AN EXPLANATION FOR "4-WAY CLOSURE" OF THRUST-FOLD STRUCTURES IN THE ROCKY MOUNTAINS, AND IMPLICATIONS FOR SIMILAR STRUCTURES ELSEWHERE

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Abstract

Structural systems in the Rocky Mountains comprised of end-to-end asymmetric (compressional) anticlines have been prolific producers of oil and gas since the early years of this century. Current geological thinking is that these systems conform to the "thrust-fold" (listric thrust) model of Stone (1984, 1993), a scenario supported by numerous seismic profiles and well-sections throughout the Rocky Mountain province. However, the thrust-fold model explains the structural closure (i.e. folding) only in the thrust direction, which is generally the short axis of the structure.

In this paper I conclude that the closure, or plunge, at the ends of the anticlines, the "longitudinal closure" along the long axis, is a result of strike-slip movement that accompanied the thrusting. I base this conclusion on the fact that there is shortening in the longitudinal direction, proven by the longitudinal folding itself. This conclusion is also supported by the finding that many of the thrusts are rooted in pre-existing basement faults, which occur at angles not always perpendicular to regional stress, a situation that, kinematically, requires a strike-slip component of movement. The resulting stress, relative to the pre-existing structure, may be termed "transpressive."

Introduction

Our understanding of the structural geology of the Rocky Mountains has undergone a profound metamorphosis in the last few decades, with most of the major advances being made in the 1980's and 1990's. In the 1950's, I was taught in a petroleum geology course in Massachusetts that, since the city of Denver was at a one mile elevation and Mt. Evans was at nearly 3 miles, there was obviously a normal fault between the two. The 1944 and 1962 AAPG Tectonic Maps of the United States(Longwall, Cohee) and the 1968 USGS Basement Rock Map of the U.S. (Bayley and Muehlberger) all showed the Front Range to be raised by normal faults. Only more recently (Jacob and Albertus, 1985) was it proven by seismic data that an enormous thrust fault, or series of such faults, created the uplift of the Front Range. Many previous workers dating back to the 1950's had realized the thrusted nature of the Front Range from geological mapping - see Jacob, 1983, p. 229, for a summary of this work - but the subject was still considered “controversial.”

A similar situation has existed in our understanding of oil field-sized structures and anticlines. Until the 1960's many people assumed that "block uplifts", i.e. near-vertical reverse or normal faults, created the observed structural folds in overlying strata, as well as raising the mountain ranges. In the 1960's and 1970's the "fold-thrust uplift" model of R. Berg (1962) became popular, but even this rendition showed the thrust fault steepening downward into basement, making it just a modified form of block uplift. In 1981 and 1983, Gries, using deep well information, proprietary seismic data, and published examples showed the prevalence of shallow-dipping, non-vertical thrusts throughout the Rocky Mountain province, and in 1983 and 1984 a realistic, restorable model that complies with this evidence was published by Stone. This model, involving a listric thrust rooted in basement, is now referred to (Stone, 1993) as "thrust-fold" (see Figure 1) and is

