Supplementary Material

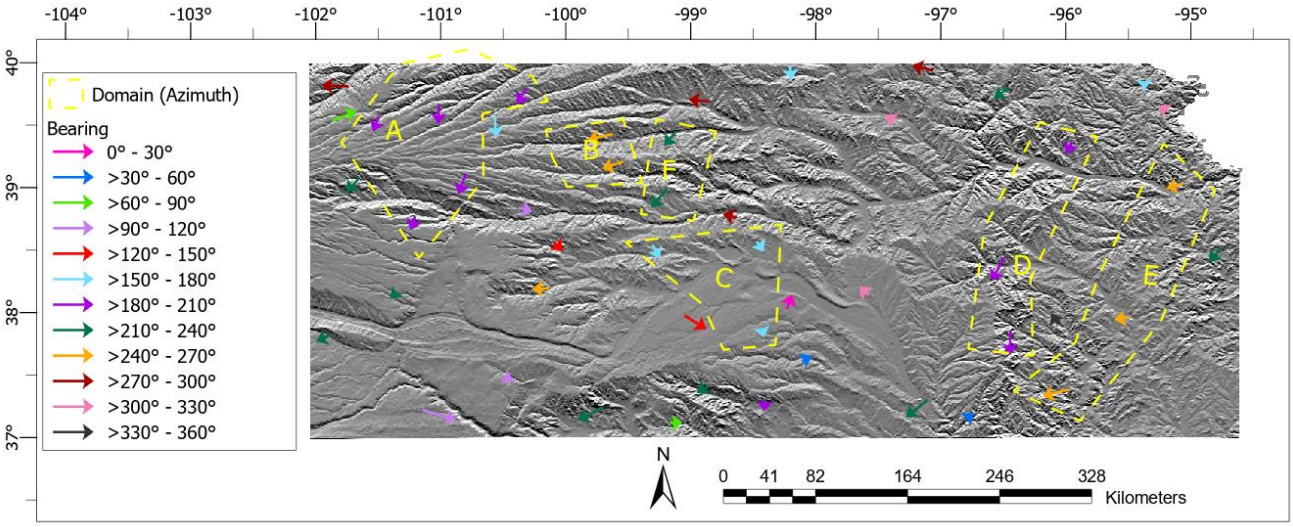
1 Attributes of the Asymmetry Domain

1.1 Transverse Basin Asymmetry Index (TI)

The findings of the asymmetry vector and associated vector domains for TI are presented in the following sections.

1.1.1 Asymmetry vectors and vector domains in Kansas

This section is laid out separately for Kansas and Oklahoma, reflecting the distinct nature of the datasets of the two states. In Kansas, a total of six azimuthal-vector domains were delineated based on the preferred azimuthal direction of asymmetry of the mean vectors. The azimuthal-vector domains labeled A through F in S1 are delineated based on the preferred azimuthal direction of asymmetry of the mean vectors.



S1: Azimuthal asymmetry vectors and vector domains on a shaded relief map of Kansas.

Domain A

Domain A encompasses the sub-basins the Beaver, the South Fork Beaver, the Upper Republican, the Little Beaver, the Upper Sappa, the Lower Sappa, the North Fork Smoky Hill, the Smoky Hill Headwaters, Ladder, Hackberry, Upper Smoky Hill, Upper Saline, Upper North Fork Solomon, and partially the Prairie Dog. The azimuth of the average asymmetry vectors within this domain is predominantly directed toward the south-to-southwest (S1). This area exhibits minimal to no seismic activity and is located at the northwest end of the CKU (S2). The surface geology of Domain A is primarily characterized by loess deposits and alluvium, with the Ogallala Formation, and sparsely distributed Pierre Shale cropping out along the banks of streams that originate in the Rocky Mountains to the west. In domain A, the bedrock is near horizontal.

Domain B

Domain B partially includes the Upper South Fork Solomon and the Upper Saline sub-basins. The mean vectors within this domain predominantly have an azimuth oriented toward the southwest-to-west (S1). This domain experiences moderate seismic

activity to the southeast. The domain contains basement faults that are part of the CKU (S2). The surficial geology of this domain consists of loess, the Ogallala Formation, some Niobrara chalk, Carlile Shale, and alluvium. In Domain B, the bedrock dip is near-horizontal.

Domain C

Domain C accommodates the sub-basins of Lower Walnut Creek, Con-Pickerel, Rattle Snake, Cow, North Fork Ninnescah, and Gar-Peace. The mean vector azimuths in this area are predominantly oriented southeast-to-south (S1). This domain contains faults that are part of the CKU, which lacks seismic activity (S2). Domain C's surficial geology is mainly comprised of sediments from the loess, Dakota Formation, dune sands, Carlile Shale, Greenhorn Limestone, and Graneros Shale. The bedrock dips near horizontal.

Domain D

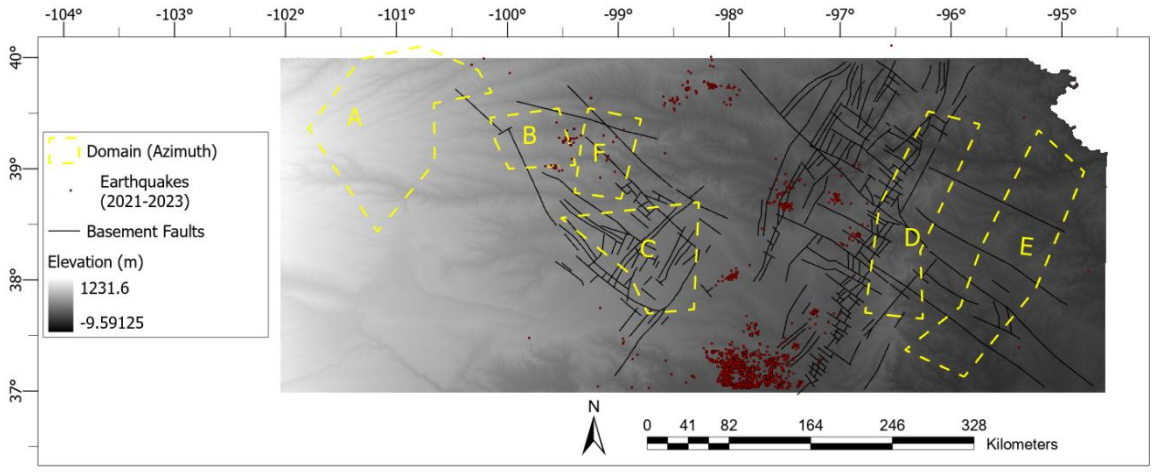
Domain D includes the sub-basins of Middle Kansas, Neosho Headwaters, and Lower Cottonwood and accommodates some parts of the Upper Walnut River, Fall, Upper Verdigris, and Upper Marais Des Cygnes to a minimal extent. The azimuth of the mean vectors in this domain is oriented due south-to-southwest (S1) with almost no seismic activity (S2). This domain contains faults that are part of the HFZ and BAC. The surficial geology predominantly comprises Chase Group, Council Grove Group, Admire Group, Wabaunsee Group, and drift and alluvium. In Domain D, the bedrock dip is west-to-northwest.

