Basement-controlled deformation of sedimentary sequences, Anadarko Shelf, Oklahoma

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Abstract
Structures rooted in the crystalline basement frequently control the deformation of the host bedrock and the overlying sedimentary sequences. Here, we elucidate the structure of the c. 2-km deep Precambrian granitic basement in the Anadarko Shelf, Oklahoma, and how the propagation of basement faults deformed the sedimentary cover. Although the basin is foreland in origin, the gently dipping shelf sequences experienced transpressional deformation in the Late Palaeozoic. We analyse a 3-D seismic reflection data set and basement penetrating well data in an area of 824 km$^2$. We observe: (a) pervasive deformation of the basement by basement-bounded interconnected mafic sills, and a system of subvertical discontinuity planes (interpreted as faults) of which some penetrate the overlying sedimentary cover; (b) three large (>10 km-long) through-going faults, with relatively small (<100 m) vertical separation (Vsep) of the deformed stratigraphic surfaces; (c) upward propagation of the large faults characterized by faulted-blocks near the basement, and faulted-monooclimes in the deeper sedimentary units that transition into open monoclinal flexures up-section; (d) cumulative along-fault deformation of the stratigraphy exhibits systematic trends that varies with offset accrual; (e) two styles of Vsep—Depth distribution which include a unidirectional decrease of Vsep from the basement through the cover rocks (Style-1) and a bidirectional decrease of Vsep from a deep sedimentary unit towards the basement and shallower sequences (Style-2). We find that the basement-driven propagation (Style-1) shows greater efficiency of driving the fault deformation to shallower depths compared to the intrasedimentary-driven fault nucleation and propagation (Style-2). Our study demonstrates an evolution of cumulative Vsep trends with offset accrual on the faults, and the partial inheritance of the heterogeneous intra-basement deformation by the sedimentary cover. This contribution provides important insight into the upward propagation of basement-driven faulting associated with structural inheritance in contractional sedimentary basins.

KEYWORDS
basement faults, fault propagation, igneous sills, intra-basement reflectors, strike slip, structural inheritance, transpression
Contractional basement-involved structures in sedimentary basins have been studied both in the field, geophysical data sets and through modelling experiments (e.g. Coward, 1983; Hardy & Ford, 1997; Harper, Fossen, & Hesthammer, 2001; Lacombe & Bellahsen, 2016; McClay, 2011; McClay & Ellis, 1987; Naylor, Mandl, & Suppesteijn, 1986). The nucleation and development of contractional structures are often found to be controlled by structural inheritance from the underlying crystalline basement, typically in the form of faults and fracture networks (e.g. Iaffa, Sábat, Muñoz, Mon, & Gutierrez, 2011; Keller & Stephenson, 2007; Liou & Allen, 1996; Lowell, 1995; Turner & Williams, 2004), magmatic intrusions (Gwon & Kim, 2016; Lee & Kim, 2018), metamorphic foliation and ductile shear zones (e.g. Collanega et al., 2019). Zones of structural weakness in the basement may preferentially localize strain such that their tectonic reactivation can influence the structural architecture and deformation of the sedimentary sequences within a basin (e.g. Erslev & Koenig, 2009; Kolawole et al., 2018; Kolawole, Phillips, Atekwana, & Jackson, 2019; Yonkee, 1992).

Contractional basement-involved structures are most common in foreland basins where they occur within major fold and thrust belts and in the region between the fold and thrust belt and the undeformed craton (e.g. Lacombe & Bellahsen, 2016; Mitra & Mount, 1998; Rogers, 1987). This category of basement-involved structures is typically characterized by a major basement-rooted fault that is overlain by a long chain of anticallylinal folded sedimentary sequences with steepened (to overturned) forelimbs and gently dipping backlimbs (e.g. Mitra & Mount, 1998). The associated fault may be steeply dipping in the basement, but more shallowly dipping in the sedimentary cover (anticlinal fault bend; e.g. Berg, 1962; Prucha, Graham, & Nickelson, 1965). In other cases, the fault may be steeply dipping at shallow basement depths, but less steep (synclinal fault bend; Mitra & Mount, 1998) or very gentle at deeper depths (thrust; Berg, 1962; Brown, 1983; Stone, 1993). Also, the structures may develop by reverse slip, strike slip or a combination of both kinematics (transpression), commonly associated with flexural slip in the sedimentary cover (anticlinal fault bend; e.g. Berg, 1962; Prucha, Graham, & Nickelson, 1965). In other cases, the fault may be steeply dipping at shallow basement depths, but less steep (synclinal fault bend; Mitra & Mount, 1998) or very gentle at deeper depths (thrust; Berg, 1962; Brown, 1983; Stone, 1993). Also, the structures may develop by reverse slip, strike slip or a combination of both kinematics (transpression), commonly associated with flexural slip in the sedimentary cover (e.g. Reches, 1978; Stearns, 1975, 1978; Suppe, 1983; Tindall & Davis, 1999). Additionally, the deeper sedimentary units may or may not be welded to the underlying crystalline basement, each case producing distinct structural styles of predictable mechanical deformation (Mitra & Mount, 1998).

Above a propagating contractional basement-rooted fault, a major fault-propagation fold develops with a triangle deformation field that converges downwards towards the tip of the basement fault trace (e.g. Erslev, 1991; Hardy & Allmendinger, 2011; Hardy & Ford, 1997; Mitra & Mount, 1998). This triangular deformation field above the basement fault represents a ‘halo zone’ of fault influence within which intense penetrative contractional deformation may be expected (e.g. Burberry & Lowe, 2019; Mitra & Mount, 1998). Furthermore, the associated styles of deformation may be influenced by a combination of position relative to the basement fault trace (i.e. height of the unit above the basement) and the mechanical behaviour of the various rock units (Reches, 1978).

Most studies of contractional basement-involved deformation of sedimentary sequences have focused on the faults that accommodate dominant thrust kinematics. There is limited understanding of the strain distribution and structural styles associated with those that accommodate transpressional kinematics (e.g. Schmidt & Hendrix, 1981; Tindall & Davis, 1999). Although these little-understood faults have accommodated a minor component of reverse slip, the net slip is dominated by a larger component of strike slip. A few attempts to address this problem employed a numerical modeling of the geometrical modification of stratigraphic surfaces resulting from transpressional fault displacement (Anderson, Ellis, Muir, & Macaulay, 2015). Nevertheless, robust numerical models should incorporate detailed observations of the structural and mechanical controls.

Here, we will investigate intra-basement deformation, and structural inheritance of the basement by analysing the overlying sedimentary sequences in the transpressationally deformed Anadarko Shelf, Oklahoma (Figure 1a). We will first analyse intra-basement deformation, and subsequently, show how components of the deformation are propagated up into the sedimentary cover. Our study will reveal a pervasive deformation of the granitic basement by: (a) basement-bounded mafic igneous sills, and (b) subvertical discontinuity planes interpreted as faults, some of which penetrate into the overlying sedimentary cover. We will show that deformation along the basement fault is propagated up over three structural domains: (a) basal faulted-block, (b) faulted-monocline that transitions into (c) monoclinal flexure. Also, our analyses will reveal two styles of vertical separation (Vsep)—Depth relationships, which include a basement-driven unidirectional fault propagation (Style-1), and an intrasedimentary-driven fault nucleation and bidirectional propagation (Style-2). Furthermore,
we will demonstrate that along-fault deformation of affected stratigraphic surfaces exhibits systematic trends that varies with offset accrual. We will show that the basement-driven fault propagation has greater efficiency of propagating the fault-related deformation to shallower depths compared to the intrasedimentary-driven nucleation and propagation. Overall, this contribution will show that the sedimentary deformation in parts of the Anadarko Shelf represents a partial inheritance of the heterogeneous intra-basement deformation. The results presented here will provide insights into the upward propagation of basement-driven faulting associated with structural inheritance in contractional sedimentary basins.

