THE NEMAHA TREND-A SYSTEM OF COMPRESSIONAL THRUST-FOLD, STRIKE-SLIP STRUCTURAL FEATURES IN KANSAS AND OKLAHOMA, PART 1

S. Parker Gay, Jr., Applied Geophysics, Inc., Salt Lake City, Utah.

ABSTRACT

Much has been written about the buried Nemaha uplift in Kansas and Oklahoma since drillers and geologists first became aware of it from oil-well drilling in the early years of the twentieth century. It has been described as extensional, compressional, and strike-slip. In this paper I will present data to show that the Nemaha was formed by compressional or thrust faulting that is rooted deep within the Precambrian crust and extended in listric fashion to the ground surface coincident with the Humboldt fault zone, or east-bounding fault. Compressional effects observed from well data and seismic surveys do not permit an extensional origin.

Two additional effects occurred simultaneously with the thrusting. A back thrust evidently formed locally in a manner similar to that mapped in many compressional environments, for example the Front Range of Colorado (Jacob, 1983), the Uinta Mountains in Utah (Stone, 1993b), and the Wichita Mountains in Oklahoma (Brewer and others, 1983), essentially making the Nemaha uplift a V-shaped "pop-up" block in many places, thus explaining the up-to-the-east fault or fold on the west. A strong component of strike-slip motion resulted in end-closures of structures along the uplift including many petroleum traps, plus additional complexities that have made the Nemaha system difficult to interpret. Small, near-surface normal faults indicate that extension played a minor role in post-Permian time.

The main movement of the Nemaha system began in early Pennsylvanian time or perhaps latest Mississippian, and extended to (or into) Permian time, coincident with the Alleghenian orogeny on the eastern seaboard 800 mi (1,300 km) to the east. Earlier periods of lesser movement occurred in mid-Ordovician and mid-Devonian time, coincident with the less extensive Taconic and Acadian orogenies of the eastern U.S. The relationship in time between these compressional events on the eastern seaboard and the compressional Nemaha system is clear.

Introduction

Merriam (1963) stated that the Nemaha uplift in eastern Kansas is "probably the most famous of all Kansas structures." He gives a good overall description and states that it is "...faulted along the east side in several areas, and seemingly there are both high-angle and reverse faults." Earlier descriptions of the Nemaha uplift are presented in the regional discussions of Lee (1943) sixty years ago; and Jewett (1951) and are similar to, and predate, Merriam's. More recently, Luza and Lawson (1983), in their comprehensive study of the Oklahoma part of the Nemaha, stress the presence of "near-vertical faults on the east side that are downthrown to the east", implying normal faulting. They were evidently unaware of the many well-documented reverse faults in their study area. Serpa, Setzer, and Brown (1989) in their discussion of the Nemaha in northeastern Kansas likewise ignore several reverse faults shown in published studies in that area and state: "the inferred geometry of the Humboldt fault zone...moderately east-dipping...is extensional." U.S.G.S. geologists Dolton and Finn (1989), in another comprehensive study of the Nemaha, mention "upwarping" and "uplift", but do not discuss compression or shortening. Berendsen and Blair (1992) take a new tack and attribute the uplift to wrench faulting and state that the "entire fold-fault system was subjected to a sinistral [left-lateral] strike-slip motion in the Pennsylvanian", which is correct, but which is only part of the story.

We are thus confronted with a potpourri of ideas on the origin of the Nemaha uplift. For the present study I have followed the conclusion prevalent among many Oklahoma and Kansas petroleum industry geologists I have known, that the Nemaha system has a compressional origin. I have researched the literature extensively and have also solicited unpublished occurrences of repeated section and reverse faulting from geologists and geophysicists. The research, at this date, has yielded more than 29 separate localities of documented reverse faulting on the Nemaha, from both subsurface and seismic data, and from published and unpublished sources, extending from the Kansas-Nebraska line to its southernmost limit south of the Oklahoma City oil field; a distance of about 400 mi (650 km). Cross-sections or maps of many of these are presented herein. In a previous paper Gay (1999) included only a limited number of the examples. Many of the examples I show are on structures offset from, but parallel to, the Nemaha uplift proper; structures which had a similar structural history and are part of what is properly called the Nemaha structural system in Kansas and Oklahoma.

Because of the many examples of compressional tectonics that occur on the Nemaha system, extending from its northernmost to its southernmost limits, my conclusion is that the Nemaha system formed as a result of compression. To properly understand this compressional regime I turn to the Rocky Mountains, where in the last 10 to 15 years geologists have deciphered the geometry of the faulting in a similar compressional environment. Most of the main stress-relieving, crustal-shortening faults in the Rockies are listric thrust faults that have gentle dips deep within the basement, steeper dips near the basement-sedimentary section interface, and are vertical or near-vertical near the surface (Figs.1 and 2). This latter characteristic should alleviate the doubt in the minds of many competent Kansas and Oklahoma geologists who are convinced that the observed vertical or steeply dipping faults *continue to be vertical or steeply dipping to great depths* and are thus necessarily normal faults.

Also, confusion has perhaps resulted from the idea that some reverse faults in the Nemaha system dip the "wrong" way; for example, the long-known east-dipping reverse fault at Voshell field in McPherson County, Kansas (Bunte and Fortier, 1941). Under strain theory, in a compressional system there is no preferred direction of thrusting or reverse faulting. It can be either east-directed or west-directed. There are many cases of this in the Rockies. For example, both the Big Horn and Hoback basins in Wyoming experienced major north-south trending thrusts converging on them from east and west at the same time.

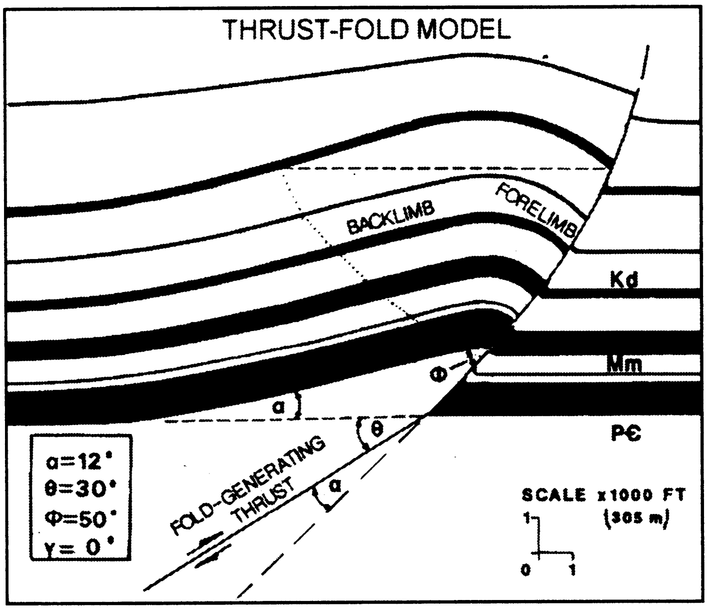

Figure 1. *This thrust-fold model for Rocky Mountain structures, unlike earlier models, is not theoretical. It is documented by oil and gas industry seismic and well data for innumerable anticlines in the region. From Stone, 1993a. Reprinted by permission of the GSA whose permission is required for further use.*

Additional features of compressional systems in the Rockies that undoubtedly apply equally well to the Nemaha system are back thrusts, late relaxation normal faults, and crustal depression resulting from tectonic loading. The conclusion is that the Nemaha was uplifted mainly in late Mississippian-early Pennsylvanian time, contemporaneous with the elevation of the Ancestral Rocky Mountains in Colorado (Ye and others, 1996) and the Alleghenian orogeny to the east, and thus would have been subjected to the same massive compressional forces. Two earlier periods of lesser compressional movement in the Nemaha system have been noted, and these also coincided with thrusting in the Appalachians to the east. Some Mid-continent geologists believe the Nemaha system is unique and dissimilar to Rocky Mountain geology or Appalachian geology, but geological principles apply equally throughout the world.

There has likewise been an apparent large amount of strike-slip movement on the Nemaha system. This has been discussed by Blair and Berendsen (1988), Berendsen and Blair (1992), Davis (1986), Fenster and Trapp (1982), and McBee (1999). The strike-slip movement is believed to be contemporaneous with the later stages of thrusting. This movement created, or accentuated, the cross-folding that forms traps in many oil fields.

Another apparent misconception of the origin of the Nemaha system is that it is somehow related to the 1.1 Ga old Proterozoic midcontinent rift system (MCRS). This system lays 25 to 40 miles (40 to 60 km) west of the Nemaha and is not parallel to it; it is more than 600 million years older and was formed under a distinctly different structural regime (McBee, 1999). There may have been relict weakness zones left by the MCRS that were later reactivated in Paleozoic time, but I am not aware of any specific examples and I have not seen this on the magnetic data.

Nebraska and Kansas Examples of Reverse Faulting/Repeat Section on the Nemaha System

The locations of reverse faulting, both published and unpublished, reported along the Nemaha system in Nebraska and Kansas appear on the map of Kansas (Fig. 3). A list of these examples is shown in Table 1.

A very illustrative cross-section of the Nemaha uplift was published three decades ago by Carlson (1971) of the Nebraska Geological Survey (Fig.4). This cross-section may be seen to be similar to the classic asymmetric (compressional) folds of Figures 1 and 2, although with more vertical exaggeration.

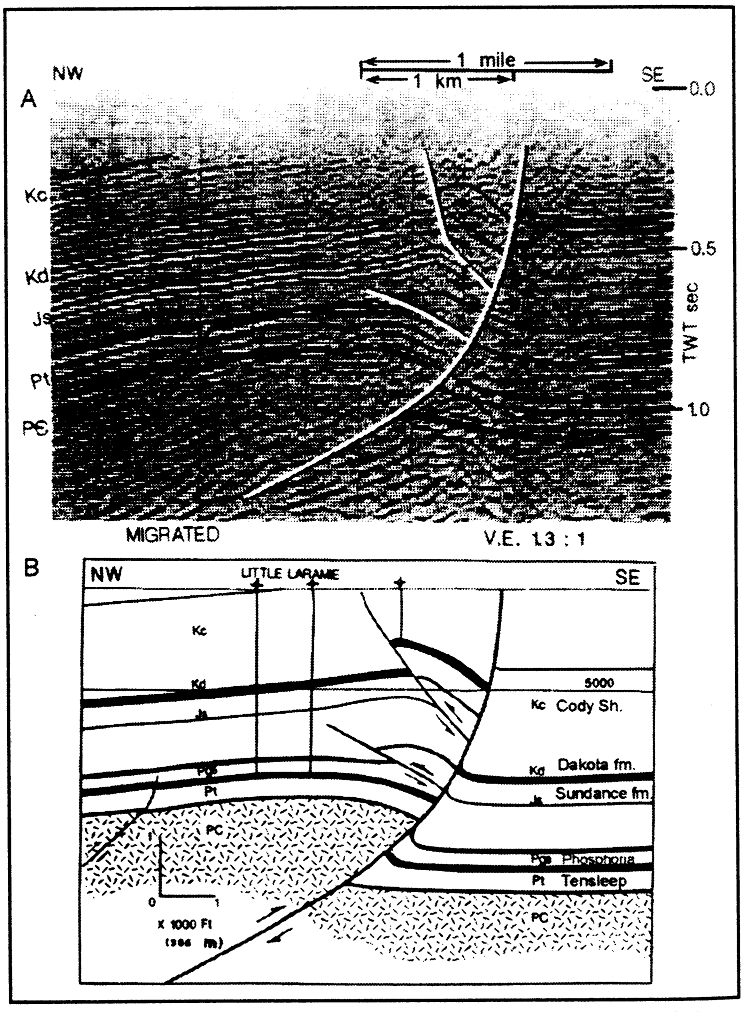

Figure 2. *One of many seismic lines that support the geological model of Figure 1. This seismic line is across the Little Laramie anticline in south Laramie Basin, Wyoming. Note the near-vertical attitude of the fault near the ground surface and the shallow dip at depth. Also, note the back thrusts on the NW side of the principal thrust. From Stone, 1993a. Reprinted by permission of the GSA whose permission is required for further use.*

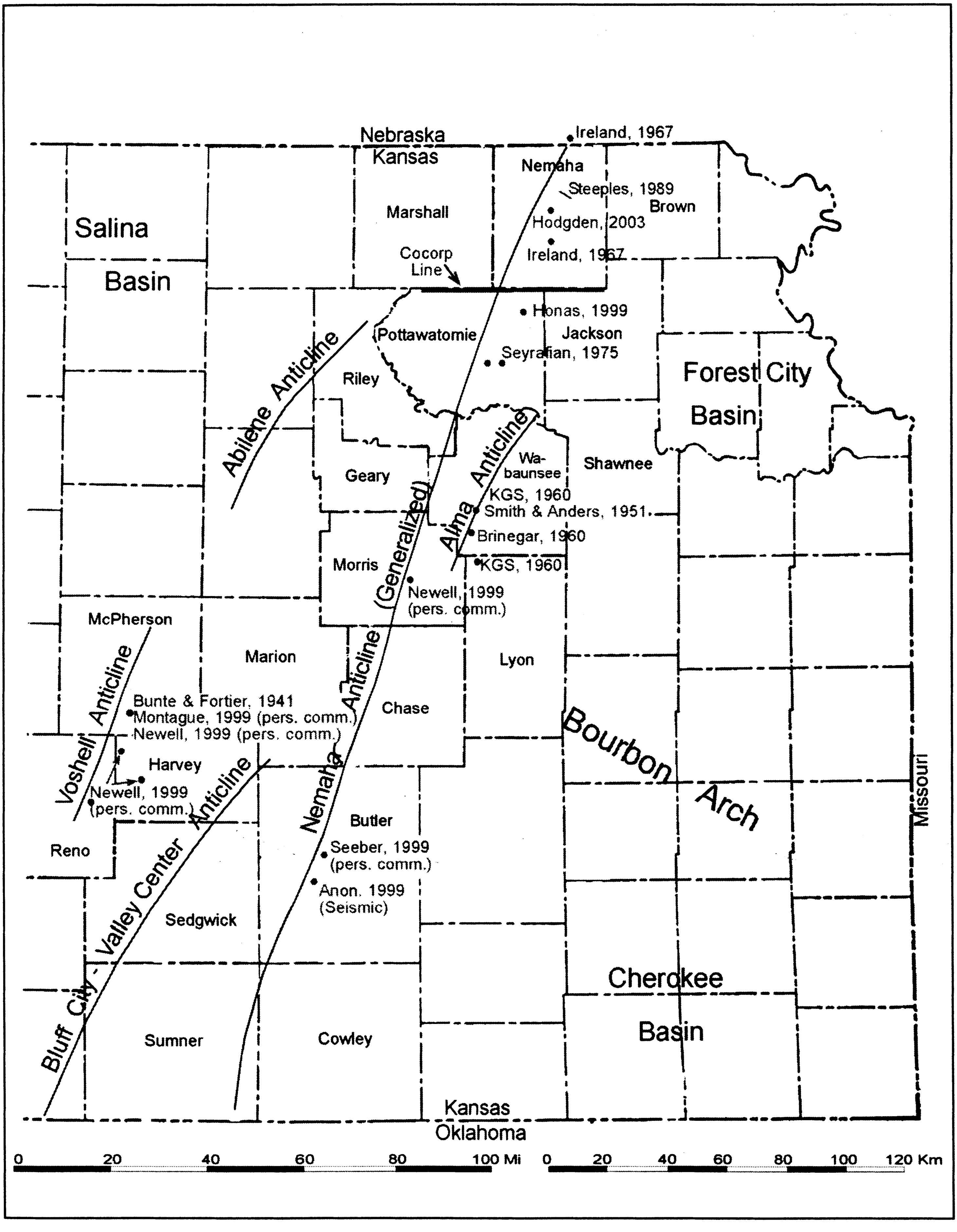

Figure 3. *Map of principal anticlinal structures of the Nemaha System of eastern Kansas showing locations where reverse faulting has been demonstrated. See Table 1 for a list of the examples.*

Table 1. Examples of reverse faulting along the Nemaha System in Nebraska and Kansas, listed from North to South. See Figure 3 for map location.