Domain E

Domain E encompasses the sub-basins of Lower Kansas, Kansas, Upper Marais Des Cygnes, Upper Neosho, Upper Verdigris, and partially the Fall, Elk, Caney, Kaw Lake, Lower Walnut River, Middle Arkansas-Slate, Ninnescah, and Chikaskia sub-basins. The mean vector azimuths in this area are predominantly oriented southwest-to-west (S1). This domain includes faults associated with the BAC and has no seismicity (S2). The surface of the domain is chiefly composed of Shawnee Group, Douglas Group, Lansing, Kansas City Group, drift, and alluvium. In Domain E, the bedrock dip is west-to-northwest.

Domain F

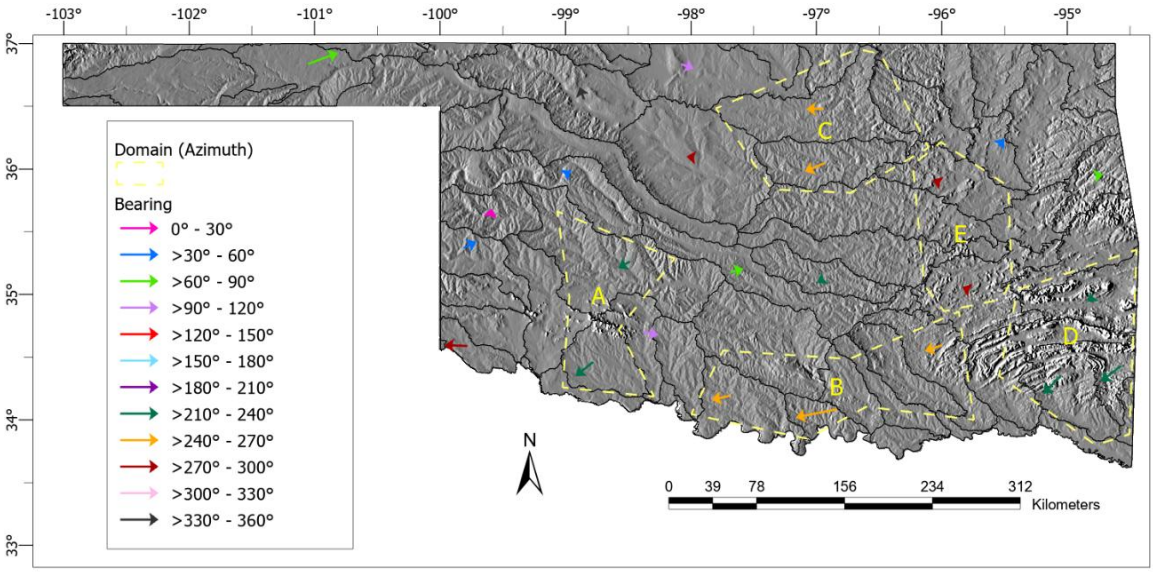
Domain F partially includes the Upper South Fork Solomon, the Upper Saline sub-basins, and the Big sub-basins. The mean vector azimuths in this area are predominantly oriented southwest (S1). This domain contains dispersed seismicity (S2) and faults from CKU extended towards the northwest. The surficial geology of this domain consists of loess, the Ogallala Formation, Niobrara chalk, Carlile Shale, and alluvium. In Domain F, the bedrock dip is near-horizontal.



S2: Basement faults, seismicity, and azimuthal vector domains in Kansas.

1.1.2 Asymmetry vectors and vector domains in Oklahoma

In Oklahoma, the azimuthal-vector domains, A through E, are delineated based on the preferred azimuthal direction of asymmetry of the mean vectors. The azimuthal-vector domains with the average-asymmetry vectors in Oklahoma are shown in S3.



S3: Azimuthal vector domains based on the bearing of the asymmetry vectors on a shaded relief map of Oklahoma.

Domain A

Domain A includes the Upper Washita and West Cache sub-basins. The azimuth of the average asymmetry vectors within this domain is predominantly directed toward the southwest (S3). The domain contains WWF and NU basement faults. There is limited number of recorded earthquakes in this area suggests a low level of seismic activity in the region (S4). The surficial geology primarily comprises terrace deposits, the Hennessey Group, the Wichita Granite Group, the Rush Springs Formation, the Marlow Formation, the Dog Creek Shale, the Garber Sandstone, the Cloud Chief Formation, the Duncan Sandstone, and the Flowerpot Shale. In Domain A, the bedrock dip varies from steep to nearly horizontal.

Domain B

Domain B includes the Farmers-Mud, Lake Texoma, Lower Washita, and partially the Blue, Clear Boggy, Muddy Boggy, and Middle Washita sub-basins. The azimuth of the average asymmetry vectors is mainly oriented between southwest and west (S3). The domain has several dispersed earthquake clusters associated with the basement faults of the WWF system (S4). The surficial geology primarily consists of Garber Sandstone, Boggy Formation, Antlers Sandstone, Caddo Formation, and Lynn Formation. Woodford Shale, Wellington Formation, Kiamichi Formation, Deese Group, terrace deposits, and alluvium. In Domain B, the bedrock dips moderately to steeply in multiple directions.

