NEW ADVANCEMENTS IN UNDERSTANDING THE FORMATION OF ANTICLINES

Introduction

Anticlines are one of the two most common structures known in geology. Only faults (including fractures and joints) are more numerous. The name anticline dates from the 1860's, but prior to that these structures were simply called folds, and often still are. Their first recognition seems to be lost in antiquity as well as who first used the term "anticline." [If anyone knows the answers to these questions, please let me know.]

Since anticlines and folds have been recognized for such a long time and have been mapped, studied and written about by hundreds, if not thousands, of geologists, one would presume that we know everything there is to know about them and how they form. But such is not the case. As recently as 2004 a prominent geologist said to me when I stated that anticlines have an underlying, causative reverse, or thrust, fault: "Not in my area." In other words, he evidently subscribed to anticlinal formation as understood and illustrated in the 1930's and before (see Fig. 1) - sine-wave-like folds resulting from compression of the sedimentary section over a yielding substrate with no involvement of basement or underlying rocks and no underlying faults.

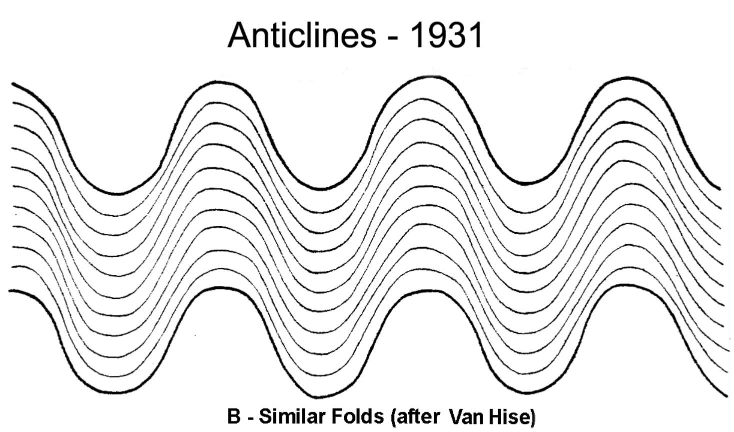
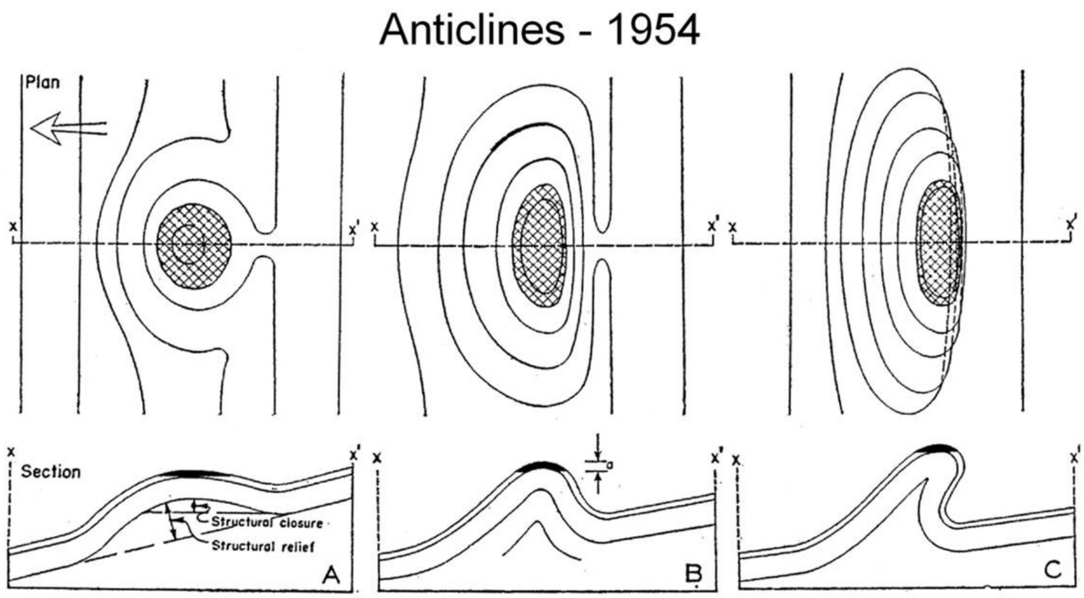


Figure 1. Idealized folds from C. M. Nevin, 1931: Principles of Structural Geology, Wiley & Sons, N.Y.

This picture had improved dramatically by the 1950's, at least in the textbooks of some authors. A figure in a nationally known, widely used textbook (Levorsen, 1954) probably was as close to an accepted model of anticline formation as existed at that time. It is shown in Fig. 2. This figure infers an underlying detachment, which is not labeled, but shows no other faulting.



Idealized structural maps and sections of typical anticlinal dome folds; such folds are characteristic of many traps containing oil and gas pools (oil, shaded and black).

Figure 2. This early model of anticlines was much farther advanced than the one shown in Fig. 1, as it infers a detachment surface, but still shows no underlying fault. From Geology of Petroleum, A. I. Levorsen, 1954, 703 p.

My own experience with anticlines has been mainly in the Rocky Mountains, U.S.A., and at this point I will very briefly summarize the evolution of our understanding of anticlines as I saw it take place in this region from the 1960's to the 1990's. In the latter half of the 1900's, after World War II, petroleum exploration became very active in the Rockies, resulting in many oil and gas discoveries and much geological mapping in this region of high relief and good 3-dimensional rock exposure. Gradually, over a period of 20-30 years a better explanation of anticlines evolved. In 1962, Prof. Robert R. Berg (Rocky Mtn. Petroleum geologist, later professor, Texas A&M)

published a cross-section of the Wind River Range (Fig. 3) showing that the range was raised along a partially listric, sub-horizontal thrust fault. (Here I equate this large range-forming fault to the similar, but smaller, thrust, or reverse, faults that form individual anticlines.) That same year, 1962, Berg also postulated that a similar fault uplifted the Colorado Rockies west of Denver (Fig.4). [I was taught in undergraduate school in 1950 that this fault was normal because Mt. Evans at over 14,00 feet on the up-thrown block west of Denver was many thousands of feet higher than the Mile-high city - an obvious normal fault!] However, there is a major problem with Berg's cross-sections. He shows the down-dip portion of the fault plunging at depth, a physically impossible situation, which most geologists at the time seem to have overlooked. This plunge could only be accommodated if the basement rocks were extremely plastic, or ductile, but at the relatively shallow depths involved they are brittle.

Another prominent Rocky Mountain geologist in the 1960's, Prof. Wm. G. ("Bill") Brown (Chevron Oil Co., later prof., Baylor Univ.), drew cross-sections similar to Berg's, but by the 1980's had developed a twin thrust model (Fig. 5). Geologist David Stearns also published a number of Rocky Mountain cross sections during this same time period hypothesizing that the basement consisted of a multitude of thin, fault-bounded slices that were positioned so as to mimic the overlying folded sedimentary rocks - an unrealistic explanation not explainable by any known geological or physical process and thus not illustrated here. Geologist Don Stone followed the Bob Berg model in a cross-section of Moffat Field, Colorado, published in 1975 (Fig. 6).

Parallel to the above developments in the U.S. Rockies, ideas were also evolving on the formation of anticlines by geologists in the Canadian Rockies to the north. Rock exposures in the Canadian Rockies are even more spectacular than those in the U.S. Rockies, and a fairly comprehensive body of knowledge of thrusted structures and how they formed was being developed

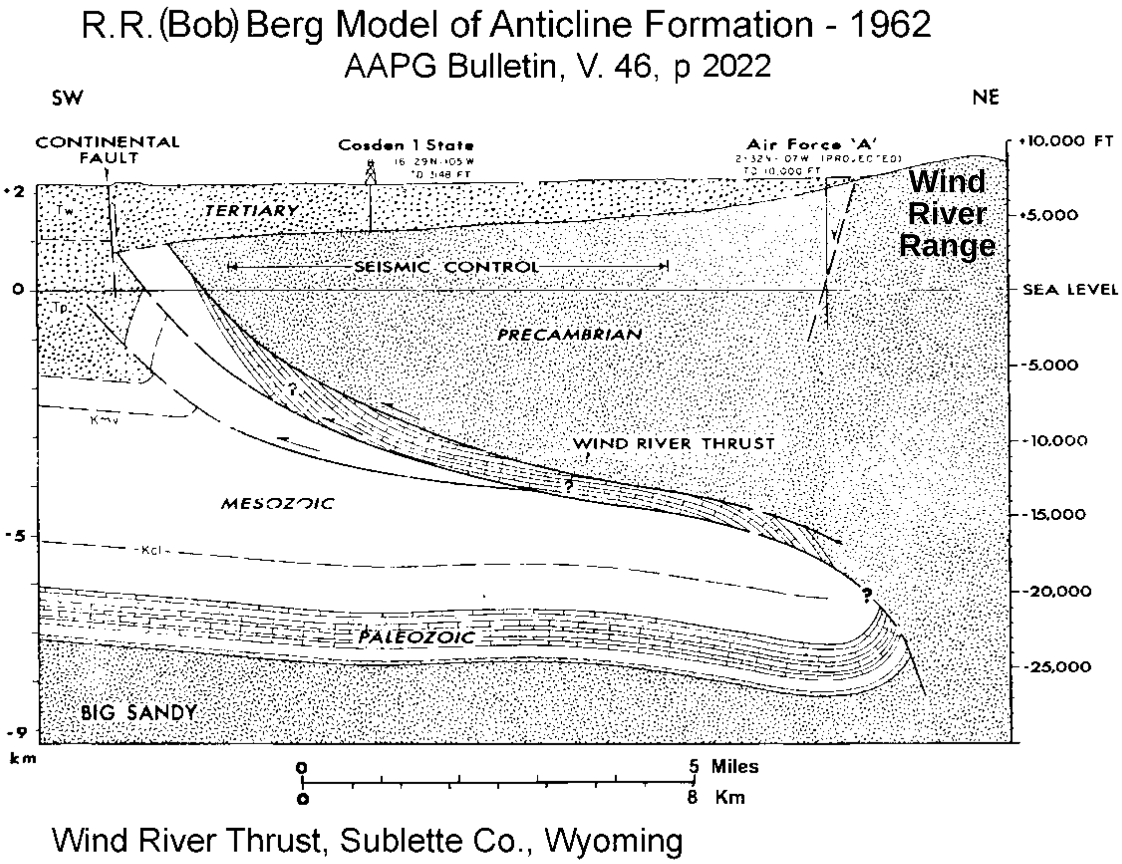


Figure 3. The Bob Berg model of anticline/range front uplift was considered, for a good 30 years, the most likely way that these structures formed.

