FINAL TECHNICAL REPORT

EVALUATION OF POTENTIAL ASEISMIC CREEP ALONG THE OUACHITA FRONTAL FAULT ZONE, SOUTHEASTERN OKLAHOMA

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ABSTRACT

Previously reported evidence of aseismic creep along the Choctaw fault in southeastern Oklahoma suggested the possibility of a potentially active fault associated with the southwestern part of the Ouachita Frontal fault zone (OFFZ). The OFFZ lies between two known active tectonic features in the mid-continent: the New Madrid seismic zone (NMSZ) in the Mississippi embayment, and the Meers fault in southwestern Oklahoma. Possible evidence of aseismic fault creep with left-lateral displacement was identified in the 1930s on the basis of deformed pipelines, curbs, and buildings within the town of Atoka, Oklahoma. This investigation compares geologic and geomorphic evidence of possible fault creep along the southwestern OFFZ with previously developed criteria designed to differentiate between features produced by tectonic and non-tectonic processes. The assessment of possible evidence of fault creep involved analysis of aerial photography, aerial reconnaissance, and detailed field observations.

Within residential areas of Atoka, several features identified previously as potential evidence of fault creep can be more easily attributed to northeasterly slope movement. The locations of several left-lateral deformations along a mapped lithologic contact were re-occupied, although the existence of other previously identified "fault creep" features was not confirmed. Deformation of several other features within the residential area, but northeast of the originally identified left-lateral offsets, suggest that the area of active deformation is broad and not restricted to a linear zone along the offsets originally attributed to fault creep. The deformation of sidewalks, curbs, pipelines, and house foundations are most likely related to northeasterly slope movement, rather than creep-related left-lateral offset. The primary evidence against a fault origin for the features in Atoka includes: (a) inconsistent amount of lateral slip along strike, (b) the broad areas of deformation northeast of the originally identified features, (c) episodic deformation, and (d) the discontinuity of deformation along strike. All other observations of deformation can be most easily explained either by differential settlement of vintage buildings with poorly built foundations or by soil processes that differ between areas underlain by sandstone and shale bedrock. All available field observations are consistent with, and strongly suggestive of, a landslide origin for the deformation features in residential Atoka.

Analysis of vintage aerial photography identified two areas in the Muddy Boggy Creek valley north of residential Atoka containing possible liquefaction-related sand blows on alluvial surfaces. Field reconnaissance of these areas and other alluvial surfaces near the active creek channel showed no evidence of liquefaction-related features. In addition, aerial and field reconnaissance in the area south of Atoka showed an absence of evidence of fault-related features in Cretaceous bedrock overlying the mapped trace of the Choctaw fault. Coupled with the re-assessment of features in Atoka previously attributed to aseismic creep, there is no compelling evidence of fault creep along the Choctaw fault and the OFFZ. Therefore, this analysis suggests that the Choctaw fault is not an active fault, and that the southwestern OFFZ likely is not a capable tectonic source.

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1.0 INTRODUCTION

This technical report presents the results of a detailed study to assess the southwestern part of the Ouachita Frontal fault zone (OFFZ) in southeastern Oklahoma. Previously reported evidence of possible aseismic creep along this fault suggested that the OFFZ may be a previously unrecognized seismic source in the central United States. If evidence of active creep along the OFFZ is attributable to tectonic processes, the fault zone could be a possible source of earthquakes and raises the question: Is the southwestern part of the OFFZ an active tectonic feature?

In this research, we evaluate the possibility of aseismic creep along the Choctaw fault, a component of the southwestern OFFZ that strikes north-northeast across Atoka County and is the westernmost of a series of thrust faults within the Paleozoic southern Ouachita fold and thrust belt. The orientation and location of the fault are favorable to re-activation in the present-day stress field observed in the mid-continent, and observations made in the 1930s raised the possibility that the Choctaw fault may experience aseismic creep. In the town of Atoka, the fault traverses a small, linear hill upon which there is an alignment of historic damage to cultural features (e.g., sidewalks, curbs, pipelines, rock walls) from left-lateral ground movement (Knechtel and Rothrock, 1935).

We document the characteristics of deformation, identify the presence or absence of geologic features consistent with faulting, and compare these with previously developed criteria (NUREG/CR-5503; Hanson et al., 1999) to differentiate between features produced by tectonic and non-tectonic processes. The products of this research are the documentation of features that address the presence or absence of active creep within the town of Atoka, and an assessment of whether the Choctaw fault, as part of the southwestern OFFZ, is a potentially active seismic source.

2.0 GEOLOGIC SETTING OF THE OUACHITA FRONTAL FAULT ZONE

The Ouachita Frontal fault zone (OFFZ) forms the border between the Ouachita Mountains uplift on the south and the Arkoma basin on the north (Figure 1a). The OFFZ represents a major crustal discontinuity that developed during north-vergent (and locally west-vergent) late Paleozoic folding and thrust faulting (Viele, 1989; Suneson, 1988, 1990). The Ouachita fold and thrust belt consists of three regional belts, of which the OFFZ is the most northerly. The surface outcrop of the Ouachita fold and thrust belt extends from the town of Atoka, Oklahoma on the southwest to the Mississippi Embayment in central Arkansas on the east (Figure 1a). Directly southwest of the town of Atoka, undeformed Cretaceous Gulf Plain sediments overlie the southwestern end of the OFFZ. In the subsurface south of Atoka, the fault zone intersects the Arbuckle uplift (Figure 1b), which is considered part of the southeastern extension of the Wichita uplift (Ham and McKinley, 1954). Thus, the town of Atoka lies in a unique location at the intersection of the Ouachita uplift on the east, undeformed Cretaceous sediments on the south, the Arbuckle uplift on the west, and the Arkoma basin on the north (Figure 1b).

The OFFZ lies between two known active tectonic features in the mid-continent: the New Madrid seismic zone (NMSZ) in the Mississippi embayment, and the Meers fault in southwestern Oklahoma (Figure 1a). These seismic sources are associated with the only documented surface deformation related to large earthquakes in the mid-continent. The NMSZ occupies, in part, the buried Reelfoot rift, which trends northeast beneath the Mississippi embayment (shown in yellow on Figure 1a) and is a major crustal structure that has undergone repeated reactivation (Ervin and McGinnis, 1975). Similarly, the Meers fault lies along the northeastern margin of the Southern Oklahoma aulacogen, a failed Paleozoic rift that extended from the present-day Gulf of Mexico to western Oklahoma (Budnik, 1986). The active Meers fault is also associated with the Wichita uplift (Geomatrix, 1990; Kelson and Swan, 1990; Swan et al., 1993), and the southeasterly extension of this uplift intersects the OFFZ near Atoka. The OFFZ coincides with the northern margin of the Ouachita fold and thrust belt, which is a major crustal feature that uplifted sediments deposited in the early Paleozoic Ouachita trough (Suneson, 1988, 1990). At its southwestern end, the OFFZ abuts the Arbuckle Mountains uplift, which is a reactivated part of the southern Oklahoma aulacogen (Budnik, 1986). In addition, both the OFFZ and the Meers fault border Paleozoic uplifts on the south and deep structural basin on the north (Figure 1b).