	Source	Location	Comments
		Nebraska	
1.	Ireland, 1967	9–T1N–R14E	This was an early use of forams to decipher stratigraphy.
		Kansas	
2.	Steeples, 1989	3–T3S–R14E	The seismic profile here shows a reverse fault but it was labeled "reverse or vertical."
3.	Hodgden, 2003 (Pers. comm.)	T1S-4S- R13E	"Ten to twelve reverse faults have been mapped with seismic in this area."
4.	Ireland, 1967	25–T3S–R13E	See comment for No. 1, above.
5.	Honas, 1999 (Pers. comm.)	6–T7S–R12E	#1 Handley well has repeated section.
6.	Seyrafian, 1978	10–T8S–R11E	Two reverse faults in M. S. thesis. One of these was rediscovered by Honas (1999).
7.	Smith & Anders, 1951; Anon. 1, 1960	4–T14S–R10E	Davis Ranch field – One reverse fault intersection mapped in KGS write-up, two others mentioned in Smith & Anders.
8.	Brinegar, 1960	29–T14S–R 10E	Ashburn field – Reverse fault was described; cross-section was redrawn.
9.	Dillard & Feige, 1998 (Pers Comm.) Anon. 2, 1960	T15S–R9E	John Creek field – 1982 seismic showed reverse fault.
10.	Newell, 1999 (Pers. comm.)	18–T16S–R8E	"2 wells show repeated section", including #1 Bosch 'B' well.
11.	Bunte & Fortier, 1941	9–T21S–R3W	Voshell field – Earliest cross-section published of repeated section on Nemaha. Two additional wells mentioned in 1933, two more in 1999.
12.	Newell, 1999 (Pers, comm.)	12–T22S–R3W	Murty No. 1 well.
13.	Newell, 1999 (Pers, comm.)	18–T22S–R3W	5 wells in Hollow-Nikkel field show repeated section.
14.	Newell, 1999 (Pers, comm.)	17–T24S–R4W	Fairchild No. 1 Collins well in Burton field shows repeated section.
15.	Seeber, 1999 (Pers. comm.)	3–T26S–R3E	1982 well in El Dorado field.
16.	Anon., 1999 (Pers comm.)	34–T26S–R4E & 3–T27S–R4E	Defined by a seismic line north of North Augusta field.

For the examples of compression, I will start on the north and proceed south. The farthest north example is located in Richardson County, Nebraska, just north of the Kansas line (Fig. 3) and is from a 1967 paper by H. A. Ireland, then Professor of Geology at the University of Kansas. Ireland, a self-taught expert on foraminifera (with publications dating back to 1939), wrote this paper to illustrate that Paleozoic strata could be definitively identified with forams, and that this knowledge would, in turn, serve to identify faults, including reverse faults. His Nebraska cross-section appears as Figure 5, and another cross-section in Nemaha County, Kansas, 13 miles south, is shown as Figure 6.

A shallow high-resolution seismic line (Steeples, 1989), presented a clear image of a reverse fault in northeastern Kansas, 13 miles south of the Nebraska line (Fig. 7), although the author stated that it was "... a reverse or vertical [normal] fault ...".

In the same area, also in Nemaha County, H. J. Hodgden of Hodgden Oil Company, Golden, Colorado (personal communication, 2003), mapped nearly a dozen reverse faults from seismic data in the area, extending from T1S to T4S and centered on R13E.

Farther south, in Pottawatomie County, Kansas, two wildcat wells cut reverse faults, the No.1 Bairow in Sec. 26, T8S, R10E and the # 1 Handley in Sec. 6, T7S, R12E. The reverse fault in the Bairow well had already been recognized by

Seyrafian (next paragraph), but the fault in the # 1 Handley well is unpublished (Fig. 8). This information is from G. Honas, consulting petroleum geologist, Wichita, Kansas (personal communication, 1999).

Also in Pottawatomie County, Ali Seyrafian (1978) recognized two reverse faults along the main Humboldt fault trend (Fig. 9).

On the "Alma trend," 10 miles east of the Nemaha trend in Wabaunsee County, Kansas, reverse faulting is documented for the Davis Ranch field by three sources: Smith & Anders (1951) describe reverse faults in 3 wells on the east flank; and the 1960 article on this field (Anonymous 1, 1960) shows a cross-section of one of these wells (Figs.10 and 11). In addition, an Exxon seismic line showed this to be a reverse fault (J. L. Evans, personal communication, 1999).

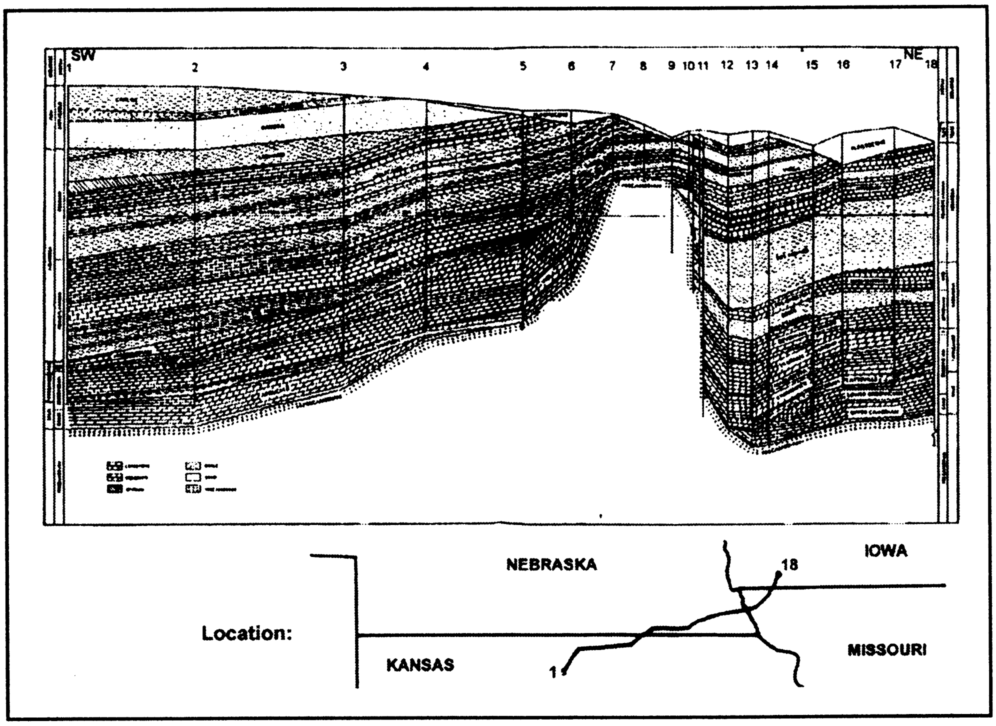

Figure 4. *Highly illustrative cross-section of the Nemaha Ridge in N. Kansas, SE Nebraska, and SW Iowa. From Carlson, 1971. AAPG© 1971, reprinted by permission of the AAPG whose permission is required for further use.*

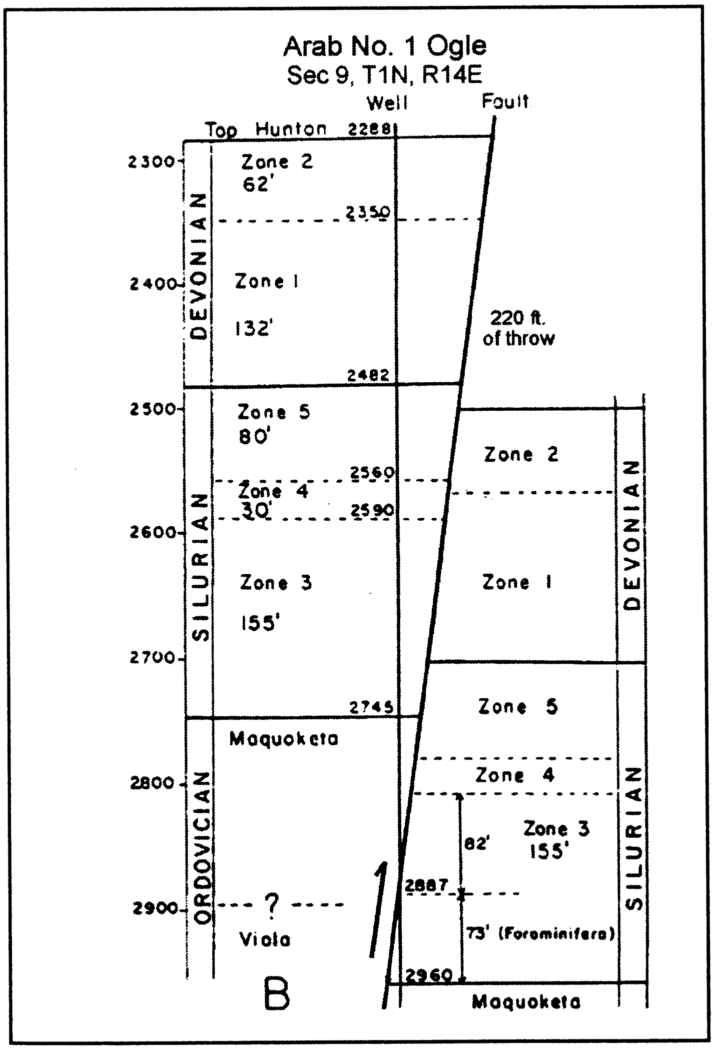

Figure 5. *Reverse fault recognized in a wildcat well in Richardson County, Nebraska, from detailed stratigraphic studies based on foraminifera. From Ireland, 1967.*

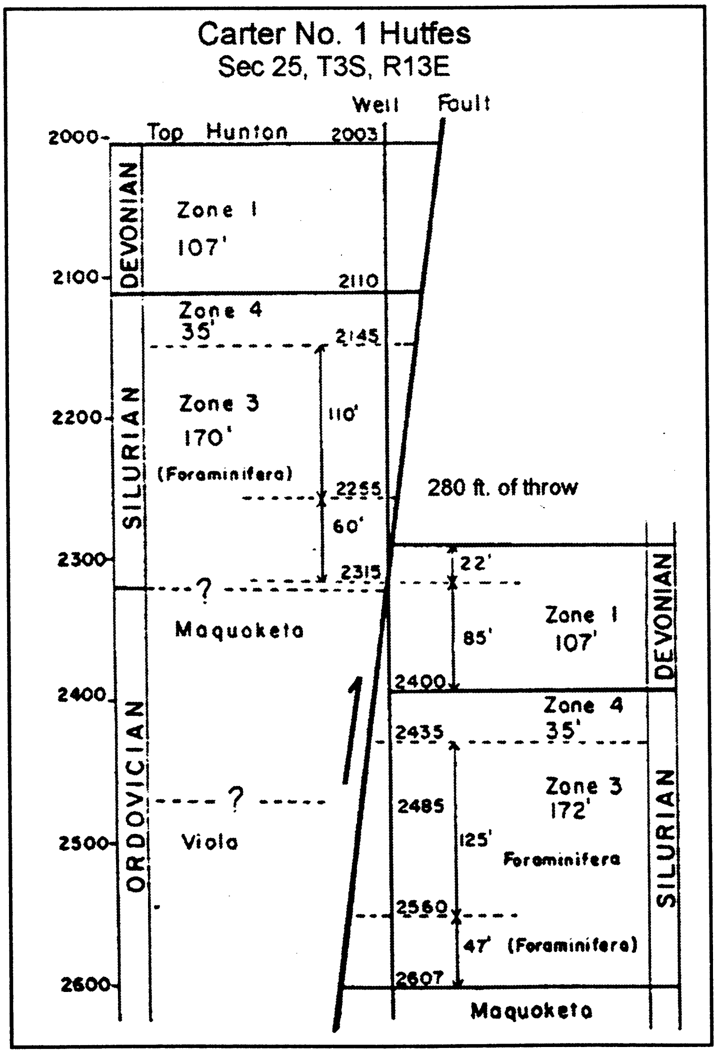

Figure 6. *Reverse fault recognized in a wildcat well in Nemaha County, Nebraska from detailed stratigraphic studies based on foraminifera. From Ireland, 1967.*

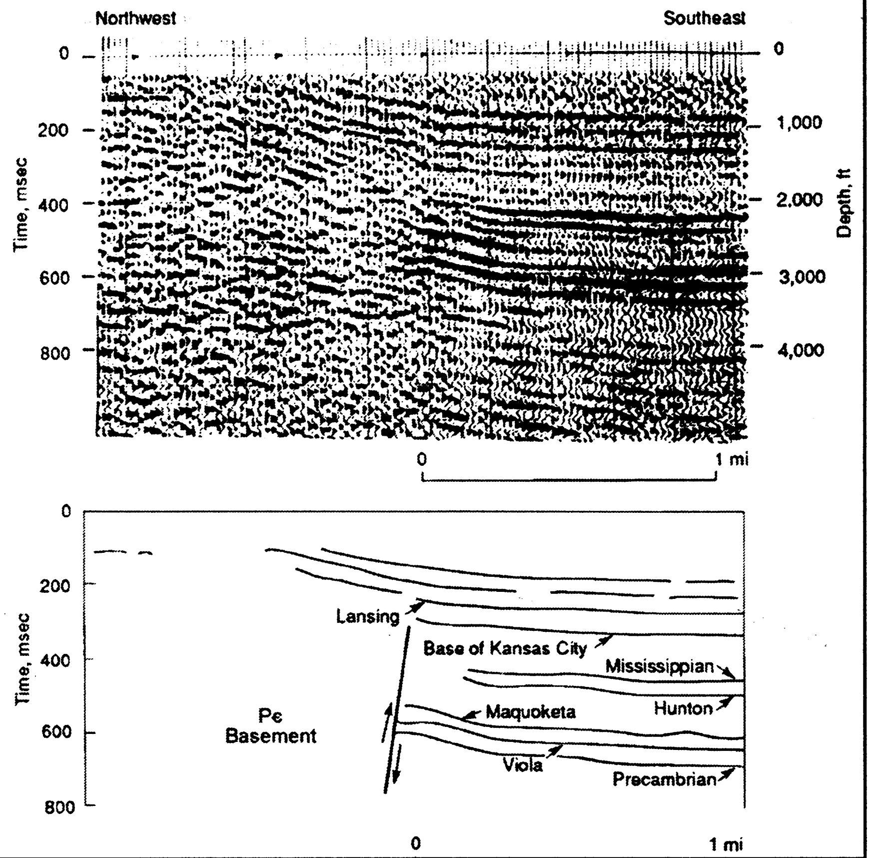

Figure 7. *NW-SE high-resolution seismic line in T.3 S. - R.13-14 E., Nemaha Co., Kansas on east flank of the Nemaha uplift. Steeples (1989) termed this a "....reverse or vertical fault..." (The dip would indicate that it is a reverse fault.). From Steeples, 1989.*