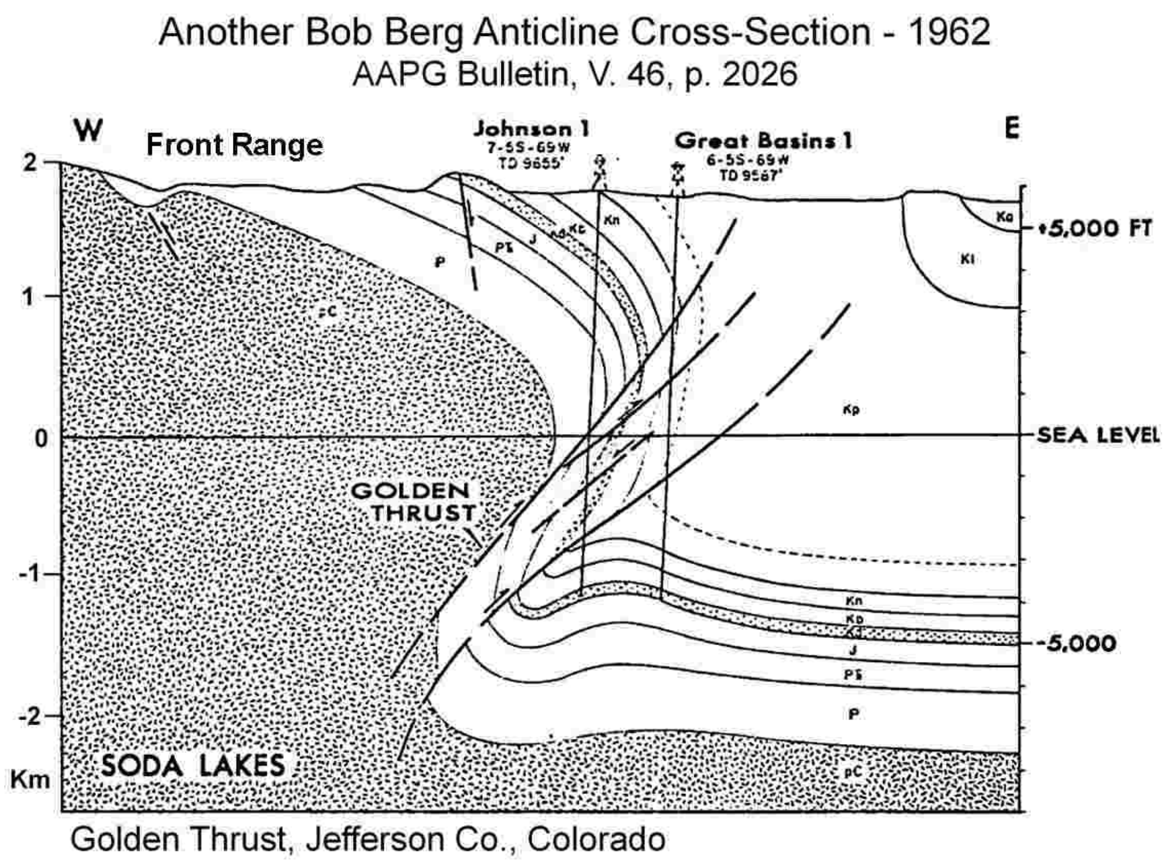
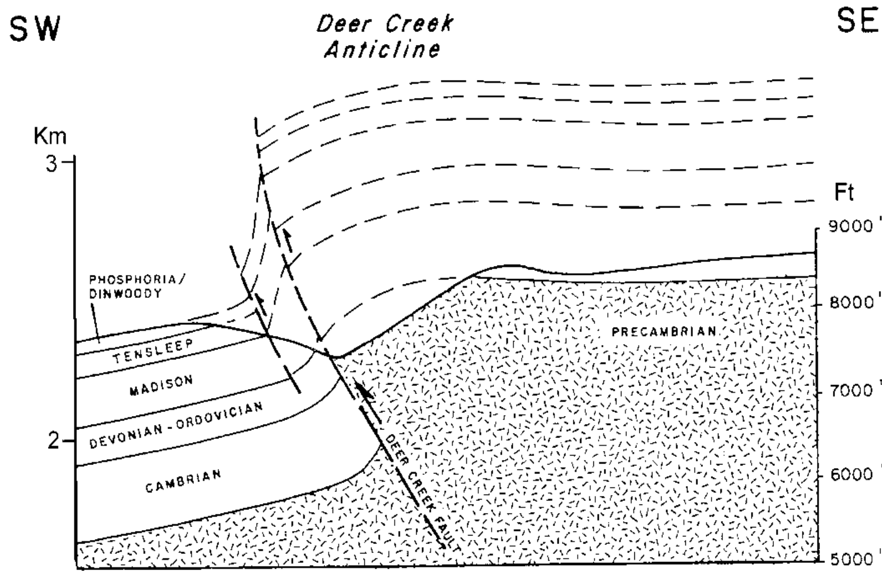


Figure 4. Another Bob Berg cross-section explained the uplift of the Front Range west of Denver.

Wm. Brown Model of Anticline Formation, 1983
Big Horn Co., Wyoming
1983 RMAG Guidebook, pp. 57-64



Horizontal scale not given

Figure 5. The Bill Brown model of anticline formation was favored by some in the 1970's-80's. He used two thrusts to explain the geometry observed in outcrop.

Anticline Formation by Stone, 1975
1975 RMAG Guidebook

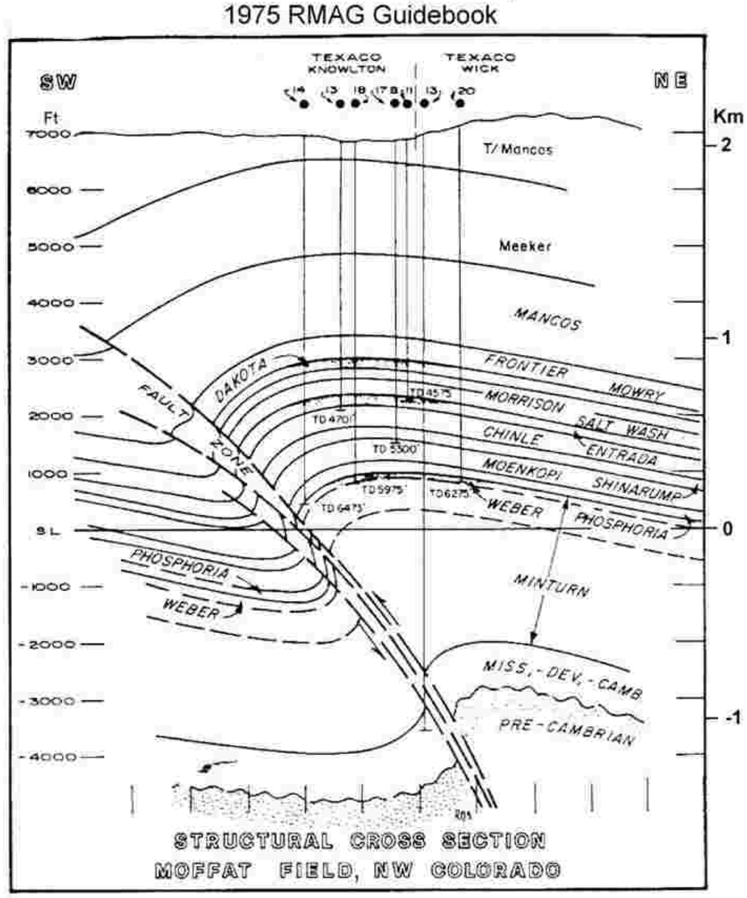


Figure 6. Don Stone, Denver geologist, favored a model similar to Bob Berg's in this 1975 cross-section.

by a number of Canadian geologists. This knowledge culminated in a classic paper by C. D. A. ("Clint") Dahlstrom (Chevron Oil) in 1969 that was published in the Canadian Journal of Earth Sciences. The title was "Balanced Cross Sections," and Dahlstrom stated:

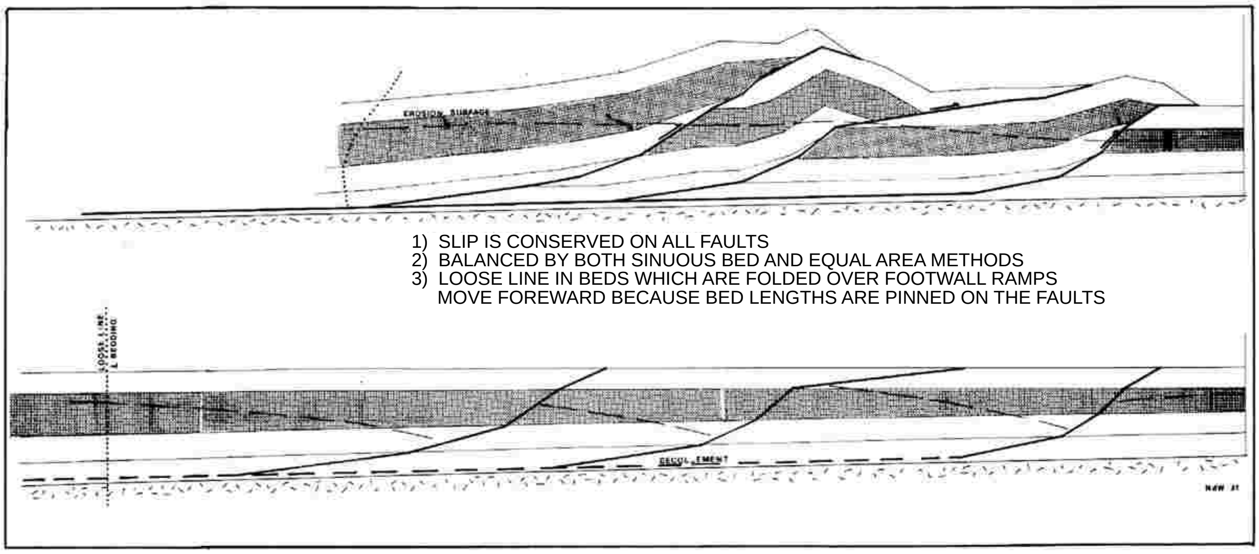
> "In a geological cross-section one flattens out the deformed beds and returns them to their original horizontal position. If this can be done successfully the cross-section is geometrically possible...."

One could also say that a balanced cross-section is <u>physically</u> and <u>geologically</u> possible. In Fig. 7, I show a schematic illustration of this process that was published later (Woodard, Boyer, and Suppe, 1989).

Balanced cross-sections are now standard practice in structural geology worldwide. If the U.S. Rockies' geologists had been aware of and had studied (and believed) Dahlstrom's paper at the time it was published, it would have saved them years of work, for they eventually (20+ years later) arrived at the same end result - balanced cross-sections - but without calling them that. In the U.S. Shankar Mitra (1993, 1998, etc.) has been the leading worker in balancing cross-sections and has contributed many valuable techniques to make the method more useful.