Seismicity in the region shows a broad spatial correlation with the OFFZ even though the level of seismic activity is relatively low. Luza and Lawson (1983) and Gordon and Dewey (1985) acknowledge that seismicity has been coincident with the OFFZ, which is an exception to the general inability to associate

earthquakes with known geologic features. The Electric Power Research Institute (EPRI, 1986) evaluated the OFFZ as a capable seismic source; they assigned a high probability (35-46%) for seismic activity and a low probability (~6%) for a large (>6.0Mw) earthquake (EPRI, 1986). This assessment indicates that EPRI (1986) considered the OFFZ to not represent a significant seismic source. With this in mind, and given the findings of Knechtel and Rothrock (1935), described below, it is important to re-assess the 50 km long section of the southwestern OFFZ, including the section through Atoka, and determine if in fact the documented deformation is related to aseismic creep – indicating the potential for larger seismic events – or whether it is related to non-tectonic processes.

2.1 Previous Observations of Possible Aseismic Creep Along the Ouachita Frontal Fault Zone

Knechtel and Rothrock (1935) first identified possible aseismic creep along the Ouachita Frontal fault zone through the town of Atoka, Oklahoma (Figures 2 and 3). These workers provide detailed observations of historic deformation of pipelines and buildings in a distinct alignment, and consider several possible origins for the deformation. As summarized below, Knechtel and Rothrock (1935) interpret that the phenomena are due to aseismic fault creep along the Choctaw (Pine Mountain) fault within the OFFZ (Figure 2).

Near Atoka, the OFFZ consists of several large, northwest-vergent thrust faults and intervening folds, with the largest amount of stratigraphic separation along the Ti Valley fault (Nielsen and Leonhardt, 1983; Suneson, 1990). The Choctaw fault is one of the primary faults within the OFFZ, which in the town of Atoka deforms Carboniferous sedimentary rocks to form several northeast-trending strike ridges. In the western part of Atoka, alternating shales and conglomeratic sandstones form a ridge about 20 m high (Figure 3). In the residential areas on this ridge, water and sewer pipelines were installed in 1906 and 1913, respectively. Knechtel and Rothrock (1935) note that these pipelines repeatedly failed at specific locations aligned parallel with a conglomerate bed (and parallel with Montana Avenue, Figure 3). In 1933, excavation of the pipeline at the corner of A Street and Montana Avenue (Figure 3) showed that the pipeline was sheared at right angles to its longitudinal axis, along an orientation of N20˚E. The trench was excavated into sandstone bedrock, and the trench and pipeline both were offset in a left-lateral sense. Knechtel and Rothrock (1935) also document that another pipeline failure at the corner of Court Street and Montana Avenue (Figure 3) coincides with repeated distortion and cracking of a stone building foundation. Other buildings along the same alignment showed deformation and cracking, and water and sewer lines repeatedly failed at locations along the N20˚E orientation. Knechtel and Rothrock (1935) note that other buildings of similar construction throughout the town, but not along this alignment, are undeformed.

Knechtel and Rothrock (1935) interpreted that the left-lateral displacements occurred continuously, because of the absence of moderate or large earthquakes during the period of deformation, and because all of the pipeline failures did not occur at the same time. They ruled out the possibility that the deformation is a result of dissolution collapse, because there are no limestone or other soluble strata in the region. Also, they dismissed the possibility that hillslope creep caused the deformation because the direction of the left-lateral movement is parallel to the trend of the linear ridge (Figure 3), rather than in a downslope direction. The possibility of freeze-thaw soil movement was discarded as a possible non-tectonic origin for the features, because of the mild climate in southern Oklahoma, and because the deformation also appears to be associated with sandstone bedrock. Knechtel and Rothrock (1935) conclude, "It appears, therefore, that the phenomena are due to faulting, though no earthquakes have been felt in the immediate neighborhood". With this information as a seed, this investigation was completed to assess the possibility of aseismic fault creep along the Choctaw fault in Atoka.

3.0 APPROACH AND METHODS

Given the detailed information and logical conclusions presented by Knechtel and Rothrock (1935), we conducted a field reconnaissance of the Choctaw (Pine Mountain) fault in the town of Atoka and evaluated observations using guidance outlined in NUREG/CR-5503 "Techniques for Identifying Faults and Determining their Origins" (Hanson et al., 1999). Prior to the field investigations, we obtained stereo-paired aerial photography and identified geologic and geomorphic features to help guide the field reconnaissance. The reconnaissance involved field observations of previously identified features, mapped using a standard hand-held GPS unit, as well as discussions with residents in the affected area about the amount, direction, and timing of the active deformation to homes and other structures. The reconnaissance also involved an aerial flight above and around Atoka to look for geologic and geomorphic features that would provide information on the origin of the features noted by Knechtel and Rothrock (1935).

Based on the aerial-photo interpretation, we investigated three primary areas within Atoka (Figure 4): (a) residential Atoka, (b) an area north of residential Atoka, and (c) an area south of residential Atoka. The area within residential Atoka included the features previously investigated by Knechtel and Rothrock (1935) and also included the streets adjacent to Montana Avenue (Figure 3). We documented the presence or absence of deformation, cracks and scarps developed in the sidewalks and curbs and other cultural features, and noted the sense and direction of deformation at each locality. We also conducted ground and aerial reconnaissance of potentially fault-related features identified via air-photo analysis in areas north and south of Atoka, which involved a search for evidence of active surface faulting and liquefaction in late Quaternary deposits. The results of these investigations are summarized below.

4.0 RESULTS OF FIELD RECONNAISSANCE ALONG THE CHOCTAW FAULT

4.1 Residential Atoka

On the basis of the previous literature, analysis of air photos, field reconnaissance, and the aerial overflight, we identify three areas within residential Atoka that display different levels and types of deformation (Figure 5): (a) the northeastern residential Atoka, (b) southern residential Atoka, and (c) northwestern residential Atoka. The northeastern residential area is defined by the area directly west of North Montana Avenue, West Sandy Creek Road, Mississippi Avenue, and the midpoint between West First Street and West Second Street (Figure 5). The southern residential area is defined by South California Avenue, West Fourth Street, South Montana Avenue, and the midpoint between West First Street and West Second Street. The northwestern residential area is defined by the streets of West Second Street, Oregon Avenue, West A Street, and the area just west of North Montana Avenue.

Built cultural features in residential Atoka provide an abundance of long-term historic strain gauges. For example, almost all of the residences in this hilly part of Atoka have been present since at least the mid-1930s, and probably were built in the early 1900s. Most appear to have original foundations constructed of stacked sandstone slabs, sometimes fortified with concrete. While most streets have been paved with asphalt in recent years, the sidewalks are weathered concrete that appear to be original and generally contain date-stamps in the 1910s or 1920s. Drainage gutters in the streets also appear to be the originals as built in the 1910s and 1920s, and are composed of slabs of resistant sandstone. In all, these features are likely to be responsive to subtle changes in the ground surface, and thus are good strain gauges for identifying and measuring surficial deformation related to fault creep or other surface processes.

