Joints, Linears, and Lineaments – The Basement Connection*

S. Parker Gay, Jr.[1]

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[1]Applied Geophysics, Inc., Salt Lake City, UT (spgagi@aol.com)

Abstract

Although some geologists understand the connection between basement faults and (1) joints, (2) linears, and (3) lineaments, many do not, and a few even disparage the idea of a connection, in spite of well-documented proofs dating back to the 1960's and 1970's. Briefly, small meter-scale movements of basement faults under recently lithified sedimentary rock create joints. These joints are parallel and cover large areas because the underlying basement faults (actually shear zones) fall into parallel sets that cover large areas. Most areas of earth's continental crust are underlain by three or more basement fault sets, thus resulting in three or more directions of jointing. Some joints also result from later stresses in the sedimentary section that create folding. These overprint the original basement-related joints. Basement-created joints are not evenly spaced, and where they are more numerous due to inhomogeneities in the sedimentary section and/or where groundwater is channeled along them, airphoto linears and Landsat lineaments result - features which are parallel to, but not necessarily coincident with, the underlying causative basement faults. Continued movement of some of the basement faults will result in fracturing and the formation of faults, folds, stratigraphic features, linears, and lineaments that are directly coincident with the underlying faults. Later migration of ore fluids, oil, and gas into these structures result in economic deposits important to man.

Introduction

Few geology teachers pass on the understanding of basement control to their students, even though almost all geologists will be concerned at some time in their careers with these very common linear features. It is for this reason that I herein review past and present knowledge of joints, linears and lineaments and outline the proofs of their interconnected origin via basement faults. This should dispense with the mystery long surrounding these, as some say, “enigmatic” features, and statements such as “lineaments don’t mean anything.”

Much of the material connecting joints, linears, and lineaments (as well as fractures and hence fracture porosity, which is so important in petroleum and mining geology) has already been published, so this article will be mainly a tutorial, rather than an exposition of new material.

I start with the definitions of a joint, fracture, and lineament from the Bates and Jackson Glossary of Geology, 2nd Edition, 1980 (Table 1). They define a joint as “a surface of fracture ... within a rock, without displacement ...,” and a fracture, as a “general term for any break in a rock, whether or not it causes displacement ... [including] cracks, joints, and faults.” Definitions I have seen in other publications speak of “measurable displacement,” rather than simply “displacement.” It must be realized that a joint or fracture physically cannot form without some displacement, however small it may be. I know of no studies that have measured actual displacement across joints, but this could readily be accomplished by (1) saturating a jointed rock en situ with epoxy, (2) sawing a sample from the rock, (3) making a thin section, and (4) examining the thin section under a petrographic microscope. I make this point because joint sets evidently form by taking up the displacement from small meter-scale movement of basement faults, a subject I will discuss later.

I would like to redefine Bates and Jackson’s definition of a fracture to be more in line with that used in the petroleum industry, i.e. a planar break in a rock intermediate between a joint and a fault that, if not re-cemented with silica, calcite or other minerals and not occluded by clays, is capable of transmitting fluids, such as oil, gas, and water.

Note that Bates and Jackson (Table 1) properly define a *lineament* as a “linear topographic feature that is believed to reflect crustal structure.” However, they recommend against the term “linear” which conflicts with accepted practice in the photogrammetric and some geologic, literature, where a linear is a short feature a few kilometers or less in length identified on airphotos, and a lineament is many kilometers or tens of kilometers in length usually identified on satellite or radar images; I prefer these latter definitions and will further distinguish between a lineament in basement rocks and a lineament in cover rocks later in this article.

History

In March 1973, a few months after the first EROS satellite (later called ERTS, and later called Landsat) was launched in 1972, a “Symposium on Significant Results” was held at the NASA facility outside Washington, D.C. Talks were presented by many academic institutions and industry groups that had acquired, or been provided, satellite images from NASA. Nicholas Short (1973), in summarizing the talks said, “The principal topic in more than half the [geological] papers presented ... was lineaments.” This is highly significant. It reflects the fact that lineaments are obvious and very numerous in large-area images of the Earth's crust (a few tens of kilometers on a side) indicating that they are very common geological features. To not attempt to understand lineaments is to ignore one of the most common and basic features in geology.

Many photogeologists knew of the lineated nature of the Earth's crust years before the launching of satellites. In Figure 1, I show one example: H.N. Fisk's 1944/47 drawing of the lineaments mapped from hundreds of standard airphotos (9" x 9" sq.) mosaicked together in the lower Mississippi River Valley. Following a talk in which I showed this figure some years back, geologist Gene Saucier, one of Fisk's ex-students, approached me to say that there were so many photographs in this study that the only place large enough to lay them all out was on the floor of the college gymnasium (Louisiana State University), and that when viewed from the balcony the presence and the pervasiveness of the lineament sets was particularly obvious.

Aerial photographs played an extremely useful role for the Allies in intelligence operations during World War II (1939-45), and it was claimed that airphotos furnished as much as 85% of all intelligence gathered (U.S. Air Force instructor, personal communication, 1953, airphoto interpretation school, Lowry Air Force Base). Following the war, many airphoto interpreters returned to their jobs as, or became, geologists and the 1950's and 1960's were the heyday of airphoto geology. One of the leaders and the most prominent and published of the interpreters of that time was Larry Lattman of Pennsylvania State University. Below are selected quotes from Dr. Lattman's publications:

1958: "There is a regional parallelism of fracture traces [i.e. linears and lineaments], joints, and faults."
(AAPG Bull., v. 42, p. 2244) [Note: Lattman used the term, "fracture traces" for airphoto linears and lineaments.]

1961: "Long, narrow, relatively straight vegetation, soil tonal, and drainage alignments visible on aerial photographs and mosaics have recently attracted the attention of photo geologists." (Photogrammetric Engineering, v. 27, p. 438)

1961: "Zones of concentration of joints ... give rise to fracture traces [airphoto linears]."
(Photogrammetric Engineering, v. 27, p. 438)

1961: "In folded rocks the fracture trace orientations are not affected by local folds but do maintain a constant angular relationship to the regional structural trend." (Photogrammetric Engineering, v. 27, p. 438)

It is seen that Lattman recognized (1) the parallelism of joints, faults, and linears, (2) that linears [in the sedimentary section] arise from *"concentrations of joints*", and (3) that many linears (and their associated joints and fractures) do not necessarily result from later folding processes.

Other observations made in 1964 by U.S. Geological Survey geologist George Plafker in the Beni Basin of Bolivia, and later in Alaska are particularly pertinent to understanding the formation of joints:

1964: "Development of lineaments [and presumably joints] in the thin Recent alluvial deposits ...

> shows that they can form in relatively unconsolidated sediments almost simultaneously with sediment accumulation." The same sets of lineaments are also present "in parts of the basin where the sedimentary section is at least 10,000 ft thick" and is presumably well consolidated or lithified.
>
> "Because... [the lineaments] occur in a sequence of essentially flat-lying sediments, they cannot be interpreted as having been formed by ... stress related to superficial folding."
>
> "Lineaments could be a clue to the elusive orienting mechanism for systematic regional joints in undeformed sedimentary rocks." (R.A. Hodgson, 1961, is cited here.) (Above quotes are from GSA Bulletin, v. 75, p. 503-522)

To reiterate, Plafker found that joints and lineaments were present very early in the history of sedimentary rocks, before they could have been subjected to later compressional or extensional tectonic stresses. Thus, they evidently arise from small (meter scale) movement of underlying basement faults which could result from sedimentary loading of the basement blocks.

Observations and Evidence

In 1967 the present author developed a manual technique for making stereo pairs of contour maps, such as aeromagnetics, gravity, structure contours, and topography (U.S. patent #3928925, issued 30 December 1975, and since expired), and began using this technique regularly, mainly on aeromagnetic maps. The use of such stereo pairs was found to be a powerful interpretation tool for contour maps and allowed the interpreter to see many features not otherwise obvious, or even visible, on such maps. After preparing and studying stereo aeromagnetic maps of many areas in the western U.S. for nearly 2 years, he was struck by the many linear features <u>always present</u> on these maps.

Because of this, the author in 1970 decided to make a more definitive study to try to determine the origin and characteristics of the pervasive linear features. He selected the Paradox Basin of Utah and Colorado for this work, as the U.S. Geological Survey had just open-filed a composite aeromagnetic map of the basin, and there was good published material available on the structural geology of the area (e.g. Kelley, 1955a, 1955b; Kelley and Clinton, 1960). The writer's lineament interpretation of the Paradox Basin (published in Gay, 1972) appears in Figure 2. Some of the writer's contemporary colleagues dismissed this study as having little geological significance ("it looks like pick-up sticks"), but lo and behold! after the EROS satellite was launched later the same year (1972), geologists were suddenly bombarded with articles showing many other maps that looked like "pick-up sticks". There is an important difference, however, between the map of Figure 2 and maps of sedimentary basins resulting from satellite images. Figure 2 shows linear geological features that arise from the basement underneath the sedimentary section. Note that the sedimentary rocks here at the flying heights employed, are essentially non-magnetic and so the basement pattern prevails. Figure 3 shows an actual satellite image of outcropping basement on the African Shield. Its similarity to Figure 2, the magnetically-derived basement lineament map, may be noted. Figure 4 shows the northern portion of the eastern Ontario Basin in Canada and the adjacent basement outcrop of the Canadian Shield on the northwest. The Shield area is characterized by the "pick-up stick" pattern, whereas the basin is not lineated (except for property boundaries - seen better at a larger scale). Figure 5 shows another image of outcropping basement, this one a SLAR image of a portion of the South American Shield. SLAR images show the lineaments well under all weather conditions, whereas Landsat only shows the images well when there is no cloud cover or haze, and at a low sun angle (35º or less). I must emphasize the low sun angle aspect, as high sun angle images I have examined show very few lineaments, or the lineaments are not obvious.

