FUNDAMENTAL ADVANCES IN STRUCTURAL GEOLOGY BASED ON ONGOING STUDIES IN REACTIVATION TECTONICS

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ABSTRACT

Basement shear zones, as observed on surface geological maps and airphoto, Landsat, and radar images of outcropping basement on all the world's Precambrian shields, occur pervasively in parallel sets on the cratons and cut the earth's crust into a series of separate blocks. These bounding shear zones/weakness zones are reactivated under sedimentary basins in subsequent tectonic events or by later sedimentary or tectonic loading, affecting all younger rocks. This process is termed "reactivation tectonics," and its reality requires reconsideration of many geological phenomena. For example, one-on-one correlations obtained in the Paradox Basin of the 4-Corners region in the western U.S. between basement shear zones mapped with aeromagnetics and 1) Kelley and Clinton's map (1960) of the Comb Ridge monocline and 2) Hodgson's classic study (1961) of jointing showed that basement shear zones controlled the Laramide-age monocline and were also responsible for the joint pattern (Gay, 1972, 1973). In the 35 years since 1973, basement faults have been mapped in sedimentary basins throughout the U.S. with the same rigorous aeromagnetic techniques and compared to the locations of hundreds of known, reliably-mapped faults and stratigraphic features in the sedimentary section. From this work it can be stated definitively that most faults in the sedimentary section (excluding thin-skinned thrusts and "growth faults") are reactivated basement faults, and that a majority of stratigraphic features also arise from lesser movements of basement faults.

The work on reactivation tectonics has also explained some very common geological features that geologists thought were well understood but weren't, such as basement involved anticlines and domes. Anticlines are nearly always asymmetrical in cross-section and arise from compression across underlying reverse or thrust faults. This compression created the required transverse basement shortening under the anticlines that results in the primary closure parallel to the long axis of the anticline. However, since the causative reactivated basement fault is seldom at right angles to the compressional direction, there is thus always a component of longitudinal compression on the anticline, resulting in "end-closure," rounding out the necessary "4-way closure," of petroleum geologists. Additionally, the author has realized recently that the size of anticlines (i.e. the length) is also controlled by basement, as it is the basement cross-faults that cut an advancing thrust front or reverse fault into segments that, with more movement, become individual anticlines.

A structural dome, as opposed to salt domes or compactional domes over underlying basement hills, apparently results when the angle between the underlying fault and maximum compressive stress varies considerably from 90º, for in this situation the longitudinal compression becomes a sizeable percentage of the transverse compression. Another geological situation, also not fully understood previously, is the sidestepping of a fault, or a side-stepping system of faults, frequently confused with en-echelon faults. This results when a series of parallel basement faults are reactivated by maximum compressive stress oblique to the strike of the faults.

Finally, reactivation tectonics explains the origin of regional jointing in sedimentary rocks and the connection between jointing, fracturing, lineaments and linears, of which the latter two to this day, in spite of their ubiquity, are still considered "controversial." The clear connection of these features to basement faults, as demonstrated herein, should dispense with that uncertainty.

Introduction

This paper is multidisciplinary. It involves several diverse geological/geophysical topics, i.e. 1) Precambrian igneous and metamorphic geology/petrology, 2) potential field geophysics, especially magnetics, and 3) structural geology, including elementary physics. It is because of the integration of these disparate fields that it has been possible to make new advances in structural geology. Assuming that many readers will lack extensive knowledge in all three unrelated disciplines, the reader's indulgence is therefore requested to read some of the cited literature in order to better understand the subject matter. For example, structural geologists have rightfully asked "how can airborne magnetics possibly map shear zones in the basement?" The answer is that the shear zones are not mapped directly, but instead, the locations of basement blocks of differing rock types (and hence differing average magnetic susceptibilities) are mapped, and it is the geological boundaries between these blocks that coincide with shear zones (Gay, 1995). That is a very simple geologic/geometric relationship. The fact that shear zones in the basement usually separate different rock types will probably not be common knowledge to most readers of this paper. To those geologists who are experienced in the various listed disciplines, the material I am going to present is quite straightforward and well-documented. Every question that could possibly be asked of this material has been asked and satisfactorily answered many times over by the writer himself, not to mention the many qualified reviewers who have looked at it. Every correlation found between magnetically mapped basement faults and structural and stratigraphic features in the sedimentary section is therefore an independent proof of the premises set forth herein (there have been hundreds of correlations).

Alfred Wegener (1925), in answering critics of his continental drift theory, stated there was only a one-in-a-million chance he was wrong. He arrived at this rather high number by pointing out that there were six major geological structures on opposite sides of the Atlantic that lined up when the continents were joined back together. By assigning a probability of ten to one that a single correlation would not be random, then six such events gave him a probability of 10^6 that he was right. If I used this same rationale in my own work, where I have hundreds of correlating structures, then the chances of my conclusions on basement control of faults being wrong (not necessarily everything I propose herein) is infinitesimally small. Even if I use a 2:1 probability for a single event rather than 10:1, it is still infinitesimally small. (What is 2^{-100}?)

The two basic premises of this paper are 1) that pre-existing shear zones in the basement are mappable with properly flown and processed aeromagnetic data, and 2) that some of these shear zones have been reactivated later to create almost all structure and much stratigraphy in the Phanerozoic sedimentary section. The latter finding I call "reactivation tectonics." Geologists have recognized reactivation of many specific individual structures in the past, but none have made multiple comparisons over large areas. By knowing the precise locations of a great many basement shear zones/weakness zones underneath large areas in well-mapped petroleum basins, one should therefore not be surprised that a better understanding of structural geology is emerging. More specifically, comparisons between faults in the sedimentary section and basement faults in 21 U.S. sedimentary basins over a combined area of about 750,000 km², reveal hundreds of correlating faults and sedimentary features. Most faulting in the sedimentary section therefore results from reactivation of basement shear zones and little is due to fracturing at ±30° to maximum compressive stress as hypothesized in the past ("strain theory" or "Andersonian theory of stress"). This finding has implications that go far beyond the specific areas studied (Gay, 1999a).

Reactivation of basement faults and shear zones is the controlling factor not only for younger overlying structures, such as faults, folds, and fractures, but also for joints, linears, and lineaments, as well as the locations of many stratigraphic features, such as the various types of bioherms and sandbars (Gay, 1972, 1973, 1986, 1995, 1999b, etc.). The writer apologizes to the reader that so many of the references cited in this paper are his. However, that is because much of the work in reactivation tectonics has been done by the writer, as others have tended not to appreciate the vast importance to geology that reactivation of earlier structure has had on later structure, nor have they had access to such large volumes of the pertinent data as the writer has had.

A few well-proven examples of basement control on younger rocks and an explanation of the techniques employed to map covered basement faults will be presented below. Four illustrative examples, two structural ones, a stratigraphic one, and a regional one, are included. Many other clear-cut examples can be found in previously published papers and in later paragraphs of this paper.

The first example is a fault comparison in north-central Oklahoma (Fig. 1), which will also be used to discuss the techniques employed for mapping basement faults. The sedimentary section here is 10,000-12,000 ft. thick and is essentially non-magnetic. The total intensity magnetic map (Fig. 1a) is dominated by a single magnetic high on the west and an elongated, compound low on the east about 25 km away. It is obviously not mapping the approximately three to six km wide basement blocks that we find in all of our studies. To bring out the individual basement blocks it is necessary to residualize the magnetic data or to calculate derivatives. Either will suffice, although some computational techniques are better than others, and all have been treated in prior literature. We prefer a map of residuals calculated along flight lines that produces higher resolution than other techniques (Fig. 1b). On this map each of the magnetic highs and lows represents a separate basement block, and the faults (shear zones) separating the blocks occur on the intervening boundaries, that is, on the magnetic gradients between blocks (Fig. 1c).

A detailed independent subsurface map of this area yielded two faults cutting the sedimentary section (shown in red in Figure 1d), and they occur along or very close to the basement faults mapped by the magnetic treatment. A structural dome, West Campbell oil field, is centered on a basement block between faults and is probably a compaction structure over a basement hill. Basement shear zones give rise to jointing in the overlying sedimentary section and these typically erode low along the boundaries of basement blocks compatible with the observations here.

Another structural example is shown in Fig. 2. Ponca City Field occupies an asymmetrical, or compressional, anticline (red) in Paleozoic rocks and has produced >12 million barrels of oil from multiple horizons. The structure results from reverse movement on an underlying basement fault or shear zone (see inset) that is mapped by the residual magnetic data.

The two foregoing examples - typical of many in our files, demonstrate basement control of structure. Basement control of stratigraphy, in this case the localization of a late Cretaceous sand buildup, occurs at Hartzog Draw Field in the Powder River Basin of Wyoming over an underlying basement fault (Fig. 3). Swift and Rice (1984) proposed that the sandstone reservoir in this field, and other similar fields nearby were formed by the winnowing action of bottom currents over sea floor highs. The sea floor high would have resulted from the raising of a basement block edge during Late Cretaceous Laramide compression. Nearby fields of the same geology also show similar one-on-one relationships to magnetically mapped basement faults. They are: 1) Dead Horse-Barber Creek, 2) Nipple Butte-Holler Draw, 3) Culp-Heldt Draw, 4) Poison Draw, 5) Scott, and 6) House Creek. It would be difficult to postulate another cause for these many correlations with basement faults other than basement control of the sand buildups.

An interesting example will be shown here to illustrate the benefits of magnetics for mapping regional geology (Fig. 4). The southern Kansas segment of the Midcontinent basement map (4a) by Sims (1990) is based on about 35 oil well intersections of basement (small black dots). A detailed residual aeromagnetic map of the same area (4b) contrasts markedly with the basement geological map. It is, after all, based on about 2000 times as many data points. The large amount of detail on the magnetic map and the many geologic features resolved demonstrate the utility of residual magnetic data for regional geological mapping. This comparison suggests that an updated treatise based on the magnetic data needs to be written on the basement geology of this particular area of Kansas.

Interestingly enough, a publication of an overlapping area (Fig. 5) by Sims, et al, the following year (1991) agrees with my assessment that using scattered well data is insufficient to define the basement geology. These authors state: “The number and distribution of drill holes that penetrate Precambrian basement are inadequate for delineating even first-order lithologic domains in the subsurface." They then generate regional "digital aeromagnetic and gravity maps" which are used "to define...the trend, extent, and boundaries of gross geologic rock units." This is one of the few studies I know of that employs aeromagnetic data for mapping regional geology and I salute them for it. However, their aeromagnetic data was not high resolution (i.e. close line spacing) , and I suspect their processing techniques were not as powerful as those I use (their geophysical maps are not shown), so they could not resolve the basement fault blocks to the degree shown in Fig. 4.

Up to this point, this paper may be considered a tutorial, as all of this material has been published or included in talks the author has given previously.

Advances in Understanding Structural Geology

Gay (1999b) showed how "end-closure" of anticlinal structures could be explained by regional compression reactivating underlying basement faults not at right angles to maximum compressive stress (σ_1), a subject apparently never before considered by geologists. (No references to this phenomenon were found in an extensive initial review of the literature, or a second reading of specific articles recommended by structural geology reviewers.) This work provides a better understanding of the commonly used term, "4-way closure," favored by petroleum geologists. Other related concepts of structural geology will also be discussed, to wit: 1) why anticlines with 4-way closure (rather than monoclines) are such common geological structures, 2) how enigmatic "end-member" compressional domes are formed, 3) how and where anticlines form along an advancing thrust fault, and 4) why "side-stepping" fault systems are to be expected and how these differ from en-echelon systems. A summary of an old topic from the new reactivation perspective will then be presented to show 5) how reactivation of basement faults gives rise to regional joint systems which, in turn, give rise to airphoto linears, Landsat lineaments, and drainage systems that have largely controlled both paleotopography and present day topography. Next, there will be presented two examples showing, 6) how maps of the regional basement fault block pattern can be used to possibly determine how far thin-skinned thrusts have moved. Finally, there will be shown a hierarchy of oil and gas trap-forming structures and stratigraphic features inherited from basement.

At this point, there arises a question that may be on the minds of many geologists: "How do you know that the basement movements you speak of have reactivated old faults, rather than creating new faults contemporaneous with the folds that overlie them?" First of all, pervasive fracture systems of great age may be seen in Landsat or SLAR images of all the Precambrian (basement) shields of the world. A single example of these images is shown in Fig. 6; others appear in Gay, 1995 and 2002, as well as in dozens of publications by other authors. There is abundant literature on the ancient age of these basement faults (actually shear zones). Secondly, logic tells us that if the regional basement faults were created, for example, in the Rockies in Laramide time, only 70 million years ago, then such fault systems would also have been created in all the many prior orogenies that occurred back to the oldest dated rocks in the Rockies on the Wyoming craton at approximately 3500 Ma. So why would new basement faults have been created in Laramide time which occurred after 97% of the relevant geologic time and presumably the same amount of tectonism had already transpired??

A more specific argument for reactivation of pre-existing faults can be made based on the data in Fig. 7. Here are shown all basement faults mapped from magnetics in the vicinity of the West Wind River thrust-fold system in Wyoming that includes Lander Field, Winkleman dome, Sheldon dome, and other oil fields, whose reserves total approximately 500 million barrels of oil. The red-colored basement faults are the ones that coincide precisely with the Laramide age thrusts, i.e. the only ones that were reactivated in Laramide time, resulting in overriding anticlines now filled with oil. The other basement faults show no Laramide movement and presumably no Paleozoic movement and are thus of purely Precambrian origin. Note that the reactivated faults are just isolated members of two pervasive fault sets, one trending northeast, the other northwest. Logic tells us that all the faults of a given set would have formed during the same tectonic event, i.e., that some of these evenly spaced faults could not have been created parallel to and intercalated at the same spacing at 70 Ma. with others that were created a billion or more years earlier. Note, for example, the fault trending northwest across 1S, 1E and 1N, 1W coincident with the west margin of the Sage Creek anticline, one of 5 similar parallel faults of equal spacing and length. It could not have been created separately from the other non-reactivated faults.

This particular example is one of the more illustrative proofs of the reality of reactivation tectonics because of the excellent geological control available. It complements the four examples shown at the beginning of this paper.

1) End closure and the formation of anticlines

It was demonstrated in an earlier paper (Gay, 1999b) that "end-closure" of anticlines requires a component of longitudinal compression parallel to the long axis of the anticline (Fig. 8). It was also shown that this longitudinal compression comes about by resolution of the regional stress vector into components perpendicular and parallel to a pre-existing basement fault that is not perpendicular to σ_1 (Fig. 9). [Please study Figures 8 & 9 carefully. They are as important to understanding how anticlines are created as what is written here.] Regional stress thus bears a transpressive relationship to the underlying fault and the resulting anticline. The strength of the longitudinal compression compared to transverse compression, is here termed the "stress ratio," α. In Fig. 10 are graphed the stress ratios for rotation angles varying from near 0° (basement fault $\perp$ to maximum compressive stress) to 45°, on a semi-log plot. Note that for even small angles of rotation there is a measurable amount of longitudinal stress. At a minuscule 1° rotation the computed longitudinal stress is 1.8% of transverse stress, and at a 5.7° rotation angle (Fig. 10) it is 10% of transverse stress. Surely this latter amount (10%) is more than enough to result in end closure, even though the rotation angle (5.7°) is quite small (see physical representation of a 5.7° angle at the bottom of Fig. 10). It is mainly for this reason that all anticlines must close, since few, if any, basement structures will be located precisely at right angles to maximum compressive stress.

Many structural geologists now accept the premise that 1) compressional folds always result from underlying faults, and that some believe that 2) these faults arise in basement (thin-skinned thrusting excluded). The present work shows that the basement faults are pre-existing, and thus statistically few of them could occur exactly at right angles to a later imposed maximum compressive stress. Folds are thus necessarily transpressive to their causative faults, resulting in longitudinal stress as revealed earlier (Fig. 8 & 9).

Some geologists think the problem of end closure has already been dealt with or is not important. One body of thinking is that the papers of Dahlstrom (1969), Elliott (1976), Suppe (1983), and Mitra (1993, 1998) somehow preclude the explanation I present. Starting with the last, Mitra, in all of his papers and short courses (not just the two cited above) 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 absolutely 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 somewhat controversial manner) and likewise is not pertinent to arguments on the cause of end closure of individual 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.

The work of Nickelsen (1979) on a tiny anticline (40x200m) exposed in a surface coal mine in Pennsylvania has also been cited by some as proof that my explanation for end closure is not correct. He proposes longitudinal extension on anticlines because of the presence of a set of extension faults and grabens perpendicular to the long axis of the anticline there. That this diminutive structure is typical of anticlines in general is questionable. It occupies only one-thousandth the area of an oil-field size structure only 6 km long. Furthermore, Nickelsen's map shows an adjacent anticline 60 m away that exhibits no such transverse fracturing. (Which one is “typical”?) 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 permeability anisotropy on 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.

2) Compressional domes explained.

In Fig. 11 are schematically illustrated a series of compressional anticlines formed as the rotation angle of the structure is increased in 15° increments from 0° to 45° to maximum compressive stress. The theoretical, mathematically calculated, stress ratio increases at the same time from 0 to 100%. It is assumed here that the length-to-width ratio of the anticline decreases as the stress ratio increases. Thus, when the longitudinal stress is equal to the transverse stress at 45° (stress ratio of one, or 100%), a dome should result.

> Discussion: The above assumption is undoubtedly oversimplified. Intuitively, it is thought that domes should form before the extreme rotation angle of 45° is reached. That angle probably falls within the strike-slip region, i.e. where there is movement along the fault in a strike-slip sense rather than compressional folding of the overlying strata. This points to non-linearities in the system, due perhaps to friction, which need addressing by further research.

To this author, compressional domes have always been enigmatic in their relative lack of fracturing. A dome formed by material rising from below, such as an igneous intrusion or a salt dome, is characterized by a complex net of extensional faults (see e.g., North, 1985, p. 285) because of the inability of the strata to "lengthen" or "stretch" over the structure. The other type of dome, the gravicline, resulting from gravitational compaction of strata over a basement hill (Fig. 12), is not formed tectonically, but syndepositionally, and although there is some fracturing on the flanks, it is not as extensive as on intrusive domes (see Gay, 1989, Fig. 12). The compressional dome, on the other hand, is formed by pressure exerted in both the transverse and longitudinal directions and would thus be only moderately fractured.

In Fig. 13 is again shown the West Wind River Basin thrust-fold system, this time to determine if there is correspondence of actual mapped anticlines with the concepts expressed in Figure 10. Here we see that Lander Field and the anticline extending from Steamboat Butte to Mexican Draw, the two being nearly parallel, are long and narrow, indicating they must be nearly perpendicular to maximum compressive stress. If we therefore draw our stress vector in the perpendicular direction to Steamboat Butte, that is, approximately N70°E (which correlates with the known direction of MCS for the Laramide event), we see that structures which are rotated from the perpendicular to this direction, such as Sage Creek (27° rotation) and Sheldon dome (25° rotation), are wider, or more domal-shaped. The concept does seem to apply.

