

Some Observations on the Amarillo/Wichita Mountains Thrust-Fold Belt and its Extensions Southeast into East Texas and Northwest into New Mexico



Abstract

The 400-mile-long Amarillo/Wichita Mountains thrust and fold belt, also called the “Southern Oklahoma Aulacogen,” is seen in detail in the extensive aeromagnetic maps flown by Applied Geophysics, Inc. 25 to 30 years ago. Much has been written about the geology of this system, both the overall extent as well as myriad details along its length by geologists in both Oklahoma and Texas over the years, but some new features of the system seen on the magnetic maps have never appeared in the literature. For example, the apparent thinning and dying out of this system to the west in Union County, New Mexico, just west of the Texas Panhandle is visible on the magnetics, as is the probable strike-slip offset of the system at its east end in northeast Texas. In the latter locality it may have been translated 410 miles to the northeast by a regional strike-slip fault and ended up in southeast Missouri. Thus, the Broxton Fault of Oklahoma may have its extension as the St. Genevieve Fault in the St. Francis Mountains of Missouri.

The magnetic maps indicate that an east-west strike-slip fault, the “Cambridge Fault,” offsets the Wichita Mountain block in right-lateral fashion along the south line of Beckham and Washita Counties in Oklahoma. This fault is 70 miles north of, and parallel to, the similar east-west - trending Matador Arch, which may also have had strike-slip movement. To the south, the location of the Marietta Basin on top of the Wichita Mountain block is plainly visible on the magnetics, as is the location of the Ardmore Basin in front of it.

Arguing from a strictly geological standpoint and relying on many key articles from the recent geological literature, the Wichita Mountains were raised by thrusts, and the buried Amarillo Mountains, because of their proximity and colinearity with the Wichita Mountains would necessarily have been raised by thrusts as well, in spite of fairly recent papers that show only vertical faults there. Further-more, by adding a long listric segment to the Mountain View thrust fault shown on the COCORP seismic line and extending the Muenster-Waurika Fault down to the north as a back-thrust, it is seen that the Wichita Mountain block is probably a gigantic V-shaped “pop-up block.” This makes it similar to the Front Range of the Rockies in Colorado, the Uinta Mountains in Utah, and the Central Basin Platform in the Permian Basin of Texas, among others.

Since the Amarillo-Wichita Mountain system is a classical thrust-fold belt, there may be many oil and gas fields within this belt similar to those in the prolific western U.S. thrust-fold belt. Only one such field has been found on top of the uplift: Cottonwood Creek, discovered in 1987 in Carter County, Oklahoma, by CNG Production Company (New Orleans), but there should be others on both sides of the Oklahoma-Texas line.

INTRODUCTION

Oklahoma's most spectacular structure is undoubtedly the "Southern Oklahoma Aulacogen," which in this article I refer to as the Amarillo-Wichita Mountains thrust-fold belt. My experience with this structural system dates back 30 years when Applied Geophysics, Inc. began flying a series of detailed aeromagnetic surveys that eventually extended continuously along the belt from the Texas-New Mexico border on the west, across the Texas Panhandle, then across the width of southern Oklahoma to Lamar County in northeast Texas on the east, a distance of nearly 400 miles. The aeromagnetic

mapping, because of its regional extent, yet detailed nature, reveals a number of interesting features of the system that are not common knowledge. I will focus on these specific facets of the thrust and fold belt, rather than try to make this yet another discussion of the "Southern Oklahoma Aulacogen," of which there have been many, notably those of Burke (1977), Gilbert (1983, 1987), Donovan (1982, 1984), and Perry (1989), among others.

CENTRAL REGION

My first discussion will be of the nature of the deep Anadarko basin in front of the Mountain View and Broxton Faults

in Oklahoma. This discussion does not involve the magnetic data, but it will be pertinent to later observations of the Mountain View system based on the magnetics. I start first by showing a segment of the southwest to northeast cross section of Oklahoma (see Figure 1) published by the Oklahoma Geological Society forty years ago (Witt, 1971). The most notable feature of the cross section (but not the feature which I will emphasize later) is the verticality shown by the many faults that have uplifted the Wichita Mountains. Today, of course, we know that the Wichita Mountains were raised by a series of northeast-directed thrust faults resulting from intense northeast-

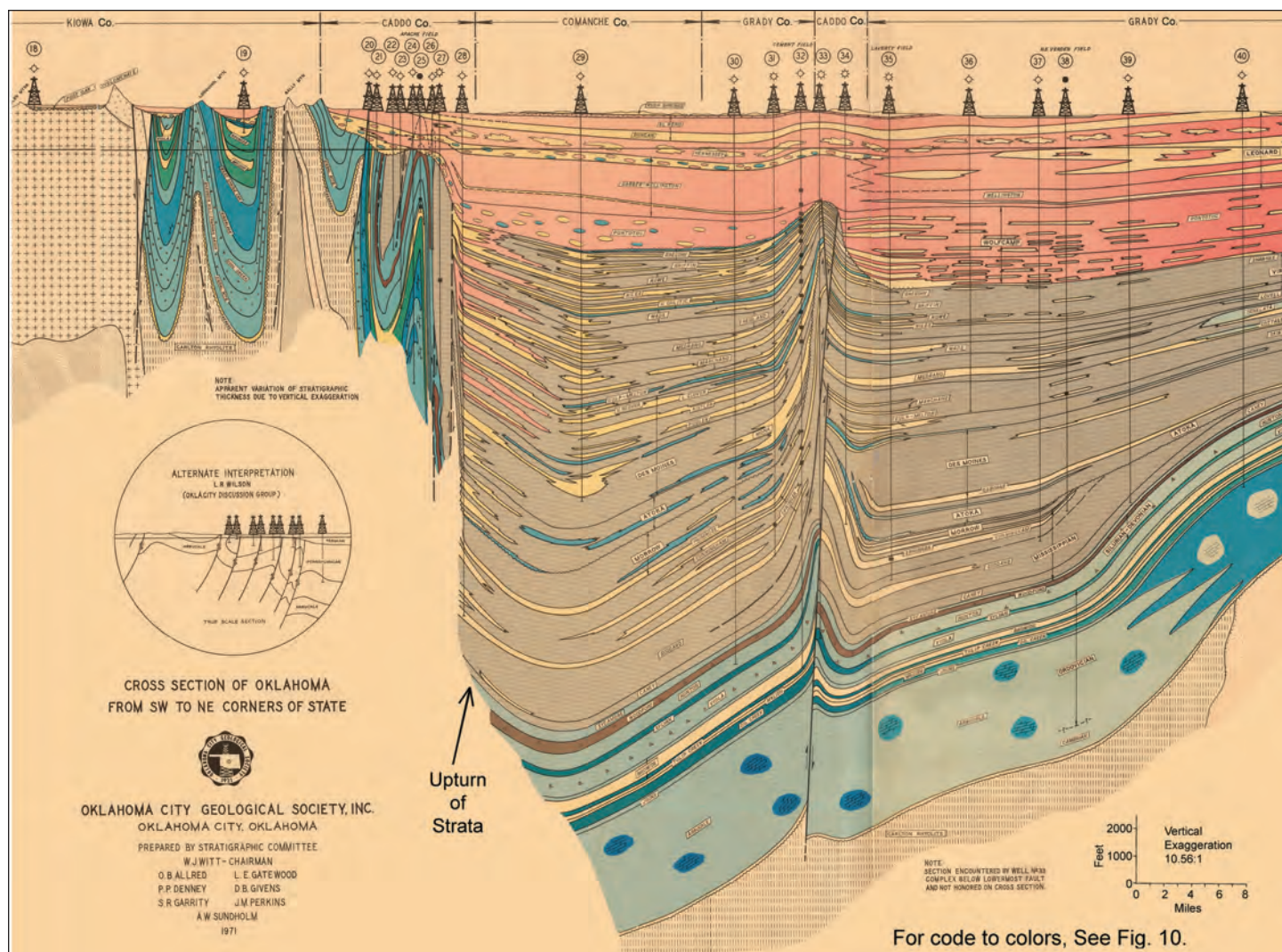
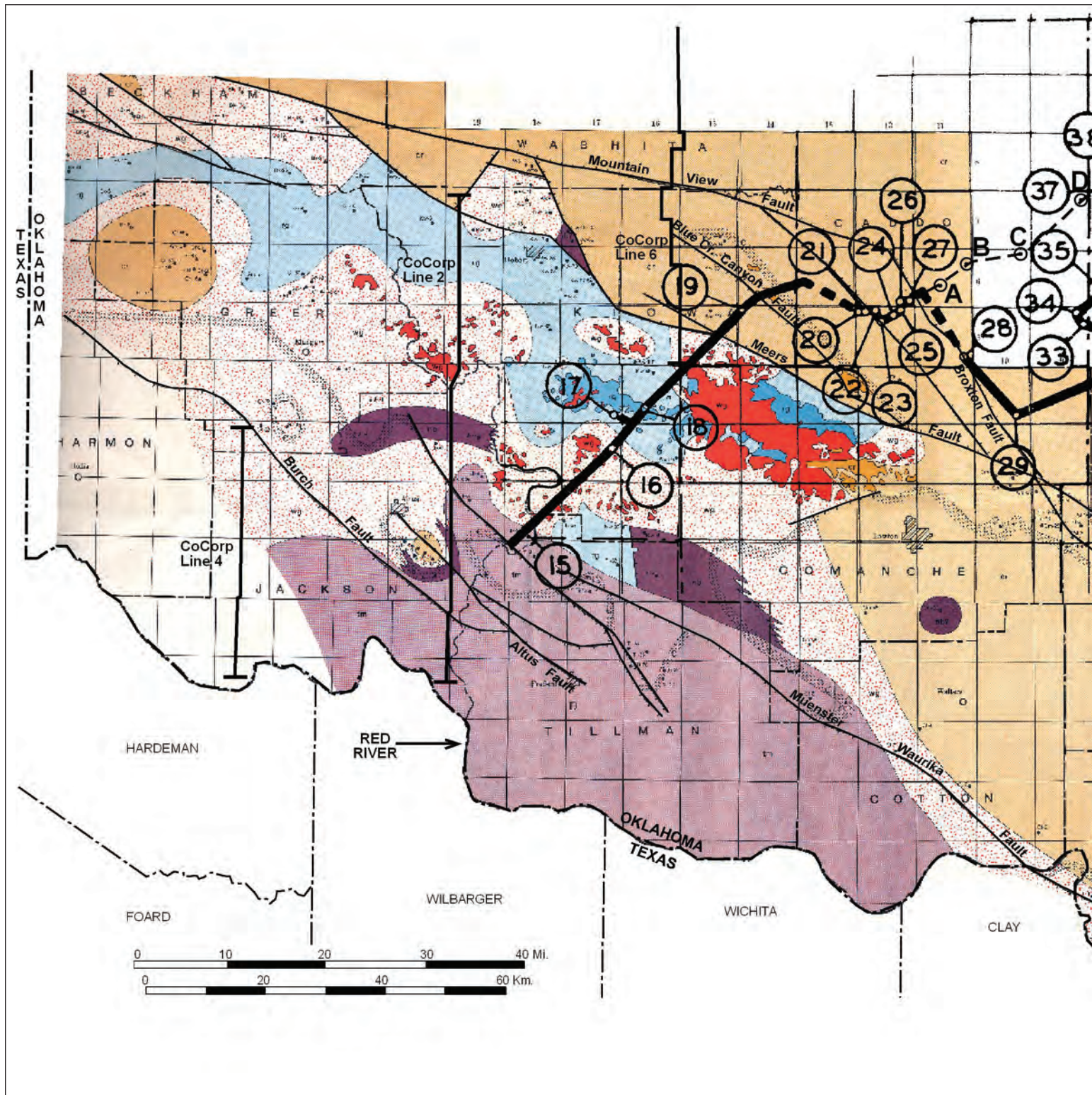


Figure 1. Part of the 1971 Oklahoma Geological Society southwest to northeast cross section of the state. There are two major flaws in the cross section, one of which was recognized at the time of publication. The other is discussed in this paper.

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southwest regional compression in Late Mississippian-Early Pennsylvanian time and perhaps earlier. At the time the cross

section was in preparation over four decades ago, many geologists in the Oklahoma City Geological Society knew, or

suspected, that the faults were thrusts, and stated they could not "condone the publishing of the cross section in its present

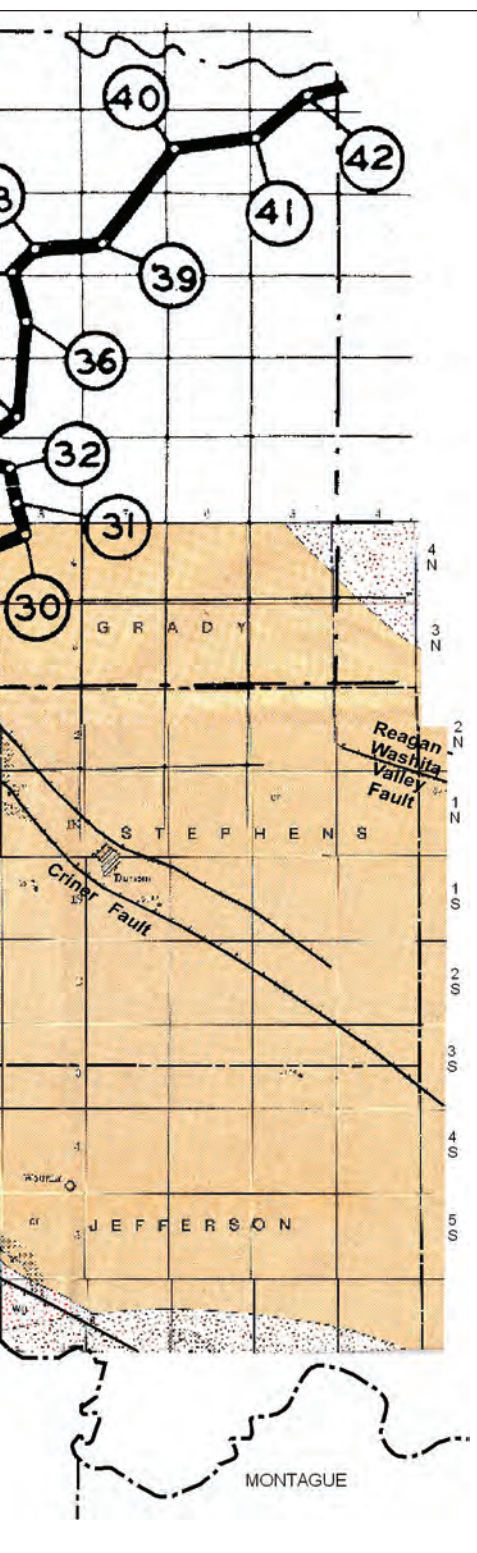


Figure 2. Superposition of the wells of the southwest-northeast cross section of Oklahoma (1971) on the geology map of Ham, et al., 1964 (Plate I), in the area of the "Big Loop." Faults are labelled as per Harlton, 1972. COCORP lines are from Brewer, et al., 1983. The discussion in the text reveals why geological cross sections are properly constructed along straight lines, or near-straight lines, without major excursions such as this.

geologists prevailed on the map committee to publish an "alternate explanation" with thrust faults (see circle on left side of Figure 1). This is interesting, in that thrust faults, not vertical faults, were shown by the committee at three other places on the original cross section under 1) Altus Field, 2) Cement Field, and 3) Oklahoma City Field (although under the latter, there is an uplift drawn in the form of a thrust but a line for the fault itself does not appear).

Apart from this flaw in the map, there is yet another major problem with the northeast-southwest cross section that I have never heard discussed or written about, but that is equally serious, in this writer's opinion. That is, the "southwest-northeast" cross section is not southwest-northeast. In Figure 2, I show what I call the "Big Loop." This is a major excursion of the cross section from its stated southwest-northeast direction – a procedure not allowable in constructing cross sections, as it can distort the geology in an unrealistic way. Cross sections are properly made by drawing a straight line or a near-straight line on a map and projecting wells onto it at right-angles from left and right sides (or sometimes obliquely, parallel to regional geology).

In Figure 2 the locations of the wells comprising the "Loop" were taken directly from the map sheet and overlain on a portion of the geological map from Ham et al's Plate I (1964) to show what effect the Loop has on the cross section. It can be seen that the right angle excursion from well 27 to wells 28 and 29 runs the cross section down along the Broxton Fault. Well 28 touches or almost touches the fault, with the result that it has evidently drilled through the uplifted hanging wall. The cross section thus shows an upturn in the basin strata here (see Figure 1), making

it appear that there is a bowl-shaped depression under, and in front of, the mountain front. This has most likely influenced later authors in showing the same upturn of the strata under the mountain front until fairly recently (e.g., Johnson, 2008, p. 7).

Underneath many thrust-faulted mountain ranges it has been shown that the down-warped strata usually continue uninterrupted without any upturn all the way to the frontal thrust. Figure 3 shows a well-controlled example from the adjacent Ouachita Mountains by University of Oklahoma structural geologist Shankar Mitra (2003) (after Hardie, 1988); Figures. 4, 5, and 6, show similar examples from the U.S. Rocky Mountains; and Figures. 7 and 8 show examples from the Canadian Rockies. In Figure 9 there may be an explanation for this configuration of strata in Mitra's (2003) diagram of the usual sequence of thrusting. The more frontal of the thrusts in such a system are the last to form (which to me is not intuitive). They thus involve strata previously undeformed by compressional events such as earlier faulting or "initial folding."