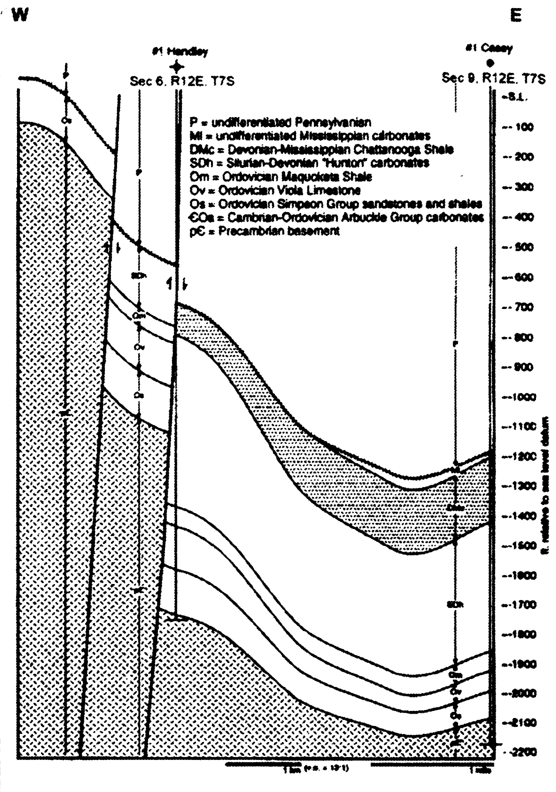

Figure 8. *Repeated section and reverse faulting documented in the #1 Handley well. This information is from G.D. Honas, personal communication, 1999. Cross-section courtesy of D. Newell, Kansas Geological Survey.*

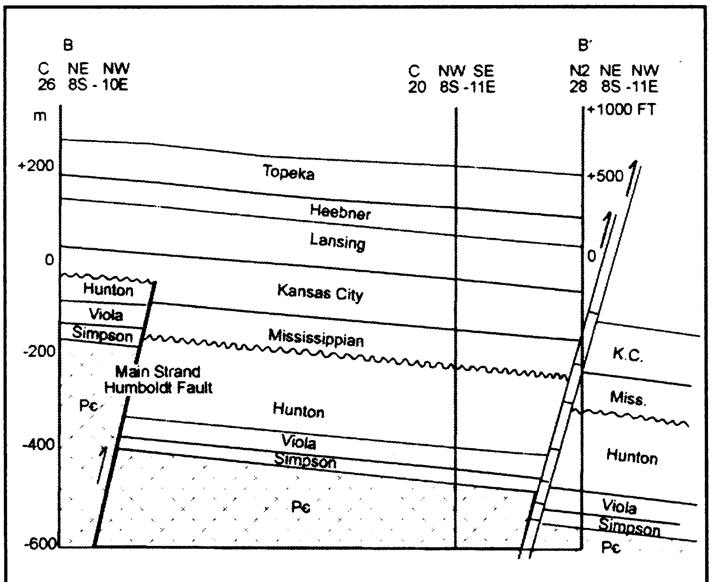

Figure 9. *E-W cross-section across the Humbolt fault in Pottawatomie County, Kansas. Modified from Seyrafian, 1978, Fig. 7A.*

Farther south in Wabaunsee County on the Alma trend, W. L. Brinegar (1960) documented a reverse fault on the east flank of the Ashburn field (Figs. 12 and 13).

Also on the Alma trend, the east-bounding fault in the John Creek field in Morris County, Kansas, is shown (Anonymous 2, 1960) as a normal fault (Fig. 14). Nevertheless, its reverse nature is documented by two sources: T. Dillard, geologist, and R. Feige, geophysicist, both

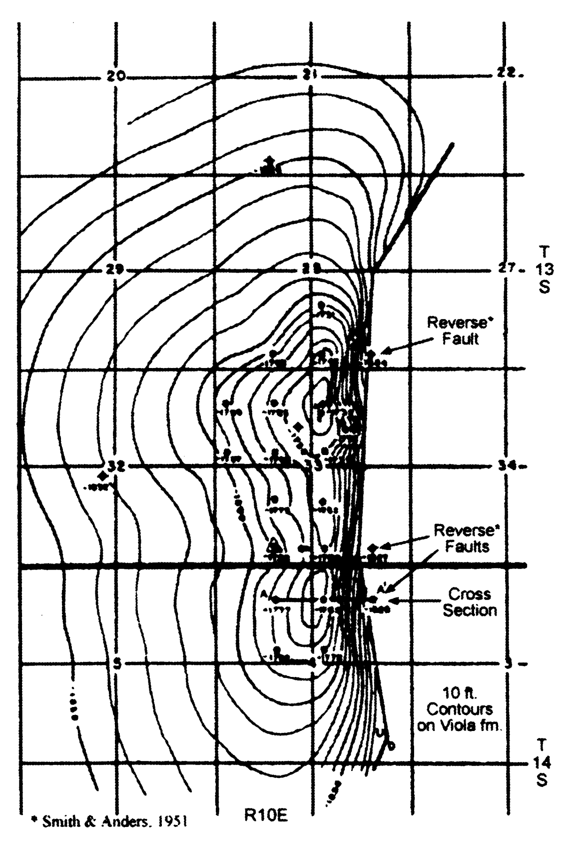

Figure 10. *Structure contour map of Davis Ranch field, Wabaunsee Co., Kansas with notations from Smith and Anders, 1951. Modified from Anonymous 1, 1960.*

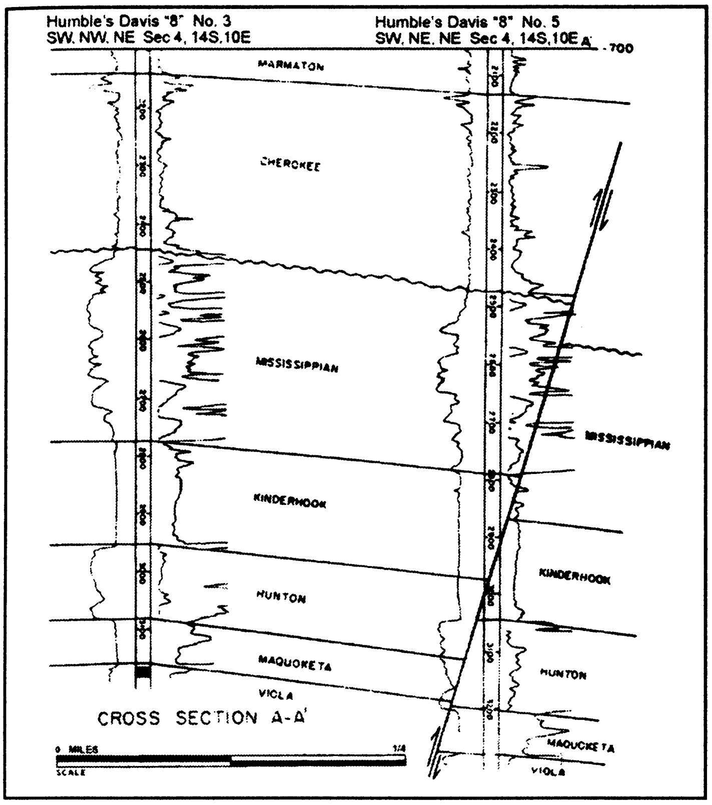

Figure 11. *E-W cross-section, Davis Ranch field, Wabaunsee Co., Kansas. From Anonymous 1, 1960.*

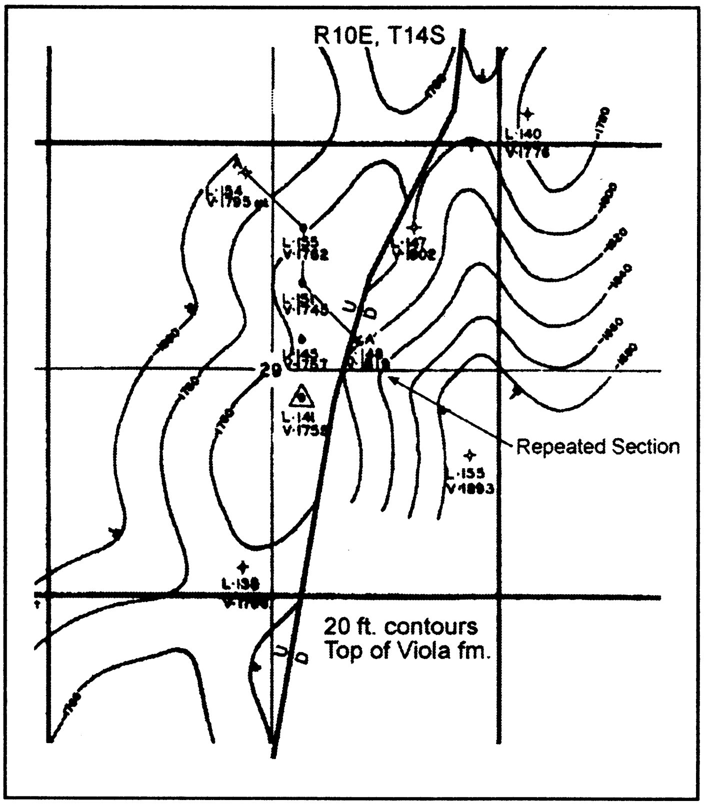

Figure 12. *Structure map of Ashburn Field, Wabaunsee County, Kansas. From Brinegar, 1960.*

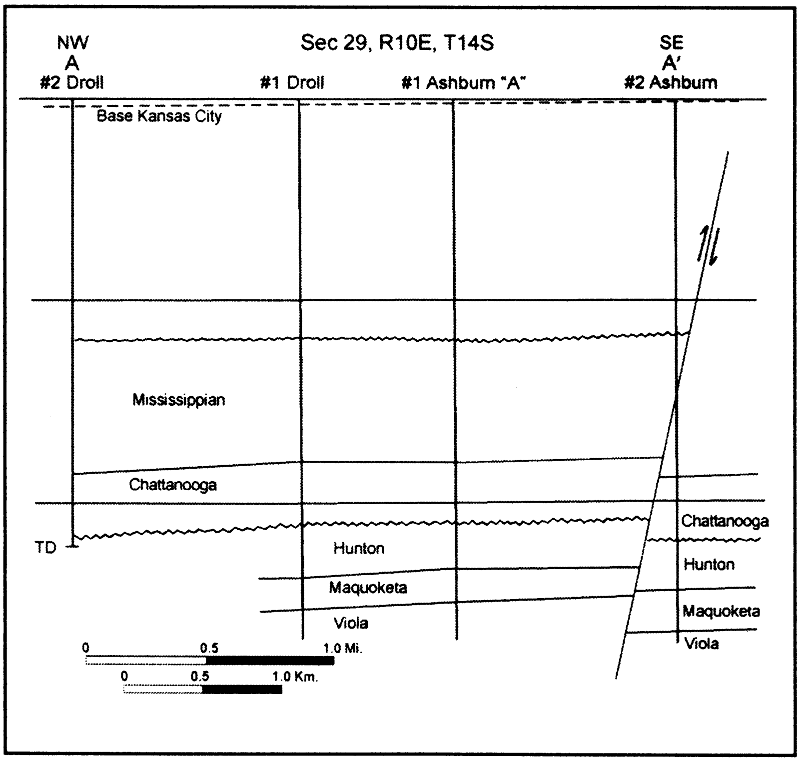

Figure 13. *NW-SE cross-section of Ashburn Field, Wabaunsee Co., Kansas. From Brinegar, 1960.*

of Oklahoma City (personal communication, 1998), interpreted an east-west seismic line here that showed the east-bounding fault to be reverse; and an Exxon seismic line also showed this to be a reverse fault (J. L. Evans, personal communication, 1999). Farther south on the main Humboldt Fault zone, the # "1B" Bosch well in Sec. 18, T16S, R8E shows reverse faulting (Fig.15).

Fifty miles west of the Nemaha Ridge is the parallel Voshell anticline. The oldest known reference to repeated section in the Nemaha system is by Hiestad (1933), who discusses this area. He mentioned 5 wells in the Voshell field with repeated or thickened section in Sec. 33, T20S, R3W and in Sec. 9, T21S, R3W. A few years later, Bunte and Fortier (1941) published a structure map (Fig.16) and a cross-section (Fig.17) of the field that showed other prominent east-dipping reverse faults. Other wells with repeated section in the Voshell field have been provided to the author by geologists Dave Montague, Sec. 16, T21S, R3W (personal communication, 1999) and D. Newell, Sec. 21, T21S, R3W (personal communication, 1999).

The Voshell anticline continues southward and forms the structure underlying the Hollow-Nikkel field in T22S, R3W. Five wells in that field show an east-dipping reverse fault (D. Newell, personal communication, 1999) similar to the Voshell fault. Another well (Murty #1 in Sec. 12 of the same township), on a parallel structure 5 miles to the southeast, also shows reverse faulting (D. Newell, 1999, personal communication). An additional well in Burrton field in Reno County, the B. Fairchild # 1, in 17-T24S-R4W, shows reverse faulting (D. Newell, 1999, personal communication).