3) How and where anticlines form

An additional advancement in our understanding of anticlines that reactivation tectonics explains is where anticlines form along an advancing thrust front and how large (long) they will likely be. These points were not considered of consequence in the earlier versions of this paper, but to exploration geologists engaged in oil and gas exploration they can be very important in directing the search effort and to academic geologists in providing a more complete understanding of structural processes. Referring to Fig.13 of this paper, already discussed, it is seen that anticlines form between the basement cross-faults that cut the thrust fault. The cross-faults divide the thrust into separate segments that move independently of each other and at different rates. Figures 14 and 15, discussed in previous literature (Gay, 1996), show two additional chains of anticlines in Wyoming and their accompanying cross-faults. These three figures (13, 14, & 15) are vivid testimony to the importance of cross-faults in locating anticlines. [The maps in Figures 14 and 15 (Gay, 1999) were published without the cross-faults as their significance was not appreciated by the author at that time.]

Examination of the three above mentioned figures also shows that where the cross-faults are located close together, small anticlines form; where the cross-faults are farther apart, larger (longer) anticlines will form. In Fig. 13, for example, it can be seen that Sage Creek anticline is double the length (and size) of the adjacent Winkleman Dome. If rock were everywhere homogenous and strain theory applied ("Andersonian theory of stress"), then whatever conditions created one anticline should have affected the other in the same fashion, creating similar anticlines at both locations. But it is seen by these examples that such is definitely not the case, as even adjacent anticlines can be quite different in size. To repeat, it is the distance between cross-faults that determines the size of anticlines.

Some may question that the basement faults shown in these examples even exist, or at the opposite end of the spectrum some may assume that they do exist and question why there are not more, even many more, cross-faults than have been mapped with magnetics. To these questions, I reply with the statement on correlations in the 2nd paragraph of the introduction of this paper:

"Comparisons between faults in the sedimentary section and basement faults in 21 U.S. sedimentary basins over a combined area of about 750,000 km², reveal hundreds of correlating faults and sedimentary features." This is not an arguable point. Additionally, Figures 13, 14, and 15 show such excellent correlations of magnetically mapped basement faults with known faults and terminations of anticlines that the basement cross-faults that truncate anticlines in these examples can now be confidently added to the other hundreds of actual fault correlations that have been obtained by the author in over 20 years of comparing basement fault maps with the locations of known, proven faults.

I will carry this exercise on the formation of anticlines one step further, which some may consider to be too far, as will be evident. If we have a basement fault interpretation that shows a long basement fault which coincides with a thrust or a reverse fault at some point along its length (thus proving that the fault has had compressional movement) and we have confidently mapped the cross-faults, then we can draw contours or form lines on the hypothetical anticlines that could occur along the length of the fault between cross-faults. We just need to make one further guess, and that is where the crest of the anticlines will be located in the transverse direction relative to the position of the underlying thrust or reverse fault. Of many actual examples I have seen that show the fault location (at basement depth) relative to the crest of the anticline, most show the basement fault directly underneath the crest, or close to it.. The location depends on the dip of the fault, depth to basement, and other factors. So in the hypothetical case, one may locate the basement fault underneath the crest with probably little error.

I performed this exercise on the Peters Point structure in the Uinta Basin of Utah, with the result shown in Fig. 16. My hypothetical contours are shown in blue, actual contours in red. This correlation is "too good to be true," yet it is true, using the procedures and assumptions described above. I doubt if I could duplicate it with such a high degree of precision in other locations, but it is certainly a technique to be considered. Whether it will work in a particular case depends, of course, on the thrust fault having had movement and whether the cross-faults chosen are the correct bounding faults for the anticline.

The above deductions and conclusions show that thrust or reverse faults become segmented by cross-faults as they move, with different segments having differing rates of movement. This will also become obvious in the next section of this paper.

4) Side-stepping fault systems.

Another point that can be made using the West Wind River Basin thrust-fold complex is to illustrate and define a "side-stepping" fault system. To the readers: please rotate Fig. 13 forty five degrees to the right, so that the northwest trending faults are vertical on the page. Starting at the bottom, we see the main NW fault stepping to the right along the cross fault (some would say "relay" fault) at Lander Field, then again stepping right on the cross fault between Sage Creek and Winkleman dome, and again between Winkleman dome and Steamboat Butte. The main fault thus steps right along these three cross faults, and in doing so, maintains an overall direction that is approximately at right angles to probable maximum compressive stress (see long, diagonal, straight line extending from upper left to lower right of the figure).

The next example of side-stepping faults is from Oklahoma and Kansas. In Fig. 17 appears a residual magnetic map of an area encompassing a segment of the Nemaha Ridge, which is a NNE-trending regional compressional structure characterized by reverse faults (Gay, 2003). The individual NNW trending basement faults (only the ones of interest are marked) occur along the gradients between magnetic highs and lows. The ENE trending cross faults occur along the truncation lines of magnetic highs and lows (see Gay, 1995, for a discussion). Note that the NNW basement faults step consistently to the right 7 times in a short 24 mile (39 km) distance. Superimposed on this basement fault system (Fig. 18) is the actual trace (at Ordovician level) of the Nemaha fault (red) as constrained by over one hundred oil wells (Gatewood, 1983).

These two examples of side-stepping fault systems should suffice to show that such systems exist. They must be fairly common but have seldom been mapped because of the past lack of our understanding of side-stepping faults, and especially because of the lack of accurate basement fault maps for comparison. This is reminiscent of a statement by Ed Wisser (1959), writing of his work as a mining engineer/geologist in the southwestern U.S. "...many... faults are zigzag in plan as if they followed now one, now another, set of a... pre-existing fracture system." That nearly 50-year old statement succinctly summarizes the first half of this paper, and could be considered as an early recognition of "reactivation tectonics.".

In Fig. 19 is shown an idealized diagram of a side-stepping fault system. Here, there is illustrated only one direction of pre-existing basement faults, and the overall trend of the system is perpendicular to maximum compressive stress, as we saw in an actual case in Fig. 13. Most areas of continental crust are cut by 3, 4, or more basement fault sets, so side-stepping systems such as this one following faults of a single strike direction are probably a special case.

Side-stepping faults resemble en-echelon faults. What is the difference? In Fig. 20 appears an en-echelon system and the definition of such a system by structural geologist J.D. Lowell (1985). These systems apparently form by strike-slip movement along an underlying basement fault, although their best representation may be in (unrealistic?) sand-box models. In the lower part of Fig. 20 is shown a side-stepping system, with a definition I have paraphrased, but modified, from Lowell.

5) Jointing, linears, lineaments and related features.

One of the most significant aspects of reactivation tectonics is the logical explanation it provides for regional jointing and the consequent effects of jointing. A much-cited study of regional jointing in a 35 x 80 mile (55 x 130 km) area of the Colorado Plateau in Utah and Arizona (Hodgson, 1961) was compared with a series of basement faults/aeromagnetic lineaments mapped and published of the same area later (Gay, 1972). The entire basement fault pattern as mapped is shown in Fig. 21; the comparison of certain of these faults with Hodgson's joint pattern is shown in Fig. 22 (those faults used in Fig. 22 are shown in red in Fig. 21). The match of strike directions of the faults with the joints is truly remarkable, an observation which is quite convincing of a genetic relationship between basement faults and joints. I proposed (Gay, 1973 p. 97-98) that small scale movements (1-10 m?) of basement faults would give rise to jointing of overlying sedimentary rocks over a broad area. Joints have been defined as "fractures with no measurable displacement," so if a 1m (vertical?)

movement on a basement fault results in the formation of 10,000 parallel, overlying joints, the average displacement of 0.1 millimeter would scarcely be "measurable" (see Gay, 1973, p. 97).

> Discussion: I know of no study that has ever precisely measured, or even looked for, displacement across joints. Such a study could be carried out by examining thin sections of epoxy-impregnated sandstone samples from jointed outcrops that are sawn in place and carefully removed to the laboratory.

Most studies of jointing have historically ascribed jointing to regional stresses or to tectonic folding (see extensive review of Pollard and Aydin, 1988, for example), but some workers have recognized that much jointing precedes folding or is independent of folding. Hodgson(1961) called these earlier joints "systematic," Engelder (1985) called them "tectonic", hydraulic," or "cross-fold" joints, Lorenz (2003) calls them "regional" joints, and Nickelsen (1976) and Bergbauer and Pollard (2004), "pre-folding" joints. However, of all these workers, only the earliest, Hodgson (1961), ascribed the earlier joints to movement of basement faults, and stated: "Any theory that postulates that systematic joints are genetically related to folding is rejected for this region [Colorado Plateau]." That statement seems to have been lost on later workers. Pollard and Aydin (1988) thought so highly of Hodgson' paper that they cited his work twelve times in their long review paper, but his statement on jointing not due to folding is not among them. This is "selective science." It is time to return to Hodgson's "antiquated" deduction on basement control, as his work has never been proven wrong, and my work on buried basement faults in the area of his study proves him right.

Reinforcement for the rejection of the folding process as the cause of all jointing, and basement as a source for much jointing, also comes from the classic work of McQuillan (1973, 1974) who made an extensive study of fracturing observed on airphotos of the large Asmari anticline in the Zagros foothills of Iran. McQuillan stated: "Fracture density has an inverse logarithmic relation to bed thickness, but it is independent of structural setting. Such findings make necessary the rejection of a theory involving a genetic relation of fractures of this scale to the folding process..." and "The identification of greater fracture lengths over azimuth classes corresponding to longitudinal fractures in the eastern part of the structure is suggestive of a relation to a larger, basement-controlled lineament."

Another interesting point is that Fig. 21, which shows aeromagnetically mapped basement faults/shear zones in a 140 x 160 mile (240 x 260 km) area in the Paradox Basin of the U.S. Colorado Plateau, predated by a year all similar-appearing lineament studies of Landsat images that were published by dozens of authors after the availability of these images in 1973.

The validity of magnetics for mapping basement faults which give rise to later structure in the sedimentary section was demonstrated early on (Gay, 1972) by a comparison of Comb Ridge, one of the better known monoclines on the Colorado Plateau, with selected, previously mapped basement faults (see faults marked in blue in Fig. 21). This comparison is shown in Fig. 23. There are seven correlating segments of Comb Ridge (as shown by the numbers in the figure) having the following strike directions: 1) NNW, 2) NS, 3) NNE, 4) WNW, 5) NNE, 6) NNE & 7) ENE. The NNE direction appears 3 times, leaving 5 separate strike directions of basement faults represented for this one structure. This contrasts with side-stepping fault systems (Figures. 13, 17, 18) where faults of only a single set (strike direction) are reactivated.

Going back to Fig. 6, a Landsat image characteristic of basement terranes world-wide in its content of regional fault sets, it is seen that sets of parallel basement faults shown are persistent over broad areas. Thus, the occurrence of parallel joint sets over large areas (e.g.Fig. 22) is a logical consequence of joint inheritance from reactivation of the parallel basement fault sets occurring over large areas.

In an insightful study of jointing in the Beni Basin of Bolivia, Plafker (1964) found that well-developed joints had already formed in very recently lithified rocks. This fact leads to the belief that the small fault movements that create joints are not necessarily tectonic; they apparently can also result from isostatic adjustments (vertical movements) on basement blocks due to sediment loading. The multiple directions of joints seen in sedimentary rocks of a given area (Fig. 22, for example) lends credence to this idea. These observations also demonstrate that folding is not essential for joint formation.

A two decades literature (1950's and 1960's) on airphoto lineaments exists in "Photogrammetric Engineering," the journal of the American Society of Photogrammetry, with a few similar papers published in the AAPG Bulletin and elsewhere. The general consensus of that work by the late 1960's, particularly the papers of Laurence Lattman (see his summary paper, 1961), was that airphoto lineaments, which appear as topographic, vegetational or tonal alignments on airphotos, result from erosion or from movement of groundwater along selected joints of a joint set. Thus, most linears/lineaments observed on airphotos, radar images, and space images reflect the presence of underlying joint sets.

A feature observed many times in comparing basement fault locations mapped from magnetics with Landsat lineaments is that they are usually, or almost always, parallel, but are not necessarily coincident. This non-coincidence has caused some petroleum geologists and structural geologists to state that linears/lineaments "don't mean anything," or even that "they don't exist." However, they obviously do exist, and their non-coincidence with underlying faults is due to the fact that they arise from selected joints that are more numerous in some areas due to inhomogeneities in the sedimentary section or that have had more groundwater movement along them due to varying topography and varying exposure to streams. As expressed earlier, joints are not only created immediately above their causative basement faults, but in between them as well.

6) Locating the basement “root” of thin-skinned thrust systems

An unexpected benefit of basement fault mapping has been the apparent ability to determine the root location for thin-skinned thrusts and therefore to measure their displacement. This has been tried in the Appalachians, but not as yet in the Western Overthrust Belt due to the lack of good quality magnetic data available to the author in the latter location.

In Figure 24 is shown the detailed magnetic data flown by the writer’s company, Applied Geophysics, Inc., in the area of the well-known Burning Springs anticline in West Virginia. Superimposed on the magnetic data (blue) are the axes of the Burning Springs and adjacent anticlines. These structures formed during the Alleghenean orogeny and were thrust westward or northwestward from an unknown starting point. (Cardwell, 1977, stated: “The Burning Springs anticline is a surface feature not reflected in Williamsport/Newberg [U. Silurian] and older beds.”)

It is readily seen that in their current location the structures are cross-cutting the underlying gradients on the magnetic map, so could not have originated at this location. See Figures 7 & 3 for comparison. (As discussed before, the gradients between magnetic highs and lows conform to the locations of the basement faults/shear zones.)

The pattern of anticlinal axes was therefore drafted onto an overlay, and this overlay was then moved easterly and southeasterly to see if a match to the magnetic map could be found in that direction. Very quickly the position shown by the red lines in Fig. 24 was located. This is a quite remarkable, nearly perfect, match of the anticlinal axes to the underlying magnetic gradient/basement faults, and therefore must be the location, to a high degree of probability, where the anticlines originated.

Following this success, it was decided to try the technique on that most famous of Appalachian structures, the Pine Mountain thrust, lying at the juncture of the states of Tennessee, Virginia, and Kentucky. Here, the fault pattern is less well constrained than at Burning Springs as we have only the one main thrust to compare to, or three if we include the end thrusts (Fig. 25). Going ESE from the thrust's present location, there are no candidate basement faults until one crosses the North Carolina line and encounters the Cranberry structure (my name) approximately 100 miles to the east. It is remarkably parallel to the Pine Mountain thrust (within 2°) and is the probable root of that structure. The possible original location of the thrust along the Cranberry structure is shown in the figure (blue lines), but its original location along strike cannot be exactly determined.

SUMMARY

In order to tie together all the many types of geological features resulting from basement fault reactivation, I have constructed a Basement Inheritance Chart, relating basement faults to joints, lineaments, and subsequent features (Fig. 26). Basement faults are considered first generation structures. With small movements these give rise to 2nd generation features: joints, fractures and faults in the sedimentary section, which, in turn, give rise to 3rd generation airphoto and space linears/lineaments, folds, and stratigraphic features. Of course, it is well known that jointing, through erosion, controls basement topography and this, in turn controls two types of oil and gas traps (the 4th generation) that come quickly to mind: fluvial sandstones in low topographic areas (drainage systems and deltaic deposits), and compactional anticlines that form over high topography, such as monadnocks, also called by some "erosional remnants" (see Fig. 12). Greater movement of basement faults, which are termed "moderate movement" here, create 2nd generation fractures which, in some cases, are reservoirs for oil and gas or mineral deposits, the 4th generation, which result from fluid flow. Moderate movement of basement faults also result in stratigraphic features of <u>many</u> kinds, which can become oil and gas traps, or in some cases, ore deposits (e.g., Mississippi Valley-type lead-zinc deposits). Larger movements of basement faults, but less than required to create mountain ranges, result in folds and can also create fault-related hydrocarbon traps.

A very important thing to remember when studying the Basement Inheritance Chart in Fig. 26, is that all the features shown on the chart are <u>parallel (in some cases, subpraralel)</u> to each other: basement faults, joints, faults in the sedimentary section, fractures, lineaments, drainage systems, folds, stratigraphic features, oil and gas fields, and ore deposits. This refers to those features that arise from a single basement fault set. However, a complexity arises, because in any area of continental crust, there are 3, 4, or more fault sets present (refer to Fig. 6 again). Figure 23, for example, showed a single fold (Comb Ridge) that is controlled by 5 different basement fault directions.

I will show two more examples that demonstrate the validity and applicability of reactivation tectonics. In Fig. 27 are documented actual 2nd generation and 4th generation features that show a remarkable parallelism of four separate strike directions. The 2nd generation features are the joint sets published for the Alberta Basin (Babcock, 1976). The 4th generation features are long axes of oil fields in the same area (Gay, 1973).

In Fig. 28 are compared 1st and 3rd generation features: airphoto lineaments by photogeologist G. Thomas (unpublished) with two directions of basement faults mapped by the author in the Silo Field area of southeastern Wyoming. These two examples are typical of the one-on-one correlations that occur when one takes reactivation tectonics into account.

In Fig. 29 is presented a preliminary attempt to categorize various kinds of structural and stratigraphic oil and gas traps by the amount of throw of the underlying, causative basement faults.

In summary, it is difficult to summarize the many new conclusions presented in this paper, as they are numerous. The entire paper is, in reality, a succession of conclusions, some new, some old, but much of which will be new to geologists who have not seen the pertinent literature, a void that this paper attempts to correct. All the conclusions herein have arisen because the reality of "reactivation tectonics" was recognized early on by the author, and the research proceeded from there. Undoubtedly, many other useful new discoveries in reactivation tectonics yet remain to be made by present and future geologists.

THUMBNAIL SUMMARY

Plate tectonics explains what causes regional compression events.

Reactivation tectonics explains what events regional compression causes.

