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# Post-Mississippian tectonic evolution of the Nemaha Tectonic Zone and Midcontinent Rift System, SE Nebraska and N Kansas

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## ABSTRACT

The geologic structures of the central Midcontinent of the USA are largely buried and known only from geophysical datasets, coupled with sparse well control and limited outcrop. Such unconstrained geophysical models preclude a deeper assessment of possible continental interior seismic hazards, which have the potential to cause appreciable damage. Within the study area in southeastern Nebraska and northeastern Kansas is an area of elevated seismic risk, with a spatial relationship to the Nemaha Tectonic Zone and the Midcontinent Rift System. Using sequential restorations of three published cross sections within Nebraska and Kansas this study demonstrates that the Nemaha Tectonic Zone and Midcontinent Rift System have each been reactivated several times since the end of the Mississippian (the details of deformation prior to the Mississippian are not considered). Our reconstructions indicate that in addition to major Pennsylvanian-Early Permian fault reactivation during the Ancestral Rocky Mountain orogeny there was also deformation both prior to the post-Mississippian unconformity associated with uplift on the Nemaha Tectonic Zone and after the deposition of late Early-early Late Cretaceous sediments in the study area, potentially due to the Laramide orogeny. Results also indicate that the magnitude of the far-field stresses is sufficient to cause seismogenic reactivation on favorably oriented pre-existing faults. This history of reactivation of geologic structures in the central Midcontinent suggests that seismic hazards in the region in the present cannot be ruled out. Though dangerous large earthquakes are uncommon in the continental interior, seismic activity along the structures in the study area would threaten several large population centers and the potential for this activity should not be ignored.

## INTRODUCTION

What we know from the Phanerozoic history of geologic structure in the central Midcontinent (Kansas and Nebraska) shows that it has possible far-field tectonic relationships that may have the potential for seismicity. These events, although rare in continental interiors, have the potential to cause serious damage (Johnson et al., 1994; Mooney et al., 2012). An area of somewhat elevated seismic risk is recognized in both southeastern Nebraska and northeastern Kansas, where two major geologic structures, the Nemaha Tectonic Zone

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(NTZ) and the Mid-Continent Rift System (MCRS) (Fig. 1) have been identified. Within this area, most seismic activity has a Mw of <3.0 (Fig. 2) but there are records of a Mw 5.1, Intensity VII earthquake in November 1877 (Burchett, 1990, USGS National Earthquake Information Center). Figure 2 indicates that this event occurs close to the northern margin of the Mid-Continent Rift System. Several other earthquake epicenters plot within 12 km of the northern limit of rift sediments (mapped on the basis of sparse borehole data), and at least five post-1850s earthquakes (MMI I-IV, but Mw unknown) are located in the vicinity of the MCRS's southern margin (Niemi et al., 2004; Ohlmacher and Berendsen, 2005). In addition, the structural history of this region is an important consideration in predicting the location and timing of trap development in petroleum-producing basins of eastern Kansas and southeastern Nebraska (Anderson and Wells, 1968; Newell et al., 1987; Carlson, 1988; Dolton and Finn, 1989; Carlson and Newell, 1997; Newell and Hatch, 2000). Lastly, the major structures under consideration extend over great distances through the interior of North America. The Nemaha Tectonic Zone extends for 650 km from near Omaha to Oklahoma City (Berendsen and Blair, 1995) and the Mid-Continent Rift System and its flanking basins extend for more than 1500 km, crossing under the Minneapolis-St. Paul, Des Moines, and Omaha-Council Bluffs metropolitan areas (Anderson and McKay, 1997), thus the results of this study area are relevant to large portions of the interior of the continent.

Understanding the fault geometry and reactivation history of pre-existing structures is paramount to assessing and predicting seismic risk, as historical seismicity is often associated with zones of weakness along intraplate structures (e.g., Sykes, 1978; Hinze et al., 1988; Johnson et al., 1994; Crone et al., 1997; Talwani, 1999; Shulte and Mooney, 2005). The reactivation of pre-existing weaknesses in the continental lithosphere is widely documented, particularly where Precambrian basement has undergone successive episodes of deformation (Sykes, 1978; Hinze et al., 1988; Johnson et al., 1994; Crone et al., 1997; Talwani, 1999; Shulte and Mooney, 2005). Tectonic inheritance - the governance of subsequent geologic structures by pre-existing ones - is frequently invoked to explain both large-scale variations in the geometry of orogenic belts and the locations of rift margins in supercontinent cycles (Butler et al., 1997, Thomas, 2004; Audet and Burgmann, 2011; Huerta and Harry, 2012). This concept can be used to explain the appearance of folds and faults or uplifted zones far from collision zones, such as the presence of Laramide-age uplifts far from the collision margin (Marshak et al., 2003). The concept is also invoked to explain variable widths of fold-thrust belts where the original rifted margin is sub-perpendicular to the compression direction (e.g., the pattern of salient and recesses along the Appalachian fold-thrust belt) (Macedo and Marshak, 1999; Thomas, 2004). Pre-existing structures that are oblique to the compression may compartmentalize deformation into zones or reactivate with a transpressional sense of motion, generating strike-slip related structures or an en-echelon series of folds or faults on the surface (e.g. the anticlines generated above the Precambrian Kazerun Fault in Iran) (Sepehr and Cosgrove, 2005). Studies of specific structures such as the distribution of oil fields in the Zagros fold-thrust belt (Burberry, 2015) indicate that subsequent structures, facies changes, and economic deposits may be affected by the motion of the pre-existing fault or faults. Other global examples are provided by Gates and Costa (1998), Molliex et al. (2010), Said et al. (2011) and McMechan (2012).

Structures such as failed rifts and ancient suture zones can provide weak zones prone to reactivation in successive deformation events. The amount of reactivated movement on any given fault is a function of the lithospheric strength, number of faults within the local sequence, and the degree of obliquity between fault orientation and the direction of compression (Handin, 1969; Dewey, 1989; Williams et al., 1989; Ranalli, 2000; Del Ventisette et al., 2006). Major faults are not expected to reactivate along their entire lengths, but the partial reactivation of a fault may lead to a region of enhanced uplift and localization of subsequent faults (Butler et al., 2006). Analog models, in which stress can be imposed on a pre-existing weakness and factors including the obliquity of the stress can be varied, indicate that an oblique subsequent imposed stress is more favorable for fault reactivation than an imposed stress normal to the structure (e.g., Sibson, 1985; McClay, 1995). Such a model has been applied successfully to the Italian Alps and the Zagros Belt (Bahroudi and Koyi, 2003; Viola et al., 2004), thereby further demonstrating that a strong reactivation of pre-existing weaknesses can occur in transpressive regimes.

The far-foreland stress (*sensu* Tikoff and Maxson, 2001) from an orogenic event may extend for over 1,000 km from the collision zone, generating layer parallel shortening strains (Craddock and van der Pluijm, 1989), but it is unclear whether this far-field stress is significant enough to reactivate

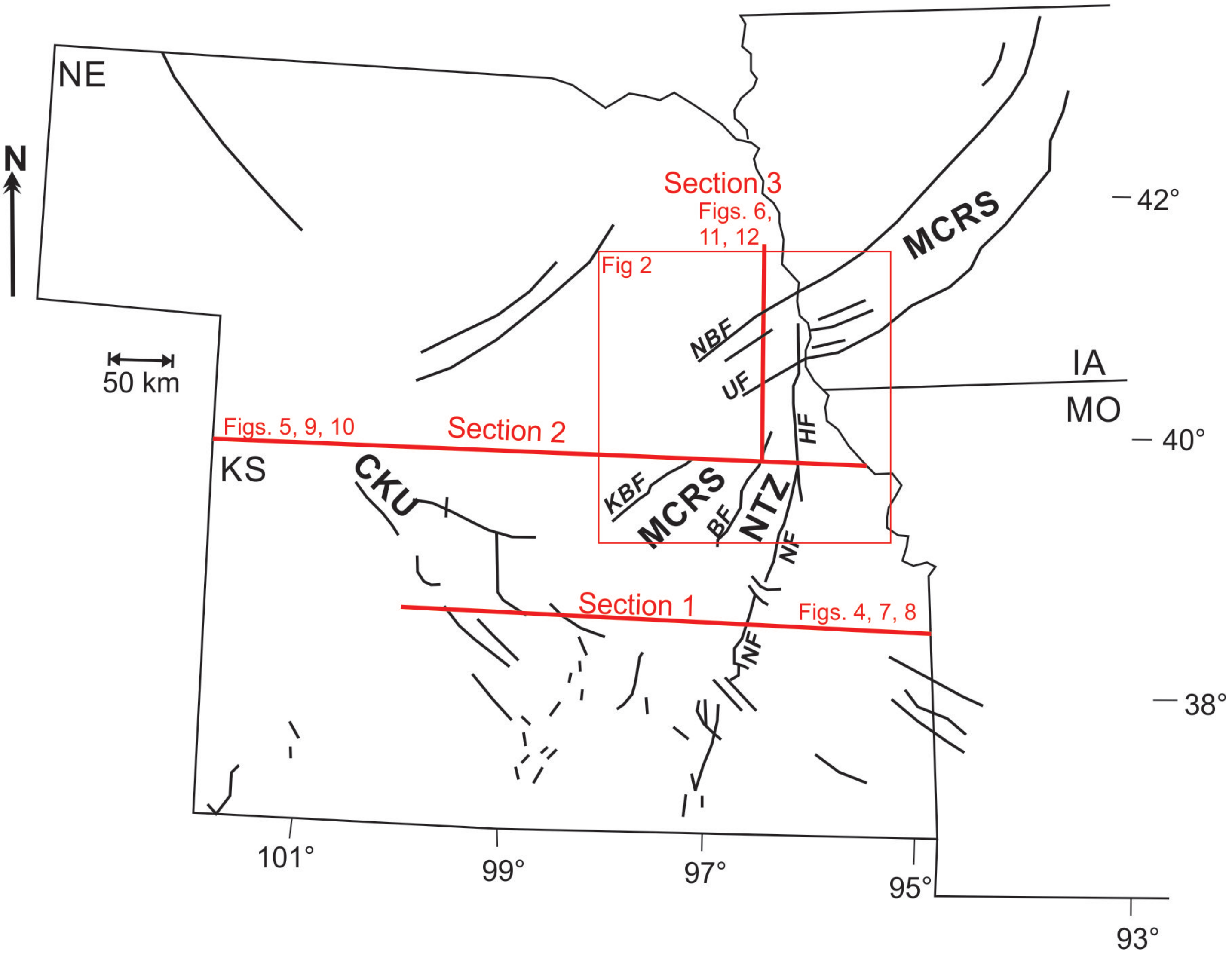

**Figure 1.** Map of Precambrian features in the study area, and locations of the cross-sections used in the study (after Dicken et al., 2001 and Steeples & Brosius, 2014). Key features noted in the text are the Midcontinent Rift System (MCRS) and the Nemaha Tectonic Zone (NTZ). The Central Kansas Uplift (CKU) is also marked. Specific faults considered in the cross-sections are also labeled; BF – Burchard Fault, CKU – Central Kansas Uplift, HF – Humboldt Fault, KBF – Kansas Bounding Fault, NBF – Northern Bounding Fault, NF – Nemaha Fault, UF – Union Fault. The locations of Figures 2-12 are also shown.

