The Basement Fault Block Pattern: Its Importance in Petroleum Exploration, and Its Delineation with Residual Aeromagnetic Techniques[1]

S. Parker Gay, Jr.[2]

ABSTRACT

Multiple episodes of tectonism, evidently related to plate tectonic movement during ≈ 4 billion years of Precambrian time, created complex patterns of basement shearing and faulting in the earth's crystalline crust. The fracture patterns thus created are observable on space imagery of outcropping shield areas on all the continents, and would necessarily exist as well under all sedimentary basins deposited on the basement complex of the cratons. Such cratonic basins include the majority of the oil and gas producing sedimentary basins of the world. Subsequent movements of the basement faults and of the rigid to semi-rigid blocks between them occurred periodically during, and subsequent to, deposition of the sedimentary rocks and localized most of the structure and much of the stratigraphy in the sedimentary section. This basement fault block pattern also controls, to a large degree, the topography of the basement, which in turn controls additional structure and stratigraphy through the mechanism of gravitational compaction.

This paper documents a number of one-on-one correlations of the basement fault block pattern, as mapped by modern aeromagnetic techniques, with structural and stratigraphic features in the sedimentary section that are important to petroleum exploration. Several pitfalls in aeromagnetic interpretation that have been detrimental to the use of aeromagnetics in petroleum exploration in the past are shown to be due to the failure to recognize the existence of the basement fault block pattern and its control on the lithology of basement. It is these basement lithologic changes, and the resulting magnetic susceptibility changes, from block to block that allow us to map the basement fault block pattern and to use this information in important new ways for finding oil and gas.

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[1]An AGI POSITION PAPER on the Recommended Use of Airborne Magnetics in Petroleum Exploration. Published 1995, in the Proceedings Volume of the 10th Basement Tectonics Conference, R.W. Ojakangas, Editor.

[2]Applied Geophysics, Inc., 675 South 400 East, Salt Lake City, Utah 84111. A short biography appears on p. 41.

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I. INTRODUCTION

This paper is an attempt to document that which has already become obvious in recent years - the tremendous influence of basement on the structural and stratigraphic development of the sedimentary section. An emerging awareness of the overwhelming influence of basement has developed over many decades, but principally in only the last 15 years or so, with references too numerous to mention here. A recent parallel development has been a vast improvement in modern aeromagnetic acquisition and processing techniques applied to basement mapping, although of all those individuals and organizations involved in aeromagnetic surveying worldwide, few have dedicated themselves primarily to mapping basement. In this paper I wish to share some of the results of an intensive twelve year basement mapping program I have been involved in. This program has covered a combined area of 275,000 square miles in 18 petroleum basins situated in the Appalachians, the Midcontinent, and the Rocky Mountain region of the United States.

Aeromagnetics as applied to petroleum exploration has a history going back 45 years. It was an oil company, Gulf Oil Corporation, that invented the first successful airborne magnetometer immediately preceding World War II, and Gulf was one of its most ardent users in the first two decades following the war. However, during the initial flurry of interest in the late 1940s through the early 1960s, aeromagnetics did not live up to expectations as an oil finding tool and was used less and less between the 1960s and present time. Meanwhile, seismic methods, which increased dramatically in effectiveness during this period, especially with the advent of tremendous advances in digital acquisition and processing, further relegated accessory geophysical techniques, such as magnetics, to an even smaller role in the oil finding process. That is unfortunate, as magnetics is the only tool which can define the basement fault block pattern in detail over large areas. It is this pattern of basement fault blocks, formed in multiple tectonic and metamorphic episodes during the Archean and Proterozoic eras, that controls most of the local structure and much of the stratigraphy within the overlying, younger, sedimentary section. I emphasize the word <u>local</u>, and use it to mean features the size of individual oil and gas fields, and not broad regional features of indirect interest to exploration that magnetics has been used to delineate in the past. This latter, limited use of magnetics has been accepted by many who are unaware of magnetics' capabilities for mapping individual oil field-size structures.

II. THE FAULT BLOCK PATTERN AS OBSERVED ON OUTCROPPING BASEMENT, ON RESIDUAL AEROMAGNETIC MAPS, AND ON SEISMIC PROFILES: <u>THE DIRECT EVIDENCE</u>

In Figure 1 appear four high-altitude synoptic views (three are Landsat, one is SLAR) of areas of outcropping basement on four continents. These are typical images of Earth's <u>exposed</u> Precambrian crystalline crust. All views show highly lineated terrains, and minimal study reveals that the linears fall into multiple parallel or sub-parallel <u>sets</u> having varying strike directions. These overlapping fracture sets cut the basement into blocks of varying shapes and sizes, and it is this collection of basement blocks that I refer to as the "basement fault block pattern." Occasionally, more through-going suture zones are observed that juxtapose entirely unlike terranes containing different lineament patterns. These are almost certainly ancient plate tectonic-related boundaries.

Coming closer to Earth, in Figure 2 is shown a geologic map of a 50x65 km area of outcropping crystalline basement radiometrically dated at 1.8 Ga (billion years) in the "driftless" area (i.e. lacking thick glacial till) of central Wisconsin, U.S.A., on the southern edge of the Canadian shield (La Berge, 1976). Here, the till is commonly only a few meters thick, and outcrops and rock exposures in shallow excavations, roadcuts, etc., are abundant. It is possible to map the basement geology in considerable detail here in contrast to the major part of the Canadian shield and other shield areas of the Northern Hemisphere where glacial cover obscures the basement geology and where outcrops comprise only a few percent of the total area. Five things stand out in Figure 2:

1) A series of parallel to sub-parallel shear zones have been mapped,

2) There is obvious periodicity to the shear zones, the spacing between them varying from about four to eight kms (2.5 to 5 miles),

3) There are rock type changes across these zones,

4) The width of the shear zones varies from about 1 km (La Berge, personal communication) up to 2.5 kms or more, and

5) The shear zones and the geology abruptly truncate and change style across the line A-A′.

Although the high-altitude images of Figure 1 furnish an idea of the basement structure, Figure 2 provides a look at the basement fault block pattern mapped in a degree of detail seldom seen. The shear zones, consisting of crushed and fractured mylonitized

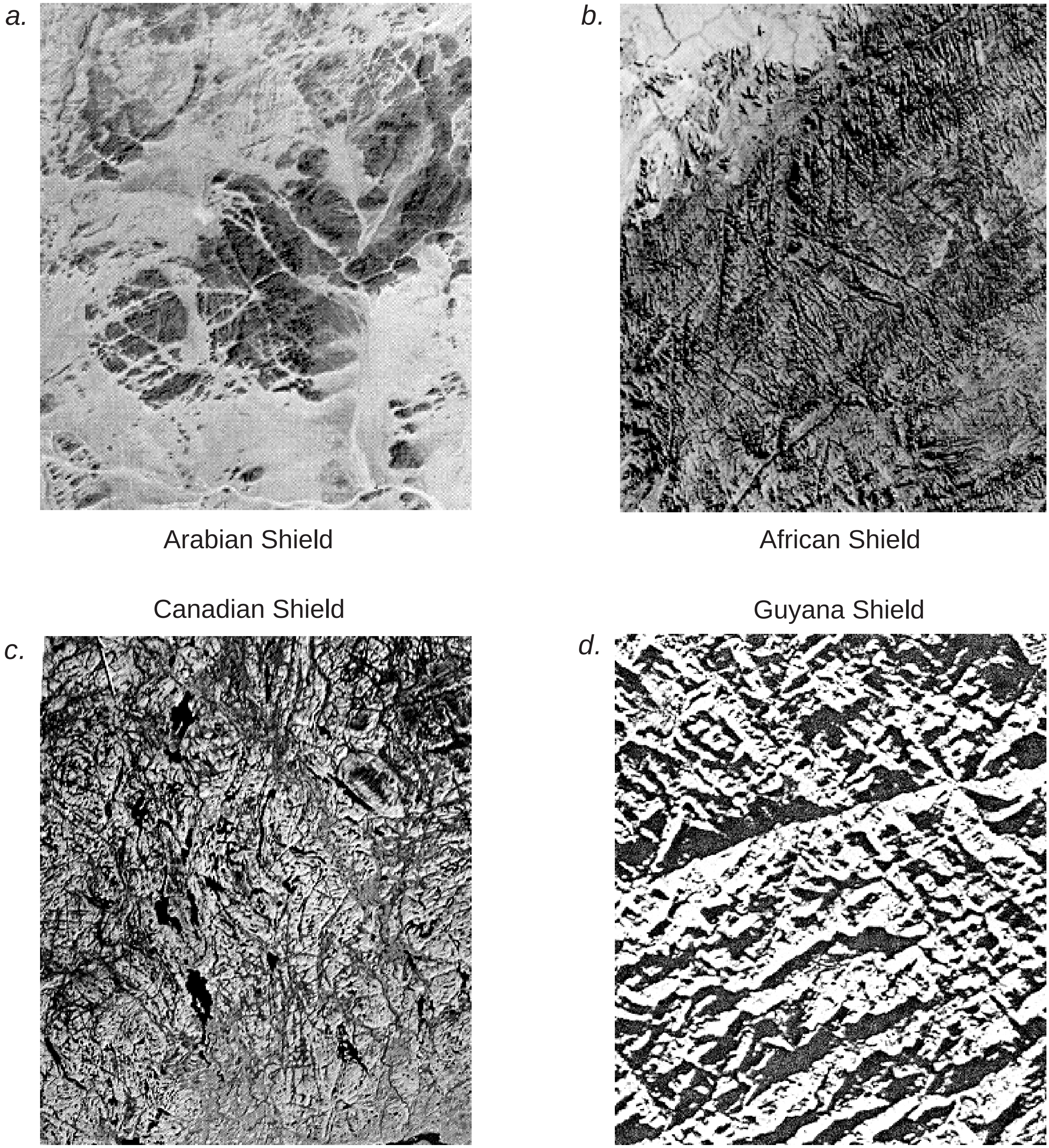


FIGURE 1: Sample high-altitude synoptic views of outcropping basement on four continents. a. *Landsat, Arabian Shield (Short, et. al., 1976, p. 312);* b. *Landsat, African Shield, (Short, et. al., 1976, p. 384);* c. *Landsat, Canadian Shield (Short, et. al., 1976, p. 194);* d. *SLAR, South American Shield (Stanford Earth Scientist, April 1972). Note the pervasively lineated nature of basement in these typical basement images.*

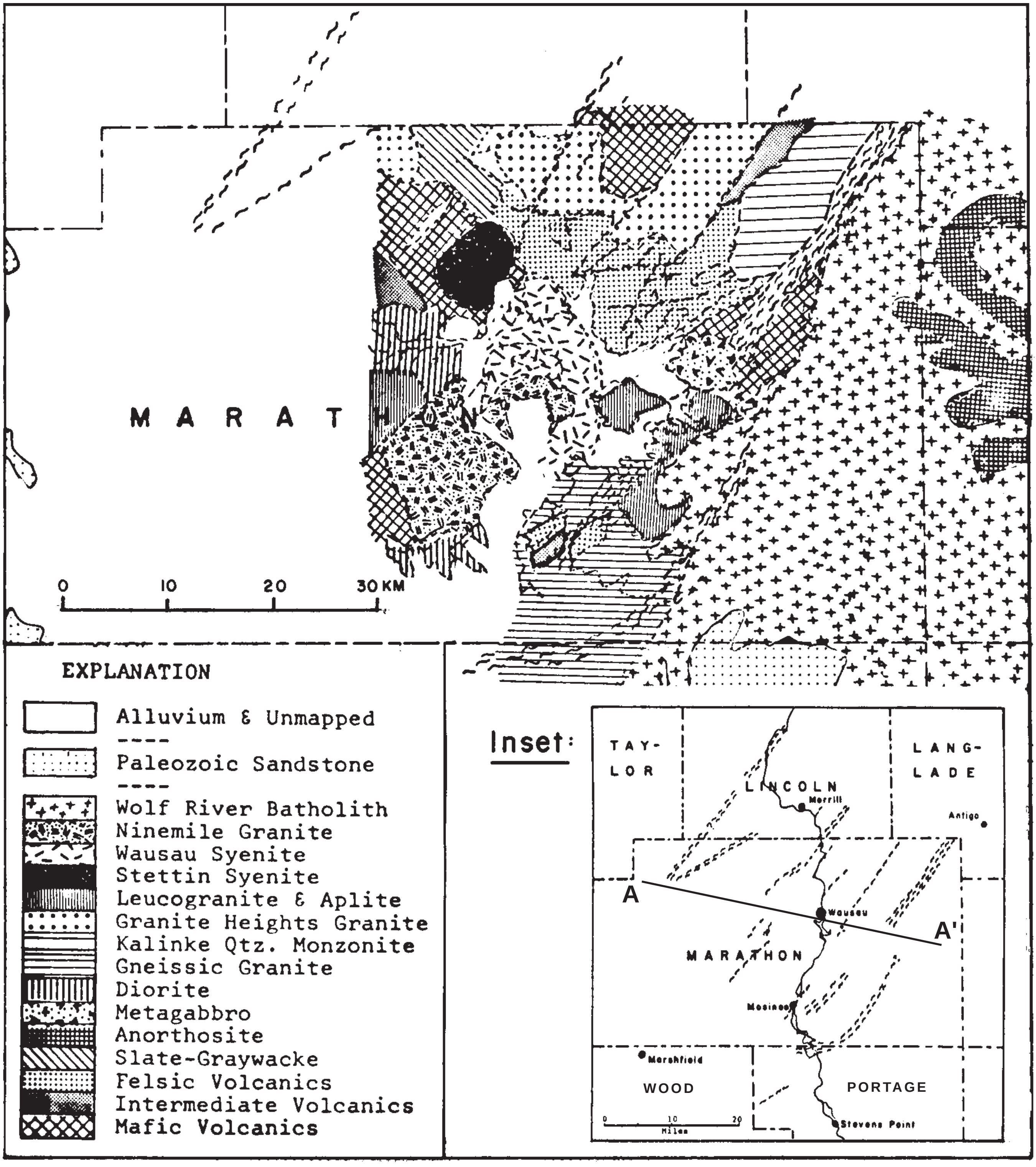


FIGURE 2: The fault block pattern as mapped by surface geology on the southern edge of the Canadian Shield in the "driftless" area of Wisconsin. Note the rock type changes that take place across shear zones, more clearly shown in the top part of the mapped area. The inset shows the shear zones by themselves. Geology from LaBerge, 1976.

rock as documented both in hand specimen and thin section, are the basement block boundaries, and the intervening areas of uncrushed (but nevertheless highly contorted, metamorphosed and jointed) rock comprise the more solid block interiors. If this area were the basement of a petroleum basin, it would be along the shear zones, or block boundaries, that we would generally find the faults in the overlying sedimentary section with seismic or subsurface techniques. These zones of weakness are the first sites reactivated by tectonic stresses or gravitational loading. If we properly residualize our aeromagnetic data, these block boundaries become readily visible as magnetic gradients, due to the rock type changes (and hence magnetic susceptibility changes) that take place across them. The rock type changes came into being because of Precambrian movement that took place long before deposition of the sedimentary section. This movement may have occurred many times during the long (≈ 4 billion years) Archean and Proterozoic eras.

I could have shown other geology maps of Precambrian shield areas of the world to illustrate patterns of fault blocks similar to those seen in Figure 2. However, most of the shields of the Northern Hemisphere have been subjected to glaciation, and as the shear zones are highly fractured and thus erode low, they do not often crop out and are generally covered by glacial till. In the Southern Hemisphere the crystalline basement rocks show similar lithology and structure, but here the shear zones are seldom directly mapped due to deep weathering, dense forest, and lack of access. Geology maps of outcropping Precambrian basement we have studied in the Rocky Mountains in Colorado and New Mexico, U.S.A., also show block boundaries, but many of the boundaries are not visible due to large vertical offsets that took place during Tertiary time and the subsequent formation of deep alluvial fans that obscure them.

Thus, in spite of their widespread nature in Precambrian rocks, shear zones have not always been reliably mapped, and their elusive nature has inhibited recognition of the pervasive nature of the basement fault block pattern. But, in all fields there are pioneers, and in 1948, Hans Cloos stated:

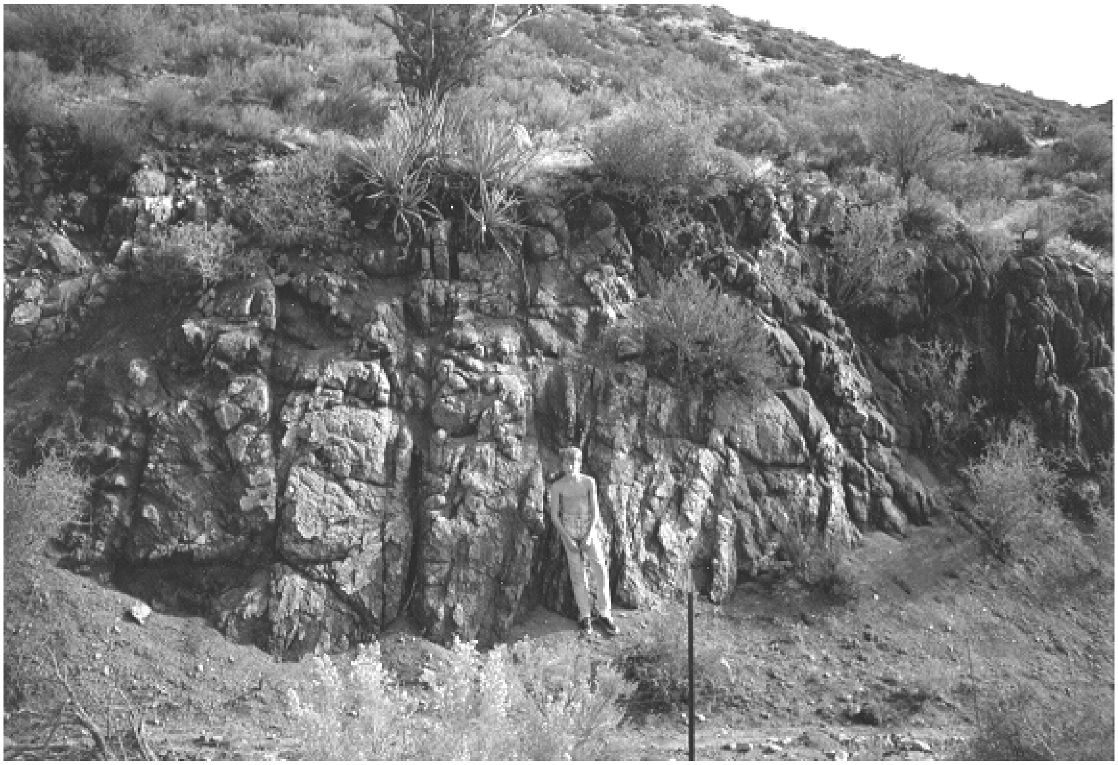
"The Earth's crust was divided into polygonal fields or blocks of considerable depth during an early stage of its history."

Coming closer to the rocks, in Figure 3 is shown a photograph of a typical shear zone in a road cut in SE Utah in the Precambrian core of the Beaverdam Mountains. This particular shear zone is over 12 kms in length and approximately 1 km in width, as mapped by airborne magnetics. The rocks within it are cut by vertical or steeply dipping fractures having an average separation of 2 to 5 cms (see Figure 3b). This calculates to 20,000 to 50,000 fractures per kilometer of width, and lends emphasis to the point that the block boundaries are the places where regional stresses are preferentially relieved by later fault movement rather than the interiors of the blocks where fracturing is less intense and more random in strike and dip. Also, the increased intensity of fracturing and mylonitization of the rocks in shear zones explains why these zones generally erode low and why they thus control, to large degree, the topography of the Precambrian surface. This surface, in turn, controls much of the structure in the lower part of the sedimentary section through gravitational compaction of the sedimentary rocks (see e.g., Gay, 1989), a subject which will be dealt with briefly in a later section.

Let us examine a typical airborne magnetic survey over a petroleum basin for evidence of the basement fault block pattern. In Figure 4a appears a profile residual aeromagnetic map of an area on the north shelf of the Anadarko Basin in Oklahoma where the sedimentary section is approximately 3.5 kms (12,000 ft) thick and basement lies about 3.8 kms (12,500 ft) beneath flight level. The residual magnetic contours at a 2-gamma interval are shown, with the interpreted shear zones traced along the linear gradients separating the residual magnetic highs and lows. (See Figure 5a for uninterpreted residual magnetic map of this area.) Note the WNW trending line B-B′ against which all anomalies abruptly terminate. This must represent a suture zone due to a tectonic event in Precambrian time that occurred after the one that formed the pattern of north-trending shears. The bottom part of the Figure (4b) shows the shear zone pattern alone with no overlying magnetic contours. Note the resemblance of this pattern to that shown in Figure 2 which was geologically mapped on outcropping basement in Wisconsin.

It could be considered that the sedimentary section here and elsewhere has recorded within it all evidence of faulting that occurred in the many tens or hundreds of millions of years subsequent to deposition. We "access" this record, so to speak, using subsurface mapping via well data or seismic surveying. In Fig. 4b, two faults located from subsurface mapping are shown. Both are located exactly along the interpreted basement shear zones, or block boundaries, as represented by gradients on the magnetic map. Note, however, that most of the interpreted basement shear zones in this area have no corresponding overlying faults. These zones were never reactivated, at least not sufficiently enough to be detected by the existing subsurface data.

In Figure 4b, also note the structural high apparent in Devonian strata about 800m (2500 ft) above basement in the West Campbell Oil Field which is conveniently nestled <u>between</u> block boundaries. I have mentioned earlier that block boundaries, i.e. shear zones, generally erode low, so it follows that the interiors of blocks must, in many cases, correspond to basement topographic highs. West Campbell Field appears to be a case in point and is most likely underlain by such a basement topographic prominence, although there are no wells to basement a.



b.