Domain C

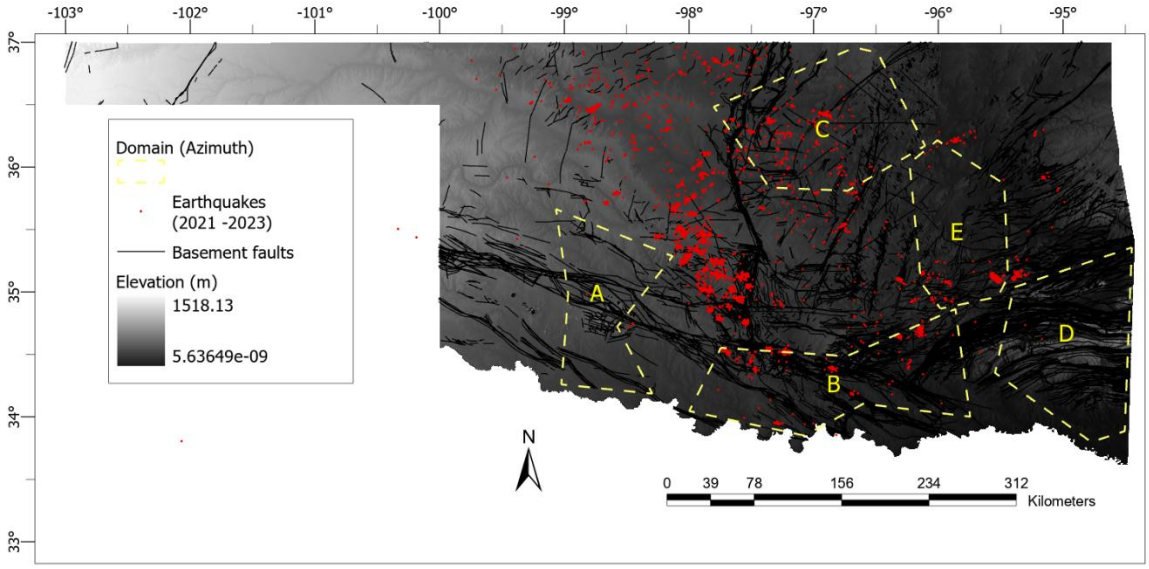
Domain C includes the Black Bear-Red Rock and Lower Cimarron sub-basins and the partially contained Bird, Kaw Lake, and Lower Salt South Fork Arkansas sub-basins. The azimuth of the average asymmetry vectors within this domain predominantly falls between southwest and west (S3). Domain C contains the northern splays of the Wilzetta fault zone extend into the domain and show significant seismicity to the southwest portion (S4). The surficial geology includes Vanoss Group, Ada Group, Vamoosa Group, Garber Sandstone, Wellington Formation, Wann and Iola Formations or Iola Limestone, Chanute Formation, Nellie Bly Formation, commonly with alluvium and terrace deposits. In Domain C, the bedrock dip is gently westward.

Domain D

Domain D includes the Poteau, Kiamichi, Upper Little, and Mountain Fork sub-basins and partially includes the Lower Little sub-basins. The azimuth of the average asymmetry vectors within this domain is predominantly directed toward the southwest (S3). The domain contains the fault system of the Ouachita Uplift. The limited number of recorded earthquakes in this area suggests a low level of seismic activity in the region (S4). The surficial geology comprises the McAlester Formation, Hartshorne Formation, Boggy Formation, Savanna Formation, Lynn Mountain Formation, Atoka Formation, Jackfork Formation, Stanley Shale, and Holly Creek Formation. In Domain D, the bedrock dips moderately to steeply to the north, northwest, south, and southeast.

Domain E

Domain E includes the Polecat-Snake sub-basins and the partially contained Deep Fork, Lower North Canadian, and Dirty-Greenleaf sub-basins. The azimuth of the average asymmetry vectors within this domain is predominantly directed toward the northwest (S3). The domain contains the southern extended faults from Ozark Uplift (S4). Domain E also has several seismic clusters on the sedimentary faults in the northern part of the domain. The surficial geology includes Wewoka Formation, Senora Formation, Boggy Formation, Holdenville Shale, Checkerboard Limestone, and Seminole Formation. In Domain E, the bedrock dips gently westward and southwestward.



S4: Basement faults, seismicity, and azimuthal vector domains in Oklahoma.

1.2 Hypsometric Integral (HI) and Stream Sinuosity Index (SI)

Results for both scalar geomorphic indices (HI and SI) are discussed in combination. The findings are divided into six geological provinces in Kansas and seven geological provinces in Oklahoma.

1.1.3 Kansas

In Kansas, HI hotspots and SI anomalies are distributed across six geological provinces. The characteristics of these hotspots and anomalies are examined by region as follows:

High Plains

HI hotspots in the High Plains are predominantly associated with an extensive alluvial fan extending from the foothills of the Rocky Mountains (S5). These hotspots and coldspots, identified at a 99% confidence level, correspond to the region's hills and river valleys, respectively. Furthermore, the Sinuosity Index (SI) map indicates an increase in sinuosity towards the eastern portion of the High Plains, coinciding with a decrease in slope (S6). The ridge-top of the alluvial fans is visible on the shaded relief map (S7). The surficial deposits in these hotspots primarily consist of unconsolidated loess. Seismic activity is rare in this region (S8).

Smoky Hills

Several substantial HI hotspots are located in the northern region of the Smoky Hills and partially aligned with clusters of seismic activity (S5). The basement structure beneath the Smoky Hills is CKU. The SI values are elevated within the range associated with HI hotspots and extend across much of the Smoky Hills region (S6). The surficial geology in these hotspots consists of loess and alluvial deposits (S8). Additionally, hotspots along the boundary of the Arkansas Lowlands exhibit similar loess deposits.