I now mention the work of Robbie Gries (1981) who, as a petroleum geologist in Denver, had the idea that long, sub-horizontal range-front thrusts on some of the uplifted Rocky Mountain ranges could be hiding productive oil fields. She published a number of cross-sections of these ranges, all of which show the thrusts extending laterally for many miles and none of them plunging. These sections are thus "balanceable," and therefore geometrically and geologically possible, and Gries is credited with being the first to publish such cross-sections in the U.S. Rockies. One is shown in Fig. 8. Shortly afterwards, Gries followed up her 1981 paper with another paper (1983) pertaining to the "anticline problem." Here, she states at least 8 times that the causative faults under anticlines and mountain ranges flatten with depth rather than steepen.

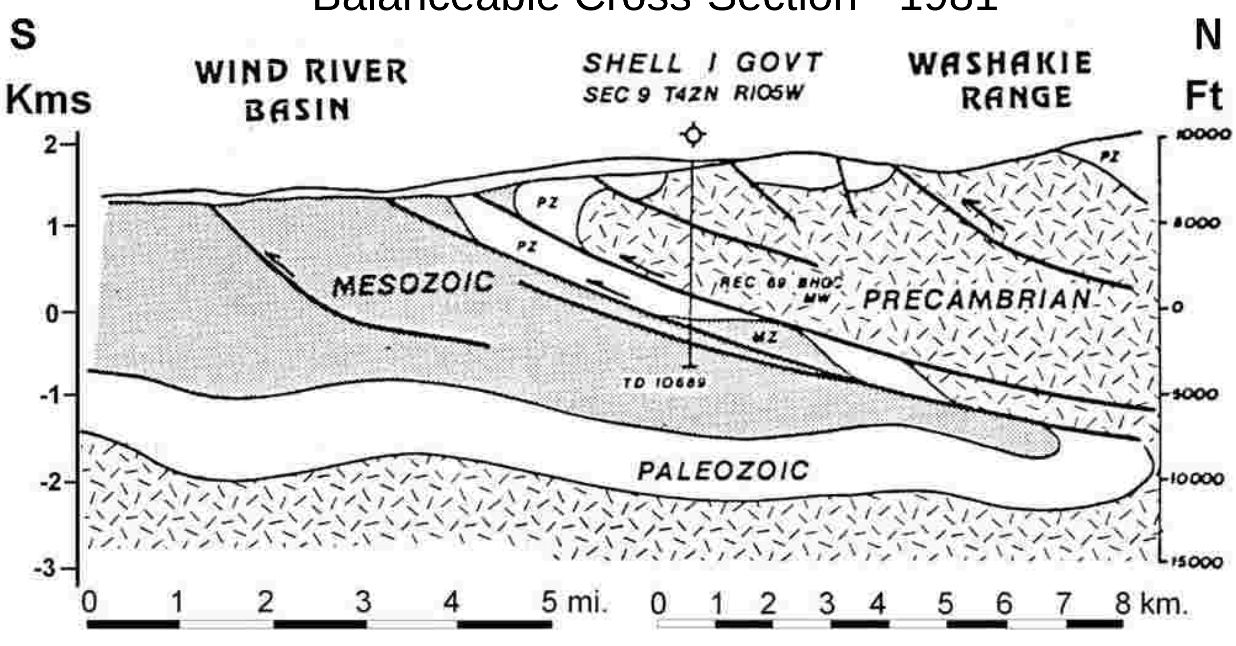
Balanced Cross-Section - 1989



From Woodard, Boyer and Suppe
AGU Short Course, 1989, for 28th Int'l. Geol. Congress

Figure 7. A perfectly balanced cross-section following the principles published by C. D. A. Dahlstrom in Calgary in 1969.

Balanceable Cross-Section - 1981



Fremont Co., Wyoming

Figure 8. This is one of several cross-sections published by Robbie Gries in 1981 suggesting that oil and gas traps could exist beneath some of the range front thrusts in Colorado and Wyoming. All her sections show the fault flattening with depth and not plunging, as did cross-sections by other geologists at that time.

Some, including the author, have credited Don Stone with being the first to draw a realistic, balanceable cross-section of an anticline in the Rockies, but in 1983, the same year that Gries emphasized the listric, non-plunging nature of faults underlying uplifts, Stone (1983) still shows a cross-section with the fault plunging at depth (Fig. 9). So Gries was really the first to solve the anticline problem, which she did simply as a sideline to her work as an explorationist.

However, Stone in 1993 published a thorough, comprehensive article on anticline formation with an illustrative cross-section (Fig. 10), that I used for many years in talks on basement control of faulting in the sedimentary section. But this cross-section suffers from a flaw that I (and others, I'm sure) overlooked. Stone shows a straight line fault segment dipping at 30 degrees into basement, but Mitra (1999) pointed out that this section of the fault should be listric as well in order for the cross-section to be balanceable. Mitra's statement was in response to a "Comment" by Stone criticizing Mitra's work on balancing cross-sections (Stone 1999). By simply removing Stone's angular information and the straight line fault segment in basement and substituting a listric fault at this level, the cross-section becomes balanceable (Fig. 11). This modified cross-section could be called the "corrected thrust-fold model" and is considered to be a realistic explanation of what occurs (in the transverse direction) when anticlines form - a long ways from what we started with in 1931 and before (Fig.1)!

Here, I would like to include some additional observations I have made on anticline formation. It is the resistance to forward movement of the layers in front causes the rocks to bend upward in asymmetric fashion, (see Figs 9, 10 & 11). This movement gives rise to shortening of the beds across the structure as the area becomes horizontally compressed. (Note that I do not use the term "contraction" for "shortening", as that word has had a different meaning in physics for a long time. In fact, I recommend against the use of "contraction" by geologists to avoid confusion with its long-standing legitimate meaning.)

Elk Basin Anticline, Big Horn Basin
Park Co., Wyoming & Carbon Co., Montana

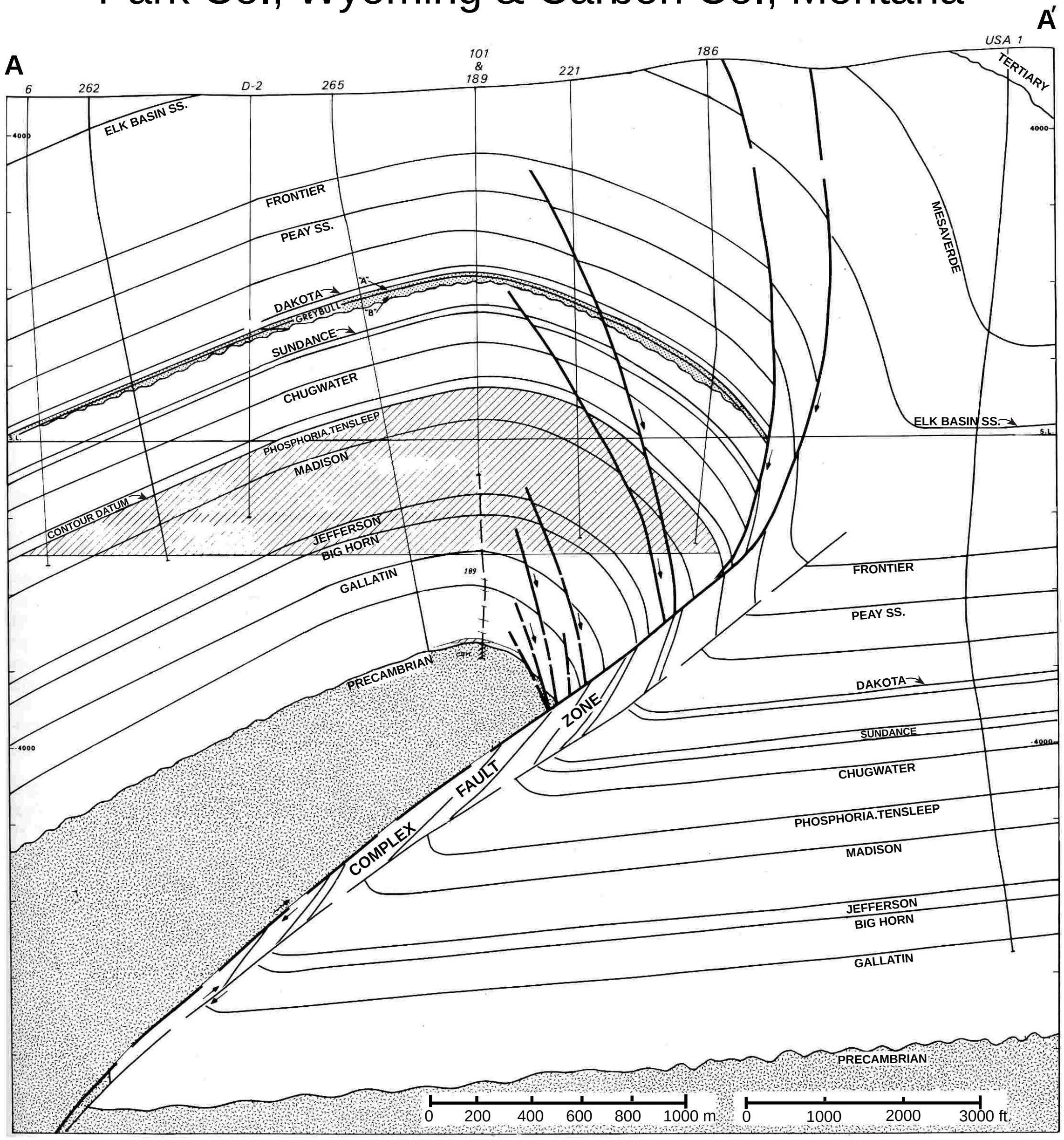


Figure 9. This cross-section of Elk Basin Field (Stone, 1983, RMAG Guidebook, pp. 345-356) shows the classic form of a Rocky Mountain anticline resulting from reverse fault movement. However, note that at this date (1983) Stone still shows the fault plunging at depth.

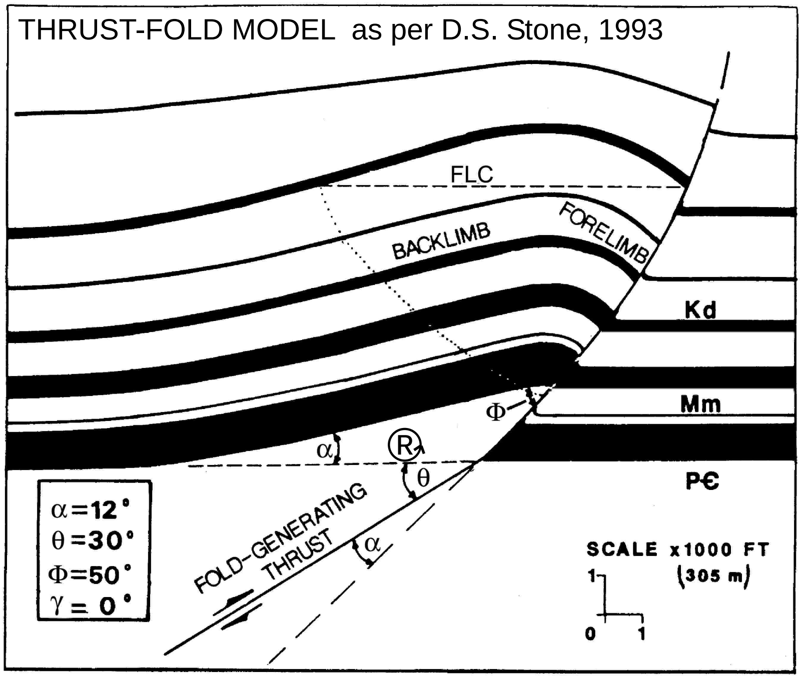


Figure 10. Stone's caption: "True-scale geologic cross-section based on interpretation of profile in A, showing backlimb, forelimb, generating thrust, and various angles used in evaluation of thrust-fold geometry; α is backlimb rotation angle, θ is initial thrust angle with top of basement, Φ is fault cutoff angle at top of hanging-wall basement, and γ is regional dip angle. FLC is fault-limited chord, and dotted line connects all FLC's on the backlimb." Note that α and Φ are assigned numbers (constants) whereas in reality they refer to curved surfaces and thus, in reality are variables.