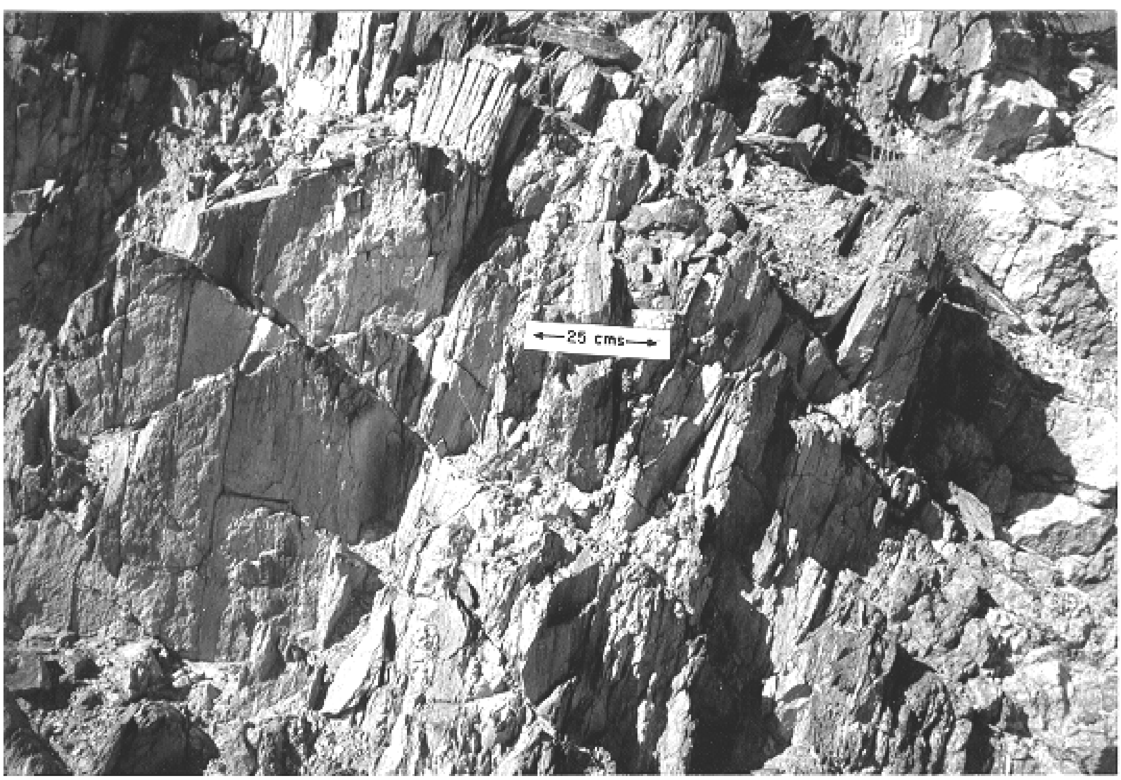
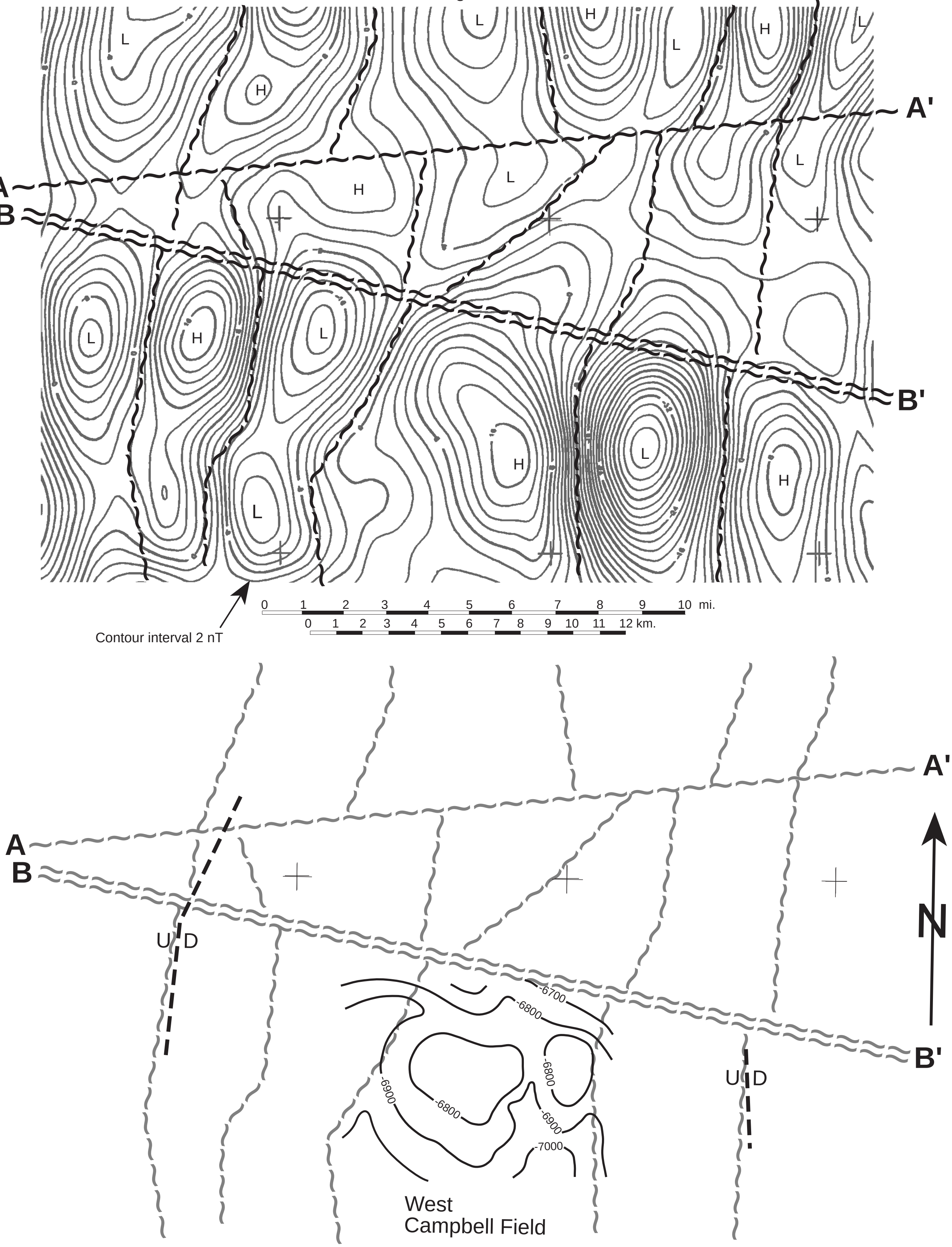


FIGURE 3: a. Shear zone exposed in a road-cut of Precambrian crystalline basement rocks in the core of the Beaverdam Mountains in southwest Utah. b. Close-up of a portion of same shear zone on opposite side of road. Note the tight spacing of fractures. Photos by Gay, 1987.

a.



b.

FIGURE 4: a. Profile residual magnetic contour map of an area in Woodward and Major Counties, Oklahoma, on the northern shelf of the Anadarko Basin. This map (and the ones in subsequent examples) was created by generating a lower order (smoother) curve along each flight line and subtracting it from original data. After contouring of the resulting values, shear zone symbols were then traced along the gradients between anomalies (northerly trends) and along the truncation lines of anomalies (A-A', B-B'). b. Shear zone, or basement fault block pattern by itself, with two known faults and one oil field structure map superimposed. Faults from S. Howery, 1983 (personal communication) and contours from Vance, 1974.

here to document it. The culmination of structural closure nearer the north end of the block rather than at its center would be due to the south dip of basement in this area.

In Figure 5b is shown the superimposed flight path and total intensity magnetic contour map of the area of Figure 4 together with the unannotated residual map (5a). Flight lines are approximately 2 kms (1.2 mi) apart oriented east-west. The total intensity map exhibits a striking non-resemblance to the residual map and would be of no benefit whatsoever for the delineation of basement fault blocks. Total intensity magnetics responds to rock types over broad areas as well as those deep within the crust. One can see by a careful examination of Figure 5b, however, that many of the features shown by the residual map are vaguely apparent in the total intensity data. Fortunately, we no longer have to interpret such total intensity maps in petroleum basins, as many enhancement techniques employing residuals, derivatives, polynomials, or downward continuation techniques exist for bringing out the subtle magnetic anomalies that result from the changes in rock type across basement block boundaries.

In Figure 6 is shown a profile residual magnetic map of another area in northern Oklahoma with structure contours and faults superimposed, also from an independent subsurface study. Here the sedimentary section is approximately 2 kms (6500 ft) thick, and the flight level was about 2.3 kms (7500 ft) above basement. The well density is high here and the faults shown are considered reliable. They also appear in nearly the same locations on a detailed subsurface study prepared by noted structural geologist L. Gatewood, 1983. The faults were mapped at the base of the Devonian Woodford Shale about 500m (1600 ft) above basement and show 30 to 80m (100 to 300 ft) of displacement. A high degree of correlation is noted between these Early Pennsylvanian-age faults and residual magnetic gradients, corresponding to the interpreted basement shear zones. Some 64% of the total length of faults, in fact, lie on the predicted shear zones following magnetic gradients.

It should be emphasized that the faults in the sedimentary section shown in Figure 6 are only about 300 million years old, whereas the basement fault block pattern that created the magnetic response is 2 to 3 billion years old. In other words, the basement faults or weakness zones, were already in place 500 million years ago at the beginning of deposition of the sedimentary section in Late Cambrian time. Note again that many magnetic gradients in Figure 6 show no faults cutting the section. These were never reactivated, and to separate them from those which were reactivated it is necessary to use seismic or subsurface techniques.

The above examples show plan-view correlations of magnetically mapped basement faults with independently mapped faults in the sedimentary section from subsurface (well) data. A geological cross-section that shows excellent correlation with a residual magnetic profile is presented in Figure 7. This section, 50 kms long (30 mi), N-S, crosses the north flank of the Arkoma Basin in western Oklahoma and was developed from 36 oil and gas wells (Wylie et al., 1988). Note the many steeply-dipping normal faults that cut the area into multiple horsts and grabens. Above the geological cross-section is plotted the corresponding residual aeromagnetic profile. There is a truly remarkable correlation of the location of most of the residual magnetic gradients with the locations of the mapped faults. Since the sedimentary rocks here are largely non-magnetic and, additionally, there is no linear correlation between the amount of fault throw and magnetic amplitude, we are forced to conclude that the faults indeed correspond to magnetic discontinuities in the underlying basement - our previously deduced basement fault block boundaries.

The correlation factor of approximately two-thirds or more between faults and magnetic gradients obtained in the above examples has been sustained in dozens of basement mapping studies the author has been involved in since 1983 in over 18 basins throughout the Midcontinent and Rocky Mountain regions of the United States. It is impossible to show more than a few such examples in a short technical paper, but some of the many dozens of examples developed to date are being prepared for more extensive publication. Additionally, magnetic patterns similar to those illustrated in Figures 4, 5, and 6 have been observed in many overseas localities, e.g: Colombia, Venezuela, Madagascar, Tanzania, Saudi Arabia, Belize, and the North Sea. In these areas there is little supporting geology to directly compare to as in the United States, but the similarity of the magnetic patterns to those shown herein suggests that the same high degree of correlation with basement faulting would also apply.

The widths of the magnetic highs and lows on the residual maps in all areas we have examined generally vary between 3 and 8 kms (2-5 miles), as in the Wisconsin geologic example, Figure 2; there are truncations of anomalies along different trends of varying strike directions; and there are occasional boundaries transecting entire data sets along which the tectonic style changes drastically, suggesting Precambrian plate tectonic boundaries. More extensive discussion on this subject appears in Gay, 1986.

Pertinent to the above observations is a study made 30 years ago (Affleck, 1963) of 3.26 million sq. kms (1.14 million sq. mi) of Gulf Oil aeromagnetic coverage from the 1950s and 1960s. It was found that the most common width of 15,350 second derivative anomalies was about 6.5 kms (4 mi). That is within the range we have found qualitively from our own magnetic data and from studying geological maps of basement. Affleck's tentative conclusion was that the spacing of anomalies was somehow related to the thickness and strength of the crust (1963, p. 394), although he was apparently not cognizant of the

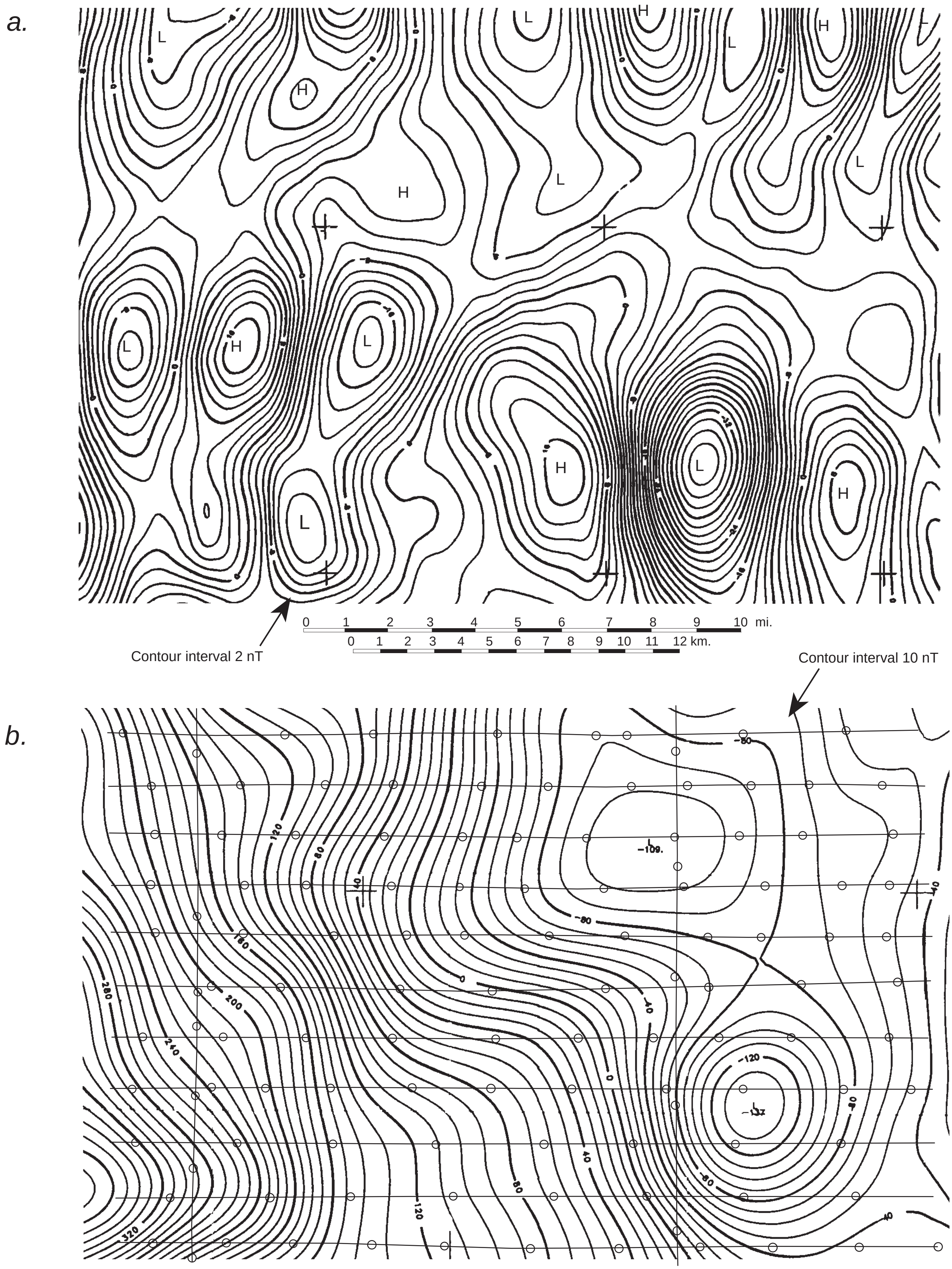


FIGURE 5: a. Uninterpreted profile residual map of Figure 4a. b. Total intensity contours of same area with flight path superimposed. Depth to basement is approximately 3.8 kms (12,500 ft) beneath flight level.

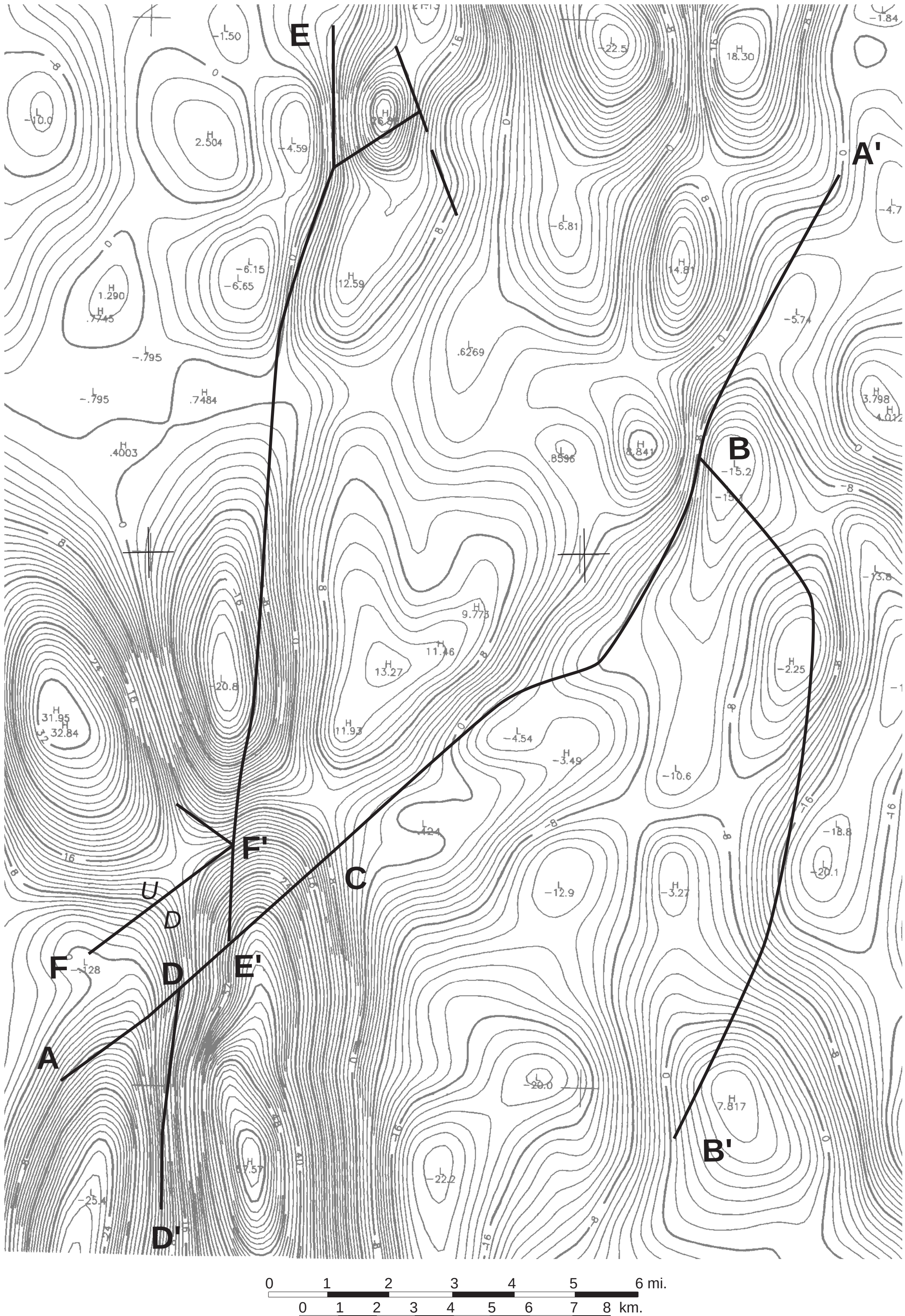


FIGURE 6: Residual magnetic contours of an area in Kay County, Oklahoma, with superimposed faults of Early Pennsylvanian age taken from a pre-existing independent subsurface study. Correlating faults, i.e. those lying on NewMag® gradients, are E-F', C-A', F-F', and D-D'. These comprise 64% of the length of faults on the map. Non-correlating faults are A-C, B-B', and E'-F'.

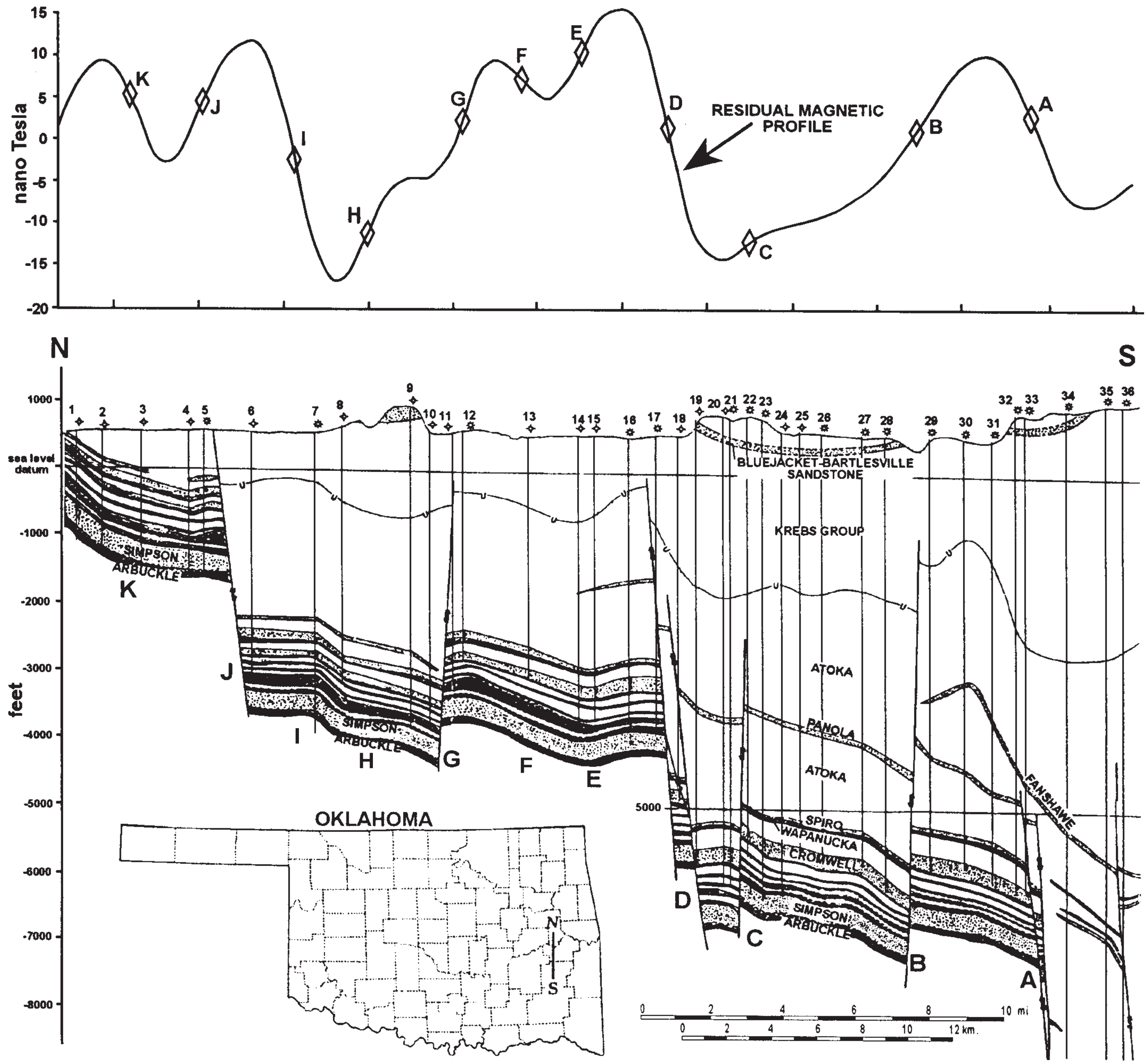


FIGURE 7: A 50 km (30 mile) long N-S cross-section on the north flank of the Arkoma Basin in eastern Oklahoma constructed from 36 oil and gas wells (Wylie, et al., 1988). The corresponding residual magnetic profile at the top is marked with diamonds at the inflection points of the curve, which generally correspond to basement block boundaries. Note the excellent correlation of these points with the indicated faults (A,B,C,D,G, and J) and pronounced dip changes (E and K).

basement fault block pattern as defined herein. Nevertheless, he was most likely correct in that the widths of the basement blocks are related to crustal properties.