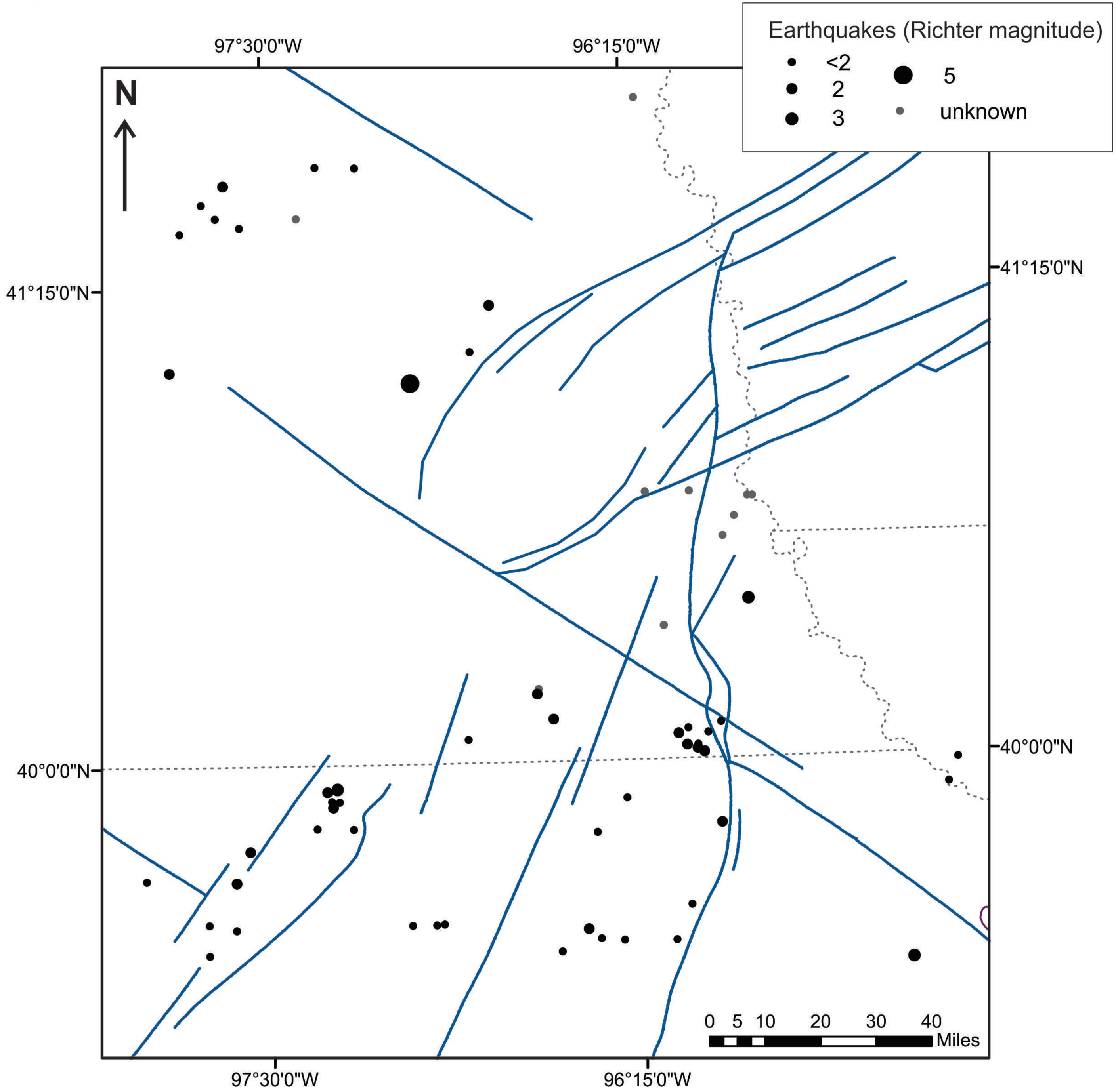

**Figure 2.** Seismicity map of the study area, compiled from data from Burchett, 1990, Kansas Geologic Survey and USGS archives. Dots represent earthquake epicenters, and size reflects Mw where known. Blue lines represent basement faults from Dicken et al. (2001), modified after Steeples & Brosius (2014). Earthquake activity in IA and MO has not been plotted.

distant weak structures. Tikoff and Maxson (2001) concluded that Upper Cretaceous and Paleogene strata in the Laramide near-foreland, approximately 900 km west of the present study area, experienced buckling approximately coeval with the uplift of basement-involved blocks during the Laramide orogeny. These authors used structural techniques to restore published cross sections across their study area, and they demonstrated that their restored cross sections imply both multiple stages of reactivation and one stage of reactivation contemporaneous with the Laramide orogeny.

The present study area was chosen because: (1) the existence of these major structures is undisputed, (2) surface maps show faulting and fracturing in the Cretaceous sections as well as in the Pennsylvanian-Permian strata, (3) historical earthquakes occur on trends related to these structures (Fig. 2), and (4) published sections show deformation and shortening that cannot be accounted for by reactivation in the Ancestral Rocky Mountain orogeny alone (e.g. Burberry et al., 2012). We use similar methodology to that of Tikoff and Maxson (2001) and demonstrate with structural restoration of published cross sections that the long-lived Nemaha Tectonic Zone and related Mid-Continent Rift System were tectonically active in both the Ancestral Rocky Mountain Orogen (approximately 300 Ma) and in the Laramide orogeny (approximately 75 Ma).

## GEOLOGIC SETTING

The oldest crust in the study area has been assigned to the Penokean and Central Plains orogens, 1.9-1.7 Ga old (Carlson, 1995). It has been cut by the NE-SW trending, 1.1 Ga Mid-Continent Rift System (Dickas, 1986; Hegarty et al., 2007) and the NNE-SSW trending pre-300 Ma Nemaha Tectonic Zone. The MCRS is an aulacogen (Black, 1955; King and Zietz, 1971), and has a counterpart failed rift arm to the east (Van Schmus and Hinze, 1985). These rift arms are considered “failed” as neither arm evolved to a true spreading center. The geophysical signal of the rift indicates a gravitational high, enveloped by gravity lows (Dickas, 1986). The gravitational high is considered to be a signal from deep-seated igneous intrusions together with a contribution from the rift-associated volcanism (Cannon et al., 1991; Stein et al., 2014). The Nebraska segment of the MCRS parallels fabrics within the Penokean crust (Carlson, 1995) and is considered to represent a central horst flanked by sedimentary basins in Nebraska (McSwiggen et al., 1987), by comparison with data from Iowa (Chandler et al., 1989). Based on seismic reflection data from Iowa, the southern boundary fault, the Thurman Redfield Fault Zone, may dip up to 60° to the west, but the northern boundary fault zone is less steep (Chandler et al., 1989). This fault geometry is inferred to be the case for the Nebraska portion of the rift as well. The MCRS segment in eastern Kansas is offset from the trend of the Nebraska segment (Dickas, 1986) and in seismic reflection data is characterized by much lower angle normal faults (McSwiggen et al., 1987). Both the Nebraska and Kansas segments of the rift are cut by a series of NW-SE trending dextral strike-slip faults, which have been the cause of earthquakes in the past (Fig. 2) (Baars, 1992; Carlson and Treves, 2005). These faults may be related to the edge of the Central Plains Province, or the boundary between the Central Plains and the Penokean provinces (Carlson, 1995, 1997; Berendsen, 1997). Additionally some authors propose similar fault trends within the accommodation zone between the Nebraskan and Kansan segments of the MCRS because the offset zone is aligned along the same trend as the Missouri Gravity Low as well as being aligned with additional NW-SE trending lineaments mapped by interpretation of gravity and magnetic data (Atekwana, 1996). More detailed mapping correlates specific trends to accretion of numerous terranes during the Central Plains orogeny (Carlson, 2007).

The NTZ is imaged by a deep 2D seismic profile shot by COCORP as a 40 km-wide uplift, bounded to the east by the near-vertical Humboldt Fault and represented by a zone of complex faulting and folding in the deep crust (Brown et al., 1983; Serpa et al., 1984; Serpa et al., 1989; Gay, 1999). Gay (1999; 2003a; 2003b) presented evidence of repeated Paleozoic section in several test wells along the Humboldt fault in Kansas. Many workers (e.g., Baars, 1992; Wilson and Berendsen, 1998) consider the NTZ to be a reactivated fault system that originated as part of the transfer zone in the MCRS and now displays a transpressive sense of relative offset (Moore, 1926; Carlson, 1997; Gay, 1999). This interpretation of the NTZ is problematic, however, because the Humboldt Fault, one of the present boundaries of the NTZ, is near vertical and the underlying rift features are much lower-angle structures (McSwiggen et al., 1987). It is not clear how a near-vertical fault can arise from reactivation of lower-angle features.

The effects of local tectonics during the NeoProterozoic or Late Precambrian and the Paleozoic are observed from stratigraphic relationships and multiple unconformities within the Cambrian-Mississippian succession, particularly in the present study area (Anderson and Wells, 1968; Carlson, 1997, 1998). Hauser (1996) and Hegarty et al. (2007) document Grenville-age inversion of the MCRS in cross sections modified after Eardley (1962) which show significant deformation of the Cambrian-Mississippian section, overlain by a lower Pennsylvanian unconformity. A major tectonic event, reactivating the NTZ and uplifting the Nemaha uplift, is documented to have occurred during the Ordovician (Anderson and Wells, 1968). Isopach maps by Lee (1943) show thickness variations that indicate nearly 300 m of Middle Ordovician structural relief on Precambrian basement and widespread truncation of strata over the uplift by both the base and top of the St. Peter Sandstone. Although this event is not resolved on our cross sections, Berendsen and Speczik (1991) and Berendsen et al. (1992) interpreted hydrous iron oxide oolites in Middle Ordovician (~460-455 Ma) strata of the Forest City Basin in northeastern Kansas and southeastern Nebraska as having been deposited alongside a contemporaneous "paleo-Nemaha Uplift trending parallel to the Midcontinent Rift," which is known to other authors as the Southeast Nebraska Arch. Other local patterns in Middle Ordovician sedimentation also indicate the presence of an earlier uplift (Berendsen and Speczik, 1991; Berendsen et al., 1992). The Kansas segment of the MCRS may have been reactivated during this event, forming the Abilene Anticline (Carlson, 1995).