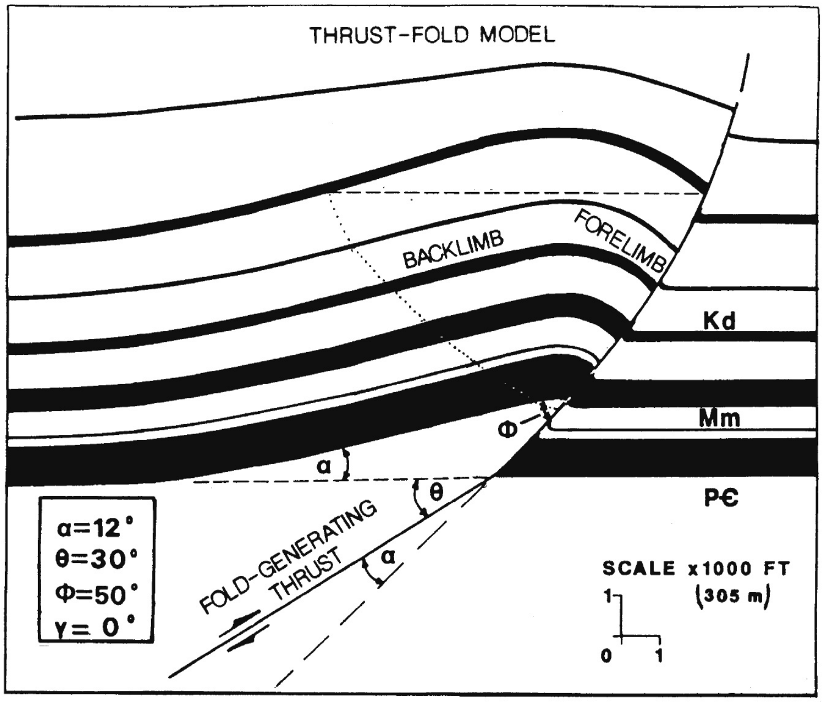


Figure 1. The thrust-fold model for Rocky Mountain structures is documented by oil and gas industry data for innumerable anticlines in the region. This most recent model is from Stone, 1993.

proven by seismic profiles and by oil and gas well drilling of a multitude of Rocky Mountain structures. An illustration of an actual "thrust-fold" structure, based on a high-quality seismic line, is that shown by Ray and Keefer (1985) for the prolific gas-producing Madden Anticline (>1 tcf) in the Wind River Basin of Wyoming (Figure 2). The Madden structure lies in front of, and is parallel to, the far-traveled South Owl Creek, or Casper Arch, thrust and is considered an auxiliary or “sympathetic” thrust to this major Rocky Mountain structure.

Good summaries of the long history of structural geological concepts in the Rockies may be had by reading Berg (1962), Harding & Lowell (1983), and Stone (1984, 1993), and will not be discussed further here. An excellent, more general discussion of the evolution of thought on thrusted structures worldwide beginning in the last century is found in Perry, Roeder, and Lageson (1984).