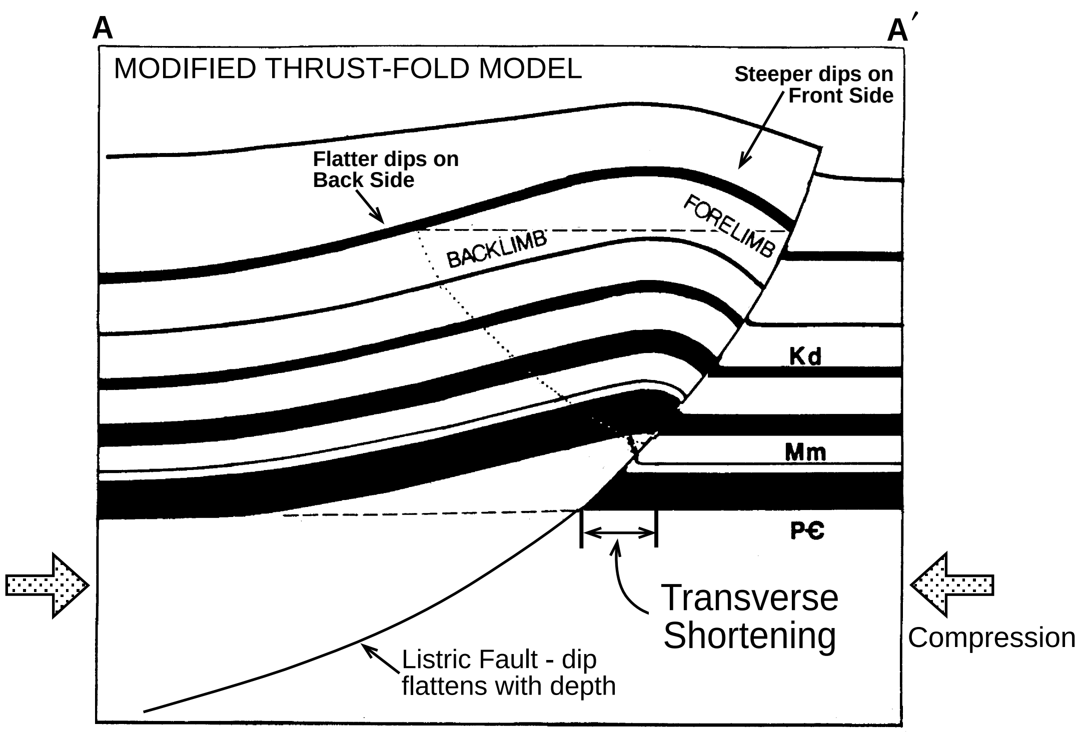


Figure 11. The thrust-fold model for Rocky Mountain structures is documented by oil and gas industry data (wells & seismic) for innumerable anticlines in the region. This model is modified by the author after Stone, 1993 (above). Note that the listric fault flattens with depth in the basement. Increasing dip with shallow depth may be due to less depth of cover, i.e. α, decreases to zero at the Laramide-age ground surface.

The fact that anticlines are formed in the above fashion does not seem to be universally known or acknowledged, as the underlying geometry, especially the causative fault, is usually not mappable with surface geology and sometimes not with subsurface geology (i.e. with exploratory wells that are not deep enough). Only with seismic data or deep wells can we map the causative fault, and when we have such data, the fault seems to always be there.

The asymmetric nature of anticlines is also not universally recognized or acknowledged by geologists. However, in examining over a hundred anticlines in the Rocky Mountain and Midcontinent regions of the U.S. and half that number in California, I could not find one that was not asymmetrical. Flatter dips always occur on the back side of anticlines and steeper dips, sometimes overturned, on the front, or advancing, sides. Where there is insufficient data to delineate the underlying fault and determine which way an anticline has advanced, it can be assumed that the steeper dips are always on the advancing side.

Before continuing the discussion of anticline formation, there are two other geologists who did breakthrough work on anticlines that deserve being mentioned here. The first is Don Blackstone whose 1940 paper on the Pryor Mountains in Wyoming showed a listric fault as raising the structure. This would be the earliest work that was on the right track, but it was largely ignored, unfortunately, as Blackstone published mostly in Wyoming and Montana journals and not in national publications. Nevertheless, Blackstone was about 40 years ahead of his time in understanding anticlines.

Another geologist I want to mention is Richard Q. Lewis of the U.S. Geol. Survey. He was party chief of a USGS team studying Comb Ridge, a prominent monocline on the Colorado Plateau in Utah, in the summer of 1955. He invited an AEC (Atomic Energy Commission) team of geologists, which included the author, to a cookout dinner one summer evening. We were mapping the uranium deposits in the same area he was working. After the cookout, around the campfire, I asked Lewis what caused Comb Ridge to form. This was my first job out of college as a geologist, and I was not well educated in structure. Lewis said that the Ridge formed over a reverse fault in [a brittle] basement, as that was the only way possible to shorten the basement the same amount as the shortening resulting from the folding in the overlying sedimentary section - a very astute observation for the time. Many years later I looked up Lewis' Professional Paper 474-B (1965) to see exactly how he had drawn the reverse fault, but it was not there. The section showed only a series of impossible vertical faults in basement, (as per the David Stearns model) as the causative mechanism for forming the monocline. I attribute this change to Lewis's superiors at the USGS who expunged his correct interpretation in favor of one of the popular, but incorrect, models of the day. Geologist Peter Huntoon (1974) later found outcrops on other monoclines near Comb Ridge that showed underlying reverse faults of the kind that Lewis had envisioned. He thus solved the "monocline problem," proving once again the fault-related nature of anticlines, synclines, and monoclines. Other excellent studies of monoclines can be found in Huntoon, 1981, and 2003.

New Advancements

It might be concluded from the above discussion that the work shown thus far brings us up to date on our understanding of anticlines and that nothing more can be said, but I will here state that all of that work by all of the above authors tell us only <u>half</u> the story of anticline formation. It explains just the two transverse closures - front and back - ("1" & "3") of the "4-way" closure of anticlines that is important in petroleum geology (Fig. 12). It <u>does not</u> explain the "end" closures ("2" & "4") that cut the longitudinal axis of anticlines on left and right sides. In fact, until we logically explain end closure, we cannot claim to know how anticlines form. The problem is <u>3-dimensional</u>, not <u>2-dimensional</u>.

4-Way Closure on SCHEMATIC ANTICLINE
Transverse closure = 1 & 3
End closure = 2 & 4

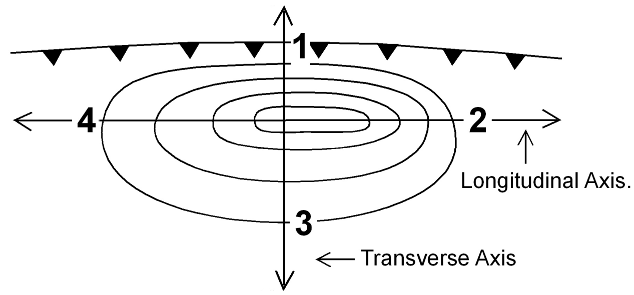


Figure 12. Anticlines must have closure on all sides ("4-way closure") in order to trap oil, and most anticlines do, indeed, have 4-way closure unless they are later tilted.

Whereas this omission may seem trivial, or easily explainable to some, it is not trivial, and in fact, its explanation leads us into an entirely new line of thought on how anticlines form. I would say that if we just explain closures "1" & "3," we have only explained how monoclines form (no end closure for the theoretical case, or distant end-closure for the real case).

Let us take a moment to examine the shortening that results from end closure on anticlines. In Fig. 13. I show a cross-section (B) that traces one of the beds of the anticline. There is clearly shortening of the overlying beds, as the cross-section shows. At right angles to this is the transverse shortening already shown in Fig. 2 and other figures. (Transverse shortening is always greater than longitudinal shortening unless we have an equidimensional dome, in which case they would be nearly equal.)

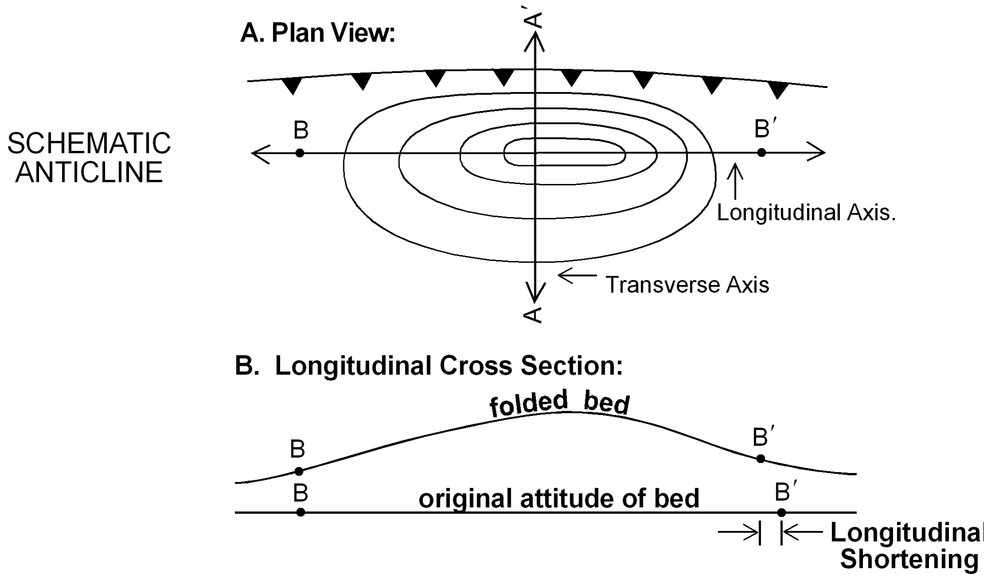


Figure 13. This simple cross-section (Gay, 1999) shows that longitudinal shortening exists.