Wellington-McPherson Lowlands

A prominent HI hotspot in the southern Wellington-McPherson Lowlands coincides with a significant cluster of earthquakes adjacent to active wells in south-central KS and the Pratt anticline (S5). The SI values in this region are higher than those observed in other parts of the lowlands (S6). The surficial geology at this hotspot includes deposits of loess, alluvium, the Sumner Group, and the Nippewalla Group (S8). In the northern portion of the region, smaller HI hotspots are present, characterized by lower SI values and primarily composed of loess.

Flint Hills

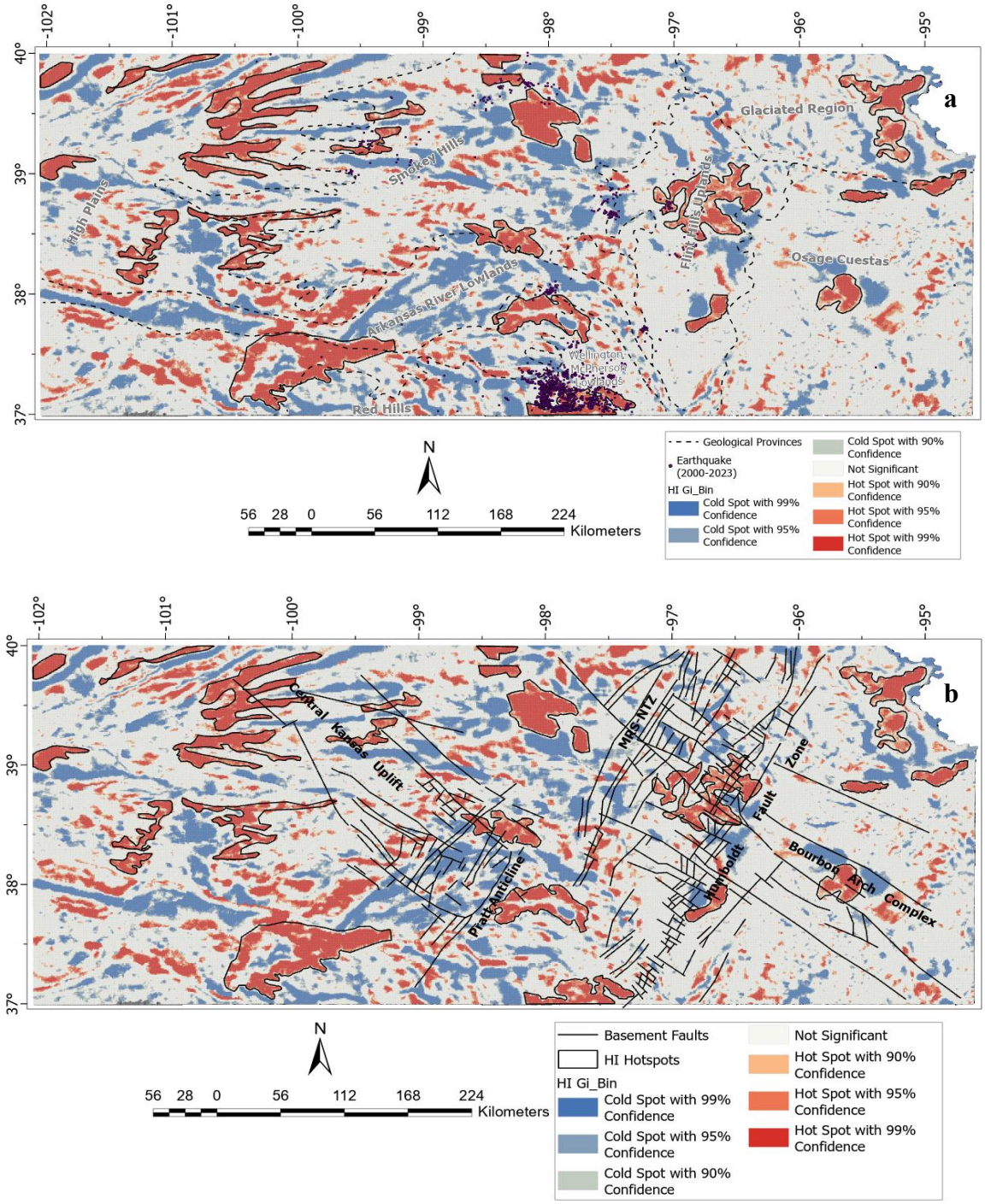
In the central Flint Hills, a distinct HI hotspot is predominantly surrounded by cold spots (S5). Several small clusters of earthquakes are present within this hotspot. Another notable hotspot is located in the southern Flint Hills. This region exhibits moderate to low SI values, regardless of the presence of HI hotspots (S6). The surficial geology within the hotspot consists primarily of Chase Group formations, with minor contributions from the Sumner Group and alluvial deposits (S8). The major basement structures are MRS-NTZ and HFZ.