The boundary between the Mississippian and Pennsylvanian strata is marked by a regional unconformity, showing large-scale exposure of the midcontinent following Mississippian deformation (Fig. 3) (Korus, 2013). The Pennsylvanian strata are represented by the mixed clastic and shallow-water carbonate facies of the Atokan, Desmoinesian, Missourian and Virgilian stages (Fig. 3). It should be noted that Figure 3 shows both the presently recognized and previously recognized tops of the Desmoinesian, Missourian, and Virgilian. Post-Mississippian erosion of the NTZ has been widely documented (Lee, 1943; Carlson, 1963, 1970). Thickness and facies patterns in the basal Pennsylvanian clastic sediments formed by the weathering and erosion of basement exposed by the NTZ (Joeckel et al., 2007) suggest that the area was tectonically active, probably as a result of the Ancestral Rocky Mountain (ARM) orogeny, (Moore, 1926; Kluth and Coney, 1981; Gay, 1999). This orogeny originated with intraplate stress from the contemporaneous Antler orogeny to the west and the Ouachita-Marathon orogeny (i.e. the docking of Gondwana) to the south-east. The Late Pennsylvanian Virgilian strata are overlain by Early Permian Wolfcampian strata across most of the study area.

During the Laramide orogeny (~80 Ma), the region is likely to have been favorably oriented for transpressional movement on the NTZ during a final period of uplift (Tikoff and Maxson, 2001; Ohlmacher and Berendsen, 2005). Bunker (1981) commented that structural mapping of the Greenhorn Limestone (Cenomanian-lower Turonian) showed evidence for Late Cretaceous reactivation of the NTZ, although he provided no documentation thereof. In addition, Franks (1979) hypothesized that the presence of the uplifted NTZ exerted control on the deposition of the Lower Cretaceous (Albian) Kiowa Formation (~105-100 Ma?) in Kansas, but no clear supporting evidence exists because the NTZ was buried during Cretaceous time. The Kiowa Formation marks the base of the Cretaceous sequence in Kansas, whereas in Nebraska, Early Permian Wolfcampian strata are overlain by the Cretaceous Dakota Group (Fig. 3). To date, there has been no satisfactory resolution to the discussion over potential reactivation of Laramide-aged structures.

## MATERIALS AND METHODS

For this study three published cross sections across the study area (Fig. 1) were digitized, modified, and restored, all of which were drawn without an emphasis on kinematics or the possibility of fault reactivation. Cross sections 1 (after Eardley, 1962, but ultimately derived from Kellett, 1932) and 2 (after Condra and Reed, 1959) were drawn before these ideas became common, and cross section 3 (from Korus, 2012) was produced to emphasize the regional hydrogeology of Quaternary strata and uppermost bedrock units. All cross sections were completed as simply as possible, using available stratigraphic evidence. Cross sections are drawn using the older marker units, the top Marmaton Group, top Lansing Group, and top Wabaunsee Group markers respectively, as the initial input for Sections 1 and 2 predates the revision of the stratigraphy. Restoration was carried out assuming plane strain and constant line length, that is, no volume loss, in accordance with common practice. The restorations are accurate representations of the relative geometries of the layers in each stage although the calculation of exact shortening in each restoration stage is problematic due to the vertical exaggeration of each cross section.

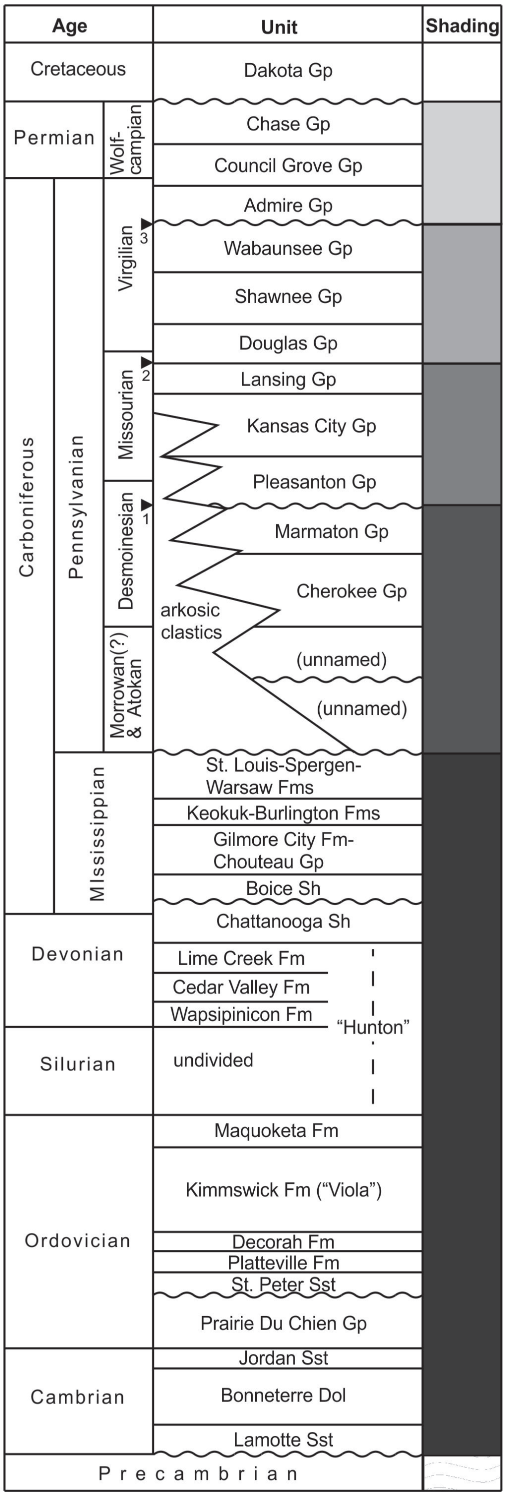

**Figure 3.** Stratigraphy of the Forest City basin and adjacent areas of southeast Nebraska, showing major unconformities. Numbered markers show (1) the former position of the Desmoinesian/Missourian boundary, recently revised by Heckel et al. (2002), (2) the former position of the Missourian/Virgilian boundary, recently revised by Heckel &Watney (2002), and (3) the former position of the Pennsylvanian/Permian boundary, recently revised by Sawin et al. (2006). Nomenclature and chronostratigraphic boundaries have been adapted from Korus, 2013, and references contained therein. The final column, 'Shading' shows the colors used in Figures 4-12 for the various units. Diagram is not to scale relative to stratigraphic thicknesses.

The segment of Section 1 (Fig. 4) reproduced herein does not use the easternmost end of the original (Kellett, 1932; Eardley, 1962), across the Bourbon Arch, because the geometries of Pennsylvanian-Permian units in the Bourbon Arch area remain unconstrained. The Cretaceous sequence is reconstructed to include (Cenomanian-Turonian) sedimentation that occurred across eastern Iowa, western Illinois, and parts of Wisconsin and Minnesota, as evidenced by outliers of the terrigenous Dakota, Bayliss, Windrow, and Coleraine formations (Stauffer and Thiel, 1941; Bergquist, 1944; Andrews, 1958; Frye et al., 1964; Sloan, 1964; Austin, 1972). Likewise, younger marine strata of the Graneros Shale, Greenhorn Limestone, and Carlile Shale have been correlated into western Minnesota (Schurr, 1979; Merewether, 1983). In Section 1, Cretaceous strata are drawn in the reconstructed cross section as continuous across the NTZ and thinning towards the east. An additional cross section was used to estimate the basal Cretaceous geometry (Kansas Geological Survey, 2008). No Jurassic or Triassic units are shown on this section, in accordance with known observations of the study area and immediate surroundings. The Triassic across the interior of the continent appears to be confined to well-defined basins, all of which are found at a great distance from the present study area. The closest Triassic units are recognized in the subsurface of northwestern Nebraska (Condra and Reed, 1959) and thus Triassic units are not considered in the reconstructions. No Jurassic units are present within the Forest City Basin. It should be noted, however, that a very thin remnant of the Jurassic Morrison Formation (latest Oxfordian-early Tithonianin in its entirety) is present in the subsurface near the center of the Kansas-Nebraska line, more than 300 km from the present study area, although the unit thickens westward (Condra and Reed, 1959). These observations indicate that the Morrison Formation was truncated by erosion during the Early Cretaceous, but its original eastward extent is unknown. Localized Upper Jurassic clastic sediments and gypsum beds, which have never been correlated to the Morrison Formation, crop out as structurally preserved outliers in the vicinity of Ft. Dodge, Iowa, some 300 km to the north-northeast of our study area (e.g., Cody et al., 1996) where they are quarried. Red clastic sedimentary rocks in the subsurface of northwestern Minnesota-northeastern North Dakota and in the Michigan Basin have also been interpreted to be of Jurassic age, although not without controversy (e.g., Mossler, 1978; Benison et al., 2010). Accordingly, Bunker et al. (1988) (Fig. 3) considered that Jurassic strata were once much more widespread in the central and northern Midcontinent, and they reconstructed Jurassic sedimentation in their reconstructed subsidence curves for the Forest City Basin and the Nemaha Uplift in southeastern Nebraska. However, due to the lack of constraints on the thickness of Jurassic material, and the uncertainty of the precise angular relationships with overlying and underlying strata, the Jurassic sequence has not been reconstructed in the present study.

Figure 4a shows the initial cross section and Figure 4b shows the modified cross section used in restoration. On the basis of geophysical maps (Xia et al., 1995a, b) small faults were added to the top Precambrian marker, to indicate the position of the Mid-Continent Rift System as it extends southwards into Kansas and intersects the section line (faults Bfa and Bfb, interpreted to be the extent of the Burchard Fault). The dip direction of the main fault associated with the Nemaha uplift (herein labeled the Nemaha Fault, NF) has been subtly altered, although the fault is near vertical to make the structure consistent with a transpressional regime as indicated by Gay (1999; 2003a; 2003b) and widely accepted in the regional geological community. We assume that the Ancestral Rocky Mountain orogeny ceased in the early Permian (Kluth and Coney, 1981) and, accordingly, we reconstruct the top Permian marker as a subdued version of the top Pennsylvanian.