Just as the basement fault block pattern mapped by residual magnetic data correlates well with subsurface mapping from well data, so it also correlates with seismic data. In Figure 8a, the trace of a seismic line in Grant County, Oklahoma, is superimposed on a residual magnetic map. A fault is indicated, and the seismic reflectors that define the fault are shown in 8b. There is near-perfect coincidence of the fault location and the magnetic gradient. However, the magnetic high appears on the down-thrown side of the fault. This is an example of the control of the magnetic pattern by the <u>lithology</u> of the basement rocks rather than by the structure, a subject I will treat more extensively in a later section of this paper.

Note in Figure 8b that the Pennsylvanian and higher reflectors are essentially flat in contrast to the easily identifiable throw on Mississippian and older strata. This indicates that in this part of Oklahoma shallower structure does not reflect deeper structure and that basement mapping would probably be more valuable in locating deeper structures than techniques based on surface features, such as airphotos or Landsat images.

The interpretation of Figure 8 was performed for a small independent oil operator who had limited access to seismic data. Note that the magnetic contours indicate a northwest strike to the fault and that the magnetic gradient extends for many kilometers north and south of the seismic line, suggesting a significant length to the fault. The trace of the fault could not be developed from a single seismic line, but can certainly be reliably postulated from the combination of magnetic and seismic data.

Figure 9 shows a seismic line in the Arkoma Basin in Logan County, Arkansas, and a residual magnetic profile corresponding to the seismic line superimposed across the bottom of the figure. The faults on the seismic data extend from the basement up through the Cambro-Ordovician (Arbuckle) section. All four faults coincide closely with the interpreted basement shear zone locations indicated by the diamonds placed on the inflection points of the magnetic curve. Because of this type of correlation, residual magnetic data has been very popular with many organizations exploring the Arkoma Basin. The seismic data is used to locate favorable horst blocks and the magnetics to determine the configuration of these blocks in plan view. The magnetic data are also useful in outlining possible structures for investigation and verification by the seismic method, that is, they are used in advance of seismic to help lay out seismic programs.

In Figure 10 appears a seismic line across the northern part of the Denver-Julesberg Basin in Kimball County, Nebraska, and Logan County, Colorado, again with a residual magnetic curve superimposed across the bottom. Attention is drawn to the syncline in the center of the profile. Its boundaries coincide nearly exactly with the basement shear zones indicated by the diamonds on the magnetic profile. The syncline may result from downdropping along faults that coincide with the shear zone, by compaction into a basement topographic low that coincides with the magnetic low at this locality, or by a combination of the two.

Dozens of other correlations of basement shear zones mapped from residual magnetics and seismically interpreted faults have been shown to the writer by oil company personnel over the last ten years, but little of that data is available for publication.

III. THE FAULT BLOCK PATTERN AS OBSERVED IN STRATIGRAPHIC DATA: <u>THE INDIRECT EVIDENCE</u>

In the preceding section were shown examples of <u>known faulting</u> of measured displacement occurring over basement block boundaries mapped by residual aeromagnetic maps. In this section, I will show examples of <u>probable</u> or <u>possible</u> faulting of small displacement that is close to, or beneath, the limit of detection by either subsurface or seismic techniques, but which correspond to <u>lithologic changes</u> within sedimentary rocks. It is known that small vertical offsets occurring contemporaneously with the deposition of certain reservoir rocks can profoundly influence their lithological characteristics. The oil and gas production maps of many basins in the United States, in fact, show areas of linear oil and gas fields, sometimes in parallel alignments, that are considered purely stratigraphic in origin but that look suspiciously similar to the parallel arrangement of basement fault block boundaries. One such area is the southwestern quadrant of the Powder River Basin in Wyoming where Upper Cretaceous Parkman, Shannon, and Sussex offshore sand bars encased in shale are prolific oil producers. Some geologists have attributed these sand bars to winnowing of clastic materials over sea floor highs resulting from underlying basement fault movement (Swift and Rice, 1984).

Figure 11 is a well-spot map showing the Upper Cretaceous producers superimposed over a residual magnetic map in Johnson and Campbell Counties, Wyoming. Basement here is approximately 5 kms (16,500 ft) beneath flight level, and mean terrain clearance is about 300m (1000 ft). There is a remarkably close coincidence between several of the field axes and the magnetic gradients that overlie postulated basement block boundaries. Note the parallelism of these oil fields as well as their periodic spacing of 6.5 kms (4 mi), which falls within the range of separation of basement shear zones previously discussed. Apparently, east-west directed Laramide compression resulted in small scale high angle reverse fault displacement of the Precambrian weakness zones which persisted up through 2-3 kms of sedimentary

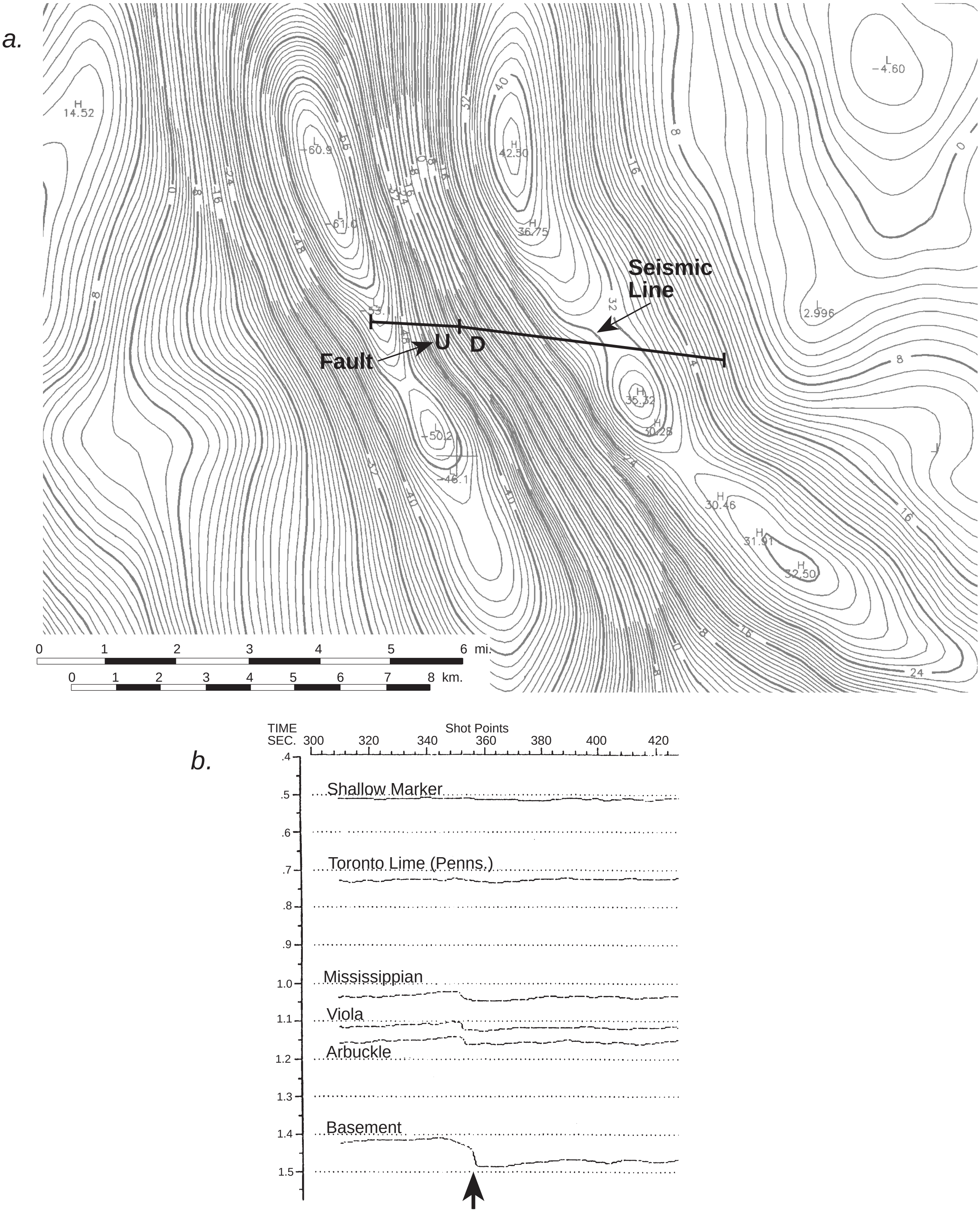


FIGURE 8: a. Residual magnetic contours of an area in Grant County, Oklahoma, with trace of seismic line superimposed. Note location of fault centered on the magnetic gradient. b. Reflectors deduced from the seismic interpretation. Data courtesy of R. Feige, 1983.

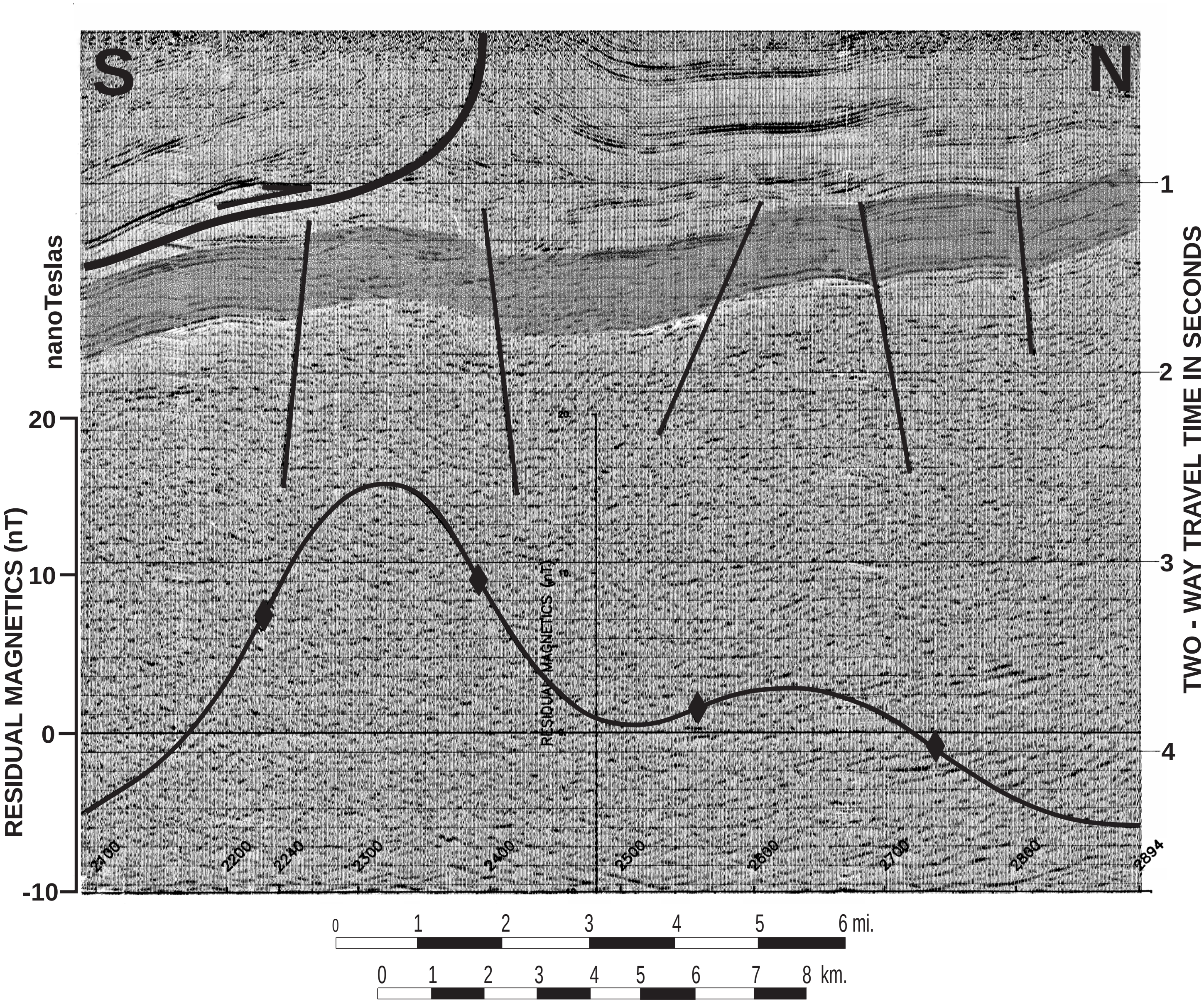


FIGURE 9: A N-S seismic line across the northern part of the Arkoma Basin in Logan County, Arkansas, shown with the corresponding residual magnetic profile. Dark band corresponds to Cambrian through Mississippian sedimentary rocks. Note that the four normal faults interpreted from seismic data coincide closely with the magnetic gradients (marked by diamonds). Seismic data courtesy of First Seismic Corporation. Interpretation by Chris Barrett.

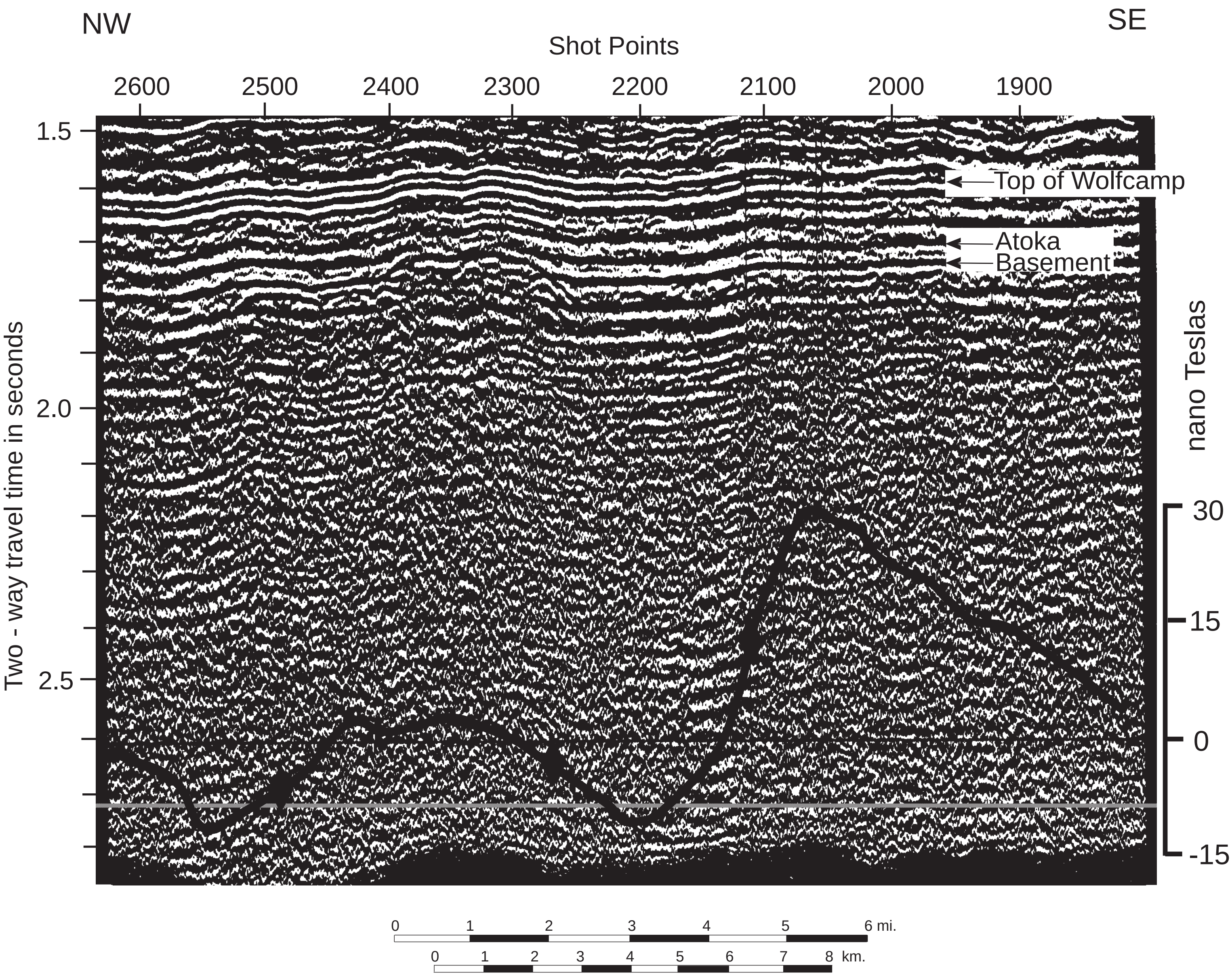


FIGURE 10: Seismic line with superimposed residual magnetic profile in northern Denver-Julesburg Basin, Kimball County, Nebraska and Logan County, Colorado. Black diamonds mark the locations of interpreted basement shear zones on the steepest part of the magnetic gradients separating magnetic highs and lows. Seismic data is courtesy of Frontier Petroleum Services, Inc.; display by Roice Nelson, Landmark Graphics Corporation.

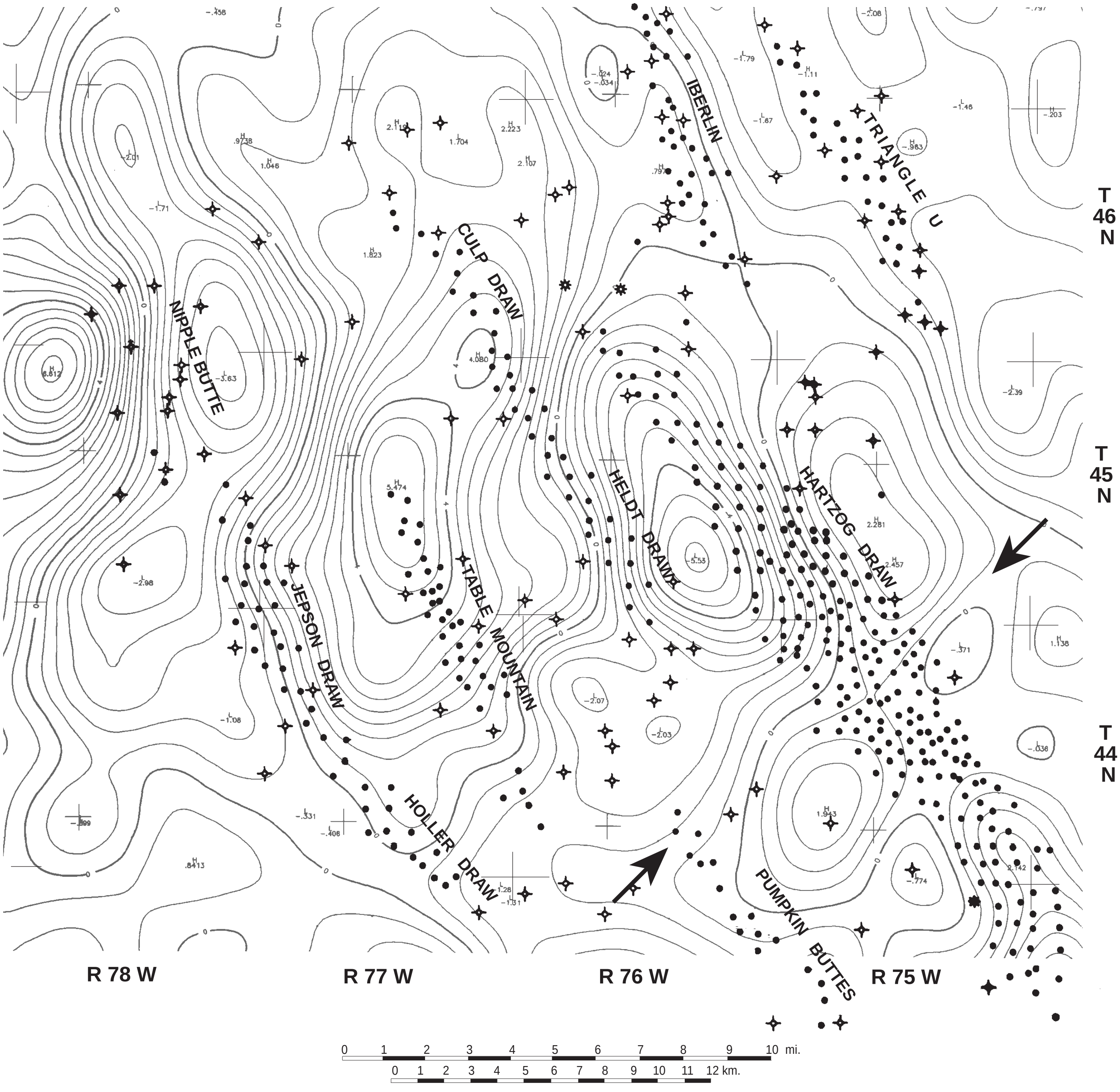


FIGURE 11: Profile residual magnetic contour map of an area in the Powder River Basin with petroleum wells and field names superimposed. Magnetic contour interval is 0.5 nT. Note the correspondence of most oil fields with magnetic gradients. Also note that Jepson Draw - Holler Draw Field makes a bend precisely where the magnetic gradient (and the assumed underlying basement block boundary) bends.

section to the Cretaceous sea floor. The resulting undulations, perhaps a few meters high on the sea bed, would have been sufficient to cause the aforementioned lithologic changes due to winnowing by bottom currents. This process resulted in deposits of clean, permeable sand - a good reservoir rock, surrounded above, below, and laterally by shales. Of further interest is a northeasterly trending basement fault through Hartzog Draw Field, defined by the magnetic gradients marked by arrows in Figure 11. This cross trend precisely separates porous Shannon sand on the south from less porous sand on the north, as indicated by the change from 80 acre to 40 acre well spacing (Dodson, 1986), and suggests that the basement block on the south rose higher than the one to the north, thus accentuating the winnowing process.

Here is one more place where it is possible to give a specific answer to the question I have been asked many times by exploration geologists and geophysicists, "How can I use magnetics to find oil?". In Figure 11 and the area surrounding it there are a number of magnetically mapped basement block boundaries parallel to the known fields that have never been tested with a well.