Glaciated Region

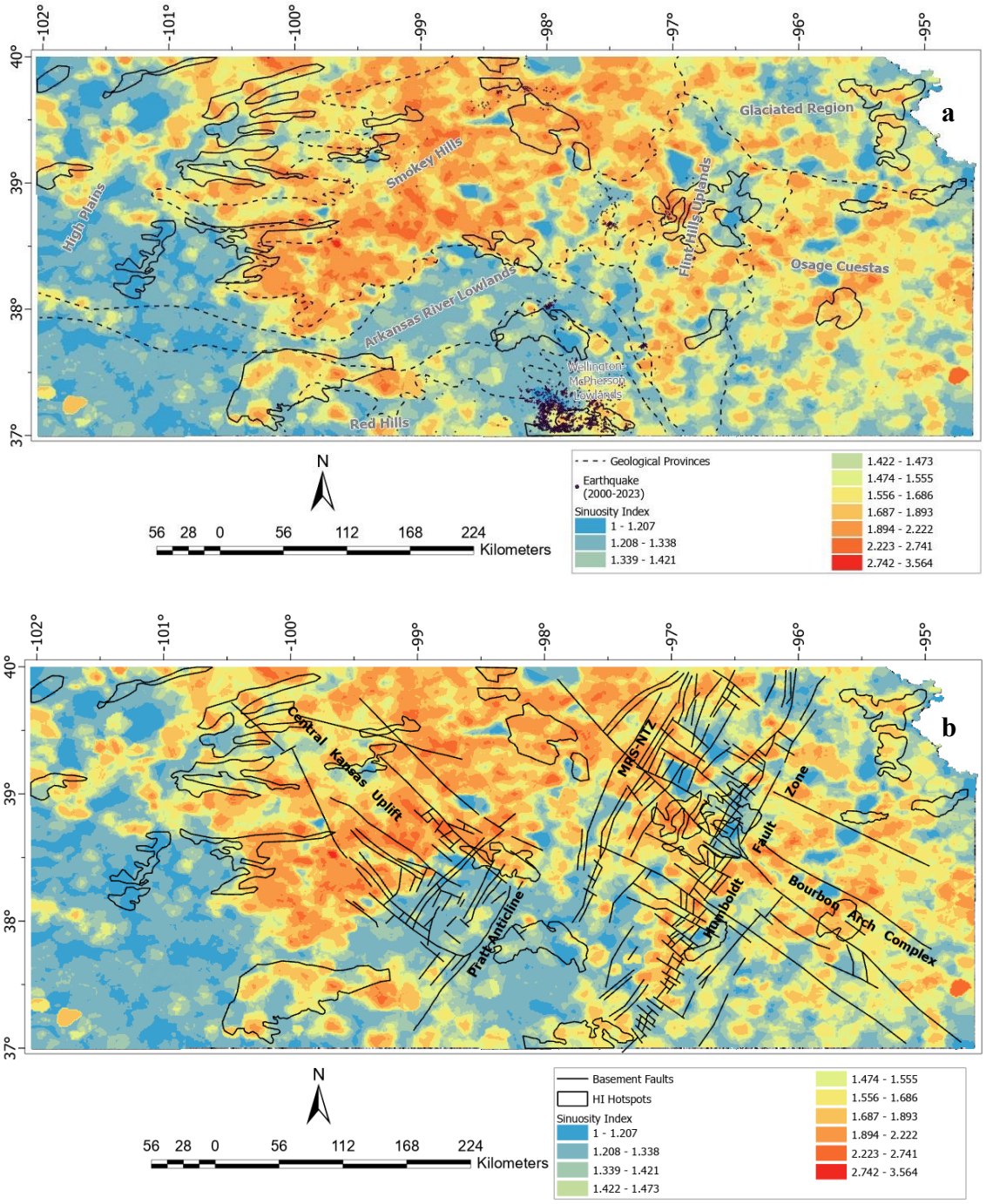
Two significant HI hotspots are located near the eastern boundary of the glaciated region of Kansas (S5). No seismic activity has been detected in these hotspots, and the sinuosity levels remain moderate (S6). SI values are randomly distributed across this province. The surficial geology of these hotspots primarily comprises drift and loess, with minor contributions from the Shawnee Group (S8).

Osage Cuestas

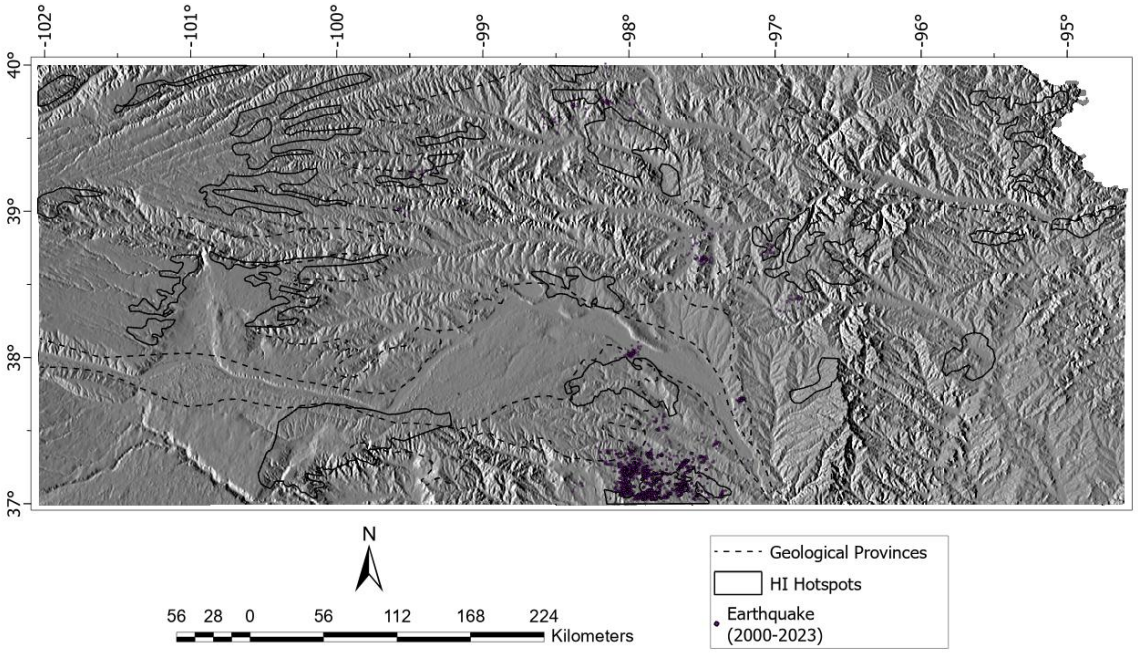
The Osage Cuestas contain sporadically distributed HI hotspots of limited size (S5). Two hotspots are located near the boundary with the Glaciated Region, and another is situated at the center of the province, accompanied by two adjacent cold spots. The sinuosity values within these hotspots fall within moderate ranges (S6). The entire region exhibits moderate to low SI values, similar to those of the Flint Hills. The surficial geology of one of the two hotspots near the Glaciated Region boundary consists of the Shawnee Group, while the other comprises the Lansing Group, Kansas City Group, minor Douglas Group, and drift deposits (S8). The Douglas Group, Shawnee Group, and alluvial deposits characterize the surface geology of the central hotspot in the province.