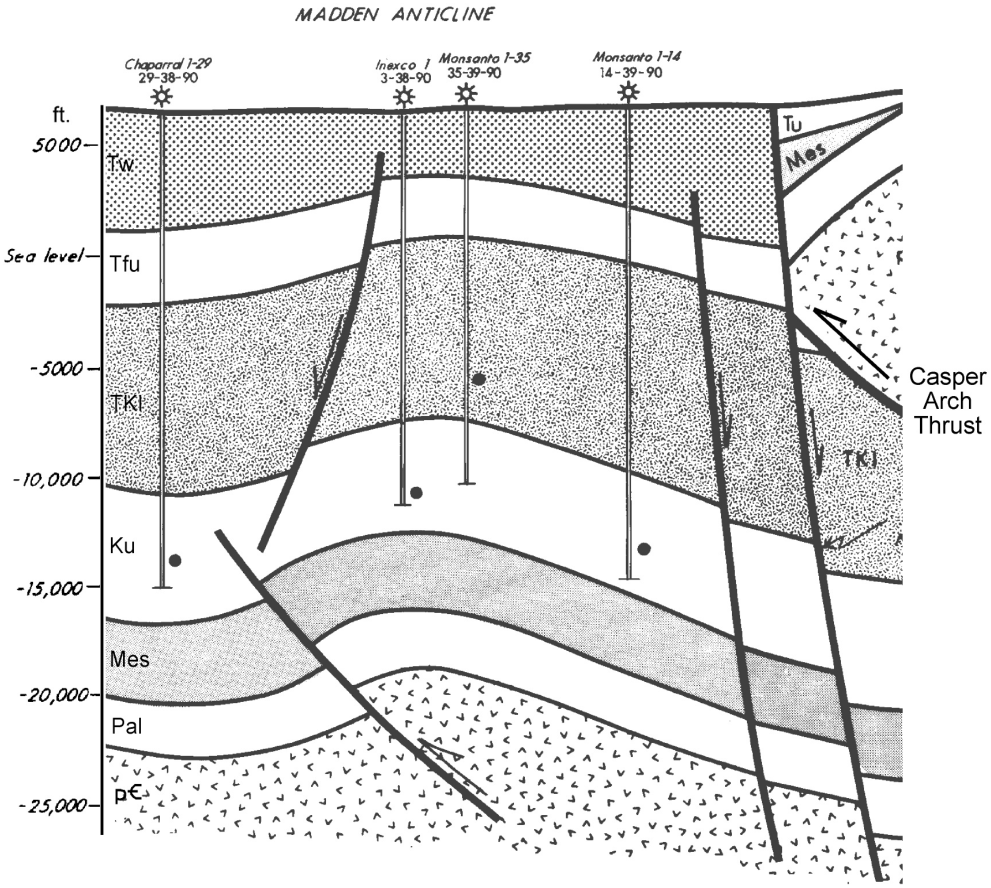


Figure 2. Example of an actual thrust-fold structure in the Wind River Basin of Wyoming, the prolific Madden anticline, as imaged by a proprietary seismic line (Ray & Keefer,1985). The thrust does not persist above the Cretaceous Cody fm. and does not steepen with depth. Geologic fms: Tw, Wind River and Indian Meadows; Tfu, Upper Fort Union (Waltman and Equivalents); TKl, Lower Fort Union and Lance; Ku, Meeteetse, Mesaverde and Cody; Mes, Frontier through Dinwoody, inclusive; Pal, Phosphoria through Flathead, inclusive; p€, Precambrian rocks.

Explaining 4-Way Closure

However illustrative and realistic the "thrust-fold" model is for explaining Rocky Mountain structure, in my opinion this model only tells half the story, structurally. It explains what I call the transverse closure on an anticline, as shown in the usual transverse cross-section, (e.g., Figures 1 & 2), but explorationists well know that oil and gas producing structures require 4-way closure in most cases. In our emphasis on studying, understanding, and balancing transverse cross-sections, we, as explorationists and structural geologists, have generally neglected to consider the closure, or plunge, in the longitudinal direction (see Figure 3). What causes this longitudinal closure, i.e., the plunge

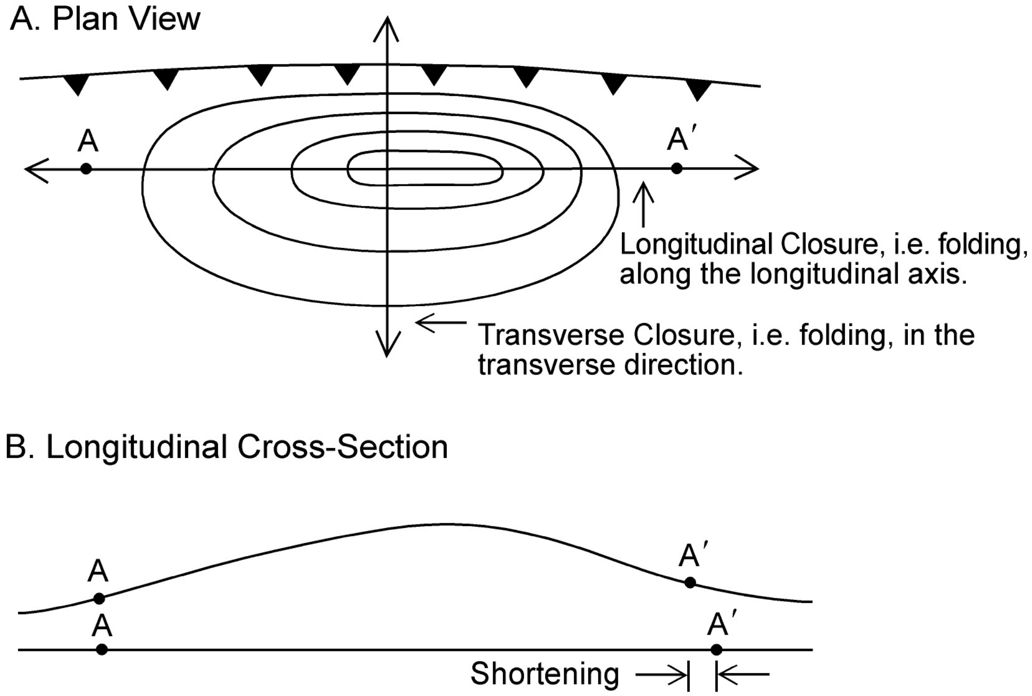


Figure 3. A. Schematic structural contours of a typical Rocky Mtn. "thrust-fold" showing the position of the underlying thrust. The transverse and longitudinal closure are labelled separately. This might be called a "doubly asymmetric fold," and is the typical form of actual structures.