2 | GEOLOGICAL SETTING

2.1 | The Precambrian basement

The Precambrian basement of Oklahoma is part of the 1.35–1.4 Ga Southern Granite-Rhyolite Province of central
The Anadarko Basin is one of the deepest basins in the United States (>12 km of sedimentary fill), and its complex subsidence history can be divided into three major phases: (a) Late Proterozoic to Mid-Cambrian aulacogen development, (b) Late Cambrian through Early Mississippian post-rift thermal subsidence (the southern Oklahoma trough) and (c) Late Mississippian to Early Permian tectonic contraction associated with development of the Anadarko intra-cratonic foreland basin on the northwestern flank of the trough.

In the late Proterozoic to Middle Cambrian, a NW–SE-trending rift system developed in southern Oklahoma and is associated with the voluminous emplacement of intrusive and extrusive igneous rocks (e.g. Figure 2a; Brewer, Good, Oliver, Brown, & Kaufman, 1983). This is the last igneous tectonic event that affected the south-central United States region (e.g. Whitmeyer & Karlstrom, 2007). Through the Ordovician to the Mississippian, the Oklahoma basement subsided, allowing for the deposition of thick sedimentary sequences, marking the onset of Anadarko Basin development (e.g. Figure 2a–c; Johnson, 2008). By the Late Mississippian through the Pennsylvanian, SW-directed compressive stresses from the Appalachian Orogeny in the east led to crustal shortening and folding in southern Oklahoma. This tectonic compressional event caused an inversion of the NW–SE Cambrian rift system in south and SW Oklahoma, and the development of a NE-trending fold-thrust belt in SE Oklahoma (e.g. Figures 1a and 2a,c; Brewer et al., 1983; Keller & Stephenson, 2007; Powers, 1928; Simpson, 2015). The inverted rift system is known as the Southern Oklahoma Aulacogen, SOA (Wichita and Arbuckle Uplifts), and the fold-thrust belt is known as the Ouachita Mountains (Figures 1a and 2c).

The crustal loading from the accelerated uplift of the SOA and Ouachita domains in the Pennsylvanian resulted in the syntectonic down-warping of the basement in SW and SE Oklahoma, forming the present-day Anadarko and Arkoma foreland basins (Figures 1a and 2c; e.g. Brewer et al., 1983; Johnson, 2008; Simpson, 2015). As the Anadarko basin foredeep subsided in the south, a broad, gently dipping shelf area developed in the central and northern Oklahoma, known as the Anadarko Shelf (Figure 1a). As the shelf area developed, the tectonic stresses induced widespread transpressional deformation in central and northern Oklahoma, which include the development of several NE, NW and ~N-trending subvertical strike slip and reverse faults that root into the basement and penetrate the Palaeozoic sedimentary sequences (Dolton & Finn, 1989; Gay, 1999, 2003; Liao, Liu, Jiang, Marfurt, & Reches, 2017; McBee, 2003a, 2003b). Among these transpressional strike-slip structures, the Nemaha Fault (and Uplift), Wilzetta Fault, Whitetail Fault, Keokuk Fault, El Reno Fault, Galena Township Fault, Stillwater Fault are most prominent (Figure 1a; Chopra, Marfurt, Kolawole, & Carpenter, 2018; Gay, 2003; Liao et al., 2017; McBee, 2003a, 2003b).

2.3 | The stratigraphy of the Anadarko Shelf and its regional significance

The stratigraphy of the Anadarko Shelf (Figure 2a–c) consists of the basal Precambrian basement with an erosional top (Benson, 2014), above which Ordovician to Mississippian carbonate, shale and sandstone sequences were unconformably deposited (e.g. Johnson, 1989; Van der Pluijm & Catacosinos, 1996). These units generally thicken southwestwards towards the Anadarko Foredeep (Figure 2c), and due to multiple episodes of subaerial exposure of the units, several unconformities exist between the packages. Within the deeper sedimentary sections of the study area, the Arbuckle Group is thickest and lies directly on the Top-Basement erosional surface (Figure 2a,b). Recently, the Anadarko Shelf had been in the spotlight for two reasons. First, the area hosts the occurrence of sporadic and widespread wastewater injection-induced seismicity (e.g. Kolawole, Johnston, et al., 2019). The Arbuckle Group is the primary zone of wastewater disposal, and the Precambrian Basement hosts most of the resulting induced seismicity (e.g.
FIGURE 2  (a) Generalized stratigraphic column of the Anadarko Basin, Oklahoma (after Elebiju et al., 2011; Henry & Hester, 1995). (b) Gamma-ray logs and associated stratigraphic tops for two basement penetration well-KF1 and -KF2 within the study area. We used Well-KF1 for our seismic-well tie. See Figure 3 and Figure S2 for more details on Well-KF2 (additional logs, drill cuttings, and geochemical analysis). (c) Cross-section A-A′ (transect in Figure 1a) across the Anadarko Basin, Oklahoma, showing the subsurface configuration of the basin, associated stratigraphic units and basement features (after Brewer et al., 1983; Johnson, 2008; Simpson, 2015). The section also shows the projected location of the study area.
Kolawole, Johnston, et al., 2019). Second, the shelf area hosts the STACK (‘Sooner Trend, Anadarko, Canadian and Kingfisher’) and Mississippi Lime Plays, which are currently some of the most active unconventional hydrocarbon exploration plays in North America (e.g. Yee, Johnston, Howard, & Ahmed, 2017). Exploration target zones include the Woodford, Hunton, Morrow, Oswego, Mississippian and Osage stratigraphic intervals (Figure 2a,b; Droege & Vick, 2018).

3 | DATA AND METHODS

3.1 | Seismic data set and fault interpretation

To investigate subsurface faulting in the Anadarko Shelf, Oklahoma, we utilize a post-stack time migrated 3-D seismic reflection survey covering an area of 824 km² in Kingfisher County, Oklahoma (Figures 1a,b and 3a; courtesy of TGS). The seismic data set has a dominant frequency of 65 Hz in the sedimentary cover and c. 56 Hz within the crystalline basement. For the sedimentary section, we assume a reasonable average velocity of c. 5,300 m/s (well log dynamic velocity for the Mississippian Meramec Fm., 2–2.5 km deep). Experimentally constrained P-wave velocity for the Oklahoma basement at effective confining pressure relevant for the interval of interest (50–60 MPa) is 6,000 m/s (Kibikas, Carpenter, & Ghassemi, 2019). These frequencies and velocities imply a vertical resolution of c. 21 m (sedimentary section) to c. 27 m (in the basement) for the data set. Through a student academic subscription to the IHS well database, we obtain access to raster wireline logs for basement penetration Well-KF1 which we digitize in the IHS Petra Software prior to integration with the seismic data. We perform a well log-to-seismic tie using the digitized Well-KF1 logs and logs from other