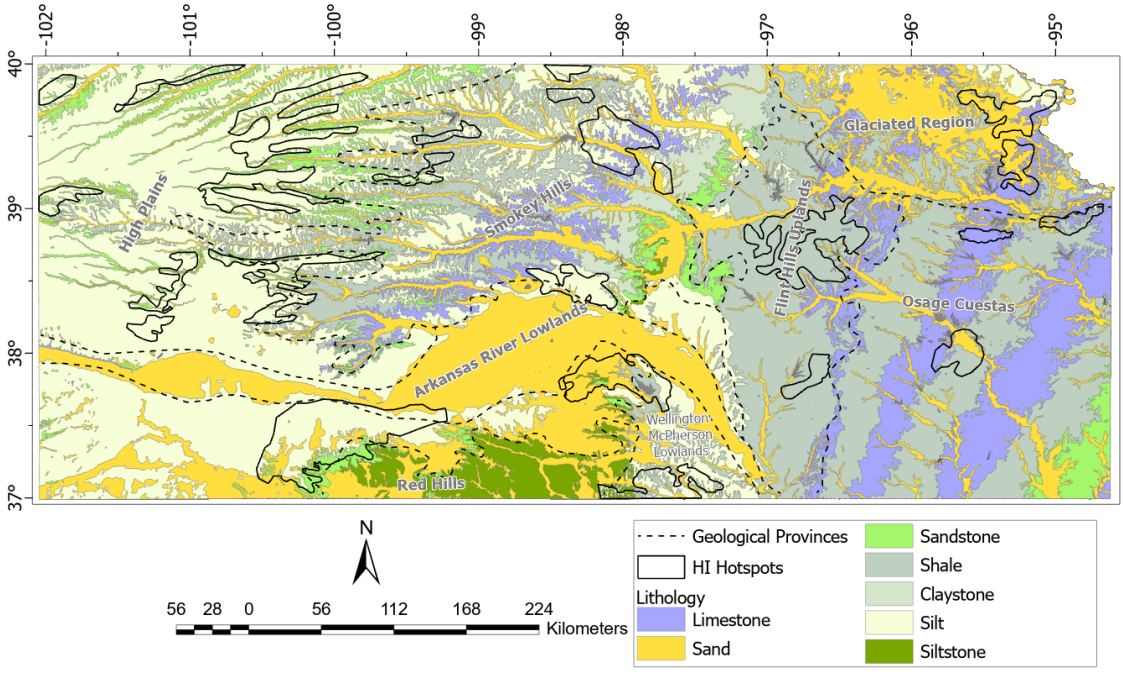
S5: Hypsometric Integral (HI) Pattern Map of Kansas with (a) Geological Province and (b) Basement Structures.



S6: Sinuosity Index (SI) Pattern Map of Kansas showing HI hotspots with (a) Geological Province, and (b) Basement Structures.



S7: Shaded Relief Map of Kansas with seismicity and HI hotspots.



S8: Lithology Map of Kansas with seismicity and HI hotspots.

1.1.4 Oklahoma

In Oklahoma, notable HI hotspots are distributed across several geological provinces. The characteristics of these areas are examined by region as follows:

Ozark Uplift

A significant HI hotspot is located in the northern part of the Ozark Uplift (S9). The sinuosity values within this hotspot and across the province remain low, indicating a relatively younger landscape (S10). The shaded relief map shows the mountainous topography (S11). The surficial geology of this hotspot comprises the Keokuk and Reeds Spring Formations, along with the St. Joe Group (S12).

Ouachita Uplift

Several moderately significant HI hotspots exist in the Ouachita Uplift, mainly located outside the mountain ranges (S9). Sinuosity values are greater near the mountain ranges (S10). The surficial geology in these hotspots consists of Antlers Sandstone, Stanley Shale, and Jackfork Sandstone (S12). Seismic activity is infrequent in this province.

Arkoma Basin

The Arkoma Basin contains multiple small, relatively insignificant HI hotspots (S9). Several earthquake clusters are present in the western portion of the province. Sinuosity values are higher in the western region than in the eastern region (S10). The surficial geology within these hotspots is diverse, including alluvium and terrace deposits (S12).