B. Longitudinal Cross-Section. Restoration of A-A' along the chord of the fold to a straight line reveals the shortening in the longitudinal direction.

at the ends of an anticline? This is a question seldom addressed in structural geology textbooks and the prolific technical literature of petroleum geology. The answer I propose is quite simple, even trivial some will say, but in my opinion it is an important advancement in our understanding of structural geology in compressional systems. It takes us one step closer to a more comprehensive understanding of regional structure in the Rocky Mountain province in general. *Longitudinal closure is due to compression ("shortening") in a longitudinal sense, that is, a stress that results in strike-slip movement along the horizontal trace of the thrust (see Figure 4).* Some would describe the causative force in this case as transpressive stress. (Transpression is a relatively new term not found in the 1957 "Glossary of Geology" (Howell), although it did appear in the 1980 (Bates & Jackson) version.)

The compressive nature of the longitudinal stress vector is proven by shortening (i.e. folding, or closure) in that direction, just as it is in the transverse direction (Figure 3B). Furthermore, I suggest that the location of the steeper dip of the longitudinal closure (plunge) shows us the direction of movement, just as it does in the transverse direction (see Figure 4). The steeper dip in both directions seems to commonly occur on the front, or advancing, edge of the fold. However, more study of longitudinal closure must be made before this observation can be accepted as fact.