The El Dorado field in Butler County, Kansas, was one of the largest producing fields in the United States in the 1920s (production to the year 2000 exceeds 450 million barrels). Discovered in 1915, it lies astride the Nemaha uplift, but was never mapped as being faulted. A 1921 structure contour

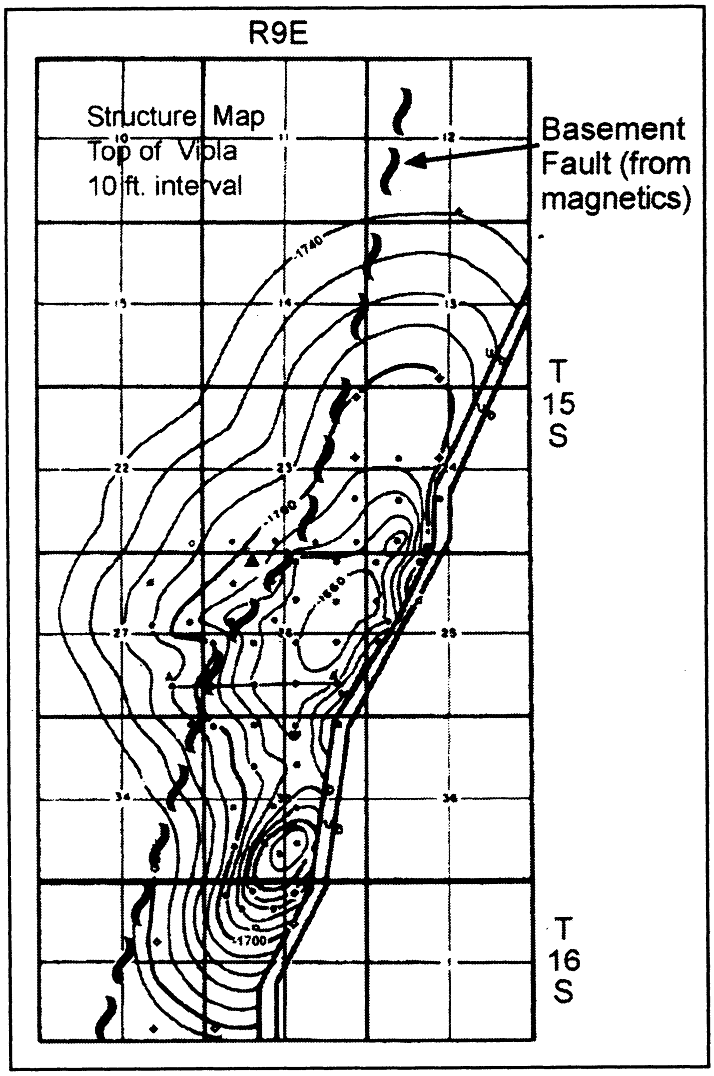

Figure 14. *Structure map of John Creek field, Morris Co., Kansas. A 1982 east-west seismic line here showed east-bounding fault to be reverse (R. Feige, personal communication, 1998). Westerly location of fault at basement level also indicates it is west-dipping, and hence reverse. Modified from Anonymous 2, 1960.*

map of the field (Reeves, 1929) is shown in Figure 18. Nevertheless, a "boom" well drilled on its east flank in the hope of resuscitating the field in 1982 clearly showed a reverse fault with 126 ft of throw (Fig. 19) (personal communication, D. Seeber, 1999). In addition, the steep dip on the east flank is coincident with a basement fault mapped from magnetics (not shown), so the structure is no doubt faulted its entire length. The fault was undoubtedly penetrated many times in the 1910s and 1920s when the field was being developed. However, at that time petroleum geology was in its infancy; the stratigraphic succession was not well known; and thus it was not possible for the early workers to recognize repeated section. Of the many articles on Kansas oil fields I have read, no reverse faults are mentioned prior to the 1930s, and faulting was even considered by some as non-existent in the whole state of Kansas in the 1920s. It is important to realize, however, that prior to 1920, there were few geologists employed in the oil industry.

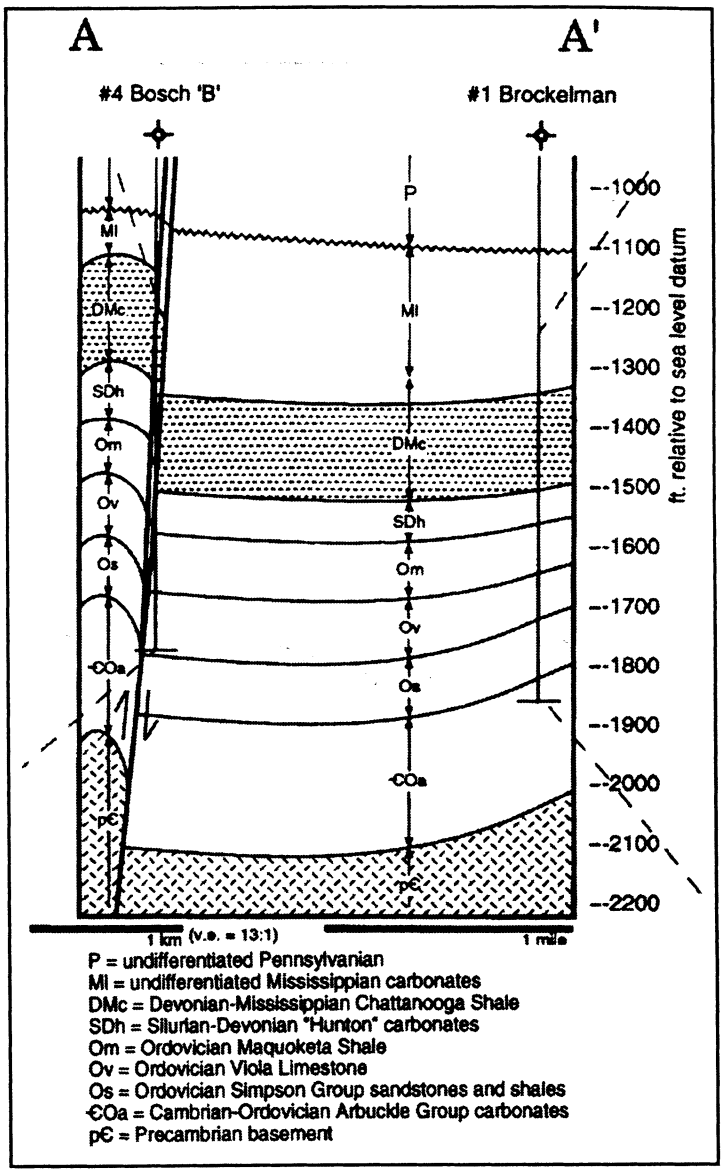

Figure 15. *Reverse fault & cross-section through the #4 Bosch 'B' well in Sec. 18, T16S, R8E in Morris Co., Kansas. Unpublished data provided by Dave Newell, geologist, Kansas Geological Survey.*

Recent (1990s) seismic surveying north of the North Augusta field, south of El Dorado, has also revealed reverse faulting in that field (Anonymous, personal communication, 1999).

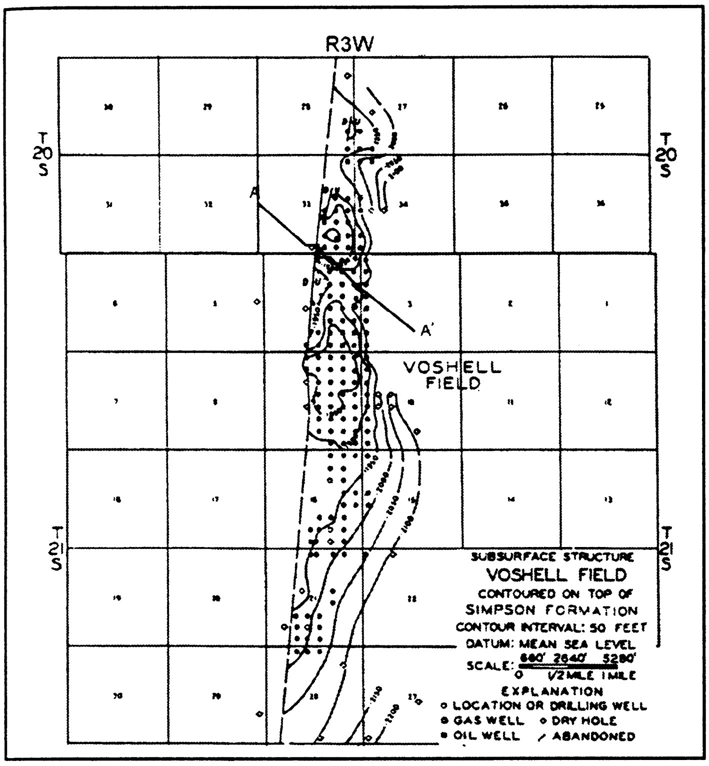

Figure 16. *Structure contour map of the Voshell field in McPherson County, Kansas. Cross-section A-A' appears in the next figure. From Bunte and Fortier, 1941. AAPG© 1941, reprinted by permission of the AAPG whose permission is required for further use.*

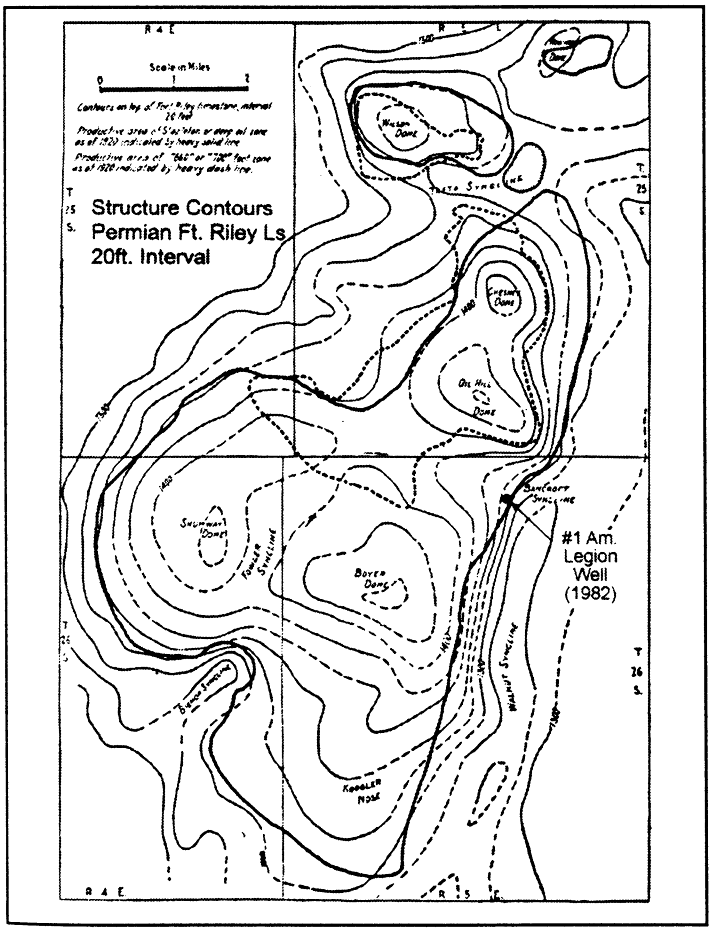

Figure 18. *Structure map of the giant El Dorado field, Butler Co., Kansas. Reverse fault in # 1 American Legion well shown in Figure 19. From Reeves, 1929 (after Fath, 1921) .AAPG© 1929, reprinted by permission of the AAPG whose permission is required for further use.*

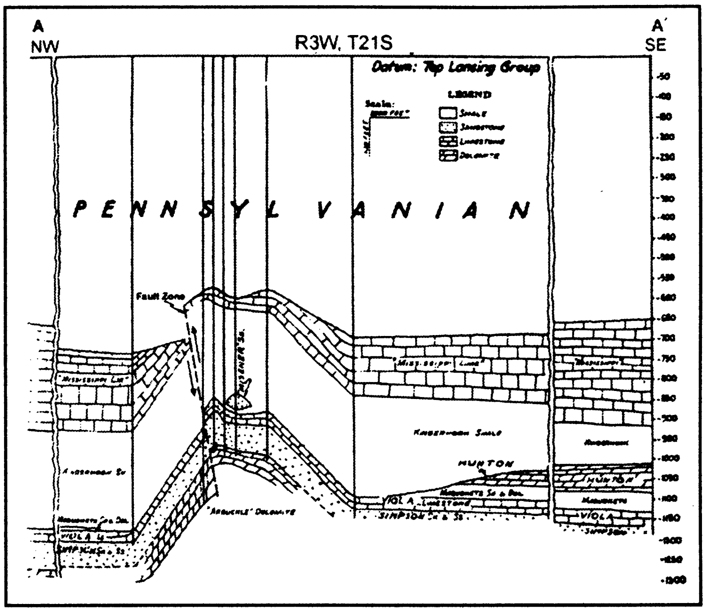

Figure 17. *NW-SE cross-section of Voshell field in McPherson County, Kansas. Location is shown in previous figure. From Bunte and Fortier, 1941. AAPG© 1941, reprinted by permission of the AAPG whose permission is required for further use.*

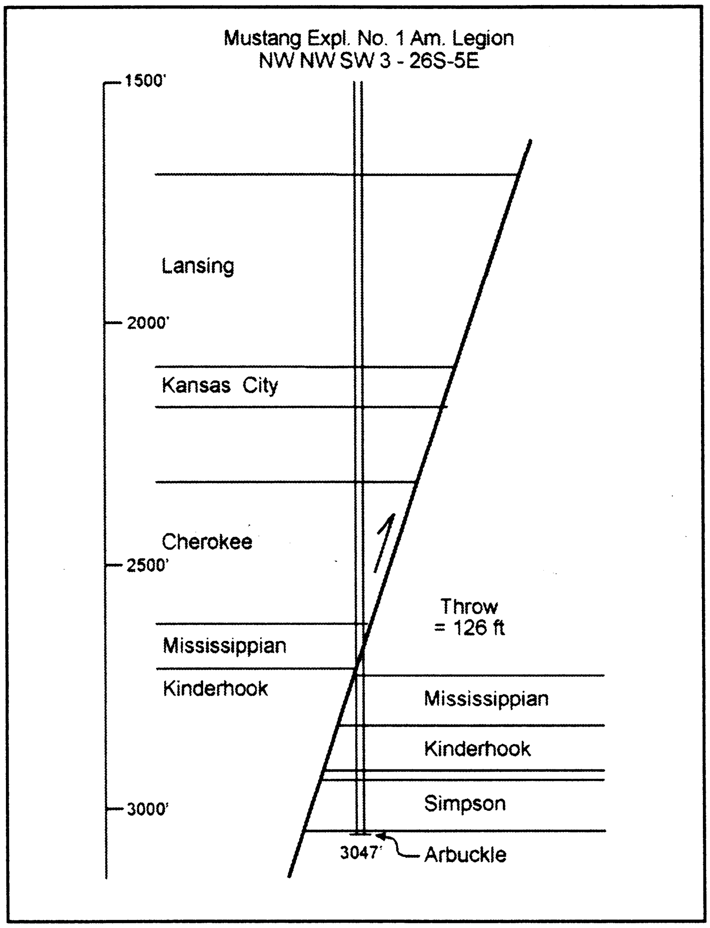

Figure 19. *Cross-section of Mustang Exploration No. 1 American Legion well drilled in 1982 in the baseball field on the east flank of the giant El Dorado field, proving the reverse nature of this 9-mile long fault. From D. Seeber, personal communication, 1999.*

End of Part 1

Part 2, with References, will appear in the next issue of the Shale Shaker-V. 54, No. 2, September-October 2003.

THE NEMAHA TREND-A SYSTEM OF COMPRESSIONAL THRUST-FOLD, STRIKE-SLIP STRUCTURAL FEATURES IN KANSAS AND OKLAHOMA, (PART 2, CONCLUSION)

S. Parker Gay, Jr., Applied Geophysics, Inc., Salt Lake City, Utah

Oklahoma Examples of Reverse Faulting/Repeat Section on the Nemaha System

The locations of documented reverse faulting, both published and unpublished, reported along the Nemaha system appear on the map of northern Oklahoma (Fig. 20). A list of these examples is shown in Table 2.

The Braman North field in T29N, R1W, Kay County, Oklahoma is "a horst block showing 400+ ft of uplift," (Schloeder, 1998) along a reverse fault on the west (F. Schloeder, personal communication, 1999). The Thomas field, 22 miles to the south, also exhibits reverse faulting (R. Northcutt, personal communication, 1999).

Ponca City field in Kay County, Oklahoma (Fig. 21) occurs on an anticlinal structure with a steeply dipping east flank. Such asymmetric folds are generally the result of compression and have "blind" thrusts or reverse faults beneath them at depth (see inset Fig. 21). This field has a prominent basement fault mapped by magnetics lying a thousand feet west of the steep east flank (Fig. 22), which would be the basement location of the blind fault, thus making it a reverse fault. Also, geophysicist K. Goodfellow (personal communication, 1999) confirmed to the author that this field had an underlying reverse fault as revealed by a Conoco seismic line.