In our Section 2 (after Condra and Reed, 1959), the full extent of the original source cross section has been included (Fig. 5a). The Cretaceous system is also continued across our section based on the evidence that the Nemaha uplift was not emergent at this time. A fault (herein named the Kansas bounding fault) marking the MCRS was added following Xia et al. (1995a, b), and the dip of the eastern fault bounding the Nemaha Uplift (known in Nebraska as the Humboldt Fault, HF) has also been altered. An additional fault has been added, separating the Nemaha Uplift and the MCRS. This fault is known as the Burchard fault in Nebraska (Burchett, 1982), and has not been mapped in Kansas, but was interpreted to extend southwards in the original Condra and Reed (1959) cross section. The top of the Permian has been reconstructed on the eastern part of the section to be consistent with angular relationships shown on the western part of the section.

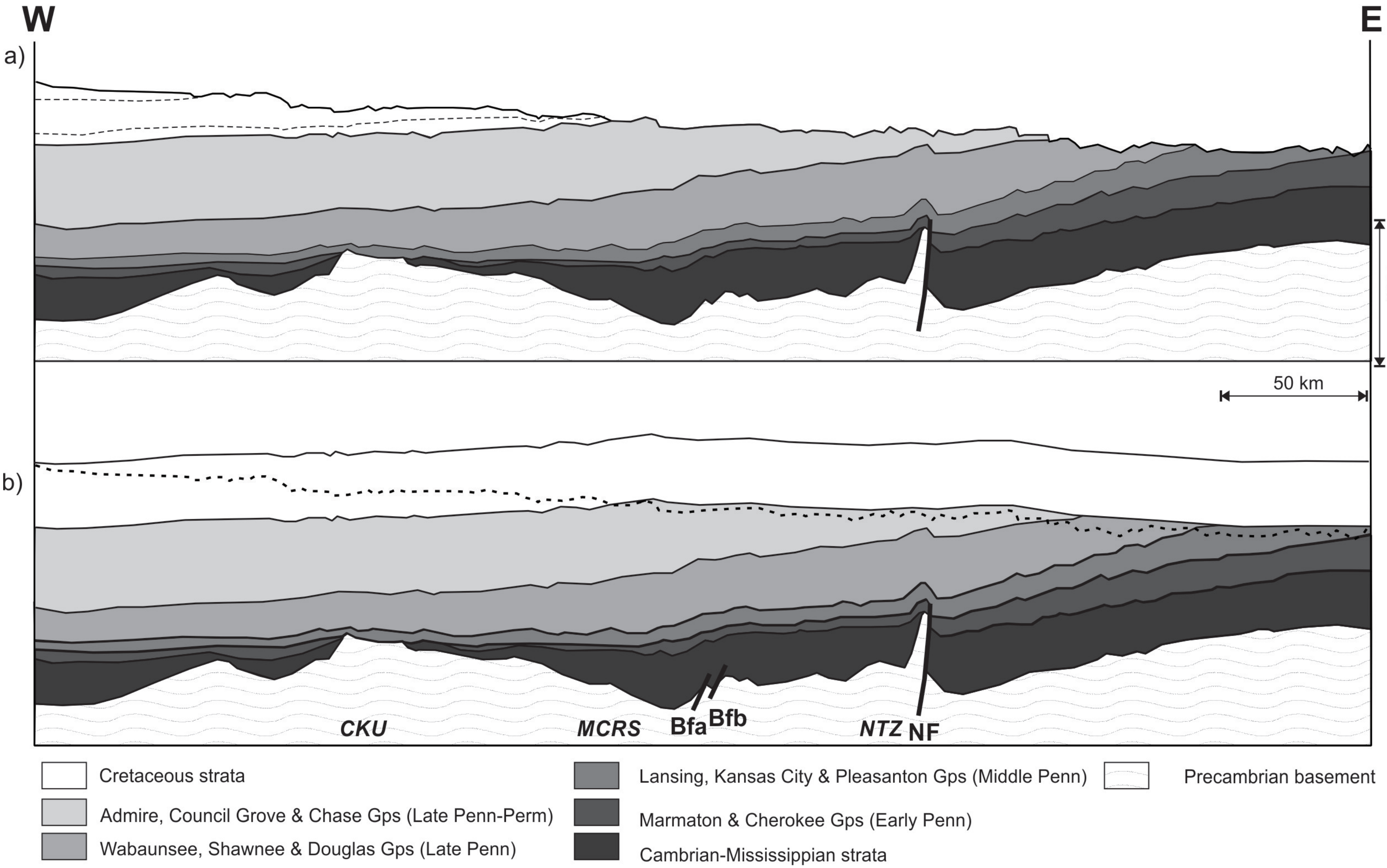

**Figure 4.** Section 1, central Kansas. a) Original interpretation of this line, from Eardley (1962). b) Edited section used for input to the restoration stages. CKU marks the Central Kansas Uplift, MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. Bfa is the projected extent of one strand of the Burchard Fault, Bfb the projected extent of another strand of the Burchard Fault, and NF is the Nemaha Fault. In part (a) the dashed lines indicate the presence of other named layers not used in our restoration. In part (b) the dashed line represents present surface topography.

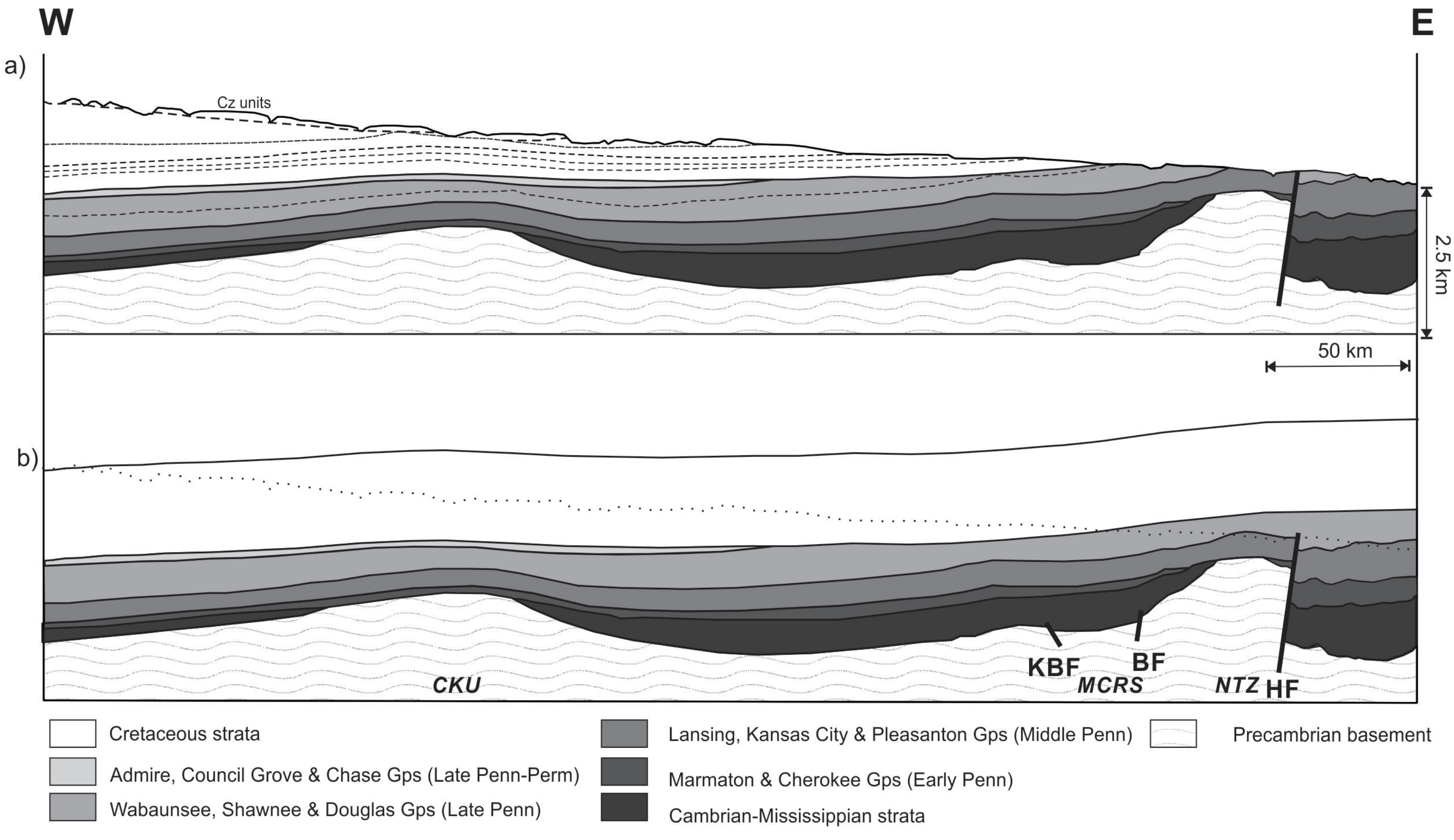

**Figure 5.** Section 2, along the Nebraska-Kansas state line. a) Original interpretation of this line, from Condra & Reed (1959). b) Edited section used for input to the restoration stages. CKU marks the Central Kansas Uplift, MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. KBF is the Kansas Bounding Fault; BF the Burchard Fault and HFis the Humboldt Fault. In (a) the dashed lines show the presence of other named layers not used in our restoration. In (b) the dashed line represents present surface topography.

Section 3 is modified after Korus (2012). The original section uses data from wells that penetrated Upper Pennsylvanian and older strata (Fig. 6a).These well tops were used to construct the initial geometries of the Paleozoic section. Underlying Paleozoic units are constrained by contour and isopach maps from Burchett and Carlson (1966). Faults bounding the MCRS (the Northern Bounding Fault and the Union Fault) were extended to depth and modified slightly according to the geometry of the Precambrian surface (Fig. 5b) and an additional south-dipping intra-rift fault was added. We made no attempt to reconstruct the Permian System in the cross section because there is no constraint on its original thickness. Note that this cross section is at a different vertical exaggeration than Sections 1 and 2 in order to preserve detail.