4.1.1 Northeastern Residential Atoka

We conducted an extensive field reconnaissance in the northeastern residential area of Atoka, and identified several localities containing damage to cultural features (Figure 5). Evidence of damage to cultural features include deformed house foundations at localities 4, 33, and 34, and cracks in sidewalks, streets, and gutters at localities 2, 3, 23, 24, 25, 26, 27, 28, 29, 30, 32, 33, 34, 35 and 36 (Figure 5). Most of the localities exhibited down-on-the-east normal displacement, but there was also a lesser component of left-lateral offset. In this area, the deformation generally is coincident with the lithologic contact between the sandstone-conglomerate bed ("Bed C", Figure 5) and the underlying shale, although damage is present over a broad area east of the lithologic contact. Additionally, the amount of deformation is not laterally continuous along the strike of the resistant sandstone bed; it ranges from several centimeters of

vertical motion to tens of centimeters. The observed lateral component is predominantly left lateral, but there also is evidence of minor right-lateral offsets. Knechtel and Rothrock (1935) noted that there were several broken water lines along the contact between the sandstone-conglomerate unit (Bed C) and the shale unit. However, we note that the damage is not restricted to this contact; whereas the damage to the residences, curbs, and sidewalks is limited to the area east of the resistant bed, the area of recent damage extends from the resistant bed eastward to South California Avenue (Figure 5). Also, this area of concentrated damage has a relatively steeper topographic gradient than the areas west of the resistant bed and east of South California Avenue, suggesting a possible slope-failure origin.

Damage to the gutters, streets and sidewalks within the northeastern residential area is confined to locations adjacent to North Montana Avenue and North California Avenue near West A Street (Figures 3 to 5). In particular, a topographic scarp along the western side of North Montana Avenue is traceable across pathways to houses and the gutters and sidewalks of intersecting streets (Figures 6 to 8). At Locality KR2 (see Figure 5), several cracks and scarps are developed in the sidewalks and curbs of Court Street, directly west of Montana Avenue (Figures 6 to 8). The deformed features on both sides of Court Street lie along a N20˚E orientation, and suggest left-lateral, down-to-the-east movement over a width of about 1 m. At Locality 4, there is evidence of left-lateral offset and damage to cultural features, including a deformed house foundation, and a deformed concrete pathway at 301 Montana Avenue. This pathway is on a flat, terraced yard, and exhibits uplift, rotation, and left-lateral displacement of concrete blocks (stamped with a date of October 27, 1914; Figure 7). Again, the zone of deformation is only about 1 to 2 m wide. The scarp is coincident with the location of resistant sandstone Bed C, which is traceable into the southern residential area and wooded areas north of Atoka (Figure 4 and 5). Most of the deformation reflects down-to-the-east displacement, ranging from several centimeters to as many as 40 centimeters.

The damage to residential foundations within the northeastern residential area mainly showed cracking and tilting. In an initial 1997 visit, we visited a house at 301 Montana Avenue (locality 4; Figure 5) and noted that the foundation was severely deformed and appeared to be rotated in a counterclockwise direction. The owner noted that the doorframes and windows underwent constant deformation, and had installed steel cables across the basement in an attempt to resist the ongoing foundation damage. By the time we visited Atoka for this investigation in 2005, the house had been torn down and the lot was abandoned. Discussions with local residents acknowledged that a primary reason for the abandonment (and razing) of the house was the substantial damage to the stone foundation as a result of northeastward slope movement. Additionally, discussions with residents documented that homeowners between Court Street, A Street, California Avenue, and Montana Avenue, are aware that their homes are moving down

slope to the northeast. Several residents had installed "Perma-Jacks" (or were considering doing so), in attempts to restrict the northeasterly movement of foundations. Other residents mentioned that they had felt movement of the house structures (in the absence of earthquakes), and had felt movement at certain times of the day, probably as a result of fluctuations in temperature or soil moisture. One resident stated that her doors would close only at night, and were out-of-plumb during daytime. Colloquially, others stated that a few houses experience slight eastward, and then westward, tilting through the day, and that this is sometimes used to frighten children into believing that the houses are haunted.

4.1.2 Southern Residential Atoka

Field observations in the southern residential area indicate a lack of cracking and deformation as compared to the northeastern residential area. A resistant sandstone/conglomerate Bed C (Figure 5) crops out directly east of South Montana Avenue within this area, and forms a local, linear topographic ridge. Knechtel and Rothrock (1935) documented several broken water pipes along the alignment of Bed C at Third and Fourth Street, although we observed no evidence of significant surface cracking or deformation on Third and Fourth streets. Our field reconnaissance included observations along most of the paved roadways and curbs in this area, including locality 39, and demonstrated an absence of deformation of cultural features. The deformation observed in the northeastern residential area does not continue southward into the southern part of residential Atoka, and the damage to the water lines noted by Knechtel and Rothrock (1935) appear to be a result of differential weathering of the two distinct lithologies, and shrink-swell in the associated soils. We interpret this section to be relatively stable and note that the damage observed by Knechtel and Rothrock (1935) is constrained to the contact between the resistant sandstone-conglomerate Bed C and the shale strata bordering the eastern side of Bed C.

4.1.3 Northwestern Residential Atoka

We visited five locations within the northwestern area, including two identified by Knechtel and Rothrock (1935; localities KR3 and KR4). We observed a tilted retaining wall at locality 37, and no deformation at localities 38 and 40. Also present is a subtle east-facing scarp formed by a sandstone-conglomerate outcrop along South Minnesota Avenue (Bed B, Figure 5). Knechtel and Rothrock (1935) observed cracking of a brick schoolhouse at locality KR3, and a severely damaged foundation at locality KR4. Additionally, a zone of cracks is present along the crest of the sandstone ridge, at the Atoka High School and stadium west of Minnesota Avenue between Second and Third Streets (Figure 5). The school is along strike from a deformed building noted by Knechtel and Rothrock (1935) at locality KR3 (Figure 5). These workers noted that deformation at the school includes as much as 6 cm of left-lateral offset of

concrete pathways, 2 cm of left-lateral offset of building walls, out-of-plumb doorways, and localized cracks in the concrete walls of the stadium bleachers. However, our observations did not confirm the presence of consistent left-lateral offset of walls or pathways, although there is some deformation that is related to large trees along the sidewalk in front of the school, along South Minnesota Street (Figure 5).

We interpret the northwestern residential area to be relatively stable, and believe the deformation observed at the stadium and at adjacent points 37 and KR3 is likely a result of differential settlement, weathering and soil processes, or minor downslope movement. These features are distributed within the northwestern residential area, and are not laterally continuous, suggesting that they are related to non-tectonic mechanisms such as soil shrink-swell, localized slope movement, and/or differential settlement.