The thoughtful geologist must pause at this point and try to understand what Figure 3 and Figure 4 (and similar images of outcropping basement throughout the world) represent. The so-called "lineaments" are long, straight, topographic alignments carved by erosion along shear zones in the basement metamorphic/igneous complex, i.e. they erode low, hence their obvious visibility (streams, rivers, lakes and vegetation occupy them); they occur in readily visible sets of parallel structures; there are sometimes four or more sets mappable in a given area; and most importantly, there are rock type changes across them, which make them mappable with magnetics. We demonstrated this latter point conclusively (Gay 1995a) with a comparison of a magnetic map in Marathon County, Wisconsin, on the Canadian Shield, with surface geological mapping of the shear zones present there (LaBerge, 1976). It is obvious, then, that these so-called "lineaments" are actually basement shear zones, readily mappable in outcrop. Should we thus call them "lineaments" or should we call them shear zones?

The fact that the Precambrian basement, where I have examined it on Landsat, is cut by three or four (or sometimes more) sets of lineaments/shear zones, means that basement is divided into a complex pattern of polygonal blocks. The results of movement of these polygonal blocks is at present readily mapped by various types of 3D seismic attribute maps, as some authors have noted (e.g. Sonnenberg, 2012). An example of a correlation of 3D seismic data with basement faults mapped by aeromagnetics is shown in Figure 6.

The geological significance of the aeromagnetic lineaments mapped in the Paradox Basin (Gay, 1973) shown here in Figure 2 was quickly revealed by the author by the many one-on-one correlations he obtained of the “lineaments” with the monoclines mapped on the Colorado Plateau by Kelley and Clinton (1960). One of these correlations is shown in Figure 7, a comparison of the “sinuous” monoclinal Comb Ridge structure with seven of the previously mapped “aeromagnetic lineaments”. U.S. Geological Survey geologists had earlier described the monoclines as not really sinuous, or curving, but rather “straight line segments with corners” from surface geological mapping. Additionally, U.S.G.S. geologist R.Q. Lewis told the author (personal communication, 1955) that the Comb Ridge monocline had to have resulted from movement on underlying reverse faults in the basement (see also Lewis, 1958). His Professional Paper No. 474-B (1965) is a standout among the many papers on Colorado Plateau geology I have read, but unfortunately the reverse faults he spoke of were edited out of his manuscript in favor of non-shortening normal faults. Such non-shortening faults are not permissible on present-day balanced cross-sections (they do not balance!), proving Lewis correct in his original assessment in the 1950’s. Another correlation of a Colorado Plateau monocline (Waterpocket fold) with basement fault mapping was recently shown in Gay (2011, p. 142).

In summary, aeromagnetics in 1970 accurately mapped the underlying basement faults that control the monoclines on the Colorado Plateau. The basement faults are actually ancient, reactivated Precambrian shear zones (see Gay, 1995a, for more clarification and edification on this point).

The above discussion of the 1970 work may seem to be a diversion from the main theme of this article - jointing and fracturing - but the 1970 work led to a convincing connection of jointing and fracturing with basement. Gulf Oil Co. geologist Robert A. Hodgson had published a classic study of jointing on the Colorado Plateau in 1961. (It is “classic” because a great many articles on jointing for the past 50 years refer to this article.) I became aware of Hodgson’s work in late 1972 after the map shown in Figure 2 had already been published, and I was urged by colleagues to compare Hodgson’s joints and my basement shear zones of the same area. The results are shown in Figure 8. The correlation is uncanny - nearly identical strike directions of five sets of underlying basement fractures with the jointing mapped high above basement in Pennsylvanian to Cretaceous rocks. For me, this was a definitive correlation of jointing (and hence fractures and linears) with underlying basement faults. Here I briefly summarize Hodgson’s many findings and conclusions. (Note: although these observations are in tabular form which the average reader will tend to skip over, I urge the serious geologist to carefully read each one.):

Hodgson's Observations (1961) on Joints

1) “The joints ... are grouped into sets within which the strike of each joint is parallel or sub-parallel with others of the same set.

Each such set in turn appears to be a distinct unit with identifiable boundaries in plan. Such a unit commonly is of considerable areal extent and is distinguished from other sets by the unique strike that it maintains...” (p. 14-15).

2) “Joints of any set will intersect joints of other sets. In plan, the angle of intersection between any two sets ranges from less than 15° to 90°, with the angle of intersection between two sets remaining essentially constant over the area” (p. 16).

3) “With very few exceptions... joints show no evidence of transcurrent movement. Movement parallel to joint faces, if present, is microscopic...” (p. 23).

4) “Each joint trend of the regional pattern crosses several folds of considerable magnitude, but does not swing to keep a set angular relation to a fold axis as the axis changes direction” (p. 1).

Hodgson's Conclusions (1961) on Joints

5) “Joints formed essentially normal to the Earth's surface early in the history of a sediment and before any significant tilting or warping of the strata has occurred” (p. 32) [Same conclusions as Melton, 1929; Pincus, 1951; and Sikander, 1969].

6) “Such reasoning implies that the joints are formed successively in each newly deposited rock unit, possibly as soon as the rock is capable of being fractured” (p. 32).

7) “The direction of the joints is considered to be inherited by upward reflection of the joint pattern in pre-existing [basement] rocks ... through a fatigue mechanism ...” (p. 37).

8) “Any theory that postulates that systematic joints are genetically related to folding is rejected for this region” (p. 29).

Hodgson later extended his studies southwest into the Grand Canyon region (1965) where basement outcrops there could be compared to jointing in the cover rocks. There, he concluded:

9) “Prominent fracture trends of Precambrian age in the basement rocks of the Grand Canyon region are present as major elements of

the joint patterns in overlying sedimentary rocks" (p. 935).

Note Hodgson's Conclusion 8 above that "Any theory that postulates that systematic joints are genetically related to folding is rejected for this region." This statement is nearly identical to the statement made by geologist Harry McQuillan from an extensive photo-linear study in the oil-rich Zagros Mountains in Iran and published in the AAPG Bulletin in 1973: These... "findings make necessary the rejection of a theory involving a genetic relation of fractures of this scale to the folding process, at least in the area studied." Earlier in this article I quoted Plafker (1964): "[Lineaments in the Beni Basin and hence joints] cannot be interpreted as having been formed by stress related to .... folding." That these three authors found it necessary to make these statements indicates that the argument of joint formation by those advocating folding and those advocating basement faulting has been on-going for a long time.

The mechanism of joint formation from movement on basement faults by "bridging" is discussed in Gay (1973, p. 98). Essentially, this says that small scale vertical, or near vertical, movements on basement faults/shear zones create stresses in the overlying rock column that are relieved by the formation of joints/fractures in a wide area above the basement fault. The total displacement across the joints (10,000 + total?) would be approximately equal to the displacement of the causative basement fault (a few meters?), resulting in a marginally measurable amount of displacement (0.1-0.001 mm?) across an individual joint. Movement of the basement faults triggered by the loading of hundreds (thousands?) of meters of overlying sedimentary rock on fault blocks would explain the near-contemporaneity of jointing with deposition of the sediments, as observed by Plafker (1964). Parallelism of joints over broad areas would be explained by parallelism of the causative basement faults over broad areas (Figure 3 and Figure 4). Multiple directions of jointing over broad areas (Figure 8) would be explained by multiple directions of basement faulting over broad areas (Figure 3 and Figure 4). In short, the origin of joints from small-scale movements of underlying basement faults satisfies all the observed major characteristics of joints. Different spacing of joints in sedimentary beds of varying thickness does not bear on the question of origin, and is readily explained by the varying rigidities of the beds. Different strike directions of joints in adjacent beds (if this is a correct observation) is more difficult to explain by any theory of origin.

Too many geologists have attributed the formation of joints only to the folding process, but a few have recognized that some joint sets are independent of folding. In Table 2, I list some of these authors, the names they have given to fold-independent joints, the dates of their papers, and start the list with Bob Hodgson.

A particularly interesting but biased study by Pollard and Aydin was featured by GSA as a "Centennial Article" commemorating the 100th anniversary of GSA in 1988, under the title "Progress in understanding jointing over the past century." The article lists 176 references, which are all mentioned in this monumental study. However, I could not find a single comment that attributed jointing to reactivation of basement faults. They refer to Hodgson's 1961 paper and quote him 12 times, but do not mention Hodgson's conclusion that “Any theory that postulates that systematic joints are genetically related to folding is rejected for this region.” They also do not attempt to refute the finding by other authors that joints arise from movement of basement faults, but they simply ignore it.