## RESULTS

Simple restoration of Section 1 (Figs. 4, 7 and 8), indicates that the unconformity at the base of the Cretaceous has been subtly uplifted and gently folded across the Nemaha Tectonic Zone during or after the Cretaceous. The lack of stratigraphic markers across the whole section does not allow a more precise age constraint for the timing of this uplift. Prior to this, Figure 7 indicates a long period of regional tilting, uplift, and erosion across the entire region before the deposition of the Cretaceous strata, as demonstrated by the truncation of the Admire, Council Grove, and Chase Groups. Cretaceous deposition began at least as early as the deposition of the Cheyenne Sandstone during the Albian (Mcfarlane et al., 1991). No Jurassic units are seen in this section and a significant thickness of the Permian succession is missing across the eastern part of the section line. The pre-Cretaceous uplift is greater to the east of the section (that is, across the NTZ) than to the west during this time period, as indicated by the deformed units beneath the unconformity on Figure 7a. Figure 7b shows a simple reconstruction of the Permian units, which are shown in Figure 7c to be nearly constant thickness across the section line, except for a subtle thinning across the Nemaha Fault and the more westerly Central Kansas Arch as a result of the assumed tectonic quiescence, or differential compaction, during the Middle and Late Permian after the Ancestral Rocky Mountain orogeny. Prior to this (during the Late Pennsylvanian) the basins of the MCRS and the Forest City basin subside as one region and the greatest amount of accommodation space is actually generated *across* the Nemaha Tectonic Zone, rather than alongside it (Fig. 8a). The upper Lansing Group and top Marmaton Group are deformed enough to indicate minor compressive stress causing reverse motion on the main Nemaha Fault despite the overall subsidence. This movement is minor in comparison to the magnitude of regional subsidence. During the Early and Middle Pennsylvanian the Nemaha Tectonic Zone is not emergent, being covered by a moderate thickness of Missourian strata (Lansing, Kansas City, and Pleasanton Groups) (Fig. 8b) and an underlying thin package of Desmoinesian strata (Marmaton and Cherokee Groups) (Fig. 8c). Slight uplift, however, appears to occur across the Nemaha Tectonic Zone from the end of the Mississippian until late Kasimovian (approx. 307-304 Ma). At the same time the Forest City Basin to the east of the uplift underwent significant subsidence. Subsidence also occurs in the region of the MCRS west of the Nemaha Tectonic Zone. By the end of the Mississippian the Nemaha Tectonic Zone as, defined by the top Precambrian marker, has positive relief (Fig. 7d) indicating that deformation of this structure had occurred prior to the Ancestral Rocky Mountain orogeny.

Restoration of Section 2 (Figs. 5, 9, and 10) indicates that the northern limit of the NTZ is considerably broader than the along-strike zone in Kansas. Figure 9a shows that when the section is restored to the pre-Cretaceous unconformity, a wedge of Jurassic sediment is truncated by the unconformity. This unconformity also truncates the Permian succession. The truncation occurs over the broad area of the Nemaha Tectonic Zone, and is interpreted to be due to folding and is one of several subtle long-wavelength folds in the Cretaceous succession. One crest of these long-wavelength folds overlies the Central Kansas Arch (the uplift zone to the west of the cross section) and the other overlies the Nemaha Tectonic Zone. This geometry is partly constrained by the regional dip observed in the original section and therefore is unlikely to be purely an artifact of reconstruction assumptions. A marker layer within the Permian, expected to be close to the top of the Permian, is reconstructed in Figure 9b. This top of Permian marker is constrained by information from the original cross section. Figure 9c shows the flattening of the reconstructed upper Permian marker and the resultant bed geometry ca. 280-270 Ma (West et al., 2010). This figure also indicates offset on the upper Pennsylvanian

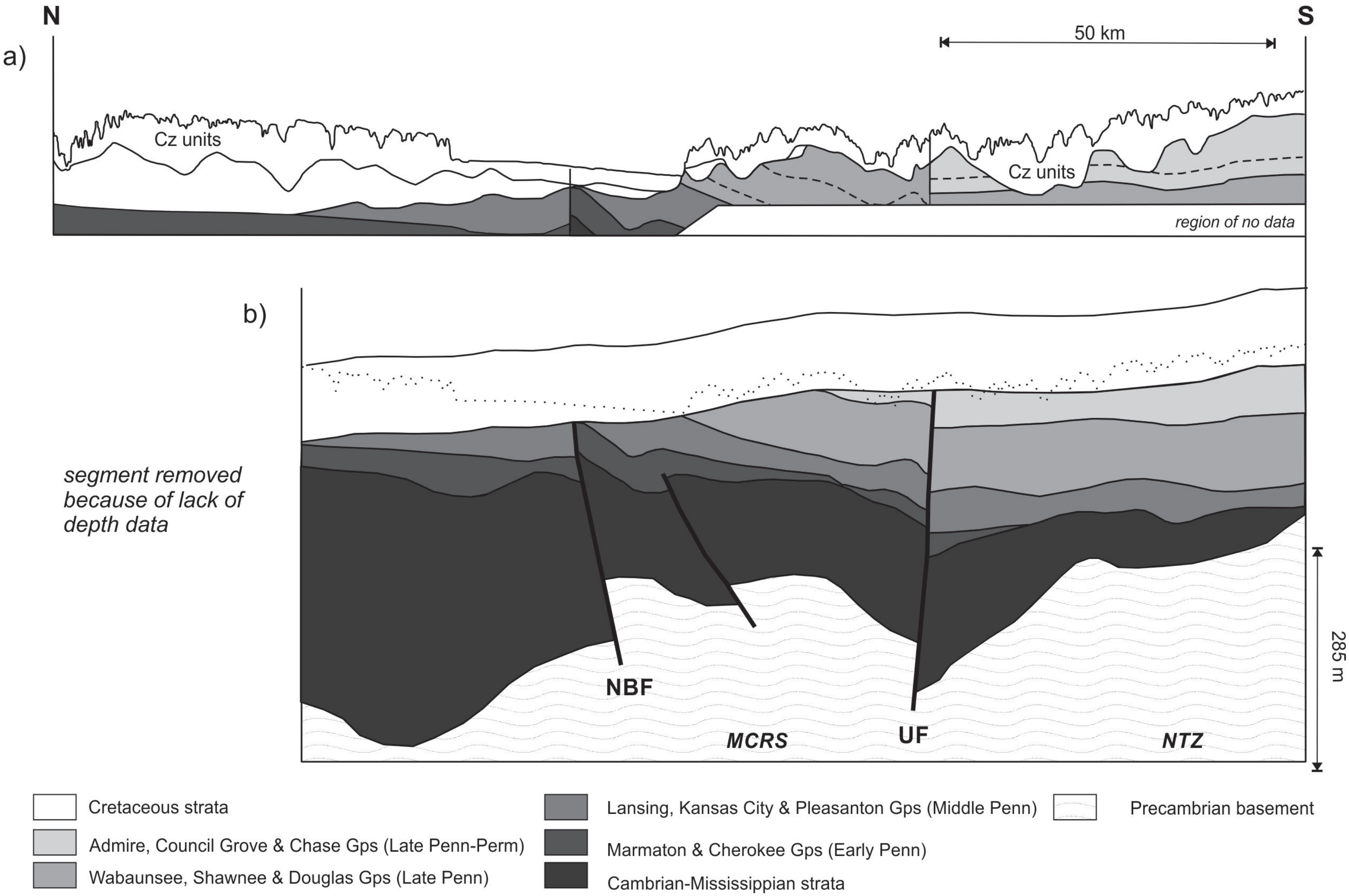

**Figure 6.** Section 3, near the eastern border of Nebraska. a) Original interpretation of this line from Korus (2012). b) Edited section used for input to the restoration stages. MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. NBF is the Northern Bounding Fault and UF is the Union Fault. In (a) the dashed lines indicate the other named layers not used in our restoration. In (b) the dashed line represents present surface topography.

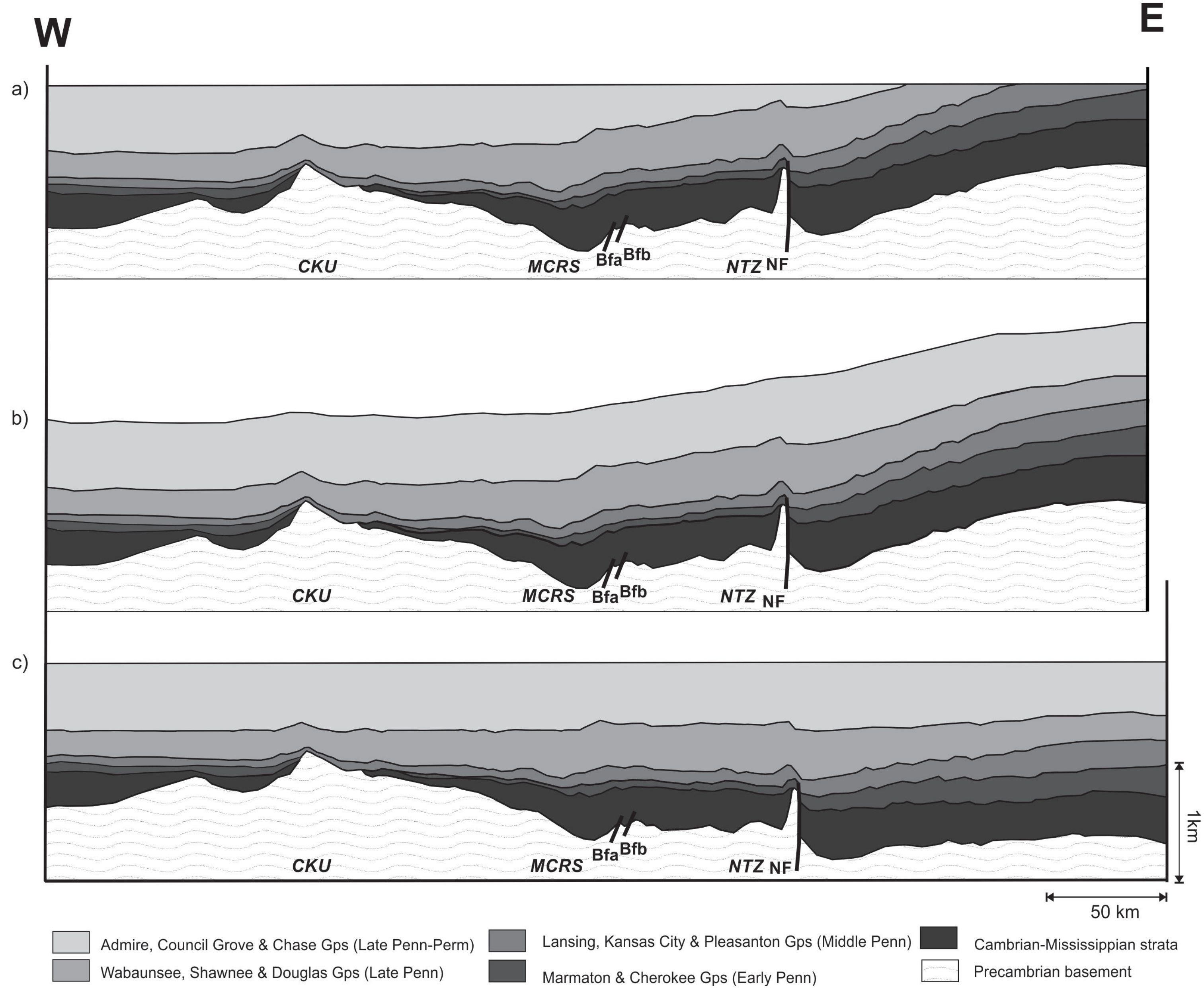

**Figure 7.** Stepwise restoration of Section 1 from the Cretaceous to the Permian. a) Flattened on the base Cretaceous unconformity; b) reconstructed "top" Permian marker; c) flattened on the "top" Permian marker. CKU marks the Central Kansas Uplift, MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. Bfa is the projected extent of one strand of the Burchard Fault, Bfb is the projected extent of another strand of the Burchard Fault and NF is the Nemaha Fault.