The east flank of the Three Sands field in Noble County, Oklahoma, is also the locus of a reverse fault (R. Fritz, personal communication, 1999). A study of Noble County by J. W. Shelton, (1979) concluded:

"Genetically, the faults are thought to be upthrusts or strike-slip faults with significant amounts of <u>dip-slip</u> displacement (underlining mine). The faults were initiated in the basement; displacement diminishes upward, and folded beds are draped over fault blocks."

The reverse nature of the east-bounding fault at Garber field in Garfield County, Oklahoma, was documented many years ago by Cary (1954) (Figs. 23 and 24). At that time proven examples of reverse faulting on the Nemaha were few. However, Cary (1954) also mentions that the No. 1 Atkinson well south of Garber field has repeated section. This well cuts a southwest trending reverse fault that has recently been verified and traced for 9 miles with 3D seismic (R. Feige, personal communication, 1999).

Martin (1943) undertook an analysis of Crescent field in Logan County, Oklahoma. His study of this asymmetric anticline included five cross-sections and four structure maps. He interpreted a west-bounding fault underlying the field, and found that one well (Texas No. 5 Denny) cut a fault and repeated part of the lower Paleozoic section. He drew a flat thrust at this locality (unknown on the Nemaha system); but I have modified his cross-section to show a pair of high angle reverse faults instead (Fig. 25).

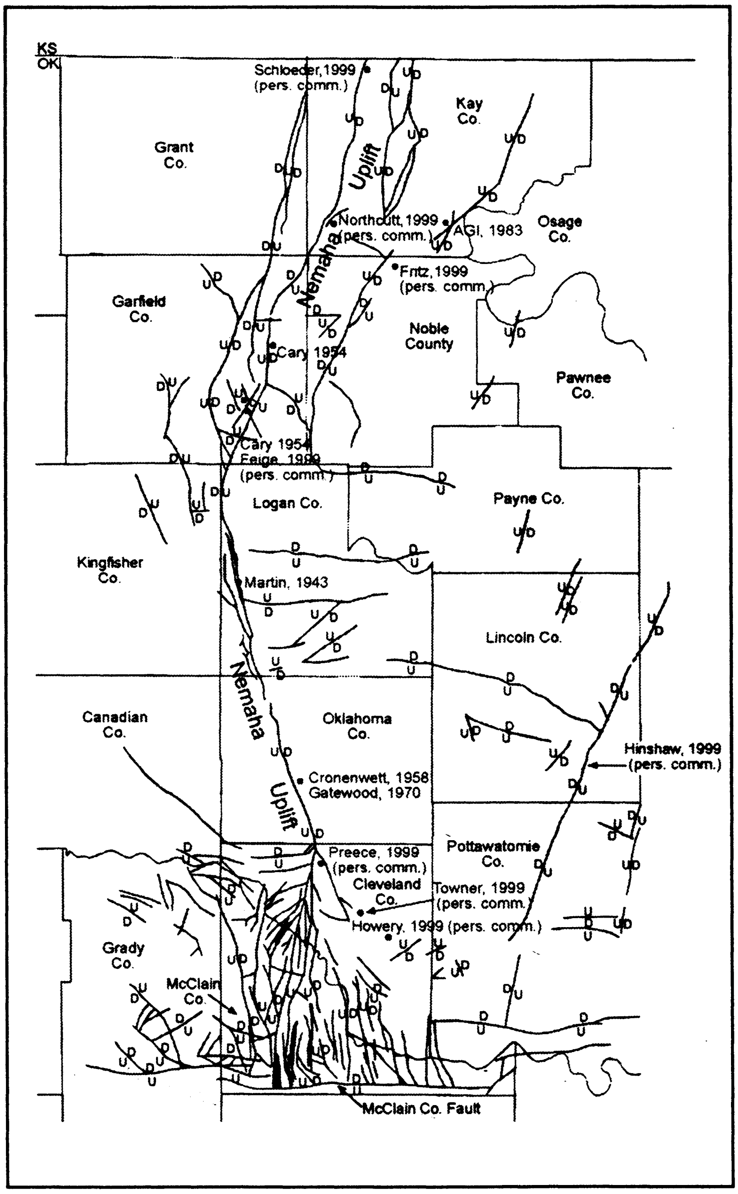

Figure 20. *Map of detailed fault pattern, north-central Oklahoma showing locations where reverse faulting has been demonstrated. See Table 2 for a list of the examples. Modified from proprietary map, courtesy of Gatewood (1983).*

The Wilzetta fault zone extends NNE 55 miles (90 km) from north central Pottawatomie County to western Creek County (Fig. 20). C. Hinshaw (personal communication, 1999) interprets it to be a reverse fault its entire length.

One of Oklahoma's best-known and largest oil fields, the Oklahoma City field, was studied by Cronenwett (1958). He clearly shows a reverse fault in the British-American #1 Tellier well, which penetrates the main east-bounding fault of the field (Fig. 26). This would indicate that this fault is a reverse fault its entire length. L. Gatewood (1970) states: "... in some sectors [this fault] appears to become a high-angle reverse fault," although he believes it is essentially a normal fault (L. Gatewood, personal communication, 1999).

Table 2. Examples of reverse faulting along the Nemaha System in Oklahoma, listed from North South. See Figure 20 for map location.

Source	Location	Comments
Schloeder, 1999 (Pers. Comm.)	21–T29N–R1W	Braman North field – Horst block showing 400+ ft of uplift on the west (Schloeder, 1998).
Northcutt, 1999 (Pers. Comm.)	9–T25N–R2W	Thomas field
Gay, 1995	T25N–R2E	Ponca City field – Magnetic data by Applied Geophysics, Inc. show west dip to fault, hence reverse throw.
Fritz, 1999 (Pers. Comm.)	7–T24N–R1E	Tonkawa ("Three Sands") field, east flank.
Cary, 1954	6–T22N–R3W	"New" Garber field (north of Garber).
Cary, 1954, and Feige, 1999 (Pers. Comm.)	12–T21N–R4W	South of Garber field – Recent 3D seismic shows this reverse fault is at least 9 mi long.
Martin, 1943	33–T17N–R4W	Crescent field.
Preece, 2003 (Pers. comm.)	T14N–R4W	W. Edmond field.
Hinshaw, 1999 (Pers. Comm.)	T8N–R3E to T17N–R7E	"Wilzetta" fault. Extends 55 mi from north central Pottawatomie Co. to western Creek Co.
Cronenwett, 1958	23-T12N–R3W	Oklahoma City field. Gatewood (1970) also mentions reverse faulting here.
Preece, (1999) (Pers. Comm.)	8–T10N–R2W & 16–T10N–R2W	Two wells a few mi south of Oklahoma City field on same east-bounding fault.
Towner, 1999 (Pers. comm.)	20–T9N–R1W	Northeast Falls field, center of township.
Howery, 1999 (Pers. comm.)	2–T8N–R1W & 20–T8N–R1W	Two wells 15 mi south of Oklahoma City field.

The next five examples of reverse faulting, which all lie south of the Oklahoma City field, were provided to me by competent, well-known Oklahoma geologists. Sources, well names, and locations are shown in Figure 27. The reader is free to investigate these examples as he chooses.

Is the Main Nemaha Fault Listric?

In the Rocky Mountains, geologists are finding that most thrusts and reverse faults are listric, that is, as they extend deeper into the earth their dips become gentler (Figs.1 and 2). This configuration allows cross-sections to be balanced, which modern day structural geologists insist is a non-negotiable criterion for reality. Does this concept apply to the Nemaha? Interestingly enough, a listric fault was proposed for the Nemaha by Koff (1978), a Russian graduate student at the University of Oklahoma, who was studying earthquake epicenters in the Oklahoma City-El Reno area. Koff's cross-section is shown as Figure 28. In the light of other findings in this paper, Koff's results appear to be quite credible.

The listric nature of the Nemaha thrust fault was apparently imaged by the COCORP line in northern Kansas (Fig. 29) as shown in Serpa, Setzer, and Brown (1989) and in Setzer and others (1983), but was not discussed. See Figure 3 for the location of this line. A west-dipping reflector illustrated by me on Figure 29 could well be the listric fault of Koff (1978).

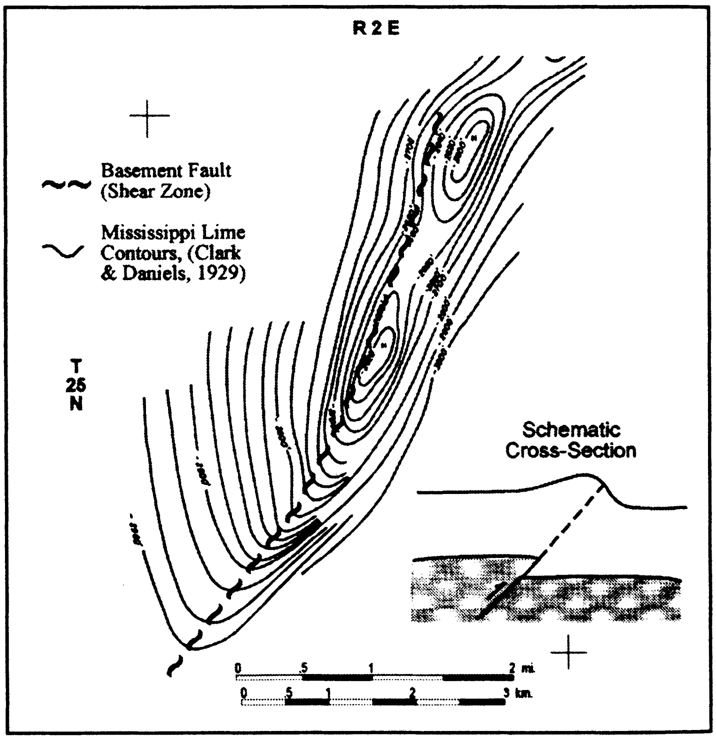

Figure 21. *Structure map of Ponca City field, Kay County, Oklahoma, contoured on Mississippi lime. Contour interval = 20 ft. Basement fault location taken from aeromagnetic data shown in Figure 22. Asymmetrical form is typical of compressional folds. Westerly position of fault at basement level proves reverse dip. Modified from Clark and Daniels (1929, fig. 6). AAPG©1929, reprinted by permission of the AAPG whose permission is required for further use.*

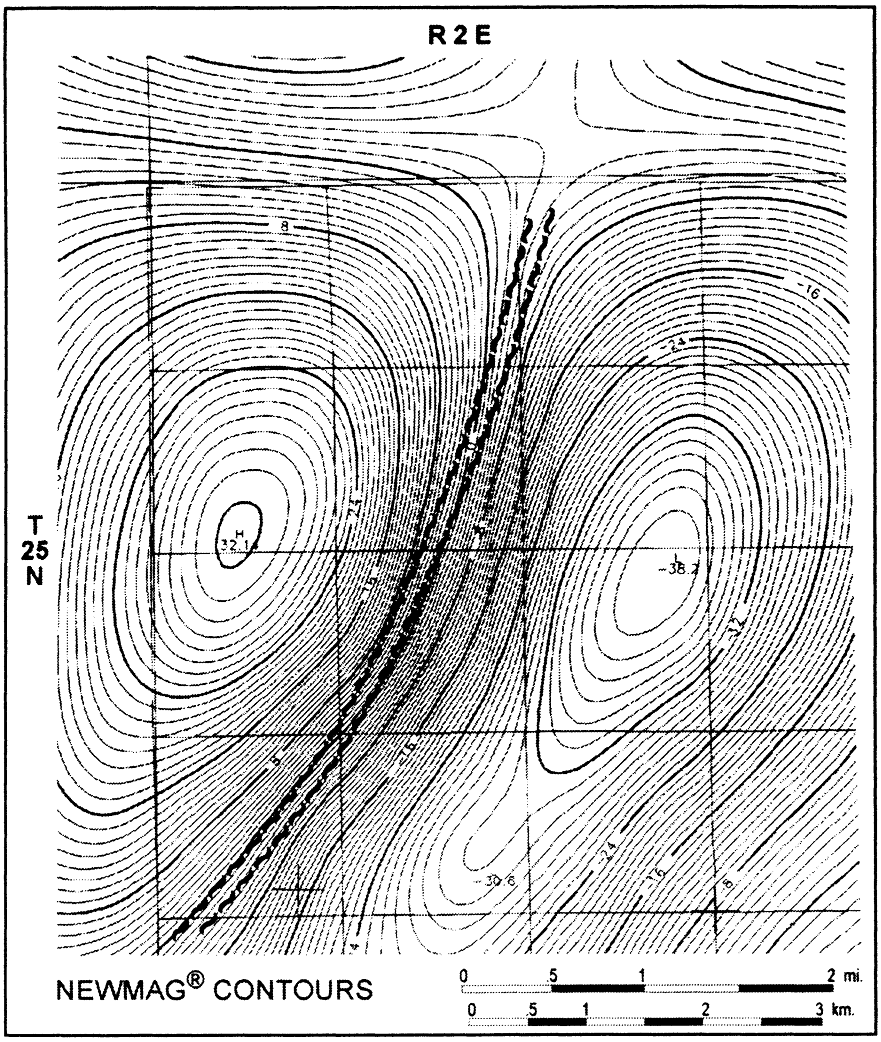

Figure 22. *NewMag® residual contours of the area of Ponca City field, Kay County, Oklahoma. The basement shear zone shown follows the area of steepest magnetic gradient. From proprietary data, courtesy of Applied Geophysics, Inc. (2002).*

However, Serpa, in her oral presentation in 1985, proposed the opposite-a listric east-dipping normal fault there-a mirror image of the one shown in Figure 29. The original seismic line is illustrated in either of the above references. A high-quality image also can be obtained directly from the Consortium for Continental Reflection Profiling at Cornell University.

Near-Verticality of Some Nemaha Faults

A feature of Nemaha faulting that has cast doubt for some on the compressional origin of the Nemaha system is the vertical, or near-vertical, attitude of many of the faults (L. Gatewood, personal communication, 1999). It has been reasoned that compressional systems are characterized by thrusts or reverse faults of shallower dip than those observed. It is characteristic of basement-rooted thrust faults in the Rocky Mountains to have low dips at depth, with the dip of the fault plane becoming more vertical upward (Fig.2). An advantage of studying such structures in the Rocky Mountains is that there is exposure by erosion at many levels; also, many of them have been investigated extensively by seismic methods. However, in the Midcontinent region, all of the basement-rooted thrust-fault structures are buried; and to date, no oil and gas play has developed that would warrant extensive seismic investigations.

A cross-section of the Little Laramie anticline in the South Laramie basin, Wyoming (Fig. 2), shows a fault that is vertical at the surface dips westerly at depth and assumes a dip of less than 45° in about a mile (Stone, 1993a).

Five additional published cross-sections of listric thrust structures with near-vertical dips near the surface are listed here for the interested reader: Southern Wind River basin, Sage Creek anticline, Grass Creek field, Garland anticline, from Stone (1993a), his Figures 6, 9, 10, and 14 respectively; and South Elk basin anticline from Stone (1983).