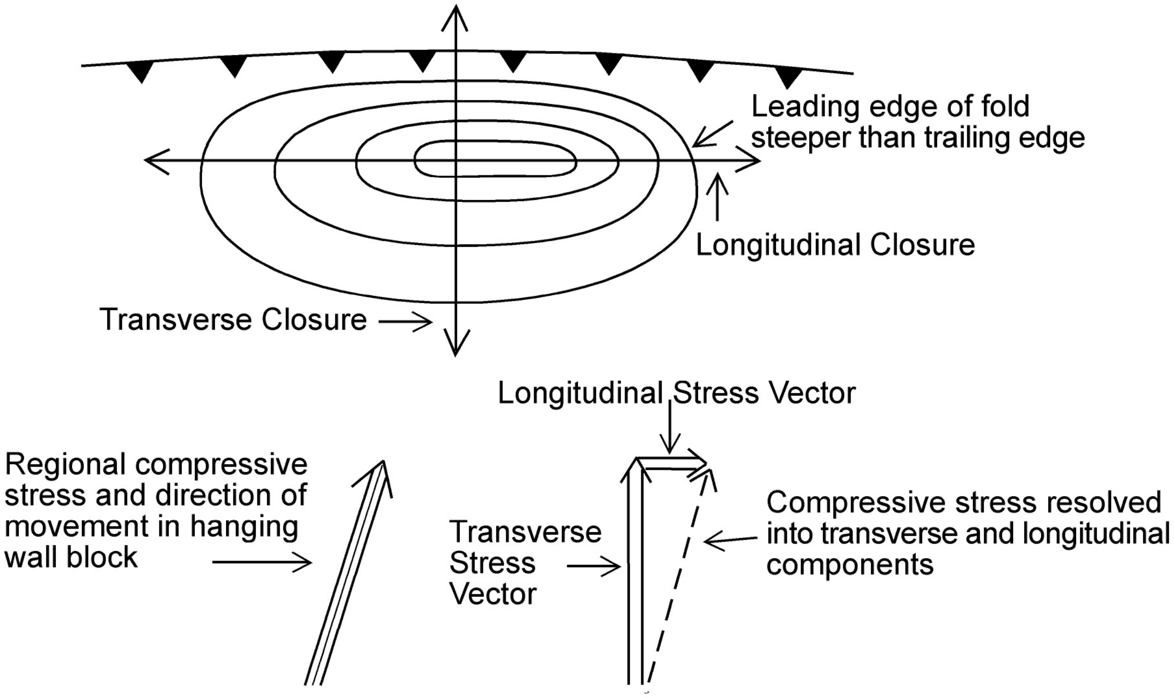
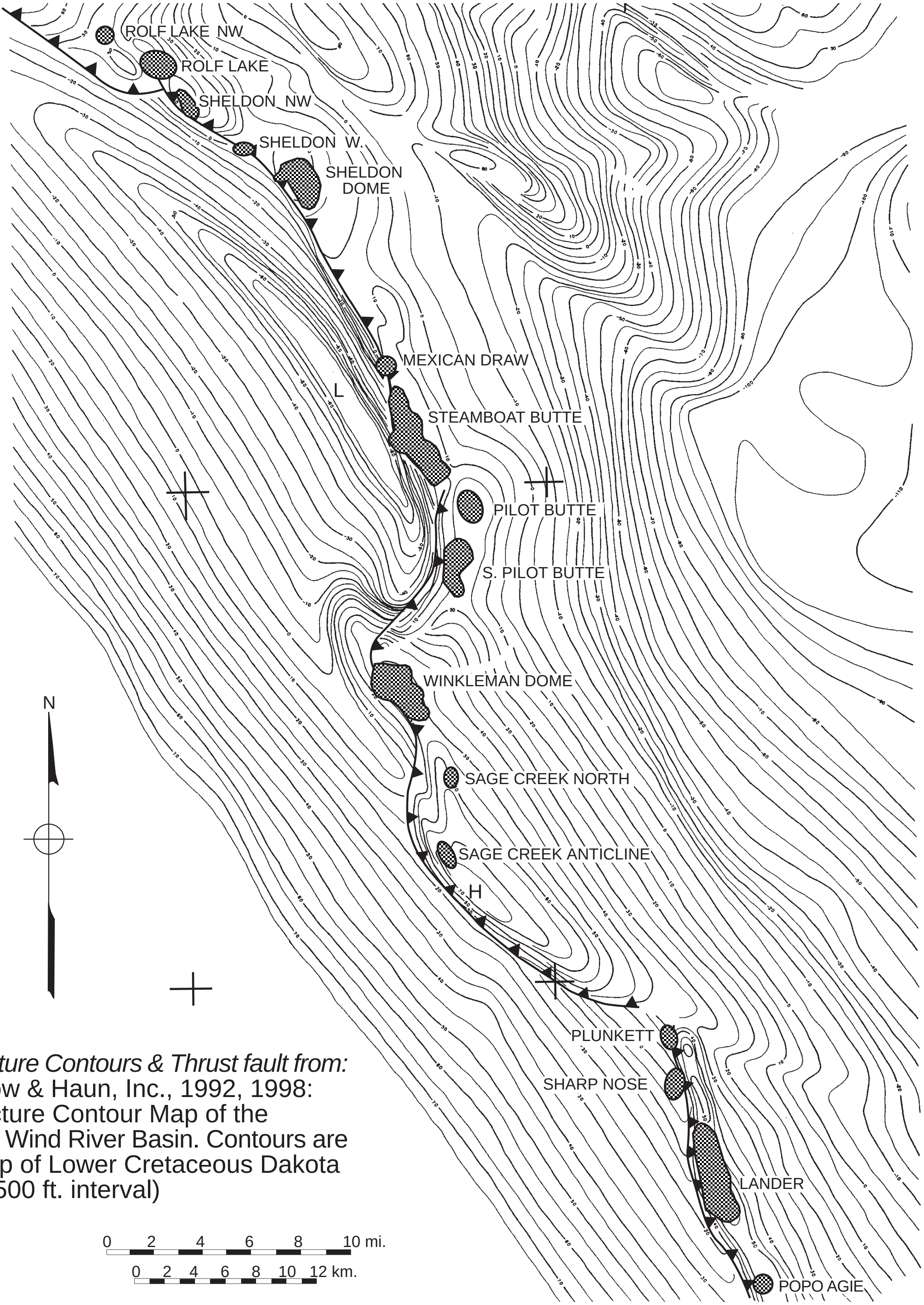


Figure 4. Typical thrust-fold structure showing the causative stress resolved into transverse and longitudinal components.

In a structural system where evidence of both strike-slip and thrust movements are present, it is possible, and some will argue that, these movements have occurred at different times. However, such a scenario requires two separate tectonic events. In the majority of cases, it is likely that both strike-slip and thrust movements occurred simultaneously in a single transpressional event.