I have summarized my findings of basement control of the sedimentary section resulting from 30+ years of study of this interesting subject with the diagram in Figure 9. If we call basement faults/shear zones first generation structures, then we see that increasing amounts of movement of these faults give rise to second and third generation structural and stratigraphic features. Joints, linears, and fractures are caused by small movements. Larger movements result in folding, faulting, and stratigraphic features. Later fluid flow results in ore deposits and oil and gas fields, the fourth generation. These conclusions have been documented by the author in many papers and talks (Gay, 1995b, 1997, 1999a, 1999b, 2001, 2002a, 2002b). A few minutes study of Figure 9 may be worthwhile, as this information is not available to date in condensed form anywhere else.

Additional Examples

I will show three more examples of geological and geophysical data that connect jointing and linears with other members of the continuum of parallel structures. Figure 10 is a correlation of airphoto lineaments mapped by a competent, well-known Rocky Mountain photogeologist, with basement faults mapped by the writer. Thus, it is a correlation of first and third generation features. Note once more the parallelism of two different strike directions of basement faults with airphoto linears (and hence joints). Skeptics have told me that the correlating basement faults/aeromagnetic lineaments must have been selected with a *priori* knowledge of the linears, joints, etc. they are being compared to. Not so! All correlations shown in this article compare features selected independently of the other. I do take some pleasure, however, from the fact that such a comment acknowledges that the correlations are very good.

Figure 11 is an elegant correlation. It shows that jointing over a large area in the Alberta Basin, western Canada, measured by another competent geologist (he later was appointed Director of the Geological Survey of Canada) has strike directions parallel to the long axes of oil fields (this comparison was published in Gay, 1973). This figure compares second generation and fourth generation features.

Figure 12 is a non-published study I made nearly 20 years ago using data resulting from the “first Bakken play” in North Dakota. Figure 12a shows the residual NewMag® map with basement faults/shear zones superimposed. In the lower right corner is the corridor used (1.5 miles wide centered on the basement fault) for evaluation of the well data. Figure 12b is a map of 158 horizontal Bakken wells drilled in the same area. Each well was studied by a competent petroleum engineer and, based on the decline curve, was assigned an EUR (estimated ultimate recovery), not shown here due to scale. The results appear in Figure 12c. Those wells cutting the corridors along the basement shear zones show 21% higher production than those wells on the interiors of basement blocks. (Most of these wells touched just the corridor and not the location of the actual shear zone, but if they had, that is, if the wells had been drilled using the basement fault map, this number (21%), would surely have been much higher). In fact, in the southeast corner of the survey they were higher, where a 41% improvement for wells drilled close to shear zones was measured. I was also curious as to the importance of intersections of faults on drilling results (that had been touted by articles I have read over the years) and was surprised to see that the number obtained at intersections was about 100% higher, i.e. wells close to shear zone intersections had double the average production. Only eight wells in the study area were located within the 1.5 mile diameter circle centered on an intersection, and their locations are shown in Figure 12d.

Conclusions

On cratons, joints, linears and lineaments, as well as fractures and faults, result from reactivation of pre-existing faults/shear zones in the underlying Precambrian basement and therefore form a continuum of parallel structures, beginning with near-zero movement on joints to many kilometers of movement on thrust faults and regional strike-slip faults, summarized in more detail as follows:

1) The Precambrian Metamorphic Complex, which comprises the major percentage of Earth's continental crust, is almost everywhere cut by three, four, or more sets of parallel long, through-going structures, actually shear zones.

2) Small-scale reactivation of these basement shear zones/weakness zones under a recently deposited sedimentary section results in the formation of joints in the sedimentary rocks.

3) Joints are pathways for groundwater movement, and where this movement is pronounced, vegetational and tonal alignments (linears/lineaments) can be seen on airphotos. More groundwater movement results in rock weathering along linear zones, leading to increased erosion and the formation of topographic and drainage alignments/linears/lineaments.

4) Increased movement of basement shear zones results in fault-coincident lineaments, but more importantly it gives rise to most of our common geological structures and to many of our stratigraphic features, as illustrated on the "Basement Inheritance Chart" (Figure 9).

5) There is thus a continuum of parallel structures, from the controlling basement shear zones to subsequent joints, fractures, linears, lineaments, faults, folds, stratigraphic features of many kinds, and with later movement of fluids along these structures, the resulting mineral deposits and oil and gas fields.

These conclusions should lay to rest the belief that “lineaments don’t mean anything.”

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Table 1 - Definitions

Joint [struc geol]: A surface of fracture or parting in a rock, without displacement; the surface is usually plane and often occurs with parallel joints to form part of a *joint set*.

Fracture [struc geol]: A general term for any break in a rock, whether or not it causes displacement, due to mechanical failure by stress. Fractures include cracks, joints, and faults.

Lineament: A linear topographic feature of regional extent that is believed to reflect crustal structure (Hobbs et al., 1976, p. 267). Examples are fault lines, aligned volcanoes, and straight stream courses. Non-recommended syn: *linear*. (Linear is used in this article for a shorter linear feature of a few kilometers in length that is not of "regional extent")

Above are from Glossary of Geology, Second Edition, 1980, by Robert L. Bates and Julia A. Jackson, Editors: American Geological Institute, Falls Church, Virginia.

Table 2 - Various Names Given to "Regional" Joints
(i.e. those not related to folding)

1961	R.A Hodgson	"Systematic:
1976	R.P. Nickelsen	"Pre-folding"
1985	T. Engelder	"Tectonic"
2003	J. Lorenz	"Regional"
2004	S. Bergbauer and D.D. Pollard	"Pre-folding"

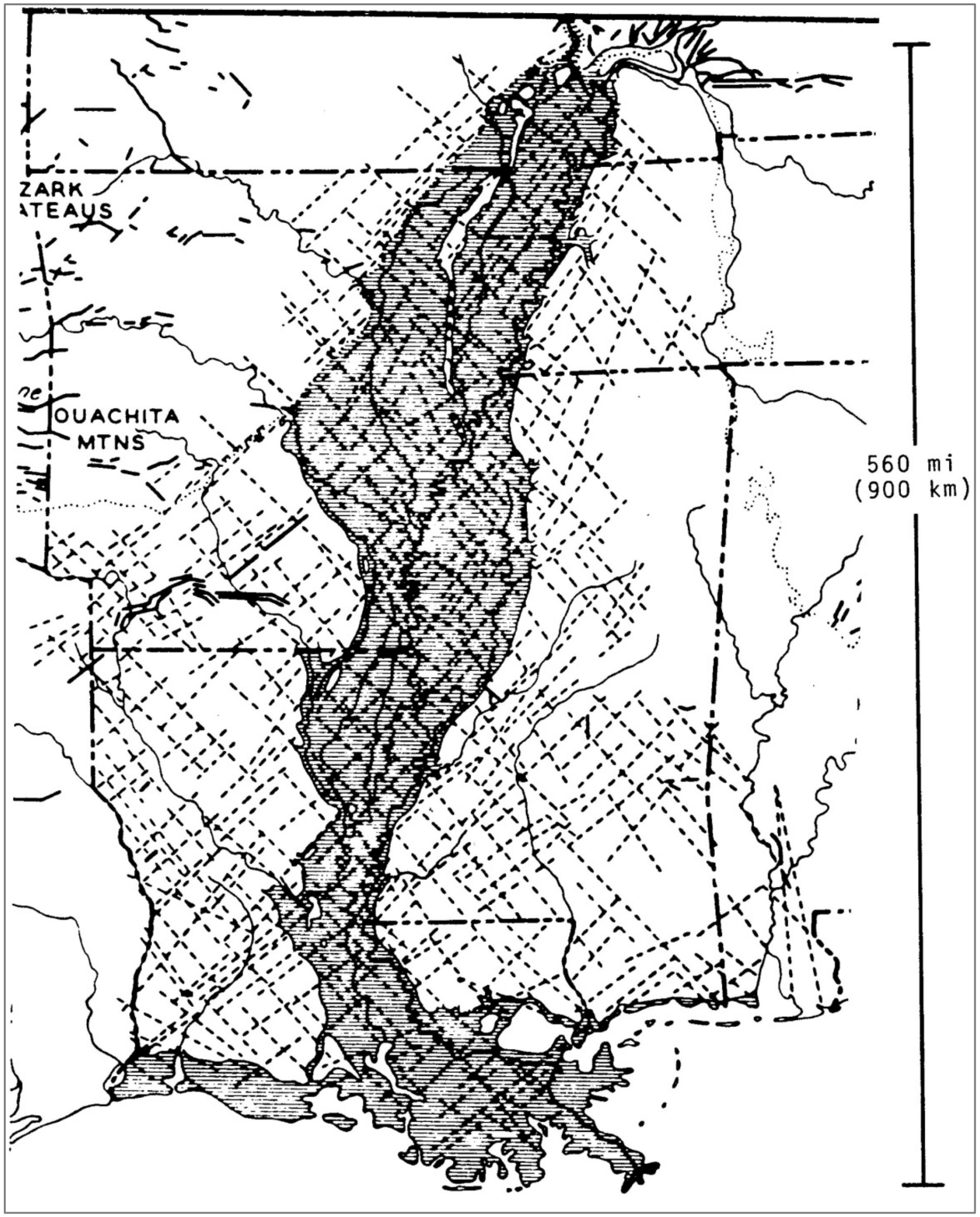

Figure 1. This early lineament study, made from a composite of hundreds of 9" x 9" airphotos, appeared in H.N. Fisk (1944) Geological investigation of the alluvial valley of the lower Mississippi River. U.S. Army Corps of Engineers, Vicksburg, MS, 78 p.