We can also have basement control of oil and gas traps in areas of carbonate depositional environments. Two decades ago the Devonian reef fields of southern Alberta were attributed to control by sea floor scarps over basement faults because of their parallelism to airphoto lineaments visible on outcropping basement of the adjacent Canadian Shield (Gay, 1973, p. 22-25, 67-68). That same year it was revealed that regional jointing mapped in sandstones throughout southern Alberta occur in sets having almost precisely the same directions as the oil fields and the basement faults (Babcock, 1973, also 1974, 1976). An explanation of the relationship of the strike directions of basement faults and regional jointing was presented in Gay, 1973, p. 97-99, after noting the identical directions of jointing in the Paradox Basin (Hodgson, 1961) and basement lineaments derived from aeromagnetic data. It was deduced that small movements along basement faults result in stresses that create joints parallel to them in the overlying sedimentary section.

A one-on-one example of stratigraphic control by basement in carbonate rocks is found in the Paradox Basin of Utah and Colorado where Bug Field, a prolific oil producer from Pennsylvanian algal mounds, is exactly located on a basement block boundary mapped by residual magnetics (Figure 12). Three other nearby fields (Hatch, Coal Bed Canyon, and East Monticello) are similarly located on magnetically-defined basement block boundaries. Many other such boundaries mapped by residual magnetics in this area remain untested by the drill. There are, however, a number of smaller, one- and two-well fields of similar geology that are not located on magnetically mapped basement block boundaries.

Basement control of Pennsylvanian algal mound buildups has been advocated for many years by geologists who have specialized in the Paradox Basin (e.g., Baars and Stevenson, 1982, 1983), but heretofore only seismic methods have been available for locating the faults and overlying algal mounds. Topography here is very rugged and seismic costs are expensive, making the seismic method impractical as a reconnaissance tool, although some companies use it for reconnaissance anyway. It would seem that magnetic basement mapping for reconnaissance, followed by the seismic method as a detailing tool would be a far more appropriate, and economical, exploration procedure in this particular play.

Another example of basement influence on stratigraphy is the control of continental fluvial systems by basement fault block movement. Such control for the Lower Cretaceous Muddy Formation in the Powder River Basin of Wyoming has been advocated by previous authors (Weimer et al., 1982, and Gustason, 1988). I will present one example, the Kitty Field in that basin, that is well documented and apparently explainable by basement block movement (Figure 13). The producing horizon, the Muddy Formation, is a continental fluvial system that was deposited in a low gradient depositional environment approximately 1.5 kms (5000 ft) above basement. A well-spot map superimposed on the residual magnetic contours appears in Figure 13. Note that the field boundaries coincide quite closely with the basement block boundaries as mapped by residual magnetic data. This has several possible explanations:

1. The correlation observed is purely coincidental,

2. A topographic low was carved on the basement block by Precambrian erosion, and compaction of the sediments into this low resulted in a topographic low on the pre-Muddy surface,

3. The entire basement block sank as a unit in response to sediment loading, or

4. The block sank due to tectonic squeezing by Laramide compression, i.e. the block was more compressible than neighboring blocks (perhaps because of increased fracturing) and its density increased more, thereby causing it to sink.

The fact that about 50% of the entire system of Muddy channels in the Powder River Basin can be explained by basement block movements (E.R. Gustason, personal communication, 1987) would seem to preclude explanation 1, above.

Explanation 4, is a new mechanism as far as I know, and I hereby formally propose the term "densification by compression" to describe it. An exact analogy is the "Cartesian diver" sold in novelty stores (see Stein, 1983, p. 227, for description of Cartesian diver).

Another common type of localization of fluvial systems by basement movement is along block <u>boundaries</u>, rather than across the entire width of a

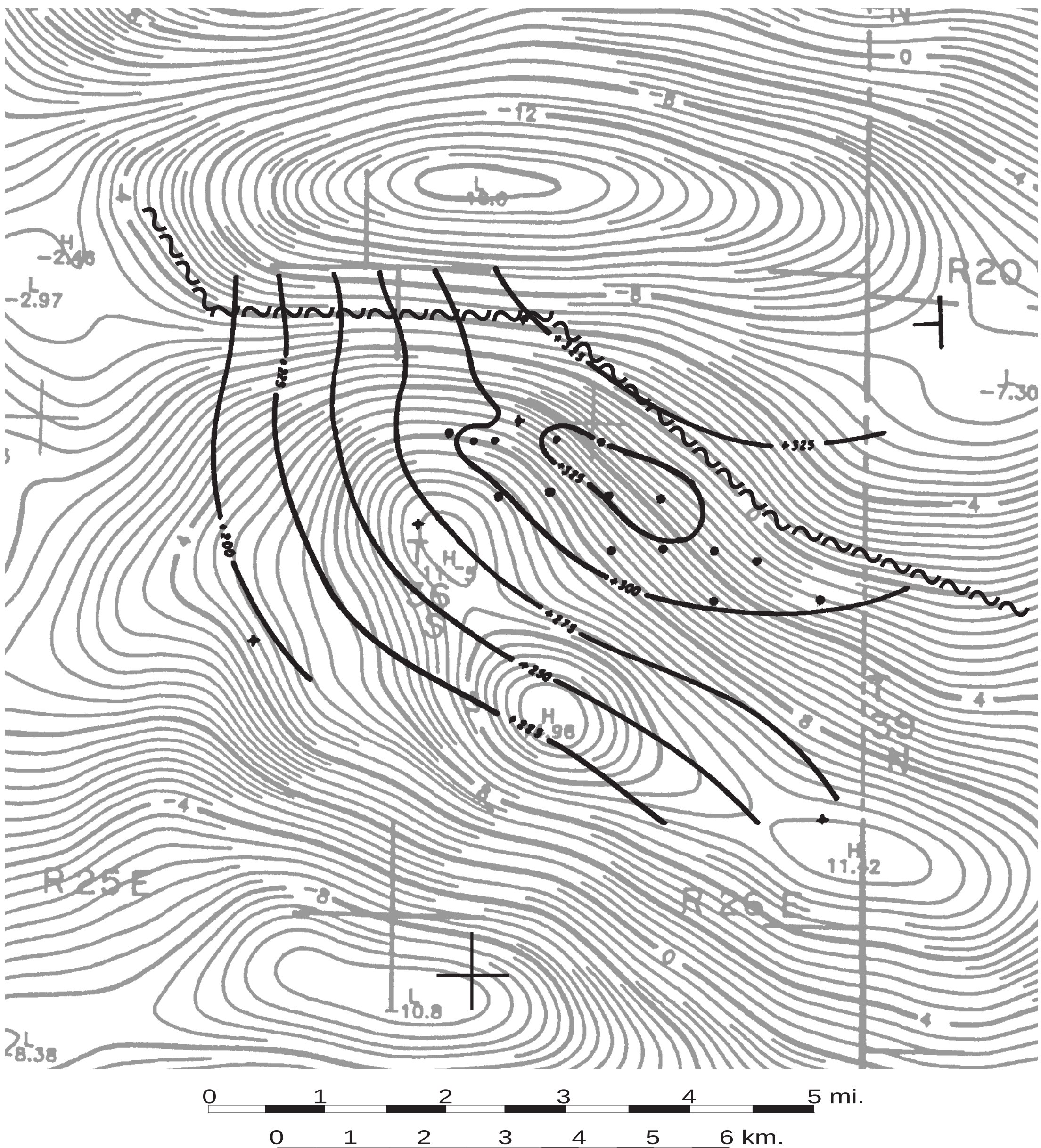


FIGURE 12: Bug Field in the Paradox Basin, San Juan County, Utah, showing a correlation between a producing Pennsylvanian algal mound buildup and a basement block boundary. Dark contour lines are Pennsylvanian Desert Creek structure; gray lines are profile residual magnetic contours at a 0.5 nT interval. The basement break (hachures) is interpreted to occupy the area of steepest magnetic gradient. The basement block corresponding to the magnetic high ("H") would have tilted to the south with its north edge being upthrown, thus localizing the buildup of the algal mound. Structure contours from Krivanek, 1983.

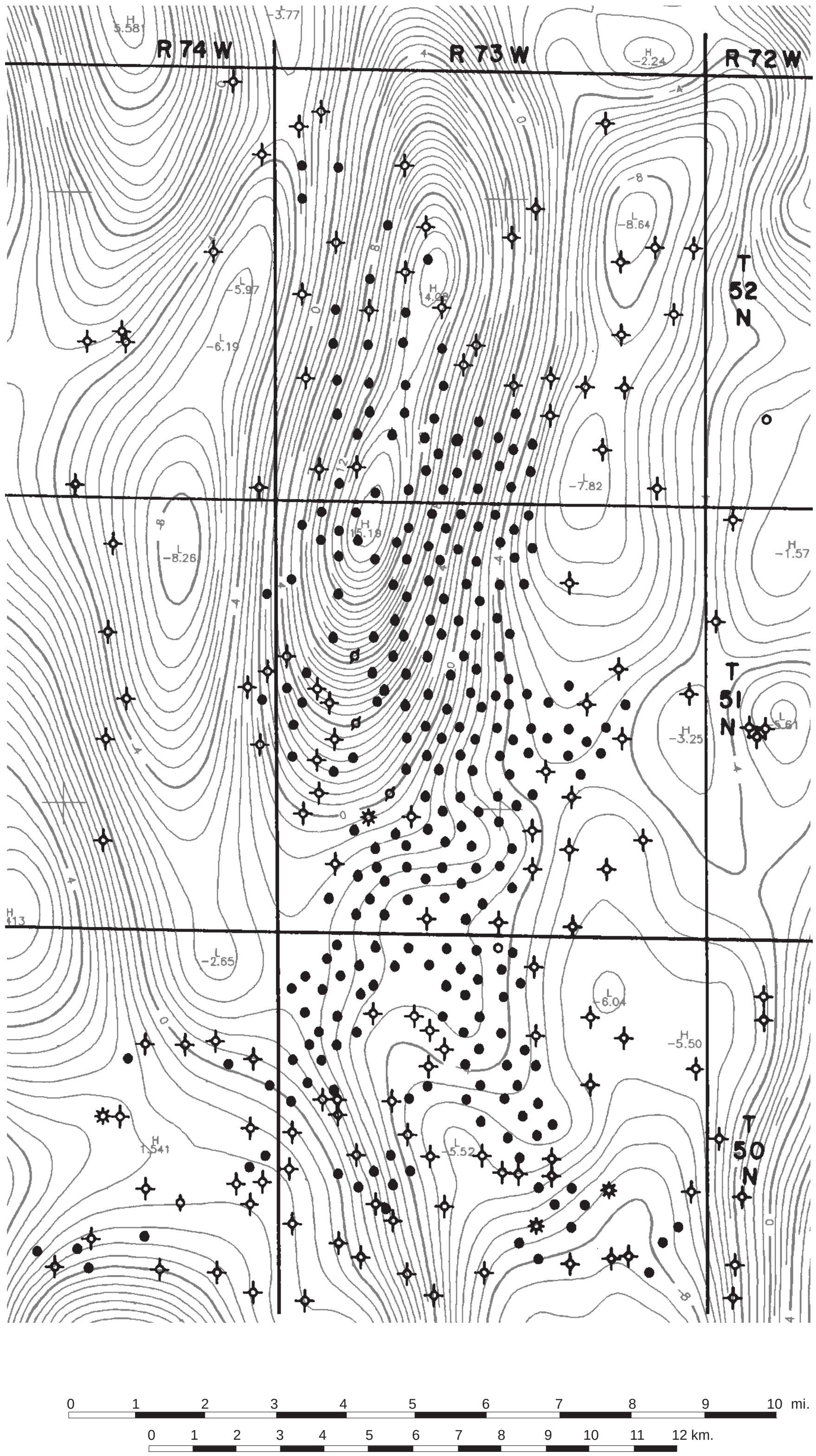


FIGURE 13: Petroleum wells, Kitty Field, Campbell County, Wyoming, in the Powder River Basin superimposed on profile residual magnetic contours. Contour interval is 0.5 nT. Note the close coincidence of the field with the underlying elongated north-south trending magnetic high. An explanation is offered in the text.

block as observed in the previous figure. Increased jointing and fracturing of the surface rocks result from minor fault movement, or "jostling," of the block boundaries at depth. This fracturing, in turn, causes increased erosion and lower surface topography along these zones. We observe this type of topographic control on present day fluvial systems on topographic maps, in standard air photos, and in satellite images throughout the world. Lack of space precludes showing examples of this type here, but they seem to be common in the sedimentary section.

IV. THE FAULT BLOCK PATTERN AS A CONTROLLING FACTOR ON BASEMENT TOPOGRAPHY, AND ITS CONSEQUENCES

The examples of basement control of oil and gas traps shown in preceding sections result from movements of the basement blocks. In this section, I will present examples of stationary basement blocks containing topographic highs, in which the sedimentary section itself moves downward to cause structural closure. The mechanism involved is "settling" (a 1920s term), or "gravitational compaction" of the sedimentary section in today's nomenclature.

The first of three examples shown here is in Kingman County, Kansas, where Willowdale Field (1.4 MM barrels of oil and 2 Bcf of gas through 1990) produces from a structural high of the Viola Formation about 300m (1000 feet) above basement (Figure 14). Because of the nearly exact coincidence of this structural high with a residual magnetic low, including straight-line boundaries on west, south and east, a basement hill underlying the field is the most likely explanation. Although there are no wells to basement in this area, the fault block on which this hill is carved would necessarily be less magnetic than surrounding blocks. It could be formed of quartzite, meta-rhyolite, or acidic granite, for example. Nearby magnetic lows of similar geometry might be prospective for oil in this area if the same basement lithologies present at Willowdale are widespread. However, it must be remembered that the situation could change only a few miles away and basement hills might be found under residual magnetic highs.

This example of a "wrong-way" magnetic correlation, i.e. a structural high over a magnetic low, again lends emphasis to the point that it is the lithology of the basement rocks that generally creates the magnetic pattern we observe and not necessarily basement highs and lows. Thus, in an exploration program employing magnetics it is necessary to check each possible magnetic lead with subsurface or seismic techniques, since knowing the fault block pattern alone is not sufficient to define a prospect. One must determine the geometry in the 3rd dimension, i.e. the vertical direction, and this can usually not be done reliably with magnetics, a point I will discuss in more detail in Section VI.

The second example of topographic control I will show is a 20+ million barrel Arbuckle (Cambro-Ordovician) producer, Garber Field, located in Garfield County, Oklahoma (Figure 15). Here the structural closure occurs over a residual magnetic high. A single basement intercept at the crest of the structural high encountered granite containing hornblende and biotite (Denison, 1981, p. 53), which would indicate a moderate to high magnetic susceptibility. In this example the fault correlation with the residual magnetic map is also excellent. Faults A-B, B-B′, and C-C′ correspond very well with the magnetic gradients shown.

Of interest is that the residual magnetic contours of Figure 15 are extremely similar to detailed residual gravity contours of Garber Field published by Ferris (1987, not shown here). The major highs, lows, and gradients are of similar shape and position on both gravity and magnetic maps. The gravity and magnetic responses must therefore arise from the same geological source, i.e., an increase in both density and magnetic susceptibility of the underlying basement block, with a possible contribution to the gravity only from the dense Cambro-Ordovician Arbuckle dolomites lying over the basement hill. Some workers (e.g., Donovan, 1974; Foote, 1984; Saunders and Terry, 1985; Andrew, et al., 1986) have attributed the response shown on residual magnetic maps over petroleum reservoirs to diagenetic magnetic minerals precipitated by hydrocarbon "leakage" from the reservoir. Since the minor amounts of magnetic minerals postulated in these cases could not create density differences in the overlying sedimentary section large enough to be measurable with gravity techniques, then the one-on-one coincidence of gravity and magnetics over Garber Field would indicate that any supposed magnetic response from diagenetic magnetic minerals here is either nonexistent or is overridden by the basement response.

Likewise, the short wavelength magnetic response from well casing, which is a proven problem over oil and gas fields flown at low altitudes, does not appear to be important in the Garber Field example where ground clearance was 425m (1400 ft). Well casing might make a contribution to the peak value of the magnetic high but would not contribute to its overall shape and position which coincides so well with the gravity response. The same conclusion could be drawn from the Willowdale field example (Figure 14) where a magnetic low coincides with a producing structural high, indicating that the magnetic contribution from casing (a magnetic high) is overridden by the basement response (a magnetic low). In these examples, both manual and automatic frequency filtering have been used to recognize and eliminate well casing and other short wavelength anomalies, to the extent possible, so that only the broader basement response is mapped.

The third example of basement topographic control I will show is a basement hill documented by a six-well cross-section located on the Amarillo uplift in the Texas Panhandle (Figure 16). The crest of the

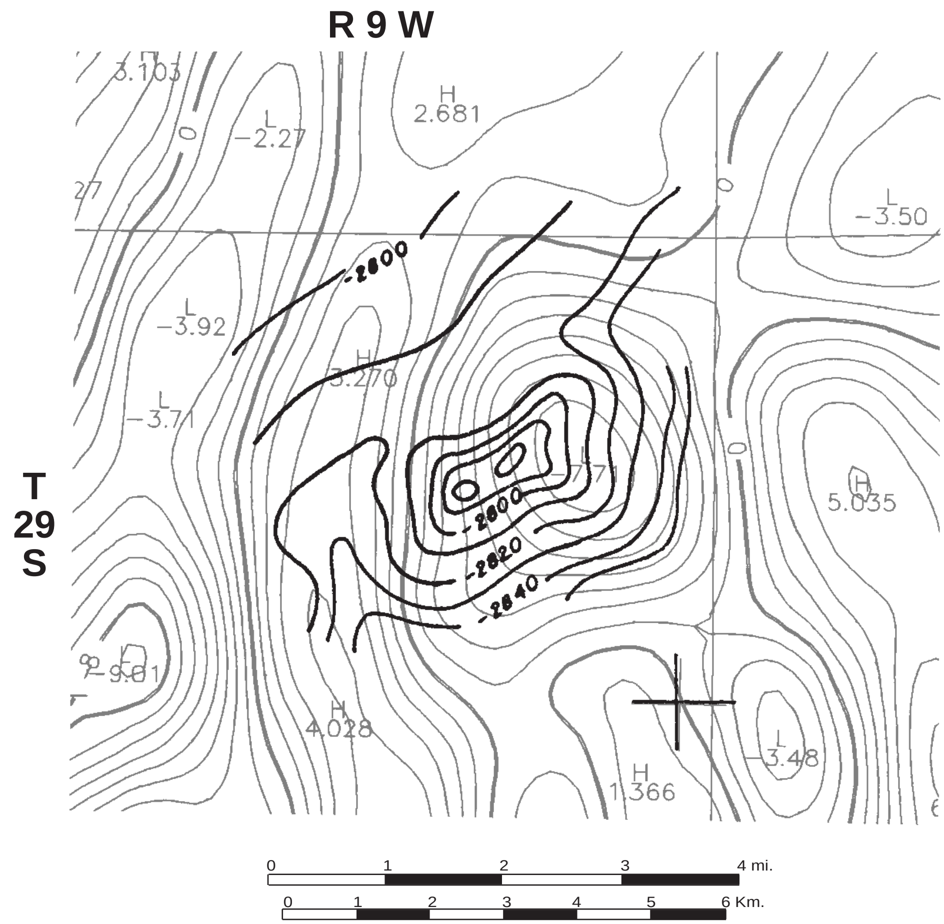


FIGURE 14: Residual aeromagnetic contours (gray) and superimposed structural contours on top of the Viola fm (black) in the Willowdale Field, Kingman County, Kansas. Magnetic contour interval is 2 nT. This appears to be a typical example of structural control resulting from compaction of the sedimentary section over a basement topographic high. Geology from Cruce, 1956.

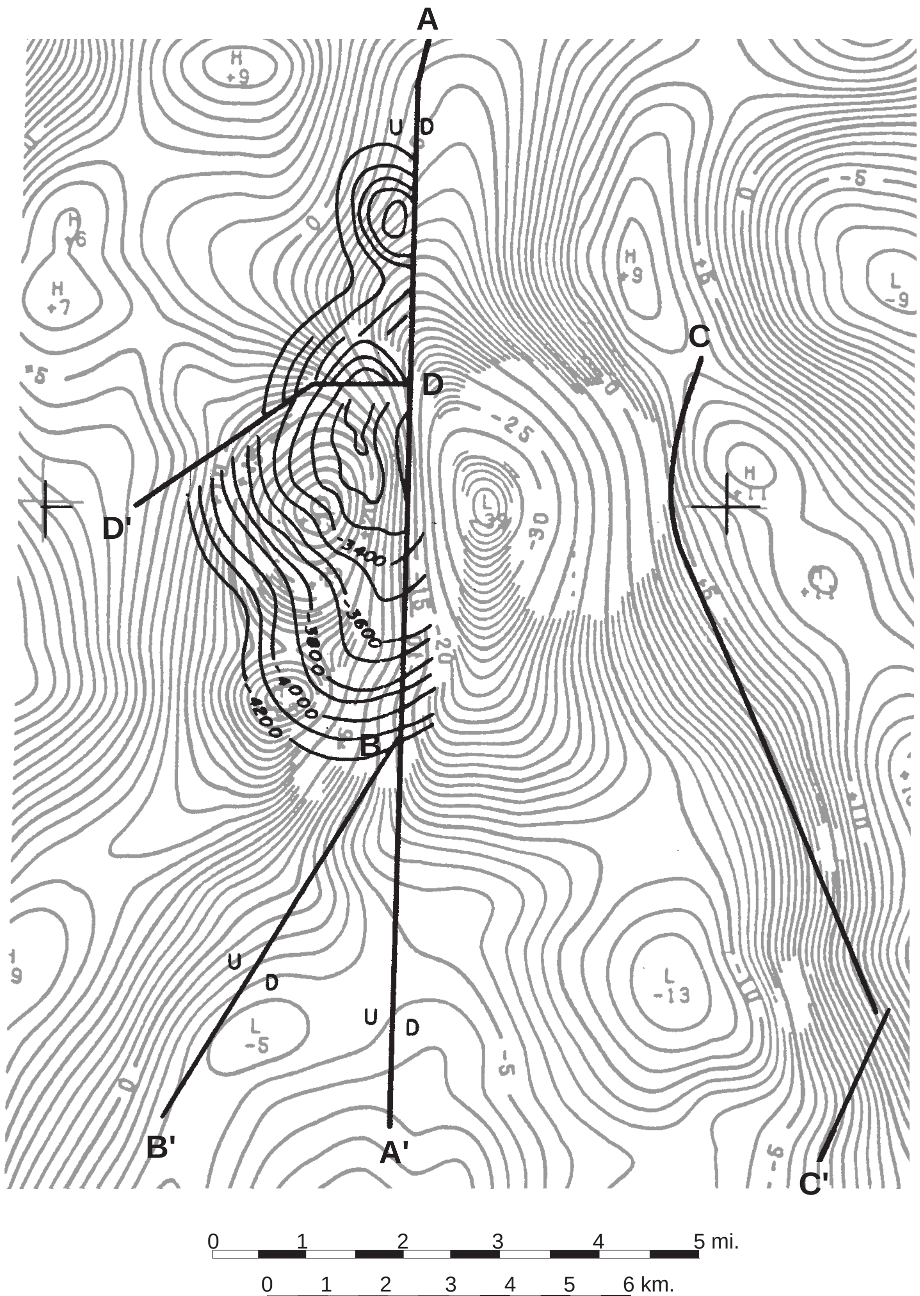


FIGURE 15: Residual aeromagnetic contours (gray) with superimposed structural contours on top of Cambro-Ordovician Arbuckle fm (black) at Garber Field, Garfield County, Oklahoma. Heavy dark lines are faults. A basement hill (one well intercept) underlies the producing structure here. Additionally, the majority of the faults shown occur along the magnetic gradients, corresponding to basement shear zones at depth. Geology from Carey, 1954.

hill, as shown on the well section, coincides almost precisely with the crest of the residual magnetic high. Equally interesting is that well 2, located on the magnetic gradient corresponding to the west boundary of the block, shows low basement. This well coincides with the location of the bounding shear zone, which would be expected to erode low, as indicated in previous discussion.