4.2 Sandstone Ridge in Northern Residential Atoka

The field reconnaissance in the northern part of the Atoka area consisted of two separate areas of investigation. One traced the resistant sandstone Bed C (and associated topographic escarpment) from residential Atoka into the wooded area north of residential Atoka, and the other investigated potential liquefaction features in open fields northeast of residential Atoka. We followed the outcrop of resistant Bed B from North Montana Avenue to its intersection with Liberty Road (Figure 4). As with our observations of Beds A, B, and C within the residential parts of Atoka, we noted that the scarp is a result of differential weathering of the resistant sandstone-conglomerate Bed C as compared to adjacent shale strata to the west and east. Based on our reconnaissance, there is no evidence of surface deformation of late Quaternary alluvial deposits along the northward projection of the scarp into the Muddy Boggy Creek valley (Figure 4).

Our analysis of aerial photography identified some features that suggest the possibility of liquefaction-related deposits within the alluviated valley to the northeast of residential Atoka (Figure 2). We analyzed black-and-white aerial photographs taken in 1965 of Atoka and the Muddy Boggy Creek valley north of town (Figure 2). Interpretation of these stereo-paired photographs show that alluviated areas within the Muddy Boggy Creek valley locally contain light-colored, circular patterns that are similar to surface sand blows present in the alluviated Mississippi River Valley (Obermeier, 1988). Field and aerial reconnaissance showed an absence of geologic evidence of sand blows in these areas. In addition, reconnaissance of 3-m-high exposures along Muddy Boggy Creek directly downstream of the railroad bridge (Figure 4) showed undeformed, sandy alluvial deposits and a lack of liquefaction-related features. The quasi-circular features interpreted on the 1965 aerial photography are a result of some process other than liquefaction, and probably are related to agricultural practices. Lastly, our aerial reconnaissance also

included review of the western margin of the OFFZ and the northern continuation of the Choctaw (Pine Mountain) fault from Atoka northward to Stringtown. This area contains many curvilinear features associated with the different erosional resistances of sandstone and shale strata; however, no features suggestive of late Quaternary surface deformation in alluvial or colluvial sediments were observed. Based on all these data, we conclude that there is no evidence to support late Quaternary displacement on the southwestern margin of the OFFZ.

4.3 Sandstone Ridge in Southern Residential Atoka

For completeness, we also investigated a topographic scarp trending southwest from West Sixth Street (Figures 3 and 4), in order to identify possible evidence of deformation of late Quaternary deposits. Field reconnaissance demonstrates that the scarp is directly associated with sandstone Bed A (Figure 5), and ranges in height from 1 to 3 meters. This area contains few cultural features, and vegetation has been removed for ranching or other land uses. (Figure 9). From West Sixth Street southward to Highway 7 (Figure 4), the scarp is associated with the resistant sandstone bed on the east, and less resistant shale lithology on the west. Changes in the orientation of the scarp coincide with slight changes in the strike of the sandstone bed, and there is no evidence of a scarp developed in surficial colluvium or alluvium. We also conducted a limited field reconnaissance in the area south of Highway 7, along several east-west paved and unpaved country roads. We observed no geologic or geomorphic evidence of recent or late Quaternary fault displacement in this area.

Lastly, the aerial reconnaissance over Atoka and analysis of aerial photography showed an absence of fault-related geomorphic features in the southern residential area, as well as areas south of Atoka that are underlain by Cretaceous coastal plain sediments (Hendricks et al., 1947). The land use of this area is generally open range or agricultural, and fault-related topographic scarps (if present) would likely be perceptible. On the basis of these observations, we concur with previous geologic maps showing that the OFFZ does not displace the Cretaceous bedrock in the area directly south of Atoka (Figure 2).

5.0 DISCUSSION

This research documents the presence of historic surficial deformation in the vicinity of the town of Atoka that may be related to tectonic or non-tectonic processes (Knechtel and Rothrock, 1935). Because differentiating between tectonic and non-tectonic features often is based on judgments formed from incomplete and disparate data sets, qualitative criteria have been developed to help judge the origin of possible earthquake-related features and differentiate between features formed by tectonic and non-tectonic processes (NUREG/CR-5503; Hanson et al., 1999).

Based on our observations, we compiled evidence for and against each mechanism presented in NUREG/CR-5503, and include our findings as Table 1. The field evidence overwhelmingly supports only one or two possible mechanisms to explain the deformation within Atoka: "Triggered Slip/Creep" and "Landslide". Other mechanisms are easily ruled out based on lack of supporting evidence, as summarized in Table 1. Both triggered slip/creep and landsliding are nonseismogenic processes, although active fault creep clearly is a tectonic process that may indicate a possible capable tectonic seismic source. Although there is evidence supporting both of these mechanisms, application of the criteria provided in NUREG/CR-5503 suggests that the evidence is more robust for a landslide origin for the deformation features in Atoka.

The key observations supporting this interpretation are as follows:

- slip is not laterally consistent – some areas have large offsets, while directly adjacent areas are un-deformed;
- deformation is not confined solely to the north-south trending resistant sandstone/conglomerate beds, but are distributed down slope to the east;
- the dominant component of slip observed within residential Atoka is down-to-east normal motion and is primarily left-lateral along North Montana and North California Avenues;
- deformation is episodic, with slip occurring at different times in different areas; and
- deformation is mainly notable within residential Atoka between West Second Street and West A Street, with little to no evidence of disturbance to the north and south of residential Atoka.

Table 1. Evidence for and against possible deformation mechanisms, Ouachita Frontal Fault Zone, Atoka, Oklahoma, based on criteria presented by Hanson et al. (1999).

Seismogenic Tectonic Features			
	Evidence For	**Evidence Against**	**Possible Condition?**
Normal Fault	Topographic scarp extends through parts of residential Atoka; sense of vertical displacement unknown	No evidence of coseismic surface rupture; no deformation of Cretaceous rocks south of Atoka	No
Reverse Fault	Topographic scarp extends through parts of residential Atoka; sense of vertical displacement unknown	No evidence of coseismic surface rupture; no deformation of Cretaceous rocks south of Atoka	No
Strike Slip Fault	Left lateral offset documented in several locations along North Montana Avenue.	No evidence of coseismic surface rupture; no deformation of Cretaceous rocks south of Atoka	No

Non-Seismogenic Tectonic Features			
	Evidence For	**Evidence Against**	**Possible Condition?**
Triggered Slip or Fault Creep	Cultural features (buildings and piping) have been continuously deformed since they were built in the 1910's and-1920's; damaged buildings such as 301 North Montana Avenue show deformation consistent with possible creep.	Deformation is not discrete, it occurs both on and away from lithologically resistant beds; slip distances are markedly different in laterally adjacent areas (order of magnitude differences); and there is no noticeable deformation occurring to the north and south of residential Atoka.	Yes
Secondary Tectonic Fault	None.	Geometry of mapped faults in the surrounding area are not consistent with compressional or extensional setting in Atoka.	No