In Figure 10, I have made an attempt to reconstruct the southwest-northeast Oklahoma cross section by eliminating the Big Loop and substituting four later wells: A, B, C, and D (locations shown in Figure 2 that span the gap between original wells 27 and 37. This procedure eliminates about 43 miles of cross section going around the loop and adds 23 miles of section across the bottom of the loop - a net shortening of the cross section (and of the basin as shown) of 20 miles. In this revision the cross section shows no upturn of strata in front of the range-front fault, the Broxton, in this case. (Some geologists consider the Broxton Fault to be just a segment of the Mountain View Fault, but this is un-

form" (Cochrane, 1971), i.e., with vertical faults. It was, nevertheless, published in that form. However, these dissenting

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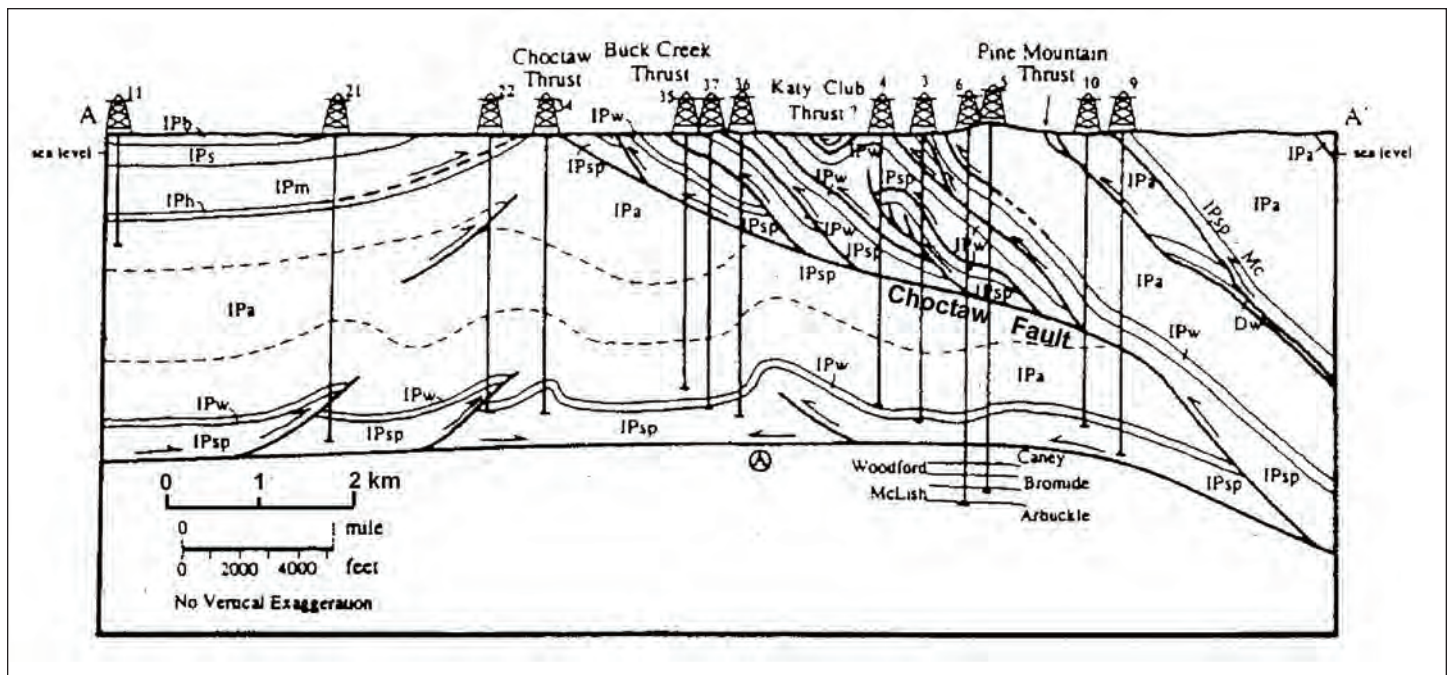


Figure 3. A structural cross-section across the Ouachita thrust system in southeast Oklahoma shows that the sedimentary strata continue uninterrupted beneath the frontal thrust of the Ouachita Mountain system, the Chocklaw fault, with no upturning - as proven by wells. From Hardie, 1988.

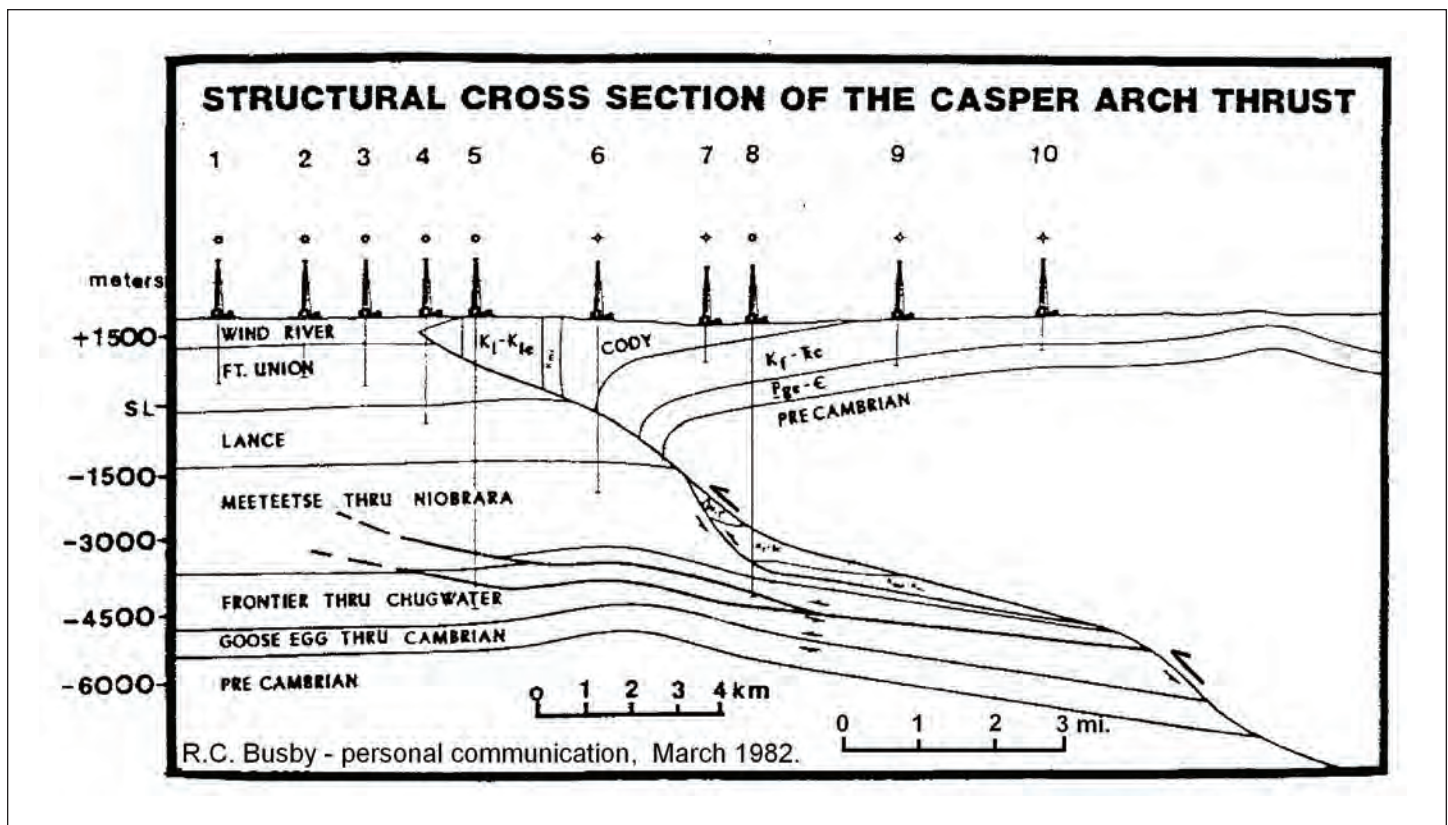


Figure 4. Another example of strata underneath a frontal thrust that shows no upturning, this one from the Casper Arch in Wyoming in the U.S. Rocky Mountains. From Skeen and Ray, 1983.

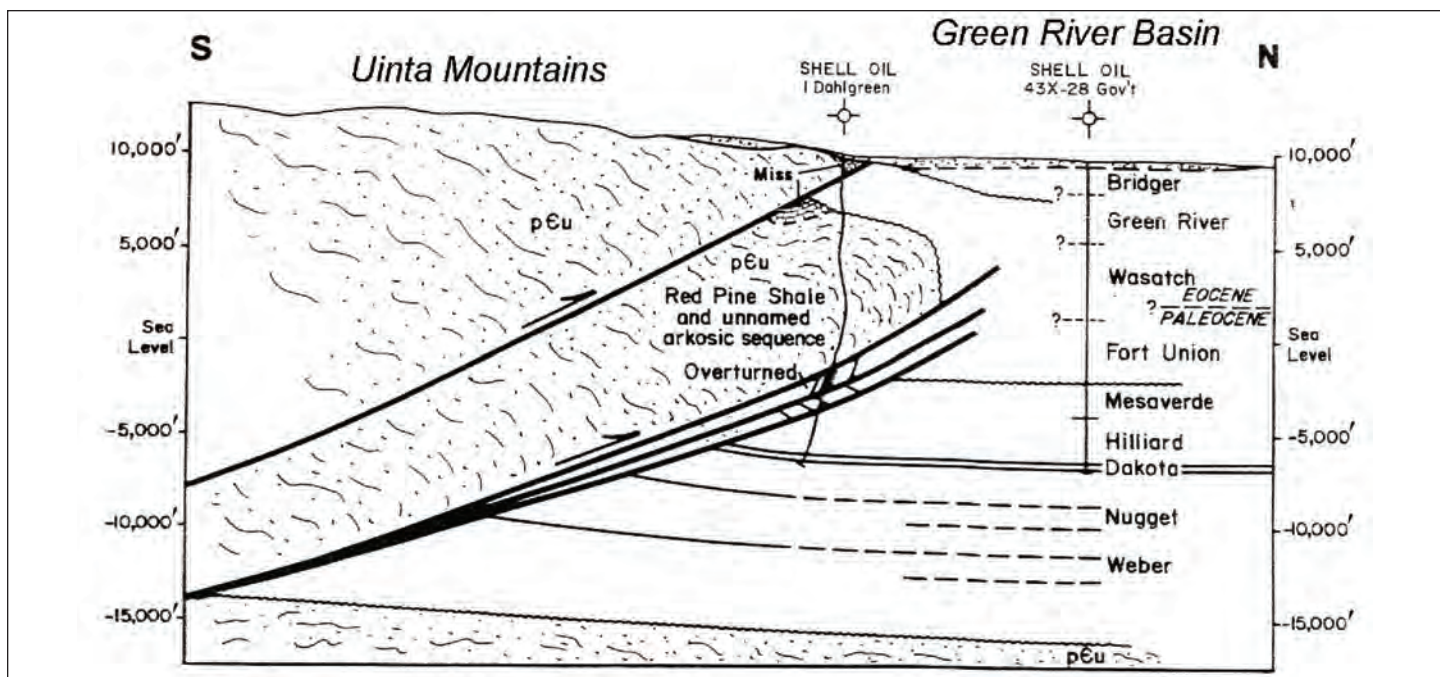


Figure 5. A second example from the U.S. Rockies that shows no upturn of strata underneath a frontal thrust fault, this one on the north side of the Uinta Mountains in Utah, overlapping the Green River Basin in Wyoming. From Gries, 1983. No vertical exaggeration.

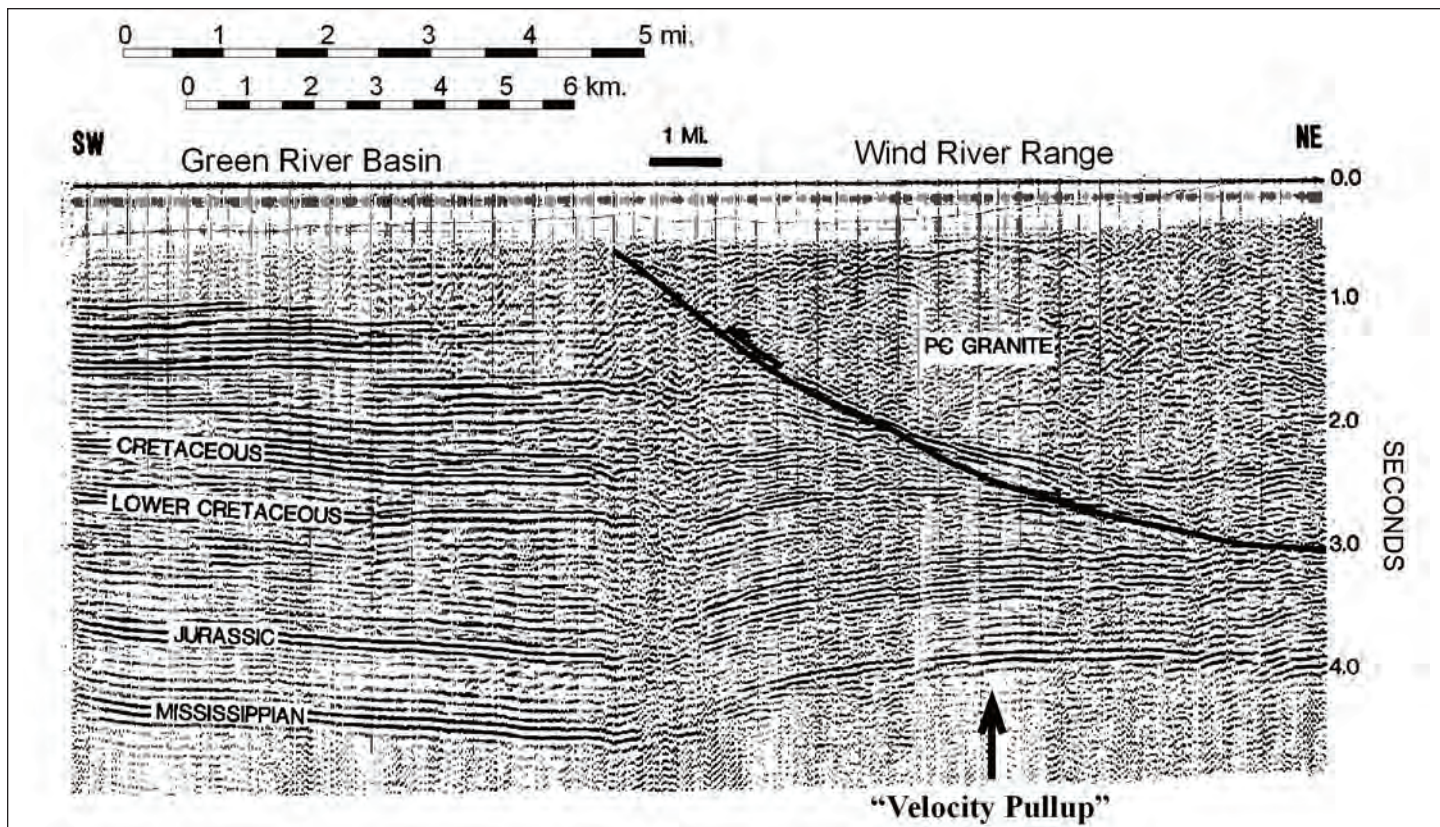


Figure 6. Seismic line that clearly shows the Wind River Basin Fault which uplifted the Wind River Range over the Green River Basin in Wyoming. Note the "velocity pull-up" under the higher velocity granite in the hanging wall. Also note the lack of any sign of an upturn of strata underneath the thrust. From Lowell (1983) courtesy of Conoco.