FIGURE 3 (a) A map of the seismic survey showing the large faults in the study area, and the 2-km interval locations at which vertical separation (Vsep) measurements were obtained (L1–L10 along F1; L1–L7 along F2). (b) Representative seismic section and (c) interpretation illustrating how the Vsep measurements were obtained at each of the locations.
basement well penetrations within the study area. For the log-to-seismic tie, we first create a velocity model approximation from the wells, which we then use to convert the seismic amplitude volume from time to depth. The log-to-seismic tie process involves a statistical wavelet extraction around multiple wells. The comparison of the average wavelet from each of the wells with a zero-phase wavelet indicates the difference in the phase of seismic traces. The seismic data were initially found to be −95° out of phase and was zero-phased prior to stratigraphic interpretation. Due to proprietary data restrictions, most of the seismic images are herein presented in the minimum phase. Our interpretation workflow consists of a manual interpretation and gridding of the Top-Basement (~3.2 km depth) and Top-Ar buckle (~2.7 km depth) surfaces. Furthermore, we interpret a surface along a broad (347 km²) deep-seated (>6 km depth) intra-basement reflector (IBR) within the survey. Studies of intra-basement reflectors in sedimentary basins of similar basement depth have used seismic reflection data to investigate structural inheritance (e.g. Reeve, Bell, & Jackson, 2014), thus validating the feasibility of our approach. We envision that fault mapping at the Top-Basement and Top-Ar buckle surfaces provide first order assessment of basement fault connectivity with the sedimentary cover. Analysis of subvertical discontinuity planes and related lineaments along the IBR surface provide an assessment of the trends of brittle deformation in the basement, and the depth extent of the major Top-Basement faults. For our surface horizon mapping, we pick the zero-crossing of the seismic reflectors near the target stratigraphic surfaces.

To better resolve structural deformation along the interpreted surfaces, we compute structure-oriented seismic attributes (e.g. Chopra & Marfurt, 2005, 2006; Infante-Paez & Marfurt, 2017) from the seismic volume and extract the attributes onto the mapped surfaces. Primarily, we use 3-D Curvature and Similarity seismic attributes. The most-positive curvature (k1) resolves up-warped zones/upthrown blocks and the most-negative curvature (k2) highlights down-warped areas/downthrown blocks. Thus, fault zones with small vertical offsets and subtle structural flexures, often typical of strike-slip faults, are well-resolved on the interpreted surfaces. The Energy Ratio Similarity (a measure of coherence) attribute is an edge-detection attribute that resolves zones of discontinuity along reflectors. Thus, the energy ratio similarity attribute reveals fault damage zones as lineaments of low coherence relative to flanking blocks of higher coherence (Chopra & Marfurt, 2005). We compute the seismic attributes with the Attribute Assisted-Seismic Processing and Interpretation (AASPI) software package from the University of Oklahoma. We perform the attribute extraction and co-rendering with Petrel Software application.

Additionally, we quantify lineament distribution on the Top-Ar buckle, Top-Basement and intra-basement reflector (Top-Intra-basement reflector) surfaces by calculating Areal Lineament Density (L_d) and Areal Lineament Intensity (L_I). L_d is the ratio of total lineament count to the area of the stratigraphic surface; and L_I is the ratio of sum total of lineament lengths to the area of the stratigraphic surface. We assess the extent of the deformation field above the basement faults, we assess the dip isogon patterns (Ramsay, 1967; Ramsay & Huber, 1987) along the large, through-going faults. Within the bounds of this deformation field, we measure the Vsep of the deformed surfaces. The low magnitude of the vertical component of fault offset and limited seismic resolution make it difficult to resolve the footwall and hanging wall cut-off markers on the faults, and consequently, difficulty in assessing fault throw. Therefore, to quantify the magnitude and spatial distribution of deformation along the large (>10 km) through-going faults in the seismic data set, we estimate the variation of Vsep of seismic reflectors along the faults (Figure 3a–c).

Here, we define ‘vertical separation (Vsep)’ as the vertical difference between the depth to a horizon in the hanging wall of a fault and the depth to the same horizon in the footwall of the fault (Figure 3b,c). Likewise, this definition includes the vertical difference between the depth to a horizon in the anticlinal segment of a monocline and the depth to the same horizon in the associated syncline. Since well log-to-seismic tie allows us to constrain the major stratigraphic packages, the similarity and continuation of reflection packages across the faults helped to ensure an interpretation of the same horizon either side of the fault. We assume that the measured VSEP values represent only the apparent vertical component of fault displacement and the associated stratigraphic flexure. Thus, we use this term, Vsep, to quantify Vsep at faulted-blocks, faulted-mono clines and fault-controlled monoclinal flexures.

At 2 km intervals along two representative faults, we measure the Vsep of six (6) stratigraphic surfaces where the data quality permits (Figure 3a,b). These surfaces include the Top-Basement (Top-Precambrian), Top-Lower Ordovician (Top-Ar buckle Group), Top-Devonian (Top-Hunton Group), a Mississippian reflector (strong, laterally continuous reflector within the Mississippian section), Top-Mississippian (Top-Chester Group) and a Pennsylvanian reflector (strong, laterally continuous reflector within the Pennsylvanian section). For these measurements, we use the zero-crossing of the seismic reflectors along the mapped surfaces as offset markers. Due to proprietary data limitations, we do not have Vsep measurements...
at the structural depth levels of the IBRs that were cut by the faults. We have provided the spreadsheets of our Vsep measurements as supplementary information files of this publication.

3.3 | Basement well penetration data

To constrain our interpretation of aspects of the structure of the crystalline basement, we obtain wireline logs (courtesy of TGS) and drill cuttings (courtesy of Oklahoma Petroleum Information Center) from the basement penetration well in Kingfisher County, herein referred to as Well-KF2 (Figure 2b). Furthermore, we utilize x-ray diffraction (XRD) and x-ray fluorescence (XRF) analyses of the drill cuttings to understand the mineralogical and chemical compositions of the drill cuttings (courtesy of the Chesapeake Energy Reservoir Technology Center), and thus, identify the associated lithological characteristics of the basement. Additionally, using standard techniques, we model a synthetic seismogram using the sonic and density wireline logs available from Well-KF2 and other basement penetration wells in the study area. Due to proprietary restrictions, both the sonic and density logs used are not shown here. We have provided the spreadsheets of the XRD and XRF geochemical data as supplementary information files of this publication.

4 | RESULTS

Below, we present our results in a bottom-up sequential manner, from the deep intra-basement domain, up through the Top-Basement, Top-Arbuckle and shallower sedimentary formations.