I have been told that the papers of Dahlstrom (1969), Elliott (1976), Suppe (1983), and Mitra (1993, 1998), among others, somehow preclude longitudinal shortening. Starting with the last, Mitra, in all of his excellent papers and short courses assiduously avoids working in any plane other than the one perpendicular to the long axis of a thrust or fold. Thus, his published work offers no opinion, and sheds no light, on end closure. The same is true of Suppe's work. Elliott's work deals with regional thrusting (in a controversial manner) and likewise is not pertinent to arguments on the cause of end closure of anticlines. Dahlstrom (1969) begins his discussion with the statement, "By ignoring changes in the *b-direction* [this author's "longitudinal" direction] as insignificant....," meaning his work is also not pertinent to the problem. These 4 authors' work are thus strictly 2-dimensional.

The work of Nickelsen (1979) on a tiny anticline (40x200m) exposed in the floor of a surface coal mine in Pennsylvania has also been cited by some as proof that longitudinal shortening does not exist. Nickelsen proposes longitudinal <u>extension</u> of the hanging wall of anticlines because he mapped a set of extension faults and grabens perpendicular to the long axis of this tiny anticline. That this diminutive structure is typical of anticlines in general is questionable. It occupies only <u>one-</u>

thousandth the area of an oil-field size structure only 6 km (3.7 mi.) long. Furthermore, Nickelsen's map shows an adjacent anticline 60 m away that exhibits no such transverse fracturing. So, which one is correct? A vast literature on oil and gas producing anticlines also does not reveal others with this type or amount of extension. Indeed, if such a large degree of extension were present on the typical hydrocarbon-producing anticline, the degree of anisotropy in permeability across anticlines would be several orders of magnitude, and it would thus be one of the better known facts of petroleum engineering. Such is not the case, so this oft-cited example does not preclude longitudinal shortening by transpressive movement of an underlying basement fault.

Mitra (personal communication, 2011) told me he also tends to believe an explanation similar to Nichelsen's because of extensional features he has seen on an anticline in Oklahoma. However, he apparently has not seen similar extension fractures on other anticlines, so his belief must be reconsidered unless, or until, in the myriad of anticlines that have been mapped by geologists, more than two are found that have such extensional fractures. The fractures in the two structures cited could well be later, that is, subsequent to anticline formation.

But there is another quite plausible solution to our dilemma of the cause of end closure of anticlines. Many geologists are aware of my work of the last 40 years mapping faults in the basement under the sedimentary section and my conclusion that most or nearly all faults of any consequence in the sedimentary section are reactivated basement shear zones/faults. Thus, I here emphasize that the causative faults under anticlines are, by and large, pre-existing reactivated basement faults. I have also pointed out that the basement fault pattern as readily seen on airphotos, Landsat images, and SLAR images of shield areas (i.e. on outcropping basement) shows that the basement faults fall into 3, 4, or 5 sets of parallel structures having varying strike directions. Now

I will point out that regional compression applied to such a ubiquitously faulted terrain - anywhere - will result in reverse, or thrust, movement of some of those faults that are close to the perpendicular to the direction of regional compression (Gay, 1999). Some of the faults at 45˚ (or somewhat less) to regional compression will exhibit strike-slip movement. And very few faults will be at exactly right angles to regional compression (the situation with monoclines).

The geometry of anticlinal formation that takes into account the reactivation of an underlying basement fault is shown in Fig. 14. Regional compression is oblique to the underlying basement fault, as the top diagram shows, and by resolution of vectors (lower left), we can determine the percentage of stress that shows up in each of the two mutually perpendicular directions perpendicular and parallel to the fault - the transverse and longitudinal stress vectors. The latter gives rise to end closure, heretofore never explained, as far as I can tell. But I must emphasize that there are not really two separate vectors (i.e., compressional forces) involved; they are just part and parcel of the regional compression that is transpressive relative to the oblique underlying fault. Resolution of vectors is only a mathematical (i.e., quantitative) way of expressing the distribution of stress.

In Fig. 15 we can see what the theoretical ratio of longitudinal stress relative to transverse stress is for different rotation angles (this does not take account of friction or other reactive forces in a geological situation.) The diagram at the bottom shows that more longitudinal stress is created than would seem intuitive. An angle of obliquity (i.e., off the perpendicular to MCP) of only 5.7 degrees creates a ratio of 0.10, that is, 10% of the stress is partitioned along the longitudinal axis at this small angle (the angle is illustrated in the figure). I think this tells us that almost all anticlines will exhibit 4-way closure, as is observed in nature.

Having thus deduced what I set out to explain from the beginning, I was surprised to later realize that other work I had done on basement faults over the years has explained yet another characteristic of anticlines that has never been set down in writing. That is, what determines the size

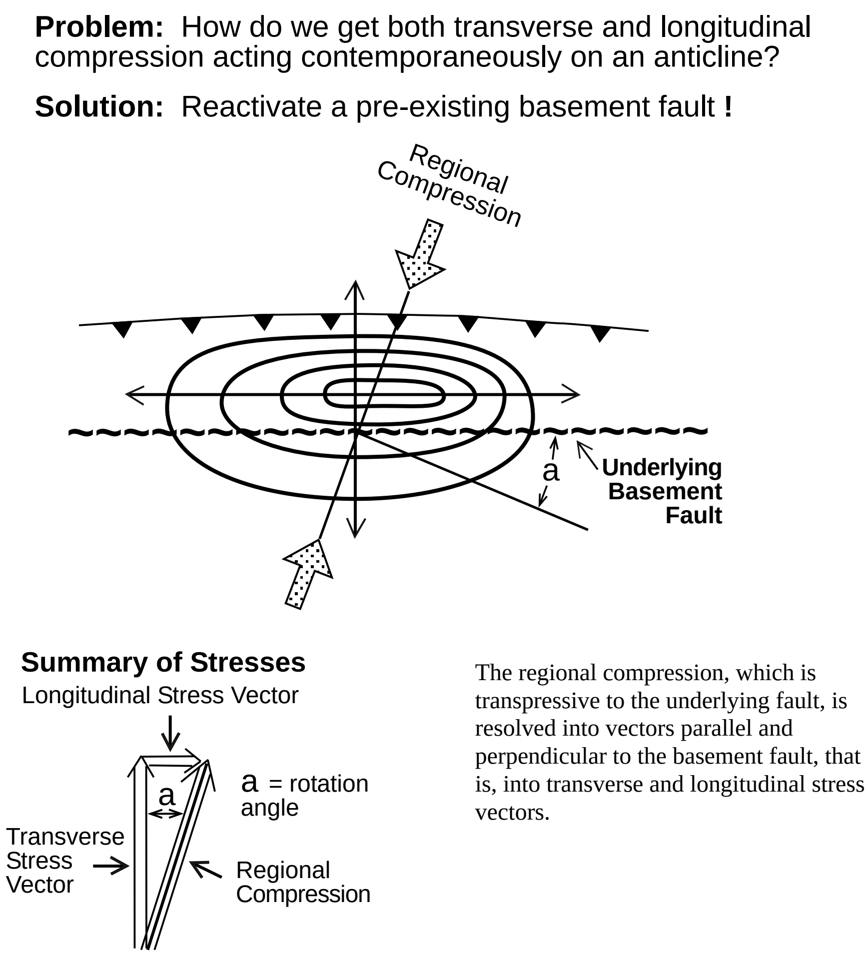


Figure 14. Strain theory dictates that faults and folds must form perpendicular to regional compression, which means that there would only be transverse stress. However, the presence of 4-way closure indicates that there is also a component of longitudinal stress. This diagram demonstrates that the longitudinal stress arises because of the reactivation of an underlying basement fault oblique to regional compression. Four-way closure may thus be considered a testament to reactivation tectonics. (Modified from Gay, 1999.)

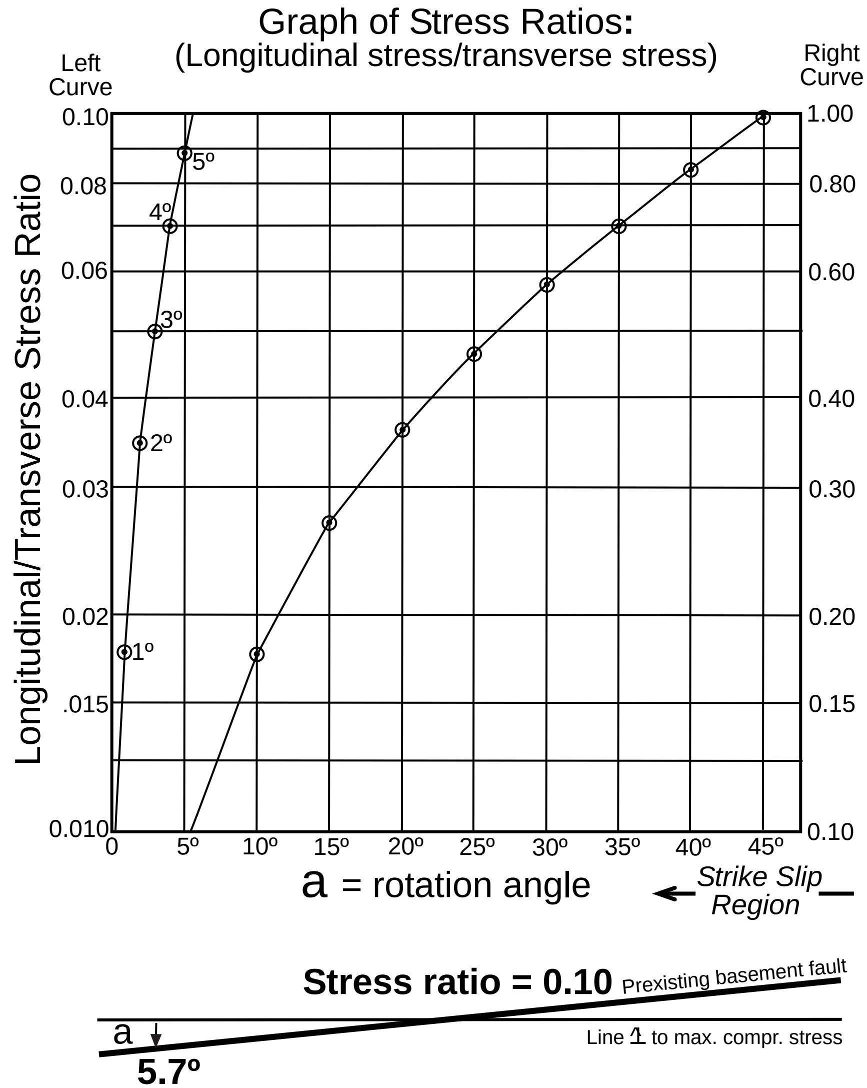
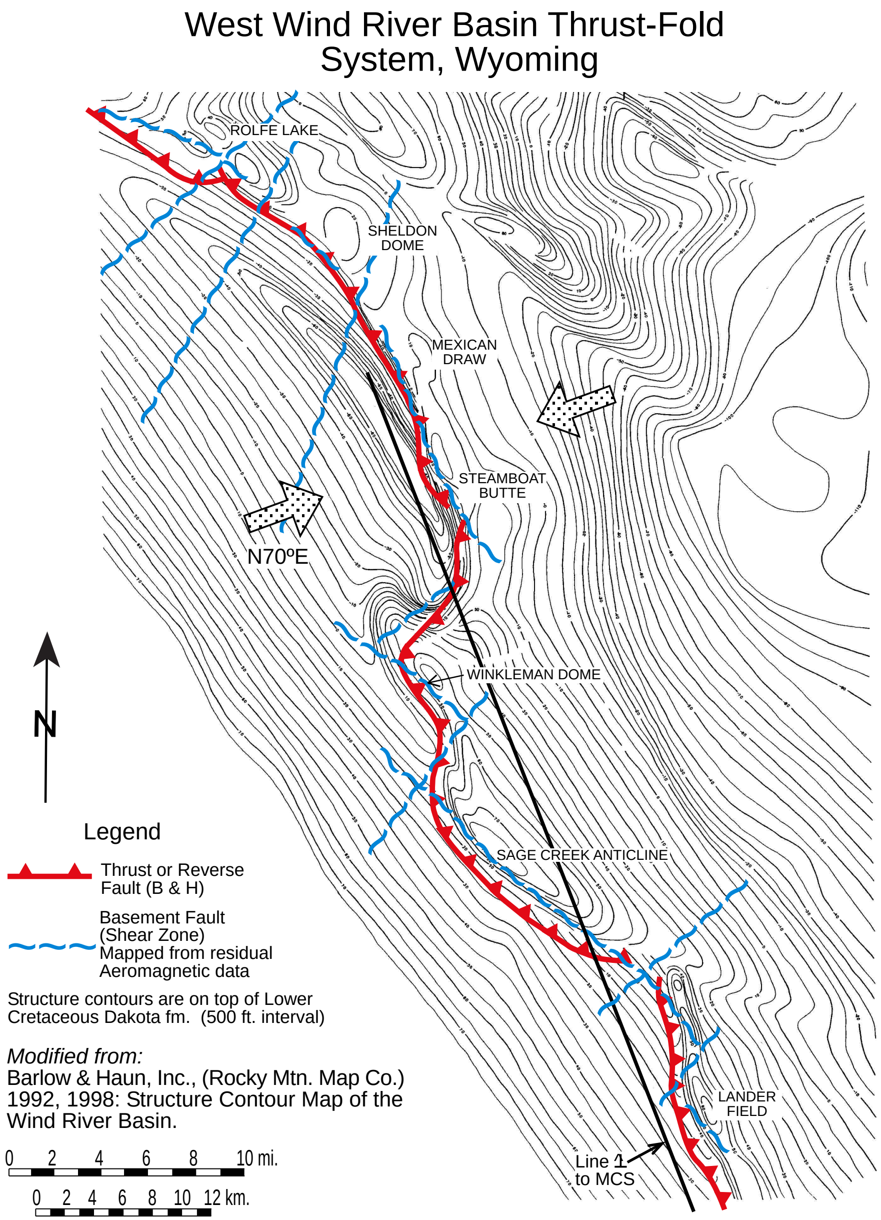