Non-Seismogenic Non-tectonic Features			
	Evidence For	**Evidence Against**	**Possible Condition?**
Land Slide	Slip is not laterally consistent – some areas have large offsets, while directly adjacent areas are undeformed; deformation is not confined solely to north-south trending resistant sandstone/conglomerate beds, but rather distributed down slope to the east; the dominant component of slip observed within residential Atoka is down-to-east normal motion (down gradient) and is primarily along North Montana and North California Avenues; deformation is episodic, with slip occurring at different times in different areas; deformation is mainly notable within residential Atoka between West Second Street and West A Street, with little to no evidence of disturbance to the north or south of residential Atoka; additionally the slides are in a relatively weak shale layer.	It is difficult to constrain/define the limits of the land slide or slides (subtle toe and headscarp) due to vegetation and human disturbance; slope gradient is subtle (approximately 6% grade); defformation is observed in areas away from the zone of slope failure.	Yes
Sackungen	None.	Scarp features are due to lithology; slope gradients are not steep enough; and the observed deformation pattern is not consistent with sackungen.	No
Gravity Structures	Area is underlain by shale.	Tectonic setting is compressional rather than extensional; hydrologic pressures are not high.	No
Stress Release	None.	No mining or large scale excavations are documented in the vicinity of observed deformation.	No
Glaciation	None.	Glaciation did not extend into southern Oklahoma.	No
Subsidence/Collapse Feature	None.	No extensive water or petroleum extraction documented in the immediate area; no karst prone strata in area.	No
Volcanic Related Deformation	None.	No documented volcanic activity in the immediate area.	No

The observations in support of active fault creep associated with these features in Atoka (Knechtel and Rothrock, 1935) are similar to features along the creeping Calaveras and Hayward faults in the San Francisco Bay area (Hirschfeld et al., 1999; Galehouse and Lienkaemper, 2003). However, the deformed residential foundations, sidewalks, and gutters within Atoka are along the western flank of a small, north-trending valley (Figure 3), and the field evidence also supports an interpretation that these are related to northeasterly slope movement. The key arguments against Triggered Slip/Creep are that the deformation is not discrete, and it occurs both on and away from the resistant beds A, B, and C. Also, over short distances, there is at least one order of magnitude difference in the amount of deformation. Lastly, there is no noticeable deformation of features located north and south of residential Atoka, and there is no geologic or geomorphic evidence of faulting of Cretaceous bedrock overlying the fault system south of Atoka.

We conclude that most deformation observed within the town of Atoka is a result of local landslide deformation, although some of this deformation may also be a result of differential weathering between the shale and adjacent sandstone/conglomerate beds. Based on topography and the pattern of deformation in residential Atoka, a reasonable interpretation is that the deformation is a result of multiple small slope failures, rather than a large coherent rotational slide or debris flow (Figure 10). Deformation within Atoka is locally variable, with some houses, curbs and sidewalks exhibiting substantial deformation, including translation and rotation, whereas others showing lesser amounts. Qualitatively, the degree of deformation varies inconsistently throughout the area between Montana Avenue and California Avenue (from west to east), as well as between First Street and A Street (from south to north), which suggests a series of small, partially independent slide masses. In general, however, the areas characterized by locally steep slopes commonly contain areas with greater damage (i.e., the destroyed house on the corner of Montana Avenue and A Street). The left-lateral component of deformation noted by Knechtel and Rothrock (1935), as also expressed in several features observed during our reconnaissance, is explained by a northeasterly direction of slide movement. This imposes a lateral component of movement relative to the resistant (and apparently immobile) near-vertical sandstone beds that comprise the upper part of the residential area of Atoka. The consistent left-lateral component of movement identified by Knechtel and Rothrock (1935) reflects northeasterly slide movement and separation from the more northerly striking resistant sandstone beds. Lastly, the overall distribution of substantial deformation in Atoka is limited primarily to the areas that slope northeasterly away from the resistant sandstone ridges; the areas in the southern part of town that slope southeast or south do not contain substantial amounts of active deformation. All other observations of deformation can most easily be explained by either differential settlement of vintage buildings with poorly built foundations or by shrink-swell processes that differ

between areas underlain by sandstone and shale bedrock. Thus, all available field observations are consistent with, and strongly suggestive of, a landslide origin for the deformation features in residential Atoka.

6.0 CONCLUSIONS

Differentiating between tectonic and non-tectonic deformation requires an understanding of the regional geologic and tectonic setting, the physical geologic and geomorphic expression of the features potentially related to tectonic processes, and the local geologic and tectonic characteristics. This investigation provides evidence that the deformation within residential Atoka is most likely a result of non-tectonic processes, involving primarily local shallow landsliding and secondarily differential weathering or soil processes related to lithologic substrata. Using the criteria provided in NUREG/CR-5503 (Hanson et al., 1999) as an investigative tool, we conclude that the historic deformation within residential Atoka is a result of landsliding and weathering processes.