4.1 | The IBRs

4.1.1 | Geophysical and geological observations

The 3-D seismic data set shows distinct, systematic patterns of reflection packets within the crystalline basement, herein referred to as IBR (see representative seismic section in Figure 4a). The original seismic data set (minimum phase) shows that each of the IBRs is characterized by a reflection packet consisting of a trough–peak–trough wave-train (top panel in Figure 4b). However, the zero-phase seismic volume (lower panel in Figure 4b) show that the IBR reflection packet consists of a peak–trough–peak wave-train. The IBRs are comprised of gently dipping systematic sets of relatively high amplitude reflectors that appear to cross-cut, but not offset, other intra-basement reflections. Through-out the seismic volume, the IBRs interconnect, commonly terminate at the Top-Basement interface (e.g. yellow X-symbols in Figure 4a), and show prominent trends along NNE–SSW (ESE-dipping), E–W (N- and S-dipping), NW–SE and NE–SW (SE-dipping). Visible in the uninterpreted representative seismic section (Figure S1a) and shown in the interpreted version (Figure 4a), we observe distinct geometrical interactions between the IBR segments. These interactions include: (a) simple truncation and/or vertical juxtaposition of the segments by subvertical discontinuity planes (IBR step), some of which extend upward and offset the Top-Basement and shallower reflectors; (b) IBR bridge structures characterized by a deeper segment overtopped by an approaching segment in which the deeper segment terminates at a subvertical discontinuity plane; (c) faulted-IBR bridge structures in which both the deeper and overtopping IBR segments are truncated or offset by a subvertical discontinuity plane. We delineate the vertical extents and geometry of the discontinuity planes by the vertical stacking of abrupt truncations of IBRs within the seismic sections.

The zero-phase seismic data set (lower panel in Figure 4b), which by standard practice is ideal for geological interpretation, shows that the upper contact of the IBRs is defined by an increase in acoustic impedance contrast, suggesting a rock that is denser than the host granite. Wireline logs, drill cuttings and geochemical analyses from basement penetration Well-KF2 within the study area (Figures 2b and 4c) provide additional insight into the lithological composition of the IBRs. Overall, the 120 m-deep basement interval, the wireline logs (Figure 4c) show high gamma-ray, high resistivity, moderate neutron-density porosity and low P.E. baseline signatures. However, there exists two distinct intervals (17 and 1.5 m-thick; yellow arrows in Figure 4c) that show abrupt excursions from these baselines. The two intervals are characterized by very low gamma-ray and resistivity values, high P.E. values and density-neutron log crossovers. These two zones of abrupt excursions of the wireline logs clearly indicate distinct rock units within the crystalline basement.

A synthetic seismogram model of the intra-basement layer reflectivity shows a strong positive reflection coefficient at the top contact of the 17-m thick layer (Figure 4c). Drill cuttings from a zone above (Sample A), within (Sample B) and below (Sample C) the intra-basement layers show that the distinct intra-basement unit is characterized by a rock that has a darker coloration compared to the host light-coloured rock. XRD (Figure 4d) and XRF (Figures S1b,c) geochemical analyses of the three samples indicate that overall, the crystalline basement is dominated by a host rock that is rich in orthoclase feldspar and quartz (Samples A and C). Whereas, the intra-basement layer (Sample B) is dominantly made up of plagioclase feldspar, amphibole, illite, smectite and augite minerals, and is deficient in orthoclase feldspar and quartz (Figure 4d) and the associated elements (Figures S1b,c).
FIGURE 4  (a) Representative cross-section through the 3-D seismic data set used in this study (transect in the bottom-right corner) showing distinct patterns of the intra-basement reflectors (IBR) in the area (yellow arrows) and geometry of interacting segments. The yellow ‘X-symbols’ indicate the shallowest reaches of the IBRs terminating at the basement-sedimentary interface. Data courtesy of TGS. (b) Top: Representative seismic section and wavelet from the interpreted volume showing that the data is out of phase by −95° (erroneously suggests negative acoustic impedance for the Top-IBR contacts). Bottom: Same section and associated wavelet after the data is zero-phased, showing positive acoustic impedance for the Top-IBR contacts. (c) Left: Wireline logs from basement well penetration Well-KF2 (Data courtesy of TGS), and modelled synthetic seismogram from density and sonic logs (not shown here) from Well-KF2 and other basement wells within the study area. Right: Photographs of drill cuttings from the indicated basement depth intervals (Courtesy of the Oklahoma Petroleum Information Center and Chesapeake Energy Reservoir Technology Center). (d) Table 1 showing the results of X-Ray diffraction (XRD) analysis of the drill cuttings.
4.1.2 | Structure of a mapped IBR

We carefully mapped the most extensive (347 km²) IBR within the seismic survey, located between 6.5 and 8.5 km depth (Figure 5a–d). The surface is undulating, generally shallow in the west (<6.9 km) and transitions across a N–S topographic gradient near the centre of the survey to deeper depths (>7.6 km) in the east. The deepest part of the IBR surface is a NW-trending narrow (2.8–6.5 km-wide) region that extends from the southeast corner of the mapped area towards the centre (Figure 5a). An overlay of Top-Basement faults shows a striking coincidence of major fault F1 with the central N–S topographic gradient (red arrows in Figure 5a) and F3 with the NW-trending deepest area along the IBR. An extraction of the
energy ratio similarity attribute onto the surface (Figure 5b) shows a high density of rectilinear discontinuity lineaments of low energy which show dominant NW-SE trend with 308°±7 mean trend, and a minor N–S (010°) trend (Figure 5c). We also observe that some of the rectilinear low energy attribute lineaments correspond to segments of the interpreted Top-Basement faults (Figure 5d; Figure S2).

4.2 Faulting at the Top-Basement, Top-Arbuckle and shallower sedimentary sequences

The interpreted Top-Basement (Figure 6a) and Top-Arbuckle (Figure 6b) structure maps show marked resemblance in that the major fault traces and concentric structural highs are co-located. Both structure maps and their co-rendered seismic attributes show coincidence of major fault lineaments (red arrows in Figure 6a,b; Figures S3a–c and S4a,b). Additionally, a major basement high on the eastern part of the Top-Basement surface (Figure 6a) is coincident with a structural dome at the Top-Arabuckle surface (Figure 6b). The two surfaces show three large faults (F1, F2 and F3) with lengths greater than 10 km. Fault F1 strikes 012° and dips west, F2 strikes 031° and dips NNW, and F3 strikes 296° and dips SSW. Along these faults, we do not observe any significant changes in thickness of stratigraphic packages within the intervals analysed (i.e. no observed growth strata in the Pre-Pennsylvanian strata). The fault segments commonly show steeper dips in the sedimentary cover than in the basement. For example, F3 dips 68° in the basement and 88° in the sedimentary cover (Figure 6c). An integration of the structural attribute maps allows us to better resolve the geometry of the large faults as well as smaller offset discontinuity lineaments at both the Top-Basement and Top-Arbaruckle surfaces (Figures S3a–c and S4a,b).

As a first order approximation of propagation of brittle deformation from the basement through the sedimentary sequences, we first compare the density and intensity of discontinuity lineaments observable on the mapped surfaces (Figure 6d). On the deep-seated IBR surface (c. 7.5 km depth), we estimate an areal lineament density of 0.458 km⁻² and areal lineament intensity of 0.634 km⁻¹. Whereas, at the Top-Basement surface (c. 3.2 km depth), we estimate an areal lineament density of 0.145 km⁻² and areal lineament intensity of 0.355 km⁻¹. At Top-Arbaruckle surface (c. 2.7 km depth), we estimate an areal lineament density of 0.078 km⁻² and areal lineament intensity of 0.256 km⁻¹. Overall, the deeper basement appears to host a larger density and intensity of discontinuity lineaments relative to the Top-Basement and Top-Arbaruckle depth levels (Figure 6d).