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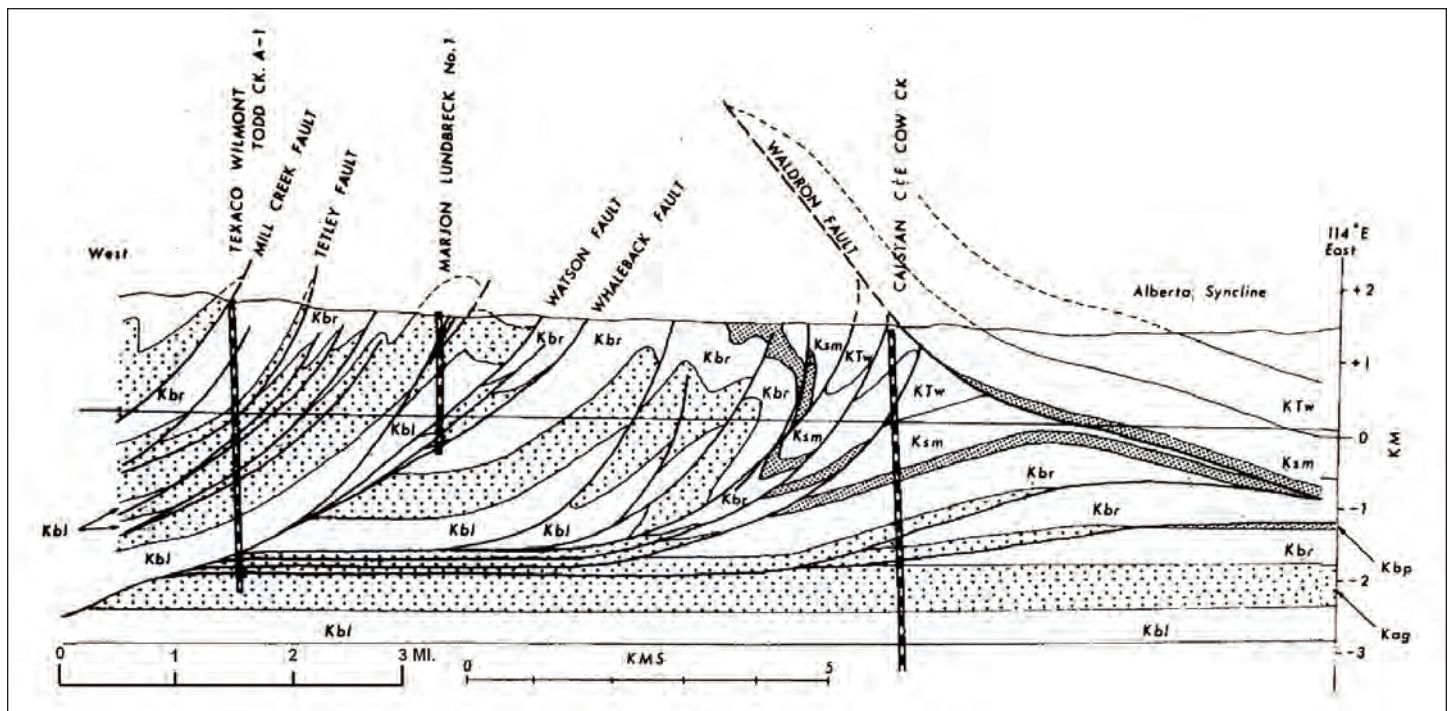


Figure 7. An example of complex thrust faulting in the Canadian Rockies that shows no upturning of underlying strata in front of the thrusting, again proven by well data. Structure of the eastern Rocky Mtn. foothills at $49^{\circ}45'$ N latitude. From Price (1981).

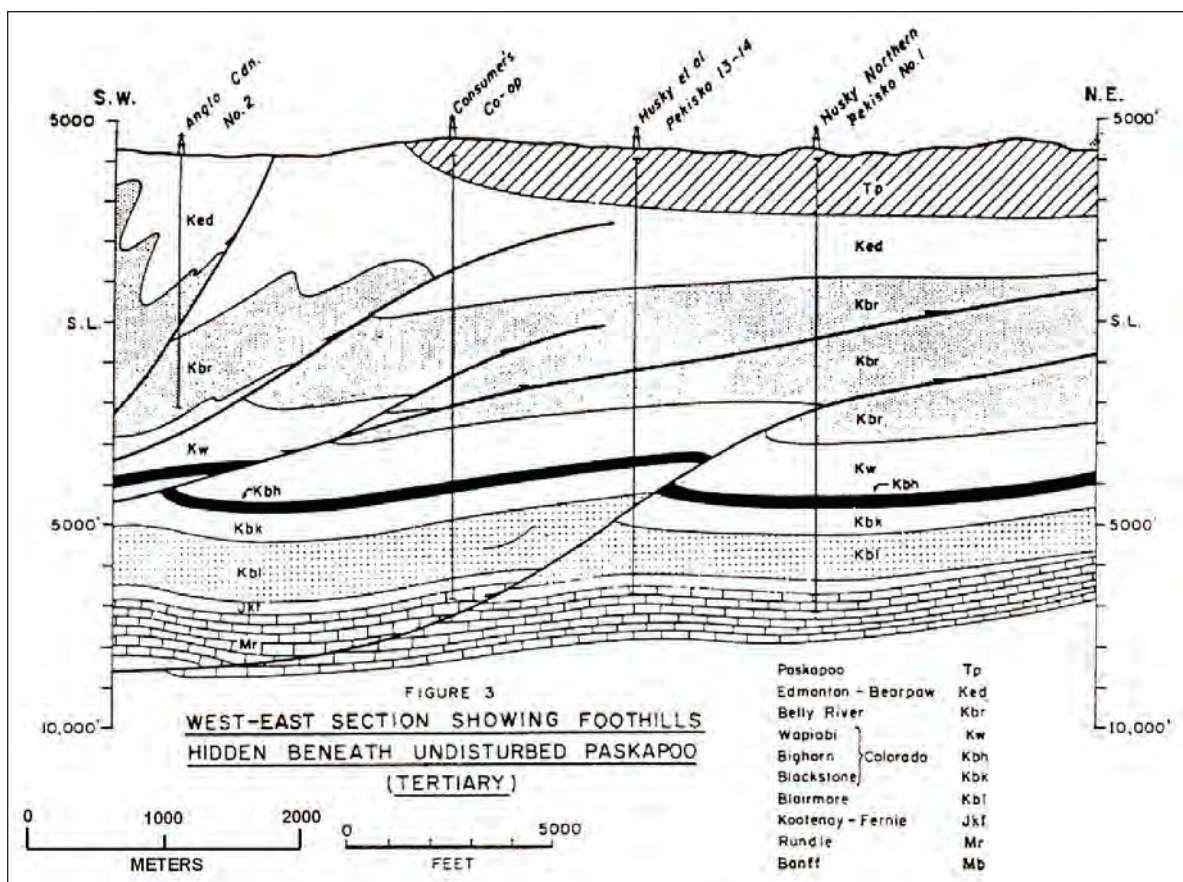


Figure 8. A second example from the Canadian Rockies that show major thrusts with no proven consequential upturning of strata underneath the thrusts. From Fox (1959).

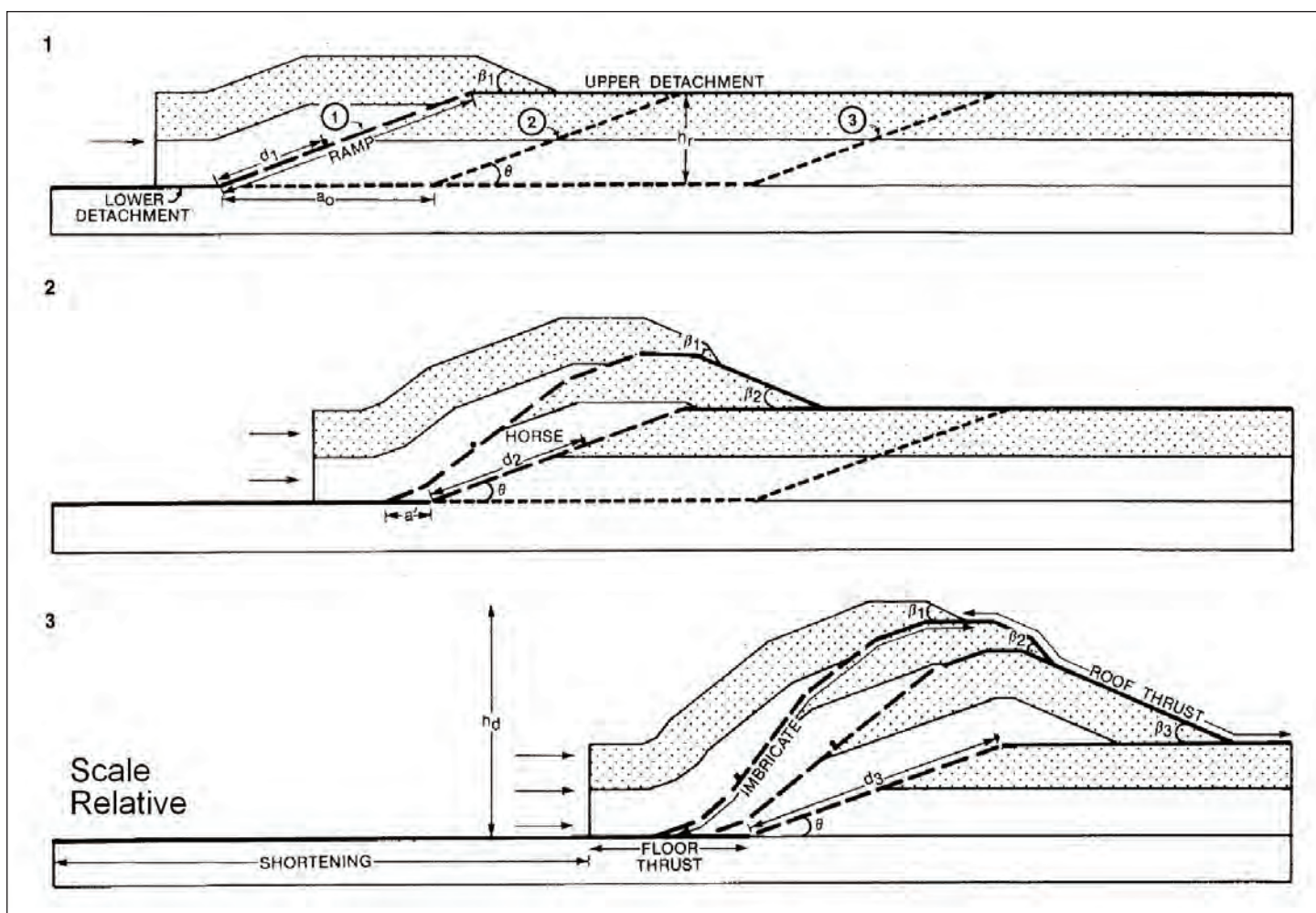


Figure 9. Explanation of multiple thrusting showing that once a thrust forms, later thrusts of this same system form successively in front of the first one, not behind it. (From Mitra, 1986.)

tenable, as the Broxton strike is some 25° different.) I consider the Broxton to be a “ 30° ” splay off the Mountain View. Such splays are common along regional strike-slip faults. See the splays off the San Andreas Fault in California (Harding, 1974, p. 131) and the Barisan Mountain Fault in Sumatra (Harding, 1974, p. 134), for example. These splay faults along the Wichita system may have been formed during an earlier episode of transpressional activity in late Proterozoic time.

In Figure 10 the placement of a thrust between wells A and B to account for higher intercepts in well A rather than drawing an upturn in strata here may be questioned by some. However, the formation tops in

wells D, C, and B fall along nearly straight lines. If there were an upturn it should be visible to a degree in well B, possibly in well C, and would not just appear in well A. Additionally, there is precedent for placing a buried thrust (or thrusts) in front of the Broxton or Mountain View Thrusts. Johnson (1989, p. 8) shows a cross section by H. G. Davis with this geometry, and Petroleum Information (1982, p. 11) shows the same but with vertical faults. McConnell (1989) says that cross sections across the Wichita Mountains “show basement-involved thrusts and folds similar to those recognized within the foreland of the Rocky Mountains” and then goes on to calculate the amount of shortening created by the thrusting, a rather definitive

statement against vertical faults. Therefore, my conclusion is that there is no upturn of strata under the Wichita frontal thrust. The strata are continuous without deviation from the shelf right down to the faults, as in the other examples I show in Figures 3 through 8. Note that these six figures are not theoretical. They are based on drilled wells or seismic data.

Knowledge of the probable configuration of the strata under the various thrusts in the Wichita Uplift is very important to oil and gas explorers, and the supposed, but non-existent, upturn of strata could be misleading for some.

The next topic I will discuss is the overall

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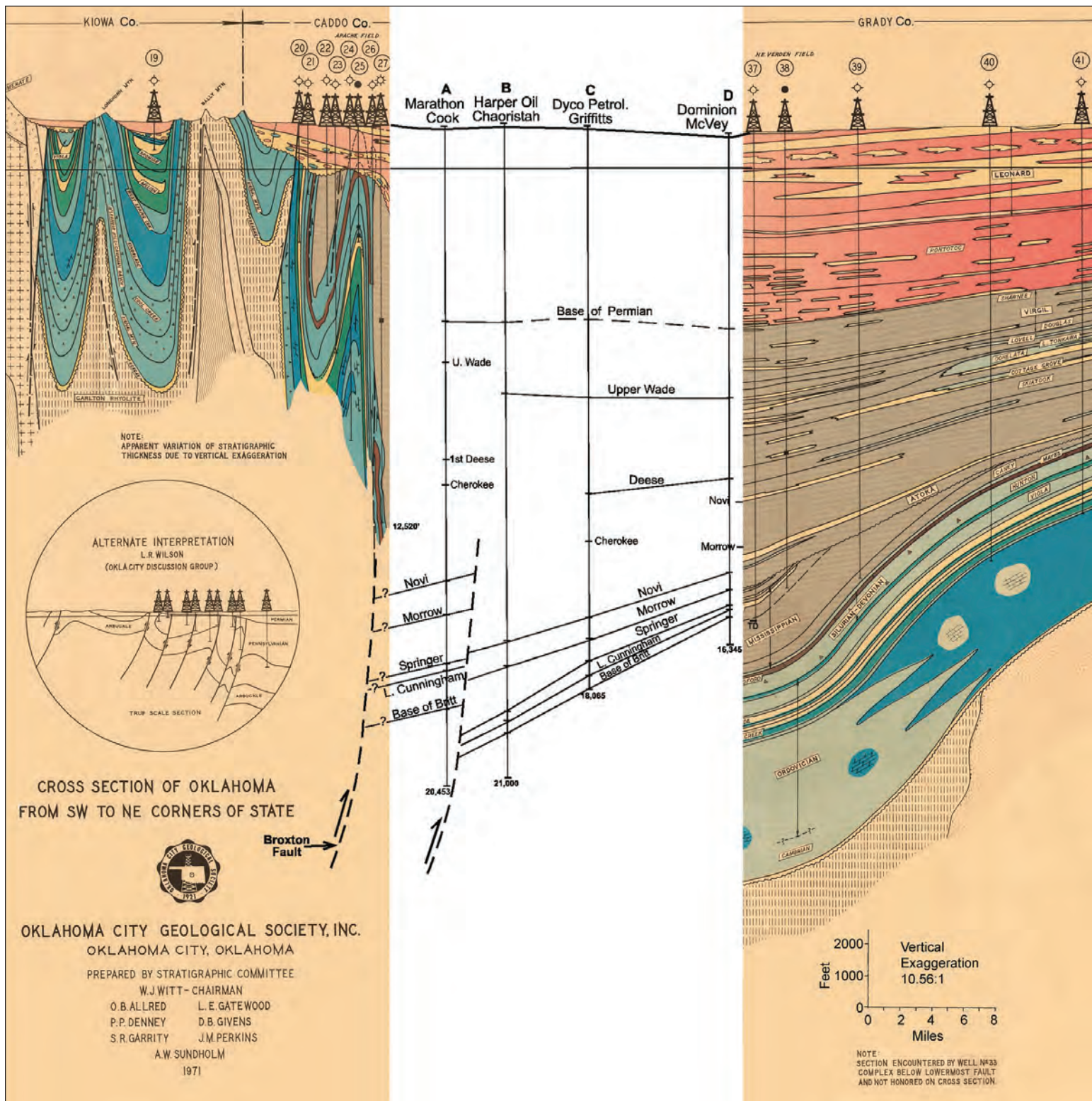


Figure 10. The author's reconstruction of the southwest to northeast Oklahoma cross section (Figure 1) that eliminates the "Big Loop" (see Figure 2). Four wells are used (A, B, C, and D) that cut across the base of the loop, shortening the section by 20 miles. In this new section the wells also eliminate the upturn in strata in front of the frontal fault, in conformance with cross sections in the Ouachitas and in the U.S. and Canadian Rockies (Figures 3 to 9).