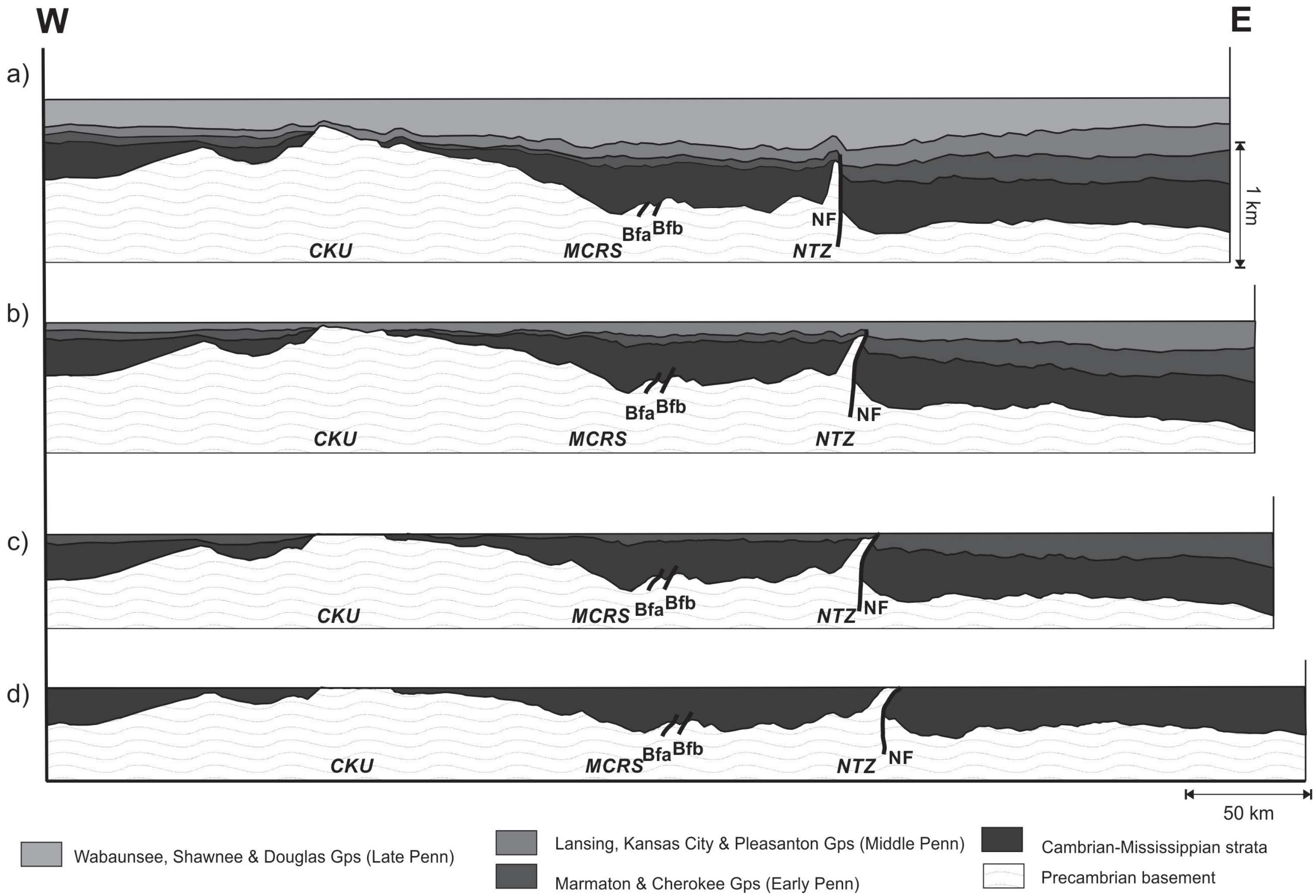

**Figure 8.** Stepwise restoration of Section 1 from the Pennsylvanian to the Mississippian. a) Flattened on the Late Pennsylvanian top Wabaunsee Group marker; b) Flattened on the top Missouri Series marker; c) Flattened on the top Des Moines Series marker; d) Flattened on the Mississippian-Pennsylvanian unconformity. CKU marks the Central Kansas Uplift, MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. Bfa is the projected extent of one strand of the Burchard Fault and Bfb is the projected extent of another strand of the Burchard Fault, NF is the Nemaha Fault.

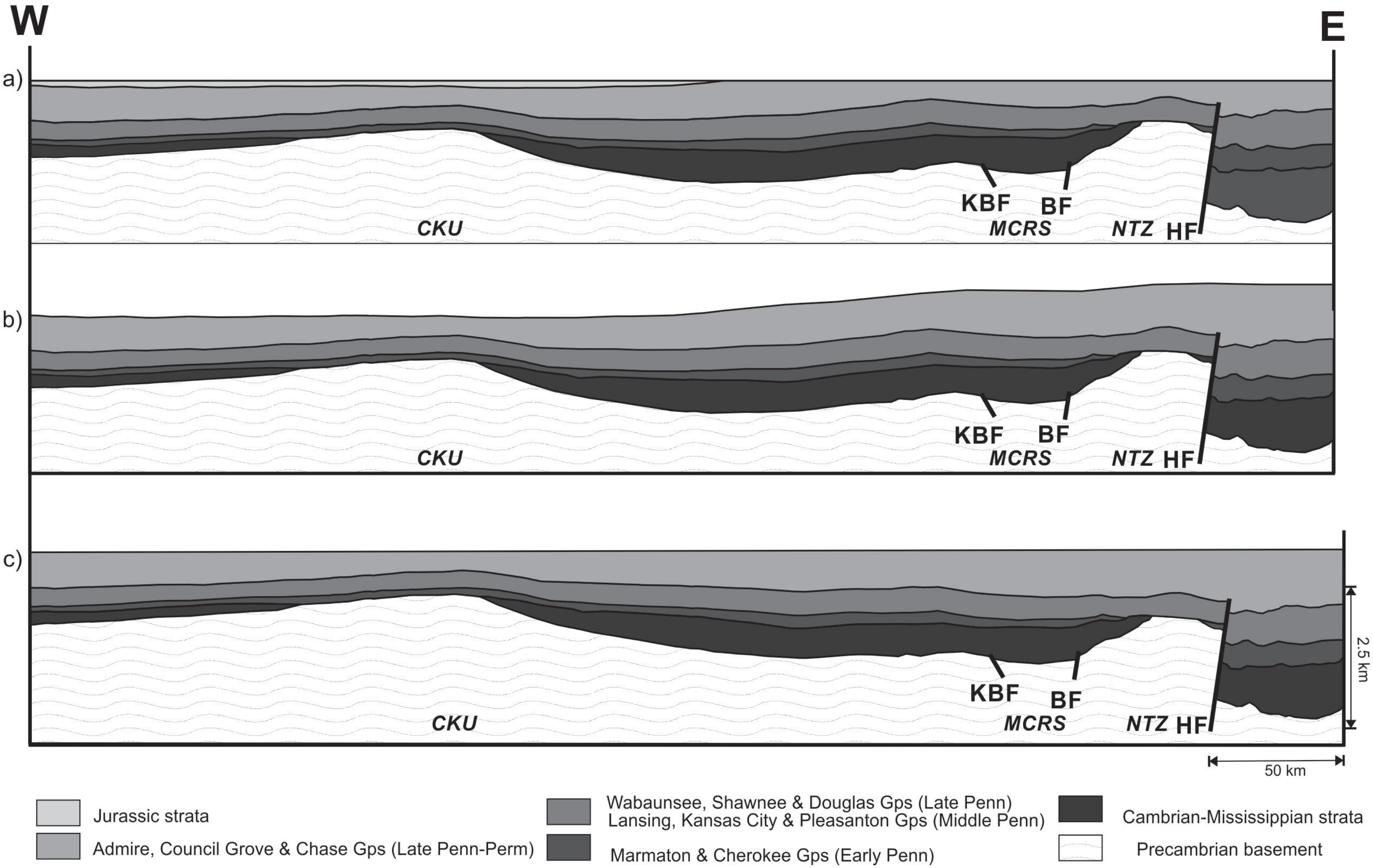

**Figure 9.** Stepwise restoration of Section 2, from the Cretaceous to the Permian. a) Flattened on the base Cretaceous unconformity; b) Reconstructed on the upper Permian marker; c) Flattened on the upper Permian marker. CKU marks the Central Kansas Uplift, MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. KBF is the Kansas Bounding Fault, BF is the Burchard Fault and HF is the Humboldt Fault.

marker and, thus, uplift on the NTZ into the late Permian. Further, this reconstruction suggests that basins of the MCRS and the Forest City Basin are subsiding as one region during the Permian, and that the greatest amount of accommodation space existed across the NTZ, as did the reconstruction of Section 1 (Fig. 7c). Thinning of the Permian section is also noted across the Central Kansas Arch/Cambridge Arch system in the west of the cross section. Given that the upper Permian marker unit was constrained by subsurface data in the original cross section (Kellet, 1932) this is likely to represent true thinning of the succession and not an artifact of assumptions as in Section 1. Figures 10a and 10b indicate that uplift along the Humboldt Fault is observed during the Middle and early Late Pennsylvanian, indicated by offset on the upper Marmaton Group marker. The marker for the top of the Missourian (i.e., the top Lansing Group) is not shown in the original cross section (Fig. 5a). Lastly, Figure 10c indicates that the NTZ is emergent during the Mississippian and that there is sufficient offset on the top Precambrian marker unit to indicate considerable reverse motion on the Humboldt Fault prior to the erosion at the Mississippian-Pennsylvanian unconformity.