S. Parker Gay, Jr .
Salt Lake City, UT
April 23, 2007

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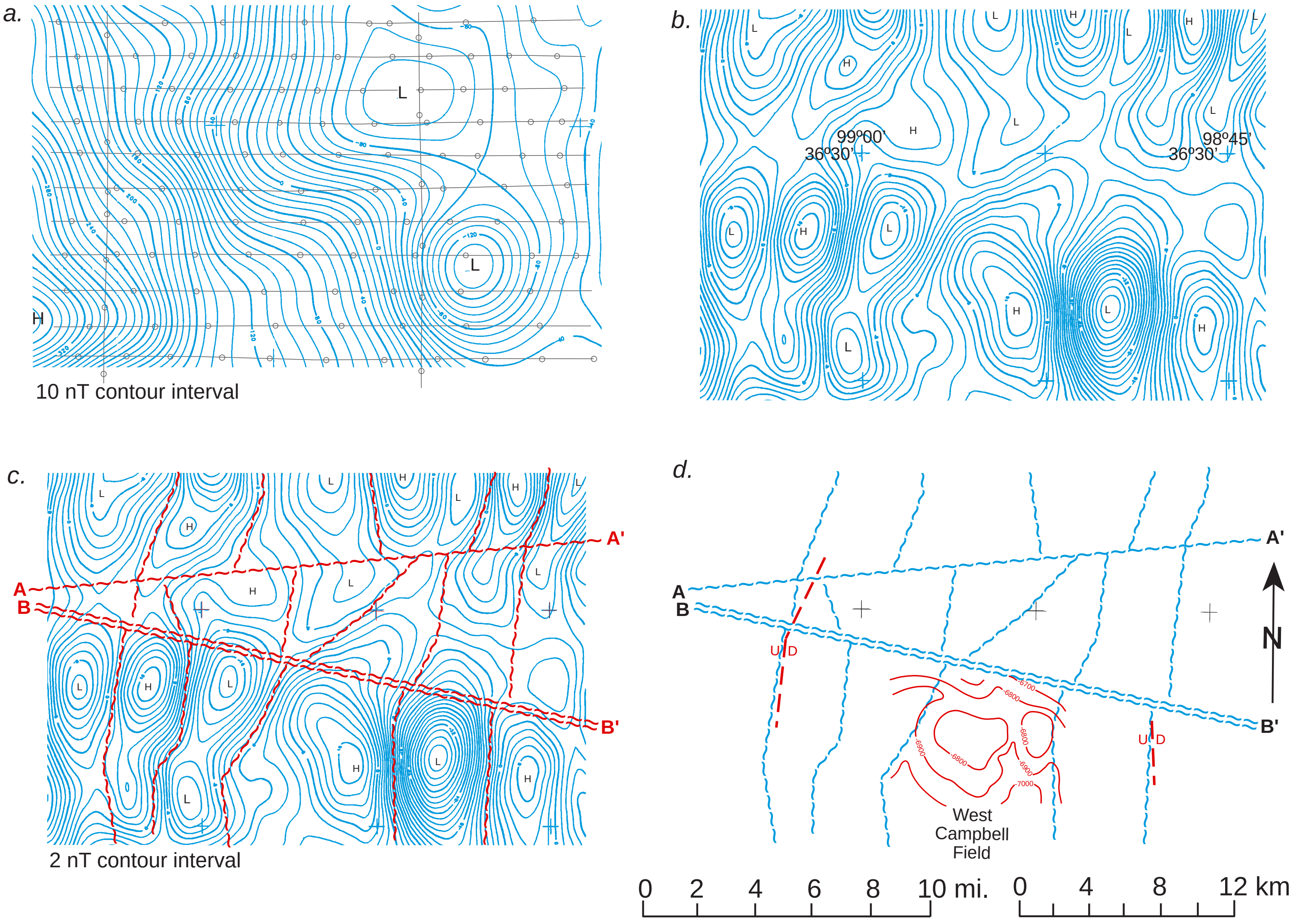


Figure 1. Example of basement mapping in Major and Woodward counties, Oklahoma, on north shelf of Anadarko Basin. Depth to basement approx. 12,000 ft. (3600m) beneath flight level. **a**. Total intensity magnetic map - not generally useful in basement mapping. E-W flight lines are spaced 1 mile apart. **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).

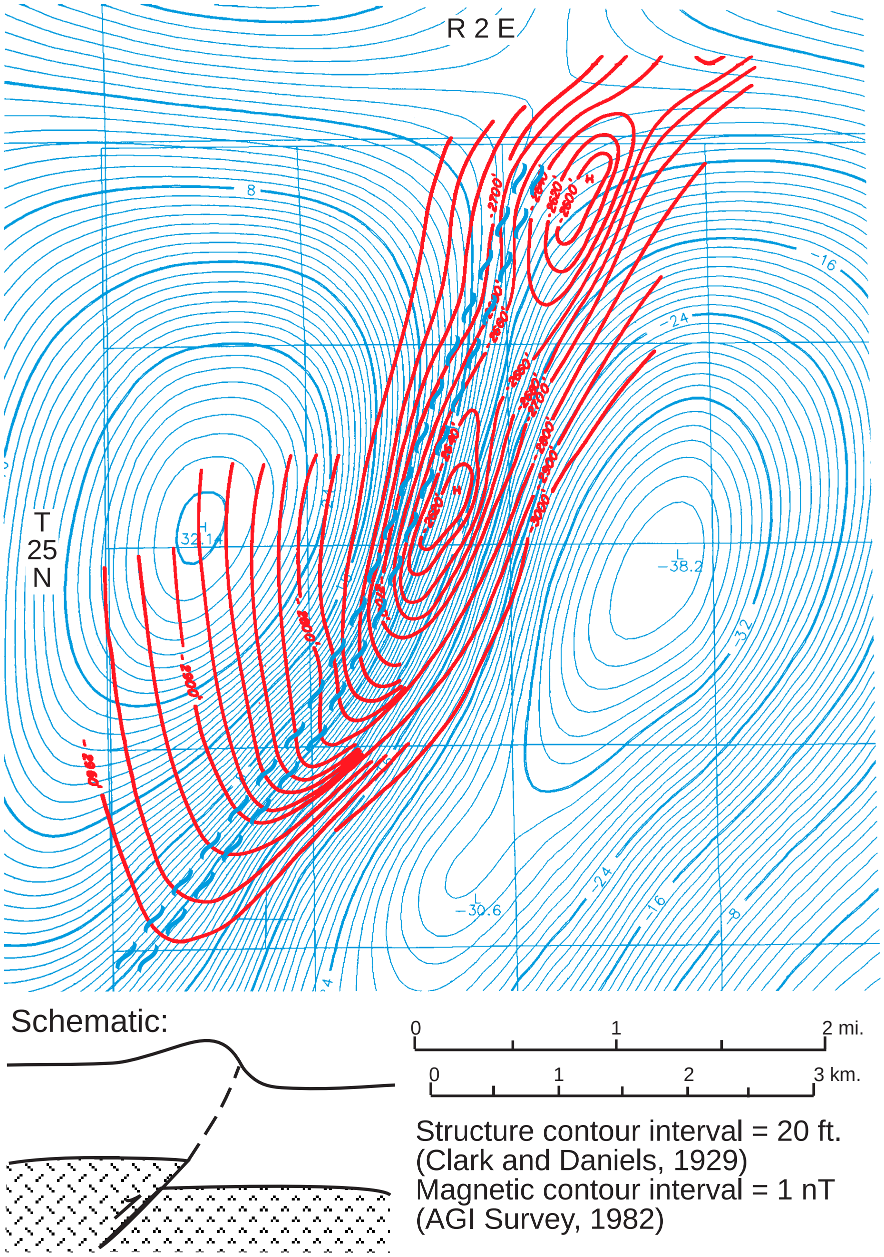
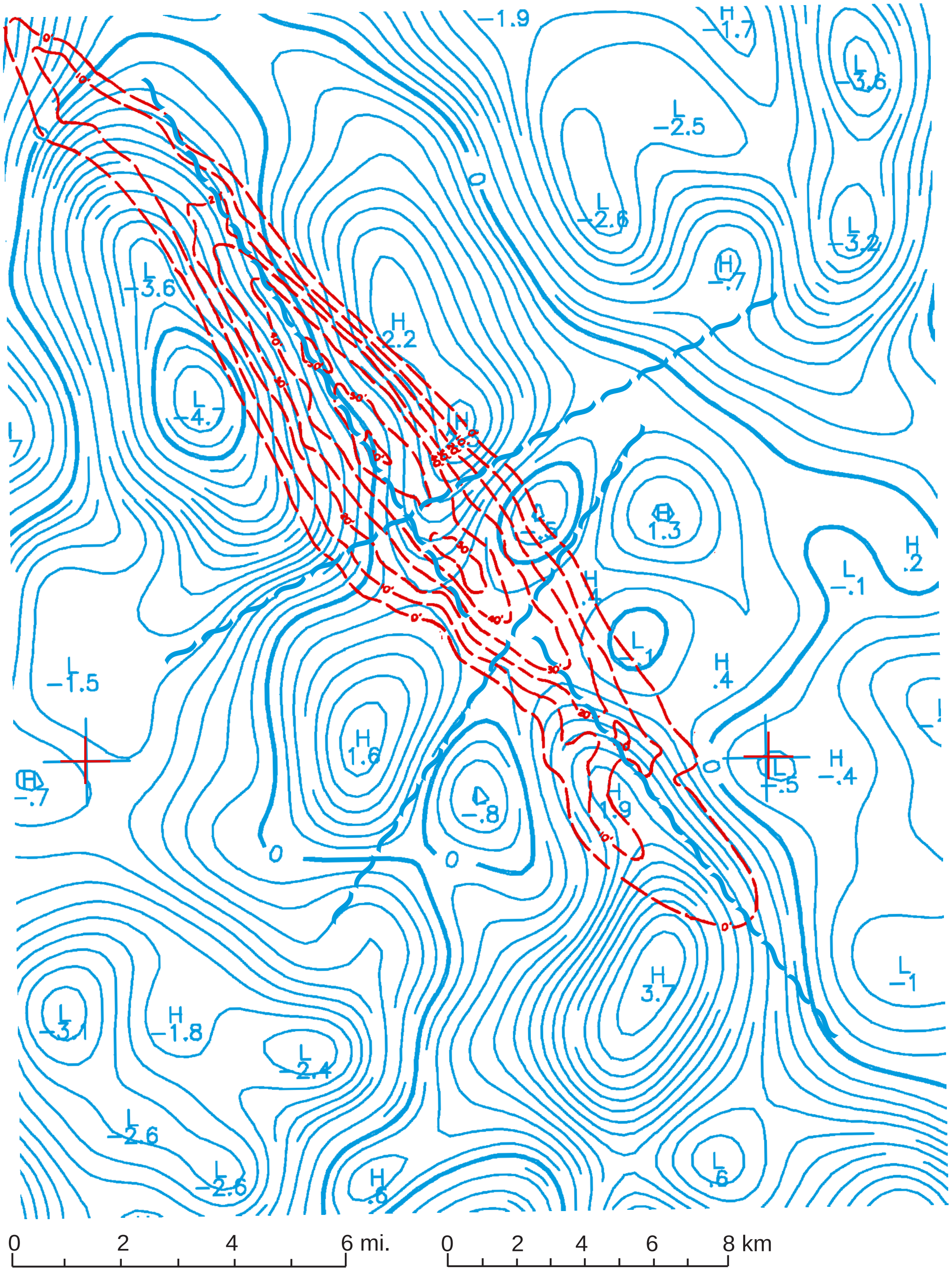


Figure 2. Ponca City field, Kay County, Oklahoma. Shear zone mapped by magnetics (blue) lies west of the steep part of the fold mapped on the “Mississippi Lime” (red), indicating a west dip for the underlying blind reverse fault (inset). The west dip on this fault has also been mapped by seismic data.



Net pay isopach, Shannon ss (red); contour interval = 10 ft.
AGI NewMag® residual magnetics (blue); contour interval = 0.5 nT.

Figure 3. Hartzog Draw field in the (Powder River Basin) in Campbell Co., Wyoming, has produced over 120 million barrels of oil from the Shannon sand. A one-on-one relationship exists between the basement faults mapped by magnetics (blue) and the late Cretaceous Shannon sand buildup (red). Ss. isopach contours are from Martinsen, 1981.

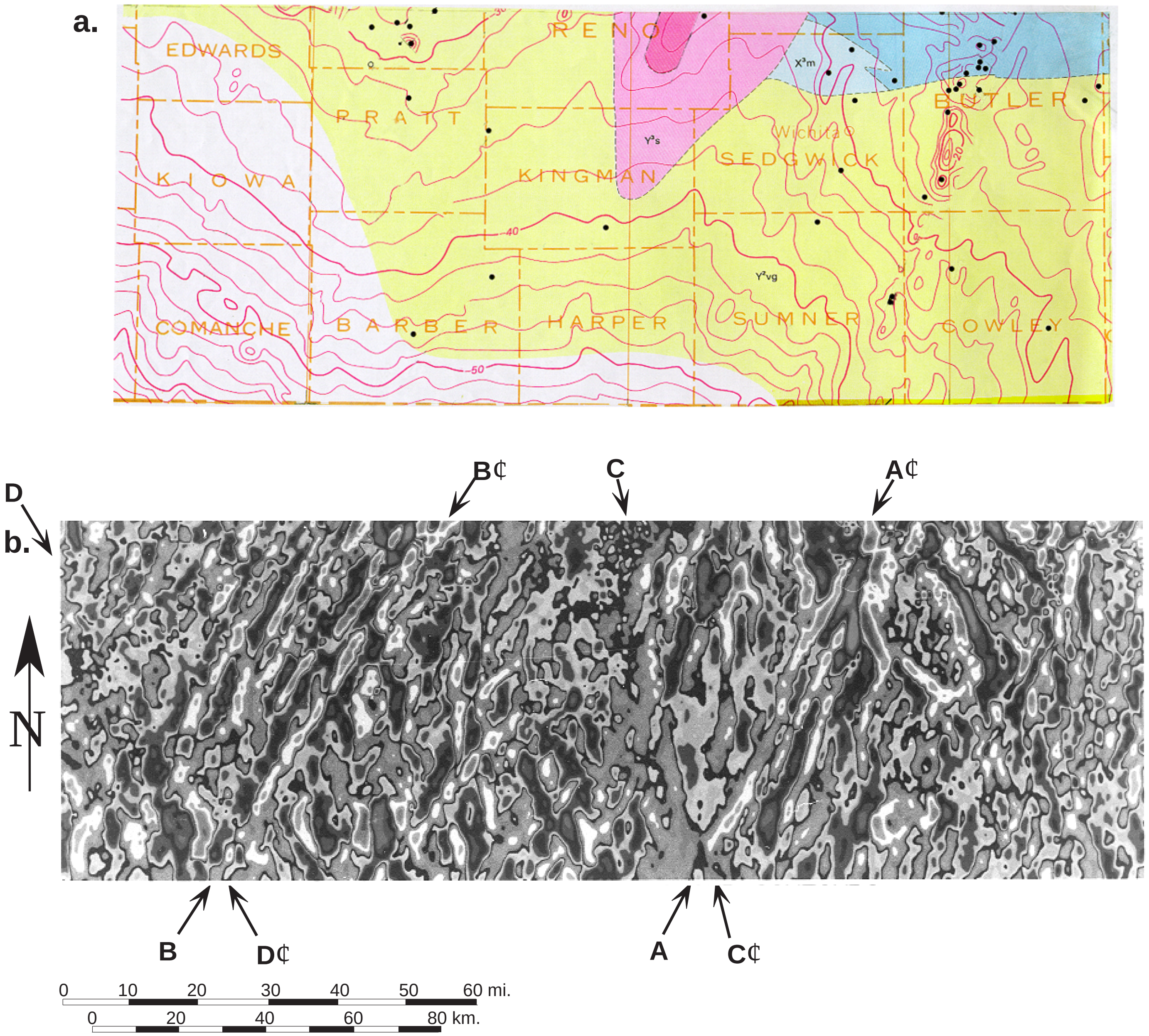


Figure 4. a. Standard USGS basement map of an 80 by 225 km area in southern Kansas (Sims, 1990) constructed from 35 irregularly distributed data points (black dots), that is, from basement rock types recognized from oil well intercepts. Note: I have deleted from this map the surface faults that Sims included hereon (from Kansas Geol. Survey maps), which were independent of, and irrelevant to, the basement interpretation.

b. E-W profile residual aeromagnetic map of same area as in **a**., flown by Applied Geophysics, Inc., 1982. This map resulted from approximately 70,000 magnetic readings. Note the hundreds of linear anomalies, corresponding to basement fault blocks, the long throughgoing sutures, identified by letters, and the faulted oval-shaped intrusion (NE quadrant), all major geological features, none of which appear on the USGS map.

PRECAMBRIAN BASEMENT MAP OF THE TRANS-HUDSON OROGEN

AND ADJACENT TERRANES, NORTHERN GREAT PLAINS, U.S.A.

P. K. Sims, Zell E. Peterman, T. G. Hildenbrand, and Shannon Mahan
U.S.G.S. Map I2214, 1991

1. "The number and distribution of drill holes that penetrate Precambrian basement are inadequate for delineating even first-order lithologic domains in the subsurface."

2. "[We] compiled digital aeromagnetic and gravity maps of the Northern Plains... These geophysical maps were used to define... the trend, extent, and boundaries of gross geologic rock units." [Note: The geophysical maps were not published in this paper]

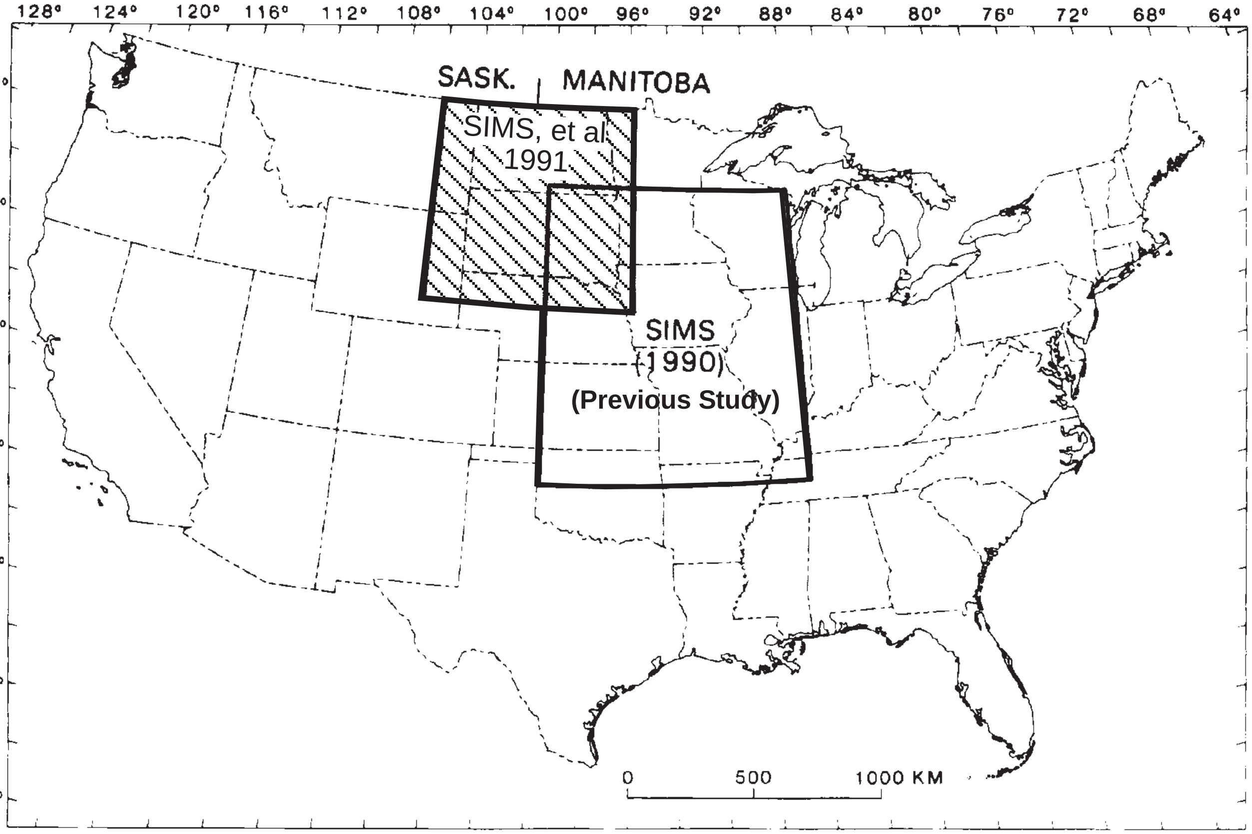


Figure 5. A subsequent study (Sims, et al, 1991) to that partially shown in Fig. 4 (Sims, 1990) clearly states in those authors' own words that their data is "inadequate" to determine geologic boundaries in the basement.