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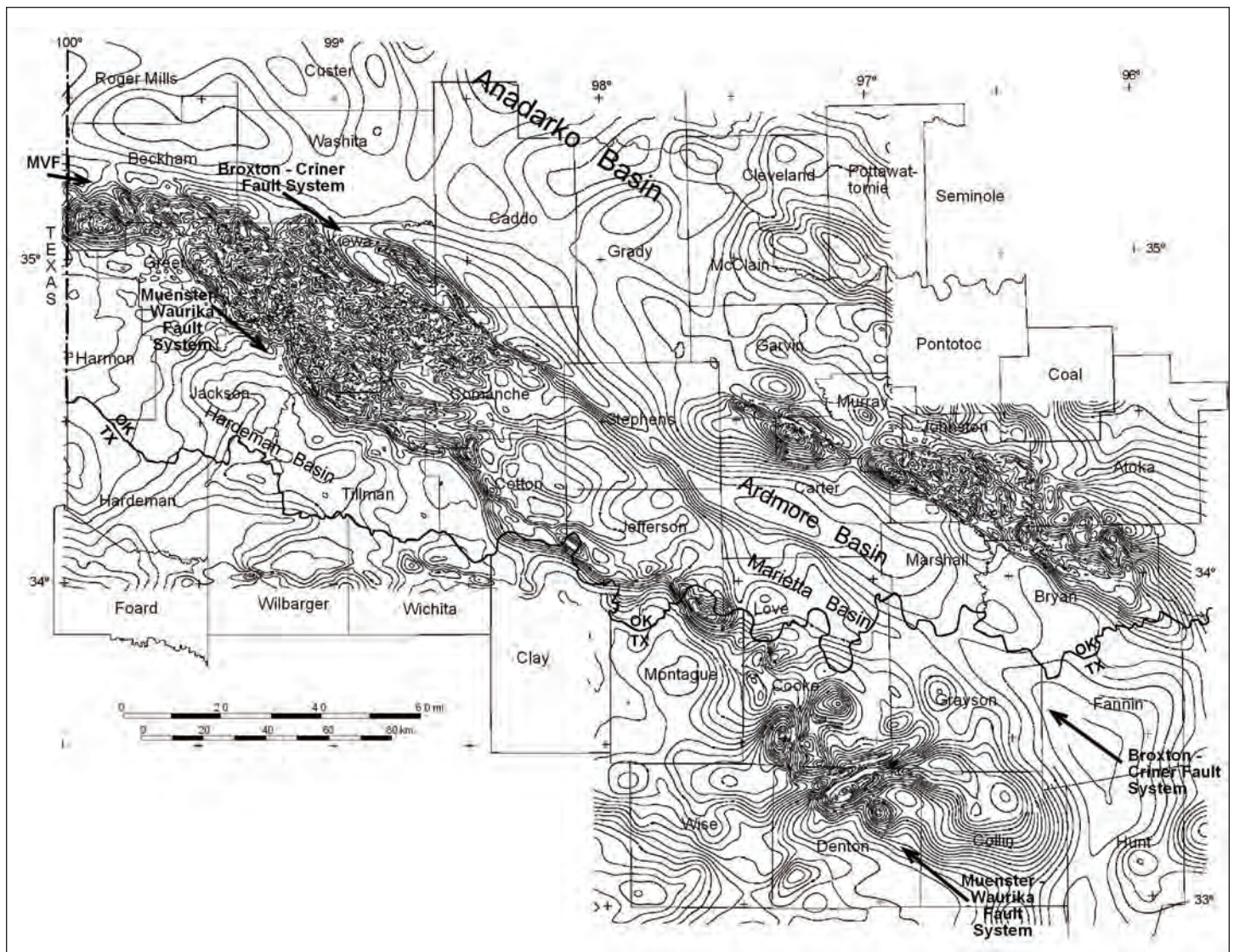


Figure 11. Small-scale regional total intensity aeromagnetic map of Wichita Mountains thrust and fold belt. Length of the belt shown here is 230 miles, extending from the Texas/Oklahoma line in Beckham County, Oklahoma, on the west to Collin County, Texas, on the east. North edge of the belt is defined by the Broxton-Criner Fault system, and the south edge by the irregular Muenster-Waurika Fault system. Note that the Marietta Basin sits on top of the southeast-plunging disturbed block. MVF = Mountain View Fault.

In Figure 12 note the form and position of the Hardeman Basin on the south side of the Wichita Uplift. The Hardeman Basin is a mirror image of the Anadarko Basin to the north but is not as deep. I explain this as follows: when thrusting first begins in a mountain building system such as this, rock is piled on top of rock, and by the law of isostasy, the earth's crust is depressed at this point. A single basin results, centered on the thrust, piled-up rock mass. As compression proceeds and more rock

is added by thrusting in front of that already present (Figure 9), then this side of the uplift is depressed more and becomes deeper – the Anadarko side in this case. I think a point is finally reached where the overlying weight becomes too great to be pushed forward again (how high were the Wichita Mountains at their highest?), and a back thrust occurs. This is undoubtedly influenced to a degree by the removal of much of the weight of the thrust-up mountain range by erosion, which is go-

ing on at the same time, making the load easier to lift compared to the formation of another frontal thrust. (The eroded debris is called “molasse” in the Alps, but in Oklahoma and Texas it’s “granite wash.”) What I have just explained is dealt with in much greater detail and with realistic examples of isostasy in an excellent article by Teresa Jordan (1981). Her deductions need to be heeded by anyone working on the structural geology of oil fields.

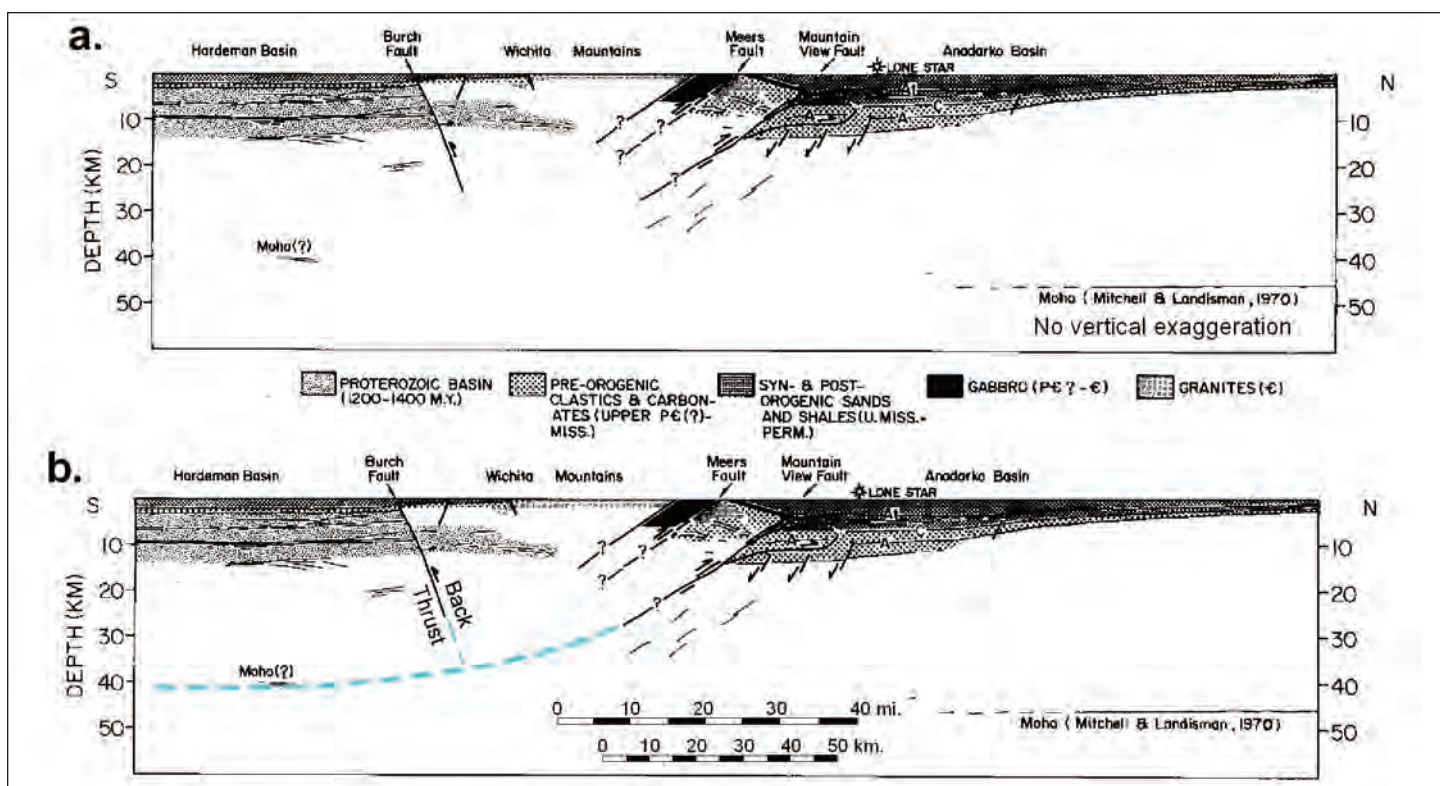


Figure 12. **a.** The COCORP deep seismic line across the Wichita Mountains fold and thrust belt. The line was shot in three segments (see Figure 2). This figure is from Brewer et al. (1983). **b.** My interpretation (blue) of the continuation of the main north- and south-bounding faults at depth, the Mountain View and the Muenster - Waurika (here called the Burch), a back-thrust.

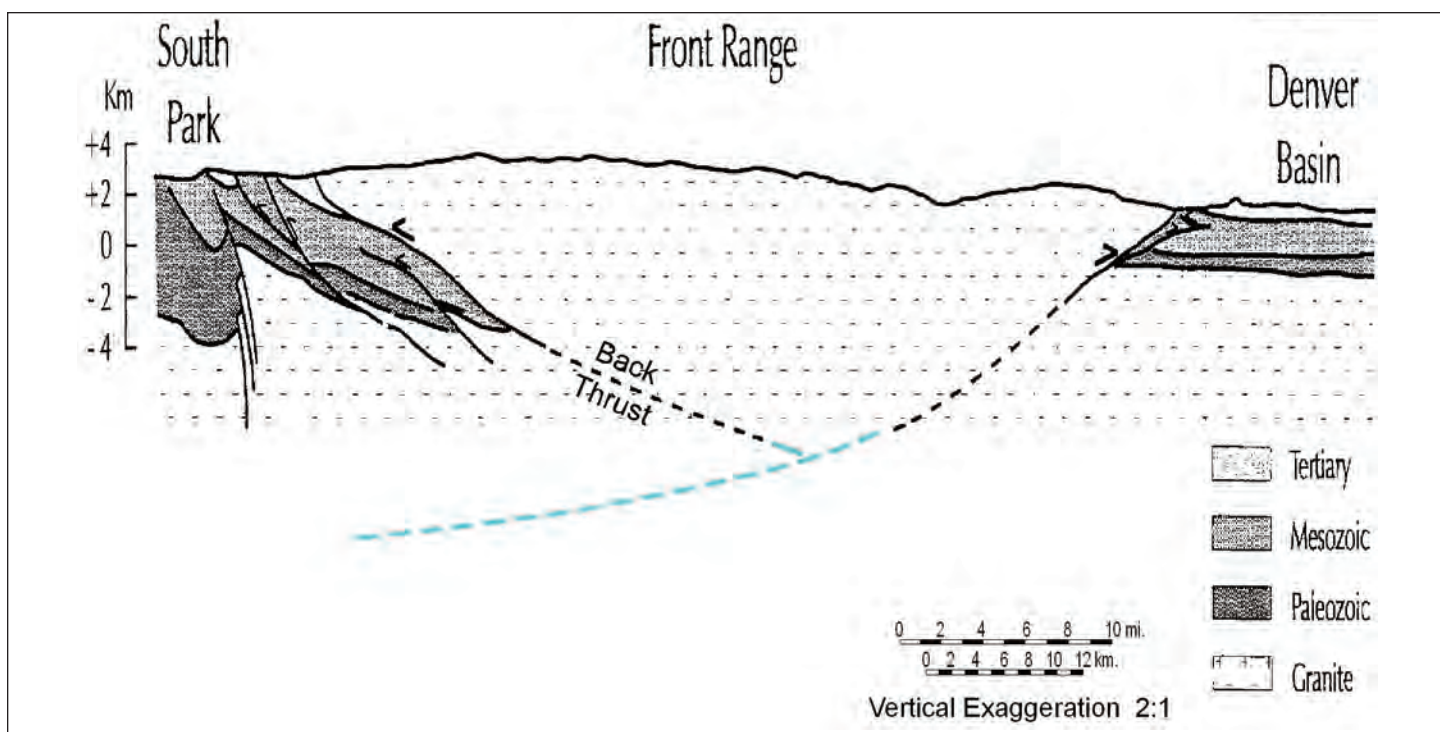
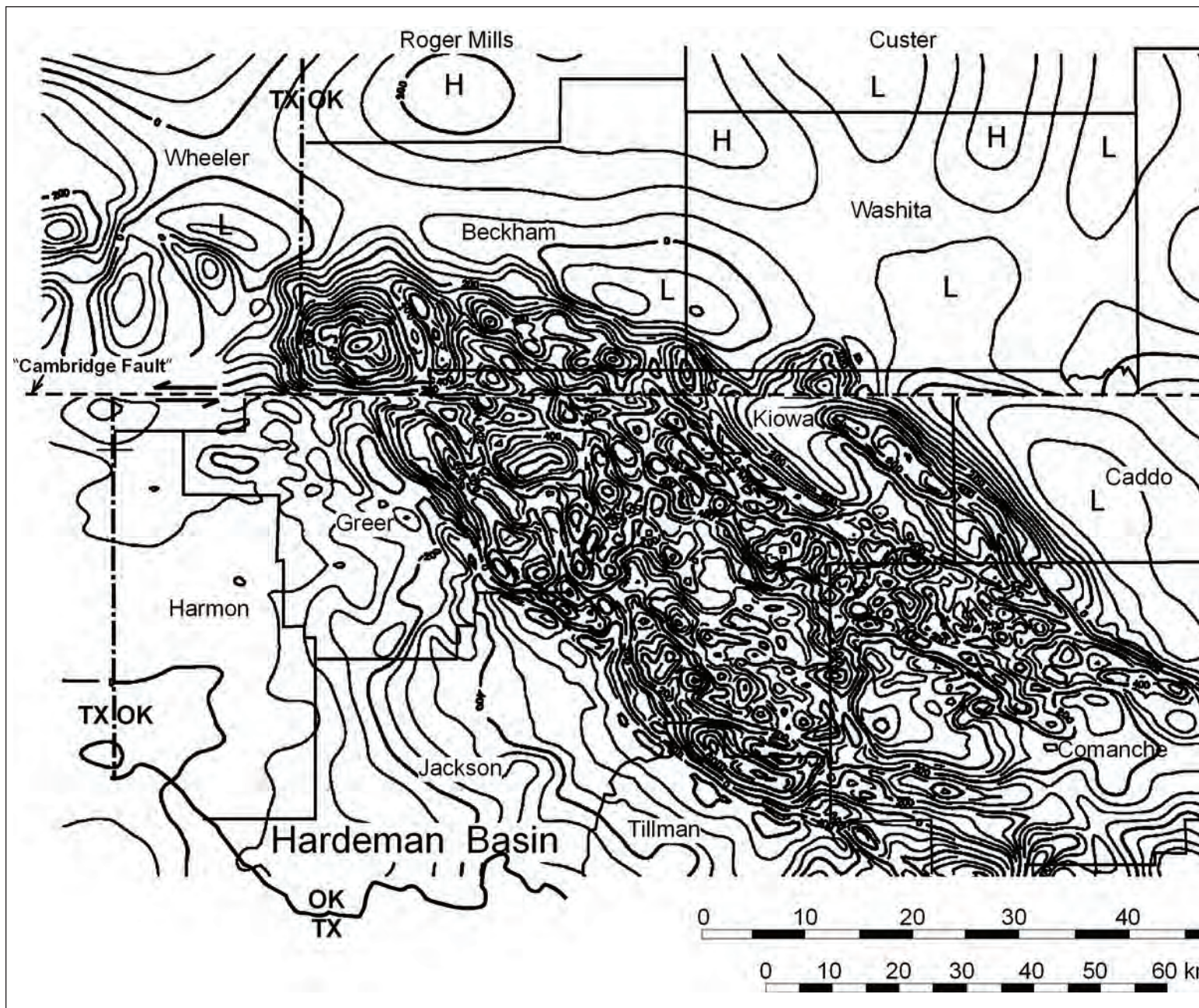


Figure 13. A regional cross-section of the Front Range in Colorado that shows a similar geometry as the Wichita Uplift. Here again, I have extended (in blue) the front- and back-thrusts at depth. From Reynolds (1997).

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The Front Range in Colorado has its Hardeman Basin equivalent – the Middle (Figure 12) and South Park Basins to the west with the Denver Basin as the main (frontal) basin. The Uinta Mountains have their Anadarko and Hardeman Basin, the Green River Basin on the north and the Uinta Basin on the south, respectively, and the Central Basin Platform of the Permian Basin has the deeper Delaware Basin on the south and the Midland Basin on the

north, indicating that the causative thrusting is from north to south, with the probable backthrust on the north, or Midland Basin, side. A cross section by Brown (1984a) supports the thrusting on the south side of the Central Basin Platform in Gray Ranch Field. However, a recent paper (Dotsey, 2012) incorrectly shows the Platform to have been raised along vertical, or near-vertical, faults, which geologists now know is not possible in such a

compressional system.