Nemaha "Foreland Basin"

Another characteristic of thrust systems in the Rockies is the occurrence of sedimentary basins in front of the thrusting, or "foreland basins". Their formation has been correctly attributed to tectonic loading (Jordan, 1981), that is, the piling up of rock-on-rock, resulting in isostatic imbalance which depresses the Earth's crust in the thrusted region. This may have occurred on the Nemaha system as well. Dolton and Finn (1989, p. 12) citing Wells (1971), state that the deepest part of the Forest City basin in northeastern Kansas occurs opposite the greatest throw of the Humboldt fault. On a lesser scale, accentuated depressions have been noted by the author in front of the prominent thrusts in the Oklahoma City and Garber fields in Oklahoma and the El Dorado and Alma anticlines in Kansas.

Note the "overhang" of the thrusts at depth in Figures 1 and 2. Can the east-bounding fault of the Nemaha system have a similar overhang, perhaps in places where the throw is large? An exploration opportunity may exist if this is correct.

Backthrusts

An additional feature of compressional systems which are not yet documented for the Nemaha, but which may well exist, are "backthrusts." In Kay County, Oklahoma, the Nemaha uplift is characterized by down-to-the-east, east-bounding faults and down-to-the west, west-bounding faults, both of which are probably reverse faults. The E-W separation between these faults is 8-10 miles, and the uplift is 200-300 ft at Viola level. At other places along the system, there are folds, but not faults, on the east and west sides of the uplift. At depth these folds may also show fault offset ('blind" faults), as I postulated earlier for the east flank of the Ponca

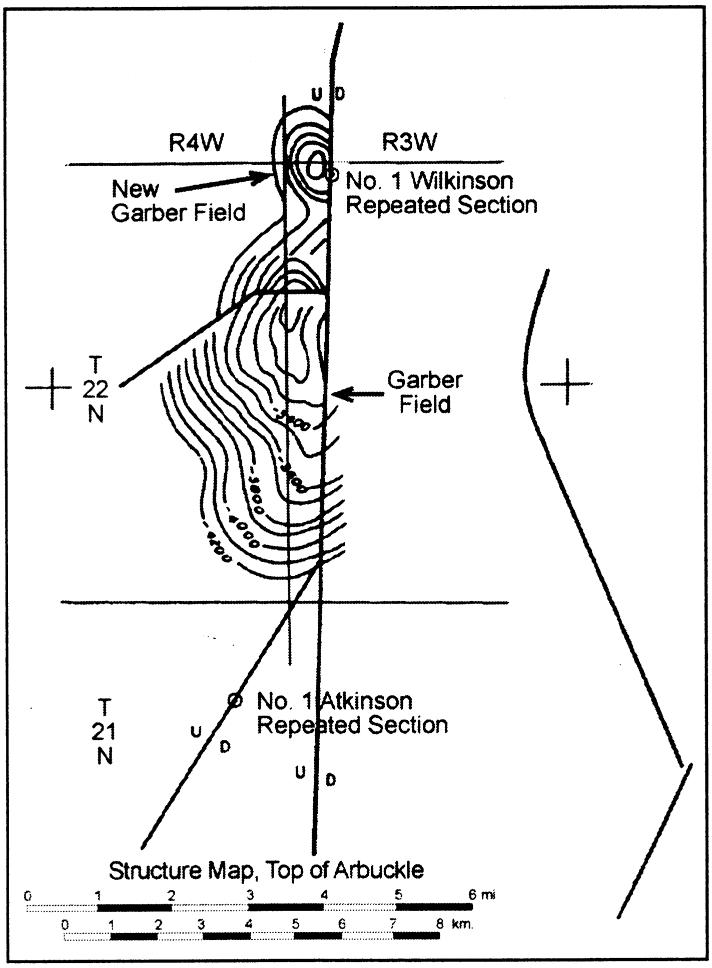

Figure 23. *Structure map of Garber field, Garfield County, Oklahoma, contoured on top of the Arbuckle showing location of two wells with repeated section. The No. 1 Wilkinson well indicates reverse nature of main east-bounding fault in this field. No. 1 Atkinson well indicates reverse nature of southwest-trending fault south of Garber. The latter reverse fault has been shown by a recent 3D seismic survey to extend at least 9 miles to the southwest (R. Feige, personal communication, 1999). Modified from Cary (1954).*

City field. Once again, by comparison to structures in the Rockies, Figure 2 shows a typical backthrust in the Little Laramie Mountains in Wyoming that, together with the main west-dipping thrust, creates a "pop-up block".

The pop-up block concept applied to the Wichita Mountains in southern Oklahoma is shown in Figure 30. The Burch and Muenster-Waurika fault systems on the south side of the range in this interpretation would be backthrusts to the main south-dipping listric Mountain View fault on the north. Incidentally, as recently as 1971, the Mountain View fault was depicted as vertical, i.e., a normal or strike-slip fault (Witt, 1971)-precisely the same concept believed by some present-day geologists to exist for the Nemaha system.

Other noted structural "pop-up" blocks shown in recent literature are the Uinta Mountains in Utah (Stone, 1993b), and the Front Range in Colorado (Jacob, 1983).

Strike Slip Movement

The favored explanation for the origin of the Nemaha system by some of the Kansas Geological Survey staff recently has been normal faulting accompanied by left-lateral strike-slip movement (Blair and Berendsen, 1988; Berendsen and Blair, 1995). See also Fenster and Trapp, 1982; Davis, 1986; Shelton, 1979, p. 34; and McBee, 1999, on this subject. That there is abundant strike-slip movement on the Nemaha is undeniable, but this lateral movement is probably late, after much, or most, thrusting had occurred. The El Dorado field in Kansas and the Tonkawa field in Oklahoma occur where prominent northwest-trending anticlines are formed as the result of shortening at right angles to the thrusting (Figs. 31 and 32).

The "Wichita pluton" (Gay, 1999), a basement feature of Precambrian age, lies west of and parallel to the Nemaha system in southern Sedgwick Co., Kansas (Fig. 33). Here, contemporaneous strike-slip movement (left-slip) along a fault caused 6 km (4 miles) of offset on the east side of the Gillian and O.S.A. oil fields. Of this fault, Shawver (1965) states: "After......Mississippian sediments were deposited...the faults on east and west sides of the Gillian pool were formed." Strike-slip movement is very difficult to document with standard petroleum exploration techniques, i.e. seismic and well data, but it is a straightforward solution with magnetics where a geologic marker is present, such as an intrusive boundary as interpreted at the "Wichita pluton".

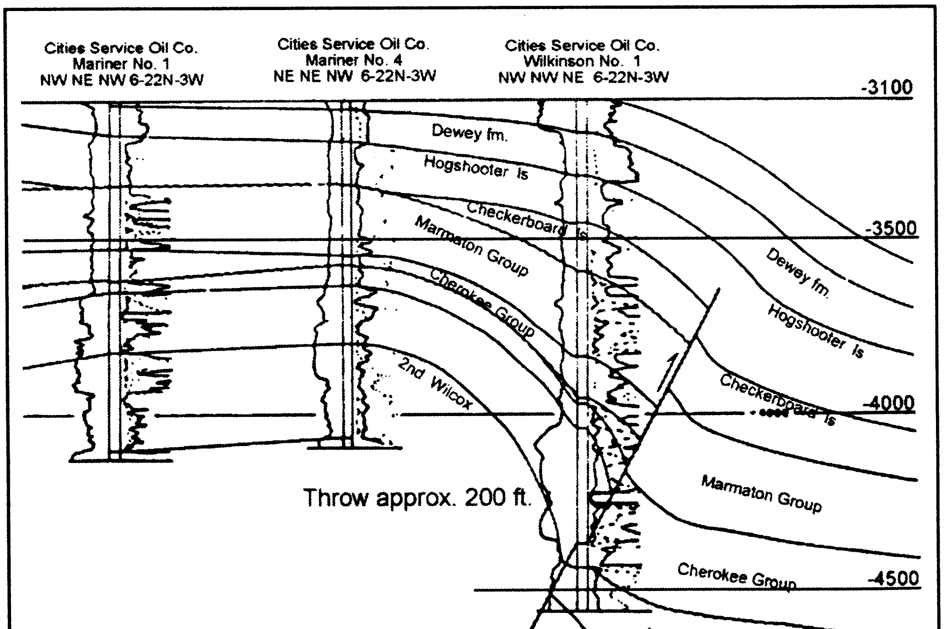

Figure 24. *Cross-section of New Garber field, just north of Garber field, Garfield County, Oklahoma, documenting a fold over an underlying reverse fault. From Cary (1954).*

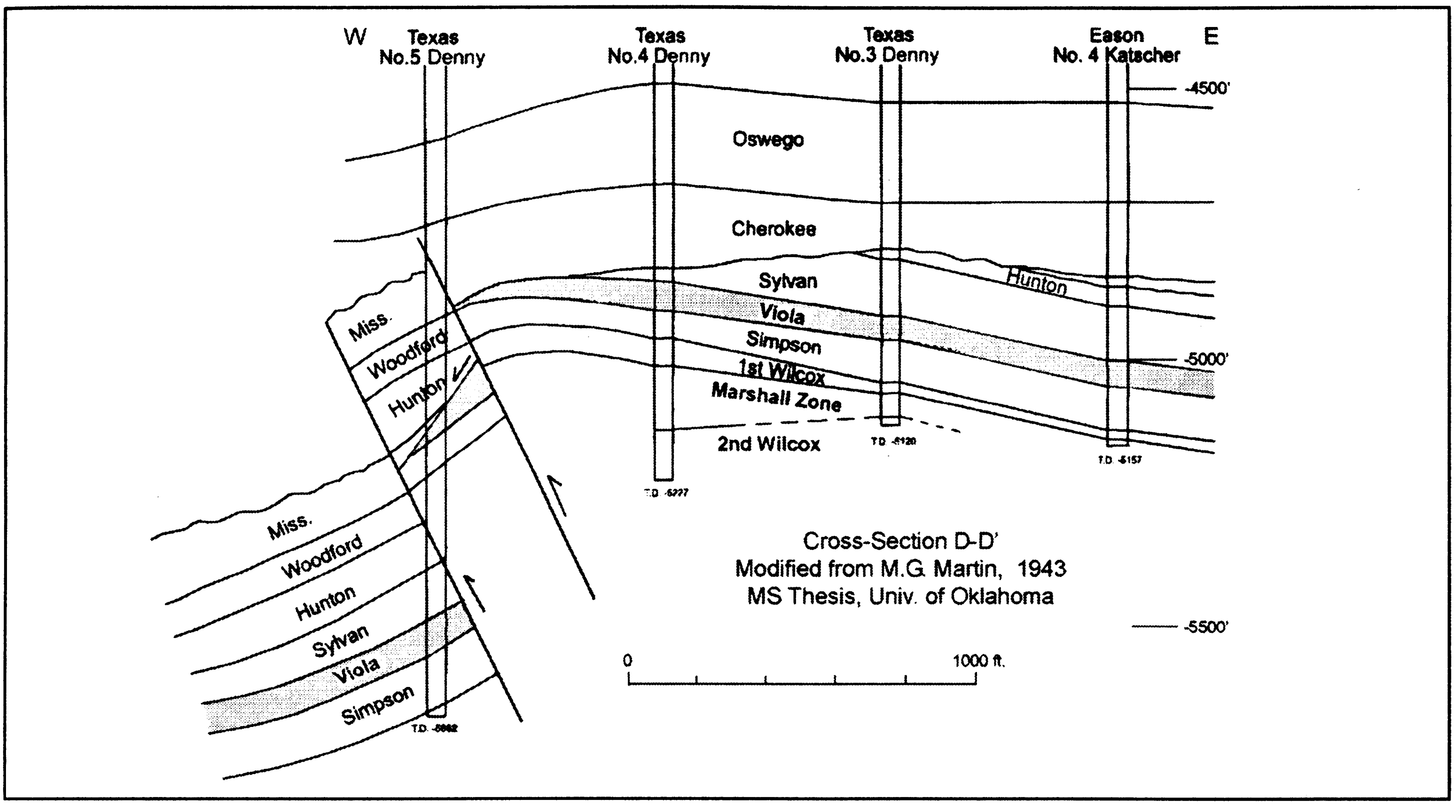

Figure 25. *Reverse fault in Crescent field, Logan County, Oklahoma. Modified from Martin (1943).*

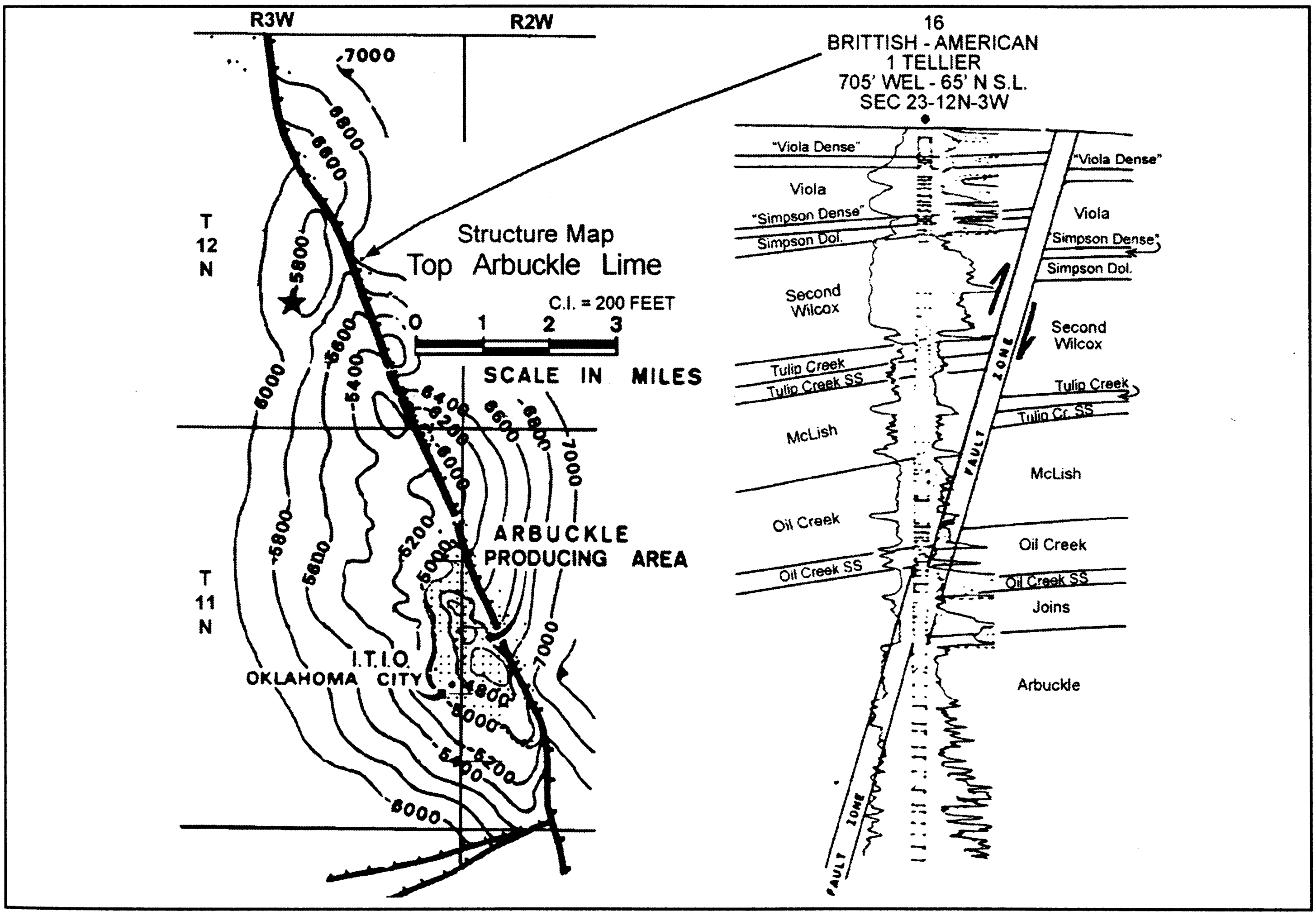

Figure 26. *Structure map on top of the Arbuckle, Oklahoma City field, Oklahoma County, Oklahoma. Contour interval = 200 ft. Modified from Gatewood (1970, fig. 14). AAPG©1970, reprinted by permission of the AAPG whose permission is required for further use. Repeated section in the British American No. 1 Tellier on the east- bounding fault of the Oklahoma City field shows this fault to be a reverse fault. Modified from Cronenwett (1958).*