The above three examples are isolated places where there is control of the lower part of the sedimentary section by basement topography. However, this is not a unique phenomenon. The lower part of the sedimentary section everywhere appears to be strongly influenced by basement topography (see Gay, 1985, 1989 for a list of 30 examples).

V. CONSEQUENCES OF THE BASEMENT FAULT BLOCK PATTERN ON CONTEMPORARY CONCEPTS IN STRUCTURAL GEOLOGY

If crystalline basement is composed of a series of discrete lithologic blocks separated by zones of weakness that fall into parallel to subparallel sets of a few given strike directions, does this not also affect current concepts in structural geology? The prevailing dogma, embodied in strain theory, which is extensively, if not exclusively, taught in our universities, forms the conceptual framework into which all structural geology mapping and structural ideas must presently fit. Yet strain theory is founded on very shaky ground. Its underlying assumption ("the fine print") which is seldom, if ever, mentioned in textbooks or classrooms, is that it properly applies only to a <u>homogeneous</u>, <u>unfractured</u> medium. Yet, we now realize that the earth's crust is far from homogeneous and unfractured in nature. Previous sections of this paper provide evidence of, and document, the existence of the extensive fracturing that has cut the crust into fault blocks. Better yet, we should again look at the high-altitude basement images shown in Figure 1 and speculate: "If we were to apply a maximum compressive stress to an earth's crust typified by these fractured crustal blocks would fractures really form along straight lines at $\pm$ 30% to that stress as postulated by strain theory?"

The alarm on strain theory was sounded over 50 years ago by Professor Sherbon Hills in his highly regarded textbook, "Outlines of Structural Geology" (1941):

"It is well known that faults of great antiquity may be rejuvenated under later stress, and in fact any large structural element in the crust, in which the rocks are markedly different from the surrounding masses, constitutes a feature that may influence structures of subsequent origin. Thus the application of idealized concepts such as the strain ellipsoid must be modified by inhomogeneities of the crust, which is very far from being an isotropic material."

It is my suggestion that we limit the role of strain theory in geological thinking to a very rudimentary starting point, i.e., determining the initial maximum stress <u>directions</u> in an area, realizing that the <u>actual</u> locus of rupture will be controlled by the pre-existing weakness zones. After fracturing is initiated along certain of these weakness zones in a basement composed of multiple, irregularly shaped, rigid to semi-rigid blocks, the stress pattern will become quite complex as regional stress is <u>redistributed</u> locally by the more rigid blocks. The blocks will move, grind against each other, rotate, and even create openings, which are areas of less strain. One might liken this situation to a shattered ice flow in which a complex pattern of discrete floating blocks is subjected to various types of horizontal stress. We could call this "ice-flow tectonics." If we know the locations of the main weakness zones in a given area of the crust, as from aeromagnetics, it would be possible to physically model the tectonic regime with floating blocks, or perhaps to mathematically model it with modern computers. In this way we could obtain an idea of local stresses and resultant fault movements as a function of time under a given regional stress field.

As suggested above, one interesting consequence of this type of tectonics is that for any given compressive or transgressive regime, it is possible, if not probable, that localized areas of <u>extension</u> will result, as well as areas of pure shear or pure compression. The localized areas of extension, to the mining geologist, would be places where diapiric igneous intrusions would rise and where open-filling ore deposits are formed, even during times of regional compression, and to the petroleum geologist, they would be the areas of formation of fracture permeability and migration pathways for oil and gas.

Past dissatisfaction with strain theory as a working tool of the exploration geologist and geophysicist has, in the last several decades, resulted in the formulation of new concepts in structural geology. One of the most popular ideas that has been embraced is "wrench fault tectonics" as proposed by Moody and Hill (1953). In this concept, long transcurrent faults give rise to splays, or secondary faults, emanating from them at approximately 30^{o} angles; these splays have splays, i.e. third order faults, which in turn have their splays, etc., etc. This situation actually applies to and explains the structure found along certain individual transcurrent faults, but cannot, in spite of its present popularity, explain the multiple geological structures existing pervasively in two dimensions over broad regions or entire basins. Its effectiveness in explaining structure in the areas to which it does apply was not predicted by strain theory. Strain theory also did not predict the types of thrust/fold relationships that we are now imaging so excellently with seismic and subsurface data throughout the Rocky Mountains and along the Wichita and Ouachita compressive-transpressive belts in the United States. It also did not predict the flat thrusts deep within basement rocks that are now being mapped so regularly by CoCorp seismic

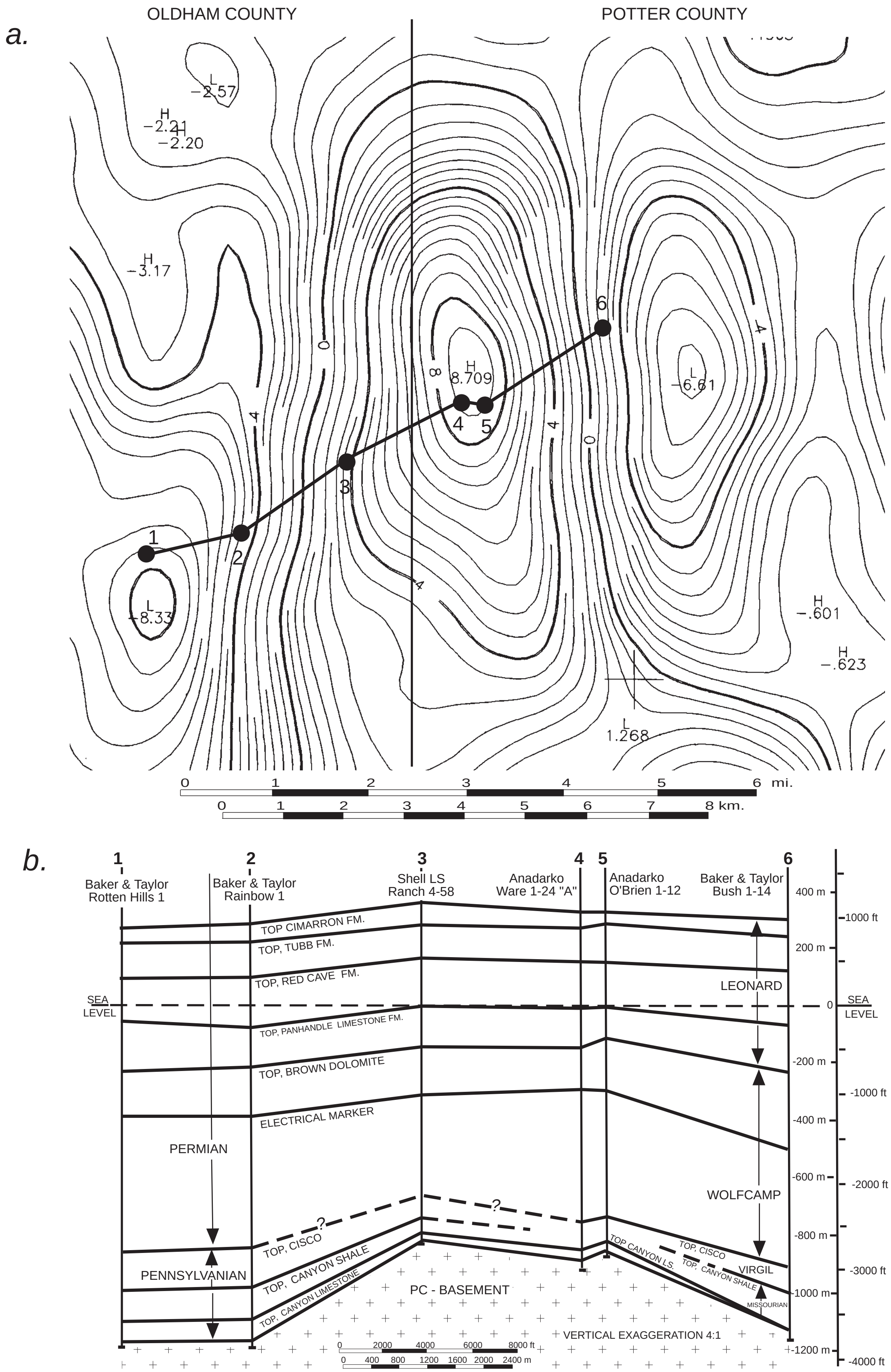


FIGURE 16: a. Residual aeromagnetic contours (0.5 nT interval) of an area in Oldham and Potter Counties, in the Texas Panhandle, with locations of wells-to-basement superimposed. b. Well section across line shown in a. Note that the basement high coincides with the magnetic high, and basement low coincides with well 2 which falls in the area of magnetic gradient. Cross-section from Gay, 1985.

lines throughout North America and by mining geologists (e.g., Frost, 1988; Spencer et al., 1988, and many others) where the thrusts crop out in the basement of the southwestern United States. When these deep sub-horizontal reflections are seen on seismic data, deeply buried packages of sedimentary rocks are generally postulated. One such predicted stratigraphic reflection, drilled through by an expensive and well-known exploration well in basement in Arizona in the 1980s, resulted in the location of a 16-ft thick gouge zone along a flat basement thrust.

An excellent case of structure that had previously been explained by strain theory but is actually due to basement control appears in Figure 6 in this paper. The fault E-D′ belongs to the Nemaha system, which is a NNE-trending zone of Early Pennsylvanian age faulting of compressive or transgressive origin in north central Oklahoma and eastern Kansas. In the area of Figure 6 and to the south of it, the basement block boundaries, or weakness zones, trend north-south, so the NNE trending fault must make a series of jogs, or "stairsteps", along the north-south weakness zones to maintain its generally NNE strike direction.

A similar situation exists one hundred miles to the northwest of the area of Figure 6, where the Pratt "anticline" in Kansas, a faulted structure parallel to, and part of the Nemaha structural belt, makes a similar abrupt jog in shifting from one basement fault to the other as it maintains its NNE strike direction. The individual segments of these fault systems would be described as "en-echelon" in strain theory, or as "incipient splays" by wrench fault concepts. In reality they are neither; they are simply the result of inheritance from pre-existing basement faults.

To summarize this section, it is not strain theory or wrench-fault tectonics that explains the detailed patterns of faulting we observe in sedimentary basins in most cases, but rather the inheritance of faulting from the underlying basement and its imbedded fault block pattern.

VI. CONSEQUENCES OF THE FAULT BLOCK PATTERN ON CONTEMPORARY AEROMAGNETIC INTERPRETATION TECHNIQUES

It has long been the goal of potential field geophysicists to become part of the mainstream exploration process for oil and gas. However, this goal has been elusive, because magnetic and gravity methods have been of prime use in few exploration plays, have aided peripherally in few others, have been of no use whatsoever in many, and have been quite misleading in others due to improper interpretations. Prominent potential field geophysicists exhort explorationists to employ their services more (e.g., Hammer, 1982, 1983, 1988, and LeFehr, 1983, 1984 a,b,c,d, 1985), but explorationists are a cautious and stubborn lot and prefer methods that are of proven benefit in finding oil, such as seismic profiling and subsurface geologic mapping.

Why have potential field techniques, and principally magnetics, then, not lived up to their earlier expectations in hydrocarbon exploration? The writer attributes this specifically to <u>the previous lack of an adequate geological model of basement</u>. Mathematical models abound (<u>ad infinitum</u>, I might add), but a realistic <u>geological</u> model of basement has never previously been presented to the exploration community. The fault block model of basement presented herein fills that void.

What are the implications of the basement fault block pattern for current aeromagnetic practice? First of all, it is obvious that we have been ignoring the most useful, and reliable, information inherent in magnetic maps - the locations of the basement block boundaries in the horizontal dimensions, $\underline{x}$ and $\underline{y}$. At the same time we have been futilely attempting to accurately define the vertical dimension, $\underline{z}$, of source bodies with magnetics, in spite of the inherent ambiguity of magnetic methods in determining $\underline{z}$ (see, e.g. Skeels, 1947). Furthermore, seismic and subsurface methods measure depth so much more accurately than magnetics that it is unwise to try to compete with these excellent techniques. This section of the paper will be devoted to showing why we should de-emphasize interpretations involving the vertical dimension with magnetics in sedimentary basins lying on crystalline basement. This is not to say, however, that we should not use magnetics to estimate the approximate thickness of the sedimentary section in a new basin, i.e. in determining whether it is 2 kms, 5 kms, or 10 kms thick, for example, to our usual accuracy of about $\pm$ 15% under favorable conditions. That is a less exacting task for magnetics than the ones I wish to address and does provide useful information for the explorationist in frontier basins.

The most common type of interpretation involving the vertical dimension that is invalidated by the basement fault block nature of basement is the calculation of the amount of throw of a fault. The present practice in aeromagnetics is to assume a uniform lithology and magnetic susceptibility of basement across a fault, as shown in Figure 17a. Given this (incorrect) assumption, it is a trivial problem to calculate the depth of the fault and its throw from the shape and amplitude of an observed magnetic curve. If one does not know the exact susceptibility, a series of curves is calculated and a range of probable values of the throw can be established. In all cases, the magnetic high necessarily appears on the upthrown side of the fault.

However, if a fault occurs on a basement block boundary precisely where there is a lithologic change, and hence a magnetic susceptibility change, then the problem becomes that shown in Figure 17b. As we do not know, and can almost never accurately determine, the average magnetic susceptibilities, k_1 and k_2, of the basement blocks, then the solution is <u>indeterminate</u>.

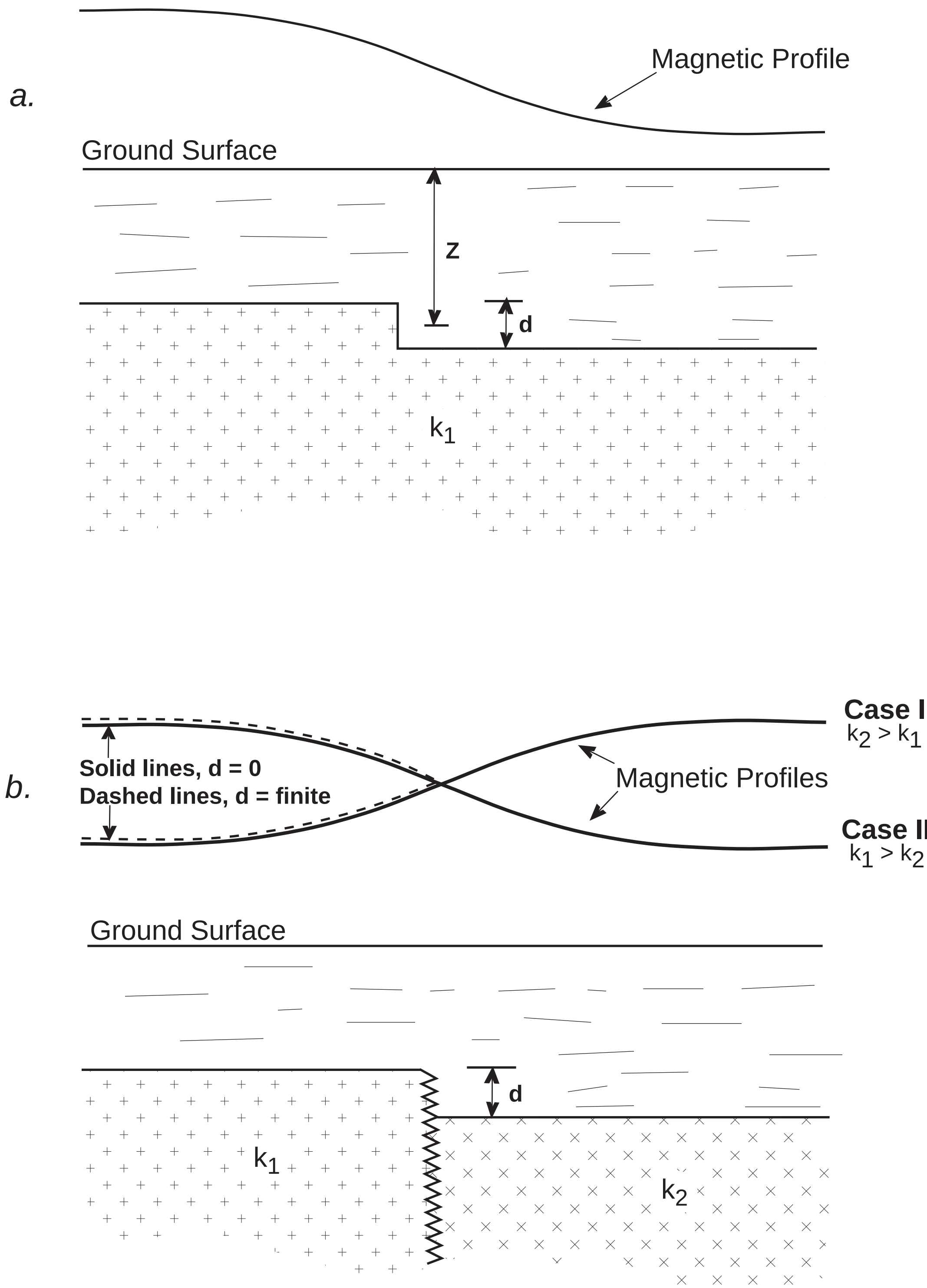


FIGURE 17: Geological cross-sections and resulting magnetic responses (schematics) for two models of a basement fault. a. Homogeneous basement. b. Basement rock type change at place where basement is faulted. k_1, k_2 *represent average magnetic susceptibilities of respective basement blocks. Magnetic field vertical.*

Not only can we not determine the amount of throw of the fault; we cannot even determine the direction of throw if the signal resulting from susceptibility overrides that due to throw. Since susceptibilities of basement rocks commonly vary by hundreds, even thousands, of percent (Heiland, 1946, p. 309-314, Jakosky, 1950, p. 164-167, Dobrin, 1960, p. 268-271), and the ratio of throw to depth of a fault can be, at most, 100%, then it follows that, in the majority of cases the magnetic response due to susceptibility will override that due to throw. The result is that many faults (40-50%?) will show a magnetic low on the upthrown side. Figure 4, Major County, Oklahoma, presented earlier, is a case in point. Both of the faults shown there, mapped independently by subsurface data, have magnetic lows on the upthrown side, as does the fault in Figure 8 already mentioned. Calculations of the throw of these faults based on a uniform magnetic susceptibility of basement would be grossly incorrect, and geological decisions made from such calculations would be erroneous.

Looking at the problem from another standpoint, let us theorize for a moment that the long linear structure B-B′ shown in Figure 4 is a basement shear zone that has been reactivated with down-to-the-north movement (or down-to-the-south, it doesn't matter). By assuming a uniform magnetic susceptibility of basement, we would necessarily have this fault "scissoring" five times across the width of the figure! A similar truncation line is shown in Figure 6 by the documented down-to-the-south fault F-F′. This fault would be "correct" magnetically on the west side but "incorrect" on the east side if basement were of uniform susceptibility.

I have seen magnetic interpretations that accurately locate the basement block boundaries much as we recommend in this paper, but which label each boundary with a U/D symbol to indicate its direction of throw, always assuming the magnetically high block to be upthrown. That this is patently ridiculous is proven by simply observing magnetic maps over flat, outcropping Precambrian terranes which have a great abundance of magnetic highs and lows, but no significant topographic relief. Merely placing a few thousand meters of sedimentary section on top of basement would not change this situation.

In summary, models of basement that assume a uniform magnetic susceptibility across faults must, according to fault block concepts, be invalid in most cases. Many magnetic interpreters have come to grief in this regard in the past with their exploration supervisors and colleagues (personal communications, too numerous to list here). This, in turn, has cast doubt upon the validity of the magnetic method itself. However, the existence of the basement fault block pattern and the susceptibility changes that we find across block boundaries explain these discrepancies in a straightforward way and set the stage for useful employment of magnetics in exploration in the future.

There does exist a fairly reliable way to determine the direction of throw of certain basement faults from magnetic maps, and this technique is outlined in Figures 18, 19, and 20. Faults that vertically offset basement or other magnetic sources generally show abrupt amplitude changes of magnetic anomalies, both the highs and lows. In Figure 18, a series of 4 NE trending magnetic anomalies on the west (2 highs, 2 lows) abruptly lose amplitude along a NW trending line (A-A') that crosscuts them. The high and low magnetic trends can be easily identified on both sides of this obvious down-to-the-east fault. The 4 anomalies disappear altogether along another NW trending line farther east (B-B'). This may be a strike-slip fault, which is not common in this area, or another down-to-the-east fault that has downdropped the 4 anomalies beneath the level of detection - the preferred interpretation.

A second example using the criterion of an abrupt amplitude change to determine the throw of faults is shown in Figure 19. In this case a banded contour map is employed. (This map may be considered a black and white version of a color-banded map.) On banded contour maps the areas of wide bands are, of course, of lower magnetic amplitude than areas of tight narrow bands. This map is taken from a magnetic survey of the west flank of the Rome Trough in West Virginia. Previous models for the Rome Trough had assumed a gently east dipping surface into the deep part of the Trough, which is located along the right boundary of the figure. However, abrupt amplitude changes along lines A-A' and B-B' indicate that at least 2 profound down-to-the-basin faults exist in this area.

The third example where fault throw is determined by a sudden change in magnetic amplitude is given in Figure 20. Two faults with obvious offset are shown along the SW and SE boundaries of a triangular shaped down-dropped block on top of the Amarillo uplift in Texas. Here, documentation of the throw occurs in structure contours of the overlying Permian Red Cave formation several thousand feet above basement. This down-dropped block is locally known as the LeFors Graben. In the same figure an even more prominent example of an abrupt change in magnetic amplitude is shown across the "Wheeler County fault" just north of the LeFors graben. Here, the Amarillo uplift abruptly drops many thousands of feet to the north into the Anadarko Basin on this "range-front" fault.