Simple stepwise restoration of Section 3 (Figs. 6, 11, and 12) indicates that the basal Cretaceous unconformity has been deformed into long-wavelength, low-amplitude folds (Fig. 6b) similar to the situation demonstrated in Section 2. Once the basal Cretaceous unconformity is flattened (Fig. 11a), it can be seen that most of the Permian sequence has been removed by erosion. No attempt has been made to reconstruct the upper Permian marker as the original section has no constraint on total thickness of the Permian, nor on the angular relationship between the Permian and any Pennsylvanian markers. Figure 11b shows a reconstructed top Wabaunsee Group marker, constrained by previous work in the area (Burchett and Carlson, 1966) and data from several deep wells. This marker is deformed by a pulse of fault activity on the rift-related faults and enhanced compression associated with the ARM, presumably within the lower Permian. Figure 12a shows subtle changes in thickness of the Late Pennsylvanian-Early Permian succession over a deformed Early-Middle Pennsylvanian section. Figures 12b and 12c show that sedimentation and syn-sedimentary deformation continued throughout the Pennsylvanian and into the Early Permian. There are noticeable thickness variations in the Missourian (Lansing, Kansas City, and Pleasanton Groups) and the underlying upper Marmaton Group marker is deformed. The Cherokee and Marmaton Groups fill restricted basins that are created during the Early Pennsylvanian by transpression and reverse motion on the MCRS faults. Lastly, Figure 12d indicates that the NTZ was emergent at the end of the Mississippian and that a deep, filled basin existed north of the line of cross section. This upper Precambrian marker shows very subtle reverse apparent offset on the MCRS faults indicating substantial oblique compression and reactivation sometime during the Cambrian to Mississippian periods.

Taken together, these three cross sections and restorations imply significant deformation prior to the Ancestral Rocky Mountains orogeny and the development of the post-Mississippian unconformity. Evidence for this pre-Mississippian deformation comes from the very subtle reverse offsets on the MCRS faults in Section 3 at this stage (Fig. 12d) indicating that all the original normal offset has been removed by reverse movement. Similarly, the Nemaha Tectonic Zone forms an emergent high at the end of the Mississippian, as indicated by Sections 1 and 2 (Figs. 8d and 10c). Compression of the region and activation of the bounding faults of the Nemaha Tectonic Zone and the MCRS continued through the Pennsylvanian and Permian. This reactivation appears to be pulsed, consisting of at least two distinct stages of activity: one in the Early to early Late Pennsylvanian and another in the early Permian. During these stages of deformation, the northern tip of the Nemaha Tectonic Zone (Section 2) appears to have been reactivated more than the southern part (Section 1). Finally, there is subtle deformation after the deposition of the late Early to early Late Cretaceous units (Cheyenne Sandstone and Kiowa Formation in Kansas and the Dakota Formation in Kansas and Nebraska) creating the long-wavelength, low-amplitude folds observed in all sections.

## DISCUSSION

Our reconstruction of three published cross sections indicates that in addition to major fault reactivation in Pennsylvanian-Early Permian, there was also significant deformation both prior to the post-Mississippian unconformity associated with uplift on the Nemaha Tectonic Zone and after the deposition of late Early to early Late Cretaceous sediments in the study area. Deformation prior

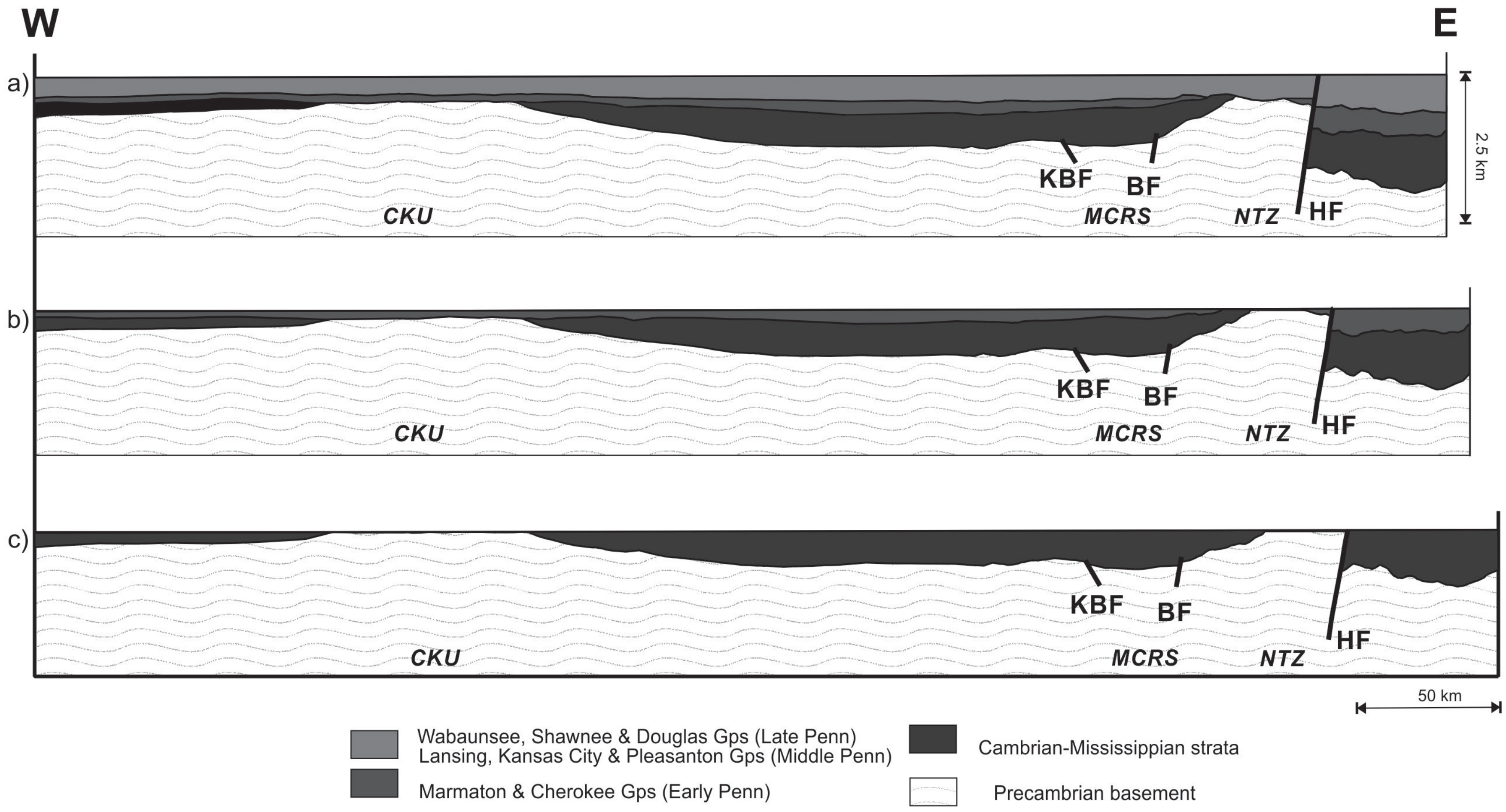

**Figure 10.** Stepwise restoration of Section 2, from the Pennsylvanian to the Mississippian. a) Flattened on the Upper Pennsylvanian upper Wabaunsee Group marker; b) flattened on the upper Des Moines Series marker; c) Flattened on the Mississippian-Pennsylvanian unconformity. CKU marks the Central Kansas Uplift, MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. KBF is the Kansas Bounding Fault, BF is the Burchard Fault and HF is the Humboldt Fault.

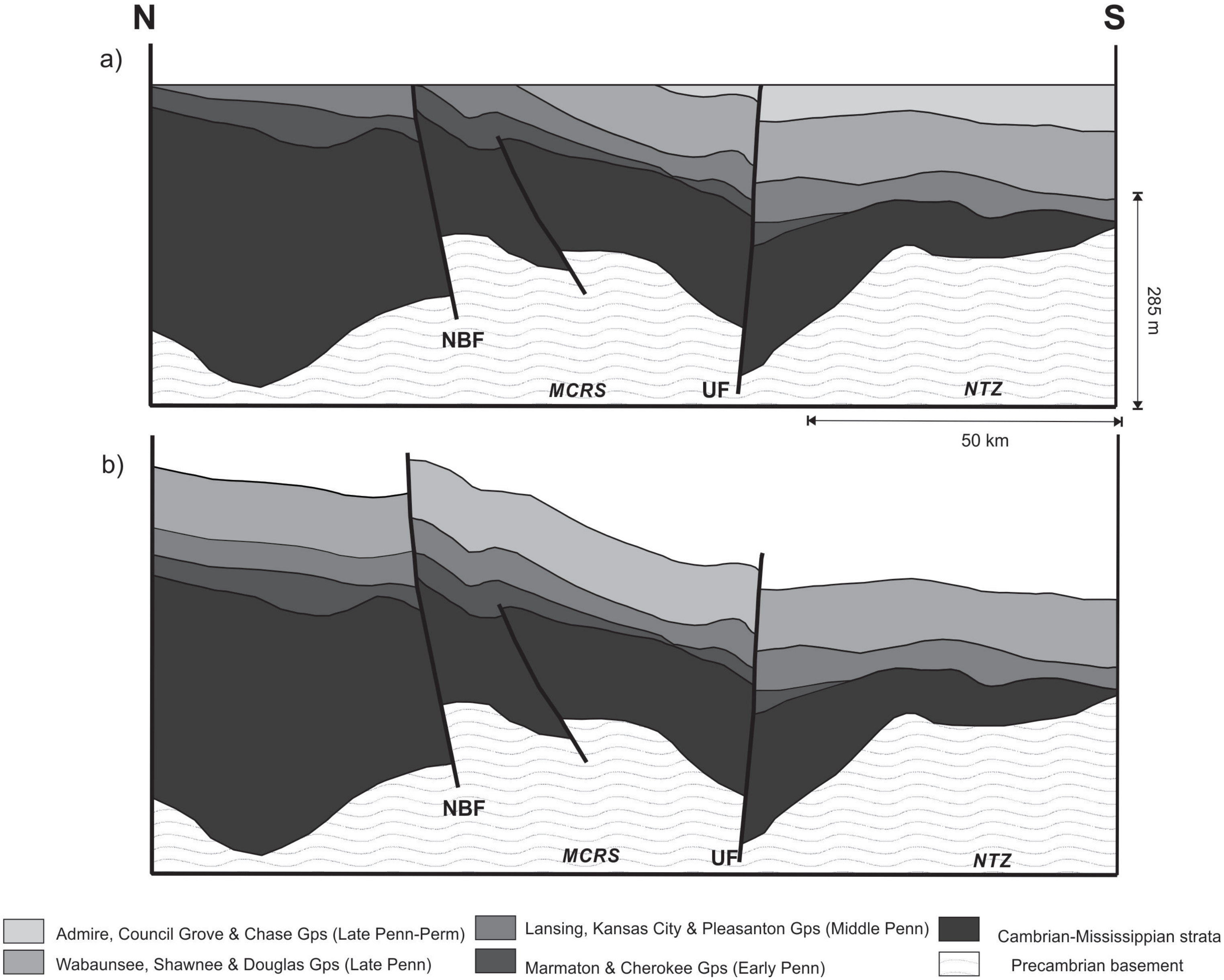

**Figure 11.** Stepwise restoration of Section 3, from the Cretaceous to the Pennsylvanian. a) Flattened on the basal Cretaceous unconformity; b) Reconstructed Late Pennsylvanian upper Wabaunsee Group marker. No Permian restorations are shown in this figure due to the lack of constraint. MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. NBF is the Northern Bounding Fault and UF is the Union Fault.