Figure 15. Stress ratio vs. rotation angle. This diagram shows that even for small rotation angles there is a significant longitudinal stress component and thus, that 4-way closure has to be common. In other words, the strike of an underlying basement fault would have to be within a very small angle of the maximum compression stress for end closure to be lacking (see discussion). (From Gay, 2011.)

of an anticline? This question has never been asked by geologists, I don't believe, because we have simply assumed it was moot - the anticline is there, let's just map it and maybe drill it!

Again, basement faulting explains this question, and I will use real geology to show it. In Fig. 16 is shown what I call the "West Wind River Basin thrust-fold system," a string of seven contiguous anticlines productive of oil and gas in western Wyoming. Structure contours and thrust faults (red) mapped by Barlow & Haun, Inc. outline these end-to-end structures along the system from Rolfe Lake on the north to Lander on the south. Basement faults mapped by magnetics appear in blue. Note the seven basement cross-faults. They almost exactly delimit the Rolfe Lake, Sheldon Dome, Mexican Draw - Steamboat Butte, Winkleman Dome, Sage Creek, and Lander anticlines. In the next example, the Buffalo Basin and Grass Creek structures are located in the SW Big Horn Basin, also in Wyoming (Fig. 17). Three prominent basement cross-faults outline these two anticlines (A, C, & D), although another cross-fault (B) cuts through the middle of the former. Evidently that fault was not reactivated. A third system also in Wyoming, but this time in the Powder River Basin, is shown in Figure 18. Here, basement cross-faults delimit 5 mapped anticlines including Salt Creek, one of the largest oil fields in the U.S. For this example, I show the magnetic map (Figure 19), so that one may see the magnetic gradients and truncations of anomalies that define the basement cross-faults. Note the lack of an oil field in T36N. The basement faults here are closer together, so perhaps this area was too fractured for a sealed trap to form. The Appendix and previous papers by the author explain the interpretation process for basement faults in more detail (Gay, 1985, 2011), and present many examples.

It is seen by the above figures (17, 18, 19) that an advancing thrust sheet is cut by cross-faults into segments, and that each segment becomes a separate anticline, in a "piano key"-like arrangement of structures. The distance between the cross-faults controls the length of the anticline and hence its size, as there seems to be a fairly constant width-to-length ratio of anticlines.



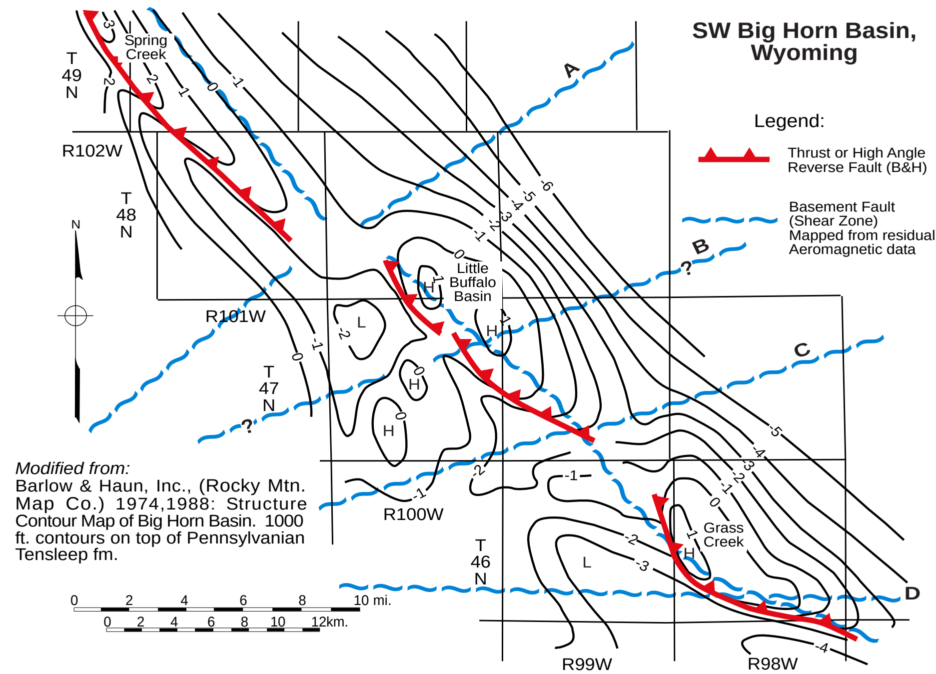


Figure 17. A thrust-fold system in the SW part of the Big Horn Basin showing the location of underlying basement faults. Note that three cross-faults (A, C, D) precisely outline the Little Buffalo Basin and Grass Creek anticlines. Another fault (B) was probably not reactivated. (From Gay, 2011, p. 22)

Figure 16. In the southern part of the West Wind River Basin thrust-fold system in Wyoming, basement cross-faults precisely delimit Winkleman Dome, Sage Creek Anticline, and Lander Anticline. (From Gay, 2011, p. 20)

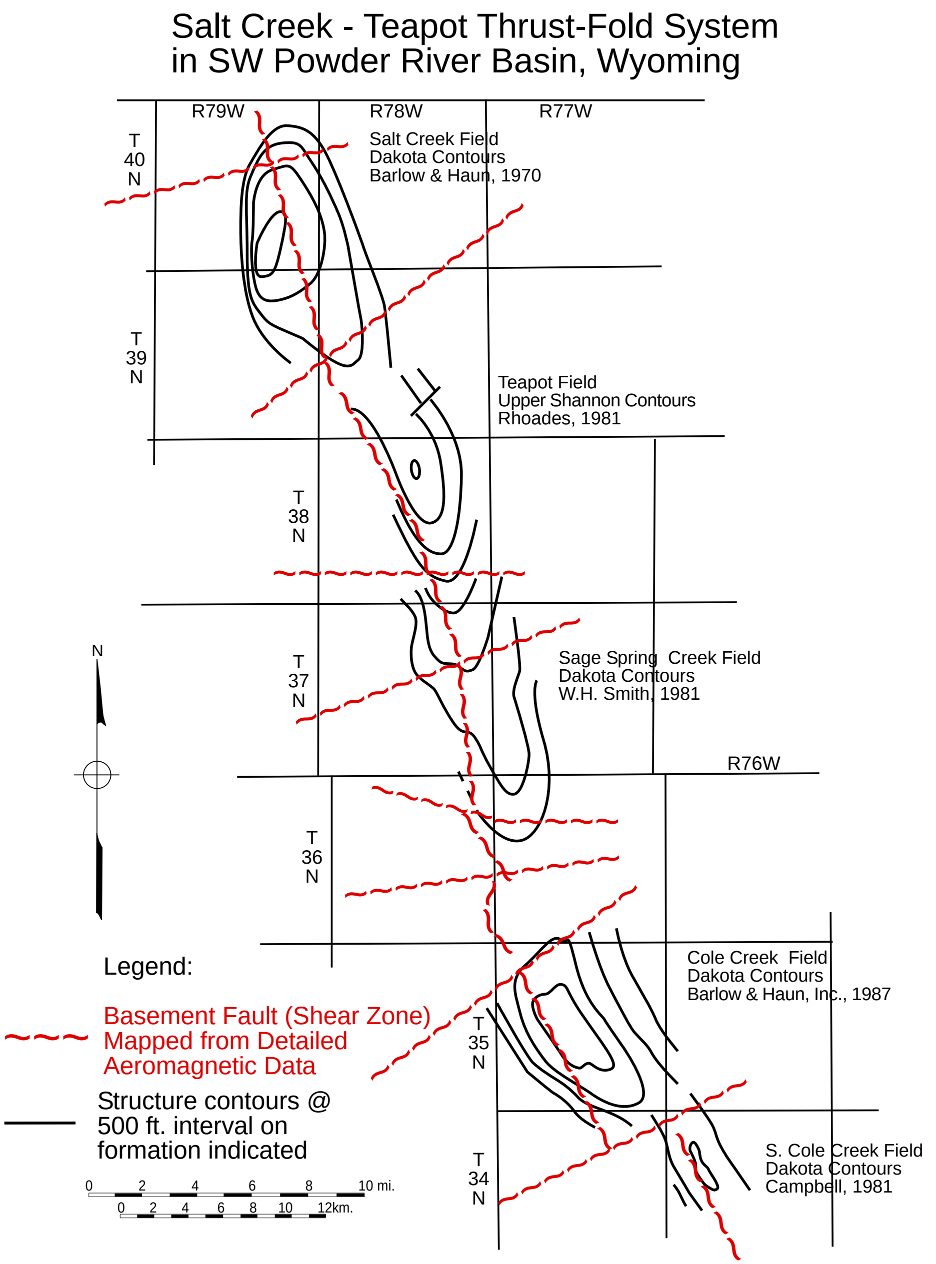


Figure 18. A chain of anticlinal thrust-fold fields on the Casper Arch in the Powder River Basin, Wyoming, are precisely outlined by the cross-faults shown. These include Salt Creek field, one of the largest oil fields in the U.S. (From Gay, 2011, p. 21)