A second concept in current magnetic interpretation practice that needs revising is the so-called "supra-basement" problem, made famous three decades ago by Steenland (1963). A supra-basement feature is a topographic prominence on the basement, i.e. a hill or knob, rising above the general level of basement. Obviously, this feature will give rise to a localized magnetic high depending on its magnetic susceptibility, size, and depth. We have generally modelled the anomaly as shown in Figure 21a, which again assumes a uniform magnetic susceptibility for basement. However, given the fault block nature of basement, is this suprabasement anomaly detectable?

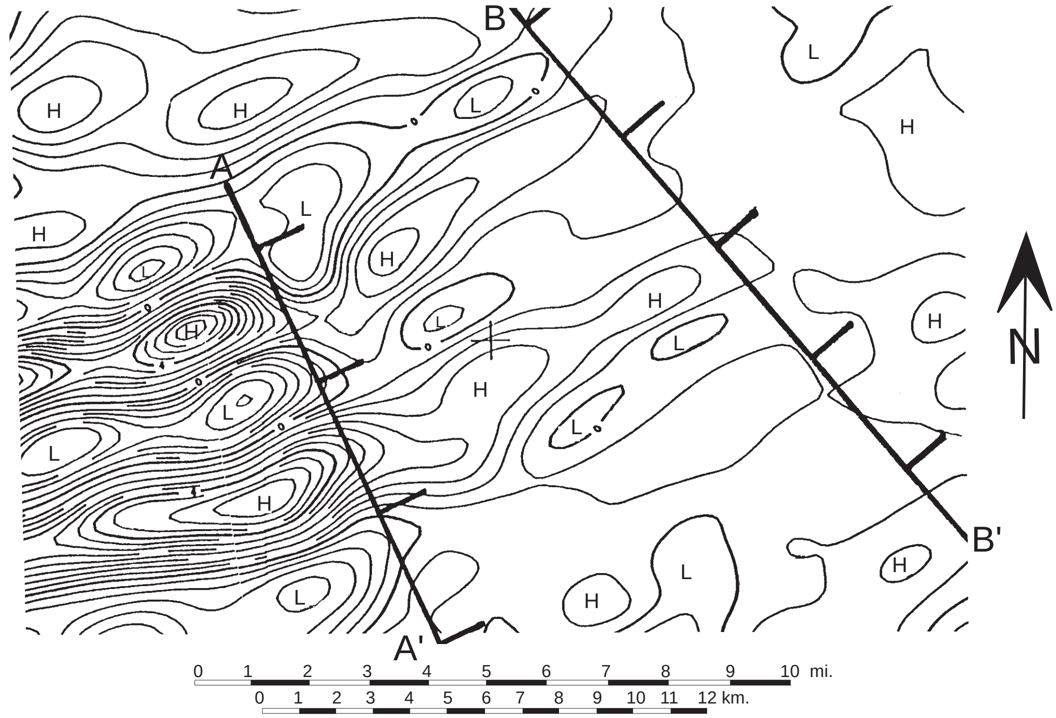


FIGURE 18: An example of a realistic interpretation of fault movement made from aeromagnetic data in southern Belize (Gay 1991). In crossing line A-A' from west to east four magnetic anomalies - two highs, two lows - abruptly lose amplitude, indicating down-to-the-east movement. Data residualized along northwest-trending flight lines; contour interval is 0.5 nT.

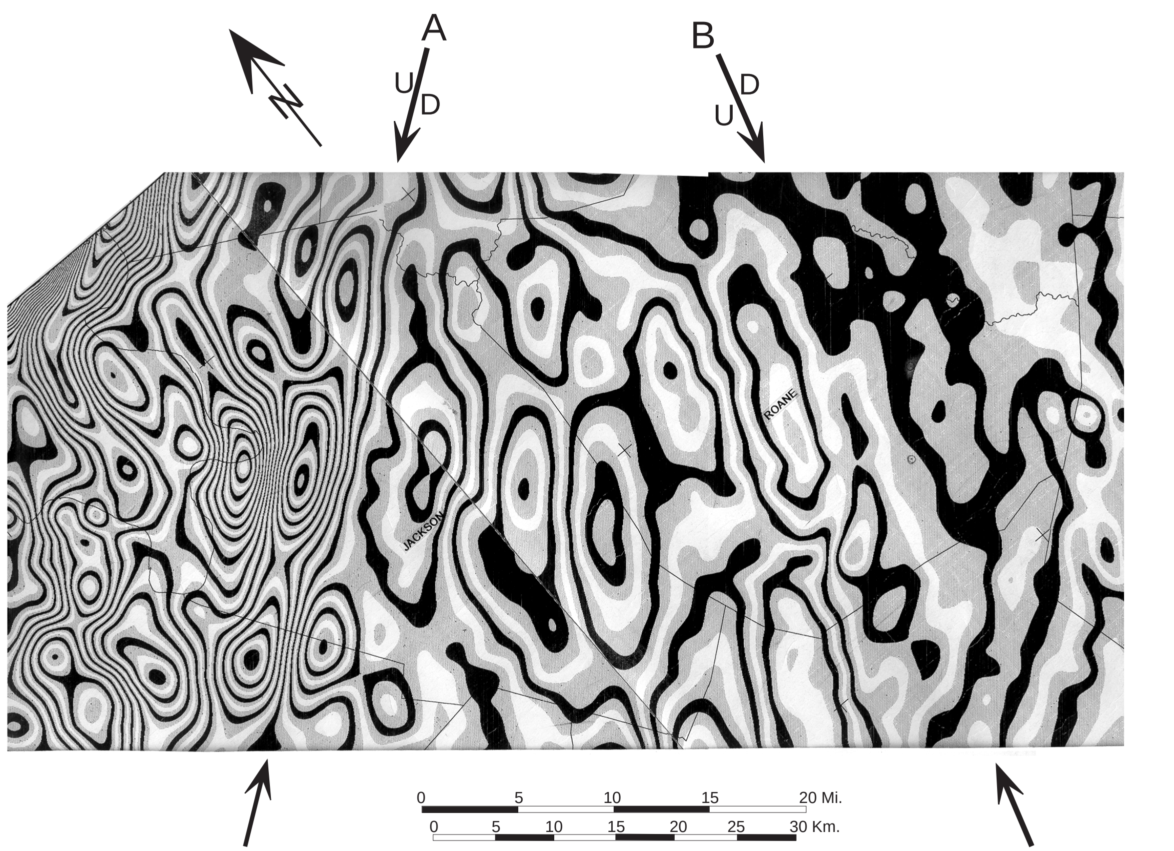


FIGURE 19: The appearance of the anomaly pattern on banded aeromagnetic contour maps changes dramatically across major faults. Here, on the west flank of the Rome Trough in West Virginia two previously unmapped down-to-the-basin (to east) faults at A-A' and B-B' are quite visible. Data (AGI, 1991) residualized along northwest-trending flight lines; contour bands are 0.5 nT in width.

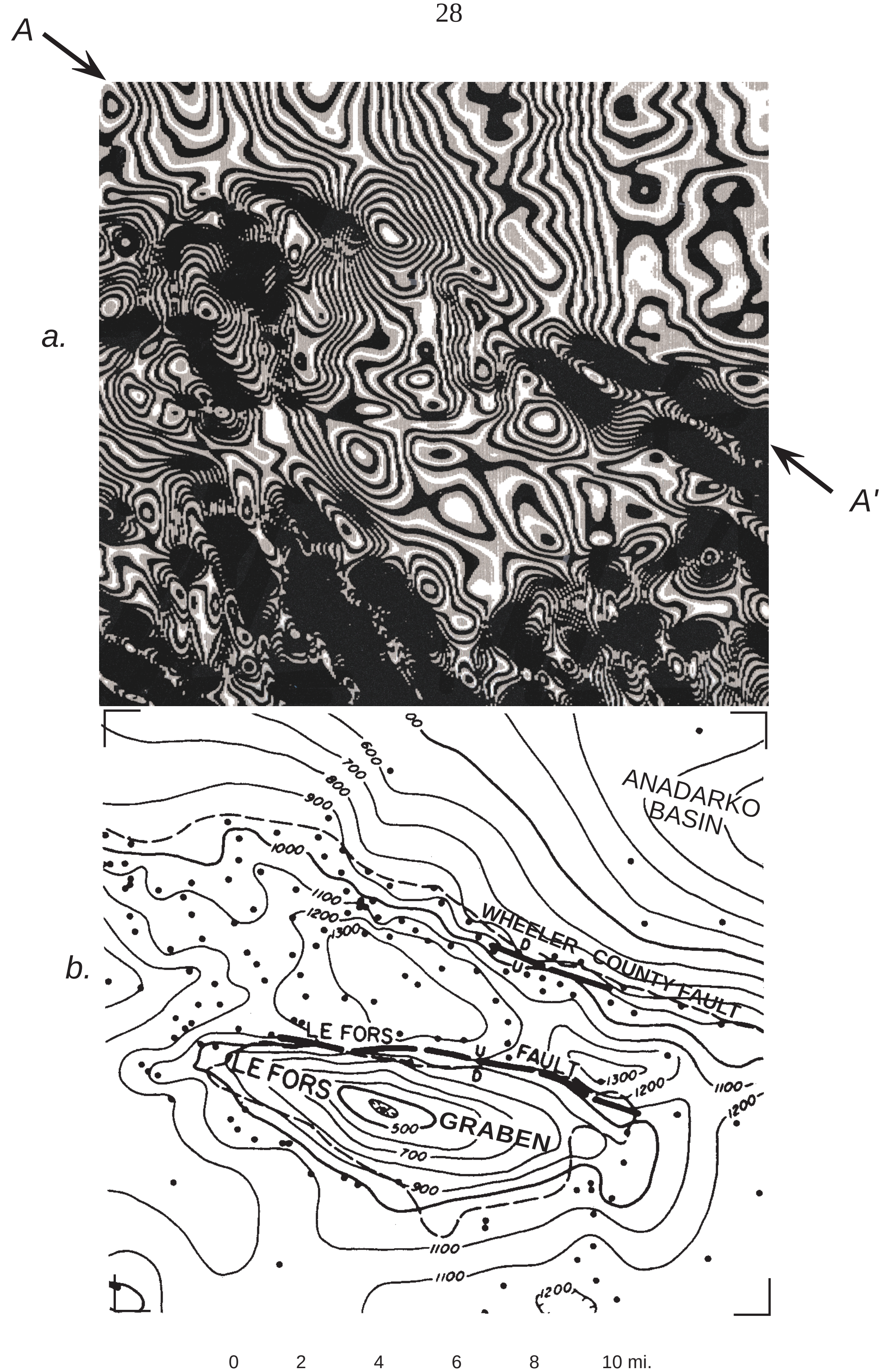


FIGURE 20: a. Banded contour maps of residual aeromagnetic data (AGI, 1986) are extremely valuable in locating faults and determining their throw. The triangular area of wide bands in the south half of this figure corresponds to the "Lefors Graben", a down-dropped block on top of the Amarillo uplift in Gray County, Texas. b. The outline of the block is shown by the Permian Red Cave structure contours, which however, do not indicate the southwest and southeast basement bounding faults as does the magnetic data. A fault of much greater throw, the Wheeler Co. fault (the Wichita-Amarillo Mountain frontal fault) corresponds to the line A-A' . Magnetic data are residualized along E-W trending flight lines; contour bands are 0.5 nT in width. Structure contours from Budnick, 1987.

I have earlier pointed out that sheared basement block boundaries generally erode low, so that topographic prominences will occur somewhere within the basement blocks and are many times centered on them. The actual well section and residual magnetic map from the Texas Panhandle shown in Figure 16 illustrate such a case precisely.

Therefore, if we are looking at a topographic prominence centered on a basement block, the detection problem then becomes that shown in Figure 21b. A series of adjacent basement blocks having different magnetic susceptibilities results in a residual magnetic pattern of alternating highs and lows (solid lines). When the basement block on which the hill is carved is more magnetic than surrounding blocks, the hill contributes slightly to the magnetic high over the block as shown. (This would be the case represented by the actual field examples from Oklahoma and Texas shown in Figures 15 and 16.) The slight increase in anomaly amplitude due to the hill (top dashed line) is not generally distinguishable from a similar increase due to a slightly higher magnetic susceptibility for the whole block; hence the hill is not generally detectable. If the block on which the hill is carved is less magnetic than the adjacent blocks, then the hill would result in a lesser amplitude of the magnetic low over that block, but the low is still present (bottom dashed line). (This would correspond to the actual field example of Figure 14.) Again the hill would not be detectable, and according to prior interpretation practice <u>it would not even be suspected</u>. Certainly it is not mathematically calculable.

The above examples point out the dilemma in interpreting magnetics over areas of Precambrian crystalline basement. Our assumption of magnetic highs over basement highs and on the upthrown sides of faults needs revising. This assumption holds true only part of the time and is thus unreliable as an interpretation criterion. It is interesting that some of the earlier workers in magnetics did not make the mistakes now presently being made. In the first full length book ever published on aeromagnetic interpretation, GSA Memoir 47, Vacquier et al., stated: "Most magnetic anomalies arise from the lithology and not the topography of the basement rock" (1951, p. 8). Dobrin also stated in his third edition in 1976 (p. 536): "The magnetic relief observed over sedimentary basin areas is almost always controlled by the <u>lithology</u> of the basement rather than by its topography." The present author thus feels he is in good company with his strong statements on this subject. Vacquier et al also in a sense predicted the existence of the basement fault block pattern: "... the magnetic maps themselves suggest the presence in the basement complex of boundaries between rocks of contrasting magnetic properties" (1951, p. 4).

There is one further pernicious misconception in magnetic practice that has been accepted by some that I would like to discuss. That is the idea that spectral analysis, or frequency filtering, erroneously referred to as "stripping" or "depth slicing", can uniquely define magnetic source bodies at different depths beneath the magnetometer. In spite of proof having long existed that this is not mathematically or physically possible (i.e., Skeels, 1947), the idea of uniqueness of magnetic depth calculations has recently been resurrected (e.g. Andrew et al., 1986; Davies, 1988; R.J. Wold, personal communication, 1988; McConnell & Phillips, 1994). Perhaps this concept has arisen because of consideration of anomalies arising from geometrically simple source bodies. If one examines the anomaly of an <u>isolated, individual</u> magnetic body buried at different depths (Figure 22) there is certainly a pronounced broadening with increasing depth of burial. This corresponds to a frequency change, which is also apparent in spectral plots (Figure 23). Nevertheless, there is a large degree of <u>spectral overlap</u> in these diagrams, and it is this spectral overlap that results in the non-uniqueness of magnetics for determining depths (or vice-versa) as pointed out many years ago by Bhattacharyya (1966, p. 97) and more recently by Pilkington and Crossley (1986, p. 2250). The most powerful, or the most novel (for example, "neural networking"), approaches cannot overcome this basic physical-mathematical limitation.

To shed further light on the above problem, an extremely interesting exercise results by placing side by side <u>several</u> magnetic source bodies of the type shown in Figure 22. This is shown in Figure 24. Such a source geometry more realistically portrays the geology of the basement. For this multi-block model we now calculate the total intensity and residual anomalies for different depths and Voila!, we see that the principal wavelength, six miles, <u>remains the same</u> for all models regardless of depth! That is, for all depths the magnetic peaks of the residual anomalies remain <u>directly</u> over their respective source bodies (vertical field inclination), which lie six miles apart, as long as separate anomalies are visible. In fact, this identical wavelength between adjacent magnetic bodies persists and pervades in spite of a 500% increase in modelled depths from 1 to 5 miles (1.6 to 8.1 kms). The belief that the width of an anomaly and hence its frequency content must always change with depth to the source is, in fact, not correct, because <u>any given anomaly is constrained in width by the anomalies adjacent to it</u>. It is obvious therefore, that it is not only the source <u>depth</u> which determines the spectral content of anomalies, but the source <u>width</u> as well, and the latter can be the more important. In Figure 25 appear spectral plots for the 3-block models of Figure 24 to emphasize further the great overlap in spectral content of geologically plausible models.

Figure 24 illustrates another well known, but important, characteristic of magnetic data for mapping the basement fault block pattern, i.e. that residual techniques have much higher resolving power than total intensity data. Whereas the total intensity anomalies over the three adjacent 3-mile wide bodies merge into a single anomaly somewhere between 3

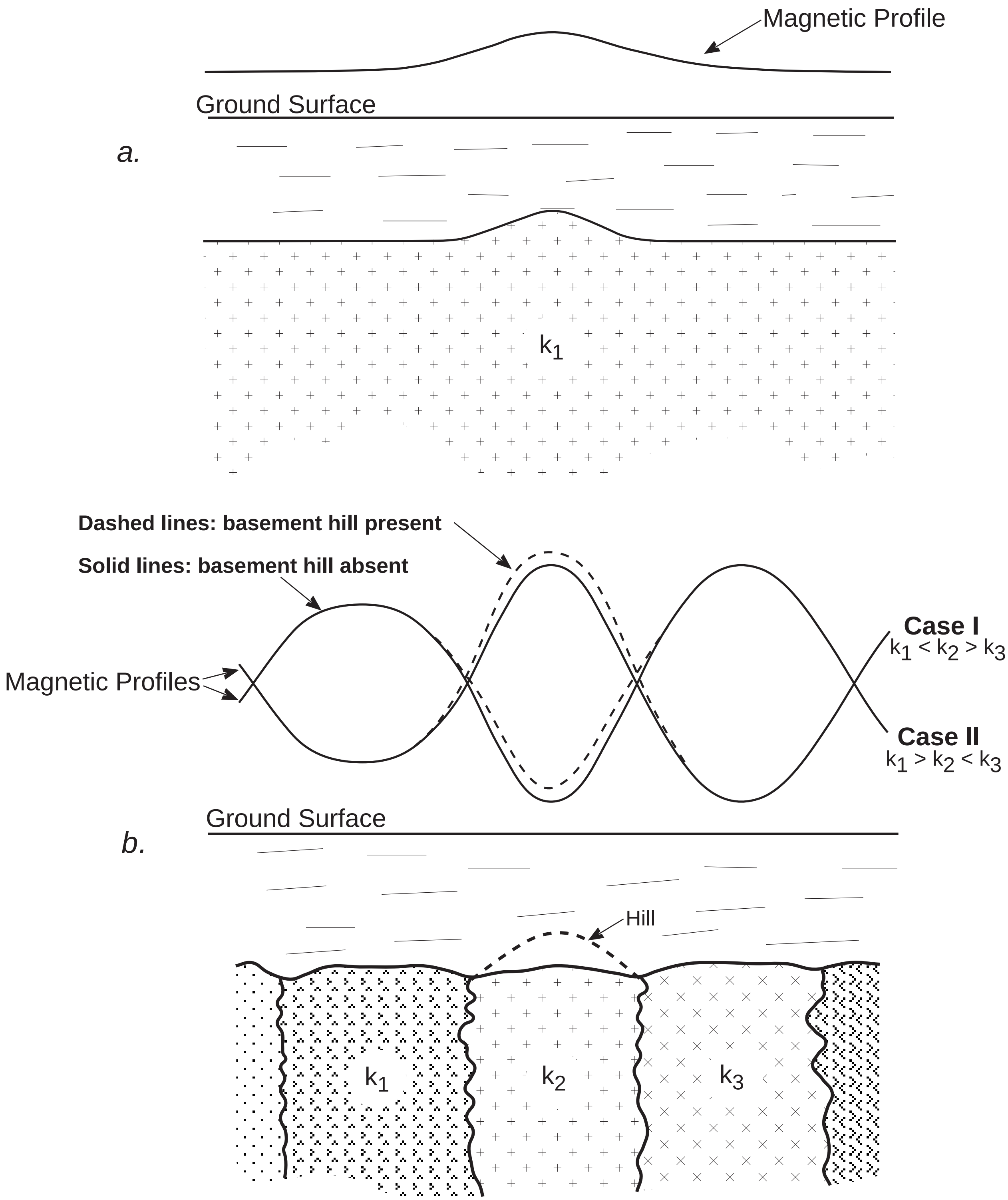


FIGURE 21: Schematic geological cross-sections and resulting magnetic responses (schematic) for two models of a basement hill. a. *Hill carved on a homogeneous basement (not very likely).* b. *Hill carved on one block of a more realistic inhomogeneous basement divided into fault blocks of varying lithologies.* k_1, k_2, k_3 *represent magnetic susceptibilities of respective basement rock types. Magnetic field vertical.*

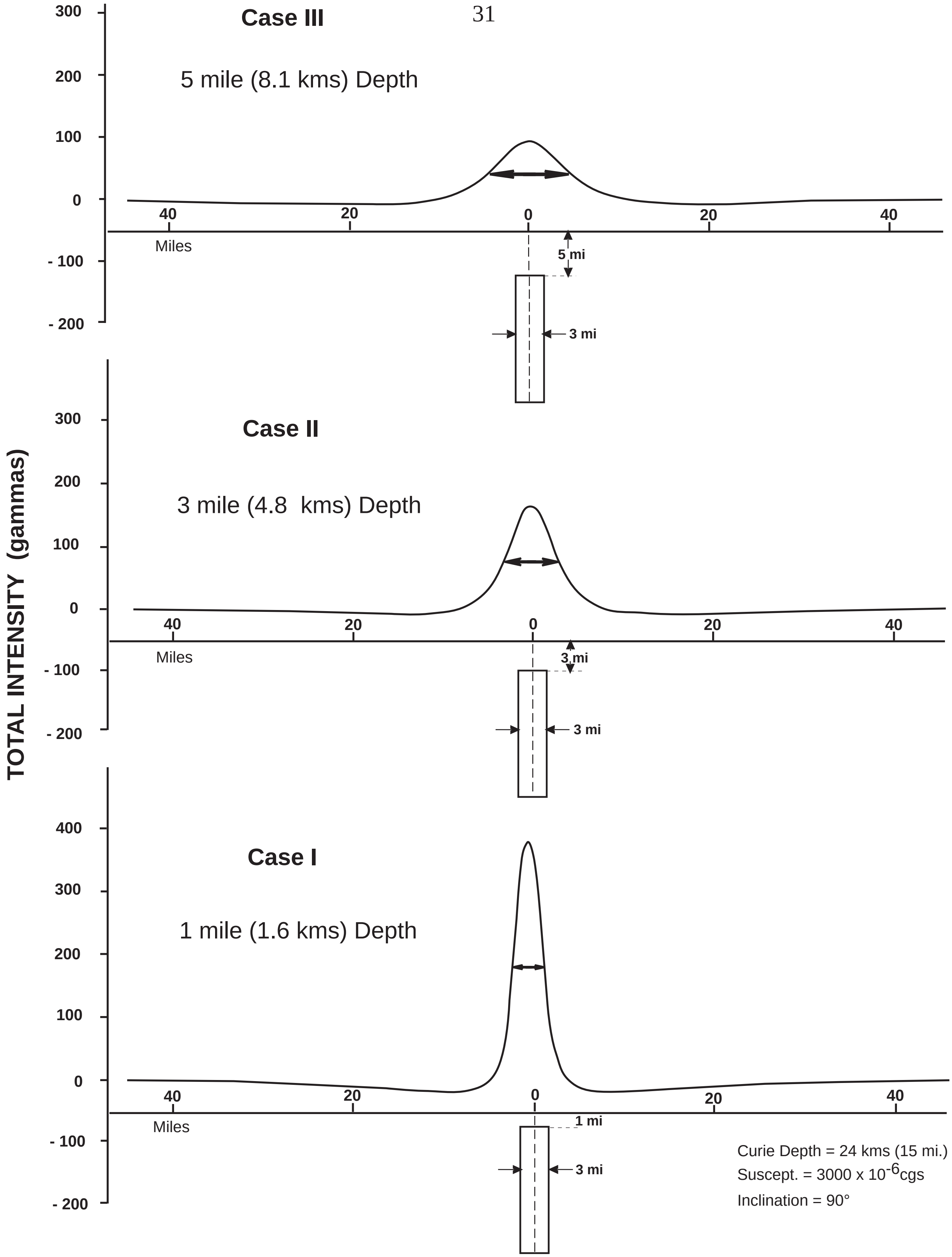


FIGURE 22: Total Intensity magnetic anomalies for a 2-dimensional magnetic source body 3 miles wide extending to a Curie depth of 15 miles and buried at three different depths: 1 mile, 3 miles, and 5 miles (1.6 kms, 4.8 kms, 8.1 kms, or 5,280 ft, 15,840 ft, and 26,400 ft, respectively).

