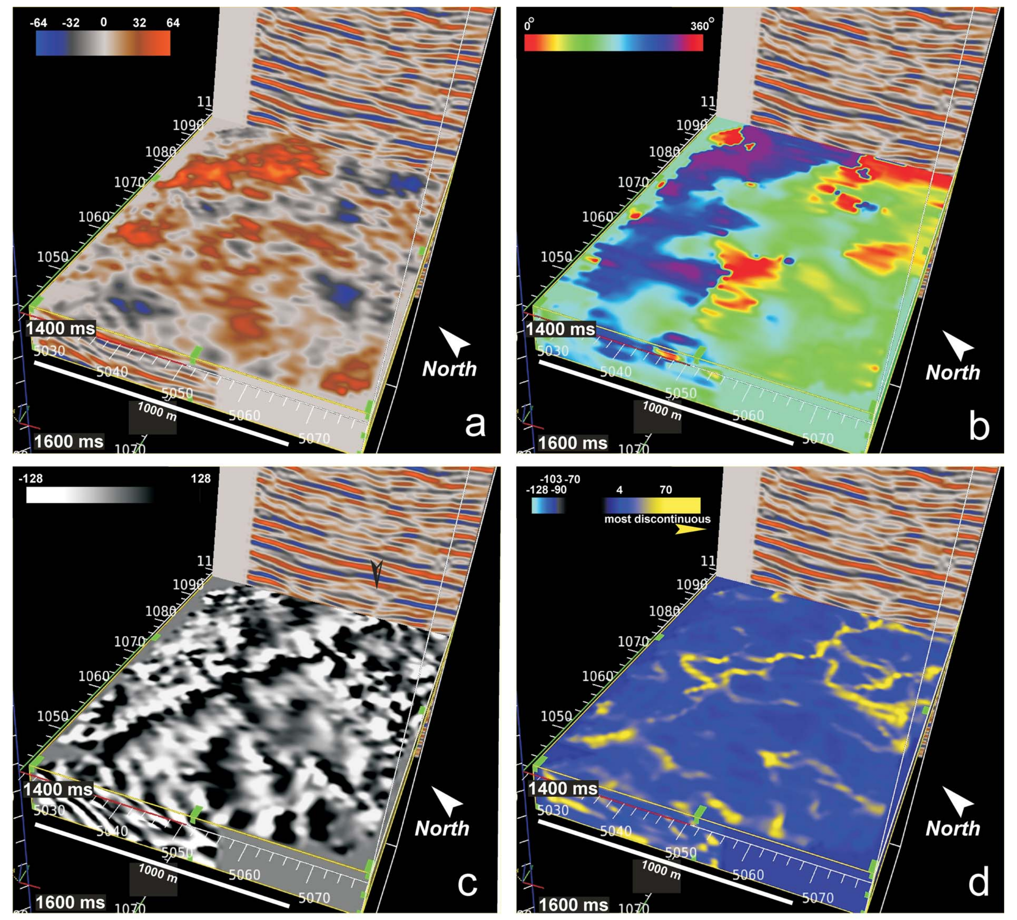

Figure 6

Figure 6. **(a)** Perspective view of seismic volume (vertical view is in-line 1099) with probe shown for travel time at 1378 ms (within Precambrian basement) showing amplitude. **(b)** Same as in (a), but showing azimuth of the dip. Colors as in Figure 5b. **(c)** Same as in (a), but showing cross-line-directed amplitude change (like shown in Figure 5c). Vertical arrow shows offset reflector zone for reference. **(d)** Same as in (a), but showing discontinuity. Colors as in Figure 5d.