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FIGURES

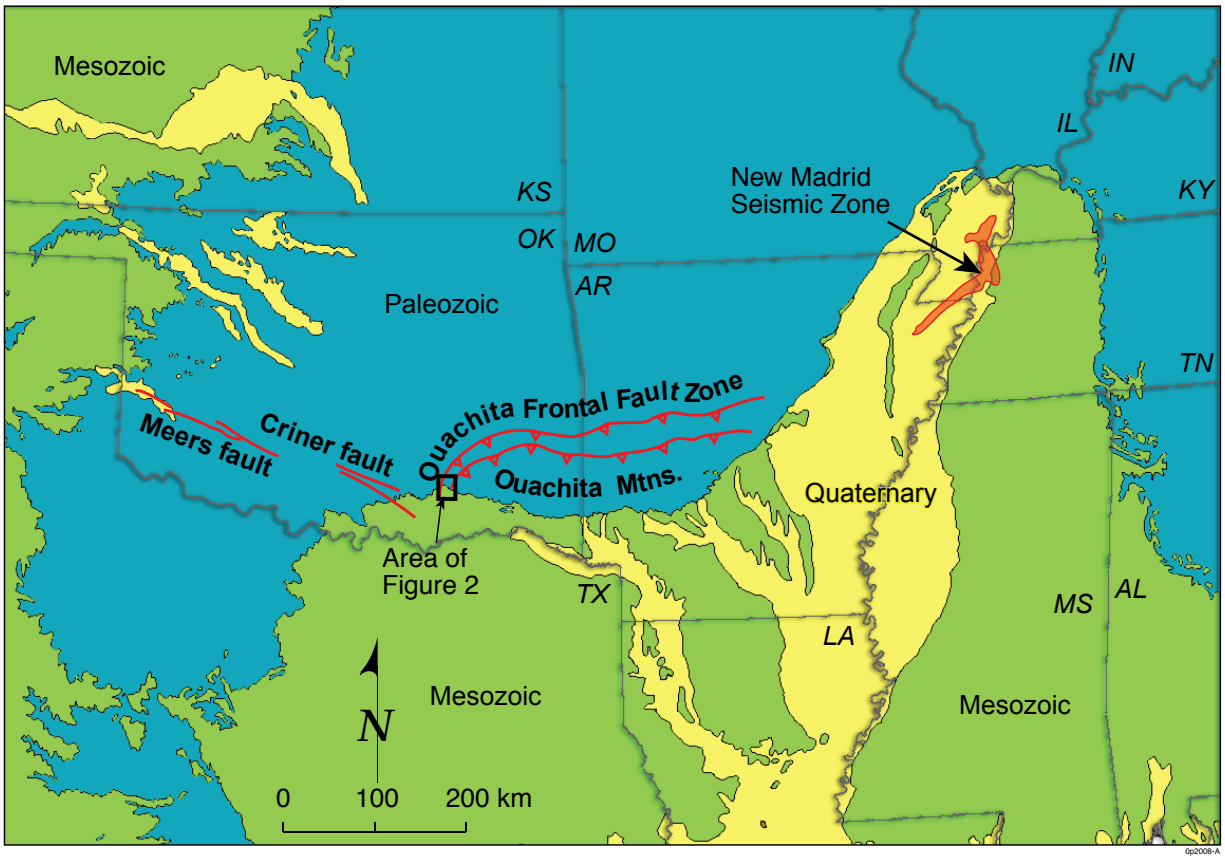


Figure 1a. Regional tectonic setting showing relationship between the Ouachita Frontal Fault Zone, the Meers-Criner fault, and the New Madrid Seismic Zone. The Meers fault and the New Madrid Seismic Zone are the two seismic sources in the central United states with documented evidence of late Holocene tectonic surface-deformation.

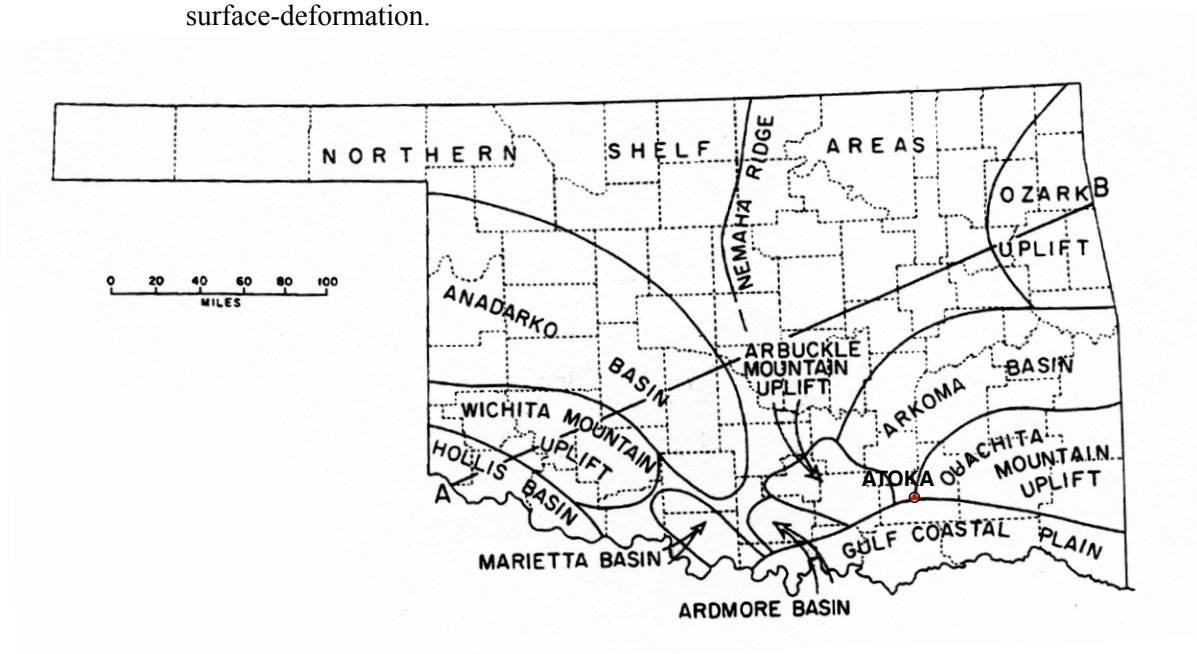


Figure 1b. Major tectonic features in Oklahoma (from Luza and Lawson, 1981)