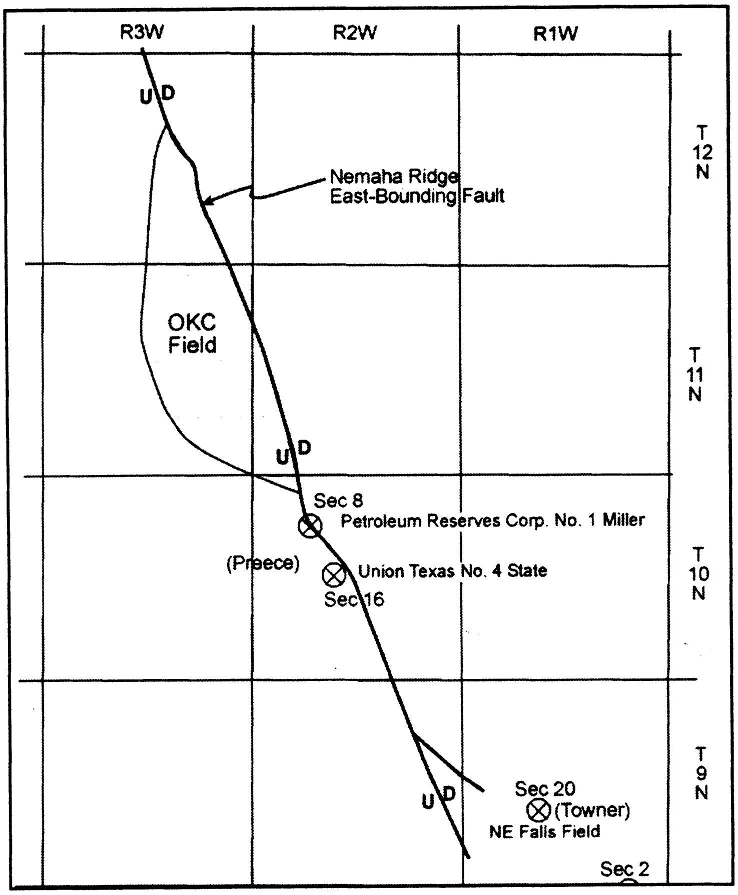

Figure 27. *Five locations on Nemaha system south of Oklahoma City field in Cleveland County, Oklahoma, where wells with repeated section have been identified. S. Howery, W. Towner, & J. Preece, personal communications (1999).*

Relaxation Faults

In regard to post-compressional normal faulting on the Nemaha system, Stander (1989) shows a high-resolution seismic line on the east flank of the Nemaha anticline in northeast Kansas with a down-to-the-east normal fault that offsets the shallow Pennsylvanian and Permian beds (Fig. 34). This situation probably occurs in other places along the Nemaha system. By way of comparison, a cross-section from seismic surveys and drilling near the tip of the granite wedge of the Owl Creek thrust in Wyoming is shown in Figure 35. Sedimentary rocks may extend as far as ten to twenty miles to the north beneath this thrust. Two normal faults are shown just west of the granite and another one farther west. These may be termed "relaxation" faults, as they apparently result from isostatic adjustments that occurred after compression ceased-perhaps the same as the fault on the Nemaha (Fig. 34) mapped by Stander (1989). Similar normal faults, also in the Rockies, are documented in front of the Wind River thrust (Basham and Martin, 1985) and the Washakie thrust (Winterfeld and Conard, 1983).

Timing

We have looked at the Rocky Mountains for structural analogs to the Nemaha system and now we will look at the Appalachian Mountains for an understanding of the timing and origin of the forces that created the Nemaha system. Lengthy descriptions and many pages of geological explanations are not necessary. One diagram suffices-Figure 36. On the left side of the figure are ages of the three Nemaha structural events summarized by J. R. Wilson, consulting geologist, Tulsa, Oklahoma (personal communication, 1991), from his experience with Oklahoma geology. (My apologies for not citing many other astute geologists whose studies I've also seen on the timing of Nemaha structural events based on well

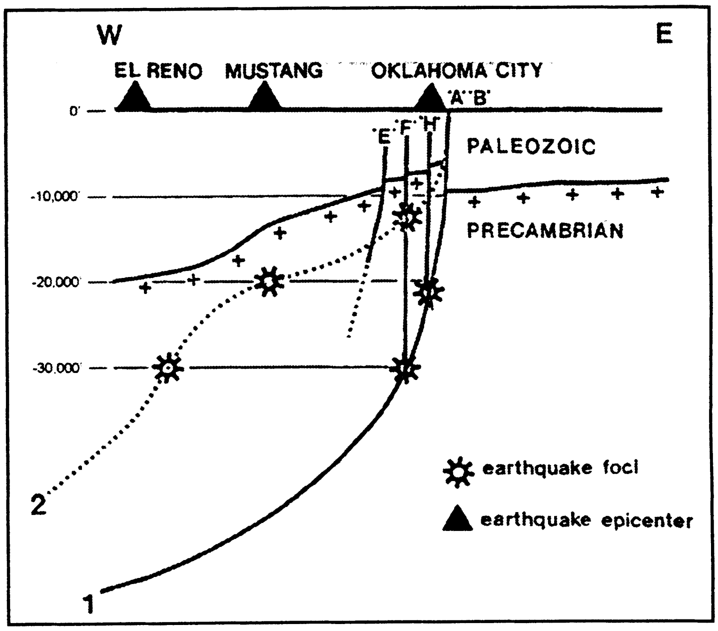

Figure 28. *Two theoretical fault traces that satisfy earthquake data for the Oklahoma City fault. Fault trace 1 was considered the more likely. 'A-B', 'E', 'F', and 'H' are known subsurface faults. From Koff (1978, fig. 6).*

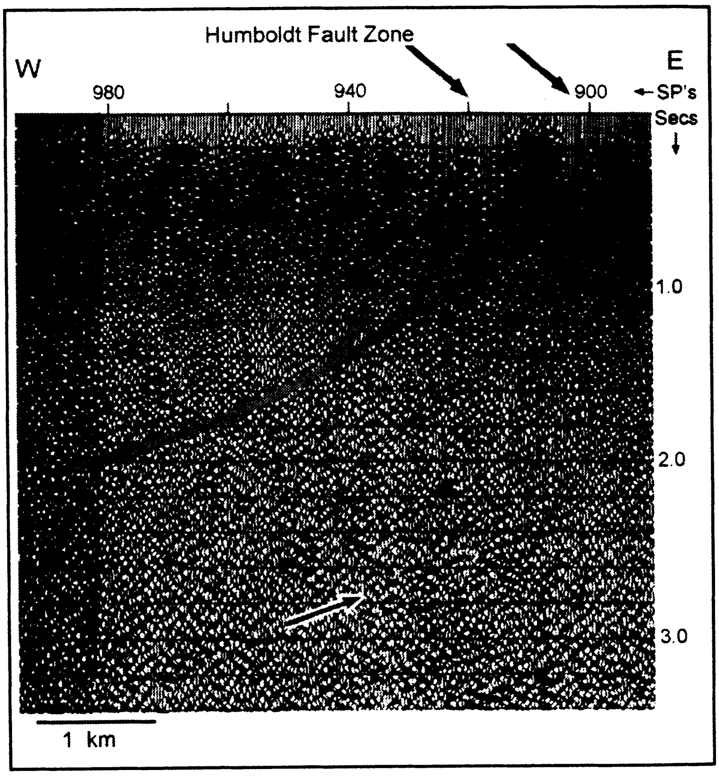

Figure 29. *COCORP line across Humboldt Fault Zone in T. 5 S., R. 12 E., Nemaha County, Kansas. The indicated listric, west-dipping reflector deep in the basement indicates author's proposed causative fault for the Nemaha uplift at this locality. Modified from Serpa, Setzer, and Brown (1989).*

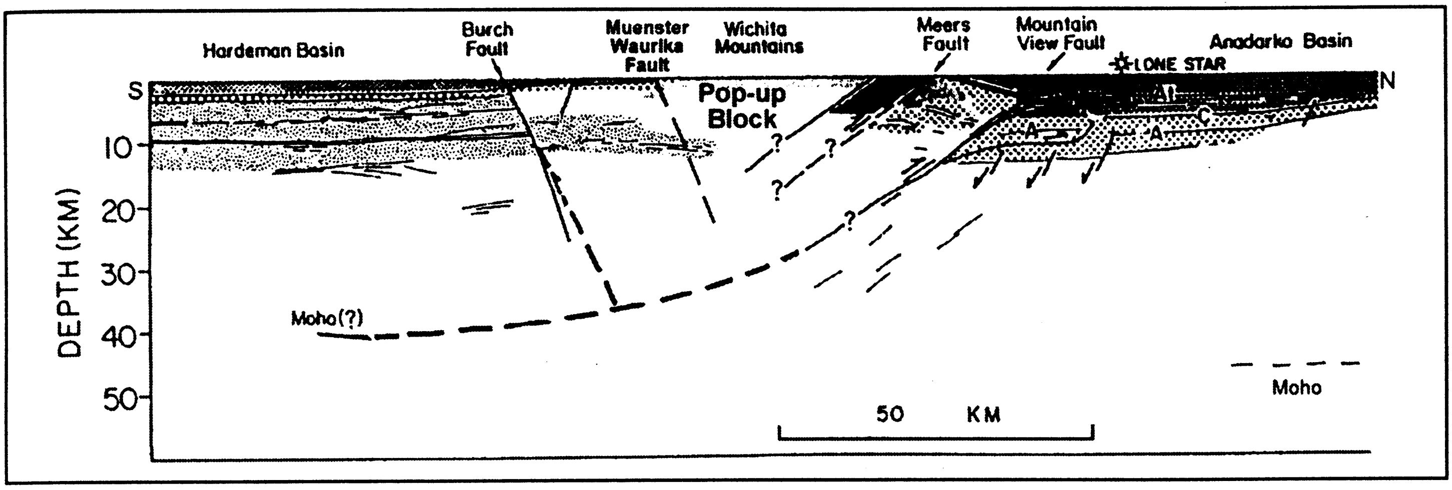

Figure 30. *Interpretation of COCORP line across Wichita Mountain uplift, southern Oklahoma. South-dipping Mountain View thrust has been extended in listric fashion to south, and Burch fault and Muenster-Waurika faults are shown as backthrusts branching from the Mountain View fault. From Brewer and others, (1983).*

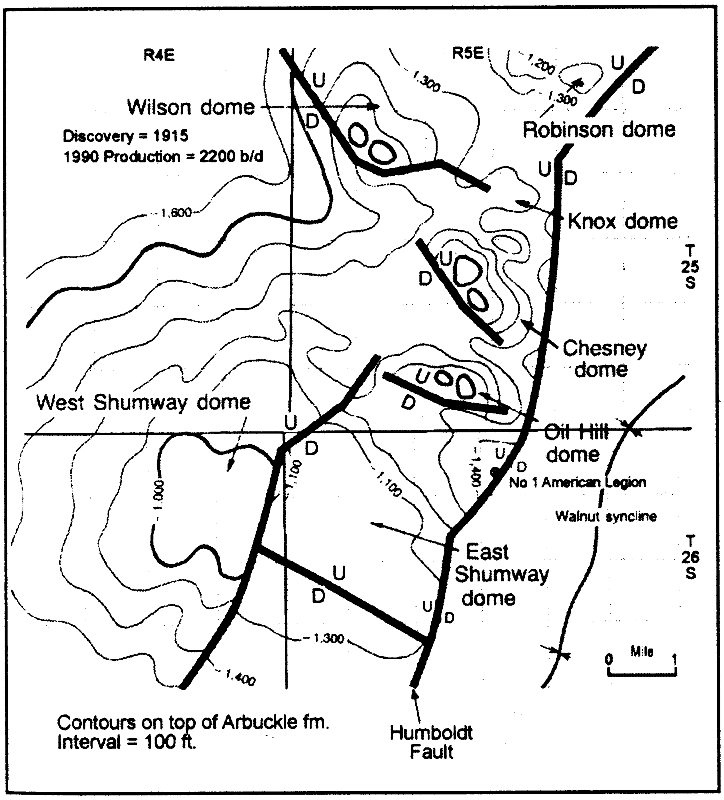

Figure 31. *Structure map on top of the Arbuckle Fm., El Dorado field, Butler County, Kansas. Contour interval = 100 ft. The main east-bounding fault was shown by the American Legion well in 1982 to be a reverse fault (see Fig. 19, Part 1). Left-slip movement in the later stages of compression is proposed as the cause of the northwest trending domes on top of this huge anticline. Modified from Ramondetta (1990). Reprinted with permission of Oil & Gas Journal.*

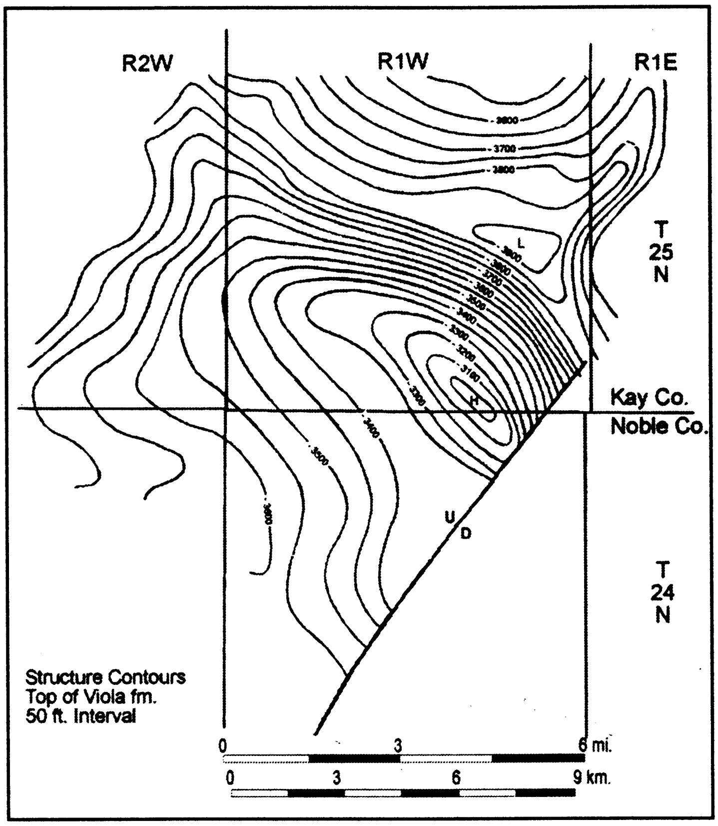

Figure 32. *Structure map on top of the Viola Fm., Tonkawa field, Kay and Noble Counties, Oklahoma. Contour interval = 50 ft. The east bounding, northeast-trending fault is part of the Nemaha system. The northwest trending fold illustrates left-lateral strike-slip movement. Modified from proprietary map, courtesy of L. Gatewood (1983).*

data.) On the right side of Figure 36 the most recent ages of the three tectonic events for the Appalachians are summarized by Shumaker (1996) and Hatcher (1999). The ages of the three orogenies, Taconic, Acadian, and Alleghenian, which resulted from plate tectonic collisions on the eastern continental margin, are identical in time to the three events that affected the Nemaha system. From this, it is my conclusion that it was these plate collisions-compressional events-principally the Alleghenian, which gave rise to the Nemaha uplift.