Tracing Offset Zone in Deep Precambrian Basement

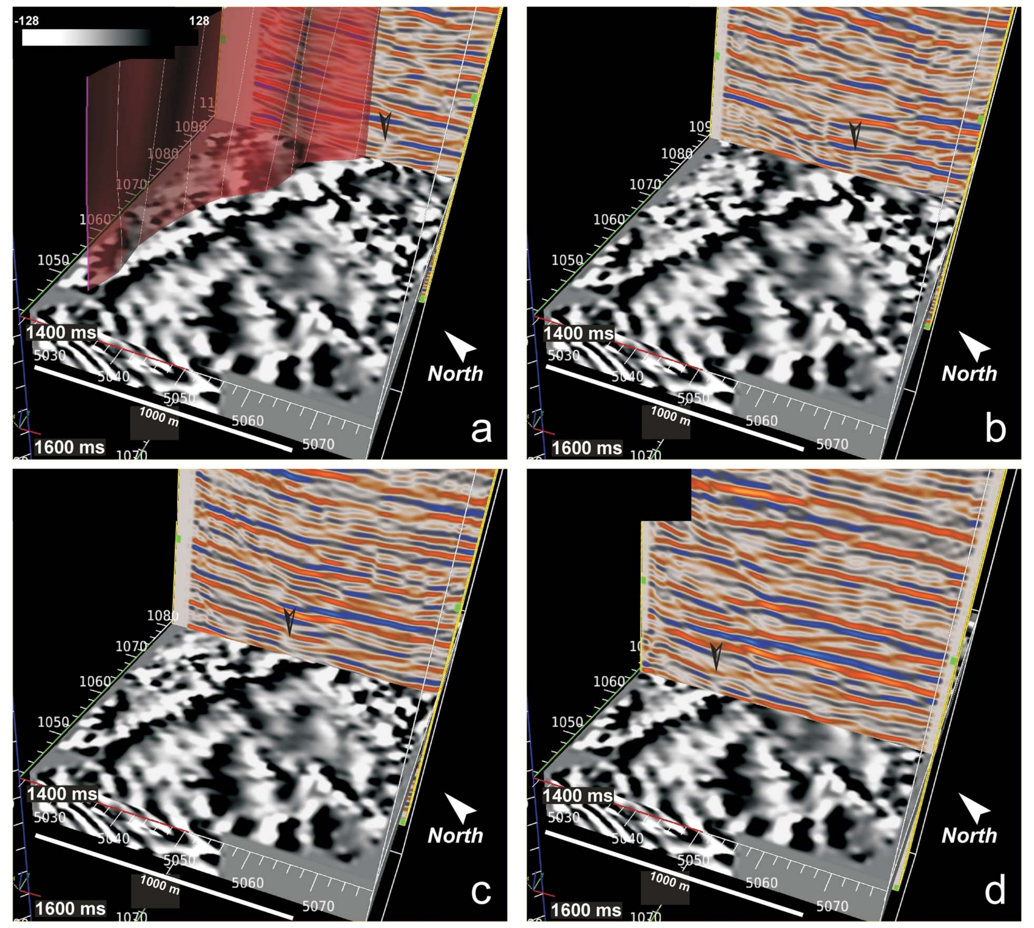

Figure 7. **(a)** Perspective views of seismic volume with probe shown for travel time at 1378 ms (as in Figure 6) showing how offset reflector zone (vertical arrow) changes across the volume. In-line 1099 is shown with fault interpretation projected down from discontinuity mapped at top of Precambrian basement (1290 ms; base of Cambrian Mt. Simon Sandstone; see Figure 8), indicating that the two discontinuities are not vertically continuous. **(b)** Same as in (b), but showing in-line 1091. **(c)** Same as in (b), but showing in-line 1082. **(d)** Same as in (b), but showing in-line 1067.

Fault likelihood attribute

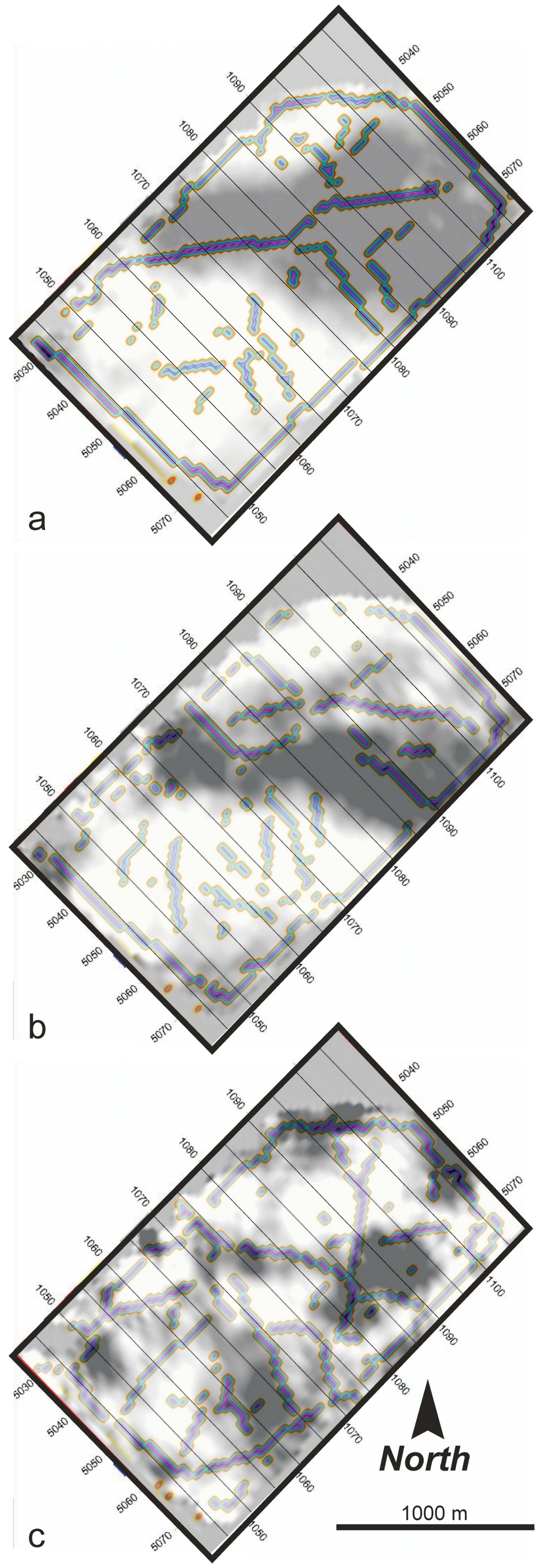

Figure 4. **(a)** Fault likelihood attribute, as described in text, for 1000 ms (near base of the Knox). This attribute provides fault or fracture definition, using values ranging from 0 to 1, with 1 indicating maximum likelihood of a fracture or fault, and 0 minimum likelihood. The attribute has been superimposed on a amplitude time slice for this level (shown as gray levels). **(b)** Same as in (a), but for 1290 ms (near top of Precambrian basement or base of Mt. Simon). **(c)** Same as in (b), but for 1378 ms (within Precambrian basement).