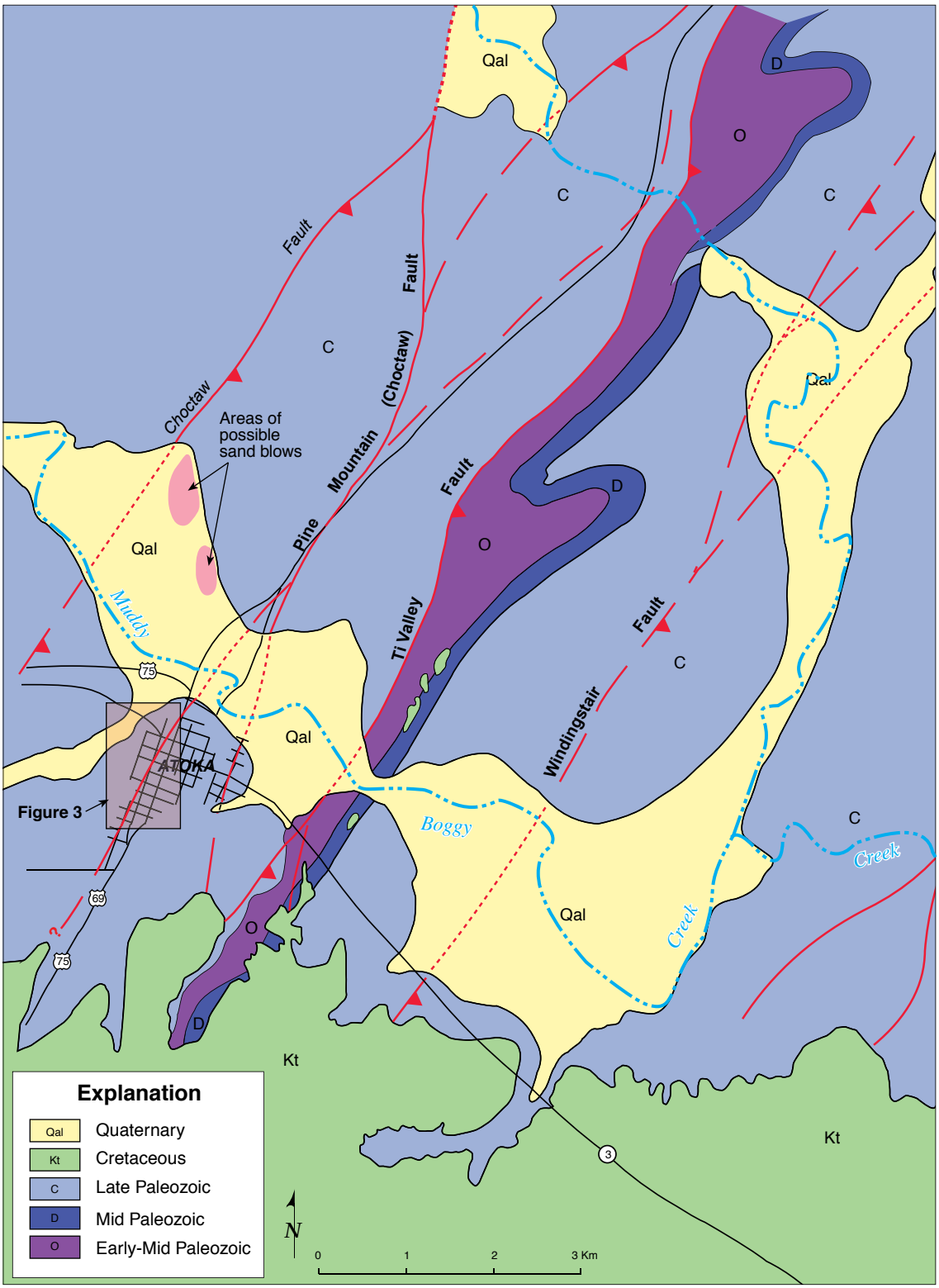


Figure 2. Generalized geologic map of the Atoka region, southeastern Oklahoma (after Hendricks et al., 1947; and Knechtel and Rothrock, 1935), this map shows the primary fault strands within the Ouachita Frontal Fault zone.

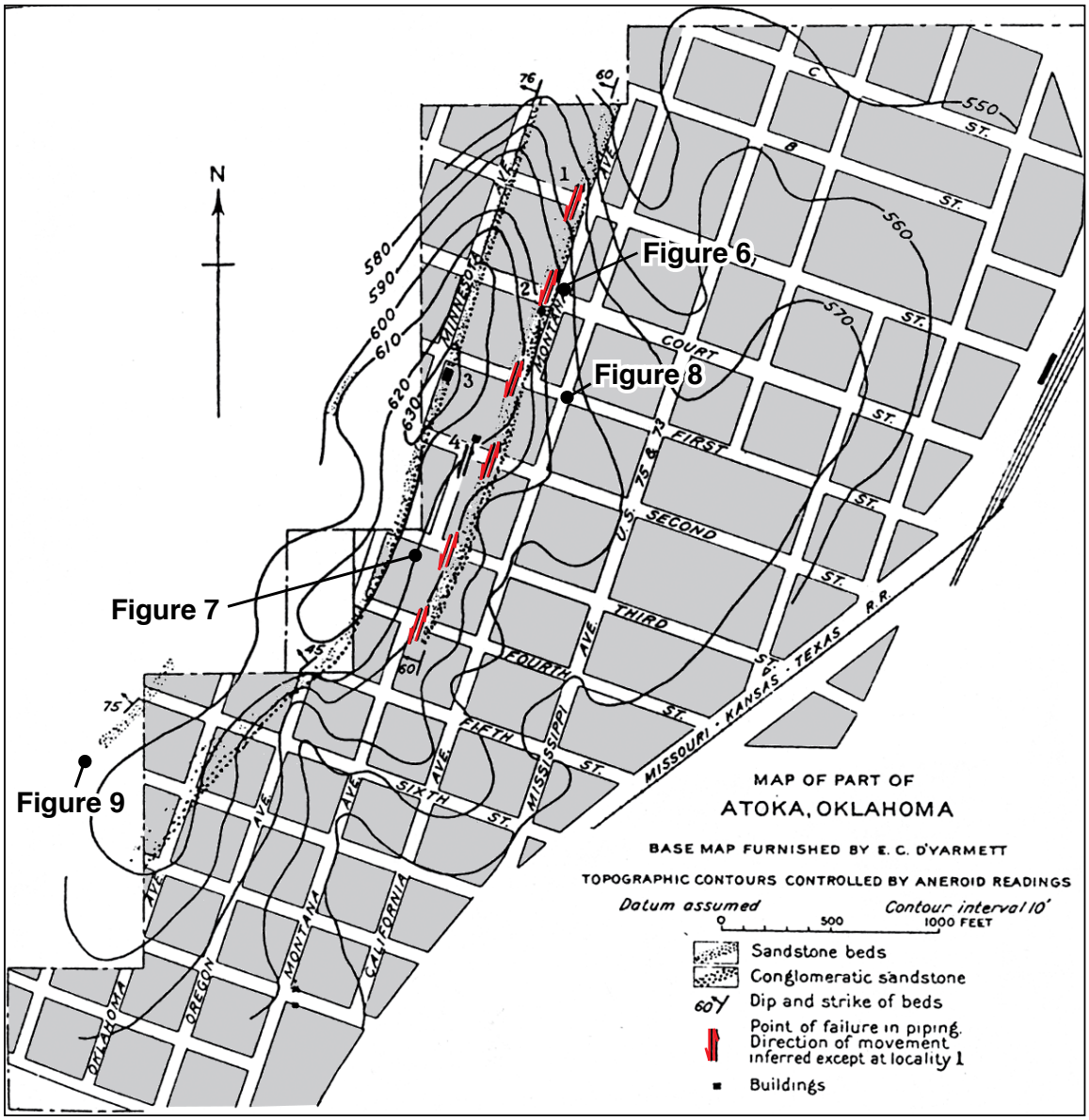
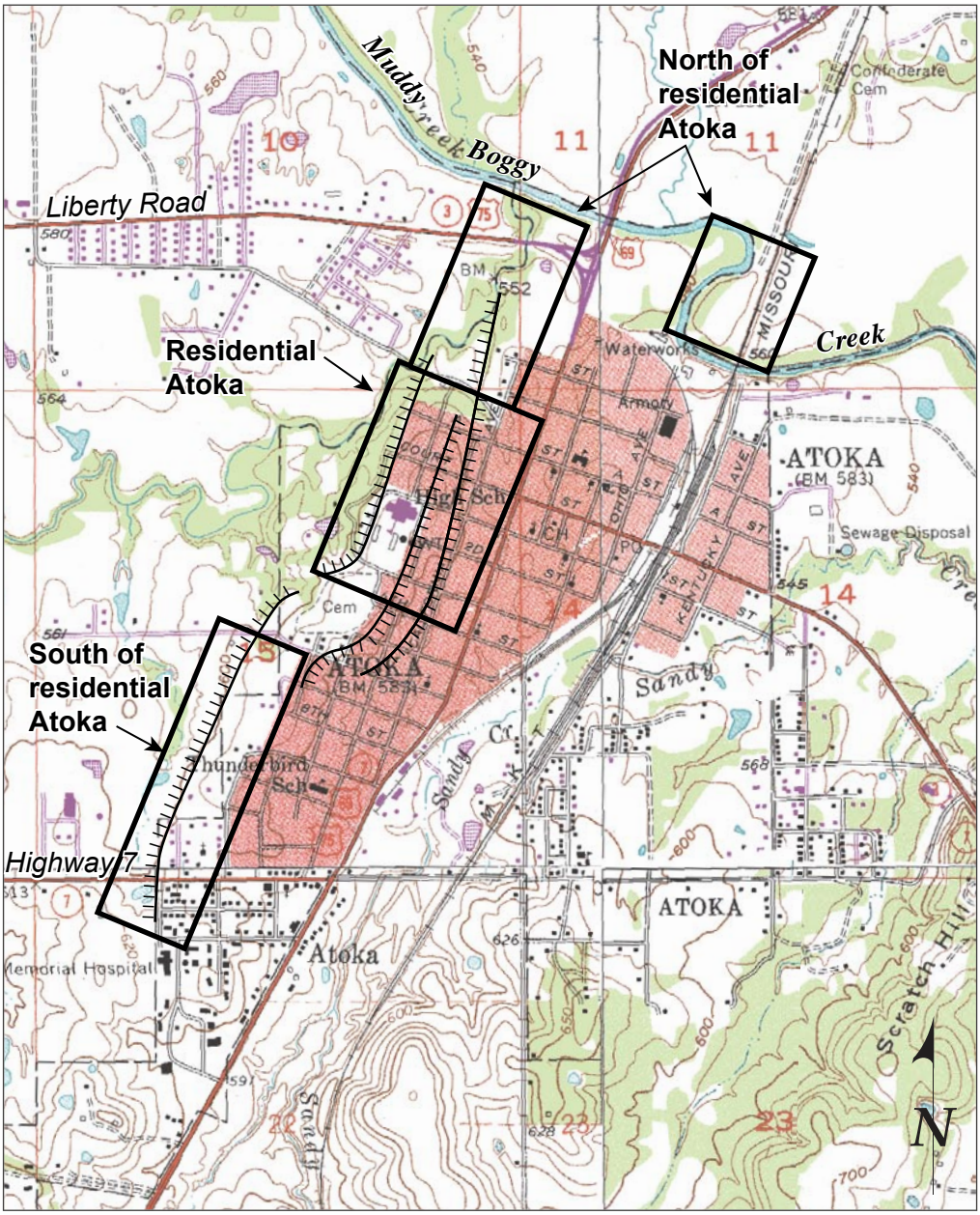