So far I have been dealing with compressional faults. At this point, I want to mention a rather enigmatic strike-slip fault that we have mapped with the magnetics but which has not been mapped geologically. It affects the magnetics on the north side of Figure 11 trending east-west near the south line of Beckham and Washita Counties, and we have given it the name

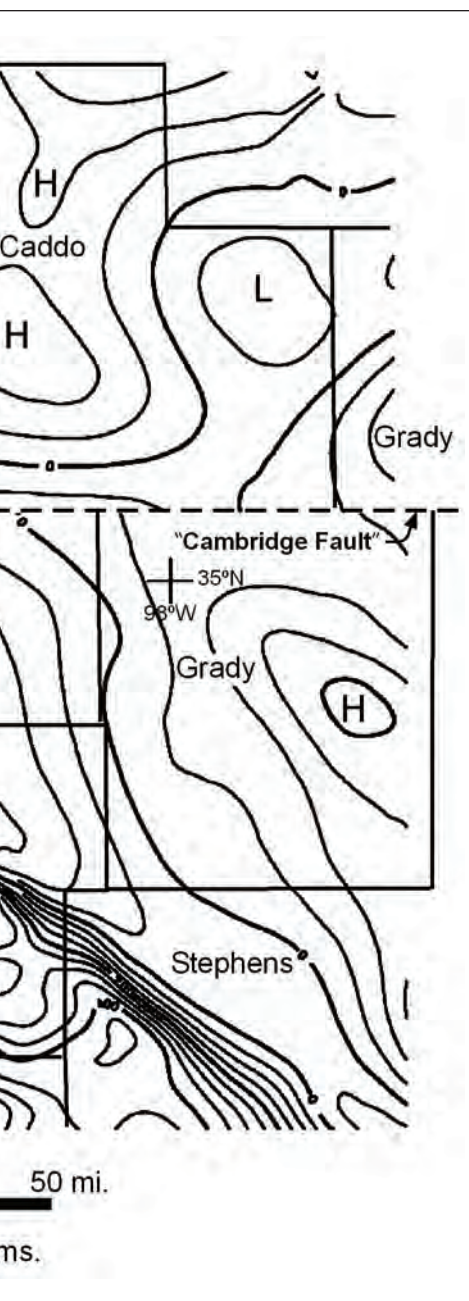


Figure 14. Restoration of the northwest termination of the Wichita Mountains fold and thrust belt on the Oklahoma - Texas state line along the near-east-west-trending "Cambridge Fault." Thirty seven miles of movement are required to line up several magnetic features here as discussed in the text. However, geologic confirmation is lacking. These are the same total intensity contours as shown in figure 11.

cut the magnetic map apart along the supposed fault and moved the north side 37 miles to the east where it matches the data on the south side quite well, both on the uplift and in the basin. As support for this long strike-slip fault, I'd like to point out another east-west trending fault system only 70 miles to the south of this fault, the Matador/Red River Arch that shows on the magnetics of Figure 11 as a series of narrow elongated east-west anomalies. Beyond that I don't know what to make of the Cambridge Fault. No evidence for it is shown on the regional structure maps of Ham, et al. (1964) or of Harlton (1972), both of which were quite comprehensive studies. Since it offsets the magnetic anomaly pattern that I believe is due to uplifted basement blocks in the late Mississippian/Early Pennsylvanian thrust belt, then it would have formed later, but no such later major strike-slip event is known here. Perhaps geologists who have drilled wells close to or along the length of the fault would be able to shed more light on its characteristics, and hence on its existence and its origin. An explanation for the origin of this fault would probably also explain the origin of the parallel Matador Arch to the south.

EASTERN REGION

So far in this paper I have mainly discussed compressional structures which were activated in late Mississippian-early Pennsylvanian time and apparently followed earlier strike-slip faults of the "Southern Oklahoma aulacogen" which formed in Precambrian and/or early Cambrian time. These faults apparently had major transverse movement over long periods of time both in the earlier fault-forming episode and in the later period of reactivation.

In Figure 15, I show several of these reactivated strike-slip faults in Johnston, Pon-

toc and adjacent counties as mapped by Lloyd Gatewood (personal communication, 1984; now deceased, 2011). I do this to illustrate that these long faults always fall along magnetic gradients and are parallel to elongate magnetic anomalies because their magnetic signatures are produced by slivers of basement rocks along them. Starting on the north, the faults illustrated are the Pauls Valley-Franks Fault, and the Sulphur, Mill Creek, Reagan, and Washita Valley Faults, all of which show very good correlations with the magnetic data. The correlations are not quite exact, one reason being that the wells used to locate the faults were scattered, and the fault traces are thus not closely controlled.

At this point, I will switch the discussion to an interesting structural feature interpreted from the magnetic data in the eastern part of the Mountain View Fault System, another feature I have never heard discussed. That is the offset of the Tishomingo/Troy Granite along the Washita Valley Fault. In the upper left corner of Figure 16, there are two notable areas of magnetic anomalies marked A and B. Anomalous Area A corresponds to the uplifted Arbuckle Mountains and consists of a magnetic high over the mountain block on the south and a magnetic low on the north, whereas Anomalous Area B corresponds to outcrops of the Troy and Tishomingo Granites (Lidiac and Denison, 1999) under the high on the north with a low on the south. The Washita Valley Fault corresponds to the strong magnetic gradient between the highs and lows in both cases. Quite soon after flying the magnetic survey in the 1980s, we noticed that anomalies A and B seemed to match, so we cut the map apart along the fault, lined up the anomalies on north and south sides, and obtained a rather remarkable fit. A computer version of the restored feature is shown in Figure 17, and I think the fit is quite convincing. For

Cambridge Fault for a location on the old Atchison, Topeka, and Santa Fe Railroad, which lies along the fault zone in north-central Kiowa County. It appears to offset the Wichita Mountain Block with left-lateral movement and then extends eastward under the Anadarko Basin where it truncates deep basement anomalies at four places until it is truncated itself by a northwest trending block corresponding to a magnetic high. In Figure 14, I have

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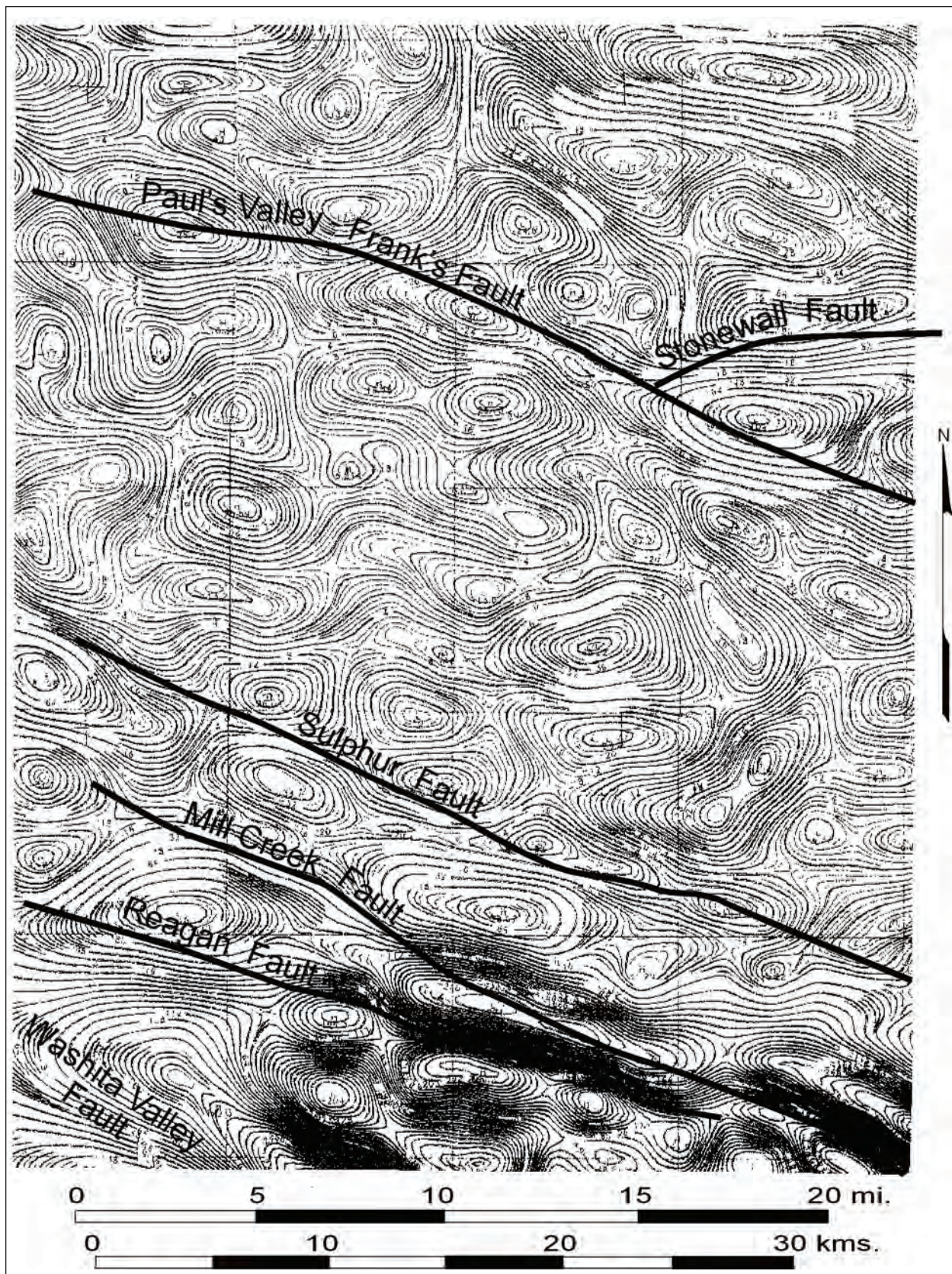


Figure 15. Aeromagnetic data (NewMag® residual) of part of Johnston, Pontotoc and adjacent counties with faults from Lloyd Gatewood's Arbuckle map (updated April 1983) overlain. Note that the faults follow magnetic gradients and elongated magnetic anomalies in all cases.

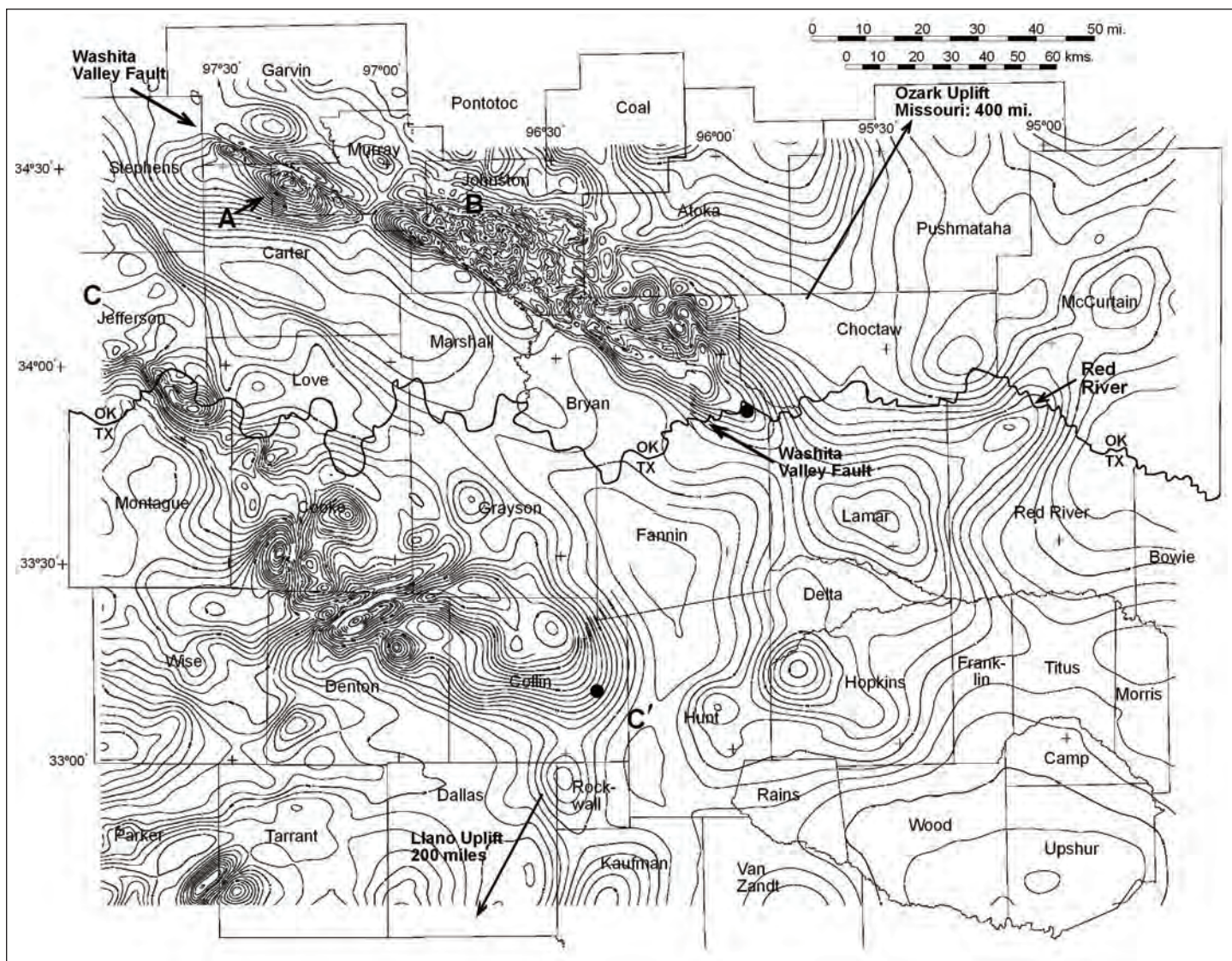


Figure 16. Regional magnetic map (total intensity) of the eastern part of this study showing Arbuckle Mountains anomaly (A), Tishomingo/Troy Granite anomaly (B), and the eastern end of the Wichita Mountains fold and thrust belt (C-C') to its termination in Collin County, Texas, (C').

detail, note the match of the linear magnetic lows in the southeast corner as well as the linear truncation of magnetic anomalies on the west side. I interpret this large composite feature (12 x 20 miles) to be a complex igneous intrusion with the various magnetic highs and lows arising from different individual intrusive cells, or plutons. One notable example of a composite intrusion is the Sierra Nevada batholith in California, well-described in U.S. Geological Survey publications. This huge well-studied intrusive complex consists of multiple plutons intruded into, beside,

and around each other, similar to what we have here (see Lidiac and Denison, 1999, Figure 2).

The horizontal offset between anomalies A and B shown in Figure 17 is 37 miles (60 kms) in a right-lateral sense, and there is a slight rotation of 6° between the two segments due to the curvature of the Washita Valley Fault in this area. Some geologists may disagree with my finding of right-lateral movement on the fault, but as the granite was intruded at approximately 1375-1395 Ma, this exercise only

shows net movement since that time, i.e. including possible late Proterozoic - early Paleozoic offset, not just the Mississippian-Pennsylvanian movement. Strike-slip movement during the Mississippian-Pennsylvanian episode has been postulated as left-lateral by several workers: 49 miles by Tanner (1967), 20 miles by Carter (1979), 36 miles by Wilkinson (1997), and zero miles by Brown (1984b), but I see no problem with the fault having had a component of right-lateral slip greater than 60 kms in Proterozoic or Cambrian time, then moving with left slip a certain amount in

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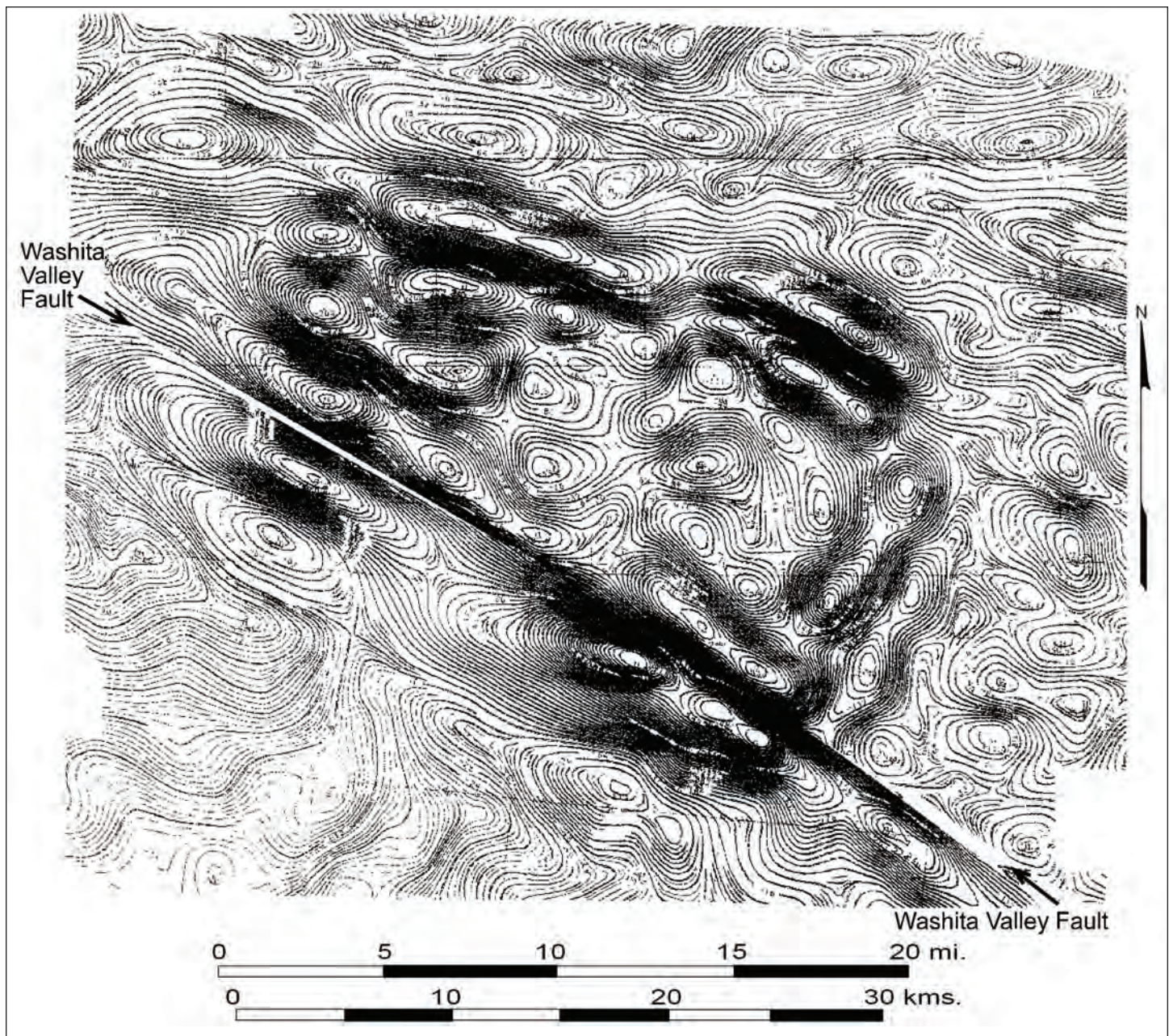


Figure 17. A restoration of detailed residual NewMag® magnetic data of the Tishomingo Granite intrusive complex along north and south sides of the Washita Valley Fault. To the north of the fault trace is the Tishomingo/Troy Granite area in Johnston County, Oklahoma (Anomaly B in Figure 16); to the south is the Arbuckle Mountain block in Garvin County (Anomaly A in Figure 16). The fit is remarkable. It indicates 37 miles (60 kms) of right-lateral movement on the fault since the granite was intruded at 1385 MA.