Figure 5 shows a series of thrust-fold anticlines that occur on the west side of the Wind River Basin. These have resulted from southwesterly-directed thrusting (and using the criteria of steep dip



Structure Contours & Thrust fault from:
Barlow & Haun, Inc., 1992, 1998:
Structure Contour Map of the
West Wind River Basin. Contours are
on top of Lower Cretaceous Dakota
fm. (500 ft. interval)

Figure 5. A continuous left-lateral thrust-fold system on the west side of the Wind River Basin, Wyoming. There are 7 major anticlines present, but some have multiple crests, resulting in separate oil fields. The 16 named fields have a combined estimated ultimate recovery exceeding 500 million barrels of oil. Steeper longitudinal dip on the northwest ends of the folds indicates left-lateral movement along the thrust.

in the direction of movement) having left-lateral slip. There are 15 separate oil fields in this 60-mile long chain of structures with total estimated reserves exceeding 500 million barrels of oil. One feature of interest is the average length of the major anticlines in the longitudinal direction - approximately 8 miles. It has been suggested that these anticlines and oil fields bear an en-echelon relationship to each other (D.S. Stone, personal communication, 1999) but there is nothing in the pattern of fields or folds to support this contention (see Figure 5).

Classical Strain Theory and Longitudinal Closure

How well does classical strain theory (e.g. Billings, 1972, 164-168, Uemura and Mizutani, 1979, p. 135-141) or the Andersonian theory of faulting (Anderson, 1951) explain the phenomenon of strike-slip movement on thrust faults? Not very well. The mathematics of strain theory is quite specific in stating that a <u>thrust plane forms only at right angles to maximum compressive stress</u> (see Figure 6). In this case there are no forces that can cause lateral movement on the thrust, so this model cannot apply to an actual thrust-fold system comprised of tail-to-tail anticlines with longitudinal closure, such as that shown in Figure 5.

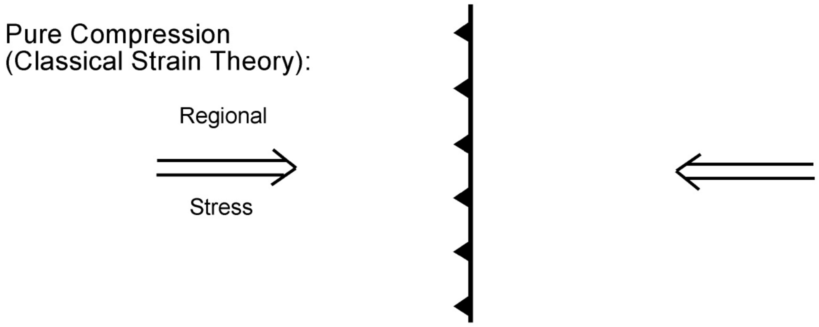


Figure 6. A thrust fault resulting from pure compression as per strain theory.

For lateral, i.e. longitudinal, movement to occur, the horizontal projection of the thrust plane <u>must be non-perpendicular to the direction of regional stress (see Figure 7)</u>. The causative stress in this case is generally referred to as "transpressive" (although it is still purely compressional for faults oriented orthogonal to it). The situation diagrammed in Figure 7 results in right-lateral movement along the thrust system. A rotation of the strike of the thrust the opposite way would create a system with left-lateral movement.