A closer look at the co-rendered seismic attributes along the large faults (Figure 6c; Figures S3a–c and S4a,b) provide

**FIGURE 6** (a) Top-Basement structure map with a seismic cross-section showing the large (>10 km-long) faults within the study area (faults F1, F2, and F3). (b) Top-Arbaruckle structure map with seismic cross-section. Red arrows point to the same large faults observed at the Top-Basement surface. (c) Structure-oriented attribute map (see Figures S3 and S4 for details) of a segment of Fault F3 at the Top-Basement surface, and associated seismic cross-section and interpretation. The map and sections show a change in geometry of deformed reflectors from the Top-Basement into the sedimentary cover. (d) Comparison of the intensity and density of discontinuity lineaments at the Top-Arbaruckle (c. 2.7 km depth), Top-Basement (c. 3.2 km depth) and Top-Intra-basement reflector (c. 7.5 km depth) surfaces. This plot shows relatively greater predominance of the subvertical discontinuity planes at depth in the basement compared to the Top-Basement and Top-Arbaruckle domains.
insight into the vertical change in the geometry of fault deformation along the faults. The energy ratio similarity attribute map (Figure S3a) shows discontinuous lineaments that coincide with short segments of the large faults and a few other fault lineaments on the basement surface. The co-rendered $k1$-$k2$ curvature maps of the Top-Basement surface (Figure S3b) show adjacent lineaments of upthrown and downthrown blocks that coincide with the large faults. Using F3 as a representative fault, Figure 6c and Figure S3c show a fault structure that comprises of an upthrown block ($k1$ lineament) adjacent and parallel to a downthrown block ($k2$ lineament), both separated by a distinct discontinuity plane (low energy lineament). Similarly, at the Top-Arbuckle surface, each of the large faults show a lineament of up-warped/anticlinal flexure ($k1$) adjacent and parallel to a lineament of down-warped/synclinal flexure ($k2$) separated by a distinct fault plane (low-coherence lineament; Figures S4b). Overall, the Top-Basement reflector show simple offset and little to no folded geometry across the large faults, whereas the Top-Arbuckle shows both offset and strongly folded geometry (cross-sections in Figures 6c and 7a).

More interestingly, farther up-section of the Top-Arbuckle surface, we observe that the seismic reflectors show further transitions in geometry that is different from that of the Top-Basement and Top-Arbuckle (Figure 7a). Again, using F3 as a representative fault, the dip isogon pattern (Figure 7b) describes a simple geometry between the Top-Basement and Top-ArBuckle surfaces primarily because of the lack of folding of the Top-Basement. However, the interval between the Top-Arbuckle and Top-Hunton surfaces show tightly folded units with sub-parallel isogon contours that transition into less-tightly folded intervals between the Top-Hunton and Top-Chester surfaces. Above the Top-Chester, both the isogon contours and stratigraphic surfaces describe predominantly open to gentle folds (Figure 6b).

### 4.3 Distribution of Vsep along the large faults

#### 4.3.1 Vsep and cumulative Vsep versus distance along-strike of the large faults (Vsep-D and CVsep-D)

As shown in Figures 4–7, the three large faults in the data set (faults F1, F2 and F3) deform the mapped broad IBR, Top-Basement surface and penetrate the sedimentary sequences. The zone of flexural curvature around these faults (i.e. the deformation field bounded by the $0^\circ$ dip isogons) describes a triangular deformation zone that can be as large as 1.7 km$^2$.
Within this flexural zone, the distribution of Vsep reveals important trends described below.

The Vsep-D plots along faults F1 and F2 show systematic variation of fault-related stratigraphic deformation along-strike of the faults (Figure 8a,b). Although the measured Vsep values along F1 are less than 100 m, they are highest in the north (96.1 m) and decreases southwards towards the intersection zone of the major faults (Figure 8a).

At the intersection zone, there is little or no change in the continuity or geometry of the reflectors. To the south of the intersection zone, Vsep is evident, although by only a small amount (<25 m, Figure 8a). Similarly, along F2, Vsep is highest in the north (c. 31 m) and decreases southwards along the fault towards the zone of intersection with faults F1 and F3 (Figure 8b). Furthermore, the distribution of cumulative Vsep with distance (CVsep-D) for both faults (Figure
8c,d; Figure S5a,b) show spatial clustering of the curves. For both F1 and F2, the Top-Basement and Top-Arbuckle curves cluster tightly at relatively higher values, whereas the curves for the shallower stratigraphic surfaces cluster at relatively moderate to lower values (<0.75·CVsep max) but the patterns differ markedly between the two faults. Along F1, most of the shallow strata curves cluster closely within the region between the 0.25·CVsep max and 0.75·CVsep max boundaries, although the Pennsylvania reflector plots near the lower boundary (Figure 8c; Figure S5a). Along F2, most of the shallow strata CVsep-D curves cluster within or just above the region below the 0.25·CVsep max boundary (Figure 8d; Figure S5b).

4.3.2 | Vsep versus depth (Vsep-Z) along the large faults

The Vsep-Z plots for F1 and F2 (Figure 9a,b) show that overall, from the Top-Basement up through the Pennsylvania units, Vsep decreases with shallowing depth. At all the measurement locations on F1 and F2, Vsep is highest at deeper depths (Top-Basement and Top-Arbuckle) and least at the shallowest depths (Top-Chester and Pennsylvania reflector). Overall, the Vsep-Z distribution along these faults describes two styles, herein referred to as Style-1 and Style-2 (Figure 9c,d). Style-1 refers to a Vsep-Z distribution in which Vsep increases linearly with depth down...
through the Top-Basement surface (Figure 9c). We observe the Style-1 pattern of Vsep distribution at L1, L2 and L5 along fault F1, and L2, L4, L5 and L6 along fault F2. Style-2 consists of a Vsep-Z distribution in which Vsep is highest within the deeper sedimentary units and decreases upwards (through the shallower units) and downwards to the basement (Figure 9d). We observe the Style-2 pattern of Vsep distribution at L4, L6 and L10 along fault F1, and at L1 along fault F2.

Furthermore, for both propagation styles, we assess the quantitative relationships between the magnitude of fault deformation at the inferred nucleation depths and the efficiency of upward propagation of the deformation. At all the measurement locations, the Top-Chester is the shallowest stratigraphic surface for which we have the most Vsep measurements along the two faults. Thus, for the Style-1 trends (in Figure 9a,b), the plot of Vsep at the Top-Basement (VsepTB) versus Top-Chester (VsepTC) surfaces (Figure 10a) describes the relationship:

$$Vsep_{TB} = 2.21 Vsep_{TC} + 2.48$$  \hspace{1cm} (1)

Similarly, for the same Style-1 measurements, the plot of Vsep at the Top-Arbuckle (VsepTA) versus Top-Chester (VsepTC) surfaces describe the relationship:

$$Vsep_{TA} = 1.81 Vsep_{TC} + 1.72$$  \hspace{1cm} (2)

Whereas, for the Style-2 measurements, the plot of Vsep at the Top-Arbuckle (VsepTA) versus Top-Chester (VsepTC) surfaces describe the relationship:

$$Vsep_{TA} = 3.33 Vsep_{TC} + 4.72$$  \hspace{1cm} (3)

5 | DISCUSSION

5.1 | Intra-basement deformation and structural inheritance in the Anadarko Shelf