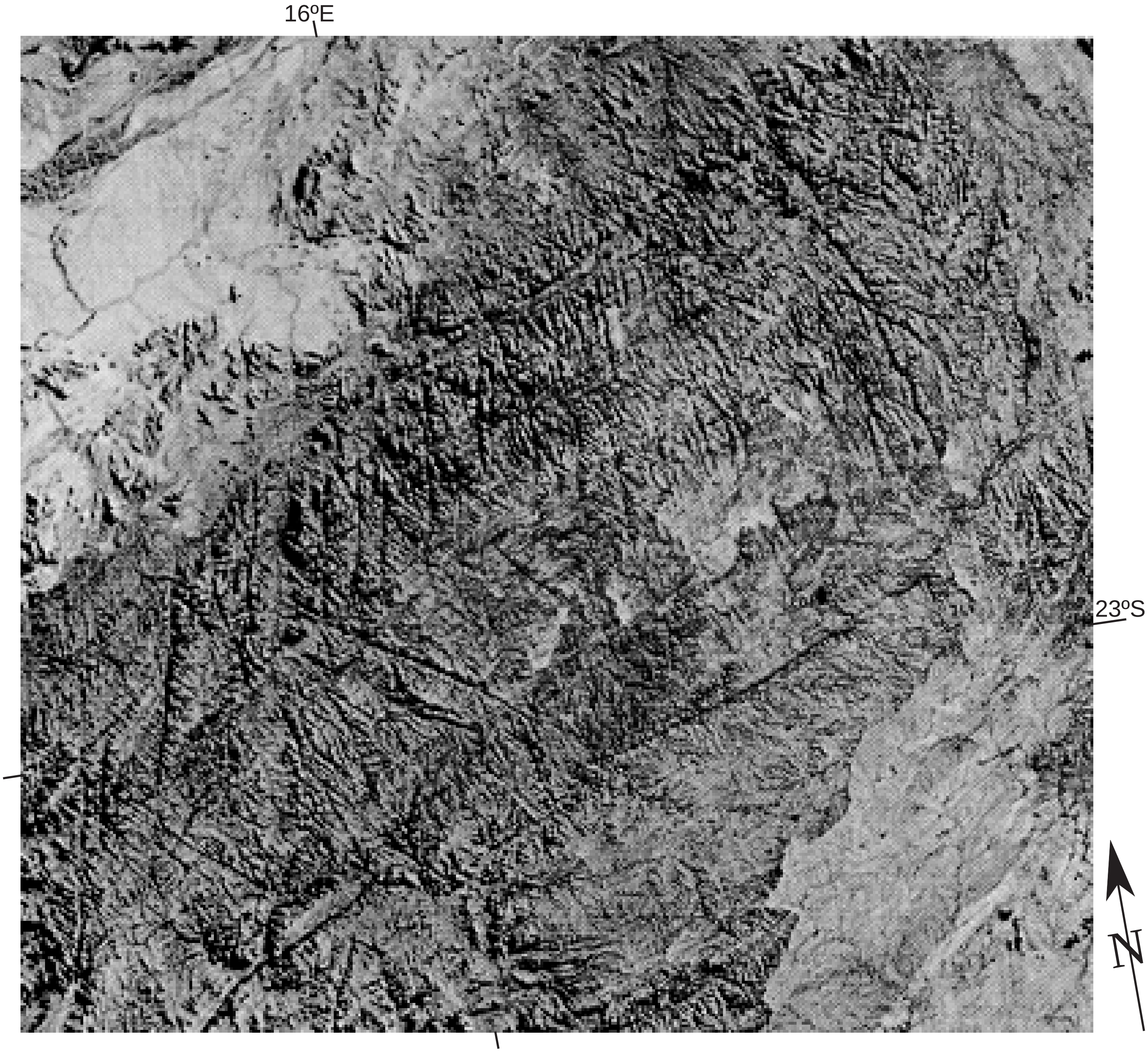


Figure 6. Landsat image of a portion of the African shield in Namibia showing 3 principal fracture sets of different strike directions. From Short, et al, 1976, p. 384. Landsat and radar images of outcropping basement worldwide show similar fracture sets, leading us to believe that all continental crust is equally fractured. In outcrop these "fractures" are, in reality, high metamorphic grade shear zones. Would a later orogeny in this area create new shear zones or simply reactivate the ones shown?

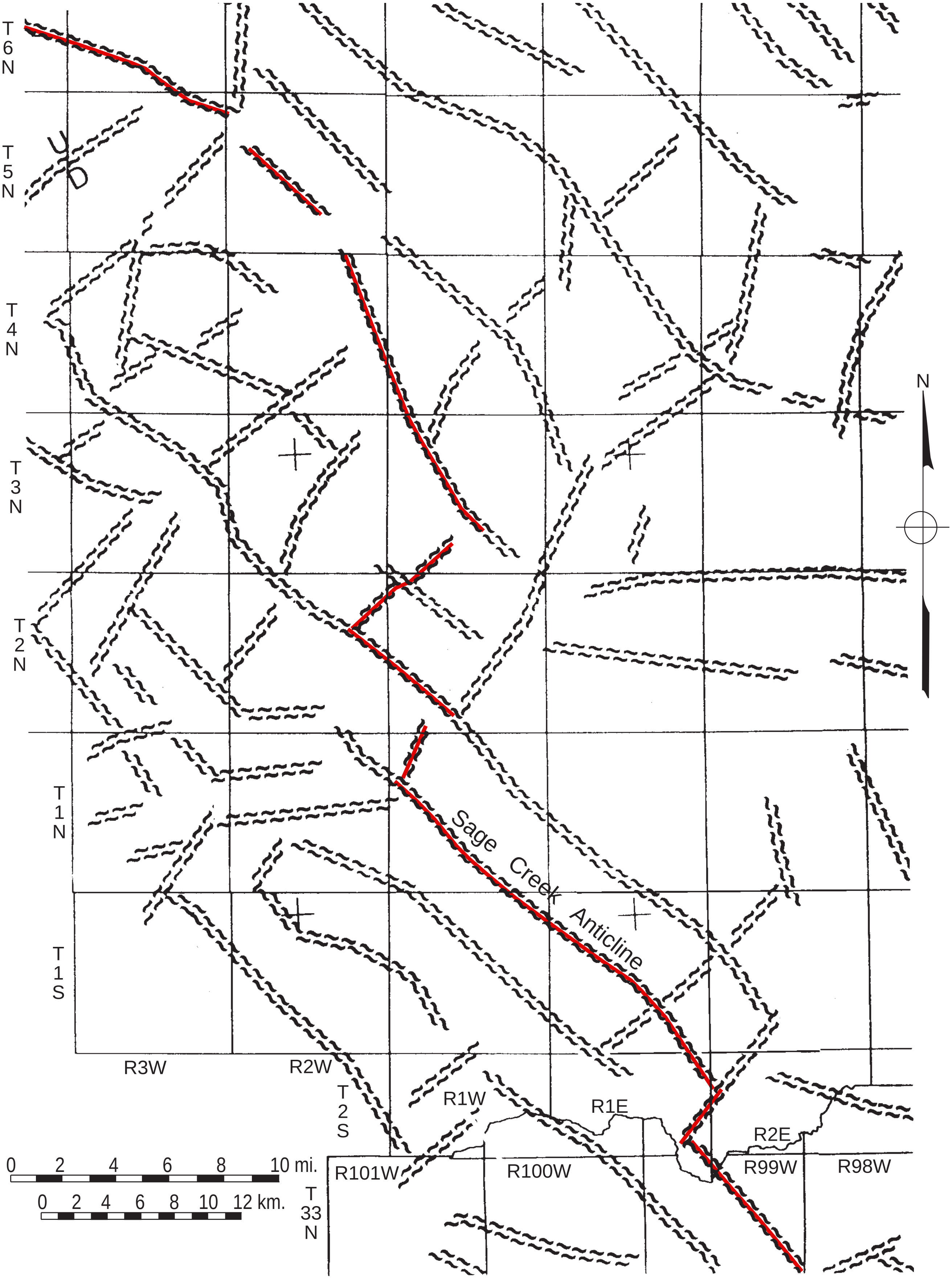


Figure 7. Map of all basement faults (shear zones) interpreted by the writer from magnetics in the vicinity of the West Wind River Basin fold-thrust system. The ones highlighted in red were reactivated by ENE compression in Laramide (Late Cretaceous - early Tertiary) time, the others were not. The geology map showing the Laramide thrust and fold locations appears in Fig. 13.

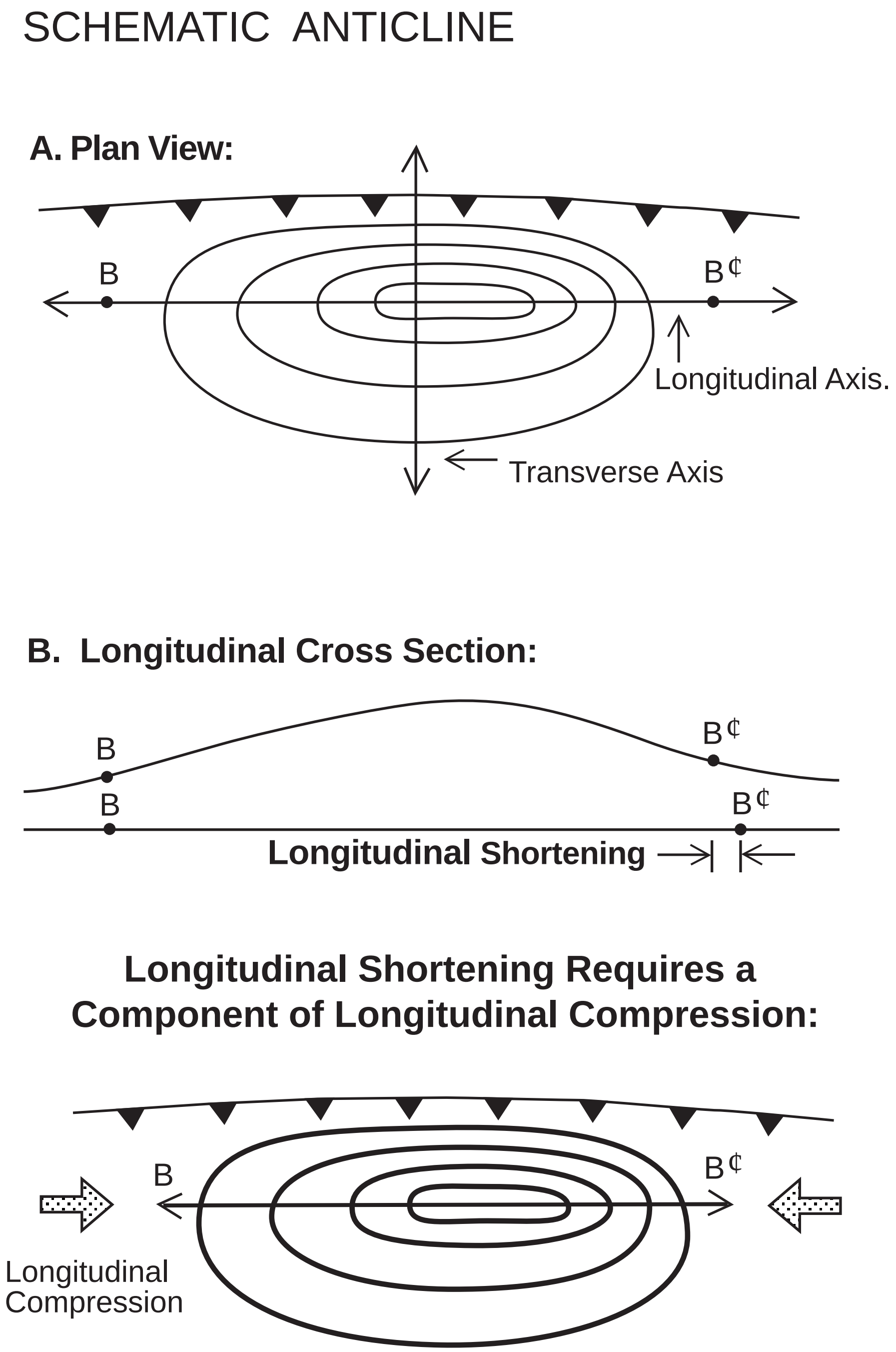
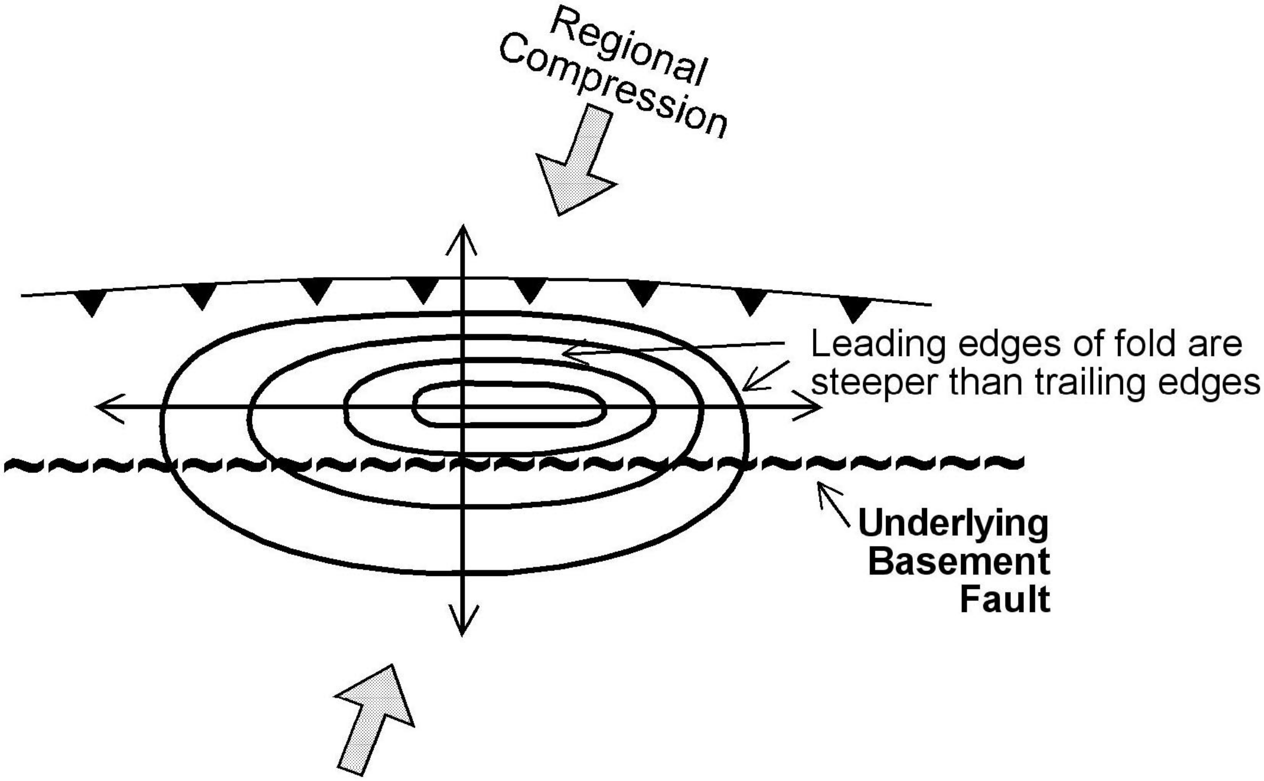
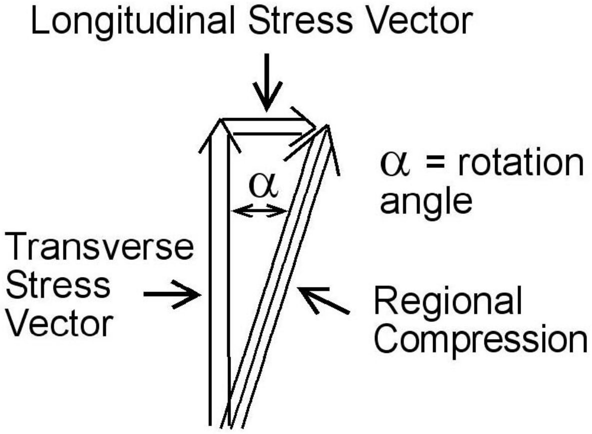


Figure 8. Simplistic diagram demonstrating that shortening of anticlines occurs in the longitudinal direction, in addition to the well-known, accepted shortening in the transverse direction. These shortenings are due to the same cause (MCS) and are therefore similar, differing only in degree. The result, of course, is "4-way closure."

Problem: How do we get both transverse and longitudinal compression acting contemporaneously on an anticline?

Solution: Reactivate a pre-existing basement fault !





The regional compression, which is transpressive to the underlying fault, is resolved into vectors parallel and perpendicular to the basement fault, that is, into transverse and longitudinal stress vectors.

Figure 9. 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 is thus a testament to reactivation tectonics.