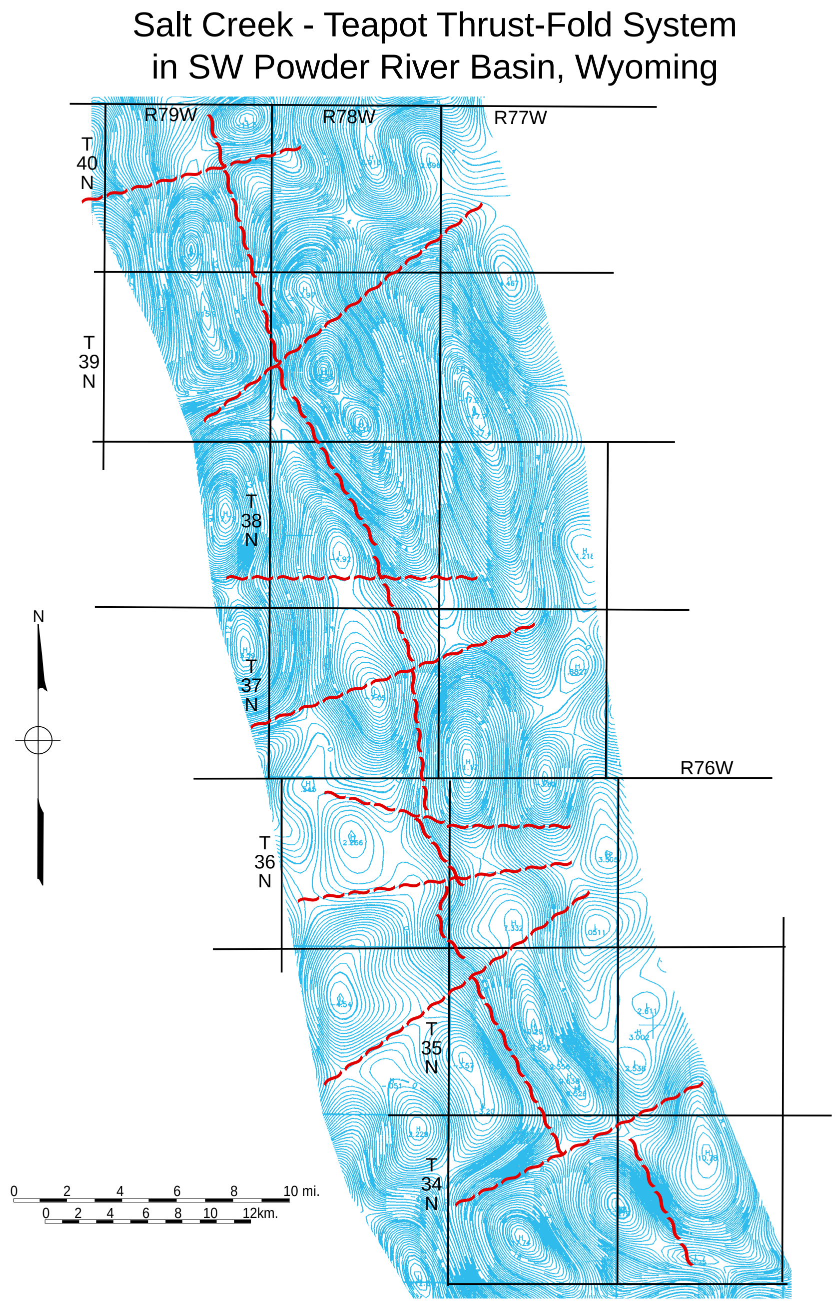


Figure 19. Residual magnetic contours corresponding to the previous figure. One may here see the magnetic gradients and truncations of anomalies that define basement faults.

To summarize this paper: Geologists in the U.S. and Canadian Rockies post-World War II developed (by 1993) the plausible, balanceable fold-thrust model of anticlines and range-front uplifts which seemed to sufficiently explain the development of these structures. However, unexplained was why anticlines have "end-closure" - the other half of the problem (that has never been considered as far as I can tell). But end-closure does have a plausible explanation. The underlying causative faults are reactivated pre-existing basement faults, which are usually slightly or moderately oblique to the perpendicular to regional compressive stress. A component of longitudinal stress is thus created, resulting in "end-closure." Finally, a second type of basement control manifests itself - pre-existing basement cross-faults which have strike-slip movement contemporaneous with compression and cut the advancing thrust into segments. Each segment subsequently becomes a separate anticline. The locations, and separations, of the cross-faults determines the lengths, and consequently the sizes, of anticlines.

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Appendix

Mapping Basement Faults with Magnetics and the Maverick Springs Example

Several times in this article I refer to mapping basement faults under sedimentary basins with magnetics, and although I have explained how this is done in past publications (Gay, 1995, 2011, and others) I will briefly explain it here again. I will also show confirming examples.

In Fig. A1a appears a typical total intensity magnetic map of part of a sedimentary basin, in this case the Anadarko Basin in Oklahoma. The total intensity data was subsequently residualized (“processed”) along the east-west flight lines to emphasize the signal from the blocks of metamorphic rocks subcropping on the top of basement (Fig. A1b). The basement block boundaries, i.e. basement faults, are defined by 1) the truncation lines of anomalies, such as A-A’ and B-B’, and by 2) the magnetic gradients between highs and lows (all other lines) in Fig. A1c. Two faults and one structure provided by Oklahoma geologists confirm the accuracy of the interpretation (A1d.)

In the West, an interesting confirmation of how accurate basement mapping can be (not all comparisons are as good as this one!) is shown in Fig. A2. On the left side is shown the residual magnetic map and the interpreted basement fault along the line of steepest magnetic gradient (red line). On the right I have placed this line on the Barlow and Haun geologic map of the structure. Note that this line, corresponding to the fault at basement level, is displaced easterly from the fault at Dakota (Cretaceous) level, but is nearly exactly parallel to it. This is the situation one would expect for an easterly-dipping thrust or reverse fault. Don Stone’s interpretation (1993) of the fault is shown in Fig. A3.

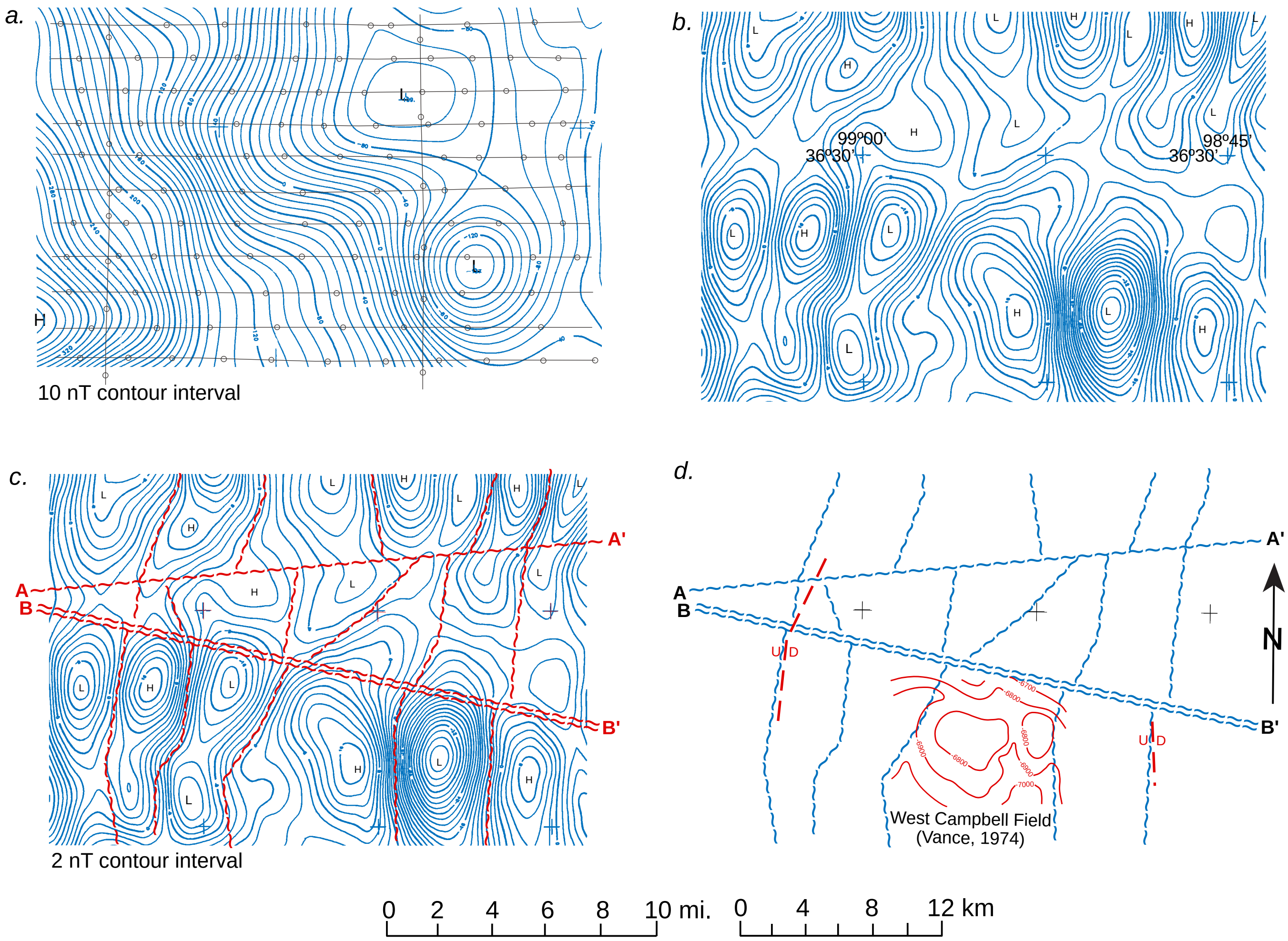
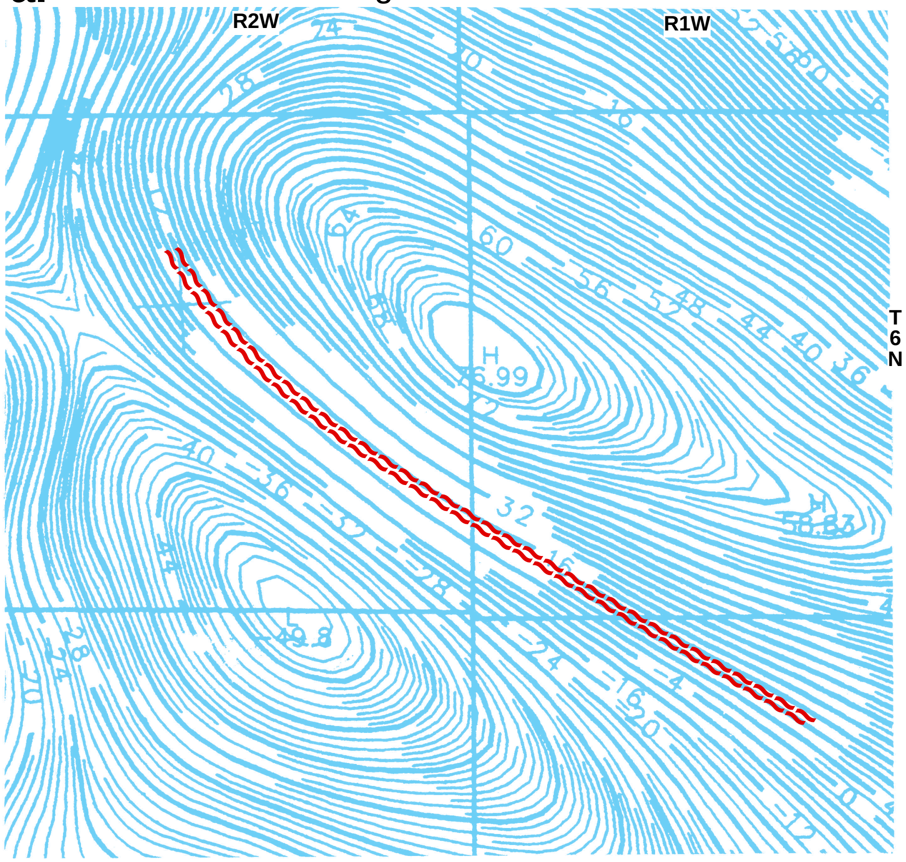