The analysed seismic data set shows distinct interconnected IBRs that commonly terminate at the Top-Basement erosional surface, giving the Anadarko Shelf basement a layered appearance (Figure 4a). This character is consistent with previous observations of enigmatic reflection packets in seismic reflection data sets from other parts of the basin (Chopra, Infante-Paez, & Marfurt, 2018; Elebiju et al., 2011; Kolawole, Johnston, et al., 2019). Wireline logs and drill cuttings retrieved from a basement penetration Well-KF2 in our study area provide the first ground truthing of the physical, mineralogical and chemical composition of the IBRs (Figure 4c; Figure S1b,c). The well data show that the host granitic basement is layered by a distinct rock that is deficient in potassium feldspar, relatively more conductive and composed of dark-coloured minerals (Figure 4c,d). Our geochemical analyses (XRD and XRF; Figure 4d; Figure S1b,c) show mineral assemblages that indicate a host felsic (granitic) crystalline basement (Samples A and C) and a mafic (diabase/gabbro) intra-basement rock units (Sample B). These results provide, for the first time, physical and geochemical evidence of mafic origins for the intra-basement reflectors in north-central Oklahoma. It is possible that the granitic drill cuttings (Samples A and C) include pegmatitic sheet intrusions; however, there is no strong evidence for this currently. Additionally, the zero-phased seismic data wavelet (Figure 4b) and synthetic seismogram model from wireline logs
(Figure 4c) show increased impedance across the top-IBR contact, suggesting that the rock defining the IBR is denser than the host granite. Thus, the geometrical, geological and geophysical evidence presented here lead us to interpret that the IBRs beneath the Anadarko Basin are Precambrian gabbro and/or diabase sills that intruded the granite-rhyolite basement. Further, the basement-bounded character of the IBRs suggest that they most-likely intruded the granitic basement sometime between the Mesoproterozoic (emplacement of the host Granite-Rhyolite Province) and the Ordovician Arbuckle carbonate units.

As shown in Figure 2a–c, a Precambrian crystalline basement unconformably underlies the Phanerozoic sedimentary cover of the Anadarko Shelf. This basement is part of the 1.35–1.48 Ga Granite-Rhyolite Province of central and Eastern United States (CEUS), mapped as an extensive juvenile terrane which extends from southwestern United States through the mid-continent (e.g. Figure 1a inset; Bickford et al., 2015; Thomas et al., 1984; Whitmeyer & Karlstrom, 2007) Legacy deep seismic imaging also shows IBR in the Cambrian basement of the Southern Oklahoma Aulacogen (SOA; Figure 1a; 2c), interpreted to be gabbro sills (Widess & Taylor, 1959) or mylonitic segments of deep thrust detachment faults (Breuer et al., 1983). Similar features have been reported in the basement of other areas in CEUS of similar age and tectono-thermal history as the basement of the Anadarko Shelf. These include north Texas (e.g. Font, 2003), southwest Texas (Kim & Brown, 2019), and the Illinois Basin (McBride, Leetaru, Keach, & McBride, 2016; McBride, William Keach, Leetaru, & Smith, 2018). However, due to the relatively deep burial of this basement in most of the places, its detailed structure and influence of its structural inheritance on the deformation of the phanerozoic cover sequences are poorly understood. Here, we present one of the first results showing a ground-truthing evidence of the composition of the widely observed intra-basement seismic reflectors across the Mesoproterozoic Granite-Rhyolite Province of central-eastern United States.

In addition to the intrusion of sills as a form of basement deformation, we also observe the pervasive occurrence of subvertical discontinuity planes that terminate or offset segments of the IBRs (e.g. Figure 4a; Figure S1a). Some of these discontinuity planes extend up into the cover rocks, offsetting and deforming both the Top-Basement surface and the sedimentary sequences (e.g. Figures 4a and 5d, 7a; Figure S1a). However, we also find that although other segments of the discontinuity planes are well-defined in the basement, they do not reach or deform the Top-Basement reflector (Figure 4a). We interpret these subvertical discontinuity planes as fault planes that constitute brittle deformation in the basement.

Some striking characteristics of these discontinuity planes are evident and may provide insight on their origin. First, although some of the discontinuity planes define IBR steps and offset IBR bridges (Figure 4a; Figure S1a), we observe cases of IBR bridge interactions where the deeper segment terminates at a subvertical discontinuity plane and both of which are overtopped by an approaching IBR segment. An example of this interaction is labelled ‘IBR Bridge’ in Figure 4a. Second, lineaments of these discontinuity planes that cut the mapped IBR surface (Figure 5b) show a dominant trend of 308° (Figure 5c). This trend is remarkably consistent with: (a) the strike of one of the largest faults in the study area (Fault F3), (b) a prominent fracture trend (308° ± 3.6) in the outcrops of this basement in southern Oklahoma (Kolawole, Johnston, et al., 2019), (c) the dominant trend of Proterozoic-Cambrian mafic dikes (300°) in the outcrops of the basement (Denison, 1995; Lidiak et al., 2014) and (d) a prominent trend of recent seismogenic basement faulting in the Anadarko Shelf (297° ± 3.6) (Kolawole, Johnston, et al., 2019; Schoenball & Ellsworth, 2017). This common NW (c. 300°) trend, a conjugate NE (c. 240°) trend, and a secondary N–S trend have been interpreted to be dominant structural trends in the Precambrian basement of Oklahoma (Denison, 1995; Kolawole, Johnston, et al., 2019).

Therefore, considering the character and trends of these subvertical discontinuity planes, our preferred interpretation is that they represent fault planes within the Precambrian basement that possibly predate the emplacement of the IBRs. Furthermore, we interpret that the extension of some of the discontinuity planes up-section and the associated deformation of the Top-Basement and shallower stratigraphic surfaces represent a reactivation of this brittle structures during the Phanerozoic. Additionally, the comparison of lineament density and intensity between the depth levels (Figure 6d) suggest that fault connectivity between the basement and the sedimentary section is defined by a relatively small proportion of the basement faults that are propagated up across the Top-Basement surface. Although pre-existing intra-basement mafic sheet intrusions can control faulting in contractional tectonic settings (Gwon & Kim, 2016; Lee & Kim, 2018), our seismic data set does not show any evidence for this in the Anadarko Shelf. However, we do not rule out the possibility. Both subhorizontal (sill) and subvertical (dike) mafic sheet intrusions occur in the outcrop exposures of the Oklahoma basement, where the sills commonly branch out from the dikes (e.g. Kolawole, Johnston, et al., 2019; Lidiak et al., 2014). However, the absence of dike-related reflections in our seismic data set may be explained by the inherent difficulty of seismic reflection imaging of dikes (e.g. Phillips, Magee, Jackson, & Bell, 2018; Wall, Cartwright, Davies, & McGrandle, 2010; Zaleski et al., 1997). Overall, based on our data set, we infer that at least the brittle component of the intra-basement deformation was inherited by the sedimentary sequences of the Anadarko Shelf.
5.2 | Propagation of fault deformation into the sedimentary sequences

5.2.1 | Implied kinematics of the large faults

The seismic sections do not show the presence of growth strata across the analysed large faults. Along the mapped surfaces (Top-Basement and Top-Arbuckle; Figure 6a,b; Figures S3 and S4), the faults do not exhibit pervasive secondary faulting patterns (e.g. Reidel and flower structures) that may be used as fault kinematic indicators. Nevertheless, to understand the most probable sense of movement on the faults, the following should be emphasized:

1. The geometry (N, NNE and WNW-ESE strikes, and subvertical dips) of the faults are consistent with those of previously studied large fault zones nearby on the Anadarko Shelf. Among these structures, the Nemaha Fault (and Uplift), Wilzetta Fault, Whitetail Fault, Keokuk Fault, El Reno Fault, Galena Township Fault, Stillwater Fault are most prominent (Figure 1a; Castro Manrique, 2018; Chopra, Marfurt, et al., 2018; Dolton & Finn, 1989; Gay, 2003; Liao et al., 2017; McBee, 2003a, 2003b). Our study area is located just north of the El Reno Fault and just west of the Nemaha Fault (Figure 1a,b). Seismic imaging (Chopra, Marfurt, et al., 2018; Liao et al., 2017) and analog modelling of these faults (Liao et al., 2017) show strong right-lateral strike-slip kinematics marked by the pervasiveness of NE-trending Reidel splay faults extending outwards from the primary ~N–S principal slip zones. The published seismic images were focused on the shallower and mechanically weaker Woodford Shale unit. Additionally, detailed structural interpretation of a subvertical >12 km-long W- to WNW-trending fault system in Grady County, Oklahoma (south of the study area) suggest left-lateral strike-slip kinematics (Castro Manrique, 2018). Farther east of the study area, published interpretations of the Wilzetta, Whitetail and the Keokuk Fault zones show mapped secondary faulting patterns and recent focal mechanism solutions consistent with strike-slip kinematics (e.g. McBee, 2003a; McNamara et al., 2015). The consensus is that these fault trends are associated with the major structural deformation of the Anadarko Shelf in a transpressional stress field. The stress field is related to SW- and W-directed compressional stresses from the southward propagation of the Appalachian-Ouachita-Marathon fold-thrust belt in the Late Palaeozoic (e.g. McBee, 2003a).

2. The generally small Vsep (<100 m) on the large faults (Figure 8a,b) may imply a relatively larger lateral component of fault slip. However, the maximum Vsep values is not a conclusive evidence since limited coverage of the fault extents by our seismic data set also makes it difficult to compare with any standard empirical throw-length relationships along faults of known kinematics.

However, the large faults in our study area (F1, F2, F3) are not only in the proximity of these known faults, they also have similar geometries and deform the same stratigraphic units as the structures. Therefore, considering the tectonic history of the Anadarko Shelf and the kinematics of the known faults, we infer that the large faults in focus must have accommodated significant transpressional strain.

5.2.2 | Structural domains of vertical fault propagation

We analyse three large (>10 km-long) through-going faults that extend from the crystalline basement up into the sedimentary cover (faults F1, F2 and F3). These faults do not show any significant growth section in the analysed interval (Precambrian-Lower Pennsylvanian), suggesting that upward fault propagation into the sedimentary cover is largely post-depositional. The vertical changes in the geometrical character of the deformed stratigraphic surfaces in the seismic cross-sections (e.g. Figures 6c and 7a,b), seismic attribute expressions of the fault zone deformation (Figure 6c; Figures S3a–c and S4a,b) suggest that fault deformation is propagated up over three distinct structural domains. These domains include: (a) basal block-faulting near (and within) the basement, that transitions through; (b) a middle faulted-monocline, into; (c) an upper monoclinal flexure (Figure 7b). To better understand the characteristics and drive of upward fault propagation through the deformed sequences, we focus on F1 and F2 as representative large faults and analyse the 3-D distribution of Vsep along the faults. Overall, we find that Vsep along the large faults generally diminishes toward the intersection zone of the faults (Figure 8a). More importantly, northwards of the intersection zone where significant Vsep is prominent, we assess the trends.

5.2.3 | Vertical Separation versus Depth (Vsep-Z): Vertical fault propagation styles

The Vsep-Z relationships along the faults describe two broad patterns which we herein describe as Style-1 and Style-2 (Figure 9a–d). Style-1 is characterized by a unidirectional, linear decrease of Vsep with shallowing of depth from the Top-Basement surface (Figure 9a,c). Style-2 is characterized by a bidirectional decrease of Vsep from a deep sedimentary unit (in this case, the Arbuckle carbonates) down towards the basement, and up through the shallower sequences (Figure 9b,d). We interpret that Style-1 involve a basement-driven propagation of faulting,
whereas, Style-2 involve an intrasedimentary-driven fault nucleation and propagation.

Along many of the segments with Style-2 Vsep distribution, the faults significantly offset the intra-basement reflectors, but show relatively smaller offset of the Top-Basement and sedimentary cover reflectors (e.g. F1 in Figure 4a; F3 in Figures 5d and 7a). Also, we commonly observe an abrupt change in the dip of the large fault segments across the Top-Basement surface (up to 20° change; e.g. Figure 7a). These observations suggest a probable difference in growth history between the basement and sedimentary segments of the large faults. Thus, we interpret that the Style-1 faulting involves a reactivation of pre-existing basement faults. Although Style-2 propagation indicates fault nucleation above the basement, it appears that the pre-existing basement faults help to control where later faults nucleate in the sedimentary cover. Thus, the two styles of vertical fault propagation essentially involve significant or partial reactivation of pre-existing basement faults. Furthermore, the observation of both patterns of fault propagation at different segments of F1 and F2 suggests that the segments of the large faults do not have the same growth history prior to their linkage and coalescence.

These patterns of fault growth may not be unique to contractional or transpressional settings, as they have also been observed in extensional tectonic settings. For example, Collanega et al. (2019) found that normal fault segments that nucleated in the cover rocks show displacement profiles that are clearly distinct from those that physically root into the basement. Of particular interest are the intra-sedimentary faults, which show a throw gradient with either the maximum throw at the fault centre that decreases towards the tips, or localization of greater throw near the upper tip line than the lower or lateral tips.

5.2.4 | Efficiency of the vertical fault propagation styles

To better understand the relative efficiency of vertical propagation of fault deformation by the two propagation styles, we assess the quantitative relationships between Vsep at the nucleation depth levels (Top-Arbuckle and Top-Basement) and one of the shallowest analysed strata (Top-Chester). For Style-1 propagation, the plot of Top-Basement Vsep (VsepTB) versus Top-Chester Vsep (VsepTC) shows that >2.5 m Vsep is required at Top-Basement to propagate deformation as high up as the Mississippian (Figure 10a). In addition, deformation at the Top-Basement could produce about half of its magnitude at depths as shallow as the Mississippian. Similarly, for this same basement-driven fault propagation style, deformation at the Top-Arbuckle will correspond to about half of its magnitude at the Mississippian level (Figure 10b). The plot also shows that only a minimum of 1.7 m Vsep is needed at the Top-Arbuckle level to propagate deformation up to the Mississippian level. However, when compared to faults that nucleate within the sedimentary cover (Style-2 propagation), deformation at the nucleation zone (Top-Arbuckle) may only produce about a third of its magnitude at the shallow strata (Figure 10b).

Furthermore, the plot indicates that a minimum of c. 5 m of Vsep is needed at the nucleation depth (Top-Arbuckle) to propagate deformation as shallow as the Mississippian. These estimates suggest that the basement-driven contractional fault propagation (Style-1) has a relatively greater efficiency of driving deformation to shallower depth levels in the sedimentary cover, compared to intra-sedimentary-driven faults.