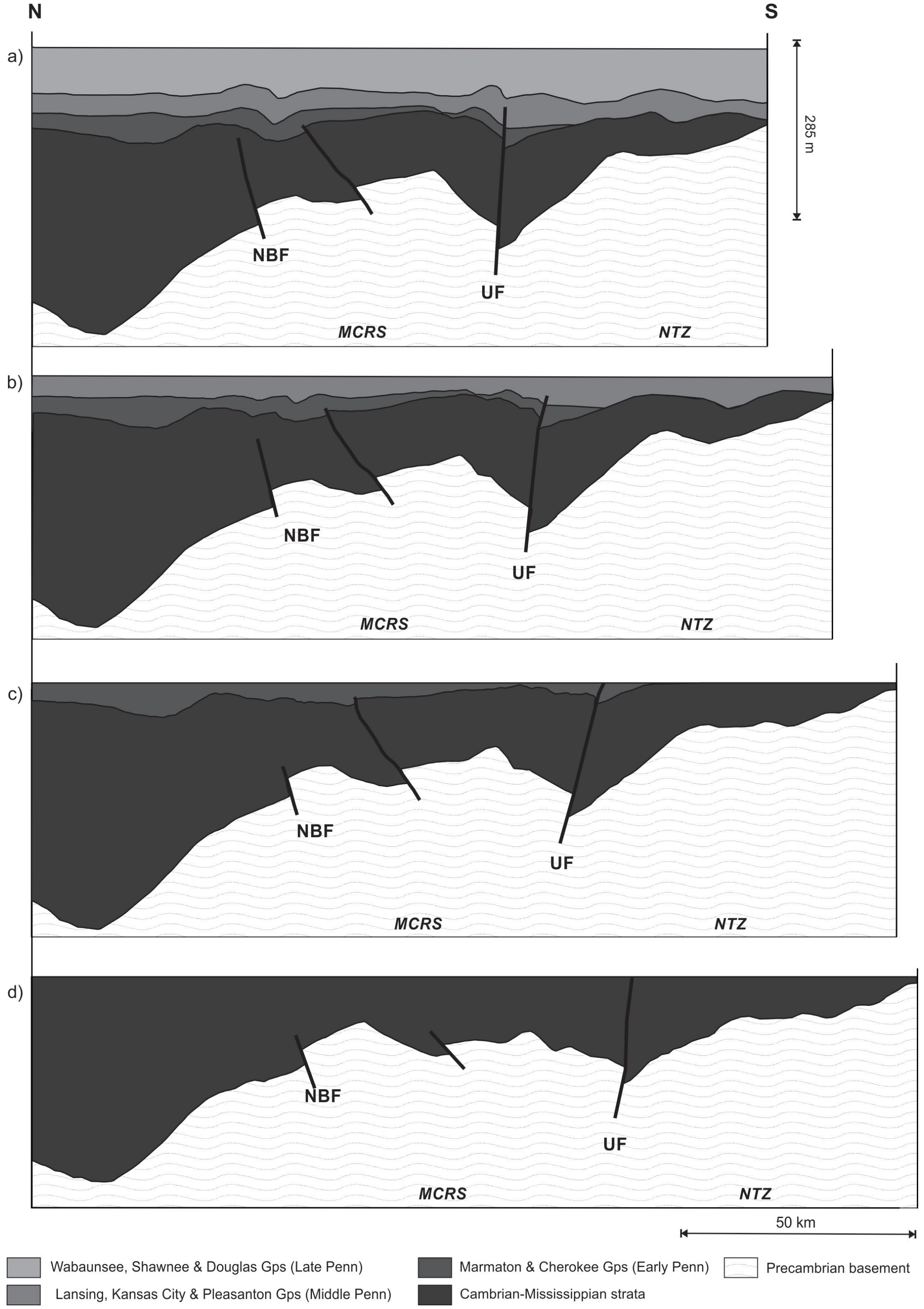

**Figure 12.** Stepwise restoration of Section 3 from the Pennsylvanian to the Mississippian. a) Flattened on the upper Wabaunsee Group marker; b) Flattened on the upper Missouri Series marker; c) Flattened on the upper Des Moines Series marker; d) Flattened on the Mississippian-Pennsylvanian unconformity. MCRS marks the Mid Continent Rift System and NTZ marks the Nemaha Tectonic Zone. NBF is the Northern Bounding Fault and UF is the Union Fault.

to the end of the Mississippian is also indicated by folded Cambrian-Mississippian strata in the original versions of Sections 1 and 2. A likely cause for this deformation is far-field stresses from the Ouachita orogeny, although earlier deformation episodes are not ruled out.

The Ancestral Rocky Mountain orogeny, with which Pennsylvanian-Early Permian fault reactivation has been associated in the Midcontinent (Hegarty et al., 2007), has been attributed to far-field stresses from the Ouachita-Marathon orogeny during the collision of Gondwana with Laurentia (Kluth and Coney, 1981). The fault reactivation observed in the study area indicates that compression occurred in a north-south orientation (Section 3) as well as in a more east-west direction (Sections 1 and 2). Reactivation on the Nemaha Tectonic Zone faults is subtle in Sections 1 and 2, compared to the large post-Pennsylvanian offsets observed in Section 3 and the implication of a dominant Early Permian stress direction sub-perpendicular to the trend of the MCRS. Therefore the dominant direction of compression is expected to have been north-northwesterly in the Early Permian, which would be oblique to the faults within the Nemaha Tectonic Zone. Because Sections 1 and 2 do not show intense deformation in the Permian, but do show considerable reactivation of faults in the Pennsylvanian, a dominant compressive stress direction more perpendicular to the Nemaha Tectonic Zone faults, approximately west-northwestly, is interpreted for the Pennsylvanian. The direction of the maximum compressive stress, therefore, rotated during the Ancestral Rocky Mountain orogeny. This conclusion is consistent with the progressive suturing of Gondwana with Laurentia during the Ouachita and Marathon orogenies (Kluth and Coney, 1981; Cox, 2009).

Deformation during the Late Cretaceous is contemporaneous with the Laramide orogeny (~80-55 Ma) indicating that the mid-continent is affected by these stresses. This result is consistent with the results of Tikoff and Maxson (2001), who suggested that the far-foreland region to the Laramide orogeny experienced long-wavelength buckling, promoting reactivation on existing structures. Our sections suggest that the long-wavelength folds discussed by Tikoff and Maxson (2001) and attributed to Laramide foreland buckling may have curvilinear hinge lines in three dimensions. The result is also consistent with observations from the Niobrara Chalk and Pierre Shale in northeastern Nebraska and southeastern South Dakota by Maher (2014) which documented Laramide orogeny tectonic activity. Similarly, Laramide compression and reactivation have been proposed for the Sioux Ridge in southeastern South Dakota (Merewether, 1983). In addition, evidence for minor tectonism during the early Late Cretaceous has been documented in northeast Nebraska and northwest Iowa (Merewether, 1983). This evidence consists of deformation of Mid to Late Cretaceous sedimentary units and the development of a basal Cretaceous unconformity above an uplift consisting of Precambrian quartzite and Paleozoic sedimentary units. These additional findings of Laramide-age reactivation of faults in the mid-continent suggest that our hypothesis of Laramide-age reactivation of the Nemaha Tectonic Zone is plausible.

Seismic activity in the region is demonstrated by the map given in Figure 2 and our work suggests that many of these events are associated with structures related to the MCRS and NTZ. However, Figure 2 also indicates a relatively poor correlation between mapped faults and seismic events, indicating that in this region, the known faults are not sufficient to account for all of the seismic activity. We suggest that the transfer zone between the rift segments, in particular, is more complex than presently mapped. In the future, we intend to investigate the location of additional faults in the area, especially given the advances in structural understanding and the improvement in geophysical techniques since geological survey work was undertaken prior to 1986, and improve the correlation between seismic activity and fault location. We also intend to apply the methods used in this study to additional basement uplifts in the interior of the continent, such as the Central Kansas Arch-Cambridge-Chadron Arch complex, part of which is depicted on our sections 1 and 2 (Figs. 4 and 5).

## CONCLUSIONS

Our results indeed clearly indicate multiple stages of reactivation of pre-existing structures in Kansas and Nebraska, chiefly the reactivation of Precambrian faults in the ARM (Pennsylvanian-Permian) and Laramide orogenies. Reactivation structures further imply a rotation of the dominant compressive stress direction during the ARM, from west-northwest-directed compression in the early stages to a later north-northwest-directed stress. In addition, these reconstructions confirm earlier work suggesting that Laramide-related stresses propagate into the Midcontinent, causing the development of long-wavelength folds related to the reactivation of the same Precambrian faults. Our results also indicate that the magnitude of the far-field stresses is sufficient to cause seismic reactivation on favorably oriented pre-existing faults, and indeed that faults related to the MCRS could have generated the Mw 5.1 event in 1877 as well as the numerous smaller events documented in the area.

The history of reactivation of geologic structures in the study area suggests that seismic hazards in the region should be expected. There is clearly a mechanism in place for generating earthquakes in that pre-existing weaknesses have persisted for hundreds of millions of years through several orogenic cycles. Dangerously large earthquakes are historically very rare in the interior of North America, outside of the New Madrid tectonic zone, but given the occurrence of a Mw 5.1 event with an epicenter above the MCRS in eastern Nebraska, seismic activity along the structures analyzed in the present study area would threaten several large population centers and the potential for this activity should not be dismissed.

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