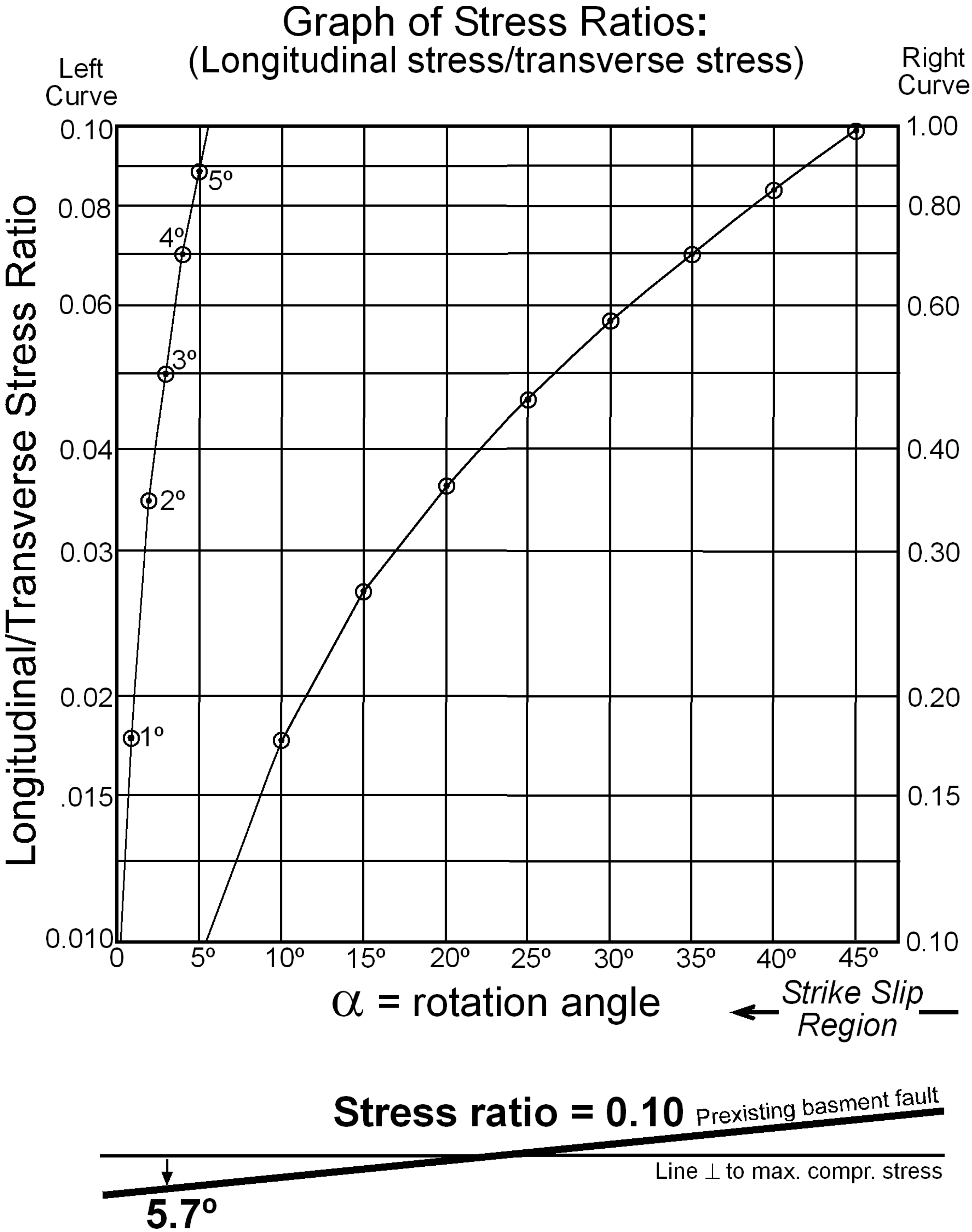


Figure 10. Stress ratio vs. rotation angle. This diagram shows that even for small rotation angles there is a significant longitudinal stress component and thus, that 4-way closure has to be common. In other words, the strike of an underlying basement fault would have to be within a very small angle of the maximum compression stress for end closure to be lacking (see discussion).

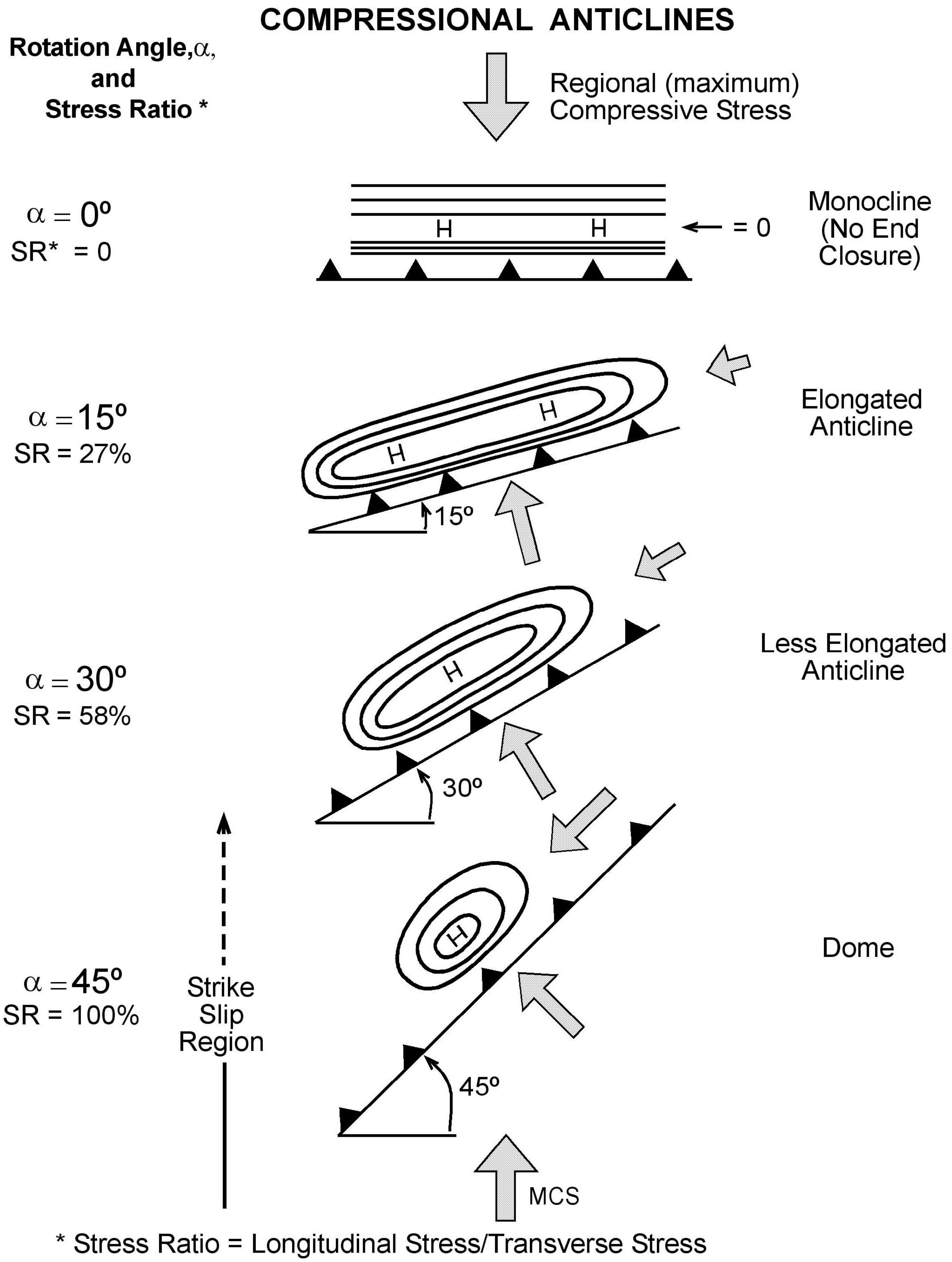
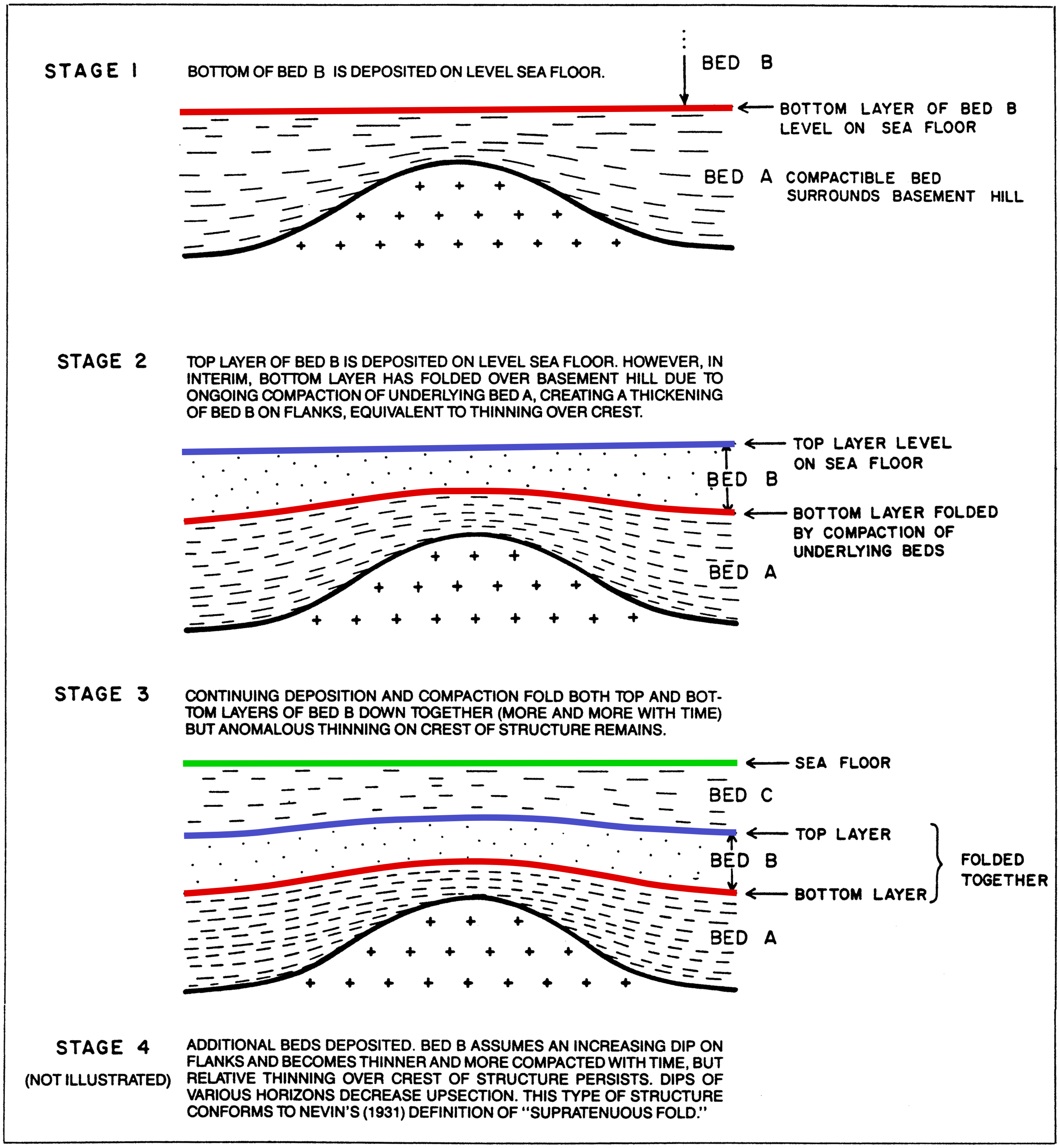


Figure 11. This diagram shows the shapes of anticlines resulting from reactivated basement faults with differing rotation angles. When the angle is 0° , i.e. when there is no rotation, there can be no end closure. This results in an elongated anticline or a monocline. For greater rotation angles the length diminishes until finally at a 45° rotation angle, a dome should theoretically result. Compressional domes are thus logically explained (for the first time, the writer believes).



STAGE I

BOTTOM OF BED B IS DEPOSITED ON LEVEL SEA FLOOR.

STAGE 2

TOP LAYER OF BED B IS DEPOSITED ON LEVEL SEA FLOOR. HOWEVER, IN INTERIM, BOTTOM LAYER HAS FOLDED OVER BASEMENT HILL DUE TO ONGOING COMPACTION OF UNDERLYING BED A, CREATING A THICKENING OF BED B ON FLANKS, EQUIVALENT TO THINNING OVER CREST.

STAGE 3

CONTINUING DEPOSITION AND COMPACTION FOLD BOTH TOP AND BOTTOM LAYERS OF BED B DOWN TOGETHER (MORE AND MORE WITH TIME) BUT ANOMALOUS THINNING ON CREST OF STRUCTURE REMAINS.

STAGE 4

(NOT ILLUSTRATED)

ADDITIONAL BEDS DEPOSITED. BED B ASSUMES AN INCREASING DIP ON FLANKS AND BECOMES THINNER AND MORE COMPACTED WITH TIME, BUT RELATIVE THINNING OVER CREST OF STRUCTURE PERSISTS. DIPS OF VARIOUS HORIZONS DECREASE UPSECTION. THIS TYPE OF STRUCTURE CONFORMS TO NEVIN'S (1931) DEFINITION OF "SUPRATENUOUS FOLD."

Figure 12. Stages in the formation of a compactional dome (gravicline) over a basement hill (from Gay, 1989). Some authors have called this a "supratenuous fold," an outmoded term.

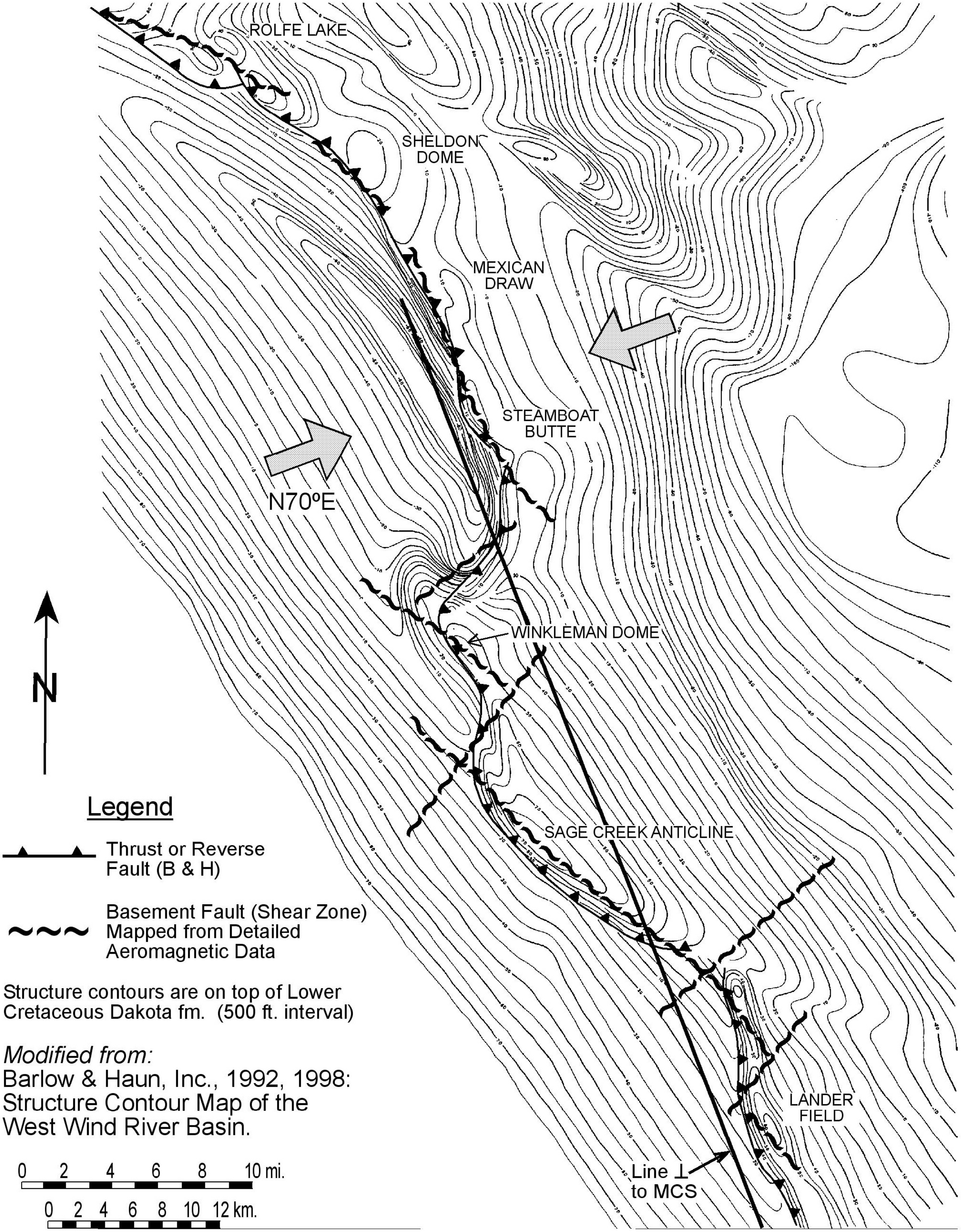


Figure 13. West Wind River Basin thrust-fold system, Wyoming. By defining maximum compressive stress ⊥ to the long, narrow anticline extending from Steamboat Butte to Mexican Draw, we see that other anticlines, such as Sheldon dome ($\alpha \approx 25^{\circ}$) and Sage Creek ($\alpha \approx 27^{\circ}$), have lesser length-to-width ratios, thus supporting the author's contention that the rotation angle of an underlying basement fault controls the length-to-width ratio of an anticline.