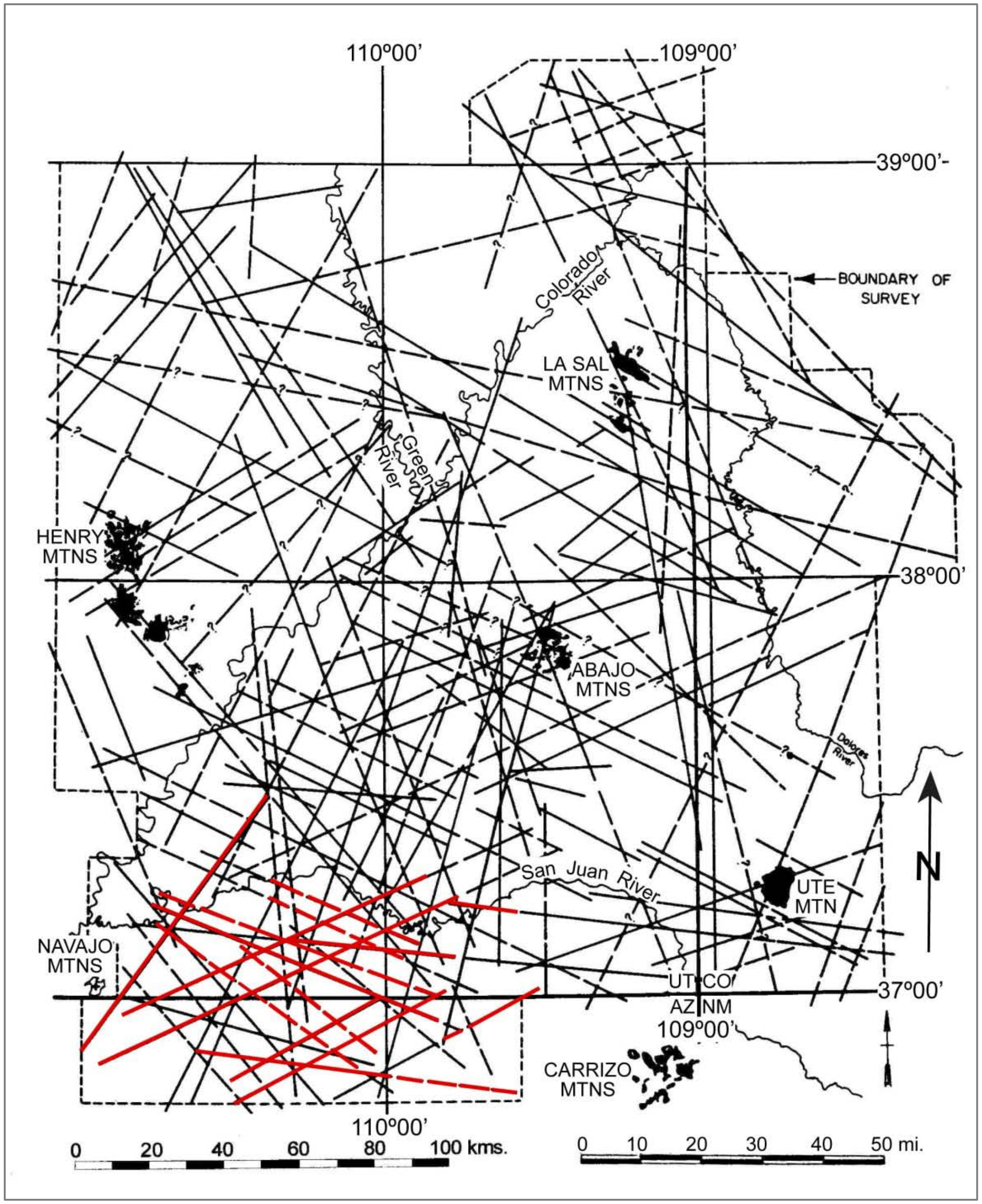

Figure 2. Aeromagnetic lineament interpretation of the Paradox Basin, Utah, USA. Aeromagnetic survey from USGS open file map of central Colorado Plateau, 1970; stereo pair by American Stereo Map Co., 1971. Red lines are those shown here in Figure 8.This figure taken from Gay (1972).

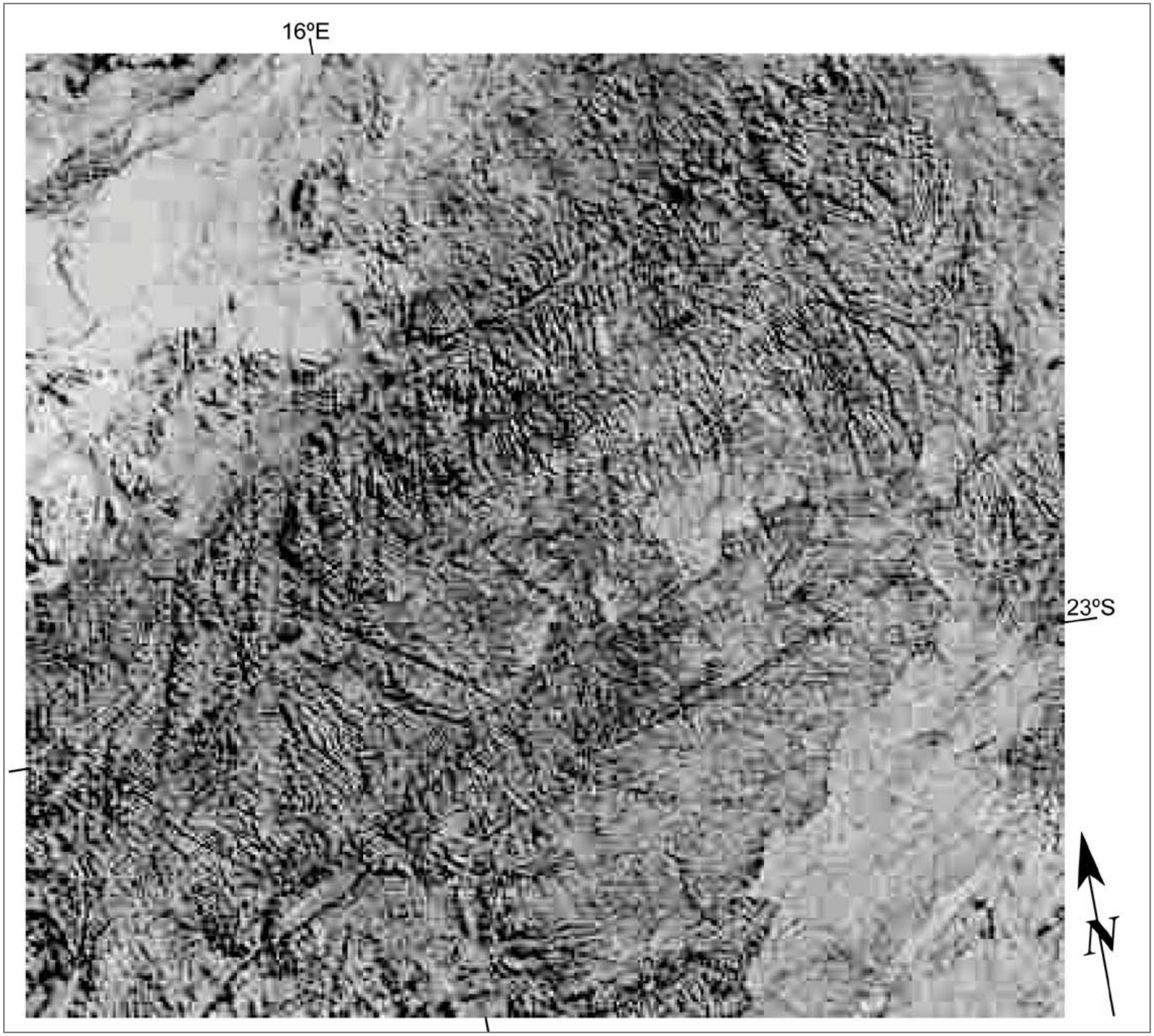

Figure 3. Landsat image of a portion of the African Shield in Namibia showing three or more fracture sets. This image, with its multiple lineament directions, is typical of outcropping basement on all the shields. From Short, et al. (1976, p. 384).