5.2.5 | Evolution of vertical separation with accrual of fault offset

Fault F1 has a Vsep max of 96.1 m suggesting a relatively larger offset fault than fault F2 which has a Vsep max of 30.64 m (Figure 8a,b). The comparison of the cumulative Vsep versus distance (CVsep-D) plots for the two faults show spatial and systematic clustering of the curves for the analysed stratigraphic surfaces (Figure S5a,b; Figure 8c,d). Based on the trends shown, we observe that for the larger offset fault F1, most of the shallow strata CVsep-D curves appear to cluster in the region between the 0.25 and 0.75 CVsepmax boundaries (Figure 8c; Figure S5a). Whereas, for the smaller offset fault F2, most of the shallow strata CVsep-D curves cluster within or just above the region below the 0.25 CVsepmax boundary (Figure 8d; Figure S5b). This is reasonable considering that with increase fault growth and upward propagation of the fault tip, more of the initially monoclinally folded strata at shallower depths become faulted. The spacing of these curves may also indicate the relative intensity of strain accommodated by different faulted-mono-cline strata (same CVsep-D region), as well as between units that have accommodated only folding and those that have experienced both faulting and folding. Therefore, we infer that with increasing accrual of offset on these faults, more of the shallow strata CVsep-D curves transition from lower value regions (<0.25 CVsepmax) into the moderate and higher value regions. Thus, we present a simplified conceptual model of evolution of CVsep-D trends that vary with accrual of offset along basement-rooted contractional and transpressional faults (Figure 11a–c).

5.3 | Implications for the structural inheritance and subsurface fluid migration

The geometry and shallow reaches of the deformation of the large faults our study area pose important significance for (a) basement-sedimentary and intrasedimentary fluid transport, and (b) modern seismic hazard in the Anadarko Shelf. The
observations presented here demonstrate that only the brittle component of the intra-basement deformation is inherited by the sedimentary sequences. Thus, the fault connectivity presents potential pathways for migration of basement-derived hydrothermal fluids into the sedimentary cover, source to reservoir migration of hydrocarbons, and downward migration of fluids from the cover rocks into the basement. This is supported by recent observations of hydrothermal alteration of carbonate reservoirs in the Anadarko Shelf (e.g. Jaiswal et al., 2017; Mohammadi, Gregg, Shelton, Appold, & Puckette, 2017). In other basins where basement-rooted transpressional faults exist, near-fault diagenetic hydrothermal alterations can localize ‘light-bulb’ structures and influence the local petroleum system and metallic-ore mineralization trends (e.g. the Appalachian foreland basins of Eastern US, Evenick, 2006; Evenick & Hatcher, 2006; Smith Jr & Davies, 2006). Furthermore, the structural inheritance of basement fault systems by the sedimentary sequences may explain the recent widespread seismogenic strike-slip reactivation in north-central Oklahoma, attributed to sedimentary-to-basement migration of fluids (e.g. Kolawole, Johnston, et al., 2019; Qin, Chen, Carpenter, & Kolawole, 2018; Qin et al., 2019).

Finally, on the timing of upward propagation of the inherited structures, based on the lack of significant growth strata along the analysed faults, the post-Cambrian ages of the gently dipping shelf sequences, and analyses of the character of the basement faults, we infer a Late Palaeozoic age. We summarize the history of structural deformation of the Anadarko Shelf as follows (Figure 11d): Stage 1: development of steep basement faults associated with the southward propagation of the Mid-Continent Rift in the Precambrian; Stage 2: Erosion of the Top-Basement and deposition of sedimentary rocks in the Early to Mid Palaeozoic; and Stage 3: Late Palaeozoic transpressional reactivation and upward propagation of the basement faults, leading to the folding and faulting of the cover rocks. We suggest that the systematic
3-D characterization of the distribution of deformation along basement-rooted transpressional faults, as presented in this study, could help provide more insight into the mechanics of inherited fault propagation in contractional tectonic settings.

6 | CONCLUSIONS

Here, we characterized the intra-basement structure of the Precambrian basement of the Anadarko Shelf, Oklahoma and investigated how the brittle component of the basement structure is inherited by the overlying sedimentary sequences. Our study revealed pervasive deformation of the granitic basement by two major structures: (a) basement-bounded mafic sills and (b) subvertical discontinuity planes interpreted as faults, some of which penetrate the overlying sedimentary cover. Overall, based on our data set, we inferred that at least the brittle component of the intra-basement deformation was inherited by the sedimentary sequences in this part of the Anadarko Shelf. We found that deformation along the basement fault is propagated up the cover over three structural domains: (a) basal faulted-block, (b) middle faulted-monocline that transitions into (c) monoclinal flexure. Our analyses revealed two styles of Vsep—Depth relationships which include a basement-driven unidirectional propagation (Style-1), and an intrasedimentary-driven fault nucleation and bidirectional propagation (Style-2). Further, we showed that along-fault deformation of affected stratigraphic surfaces exhibits systematic trends that vary with offset accrual. Furthermore, we demonstrated that the basement-driven fault propagation has greater efficiency of propagating the fault-related deformation to shallower depths compared to the intrasedimentary-driven nucleation and propagation. Finally, we suggested that the through-going basement-rooted faults in the study area are likely Proterozoic and were later reactivated in transpression in the Late Palaeozoic.

Using geophysical and geological data, we present some of the first results showing ground-truthing evidence of the composition of the widely observed intra-basement seismic reflectors (IBRs) in the Mesoproterozoic Granite-Rhyolite Province of central-eastern United States. Our study suggests that the IBRs are basement-bounded mafic sill intrusions. In the study area, the Anadarko Shelf deformation represents only a partial inheritance of the observed heterogeneous intra-basement deformation by the sedimentary cover. The systematic characterization of basement deformation and its propagation as presented in this study provide an increased understanding of the mechanics of structural inheritance in contractional tectonic settings.

ACKNOWLEDGEMENTS

We thank TGS for providing access to the 3-D Seismic Reflection and well data used in this study. We thank Chesapeake Energy Corporation, Oklahoma City for providing access to the computer software and hardware used to analyze and interpret the seismic data. We thank the Oklahoma Petroleum Information Center (OPIC), Norman, OK for providing access to the basement penetration borehole drill cuttings used in this study. Also, we thank the Chesapeake Energy Reservoir Technology Center for the photographs, x-ray diffraction and x-ray fluorescence analyses of the drill cuttings. We thank Laura Bellingar for assistance with basement well log synthetic modelling, Matthew Davis for assistance with the phase assessment of the seismic data set, and Michael Horn for assistance with the seismic attribute computation. We also thank the Editor Craig Magee, and reviewers Rebecca E. Bell and Alexander Peace for their constructive feedback.

DATA AVAILABILITY STATEMENT

The 3-D seismic data set that support the findings of this study are available on request from TGS (global.marketing@tgs.com). The vertical separation and geochemical data (XRD and XRF) that support the findings of this work are available as supplementary files of this manuscript.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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**How to cite this article:** Kolawole F, Simpson Turko M, Carpenter BM. Basement-controlled deformation of sedimentary sequences, Anadarko Shelf, Oklahoma. *Basin Res.* 2020;32:1365–1387. https://doi.org/10.1111/bre.12433