Salt Creek - Teapot Thrust-Fold System in SW Powder River Basin, Wyoming

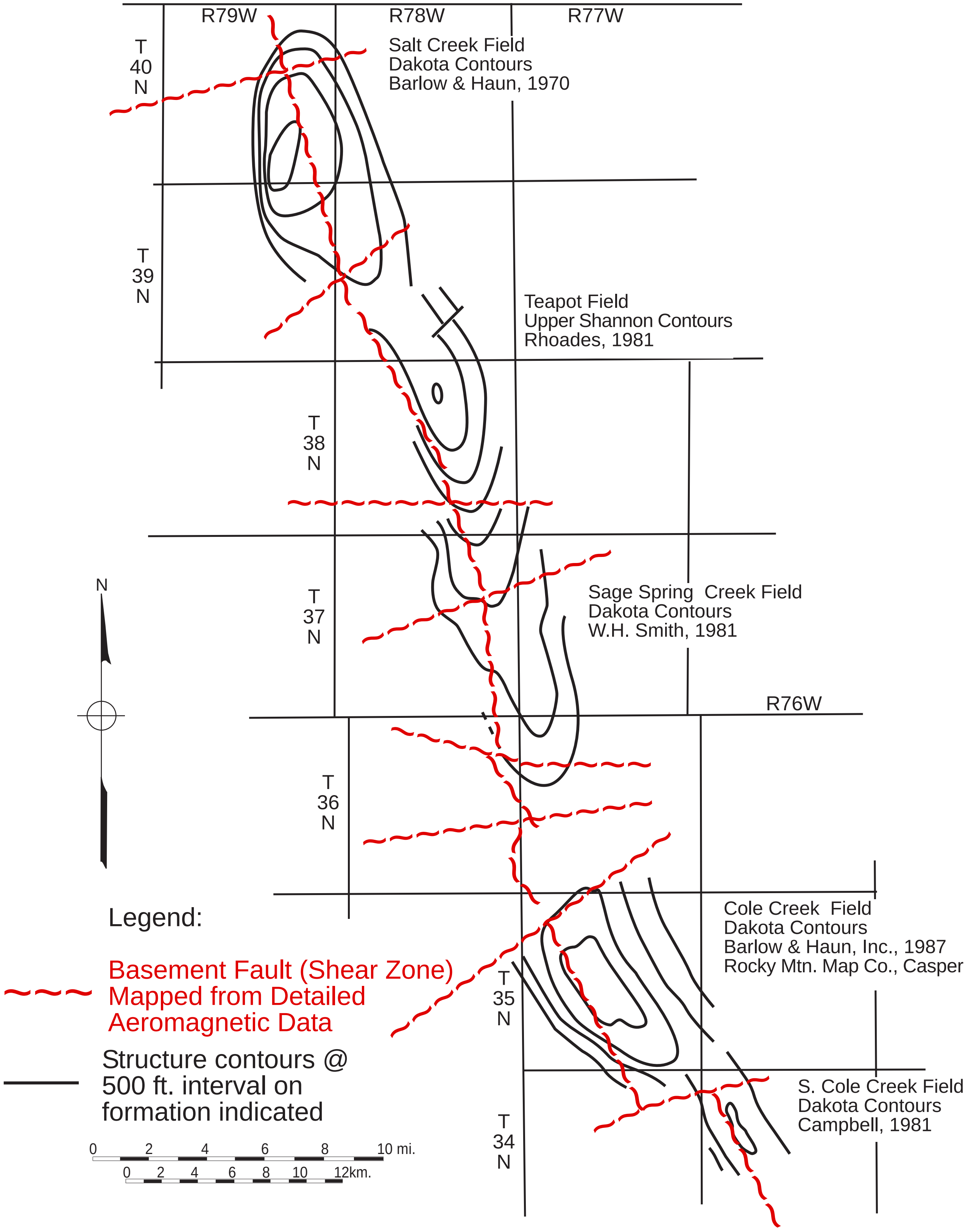
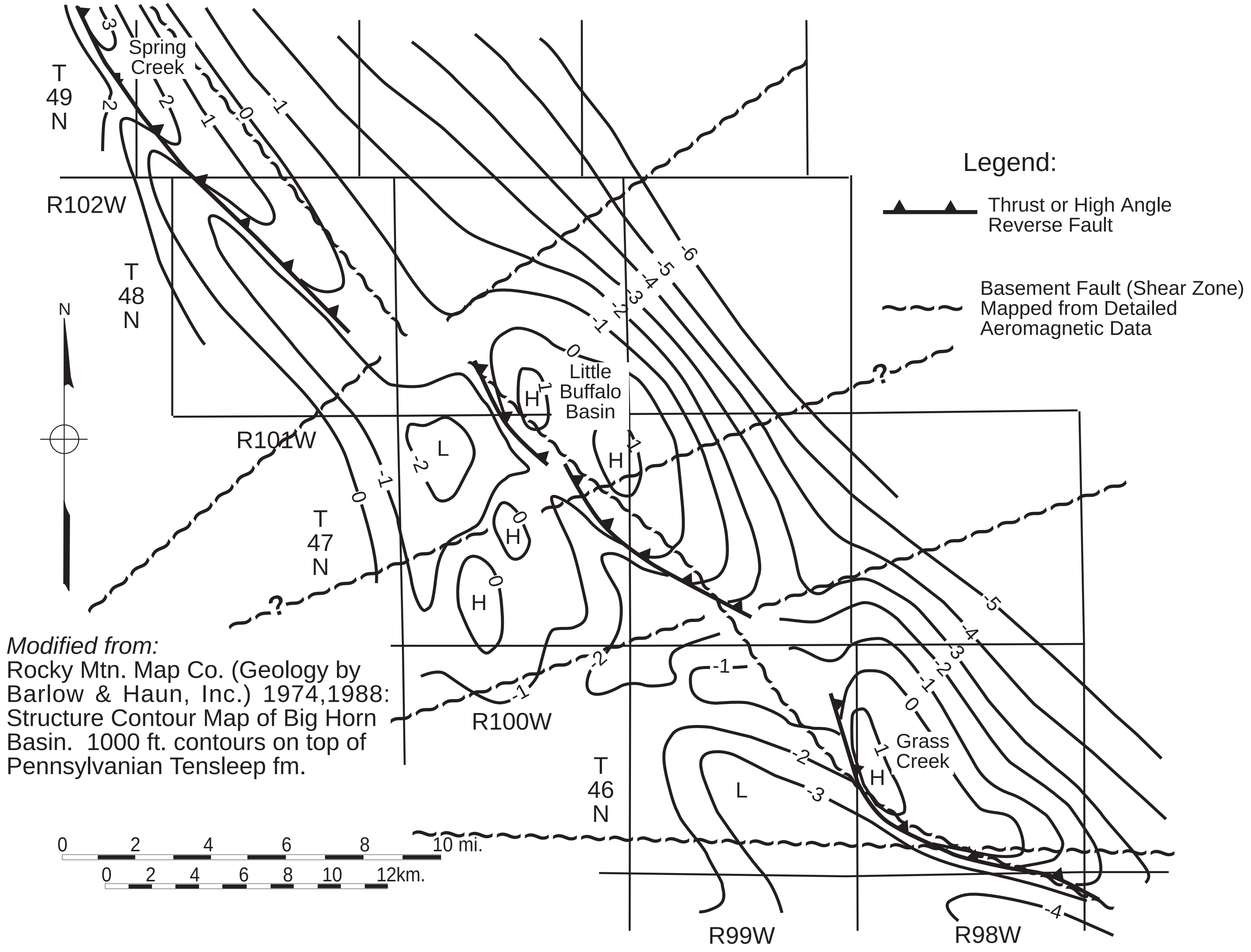
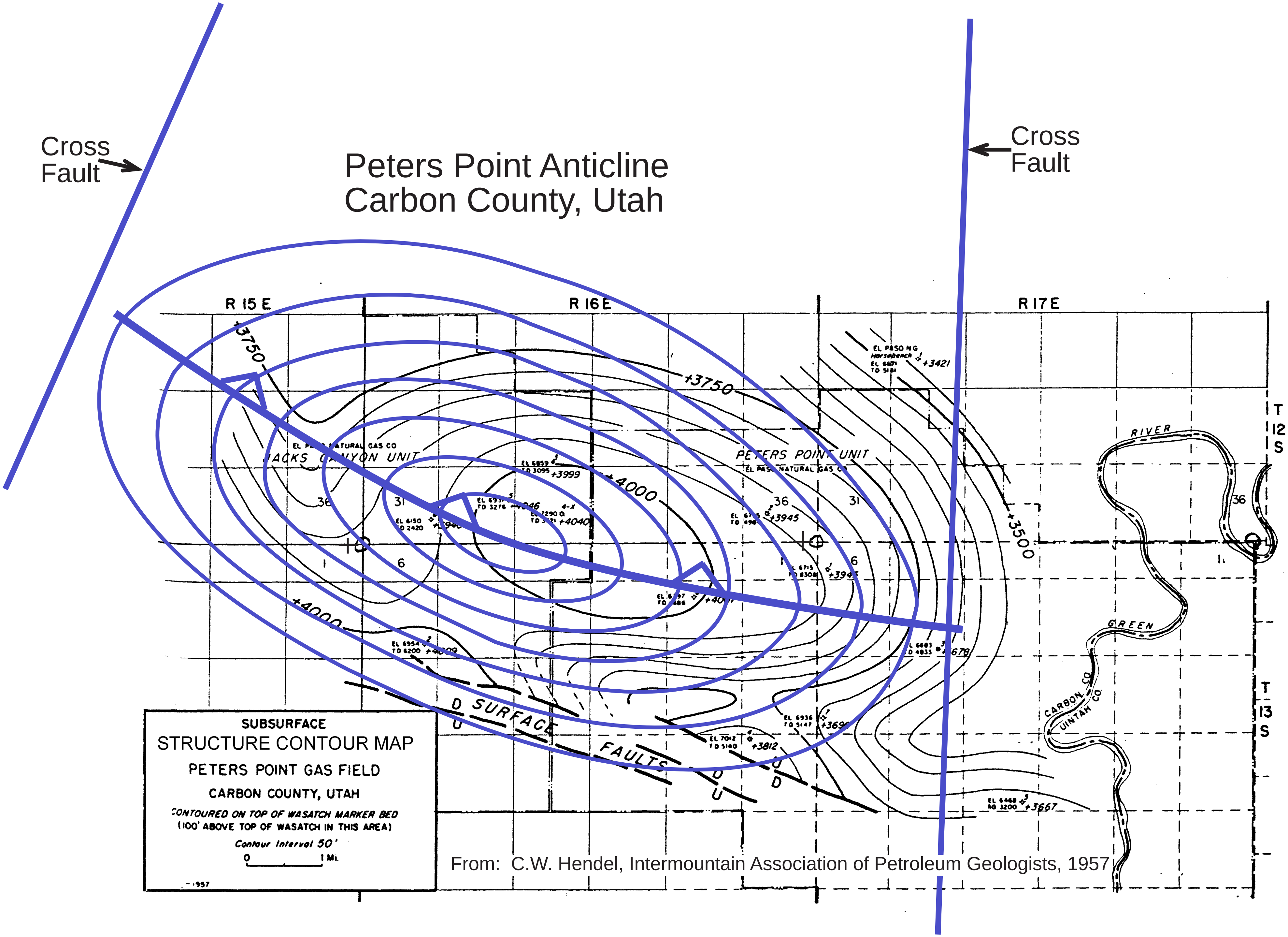


Figure 14. A chain of anticlinal thrust-fold fields on the Casper Arch in the Powder River Basin, WY. None of the published maps show an underlying thrust, but basement faults occur in precisely the right locations for giving rise to blind thrust or reverse faults that create the asymmetric folds. The northernmost of these fields, Salt Creek , has produced over 680 million barrels of oil.



Modified from:
Rocky Mtn. Map Co. (Geology by Barlow & Haun, Inc.) 1974,1988: Structure Contour Map of Big Horn Basin. 1000 ft. contours on top of Pennsylvanian Tensleep fm.

Figure 15. A thrust-fold system in the SW part of the Big Horn Basin. The increasing distance between the basement fault trace and the thrust fault trace toward the northwest indicates a flattening of dip of the thrust to the northwest.



From: C.W. Hendel, Intermountain Association of Petroleum Geologists, 1957

Fig.16. The author's speculative contours (blue) constructed from the locations of the interpreted basement faults alone superimposed on the subsurface map of the field made from well data.

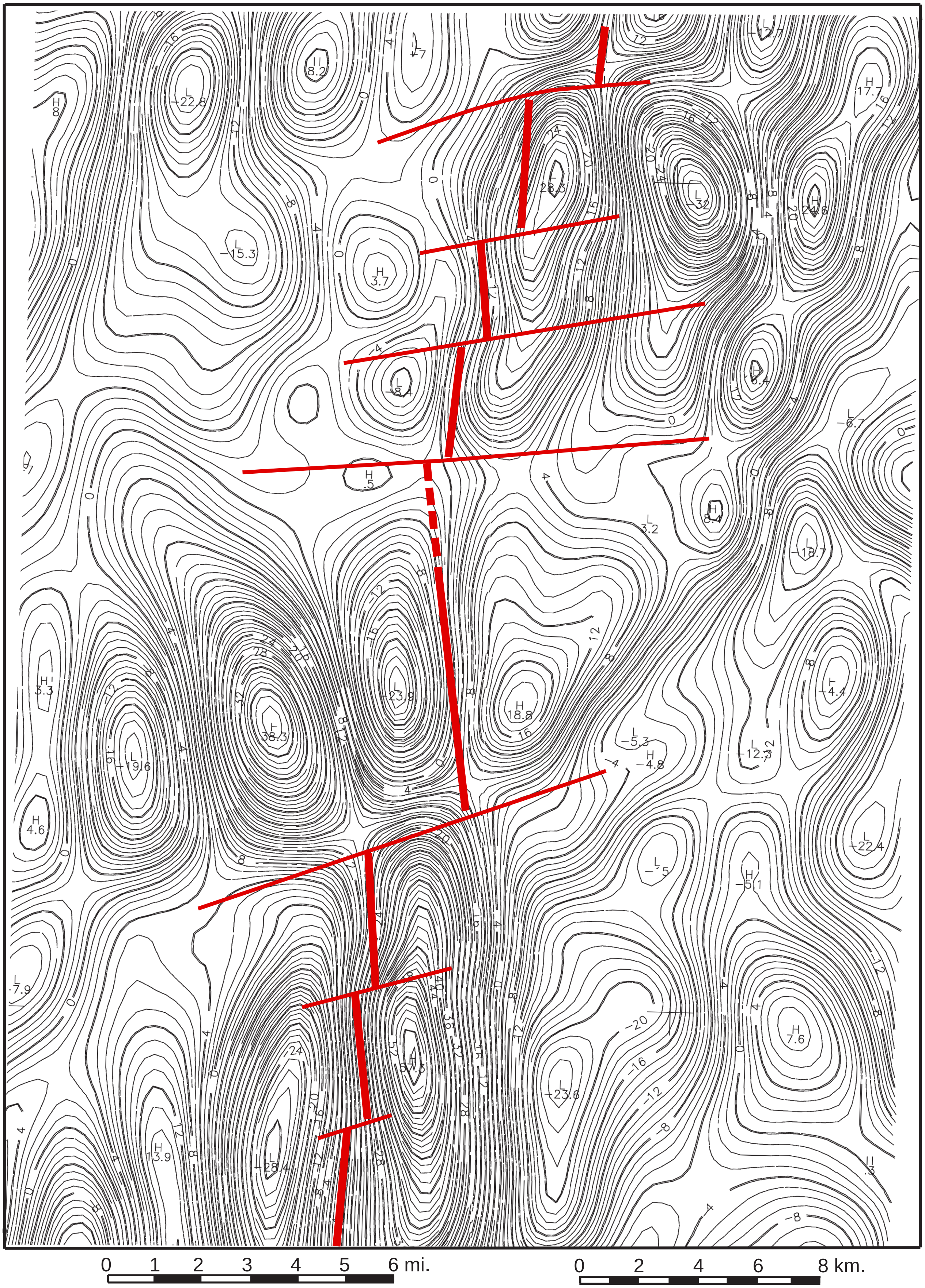


Figure 17. Residual magnetic map of part of Nemaha Ridge area in Kay County, Oklahoma, with pertinent basement faults superimposed.

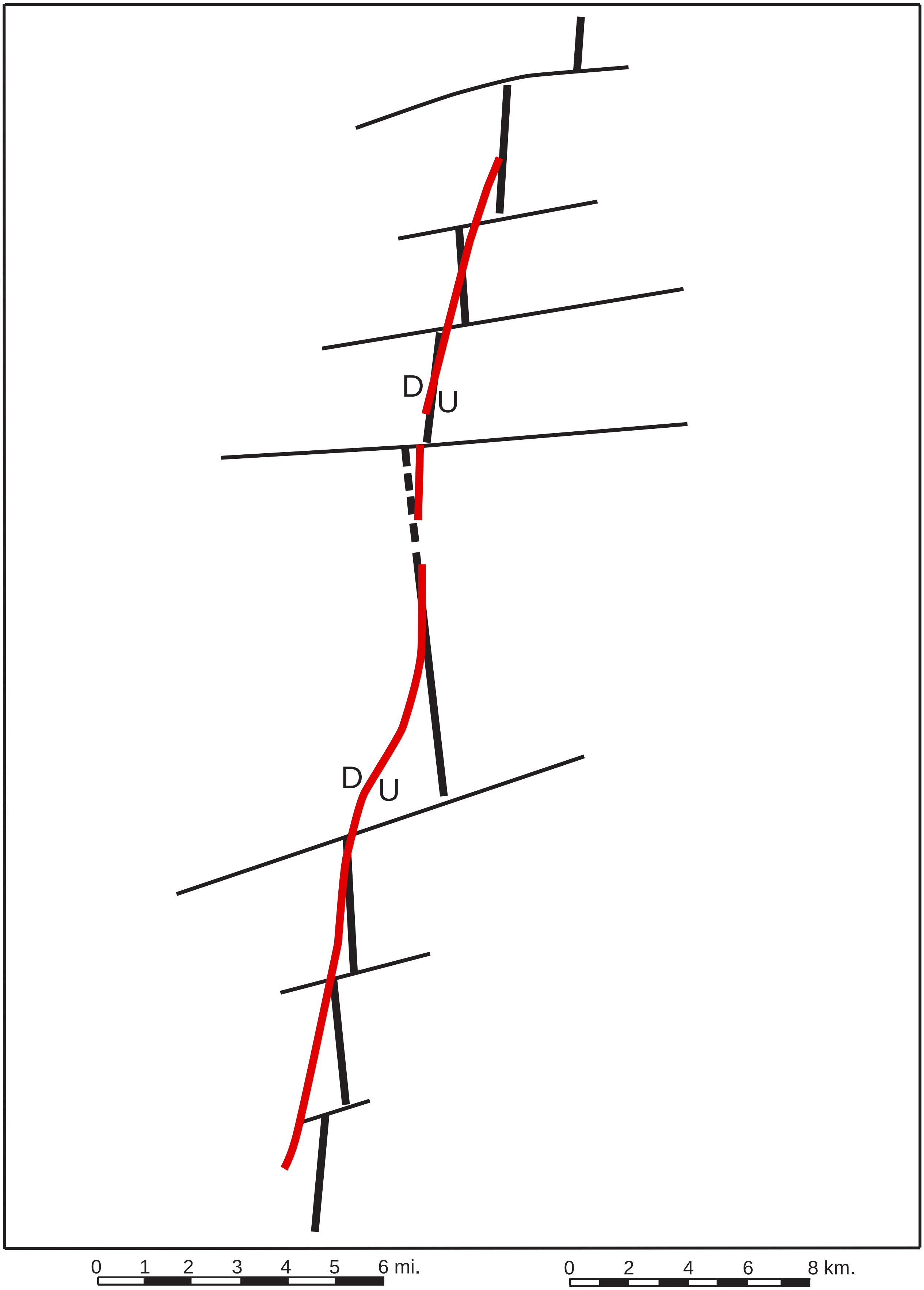


Figure 18. West-bounding Pennsylvanian-age Nemaha Fault (red) vs. basement fault system interpreted from aeromagnetic data. The Nemaha fault trace is from Gatewood, 1983. Basement faults are from map in Fig. 17.