Mississippian-Pennsylvanian time to its present position. (I hope this finding of 37 miles of right-lateral slip on the Washita Valley Fault since approx. 1385 Ma before present does not confuse those working out the structural history of this region in mid-to-late Paleozoic times.)

What of the extension of the Wheeler County–Mountain View Fault to the east? In Figure 18 one can see that the fault extends in a straight line through Caddo and Grady Counties to the middle of McLain County and may have an offset in the northeast corner of Garvin County, then

extending into southern Pittsburg County and northern Pushmataha County, where it evidently ends or is cut off. This fault, mapped by the magnetics, would correspond to the Wayne Fault of Axtmann (1983).

Now let's return to Figure 11 and look at the bend in the Wichita Mountain Block in Kiowa County where the Mountain View Fault on the west appears to turn southeast into the Broxton Fault. Apparently, the Mississippian-Pennsylvanian compressional thrusting episode connects these two faults, but the earlier strike-slip movement (Precambrian-Cambrian) on the Mountain View would have been linear – no such bend possible. The Broxton and other faults parallel to it and the Washita Valley Fault appear to be splays off the Mountain View, as stated earlier. Regional strike-slip faults are always linear, but many times they are offset by cross-faults where they can be interpreted as being bent if there is insufficient well control.

The next, and final, topic of the eastern region of the Amarillo-Wichita thrust-fold belt that I will discuss is where, why, and how does this long, prominent system of faults end? In Figure 16, I have placed black dots at the truncation points of 1) the Wichita Mountain block and 2) the Washita Valley/Arbuckle block. (Note that these dots fall inboard of the last magnetic contour lines, because in plan view magnetic anomalies are always larger than their source bodies and the anomalies become broader as their sources get deeper.) Note that on the magnetic map of Figure 16 there appears to be no obvious extension of either of these features towards the southeast, so I believe they are truncated as shown. But why?

The first explanation that comes to mind is that they are simply cut off by the Ouachita structural system. That is, the continent ended here as shown by many authors, and oceanic crust (later subducted?) existed to the southeast. Having these faults extend across the continent-ocean boundary into oceanic crust would readily dispense with the truncation problem.

However, there is another possibility. Perhaps these anomalies were faulted off by a regional strike-slip fault. Connecting the

dots of Figure 16 produces a straight line striking about N29°E, which would give the approximate strike of the postulated fault. If this line is extended 200 miles southwest into Texas, it falls precisely along the east side of the Llano Uplift (cored by Precambrian basement), and a segment of it is exactly parallel to the boundary of the uplift, as per Bayley and Muehlberger's basement map (1968).

Next question: If such a long regional fault exists would it have carried the Wichita extensions to the northeast or the southwest? Examination of the "Magnetic Anomaly Map of the United States" (Zietz, 1982) shows no possible west-northwest structural trends as one goes southwest through Texas and into Mexico, but as one goes northeast into Missouri, there are many possibilities. The detailed magnetic map of the St. Francis Mountains in southeastern Missouri (flown in sections by the U.S. Geological Survey starting as far back as 1949) shows several candidates west-northwest basement faults, including the well-known and well-mapped St. Genevieve Fault system, which has the same strike. Also, the northeast-trending offsetting fault shows well in the magnetics in this area. It passes approximately through the town of Springfield, Missouri, and over the center of the Ozark Uplift. It is about 410 miles along this line from the truncation of the Washita Valley Fault on the Texas-Oklahoma line to the intersection with the St. Genevieve system in Missouri. I would suggest that here we might find the Wichita Mountain and Washita Valley Fault extensions.

Before I hang my hat on that one, however, I recall that a number of years back, Kinsland, on the basis of anomaly patterns on the gravity and magnetic maps of the U.S. (Kinsland, 1982, 1986) proposed a 500-mile long offset along an hypothesized northwest-southeast fault trending almost clear across the United States. This fault was not accepted by several well-known geologists who wrote rebuttals, but I don't know that any of them actually proved

him wrong. Kinsland published many correlating features along this supposed fault then and also in later papers, and a debate judge would likely have ruled that he had won the argument. My own analysis is that he is probably right, as this supports my finding that the Precambrian crystalline crust is cut pervasively by long strike-slip faults, which control most or all of post-Precambrian structure (Gay, 2008, 2011). That being the case, the long strike-slip faults I propose in this paper do not seem so unreasonable.

WESTERN REGION

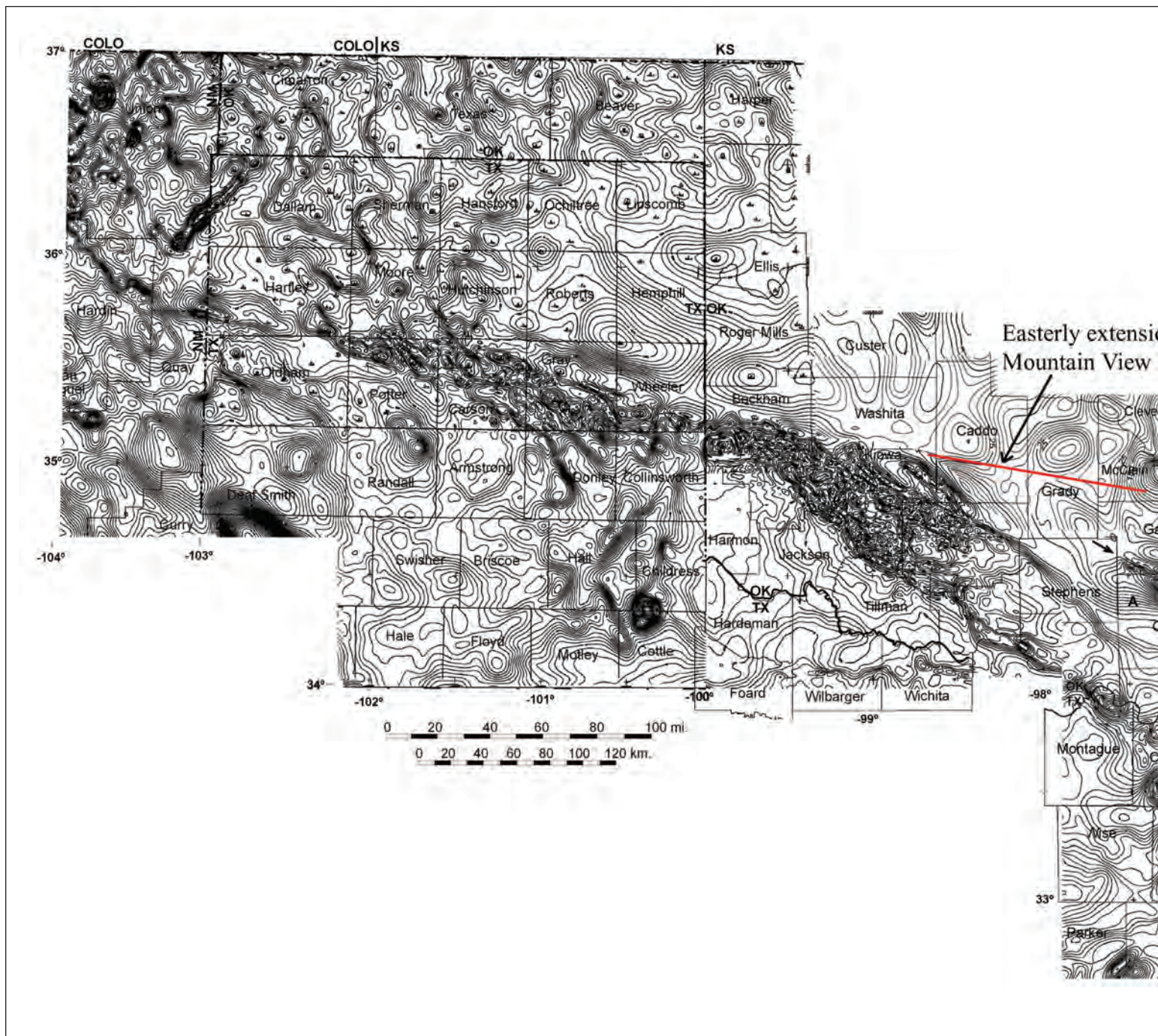
I will now move the discussion to the west and examine the Amarillo/Texas portion of the Amarillo-Wichita Mountains thrust-fold belt (see Figure 19). One of the first things this map reveals is that the width of the belt in Texas is markedly reduced from its width in Oklahoma. To better see this, look again at Figure 18. Here, the decreasing width of the belt as one goes west is quite apparent. We can express this in tabular form as follows:

<u>Location</u>	<u>Width of Thrust Belt</u>
New Mexico – Texas line	Approx. 10 miles
Gray – Wheeler Counties, Texas	Approx. 20 miles
Southern Oklahoma	Approx. 25-30 miles
Northeast Texas	Approx. 40 miles
Southeast Missouri	Approx. 75 miles

The latter entry is speculation on my part, but it cannot be dismissed as a possibility at this time (see discussion in last section).

Why the decrease in width of the thrust belt to the west? This seems to indicate a lesser amount of northeast shortening

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and hence a lesser degree of compression in that direction. We must be getting farther away from the continent-continent collision that is causing the compressive/transpressive stress here. Beyond that, I won't speculate further. I leave that to others who are better versed in plate tectonics than I and can answer this question

more reliably. But this observation may be a key piece of evidence for better understanding the "Southern Oklahoma aulacogen/thrust belt."

Going back to Figure 19, we can see that the Amarillo-Wichita thrust-fold belt terminates abruptly in Union County,

New Mexico, only 10 miles west of the Texas - New Mexico line. (Thus, not much chance of oil on this trend in New Mexico, but fortunately plenty of it on another northwest-southeast trend to the south in the Permian Basin.) I made a brief attempt to see if the system in Union County, New Mexico was offset along a

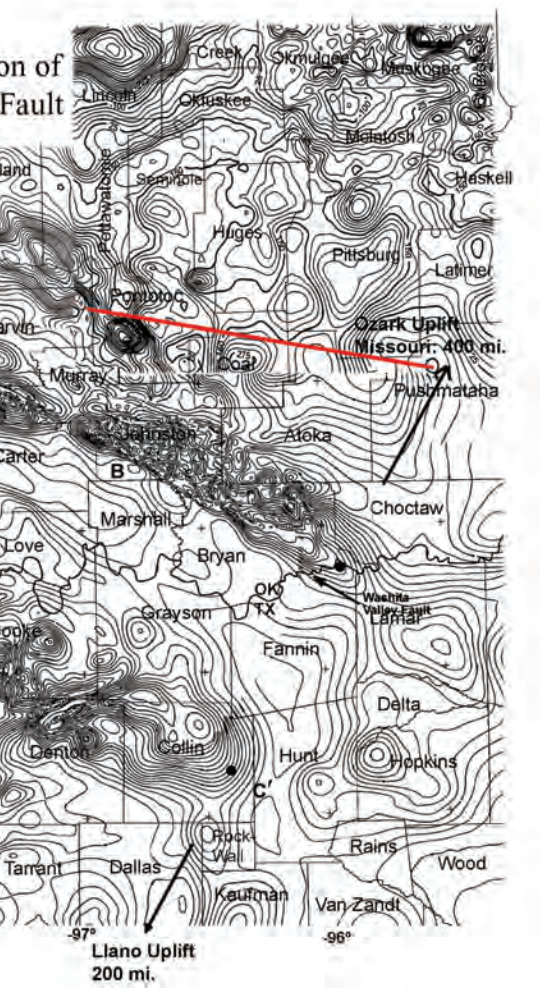


Figure 18. The entire Amarillo-Wichita thrust-fold system is shown here in one image, from northeast Texas on the east to New Mexico on the west. Note my possible/probable extension of the Mountain View Fault to the east (red). This would correspond, in part, to the Wayne Fault of Axtmann (1983).

Figure 19. This I interpret as an earlier ultramafic dike-like intrusion injected into a rift or extensional fault in Archean or early Proterozoic time and so is unrelated to the Amarillo/Wichita thrust-fold system.

The next topic I will discuss is the thrust nature of the buried Amarillo uplift in Texas. This must be treated here, because as recently as 1989 (Budnik) the uplift was illustrated as being raised along vertical faults similar to those shown in 1971 for the Wichita Mountains (Figure 1), with no thrusting. Multiple papers with cross sections constructed from well data prove beyond doubt the thrust nature of the system in Oklahoma, and I would argue that the continuity of the system across the Texas-Oklahoma line is sufficient proof that the system is thrust in Texas as well. However, there does exist one good example of the thrust nature of the system in Texas, that is, a well controlled cross section of the Mills Ranch Field in Wheeler Co. published by Jemison (1979). It is for this reason that I felt confident enough to call the entire system a thrust-fold belt in the title of this paper. Perhaps this designation might inspire some oil and gas explorers to take a new look at the Texas side of the belt from a different perspective. Surely, undiscovered hydrocarbons are hidden by complex thrusting and folding in the buried Amarillo Mountains as they are in the Wichita Mountains across the state line.

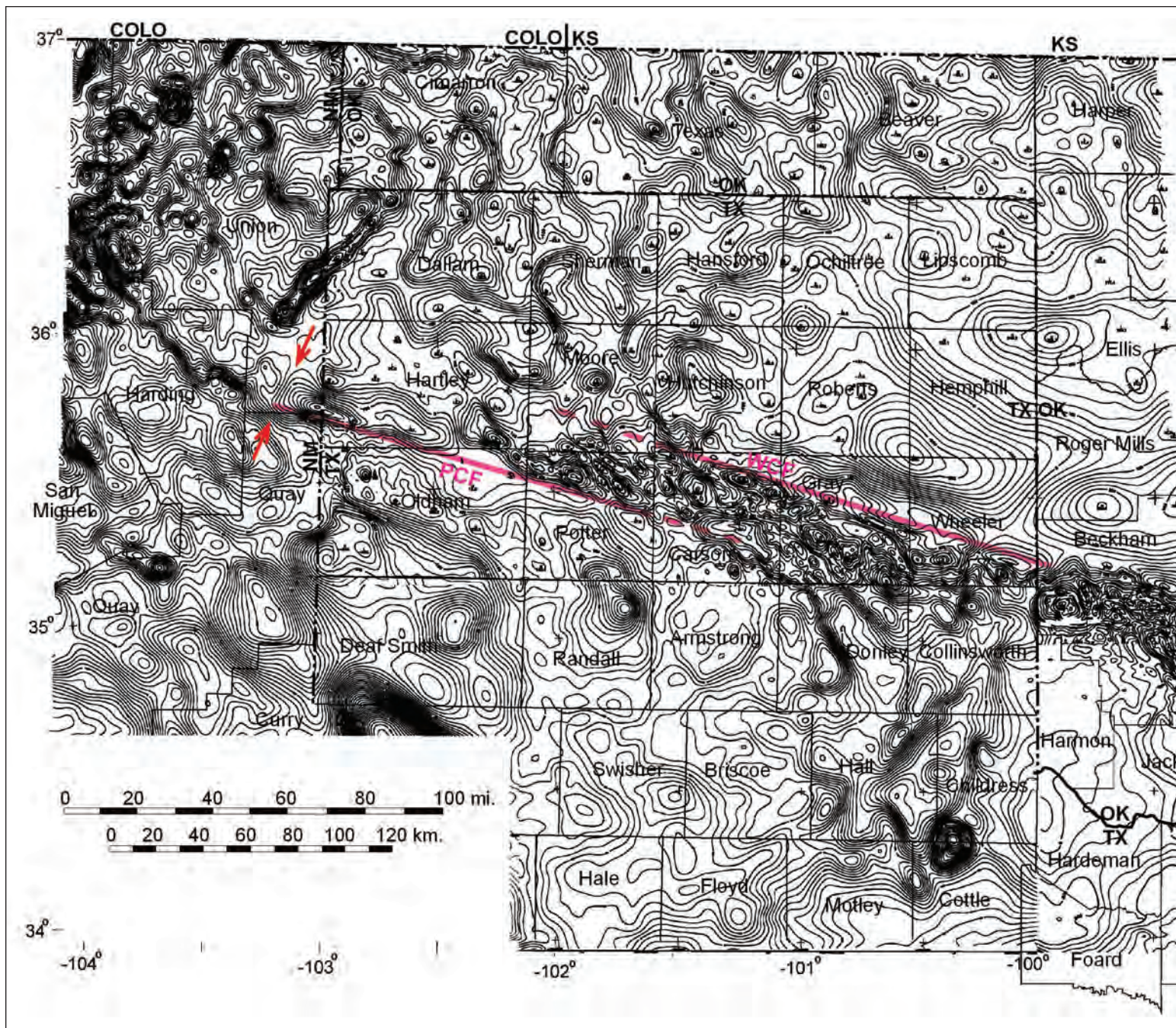
Now let's look at another prominent aspect of this system - the frontal fault. In Oklahoma it is called the Mountain View Fault and in Texas, the Wheeler County Fault (Budnik, 1987), but the two are continuous and co-linear, not separate features. There is some along-strike complexity along the mountain front on both sides of the border as the magnetic data show (Figure 18 and 19). For example, there occur

a series of slightly offset individual magnetic highs along the front rather than just one long continuous magnetic gradient as would be the case if the frontal fault were a long straight line. The magnetic data thus suggest that the front is cut by cross faults into a series of individual, probably en echelon, segments, each one topped by an anticline. The same situation occurs back of the front to the south on top of the uplifts, as the magnetic pattern shows so well (Figures 11, 18 and 19). Cross-faults undoubtedly play a role here in separating the belt into individual anticlines and synclines (see Gay, 2011, pp 18-23).