Anadarko Shelf, Cherokee Shelf, and Nemaha Uplift

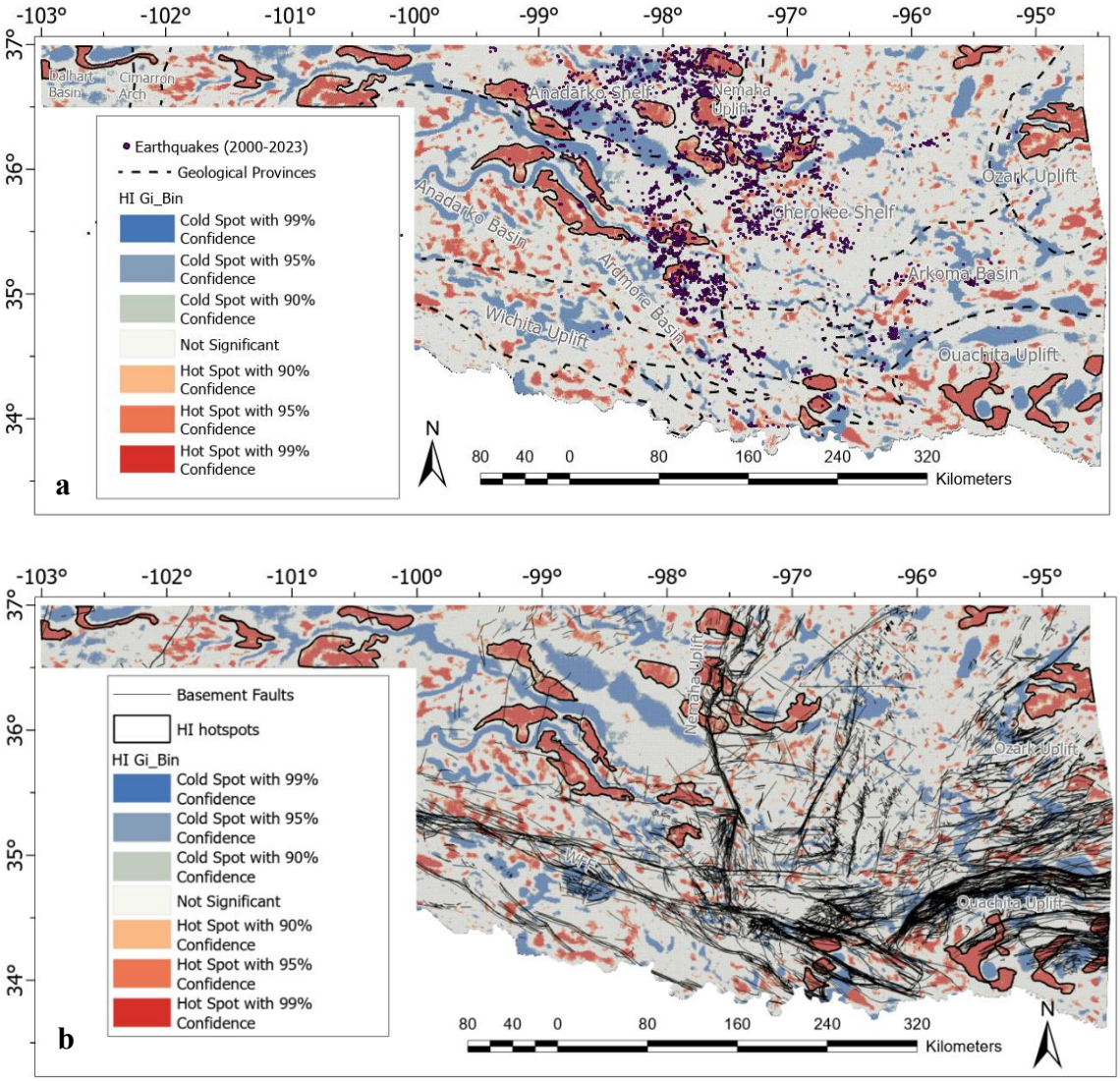
Several HI hotspots are located near and around the Nemaha Uplift on the Anadarko Shelf (S9). One extended hotspot wraps around the Nemaha Uplift and stretches into the Cherokee Shelf. A large hotspot is also observed at the boundary between the Anadarko Shelf and the Anadarko Basin. This province exhibits high seismic activity within HI hotspots, cold spots, and minor HI areas. The Anadarko Shelf and Cherokee Shelf exhibit generally high sinuosity, with exceptionally high values around the Nemaha Uplift (S10). The surficial geology of these hotspots varies, including the Hennessey Group and the Garber Sandstone (S12). The hotspot extending around the Nemaha Uplift contains Garber Sandstone, Wellington Formation, and minor formations such as Blaine Formation, Dog Creek Shale, and Marlow Formation (S12).

Anadarko Basin and Ardmore Basin

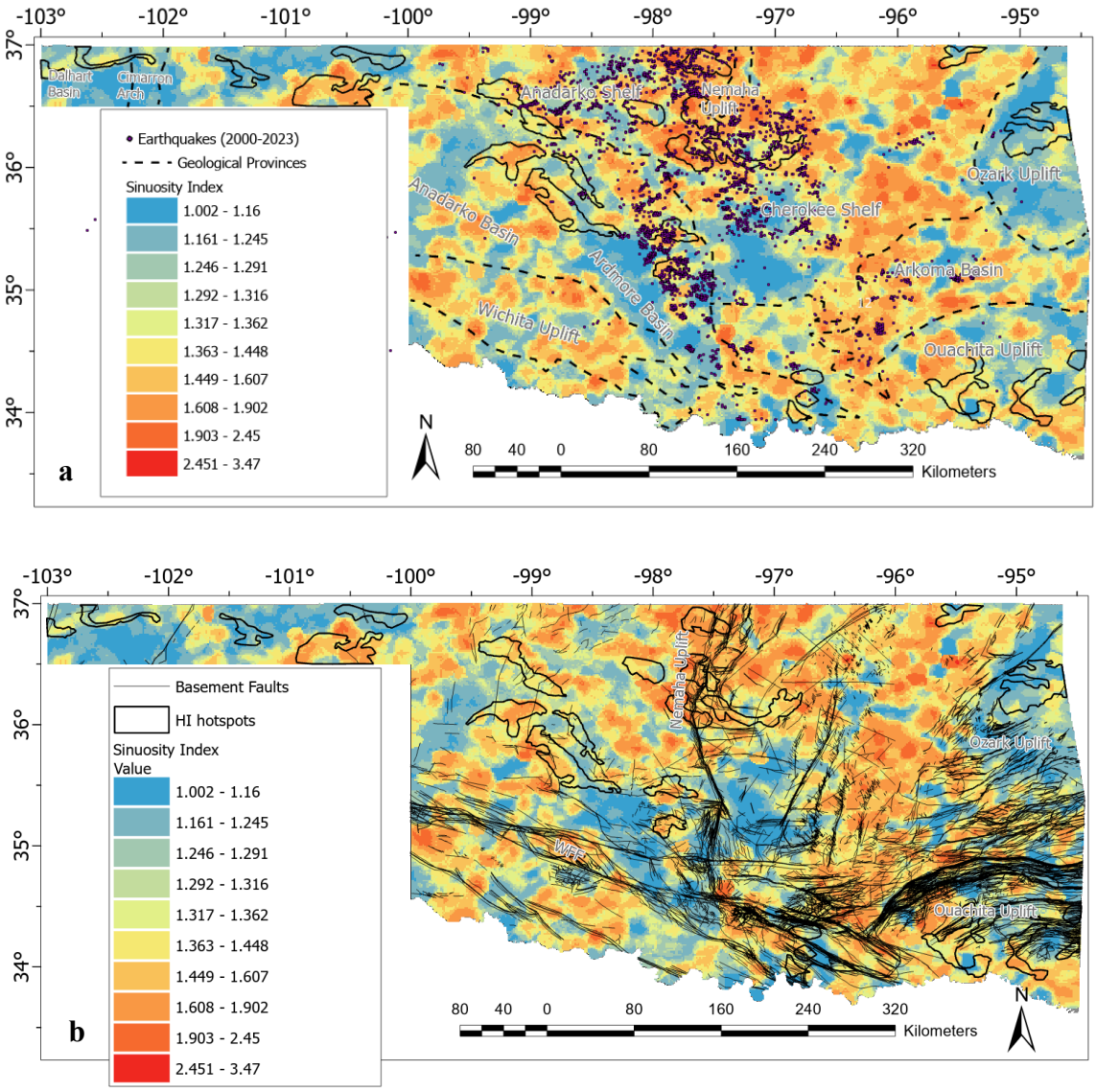
This region contains predominantly small, insignificant HI hotspots, with some significant hotspots located along the alluvium deposits of the North Canadian and Canadian Rivers (S9). Major earthquake clusters are present along the southeastern boundary with the Anadarko Shelf. The earthquake clusters are concentrated around zones with higher sinuosity (S10).