Figure 3. Map of part of Atoka, Oklahoma, showing locations of pipeline failures and direction of inferred fault movement (after Knechtel and Rothrock, 1935). Locations of photographs taken in 1997 are shown (Figures 6 and 7).



Base map from USGS quadrangles:
Lehigh, Stringtown, Tushka, Bruno.

0 1 mile

0 1 kilometer

Explanation

Scarp related to resistant bedrock

Figure 4. Location map of exploration areas within Atoka, Oklahoma.

Figure 5. Oblique aerial photograph showing exploration points.

A)

B)

Figure 6. Photographs of sidewalk and curb deformation at corner of Court Street and Montana Avenue. A) Lookingwest northwest along sidewalk on Court Street, Showing left lateral offset and Down-to-the-west displacement. B) looking north-northeast at scarp in sidewalk and deformation in stone curb along Court Street.

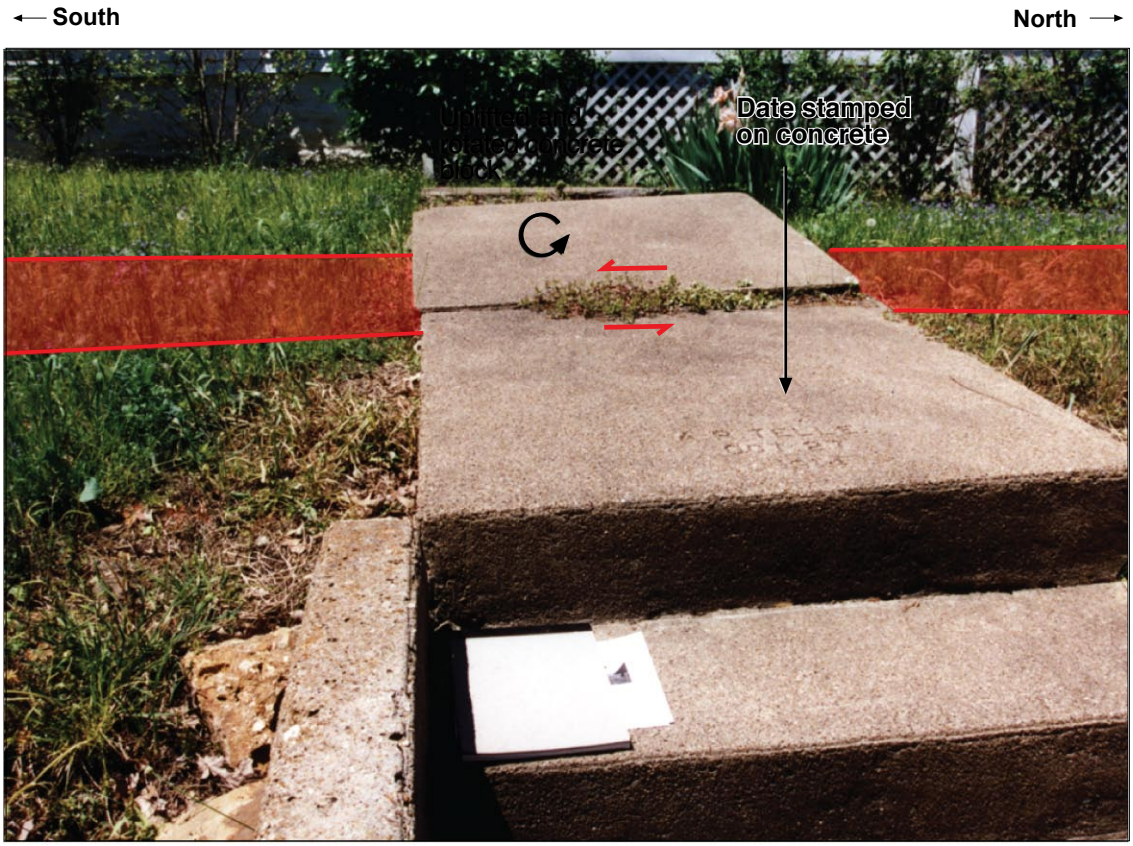


Figure 7. Photograph looking west-northwest along path orthogonal to Montana Avenue, showing left-lateral offset, uplift and rotation of concrete blocks. Concrete is stamped with date October 27, 1914. Measurement made on April 28, 1997, shows a total 14 cm of lateral offset across the entire path between wooden fence in background and steps in foreground.

Figure 8. Photograph looking west along West First street, from the corner of California Avenue.

Figure 9. Photograph looking west-northwest of lithologic scarp in southern Atoka.

Figure 10. Landslide interpretation map.