We have now traced the frontal fault from Fannin County in northeast Texas westward across southern Oklahoma, to Moore County, Texas, in the Panhandle (Figure 18). What happens to it here? The Wheeler County Fault seems to simply disappear in a maze of anomalies apparently not related to the Amarillo-Wichita belt. But look to the south. Ten miles away is a strong trend exactly parallel to it that continues on to the west. Parts of this trend are labeled as the Potter County Fault by Budnik (1989), so I use the name "Potter County Fault" for the entire trend across Potter County and parts of Oldham and Hartley Counties to, and beyond, the New Mexico line. This fault is quite pronounced on the larger scale, detailed magnetic map (not possible to show here) in its linearity and continuity. In the area between this new fault and the Wheeler County Fault occurs a series of short, parallel northwest-trending magnetic gradients that I interpret as faults comprising a possible "transfer zone" (Figure 20). This term has only appeared in the literature in the last 20 years or so, and a reasonable, theoretical depiction of it was drawn by McBride (1994) and is shown here in Figure 21. However, neither of McBride's diagrams shows the same pattern of trans-

regional cross-cutting fault, as it is at its eastern end in northeast Texas, but was not successful. The system seems to just be dying out going west, as the magnetic anomaly merges with other basement lithologic anomalies. In this regard, note the strong linear northeast-trending magnetic low just north of the red arrows in

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fer faults as the one I map in Figure 20. We must wait for an explanation of this possible transfer zone from some bright future structural geologist.

Figure 19, the small-scale magnetic map of the entire Amarillo-Wichita system, is similar in appearance to the gravity map of the system published in 1992 by Rob-

bins and Keller. However, the magnetic map is more detailed than the gravity map due to a much higher density of data, but for those who like to see the gravity data the Robbins and Keller map may be consulted.

A nagging problem arose some years ago with regard to the nature of the structures

comprising the Amarillo Uplift, and this problem must be addressed here. Budnik (1989), a structural geologist with the Texas Bureau of Economic Geology at the time published a northeast-southwest cross section of the Amarillo Uplift through Potter, Moore and Hutchinson Counties that shows only vertical faults to explain the vertical offsets on the up-

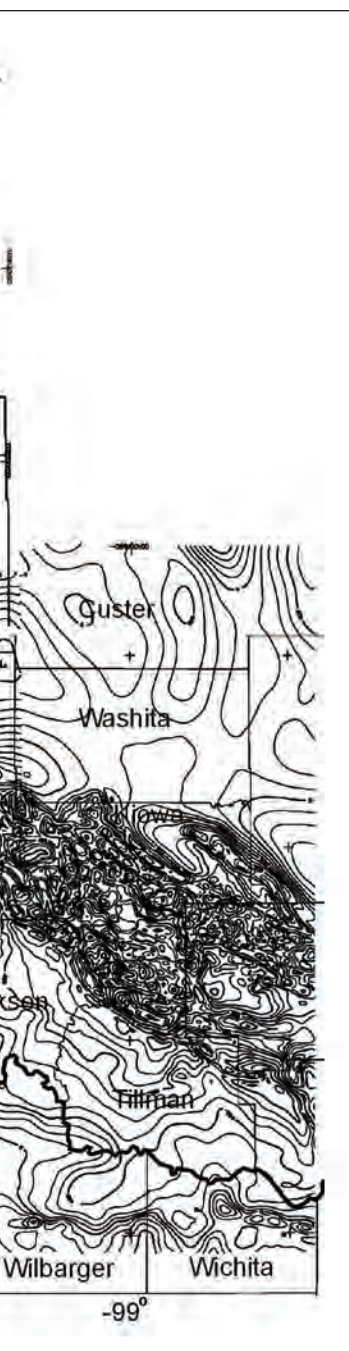


Figure 19. Aeromagnetic map of Amarillo-Wichita thrust-fold belt with extension of the aeromagnetic data west into New Mexico. Red arrows show the apparent termination of the belt in southern Union County, New Mexico. PCF = Potter County Fault. WCF = Wheeler Co. Fault. These faults are illustrated in more definitive fashion in large-scale versions of this map.

lift. The uplift itself is depicted as a vertical horst block raised by the Potter County Fault (vertical) on the south and the Wheeler County Fault (vertical) on the north. Another publication a few years earlier on this area infers vertical faults on the uplift but does not show them in cross section (Dutton, et al., 1982), but in a different article the same year Dutton

(1982) states, “. . . the Amarillo Uplift is apparently bounded by a high-angle reverse fault zone (Goldstein, 1981).” So Budnik’s vertical faults in 1989 are a little surprising. As we now know, mountain ranges are raised by thrust faults resulting from regional horizontal compression created by plate tectonic collisions. There are no known forces in the earth’s crust that could create the vertical faults shown in this setting. This same statement applies to an article and cross section published quite recently showing the Central Basin Uplift in the Permian Basin in west Texas as being raised by vertical faults (Dotsey, 2012). The work of Dahlstrom (1969) rebutted that idea in definitive fashion: if the cross section doesn’t balance, it didn’t happen that way. The prolific writings of Shankar Mitra on balancing cross sections explain the whys and wherefores with easily understandable, balanceable cross sections. Very pertinent to this subject is Jemison (1979), previously mentioned, that was published before the Dutton and Budnik articles which shows the thrust-faulted nature of the Mills Ranch Field just north of, and parallel to, the Wheeler County Fault in Wheeler County, Texas. A thought: how much prior geologic work needs to be modified based on the thrust nature of the Amarillo Uplift?

The last feature I will discuss on the Amarillo Uplift is the Lefors Graben (or “Basin”) in Gray County, Texas, illustrated in Figure 22. The structure contours (left) show a down-dropped block, approximately 20 miles long and 8 miles wide on top of the uplift 5 to 6 miles south of the frontal (Wheeler County) fault. The depth as shown by the Red Cave contours is only 500 feet, but at basement level it is probably much more, as suggested by the great decrease in magnetic amplitudes of anomalies above the graben. (The banded black and white contours that show this feature so well are a type of display used at Applied Geophysics, Inc. for many years, but I have never seen used by others. They make abrupt changes in magnetic amplitude quite obvious and are thus useful in

mapping faults with vertical offset. This type of map should be used more).

There are many other features similar to the Lefors Graben along the length and width of the Amarillo and Wichita Uplifts that are probably also grabens. In particular, look at the magnetic pattern in Kiowa County, Oklahoma, for this type of feature (Figure 11). Some geologists equate grabens with extension and will even argue that grabens prove extension. However, I think a better explanation in compressional belts consisting of multiple thrusts such as this one is that grabens form because some thrusts are more “thrustured” than others, i.e. they have advanced farther. “Grabens” thus occur over the thrusts “that got left behind,” the slower moving ones. Also, the custom of showing faults with arrows going both up and down is perhaps misleading. Thrusts should be shown with just one arrow – the one going up, because, as in the present case, all the thrust blocks evidently went up, and none went down.

Another interesting structural deduction may be made by looking again at Figure 22b. One would think that in an intensely thrustured terrain such as this, most (or all) of the thrusts would be nearly parallel, that is, perpendicular to maximum compressive stress. However, here we have (probable) thrusting in three directions along the north, the southeast, and the southwest boundaries of the graben. This complexity of faulting I will discuss in the next, and final, section of this paper.

CONCLUSIONS

Here, I am not going to summarize all the diverse geological topics I cover in this paper. They speak for themselves. I will only mention an oil field that I hope will be the forerunner of a new wave of thrust-fold discoveries in the Amarillo-Wichita belt, the Cottonwood Creek Field in Carter County, Oklahoma (Figure 23). The geological and drilling communities were amazed when the discovery well in 1987

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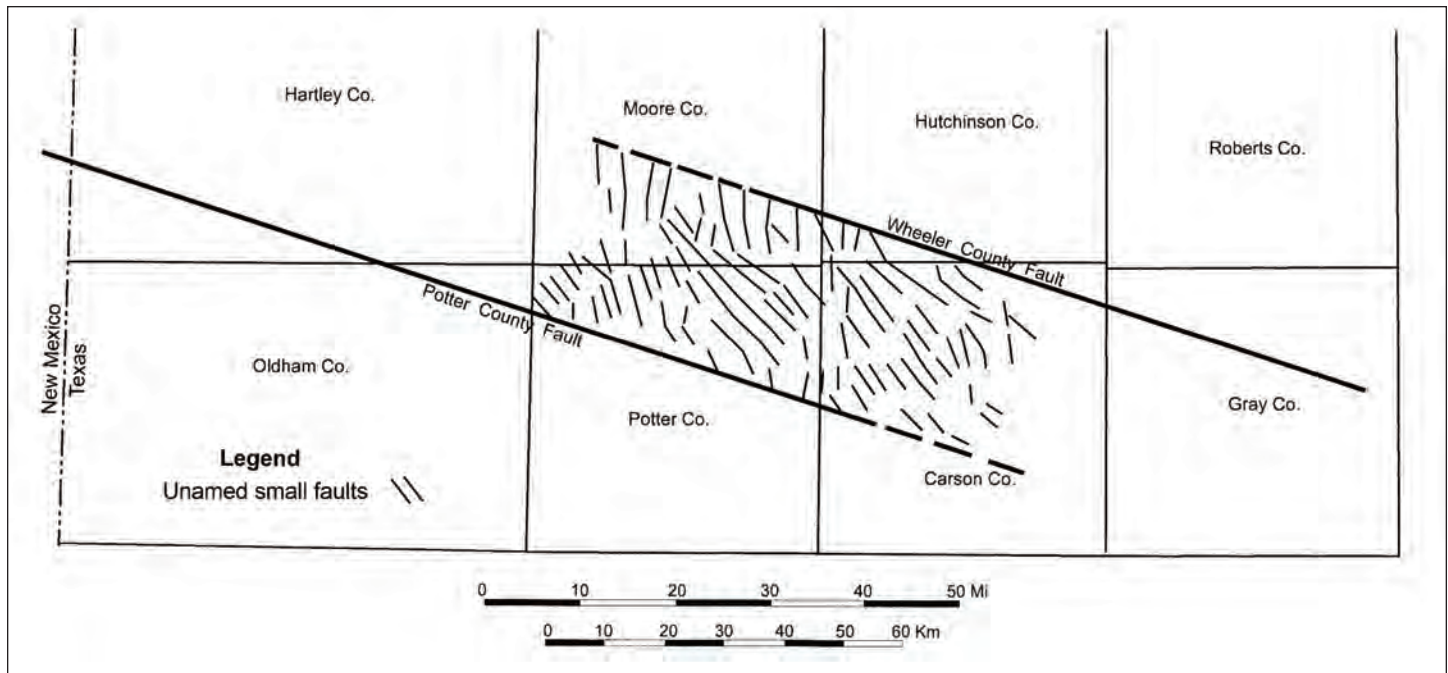


Figure 20. Possible "transfer zone" on the Amarillo Uplift between the Wheeler County Fault and the Potter County Fault, taken from the detailed NewMag® residual map at 1:275,000 scale. (Small-scale magnetic map is shown in Figure 19.) The Wheeler County Fault is approximately as shown on published geology maps, but the length and continuity of the Potter County Fault is new. However, it is quite convincingly observed on the detailed magnetic data (not possible to show here). Name of Potter County Fault is taken from Budnick (1987).

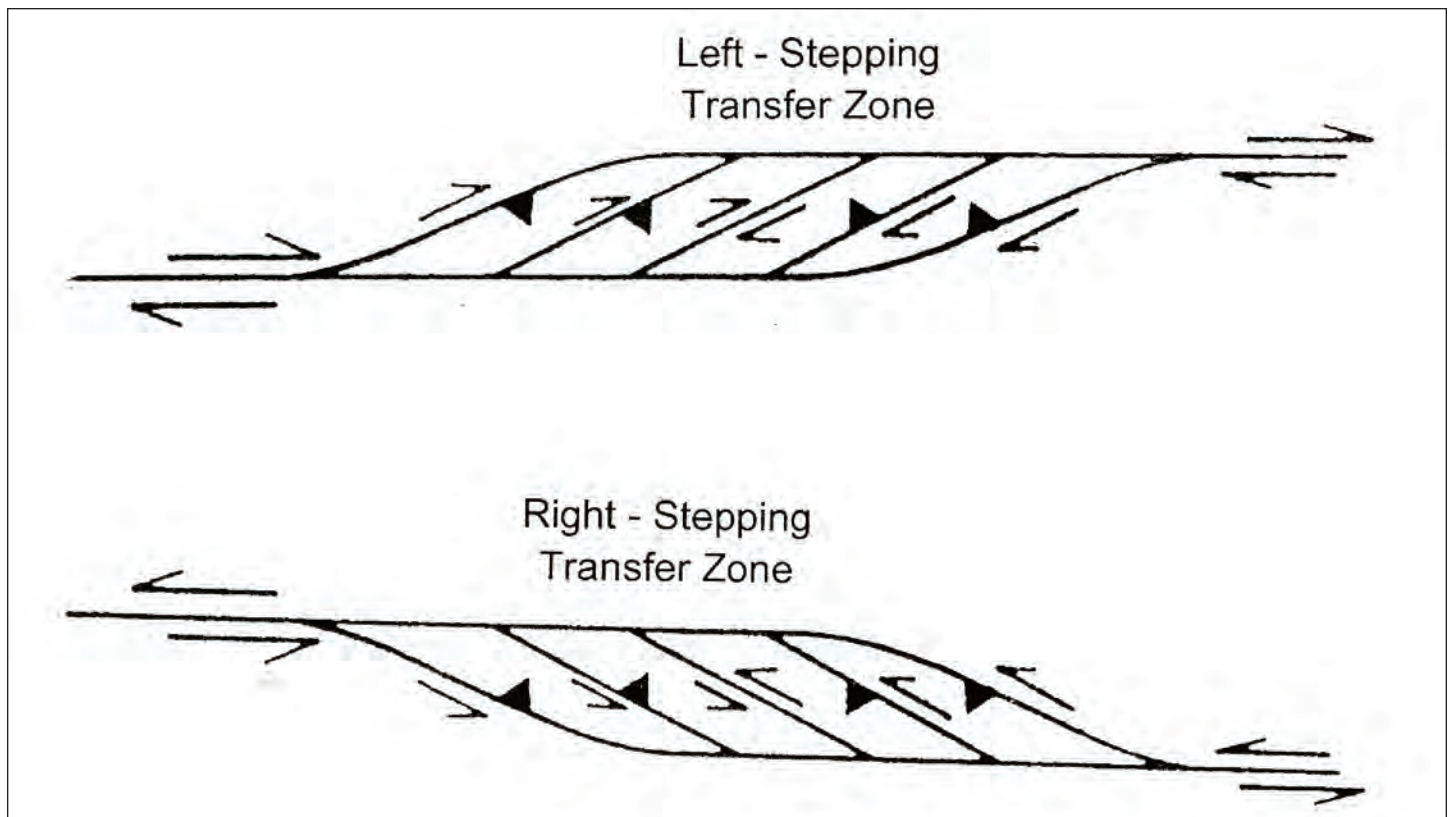


Figure 21. Two versions of a "transfer zone" constructed by McBride (1994).