Figure A1. Example of basement mapping in Major and Woodward counties, Oklahoma, on north shelf of Anadarko Basin. Depth to basement approx. 12,000 ft. (3600m) beneath flight level. **a**. Total intensity magnetic map - not generally useful in basement mapping. E-W flight lines are spaced 1.16 mile apart. **b**. Flight line residual map of same data shown in **a**. This display maps the individual basement fault blocks. **c**. Basement shear zones are drawn along boundaries between magnetic highs and lows, i.e. on gradients, and also along truncation lines (A-A' and B-B'). **d**. Fault block interpretation, with known faults superimposed and with structure contours of West Campbell oil field superimposed. Contours are on top of Hunton fm. (Devonian) at 100 ft. interval (Vance, 1974).

Maverick Springs Field, Wind River Basin, Wyoming

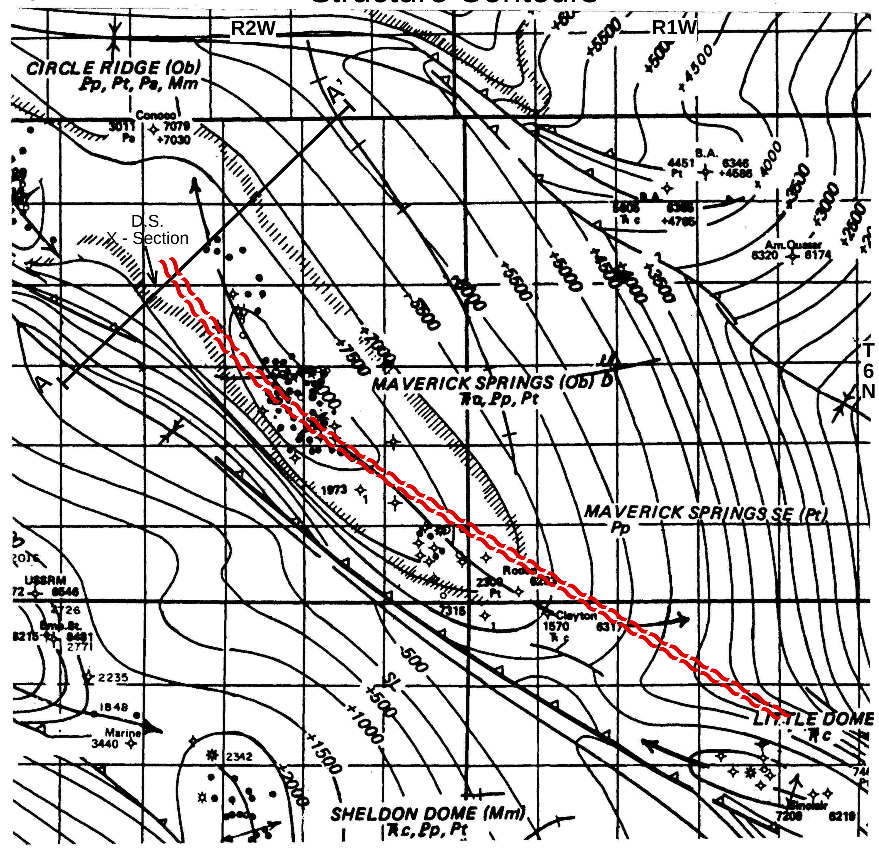
a. NewMag® Contours



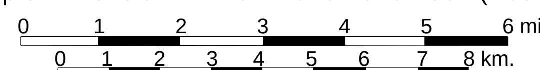
NewMag® data from Applied Geophysics, Inc., Salt Lake City, UT

NewMag® map of the area of the Maverick Springs field showing the interpreted location of the basement fault (red) placed along the line of steepest magnetic gradient.

b. Structure Contours

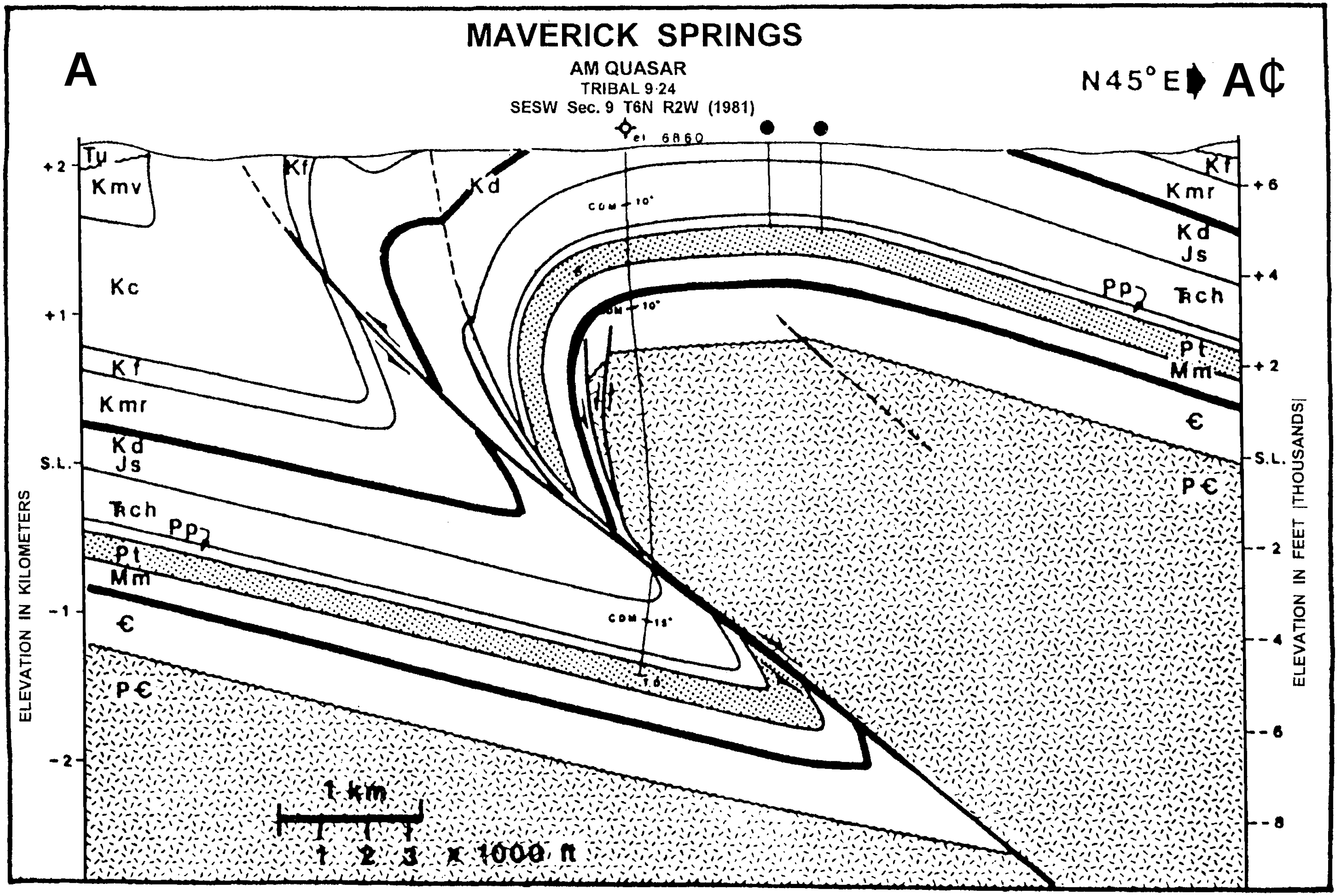


Contours on top of K Dakota fm. From Barlow and Haun (Rocky Mtn. Map Co.), 1992, 1998.



Comparison of the interpreted fault location at basement level (from figure on left) under the Maverick Springs field with its location at Dakota level. A northeast dip is inferred as the barbs on the fault indicate.

Figure A2. Maverick Springs is one of the more perfect, one might almost say mathematically precise, correlations of a basement fault with an anticline that I have seen. The causative basement fault trace **(a)** is almost exactly parallel and lies to the east of the location at Cretaceous level **(b)** in conformance with the east dip of the underlying fault (shown in next figure).



From D. S. Stone, 1993, GSA Spec. Paper 280, pp 271-318

Figure A3. This cross-section of Maverick Springs Field shows that it is a typical thrust-fold structure, as are probably most (all?) of the compressional anticlines everywhere.

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