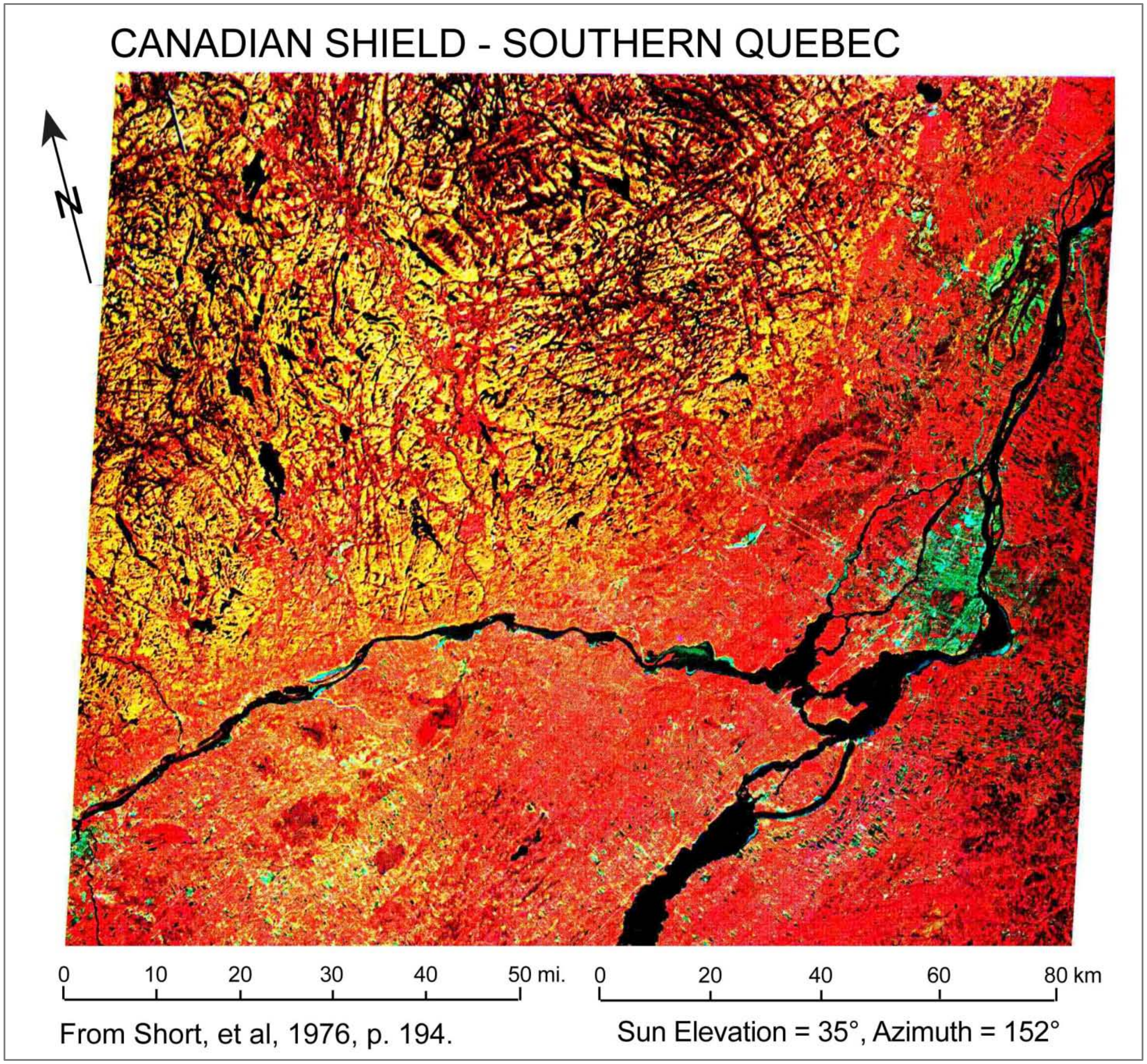

Figure 4. In this Landsat image of the Canadian Shield in southern Quebec, two things are noteworthy: (1) The Shield area, shown by mainly yellowish tones in the northwest one-half of the image, contains abundant basement fractures, which are lacking in the area of the lower Paleozoic onlap of the Ontario Basin in the south and east parts of the image. This tells us that Landsat is not always capable of mapping the basement fault block pattern in areas of later cover. (2) The parallel east-west fractures in the north-central part of the image are lacking in the northwest, indicating that a major suture, or sutures (evidently the north-south ones), separate these two areas.

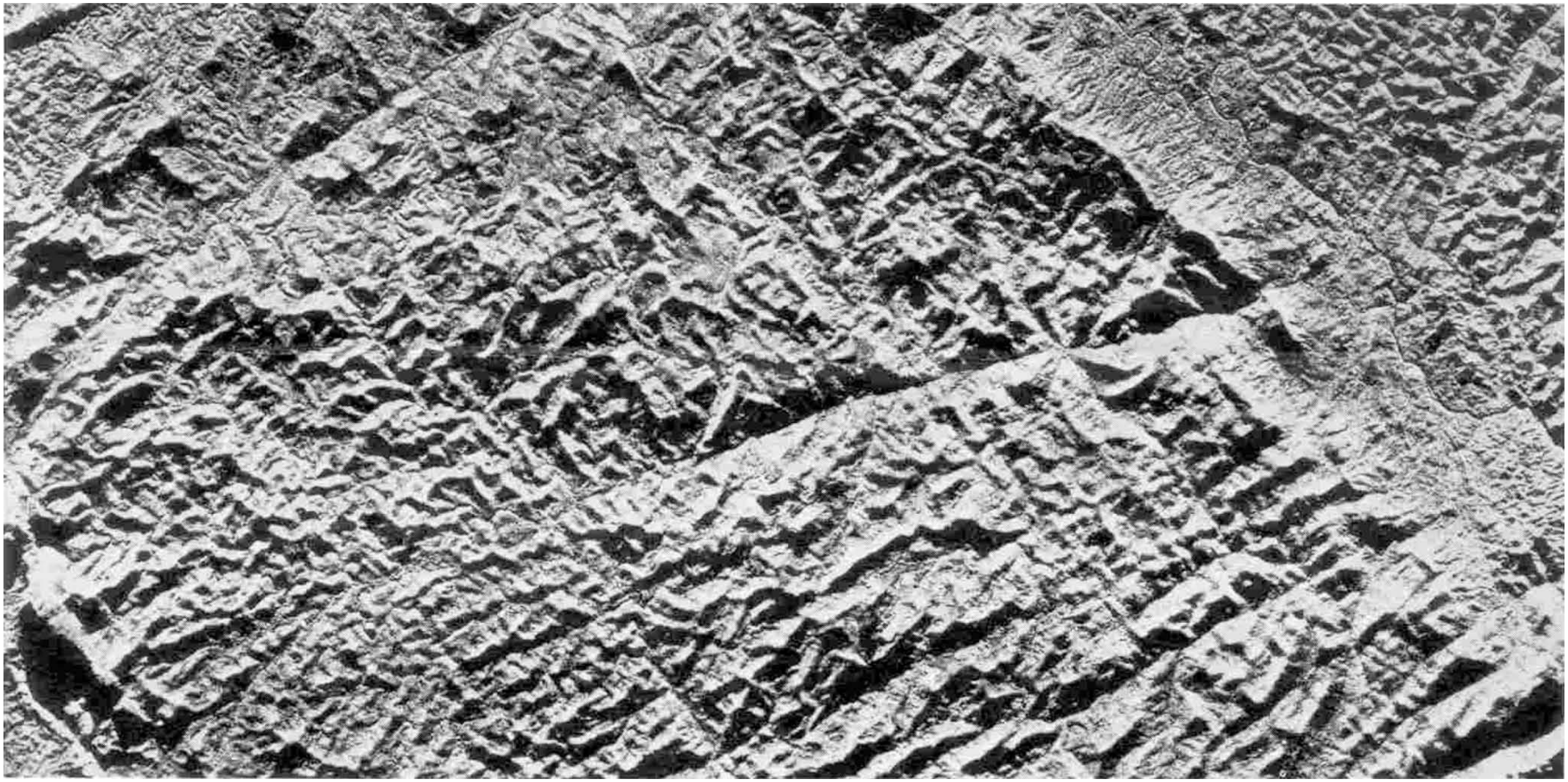

Figure 5. Side-looking airborne radar (SLAR) of a portion of the Guyana Shield, South America (Stanford Earth Scientist, April, 1972) showing 4 overlapping fracture sets.