Conceptual cartoon illustrating limited vertical extent of faulting

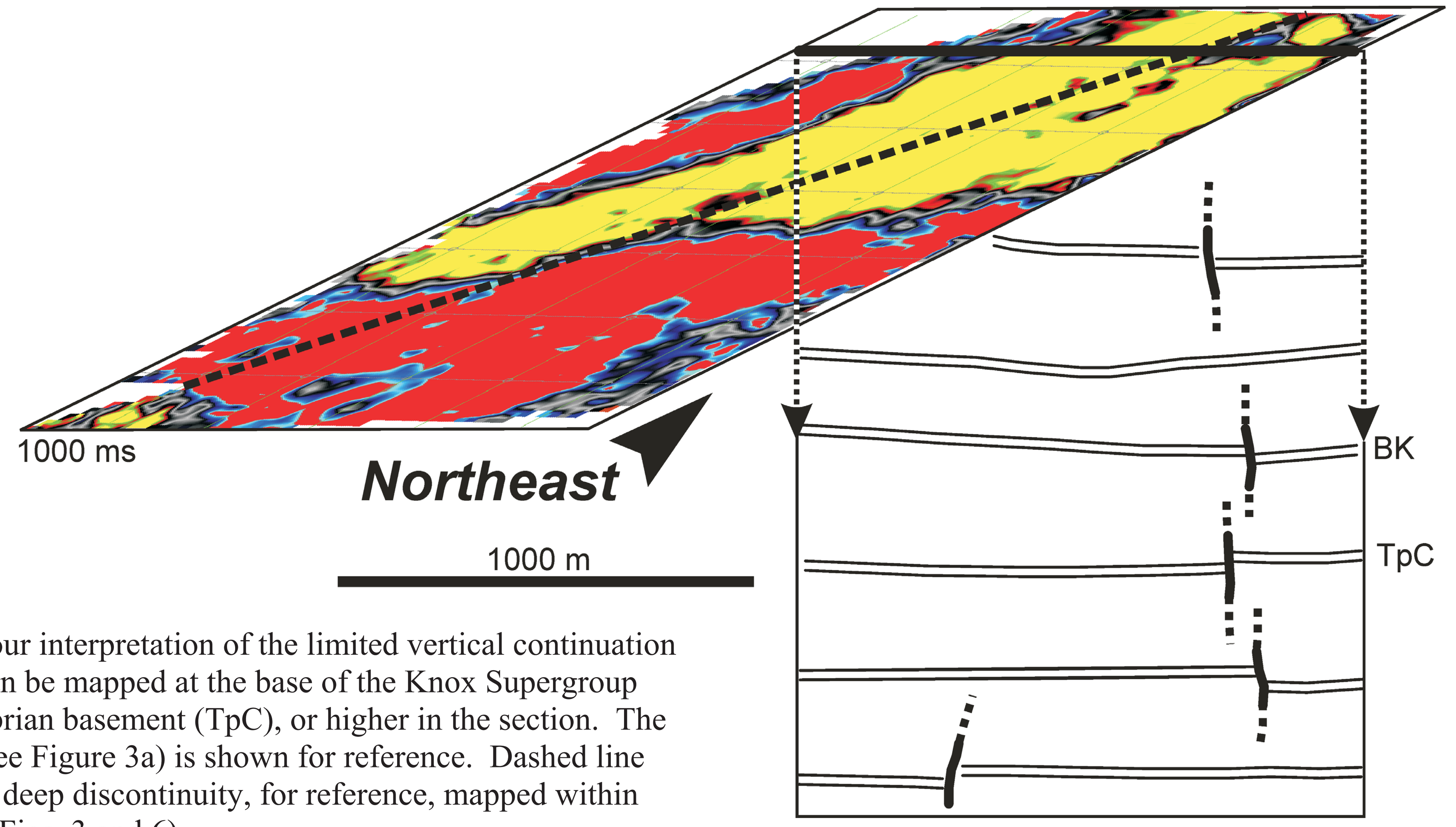

Figure 10. Conceptual cartoon of our interpretation of the limited vertical continuation of the several discontinuities that can be mapped at the base of the Knox Supergroup (BK), down past the top of Precambrian basement (TpC), or higher in the section. The amplitude time slice for 1000 ms (see Figure 3a) is shown for reference. Dashed line crossing the volume shows trend of deep discontinuity, for reference, mapped within Precambrian basement at 1378 ms (Figs. 3 and 6).

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