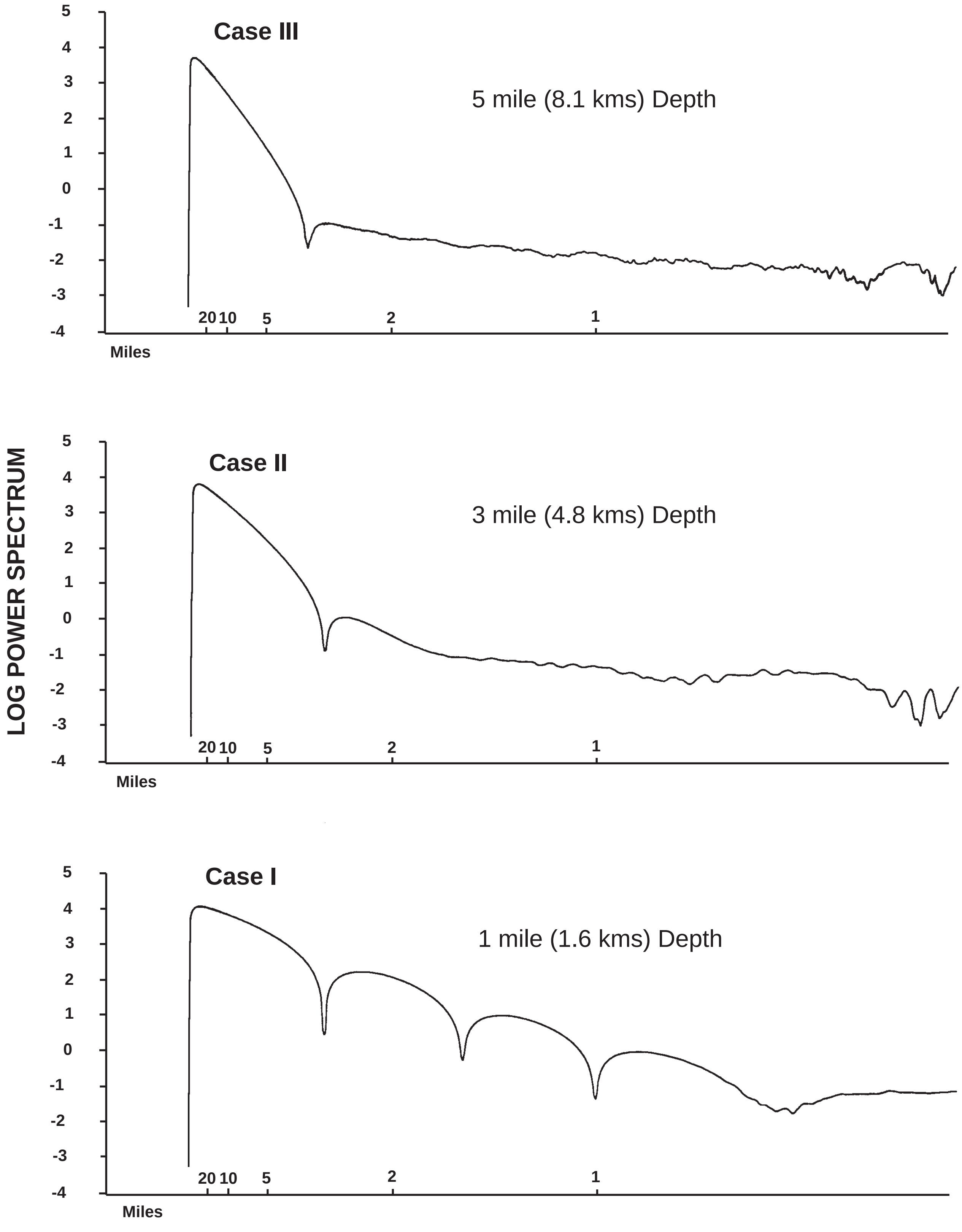


FIGURE 23: Spectral plots of magnetic models shown in Figure 22.

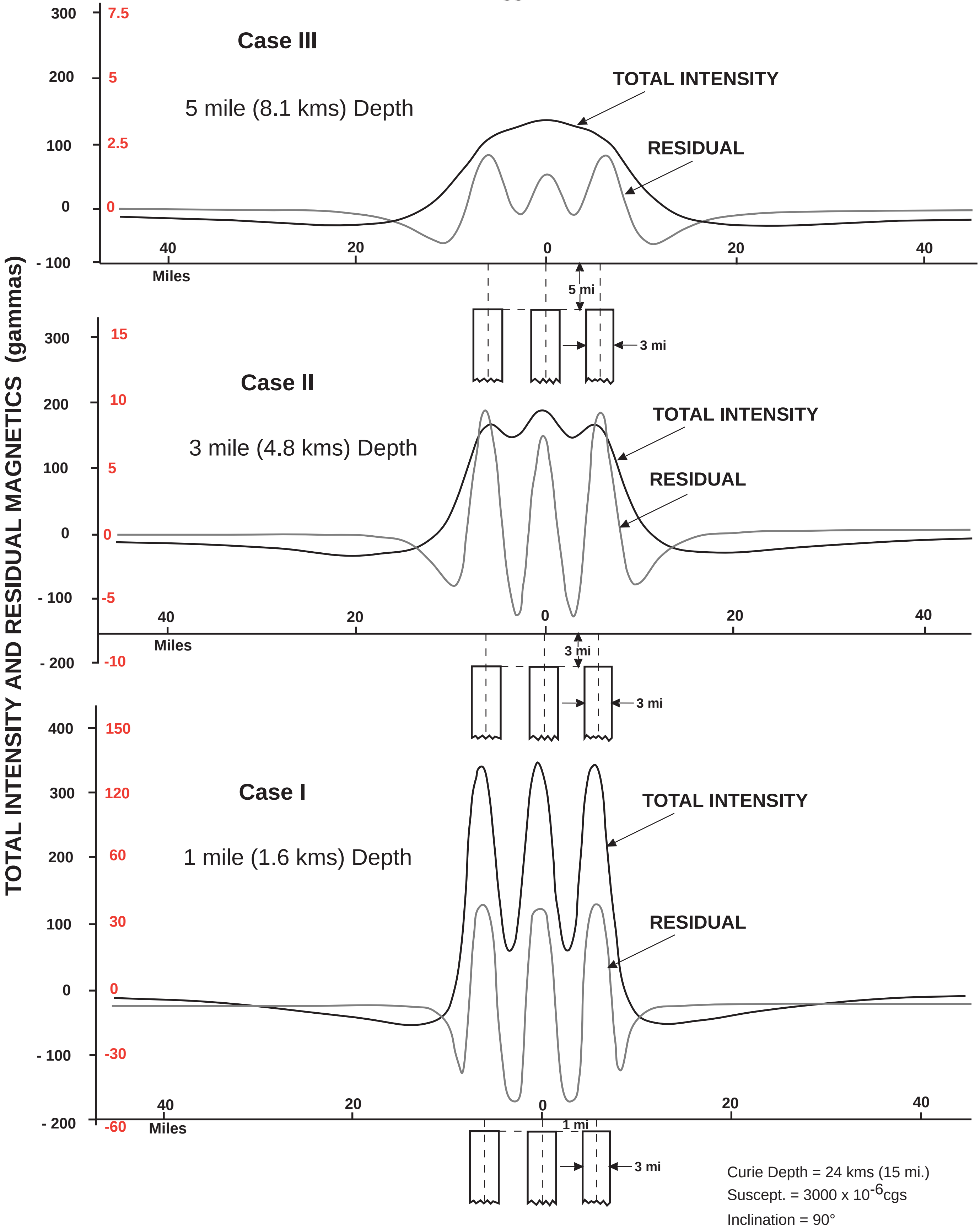


FIGURE 24: Magnetic anomalies for geologically realistic 3-body models of 2D magnetic basement blocks each 3 miles wide separated by non-magnetic gaps 3 miles wide and buried at 3 different depths as in Figure 22.

and 5 miles depth, the residual profile still resolves the anomalies well at the 5 mile depth; that is, all anomalies at this depth still exhibit magnetic "closure." The amplitudes of the residual multiple-body anomalies, however, are only a tiny fraction of the amplitudes for the individual body anomalies: one to two gammas for the multi-block model buried at 5 miles depth versus 100 gammas for the total intensity model of a single block buried at that depth. This demonstrates that in processing magnetic data we can gain resolution, but at the expense of amplitude. High sensitivity data is thus a necessity when flying the deeper petroleum basins.

To summarize this section, which is directed principally to potential field geophysicists, I have mentioned the pitfalls of magnetic interpretation that have resulted from a simplistic idea of basement, and how we need to modify our interpretations in light of its fault block nature. Such modifications would seem to make magnetic methods even less useful in petroleum exploration than before, because we now realize that some of the quantitative predictions regarding depths that we have been supplying, and which seemed so useful, have not been altogether valid. However, wrong answers come back to haunt us, and the general demise in potential field methods from the 1960s through the 1980s, I believe, are due to such incorrect interpretations. If potential field geophysicists continue to provide wrong answers, we will create a whole new generation of agnostics. However belated it has come, then, the present recognition of the basement fault block pattern furnishes us the opportunity to overcome past shortcomings and to indeed make magnetics a mainstream petroleum exploration tool. Therefore, a simple magnetic interpretation map which only shows the locations of the basement shear zones, such as that appearing in Figure 4b, represents a good interpretation in most cases. It is about as far as we should carry many interpretations with magnetic data alone unless we encounter criteria of the type shown in Figures 18, 19, and 20 for unequivocally determining the throw of faults. The fault block map can be quickly fleshed out with seismic, gravity, well, and other geological data to create a realistic picture of the subsurface and to generate reliable prospect leads.

Certainly it is possible to separate very shallow, or surface, sources, from deep basement sources (this is even obvious visually), but the accurate separation of sources at different depths within the sedimentary section is not theoretically possible because of the "mixing" of spectral content caused by variations in both source width and source depth.

VII. THE RECOMMENDED USE OF AEROMAGNETICS IN PETROLEUM EXPLORATION

This section is a brief recapitulation of certain findings and recommendations outlined in previous sections. Basically, it addresses the overinterpretation for the vertical dimension and the underinterpretation for the horizontal dimensions that has characterized standard aeromagnetic interpretation in the petroleum industry for decades. The lack of a geological model of basement (which this paper specifically defines) is a primary cause for both these shortcomings, but some of the blame must also be given to the overuse of unrealistic mathematical techniques and more recently, unrealistic *computer* mathematical techniques. These mathematical computer methods certainly work well in many other scientific and engineering fields, but they cannot overcome the basic limitation of the ambiguity of potential field interpretation, which was well explained by D. C. Skeels nearly 50 years ago (1947). To try to overcome this basic limitation is wishful thinking at best, poor science at the least, and can be costly and damaging to users of potential field data at its worst.

Thus, for example, I recommend that depth estimates from aeromagnetic data only be used to determine generalized figures for broad areas, such as the approximate thickness of the sedimentary section in a basin, or at a limited number of points within that basin. To try to use depth estimates for distinguishing between the depths of adjacent magnetic anomalies is to invite trouble. A narrower anomaly of a pair (or a series) of anomalies might be interpreted as arising from a shallow source, when it could just as likely result from a narrower source body at the same or a deeper depth. In Figure 5a, for example, a series of anomalies of widths varying over a range of 250%, arise from approximately the same basement depth. The source body width is excluded from "state-of-the-art" mathematical techniques now in vogue, but is just as important in determining the frequency content of an anomaly as is the depth.

Thus, it is not always reliable to determine which anomalies are underlain by horst blocks nor which side of a fault is upthrown from magnetic depth estimates, nor is it possible to use the criteria of magnetic highs and lows for that purpose as discussed extensively in the previous chapter. Nevertheless, if one finds an empirical relation-ship between magnetic highs (or lows) and horst blocks in a given area, then one can check similar anomalies for upthrown blocks using an independent technique - subsurface mapping, seismic, or in some cases, gravity. Furthermore, a powerful empirical technique for determining relative depths and the throw of faults from magnetics alone is shown in Figures 18, 19, and 20. This technique relies on abrupt changes in amplitude of the same, or adjacent, magnetic anomalies and their appearance on banded contour maps.

The above discussion relates to determination of the vertical dimension from magnetic maps, a subject which preoccupies the attention of potential field interpreters and many times results in overinterpretation, i.e. wrong answers. However, the most important and most reliable, information

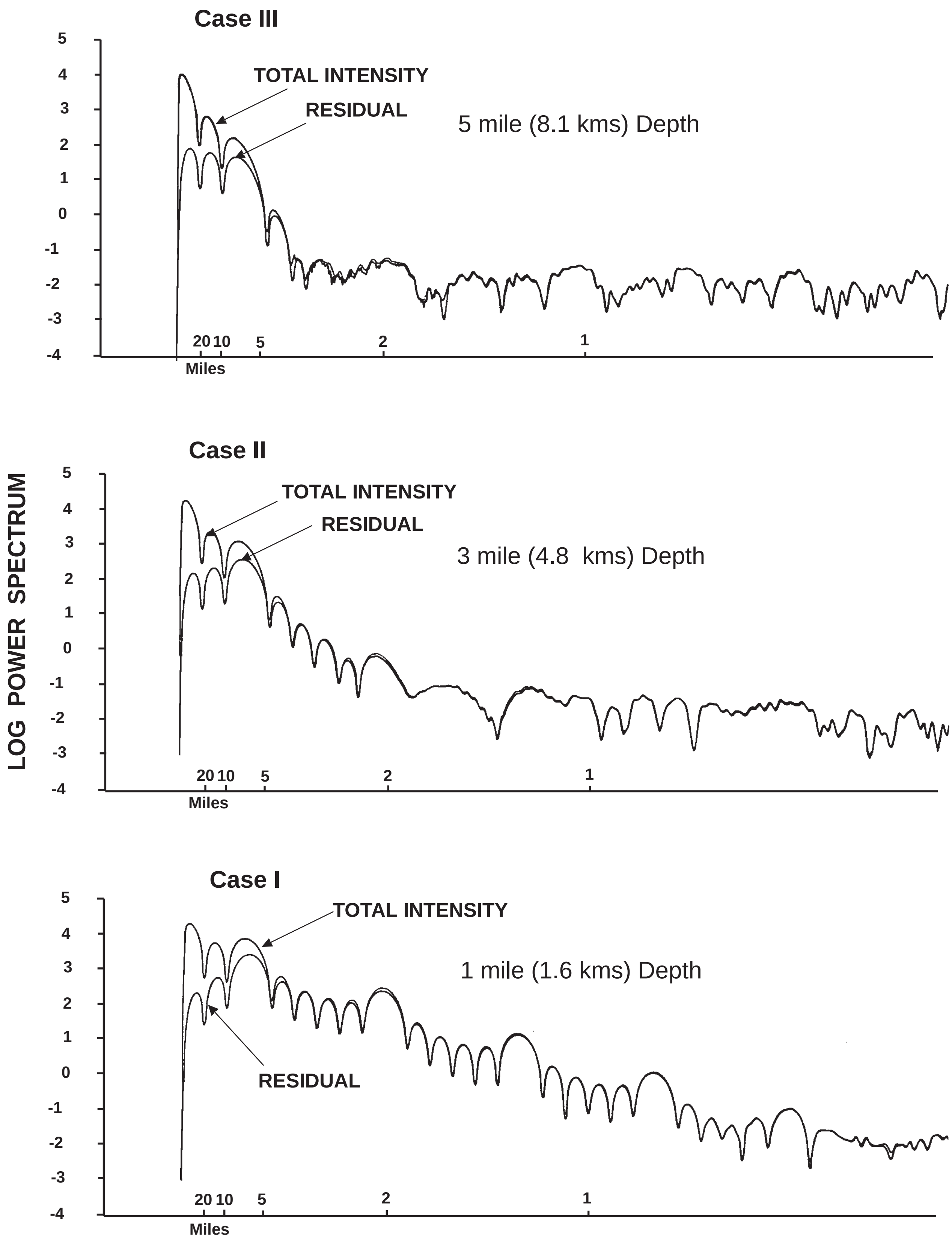


FIGURE 25: Spectral plots of magnetic models shown in Figure 24.

obtainable from aeromagnetic maps is the configuration (in plan view) of the underlying basement fault block pattern. This has not ordinarily been provided by aeromagnetic interpreters and thus represents an area of underinterpretation of magnetic data. The present paper has been primarily devoted to revealing the characteristics of the basement fault block pattern and to demonstrating the very high degree of influence it has had on both the structure and the stratigraphy of the sedimentary section.

I will not reiterate the many examples of basement control that have been provided in prior sections, but I will briefly discuss how the knowledge of this basic structural pattern in the basement can be used in hydrocarbon exploration to:

1) lay out new 2D and 3D seismic programs,
2) aid in the interpretation of existing 2D and 3D seismic programs, and
3) aid in exploration programs based primarily on subsurface (well) data.

Let us suppose that we have developed a basement fault block pattern similar to that shown in Figure 4b and reproduced in Figure 26. Let us also suppose that this area has been tectonically active and is characterized by a fair degree of faulting. This being the case, we can expect that many of the basement shear zones have been reactivated and are now the locus of faults and fractures in the sedimentary section. Thus, A,D, and F in Figure 26a would be poor places to run 2D seismic lines because of the probable poor seismic definition due to fracturing along these zones and the possibility of "sideswipe". Lines B,C, and E, on the other hand, would be good places to run seismic because of the probable lack of fracturing and faulting at these localities. In addition, gravitational compaction structures are generally found within blocks, and thus lines B or C would have found West Campbell Field (WCF) whereas line A would not have.

Magnetics can also be quite useful in the interpretation of existing seismic programs after they have been shot. An example is shown in Figure 26b where two 2D seismic lines have been purposely placed in the worst possible positions relative to the basement fault block pattern. Assuming that all the basement shear zones represent faults in the sedimentary section then "hooking up" the faults in this area would be a real problem. Fault pick C on line 1, for example, would not connect straight across to fault pick G on line 2, nor even to H or I which are some distance away, but to J - making this fault very oblique to the seismic lines. This is not a very common way of connecting faults on most seismic interpretations I have seen. The connection of B to H is straightforward, but, again, is diagonal to the seismic lines, whereas F - K runs diagonally in the opposite direction. Fault picks D,G, E, and I don't connect to the other seismic line at all; they terminate somewhere in between! Admittedly, the above is a theoretical "worst-case" example, but then, geology can many times be "worst-case". A number of seismic interpreters have stated to me they need all the help they can get in constructing a reasonable structural picture of an area from 2D seismic, and certainly a map of the basement fault block pattern can be one of the best supplementary tools available.

In 3D seismic projects, there is not generally a problem in connecting faults, so the above discussion would seem to be moot. However, 3D programs do not usually map fracturing and fracture porosity which generally follow the basement shear zones and can be very important in an exploration program. Furthermore, structures or stratigraphic features that correlate well between 3D seismic and basement mapping can be extended outside the boundaries of the 3D seismic survey by a basement mapping project, thus increasing the effective area covered by the 3D survey. Another important use of basement mapping in conjunction with 3D seismic programs is determining where to lay out the very expensive 3D surveys in the first place. Additionally, a benefit of magnetic basement mapping that has recently (1993) been employed in the Permian Basin, U.S.A., is leasing in advance of a 3D program.

One final technique in which magnetics can be very valuable in interpreting seismic data but which has been seldom used (or never used by most exploration groups) is the plotting of residual magnetic profiles along seismic cross-sections. Examples are shown in Figures 9 and 10 in Chapter II of this paper. This technique can be used with paper cross-sections by plotting the magnetic profile on vellum or mylar at the same horizontal scale as the seismic line (Figure 9) and then laying it over the seismic section, generally at the bottom. The magnetic profile is computer reproduced from a gridded data set that contains the x-y locations of the shot points.

The magnetic profile can also be superimposed on the seismic line on a workstation (Figure 10). This technique is valuable in looking for subtle stratigraphic changes that can occur along basement block boundaries, and looking for subtle fault offsets or other structural and stratigraphic features that might not have been seen at the time of the original seismic interpretation. The locations of the basement weakness zones provide focal points for examining the seismic data more closely. Of course, in structurally complex areas having steep dips, a knowledge of the locations of the basement block boundaries can be a primary feature of a structural interpretation and every bit as important as the information seen on the seismic data. The same can be said of seismic interpretations in areas of poor seismic data quality.