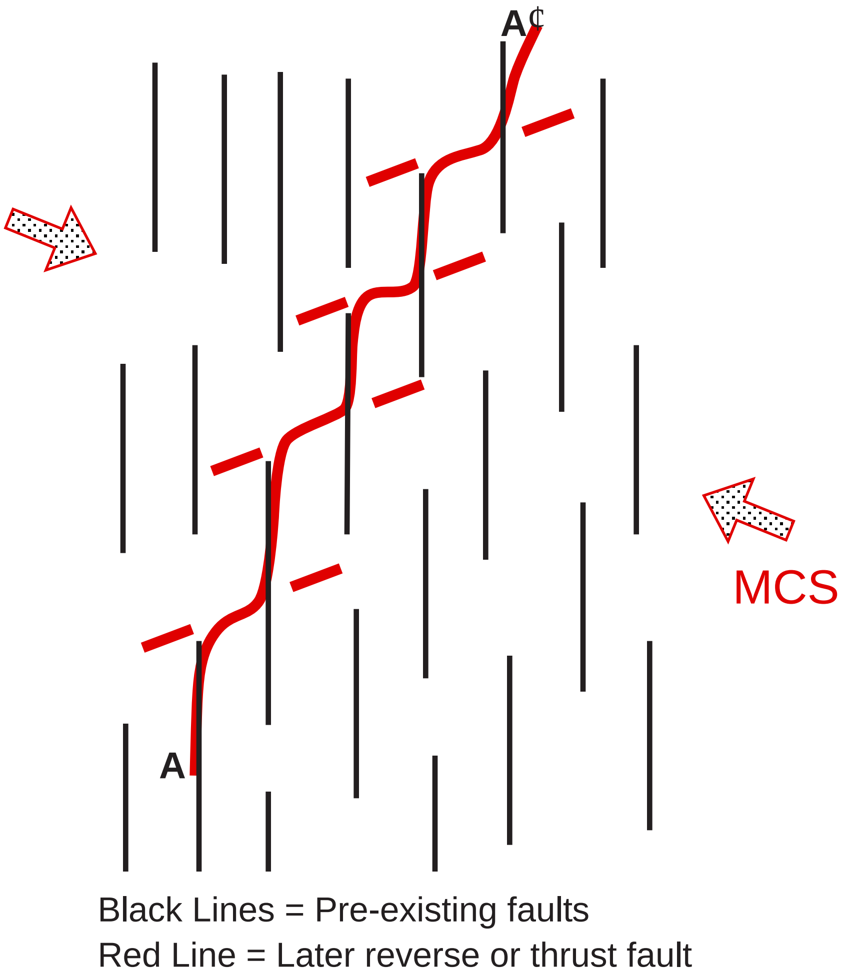
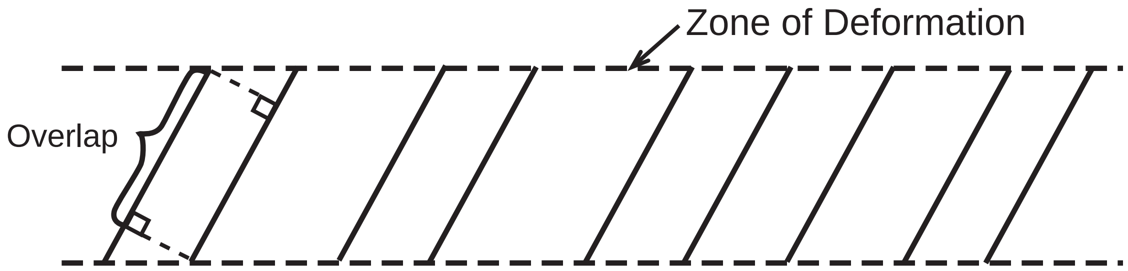


Figure 19. Idealized schematic side-stepping fault system, in an area where only a single direction of basement faults is reactivated (discounting the direction of the cross-faults). The overall, or average, trend of such a system apparently occurs at right angles to maximum compressive stress.

En echelon - “Consistently overlapped structures aligned parallel with one another but oblique to the zone of deformation in which they occur.”



Side-stepping - “Consistently non-overlapped structures aligned parallel with one another but oblique to the zone of deformation in which they occur.”

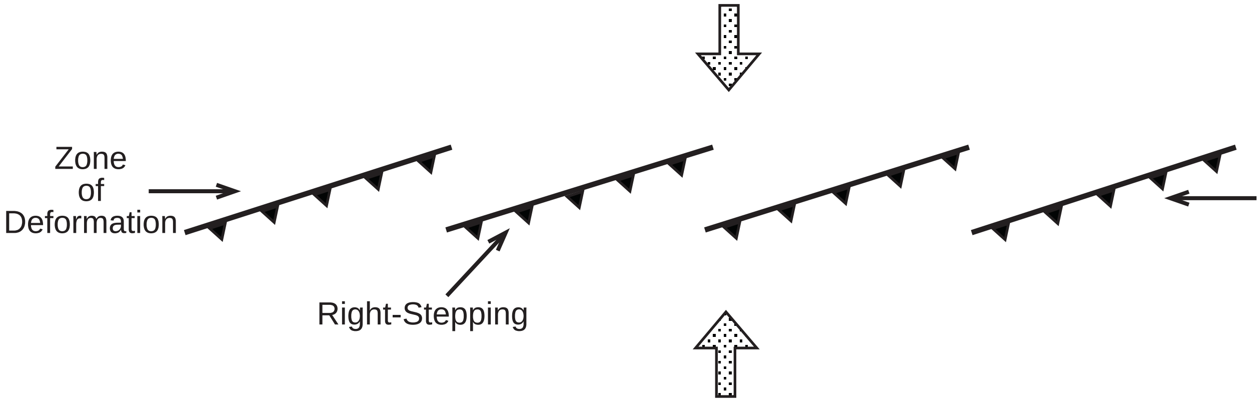


Figure 20. En-echelon vs. "side-stepping" structures (faults or folds). The definition of an en-echelon system is taken from Lowell, 1985. The definition of side-stepping structures is by the author, paraphrasing Lowell.

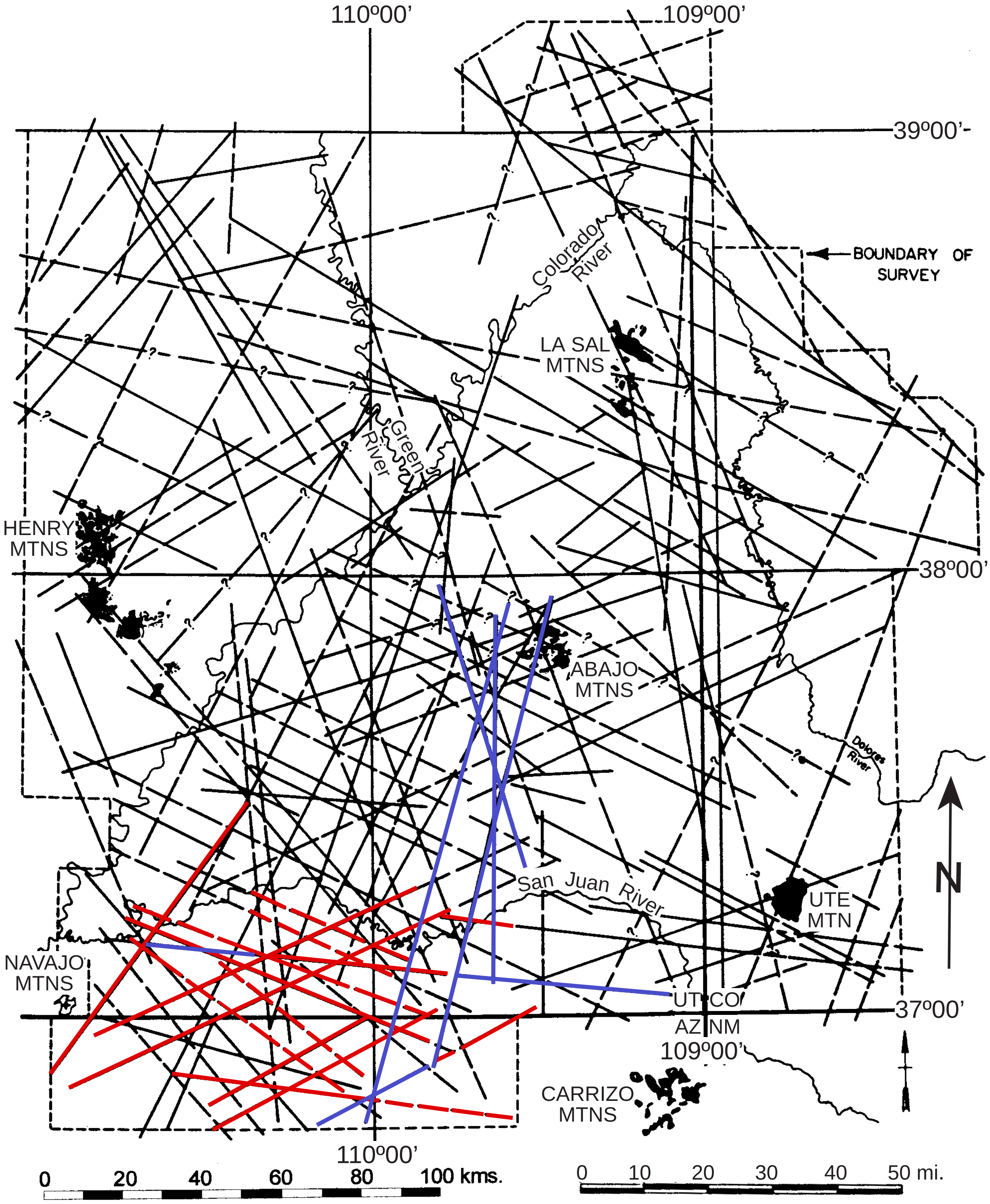


Figure 21. Aeromagnetic lineament interpretation of the Paradox Basin, Utah, USA. Aeromagnetic survey from USGS open file map of central Colorado Plateau, 1970; stereo pair by American Stereo Map Co., 1971. This figure taken from Gay, 1972.

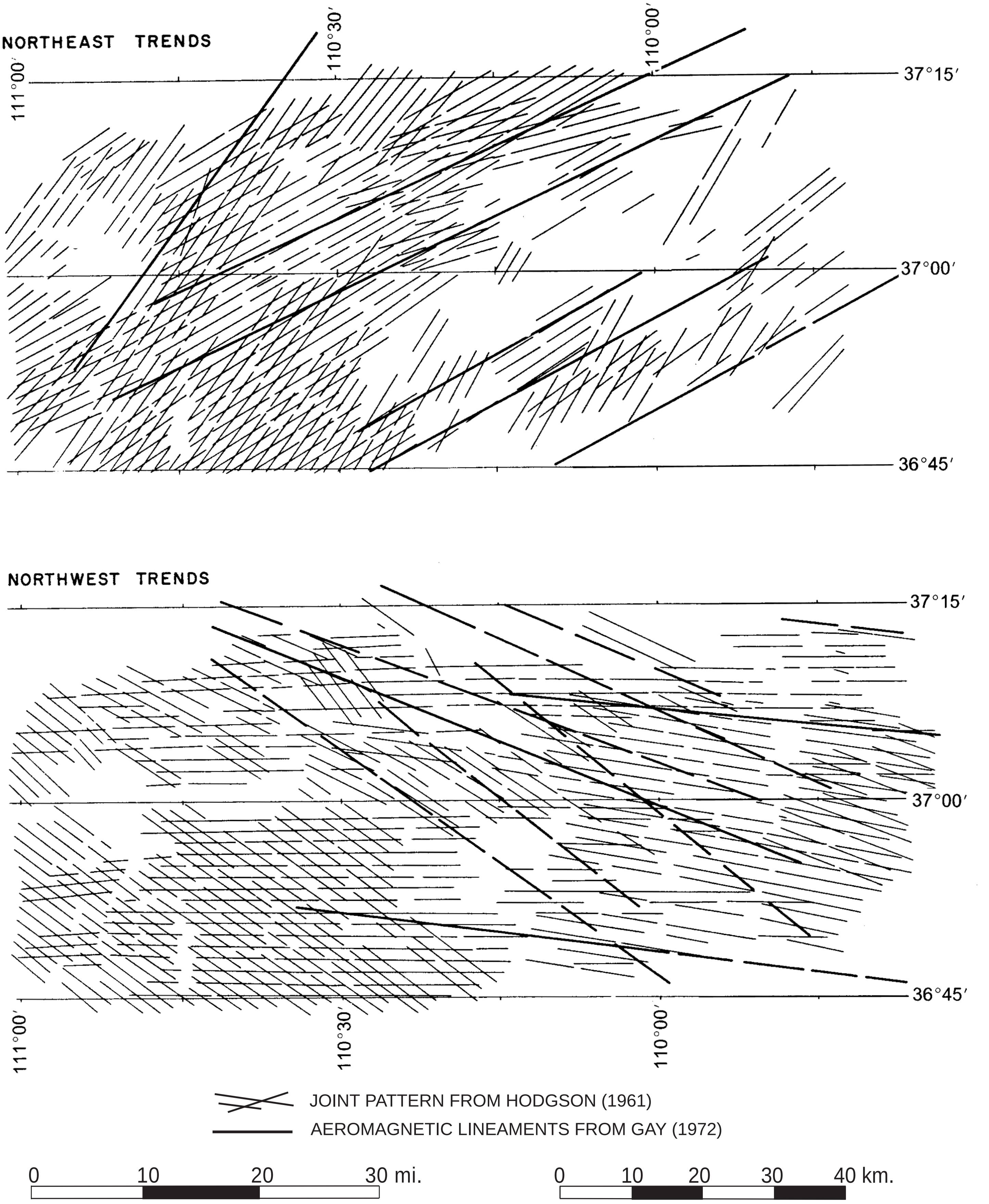


Figure 22. Aeromagnetic lineaments/basement shear zones vs. joints in a 55x125 km region (35x80 mi.) of the central Colorado Plateau.

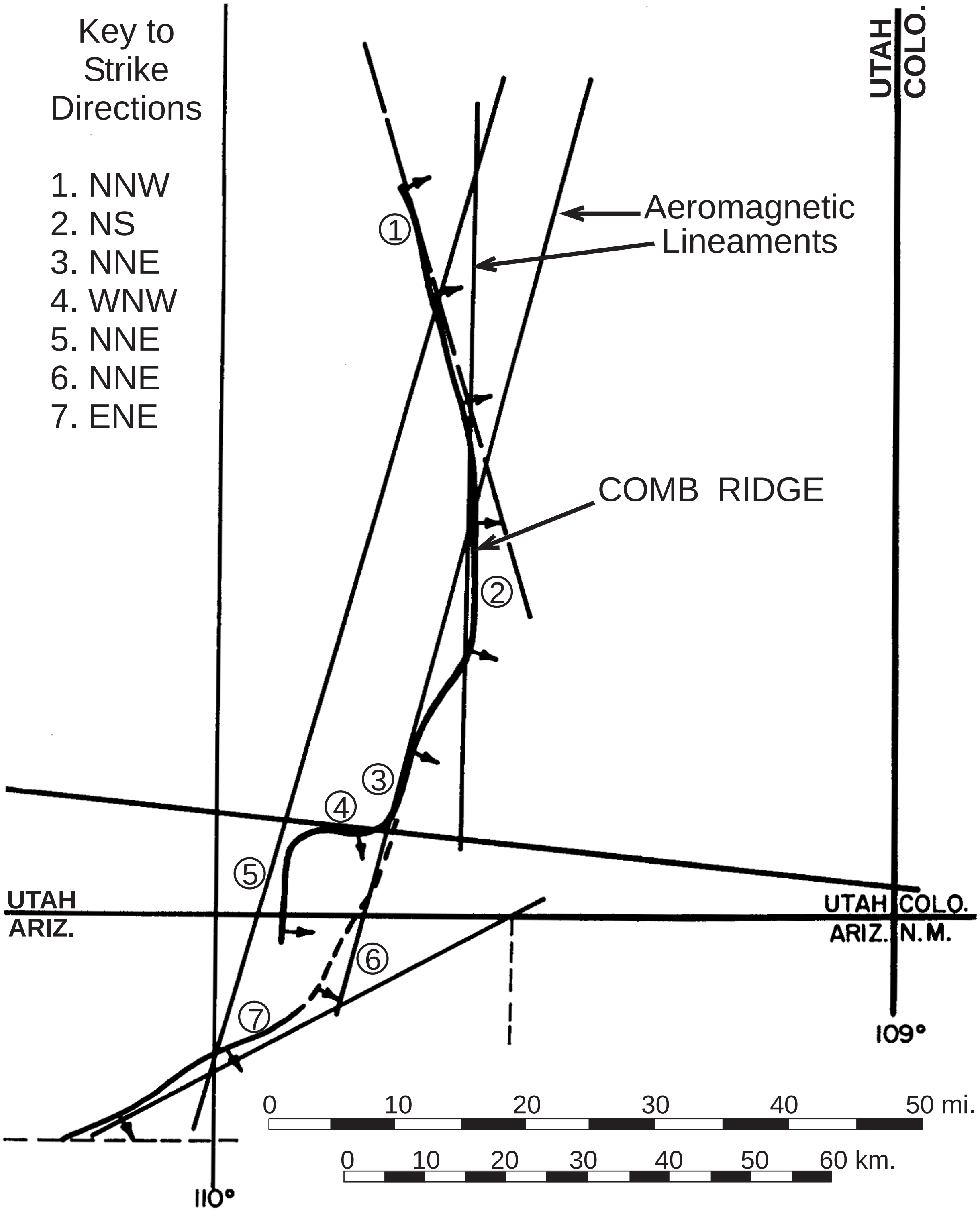
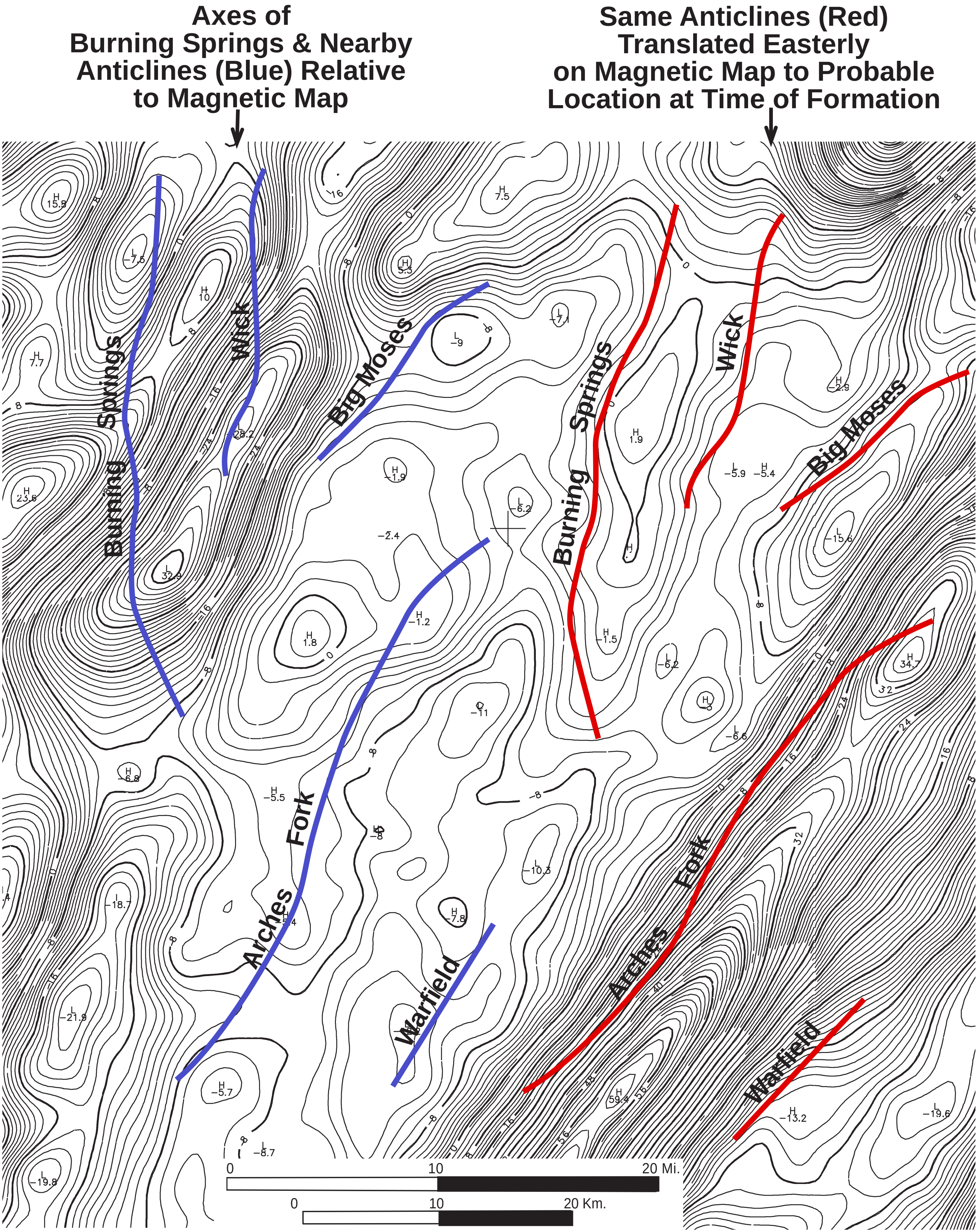