Wichita Uplift

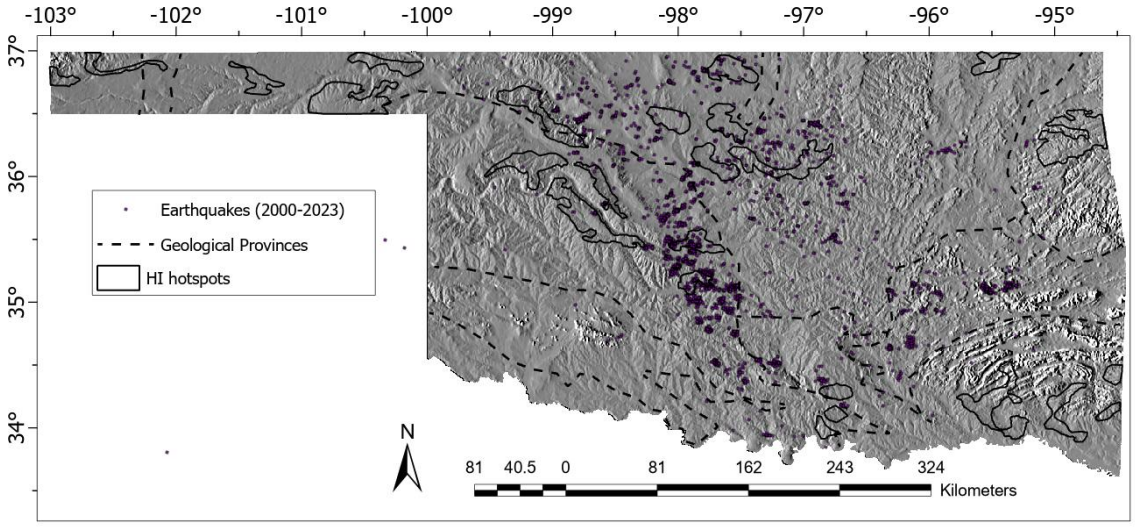
The Wichita Uplift contains several smaller, relatively insignificant HI hotspots and larger cold spots in the central part of the province (S9). Seismic activity is rare in this region. Sinuosity values are irregularly distributed and do not directly correspond to the locations of HI hotspots or cold spots (S10). Cold spots are primarily associated with wetlands, as observed in the hillshade map and satellite imagery (S11). The surficial geology of the insignificant HI hotspots consists of deposits from the Hennessey Group and terrace formations (S12).



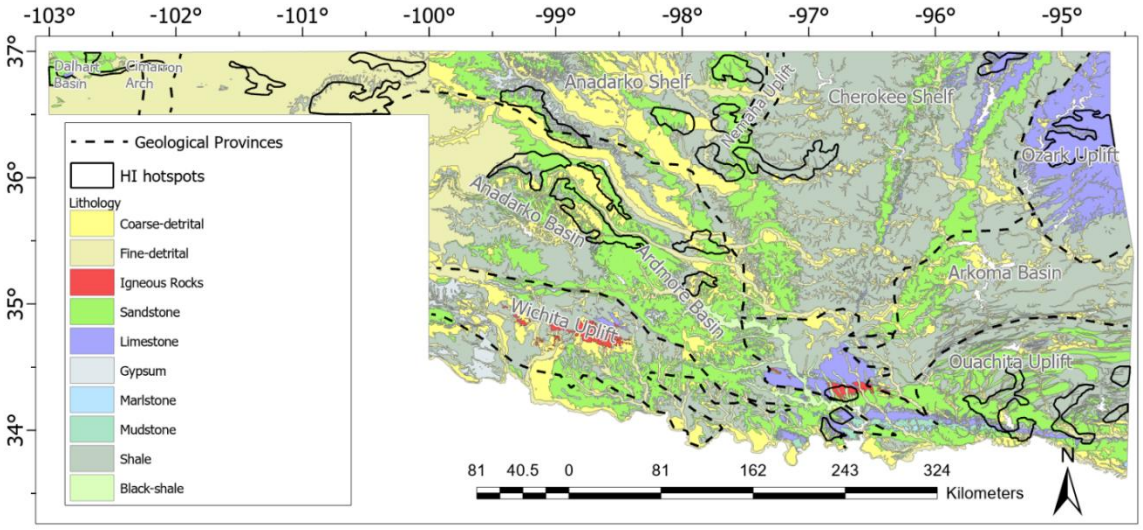
S9: Hypsometric Integral (HI) Pattern Map of Oklahoma with (a) Geological Province, and (b) Basement Structures.



S10: Sinuosity Index (SI) Pattern Map of Oklahoma showing HI hotspots with (a) Geological Province, and (b) Basement Structures.



S11: Shaded Relief Map of Oklahoma with seismicity and HI hotspots.



S12: Lithology Map of Oklahoma with seismicity and HI hotspots.