By far the most extensive and intense event in both areas was the Alleghenian, that raised the Appalachians and the Nemaha simultaneously, and created the "pre-Penn" unconformity throughout the U.S. Midcontinent. An Alleghenian-age thrust, the "Great Smoky Fault," is exposed in eastern Tennessee. Hatcher (1999) has studied the thrust, and has concluded that it has a total westerly displacement of >150 miles (250 km).

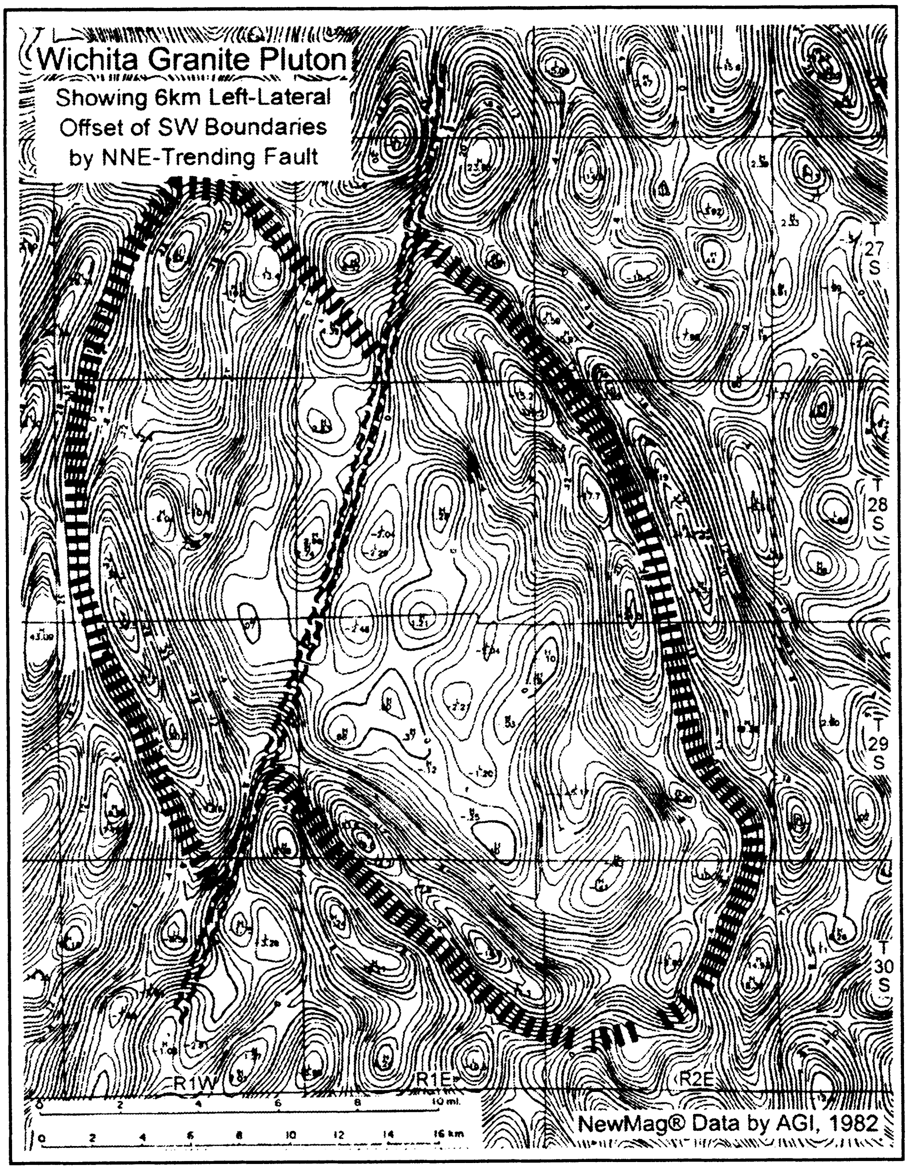

Figure 33. *Detailed residual aeromagnetic map showing the boundary of the Wichita Granite Pluton. The 6 km (4 mi.) left-lateral offset occurred contemporaneously with uplift of the Nemaha system. From proprietary data, courtesy of Applied Geophysics, Inc. (1982).*

Conclusions

1. The Nemaha Ridge/Uplift was generated by thrusting in three regional compressional events that were contemporaneous with the birth of the Appalachian Mountains on the east and probably the Ancestral Rocky Mountains on the west.
2. The main bounding thrust (generally on the east side) is steeply dipping or vertical, and has been frequently mistaken for a normal fault.
3. In many places where this fault has been intersected in wells, it has reverse displacement and dips steeply west. It is believed to decrease in dip with depth in the basement, becoming a typical listric thrust fault similar to dozens of thrusts mapped in the Rockies.
4. Thrusting has piled rock upon rock (tectonic loading) resulting in crustal downwarping in front of the thrust.
5. Considerable left-lateral strike-slip movement occurred on the Nemaha system, evidently during the later phases of thrusting.
6. "Relaxation" normal faulting occurred in response to isostatic adjustments after the compressive phase ceased in late-Permian or post-Permian time.

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I would like to thank the following geologists and geophysicists who unselfishly and graciously provided me with cross-sections, well logs, technical articles, theses, names of other people, etc., that I have used in this study of

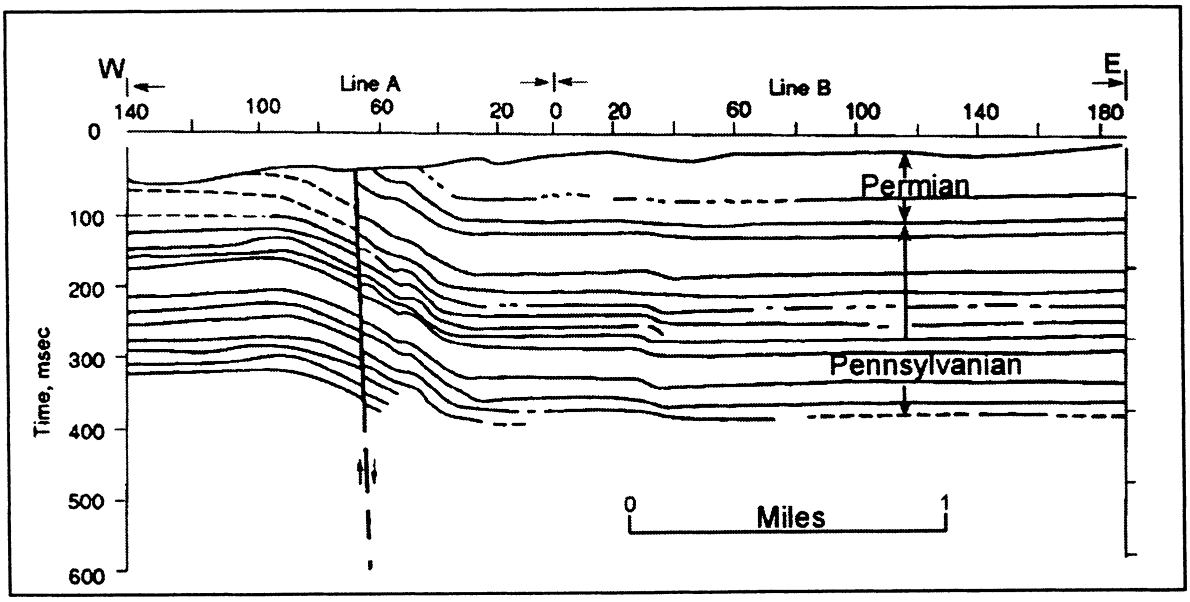

Figure 34. *A shallow high-frequency, high-resolution seismic line on east flank of the Nemaha uplift, T.1 S., R. 13 E., Nemaha County, Kansas. Note the down-to-the-east normal fault cutting the Pennsylvania Permian beds. From Stander (1989).*

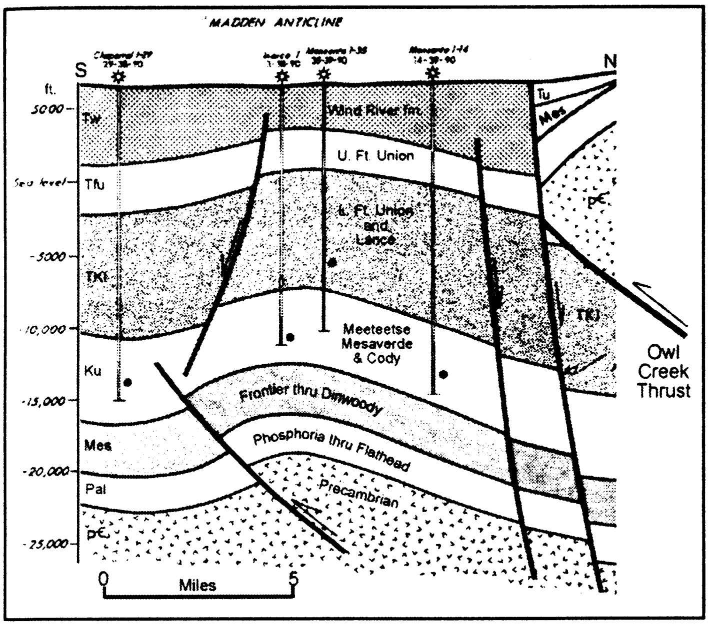

Figure 35. *Interpretation of seismic and well data of area immediately in front of the far traveled (>20 km?) Owl Creek thrust in Wyoming. Three steeply-dipping, post-thrusting "relaxation" faults occur here. From Ray and Keefer (1985).*

the Nemaha system: Peter Berendsen, Jock Campbell, Marvin Carlson, Harold Davis, Jan Dodson, Jim Evans, Roberto Feige, Rick Fritz, Lloyd Gatewood, Jerry Hodgden, Gerald Honas, Sherrill Howery, Fred James, Joseph Laravie, Dave Montague, Peter Moreland, David Newell, Bob Northcutt, Joe Preece, Dean Seeber, Frank Schloeder, John Shelton, the late Bob Slamal, Bill Towner, Lynn Watney, and Jack Wilson.

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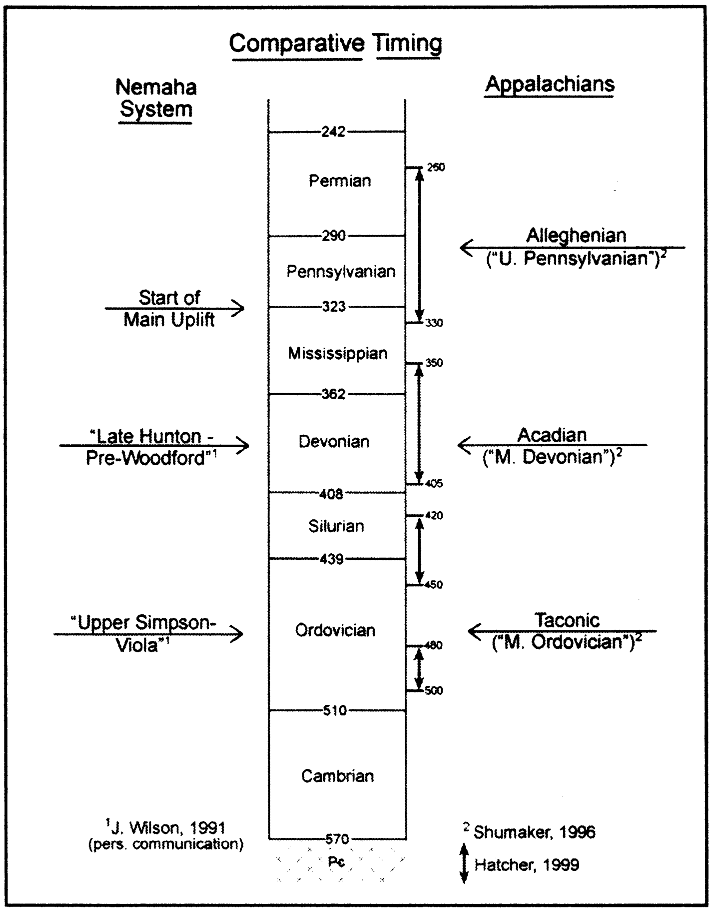

Figure 36. *Comparison of the timing of the Taconic, Acadian and Alleghenian orogenies of the eastern seaboard with the Ordovician and Devonian "disturbances" and the main late Mississippian-Pennsylvanian uplift of the Nemaha system. Ages are in millions of years. Sources of data for Nemaha System from Wilson (personal communication, 1991) and for Appalachians from Shumaker (1996) and Hatcher (1999).*

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ABOUT THE AUTHOR:

S. Parker Gay, Jr. is President and Chief Geophysicist of Applied Geophysics, Inc., Salt Lake City, Utah, USA, a company he founded in 1971. He received his academic training at MIT (B.S., 1952) and Stanford University (M.S., 1961). He served as a photo-interpreter in the U.S. Air Force, 1952-55; worked as a geophysicist and geologist for Utah Construction Company and Mining and its subsidiary, Marcona Mining Company, in the western U.S., Alaska, and Peru in exploration for iron ore and ground water, 1956-64; was a geophysicist for Asarco, Inc. in Salt Lake City, Utah, and Knoxville, Tennessee, 1964-68; organized and managed the U.S. subsidiary of Scintrex, Ltd. in Salt Lake City, Utah, 1968-70; founded American Stereo Map Co. in 1970; and founded Applied Geophysics, Inc. in 1971.

Applied Geophysics is a geophysical contracting organization that was involved in ground and airborne geophysical surveys for metallic ore deposits, uranium and, since 1982, mapping basement under petroleum basins for oil and gas companies. In 1974, Gay co-founded the International Basement Tectonics Association, has authored or co-authored 43 professional papers or books, and has presented 119 talks to professional organizations.