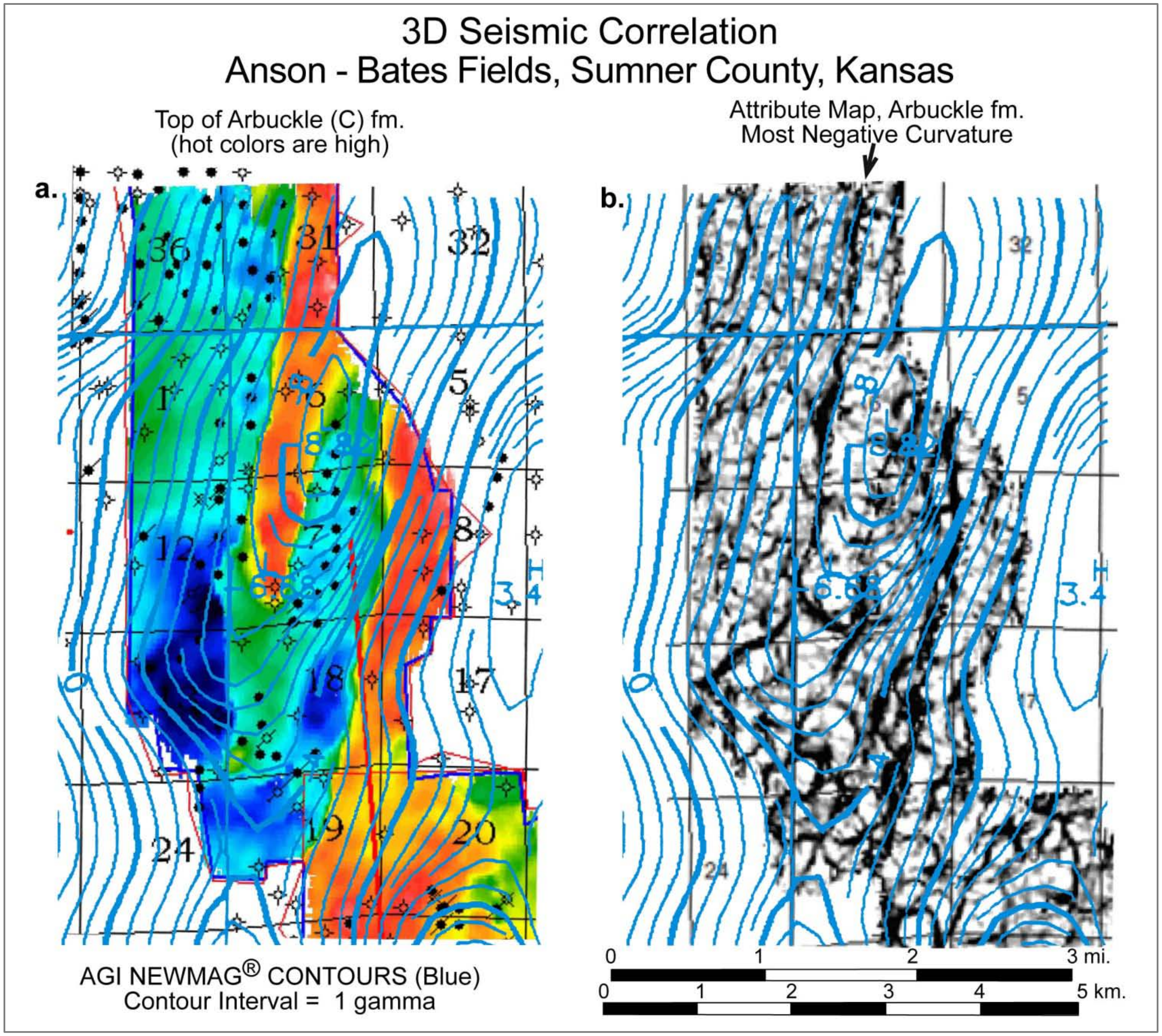

Figure 6. Correlation of 3D seismic attribute map ("most negative curvature") with 1 nT residual magnetic contours (blue). (a) The crest of Anson Anticlinal Field as defined by the top of the Arbuckle 3D seismic map lies along a residual magnetic (NewMag®) low or just to the west of it for the southern 3 ½ miles, and begins to depart slightly more to the west in the northernmost mile of the 3D data. (b) It is seen on the 3D seismic attribute map that the bounding east and west faults of the Anson Anticline occur on the magnetic gradients on either side of the residual magnetic low where we place basement faults as explained elsewhere. (Seismic data published on CD by Kansas Geological Survey, 2010, from article by D. Hedke and R. Saenger).

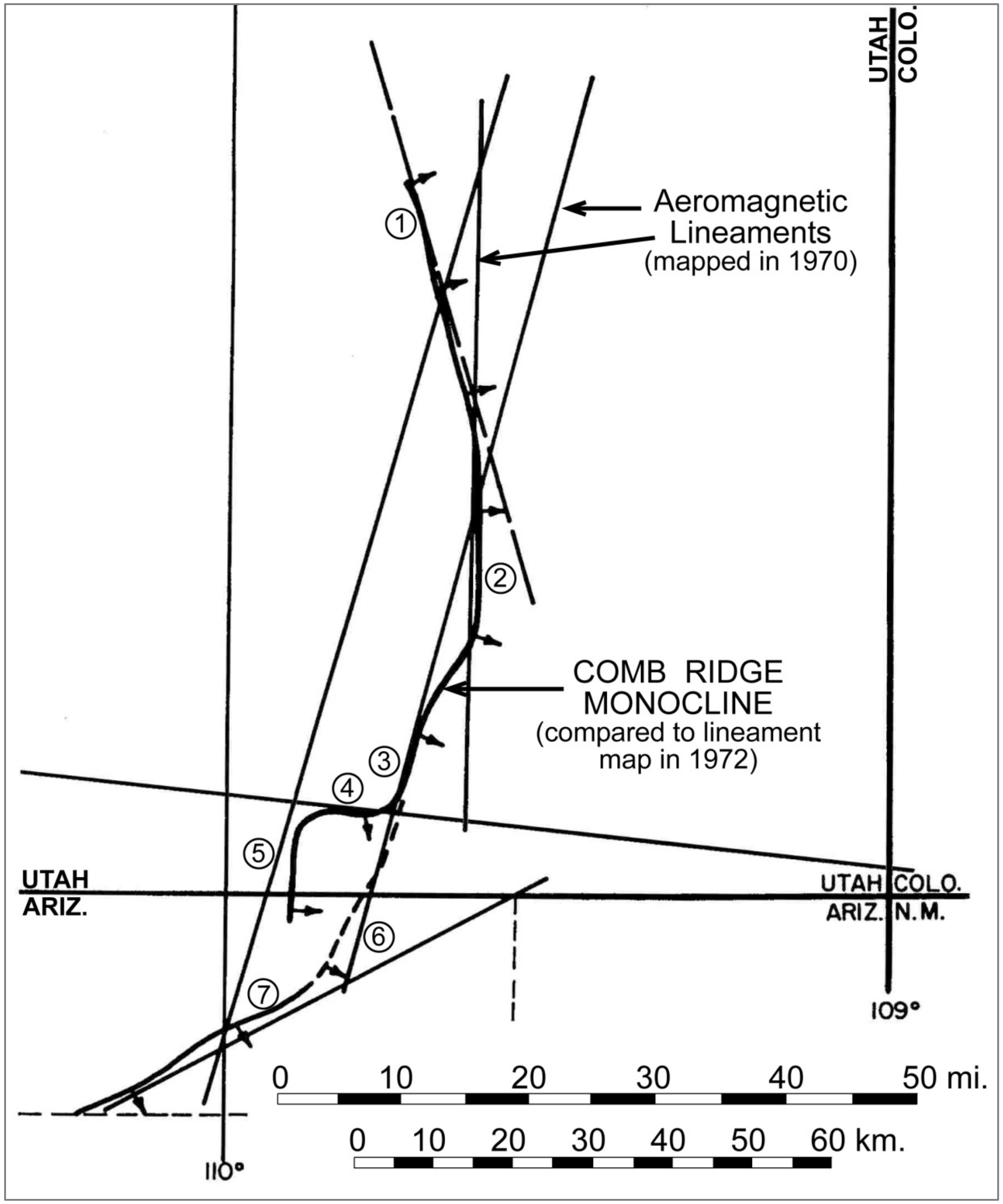

Figure 7. Aeromagnetic lineaments/basement shear zones (from Figure 1) compared to the crest of Comb Monocline on the Colorado Plateau, USA, from Kelley and Clinton (1960). This figure modified from Gay (1972, Plate 2).