Another major use of magnetic basement mapping in petroleum exploration is the search for "leads" or prospects that can be quickly and economically developed by comparing known traps or structure (and/or stratigraphy) with the basement fault block pattern. There will be areas that have never been

Basement shear zones mapped from residual magnetics : ≈≈≈≈

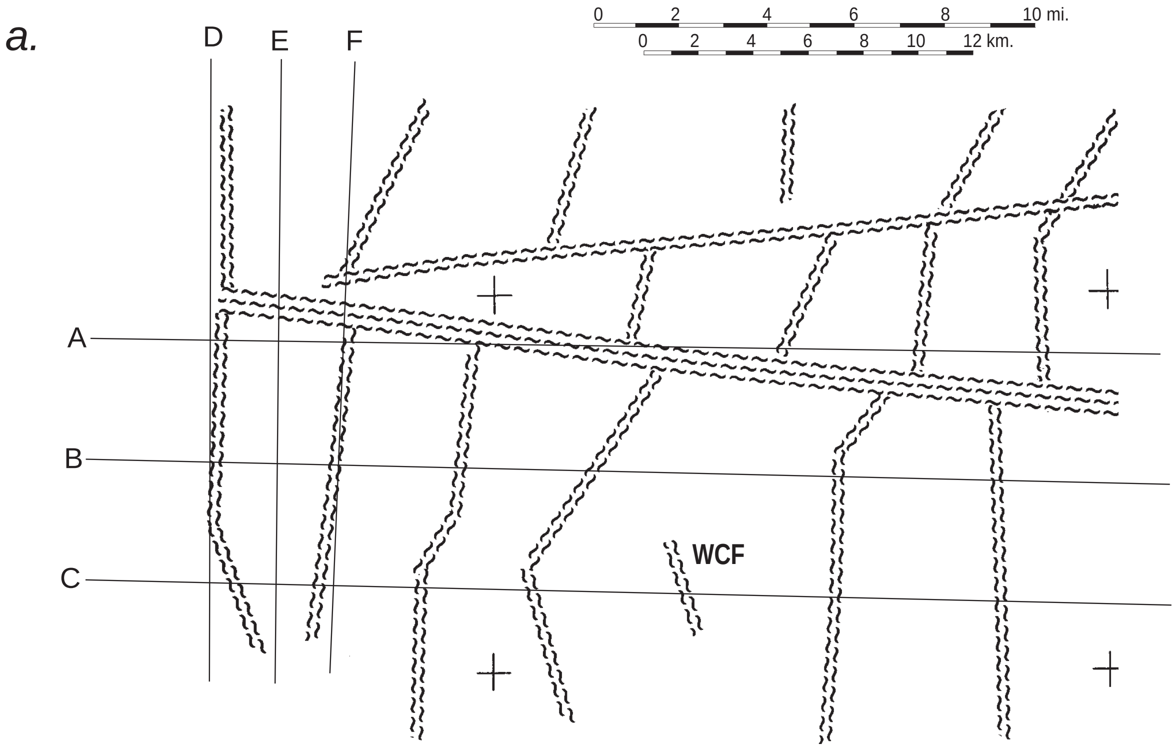


Figure 26: a. A basement shear zone map developed from detailed magnetics (Fig 4b) can be used for selecting locations for 2D seismic lines in an area that has been tectonically active: Lines A, D, and F follow along or are very closely parallel to probable faults and would be poor places for seismic lines. Line B, C, and E cross the centers of suspected blocks and would be much better locations to test for structure. WCF = West Campbell Field.

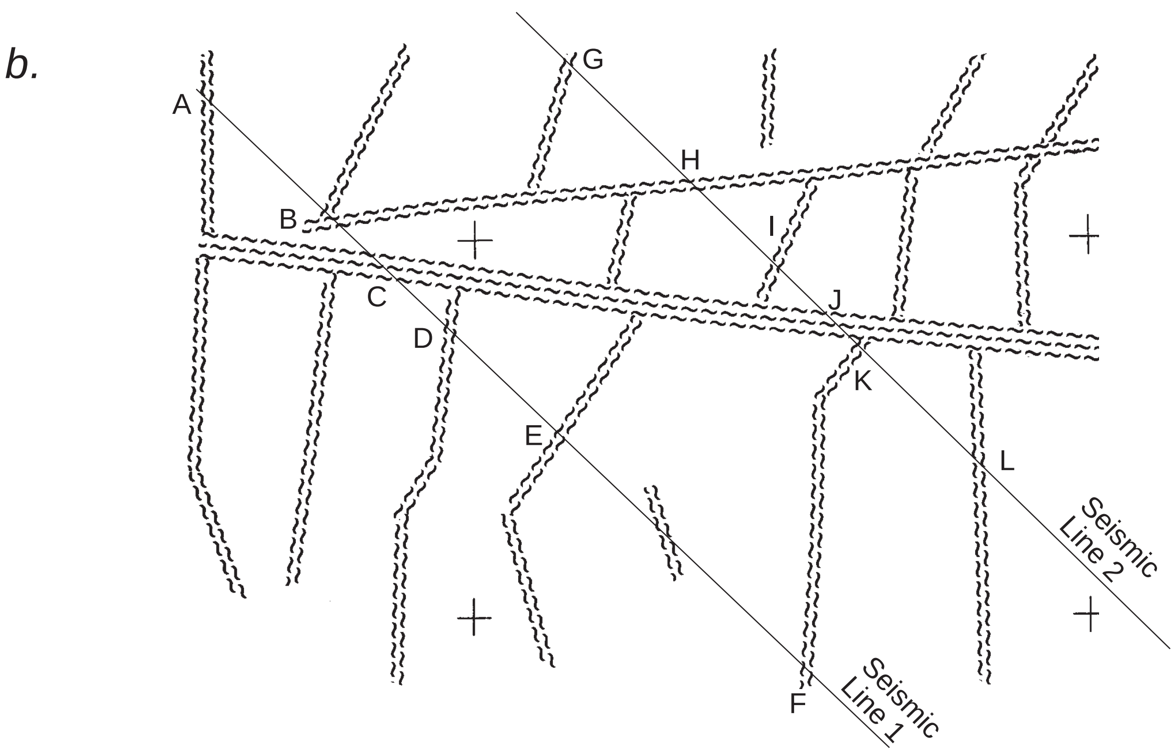


Figure 26: b. A map of the fault block pattern can aid in interpreting 2D seismic data. If all the basement shear zones in this diagram have been reactivated and now represent faults in the sedimentary section, it would be a great challenge to reconstruct the above pattern of faulting from fault picks A through F on Line 1 and G through L on Line 2 (see text).

tested by the drill where the structure at basement level is analogous to that over nearby producing properties. Some of these leads will become viable prospects when subjected to followup seismic profiling or other appropriate exploration techniques. A common type of structural or stratigraphic data used to correlate to the magnetic data is that developed from well data - "subsurface mapping". However, on overseas projects or in frontier areas, the best, or only, data available may be 2D seismic surveying. In either case, the *modus operandi* is to search for "look-alikes" on the magnetic data that correspond to features over known producing fields. Since the magnetic data can be acquired in continuous fashion over large areas at a very economical price, many good leads can be developed in a short time.

To summarize this section, magnetics can be an extremely effective and economical exploration tool when properly employed. Its proper use, however, depends on avoiding several pitfalls described herein, on integrating the magnetics with seismic, subsurface, and other data, on the development of the basement fault block pattern from the magnetic data in areas of basement control, and on the use of concepts of basement control in working with all data sets.

VIII. DISCUSSION AND CONCLUSIONS

This paper may be briefly summarized as follows: alignments of weakness zones exist in the basement underlying a large percentage of the world's petroleum basins. Taken together these weakness zones constitute the "basement fault block pattern." This fault block pattern exerted a profound control on the structure and stratigraphy of the sedimentary section as it was being deposited, and subsequently. This pattern is mappable in plan view with residual magnetics. Potential prospects can be generated from the fault block map by its integration with known geology and turned into actual prospects by follow-up seismic profiling.

Petroleum explorationists who follow the above concepts and procedures in applicable areas will soon see their finding costs for hydrocarbons necessarily reduced. For example, a $50,000 expenditure to map the fault block pattern with magnetics at a one-half mile spacing continuously and in detail over a 40x40 mile (70 x 70 km) block of ground is only a small fraction (5-10%) of the typical seismic budget for such an area. With a map of the basement fault pattern in hand, it is possible to reduce the seismic budget by 20-80% and end up with the same number of drillable prospects as in a seismic-only program. Or looked at another way, the money saved by an integrated early phase magnetic-seismic program can be invested in a later 3D seismic grid for definitive prospect definition and evaluation. This is not a theoretical situation. It has been achieved (with the exception of the 3D seismic follow-up) by exploration programs we are familiar with over the course of the last ten years.

Another important use of the basement fault block map is as an aid to seismic interpretation after the data is acquired, e.g. in determining the correct alignments of structural or stratigraphic trends that seismic lines (cross-sections) locate but are incapable of correctly extending offline or connecting between lines. (Here we are not referring to 3D seismic which is acquired with lines close enough together to completely define the structure in a limited area, but which is very expensive.)

We have recently compiled a list of the types of oil and gas traps that are, or can be, due to basement control. They were separated into two categories: 1) traps due to movement of basement blocks or basement faults, and 2) traps due to differential compaction over basement topography. In the former category there are 12 types of traps listed; in the latter, 8 types of traps. Some 85% of these 20 types of traps can be illustrated with actual field examples taken from our work of the last ten years. Hyne (1984) lists a total of 29 types of hydrocarbon traps in a well known wall poster hanging in many exploration offices, so obviously several categories of oil and gas traps are not represented by examples that are due to basement control. Of course, in many categories of traps there are examples that are both due to, and not due to, basement. Also, in areas where the sedimentary section has been "decoupled" from the basement on which it was deposited, e.g., in the growth faults of the U.S. Gulf Coast or in thrust faults in overthrust belts, there can be little or no basement control of the immediately overlying sedimentary section. However, in thrust belts, basement does manifest itself many times by controlling the location of "ramping" at prominent down-to-the-basin faults.

One of the most significant developments in petroleum exploration and development in recent years, horizontal drilling, may also benefit greatly from basement fault block mapping, perhaps even without resort to seismic, subsurface, or other data. This technology has proven capable of obtaining yields of oil and gas two to five times greater than those obtained with vertical wells in selected reservoirs. The only requirement is that the well bore cut a maximum number of vertical to steeply dipping oil or gas bearing fractures. Given the proven relationship of basement fault movement, even minor movement, to fracturing in the overlying sedimentary section, it would seem that a knowledge of the locations of the basement shear zones would be indispensable. A map similar to Figure 4b would provide the operator the ability to drill across fractured areas at right angles and to avoid the tight interiors of blocks or wells drilled parallel to the fracture system. A recent study we made of the Bakken Play in North Dakota was that the intersections of basement shear zones provided the best yields for horizontal wells by a factor of 2 or 3.

One might question the strong emphasis placed herein on magnetics for mapping the basement fault block pattern. However, is there any other way to reliably map this pattern beneath the sedimentary section? Methods that depend on surface information are of limited value. These include Landsat, SLAR, conventional photo geology, and surface geology. That leaves only seismic and gravity techniques. However, gravity does not generally separate adjacent basement blocks because of the lack of density contrast between blocks and because of interference from density differences within the sedimentary section. On seismic data, the basement reflector is usually difficult to recognize beneath complex structure and also because of a lack of velocity contrast with the dense dolomites that overlie basement in many areas. Furthermore, both seismic and gravity methods are expensive to apply over broad areas and cannot provide even a tiny percentage of the area coverage that can be obtained with magnetics for the same price. Both seismic and gravity are excellent follow-up tools for profiling, or "cross-sectioning", of specific leads developed from the basement fault block pattern by magnetics.

The purely geological aspects of the basement fault block pattern are also of great interest. Because of our continuous involvement at Applied Geophysics, Inc., for the last ten years in mapping basement over large areas and comparing the results with surface geology, subsurface geology, seismic data and production maps, we have perhaps seen more basement control than any organization anywhere. We see more basement control, in fact, than we had originally thought possible. It is present in every aspect of structure and stratigraphy. The resulting conclusion is that basement is a lot more important than is generally realized by most geologists and geophysicists.

The incorporation of basement fault block concepts into petroleum geology and geophysics and the use of basement fault block maps in the exploration process will certainly lower finding costs and increase petroleum reserves worldwide.

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IX. REFERENCES

Andrew, J.A., R.J. Graf, D.P. O'Brien, and R.J. Wold, 1986, Synergistic interpretation of near-surface magnetic anomalies and high-frequency seismic data, northeastern Montana (abstract): AAPG, v. 70, p. 1030.

Affleck, J., 1963, Magnetic anomaly trend and spacing patterns: Geophysics, v. 28, p. 379-395.

Baars, D.L., and G.M. Stevenson, 1982, Subtle stratigraphic traps in Paleozoic rocks of Paradox Basin, in M. Halbouty, ed., Deliberate search for the subtle trap: AAPG, Memoir 32, p. 131-158.

____, 1983, Paleotectonic control of Pennsylvanian sedimentation in Paradox Basin (abstract): AAPG Bulletin, v. 67, p. 1329.

Babcock, E.A., 1973, Regional jointing of southern Alberta: Can. Jour. Earth Sci., v. 10, p. 1769-1781.

_____, 1974, Regional jointing of southern Alberta (abstract): Abstracts, First Int'l. Conference on the New Basement Tectonics, Utah Geol. Assn., Salt Lake City, UT, p. 9.

___, 1976, Bedrock jointing on the Alberta Plains, in R.A. Hodgson, et al., editors, Proceedings of the First Int'l Conference on the New Basement Tectonics: Utah Geol. Assn., Salt Lake City, UT, p. 142-152.

Bhattacharyya, B.K., 1966, Continuous spectrum of the total-magnetic-field anomaly due to a rectangular prismatic body: Geophysics, v. 31, p. 97-121.

Carey, L.W., 1954, The subsurface geology of the Garber area, Garfield County, Oklahoma, in Shale Shaker Digest: Oklahoma City Geol. Soc., v. 1, p. 384-403.

Cloos, H., 1948, The ancient European basement blocks - preliminary note: Am. Geophy. Union Transactions, v. 29, no. 1, p. 99-103.

Cruce, J.D., 1956, Willowdale pool, in Kansas oil and gas pools, south central Kansas: Kansas Geol. Soc., v. 1, p. 95-97.

Davies, F.B., and W.J. Rogers, 1988, Practical approach to high discrimination filters for gravity tarkets (abstract): SEG, Abstracts with program, 58th Annual Meeting.

Denison, R.E., 1981, Basement rocks in northeast Oklahoma: Oklahoma Geol. Survey Circular 84, 84 p.

Dobrin, M.B., 1960, Introduction to Geophysical Prospecting, 2nd Ed.: McGraw-Hill, 446 p.

___, 1976, Introduction to Geophysical Prospecting, 3rd Ed.: McGraw-Hill, 630 p.

Dodson, G.S., 1986, Tectonic influence on Upper Cretaceous reservoirs in the Powder River Basin - New geophysical evidence: AAPG Rocky Mtn. Section program with abstracts, p. 96.

Donovan, T.J., 1974, Petroleum microseepage at Cement, Oklahoma - evidence and mechanism: Bull. Am. Assoc. Pet. Geol., v. 58, p. 429-446.

Ferris, C., 1987, Gravity anomaly resolution of Garber Field, Oklahoma: Geophysics, v. 11, p. 1570-1579.

Foote, R.S., 1984, Significance of near-surface magnetic anomalies, in M.J. Davidson and B.M. Gottlieb, eds, Unconventional methods in exploration for petroleum and natural gas, III: SMU, Dallas, TX, p. 12-24.

Frost, E.G., 1988, Crustal habitat of precious-metal mineralization, southeast California and western Arizona (abstract): AIME pocket program, 117th annual meeting, Phoenix, AZ.

Gatewood, L., 1983, Viola-Bromide and Oil Creek structure (map): Oklahoma City, privately sold and distributed.

Gay, S.P. Jr., 1972, Aeromagnetic lineaments, their geological significance and their significance to geology: American Stereo Map Co., Salt Lake City, UT, 94 p.

___, 1973, Pervasive orthogonal fracturing in earth's continental crust: American Stereo Map Co., Salt Lake City, UT, 123 p.

_____, 1985, Gravitational compaction, a neglected mechanism in structural and stratigraphic studies: new evidence from the Midcontinent, USA: Applied Geophysics, Inc., 109 p.

___, 1986, Relative timing of tectonic events in newly recognized Precambrian terranes in south-central Kansas, USA, as determined by residual aeromagnetic data, in Proceedings of the Sixth Int'l Conference on Basement Tectonics: Int'l. Basement Tectonics Assn., Salt Lake City, UT, p. 153-167.

_____, 1989, Gravitational compaction, a neglected mechanism in structural and stratigraphic studies: new evidence from Midcontinent, USA: AAPG, v. 73, no. 5, p. 641-657.

Gustason, E.R., 1988, Depositional and tectonic history of the Lower Cretaceous Muddy Sandstone, Lazy B Field, Powder River Basin, Wyoming: Thirty-Ninth Field Conference, Wyoming Geol. Assn. Guidebook, p. 129-146.

Hammer, S., 1982, Airborne gravity is here!: The Leading Edge, v. 1, p. 69-71.

___, 1983, Letter to Editor ("Signals"): The Leading Edge, v. 2, p. 9.

___, 1988, Letter to Editor ("Signals"): The Leading Edge, v. 7, p. 8.

Heiland, C.A., 1946, Geophysical Exploration: Prentice- Hall, 1013 p.

Hills, E. Sherbon, 1941, Outlines of structural geology: New York, Nordeman, 172 p.

Hodgson, R.A., 1961, Regional study of jointing in Comb Ridge-Navajo Mountain area, Arizona and Utah: Bull. AAPG, v. 45, no. 1, p. 1-38.

Hyne, N.J., 1984, Oil and Gas Field Classifier (Chart): Pennwell, Tulsa, OK.

Jakosky, J.J., 1950, Exploration Geophysics: Trija Publishing Co., 1195 p.

Krivanek, C.M. 1983, Bug Field [Case History], in D.L. Wiegand, Geology of the Paradox Basin: Rocky Mtn. Assn. of Geol., Denver, CO, p. 47-54.

LaBerge, G.L., 1976, Major structural lineaments in the Precambrian of central Wisconsin, in Proceedings of the First Int'l Conference on the New Basement Tectonics: Utah Geol. Assn., Salt Lake City, UT, p. 508-518.

LeFehr, T., 1983, President's Page: The Leading Edge, v. 2, no. 12, (Dec.), p. 7.

___, 1984a, President's Page: The Leading Edge, v. 3, no. 3, (March), p. 5.

___, 1984b, President's Page: The Leading Edge, v. 3, no. 4, (April), p. 5.

___, 1984c, President's Page: The Leading Edge, v. 3, no. 5, (May), p. 4.

___, 1984d, President's Page: The Leading Edge, v. 3, no. 6, (June), p. 4.

__, 1985, Why do you limit exploration to the seismic method?: The Leading Edge, v. 4, p. 54.

McConnell, T.J., and J.D. Phillips, 1994, Wilson County, Texas, high resolution aeromagnetic survey - a case study (abstract): Talk given to Dallas Society of Potential Field Geophysicists, 19 April 1994.

Moody, J.D., and M.J. Hill, 1953, Wrench-fault tectonics: Geol. Soc. of America Bull., v. 67, p. 1207-1246.

Pilkington, M., and D.J. Crossley, 1986, Inversion of aeromagnetic data for multilayered crustal models: Geophysics, v. 51, p. 2250-2254.

Saunders, D.F., and S.A. Terry, 1985, Onshore exploration using the new geochemistry and geomorphology: Oil and Gas Jour., v. 83 (September 16), p. 126-130.

Short, N.M., P.D. Lowman, Jr., and S.C. Fredan, 1976, Mission to Earth: Landsat views the world: N.A.S.A., SP-360, 459 p.

Skeels, D.C., 1947, Ambiguity in gravity interpretation: Geophysics, v. 12, p. 43-56.

Spencer, J.E., S.J. Reynolds, and J.W. Welty, 1988, Controls of mineralization by Mesozoic and Cenozoic low-angle structures in West-Central Arizona (abstract): AIME pocket program, 117th annual meeting, Phoenix, AZ.

Steenland, N.C., 1963, An evaluation of the Peace River aeromagnetic interpretation: Geophysics, v. 28, p. 745-755.

Stein, J., 1983, Random House Dictionary of the English Language (Unabridged): Random House, New York City, 2059 p.

Swift, D.J.P., and D.D. Rice, 1984: Sand bodies on muddy shelves: a model for sedimentation in the western interior Cretaceous seaway, North America, in, Siliclastic shelf sediments, R.W. Tillman and C.T. Siemers, eds: SEPM Special Publication 34.

Vacquier, V., N.C. Steenland, R. Henderson, and I. Zietz, 1951, Interpretation of aeromagnetic maps: Geol. Soc. of America, Memoir 47.

Vance, M.L., 1974, West Campbell Field [Case History], in Oklahoma Oil and Gas Fields: Oklahoma City Geological Society, p. 5.

Weimer, R.J., J.J. Emme, C.L. Farmer, L.O. Anna, T.L. Davis, and R.L. Kidney, 1982: Tectonic influences on sedimentation, Early Cretaceous, east flank Powder River Basin, Wyoming and South Dakota, Colorado School of Mines Quarterly, v. 77, no. 4.

Wylie, W.P., N.H. Suneson, and L.A. Hemish, 1988, North-south geologic cross-section through the Arkoma Basin and frontal belt of the Ouachita Mountains in R. 19 E., Eastern Oklahoma, in K.S. Johnson, ed, Shelf-to-basin geology and resources of Pennsylvanian strata in the Arkoma Basin of Frontal Ouachita Mountains of Oklahoma: Oklahoma Geol. Surv., Guidebook 25.

S. Parker Gay, Jr.
Applied Geophysics, Inc.
675 South 400 East
Salt Lake City, Utah 84111

SHORT BIOGRAPHY

S. Parker Gay, Jr. is currently president and chief geophysicist of Applied Geophysics, Inc., Salt Lake City, Utah, USA, a company he co-founded in 1971 and where he has worked continuously since. He received his academic training in geology and geophysics at MIT (B.S., 1952) and Stanford University (M.S., 1961). He has been actively engaged in geological and geophysical mapping and in oil, gas and mineral exploration for nearly 40 years, 27 of them as an independent consultant, and has several discoveries in minerals and ground water to his credit. Gay was President of the Utah Geophysical Society in 1971-72 and national Vice President of the Society of Exploration Geophysicists in 1974-75, from which he received the Best Paper Award for 1963. In 1974, he co-founded the International Basement Tectonics Association which has held conferences biennially in eleven international locations through 1994, and has published a Proceedings volume containing 380 papers (4020 pages) on basement related subjects. Gay himself has published 15 papers on the interpretation of magnetic anomalies and their geological causes, and has written many papers and given numerous talks to professional groups on basement control of geological structure and stratigraphy.

Among his scientific achievements are, 1) the solution to the 140-year old riddle of jointing of sedimentary rocks by proving that joints arise from reactivation of underlying basement faults (1973); 2) an understanding of "plains-type" folding, which he showed results from gravitational compaction of the sedimentary section over an irregular underlying basement topography (1989); 3) an explanation of thinning of beds over structural highs, which Gay showed is a direct result of the compaction of sediments over an underlying buried hill (1989); and 4) an explanation of the cause of many so-called "local tectonic disturbances" by linking them to erosion of "plains-type" folds and subsequent deposition of unconformable beds over the previously tilted ones. Gay's most important achievement, however, may be proof that most of the faulting and much of the stratigraphic change in the sedimentary section is due to reactivation of underlying basement faults (1994), a concept that largely preempts strain theory as an explanation for regional structure.