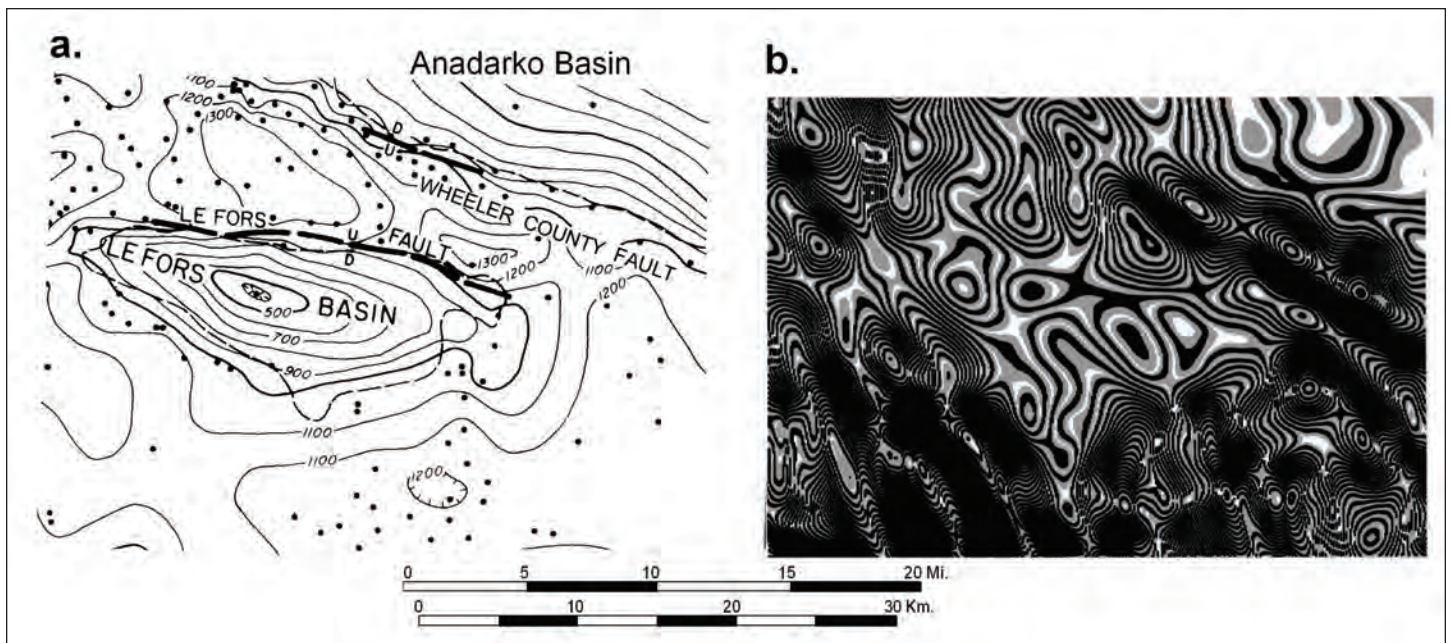


Figure 22. a. Structural geology map of Lefors Graben (Basin) in Gray County, Texas (from Budnik, 1987). Structure contours are on top of Permian Red Cave formation. b. Banded NewMag® contours of same area as a. The lighter area in center is the graben. It stands out so well because of the lower amplitudes of the magnetic anomalies, which have wider bands. Note the Lefors Fault on both maps and the probable straight-line faults on the southeast and southwest of the basin shown on the magnetic map. Magnetic data courtesy of Applied Geophysics, Inc.

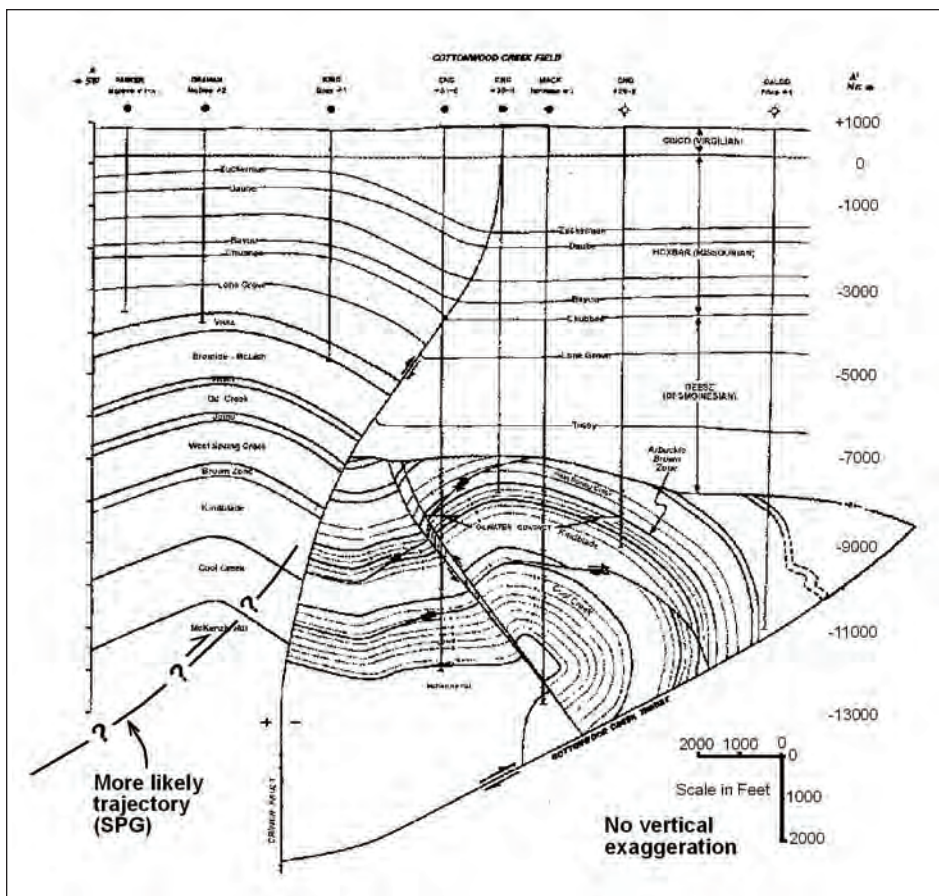


Figure 23. Cross section based on well data (Read and Richmond, 1993) of the Cottonwood Creek Field in Carter County, Oklahoma, along the overthrust Wichita Mountain front. This cross section serves as a model for the type of structural complexity that should be present along the entire Amarillo-Wichita thrust-fold belt.

Some Observations on the Amarillo/Wichita Mountains Thrust-Fold Belt and its Extensions Southeast into East Texas and Northwest into New Mexico, cont.

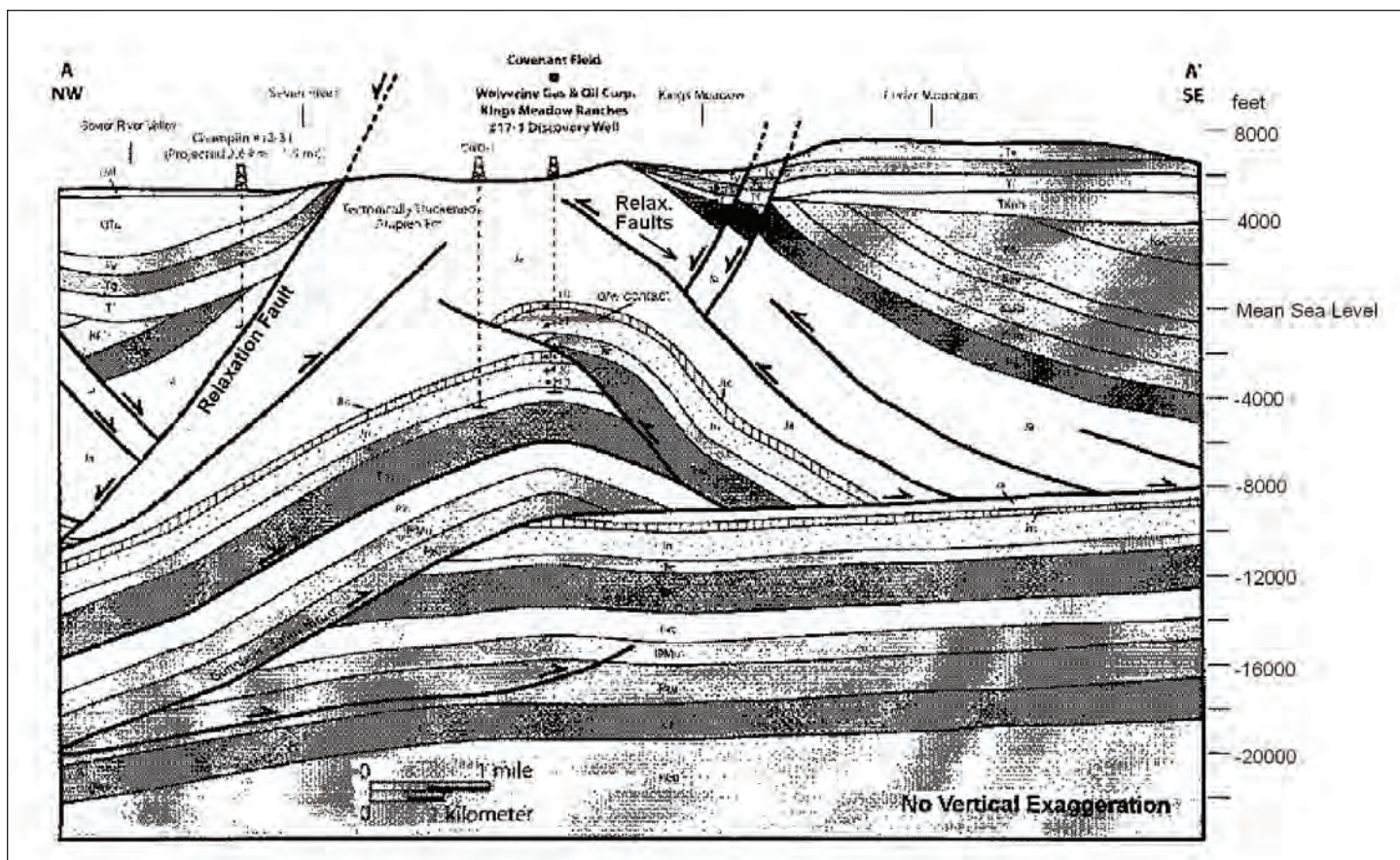


Figure 24. Cross section (Chidsey, et al., 2007) of the recently discovered (2004) Covenant Field in Sevier County, Utah, on the southern extension of the Western United States thrust belt. Note thrusting from both directions, as at Cottonwood Creek in Figure 23. Also note the post-compressional relaxation (normal) faults that are found in several places in the Rocky Mountains and should be looked for in the Amarillo-Wichita belt. These faults should not be confused with faults contemporaneous with compression.

blew out from the Arbuckle Brown Zone to the tune of an estimated 4000 bopd through a small hole in the drill bit. But to me and others, it is even more amazing that a highly accurate cross section based on well data by CNG's Dave Read (Figure 23) shows the same type of complex thrusting as one observes in regional thrust belts. Figure 24, for comparison, is a cross section of the Covenant Field in the Utah-Wyoming, or Western U.S., thrust belt, discovered in 2004 (Chidsey et al., 2007). There are overlapping thrusts coming from both directions in a complex pattern, which is not a whole lot more complex than Read and Richmond's (1983) cross section in the Amarillo-Wichita thrust-fold belt. The Covenant discovery was made by geologist Doug Strickland who worked out the geology years before

the discovery while employed by a major oil company. He presented it much later to a then-small oil company in Michigan, Wolverine Gas and Oil Corp., who drilled it. The field lies 140 miles from nearest production in the thrust belt to the north in northeast Utah, and its discovery opened up this belt to a leasing/drilling frenzy going toward the old belt to the north as well as a couple of hundred miles or more to the south, a play still ongoing to this day. However, only one further discovery has been made in this belt after ten years of exploration: Providence Field discovered in 2008, 20-25 miles north of Covenant, by Doug Strickland (died young, 2011).

Some geologists, such as Strickland and Read, seem to have a better nose for sniffing out these structures than others. Here,

I simply point out that the 400-mile long Amarillo-Wichita thrust-fold belt also has the potential for additional complexly thrust fields. To those who are interested in getting a feel for what some of the other complexly thrust producing structures look like, consult the cross sections of the Utah-Idaho thrust belt fields in Lamerson, 1982 (Pineview Field, p. 301; Painter Reservoir, p. 304; Yellow Creek, p. 333), West and Lewis, 1982 (Anschutz Ranch Field, p. 638), Kelly and Hine, 1977 (Ryckman Creek Field, p. 621), and Sieverding and Royse, 1990 (Whitney Canyon Field, p. 9). The Covenant structure is just one of the many styles of thrusting illustrated in this belt. I would like to show figures of these interesting structures, but this paper has gone on long enough.

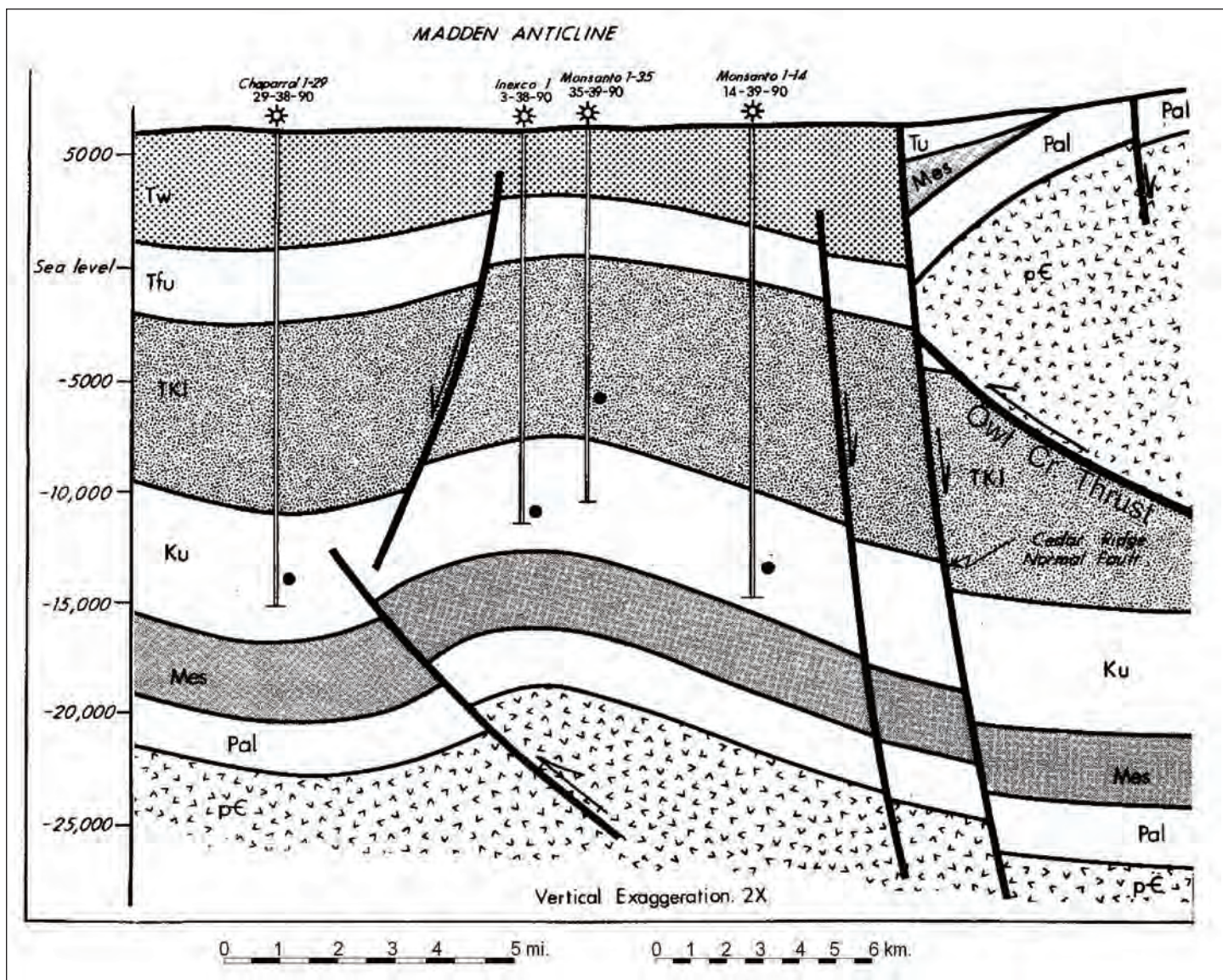


Figure 25. Cross section of the giant Madden Field in Fremont County, Wyoming. Two thrusts are shown. The large one on the right raised the Owl Creek Mountains; the one in front of it, and parallel to it, on the left raised the prolific Madden Anticline. The other three faults shown are post-compressional relaxation faults. From Ray and Keefer (1985).

I will finish with just one more Figure, No. 25. Here we see a large compressional fold with three seemingly out-of-place normal faults. These are post-compressional faults, i.e. they occurred after compression ceased and the rock was no longer partially held up by horizontal forces in the crust. They are thus relaxation faults. Due to their steep dips, it is easy to mistake them for terrane-raising faults, but they have not raised the terrane, they have lowered the flanks as this real-data (well and seismic) illustration shows. Similar

post-compressional relaxation faults are also shown in Figure 24. Do not confuse these faults with the faults that created the structure.

Footnote: All the structural conclusions I arrive at in this paper based on magnetic data were carried out on maps and overlays at a scale of an inch to 8000 ft. (1:96,000) or 1:250,000 scale. The maps in some cases, were up to six feet long. In this sense, they were regional, but the magnetic data they contain were detailed,

due to a tight magnetic line spacing (1/2 mile to 1 mile) and a sensitive magnetometer (.01 gamma). It has been difficult to condense these maps down to fit on 8 1/2 x 11 sheets of paper for this article. So if some of my figures do not seem to illustrate well the points I make in the text, I beg the reader's indulgence and suggest he spend additional time examining the figures (with a magnifying glass?) or contacting the author for further explanation with larger-scale maps.

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