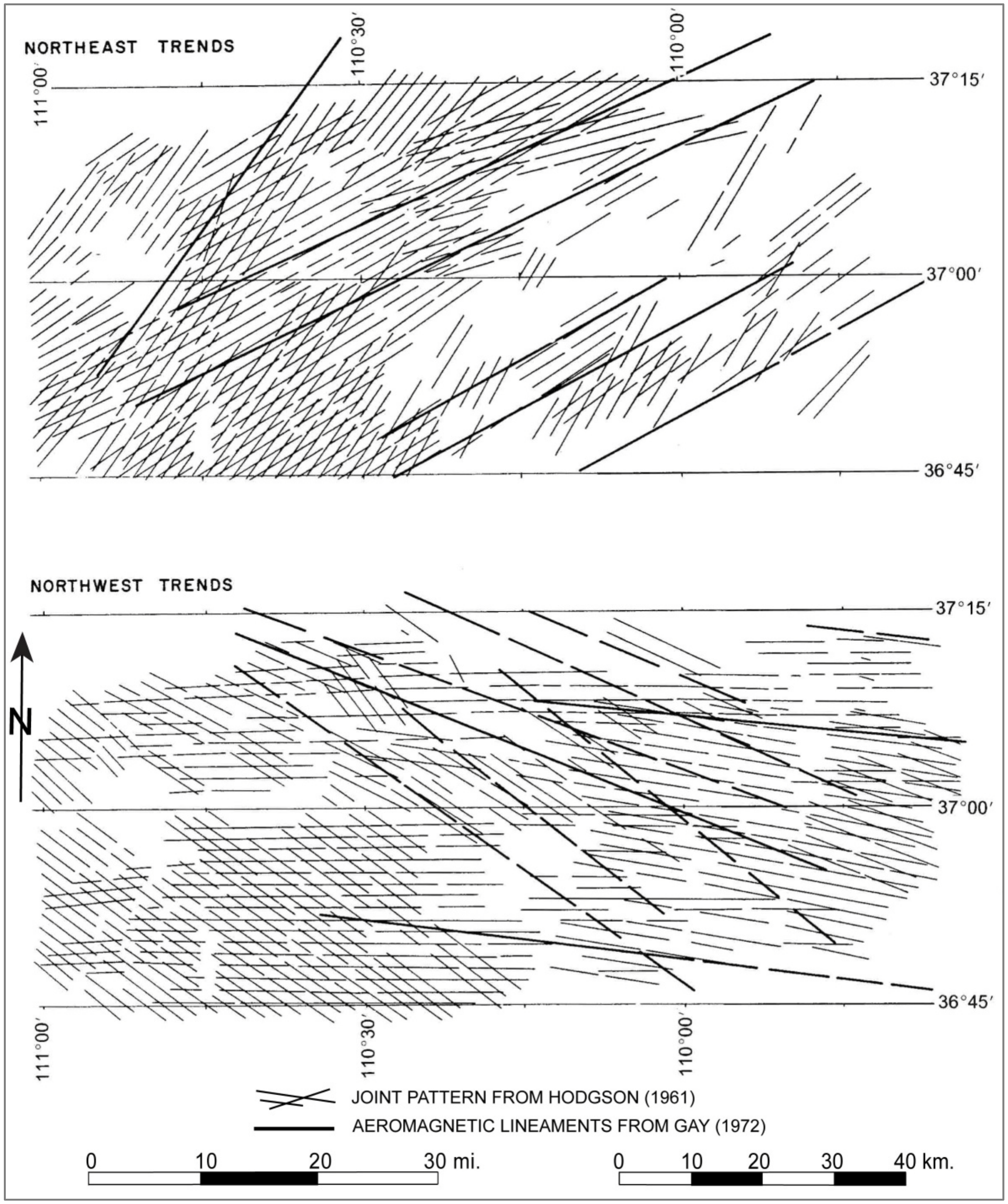

Figure 8. Comparison of the joint pattern from Hodgson (1961) with the independently mapped basement faults of Figure 2. This comparison was made in 1973 and convinced the author then of a direct connection between basement faults and jointing.

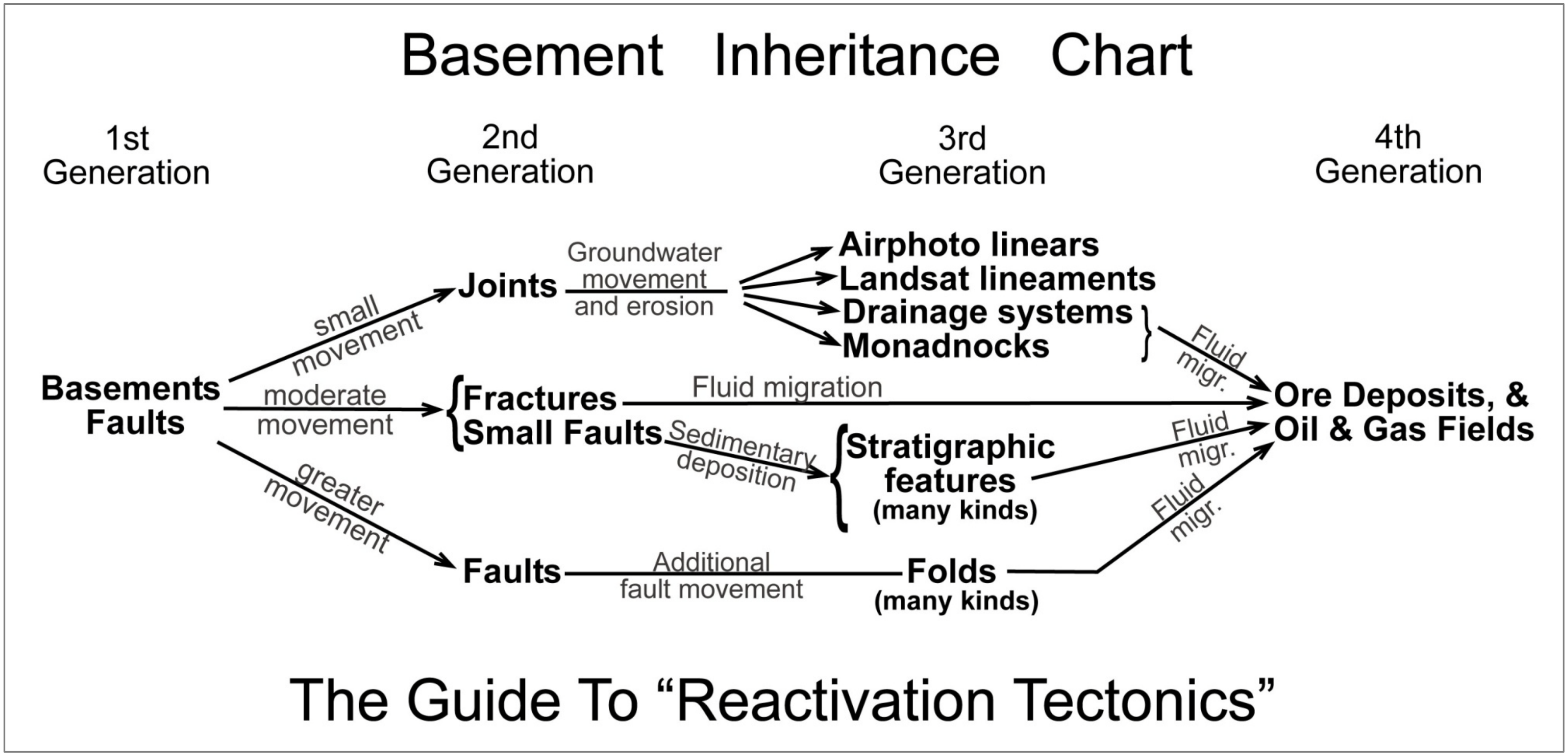

Figure 9. The relationship of most geological structures and many stratigraphic features to basement is shown by this chart. Only thin-skinned thrusting, “slump-style” growth faults, and some stratigraphic features are clearly unrelated to the underlying basement.