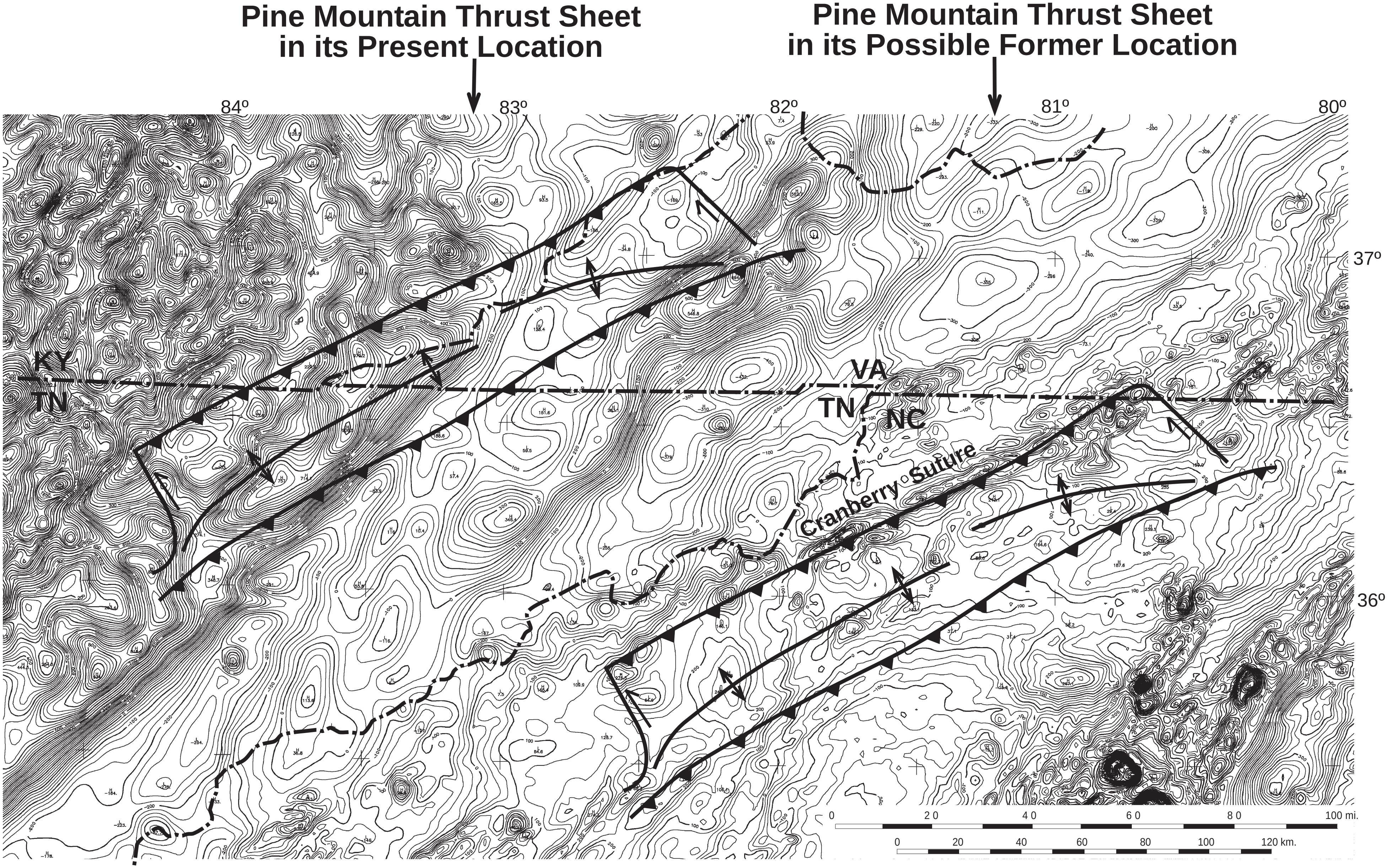
Figure 23. Selected aeromagnetic lineaments/basement shear zones (from Fig. 21) compared to crest of Comb Monocline on the Colorado Plateau, USA, taken from Kelley & Clinton (1960). This figure modified from Gay, 1972, Plate II.



Magnetics = AGI NewMag® data, 1992 Contour Interval, 0.5 nT.

Anticlines modified from M.E. Hohn, 1996, after P.L. Martin

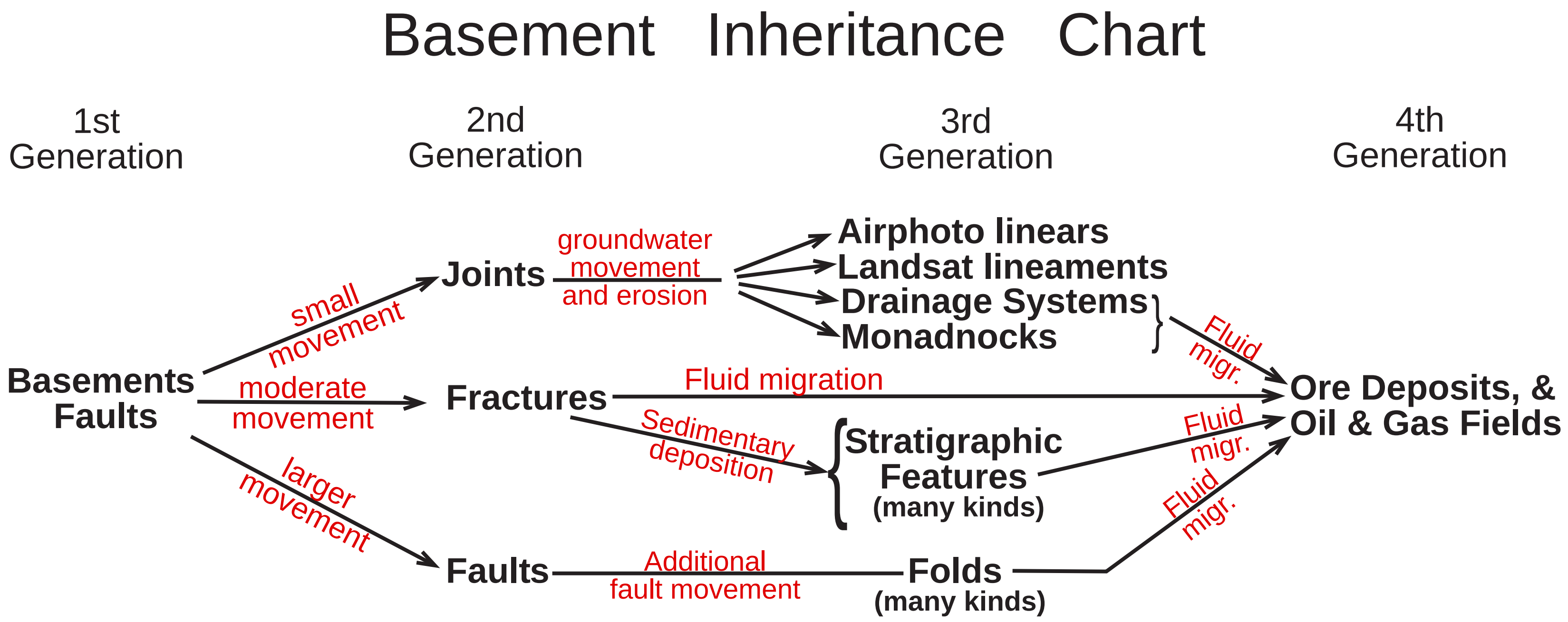
Figure 24. Detailed residual magnetic contour map of an area in northern West Virginia with the Burning Springs and adjacent anticlines superimposed (blue lines). Note the cross-cutting nature of these structures with the magnetics. The same anticlines were moved easterly 20 miles and slightly rotated to match the magnetics (red lines). This is evidently the root area where the anticlines originated before being thrust westward in Alleghenian time.



Total Intensity Regional Aero-magnetic Data from U.S.G.S. (Available on Internet)

Pine Mountain Thrust from P.B. King, 1969, Tectonic Map of North America, U.S. Geol. Survey

Figure 25. The Pine Mountain thrust (west image) at the juncture of the states of Kentucky, Tennessee, and Virginia superimposed on the USGS regional total intensity magnetic map. The east image shows its possible original location 100 miles to the east in North Carolina along the Cranberry suture.



Basement Inheritance Chart

Figure 26. Basement Inheritance Chart showing the many different types of geological features resulting from reactivation of basement faults.

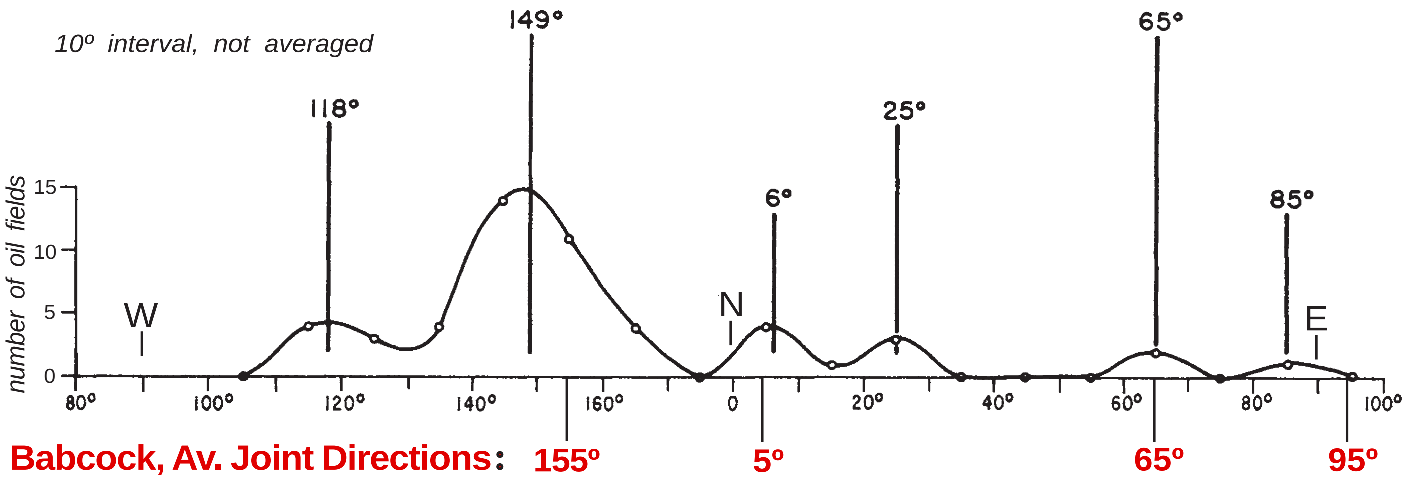
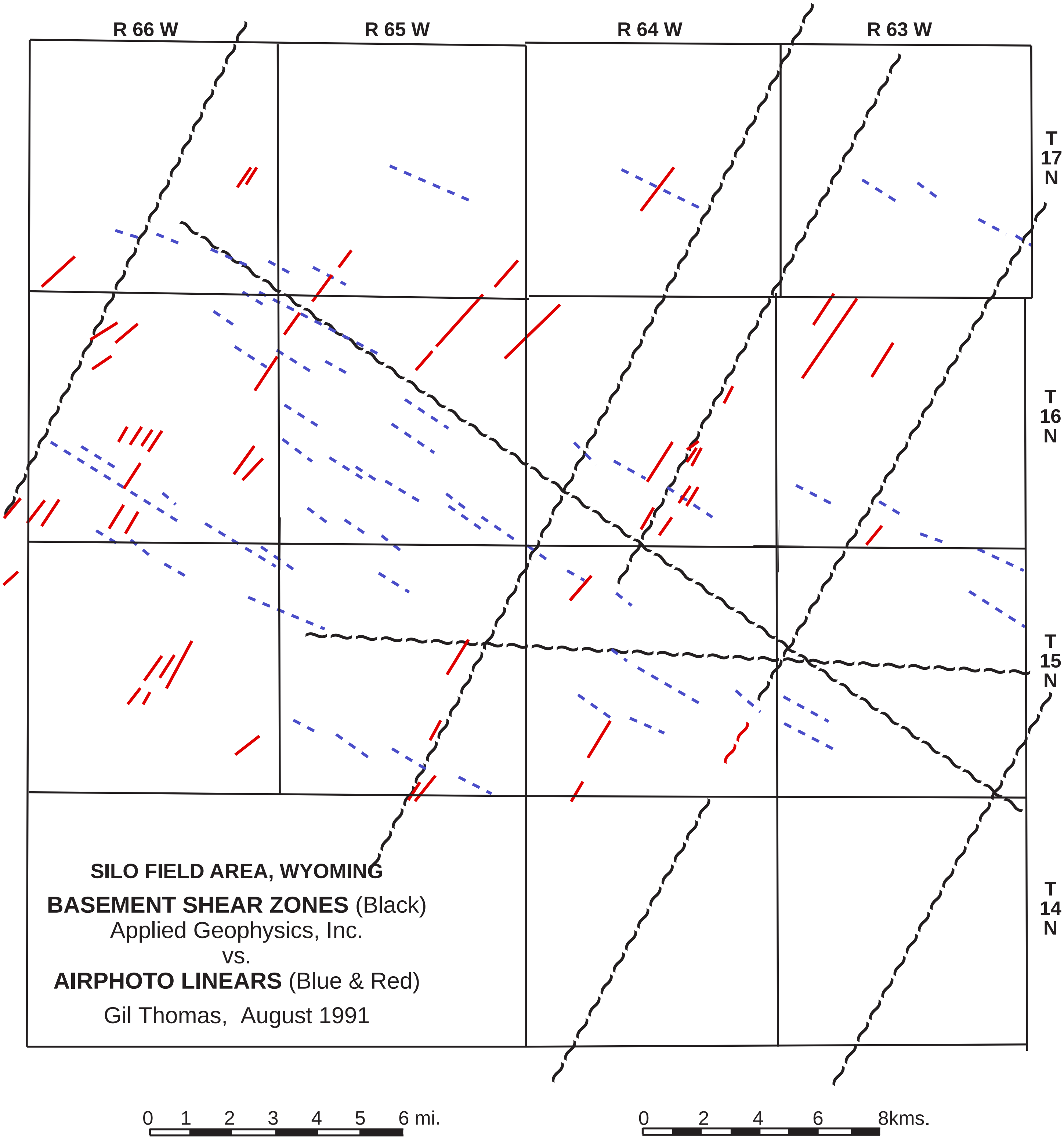


Figure 27. Histogram of long axes of oil fields in the Alberta Basin, western Canada (Gay, 1973) vs. dominant joint directions in the same area (Babcock, 1976). These were separate studies; neither study had any influence on the other.



SILO FIELD AREA, WYOMING

BASEMENT SHEAR ZONES (Black)
Applied Geophysics, Inc.
vs.
AIRPHOTO LINEARS (Blue & Red)
Gil Thomas, August 1991

Figure 28. Basement shear zones/faults vs. airphoto linears in Laramie County, SE Wyoming.

Increasing Throw of Fault

Estimated Amount of Throw of Fault*	Structural Effects of Basement Control	Resulting Oil/Gas Traps
Zero throw	Compaction over irregular basement topography. Lower part of sedimentary section mimics the irregularities. No fault involvement.	Compactional anticlines (graviclines), fluvial deposits in topo lows +15 other types of traps.
1-2 meters of throw	Joints formed, and the more intensely jointed areas over basement faults are eroded faster and drainages result.	Fluvial sands
3-10 meters	Fault scarps or topographic bulges localize shorelines	Shoreface sands
10-30 meters	Creation of sea floor highs over which sands are deposited by the winnowing action of bottom currents.	Offshore sand bars
30-100 meters	Fault scarps are created on the sea floor in a carbonate depositional environment.	Reefs, algal mounds, other types of carbonate mounds (bioherms).
100-300 meters	Asymmetric compressional folds formed - no fault mapped at level of fold.	Anticlinal fold - causative fault is at depth.
over 300 meters	"Thrust-fold" structure - fault progresses up to level of fold and beyond.	Thrust-fold anticline on hanging wall block of thrust fault.

*These estimates are approximate.

Figure 29. Basement fault reactivation effects tabulated for increasing amount of throw of the fault.