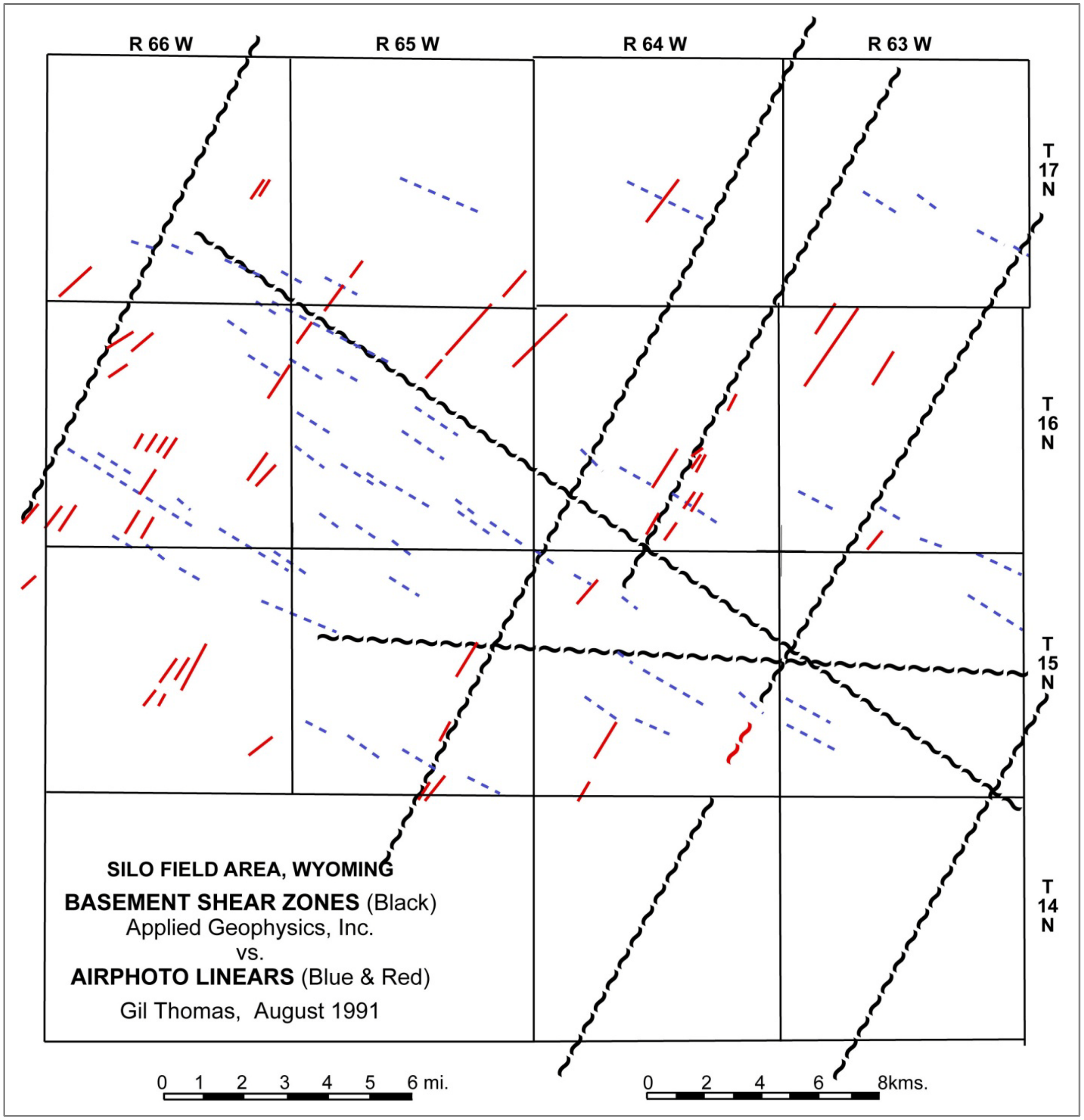

Figure 10. A close correlation of aeromagnetically-mapped basement faults/shear zones (first generation) with airphoto linears (third generation) is shown in this map. The location is in Laramie County in southeast Wyoming.

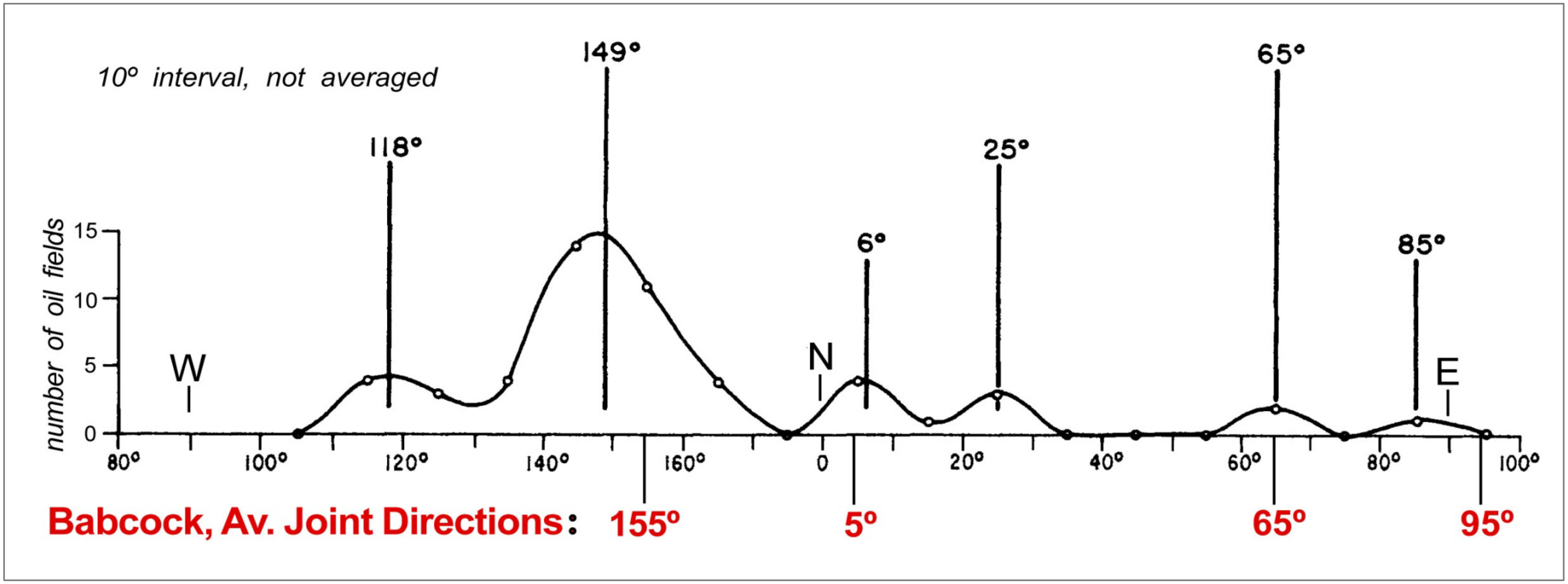

Figure 11. Another remarkable correlation of basement inheritance: joints, which are second generation features vs. oil field traps, the fourth generation. Again, neither of the studies on which this comparison is based had any influence on the other.

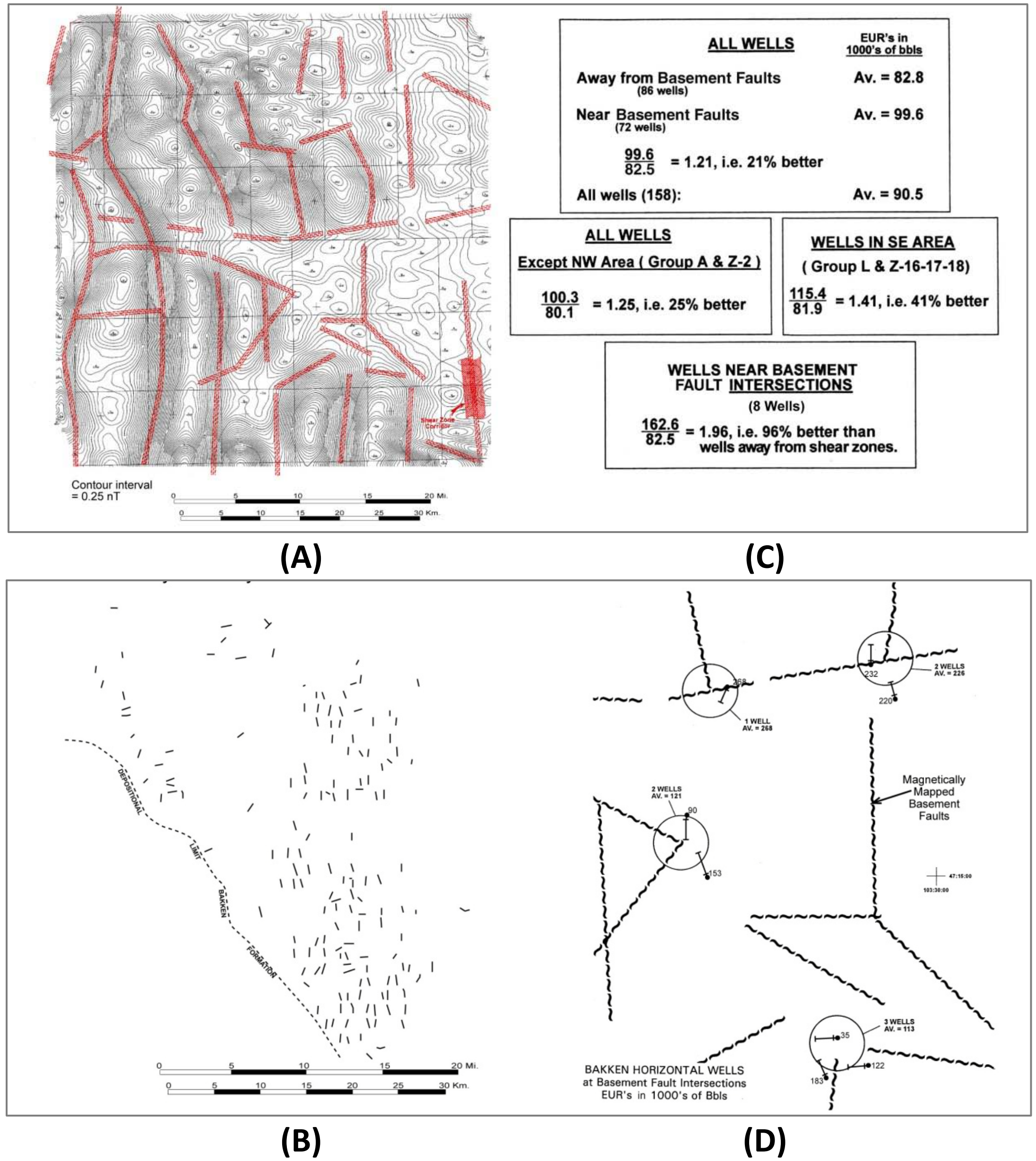

Figure 12. First Bakken play in North Dakota, late 1980's, Golden Valley County and vicinity. (a) Magnetic residual map and basement fault interpretation. Note sample corridor on lower right used for calculating well yields in proximity to basement faults. (b) 158 horizontal wells used for comparison with basement fault locations (yields, i.e. EUR's, not shown here). (c) Results of comparison - see text for explanation. (d) Segment of comparison map, showing wells close to basement fault intersections.