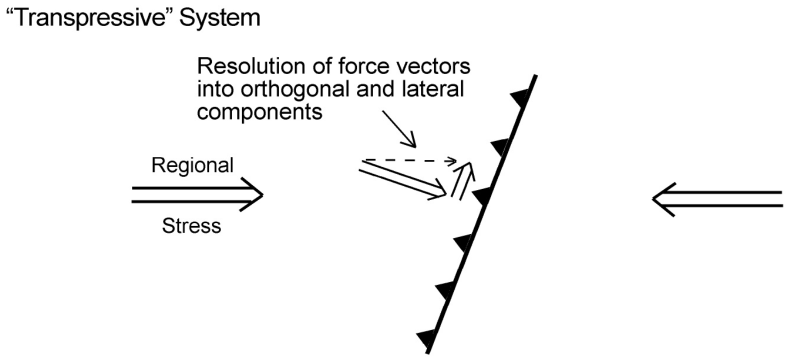


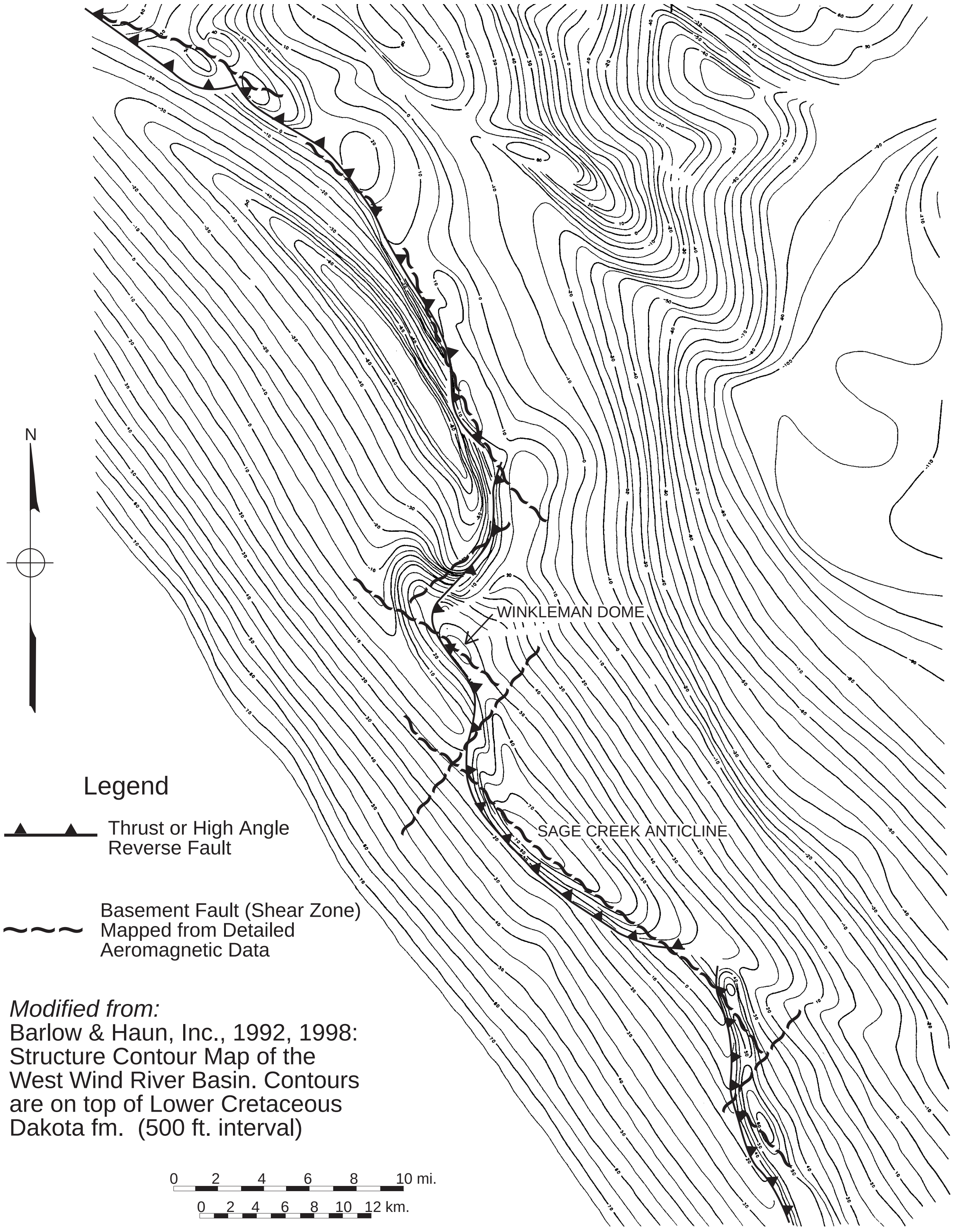
Figure 7. A thrust fault located in a so-called "transpressive" regime. The force in the lateral direction is responsible for the longitudinal closures on folds that form in the hanging wall block.

If strain theory dictates that thrusts must form at right angles to regional compression ("pure compression"), how can thrusts actually occur at an oblique angle to regional compression as in Figure 7? There are two possible answers:

1) The thrust plane forms under one compressive regime, and the direction of stress <u>later rotates</u> - a special case. This is what many geologists would propose, as it does not violate the rules of strain theory too severely, or

2) The more likely scenario, regional compression <u>reactivates a pre-existing basement fault</u> that is <u>not</u> at right angles to maximum compressive stress - the more general case.

Figure 8 shows the <u>actual</u> <u>mapped</u> <u>locations</u> of the underlying reactivated basement faults on the West Wind River Basin thrust-fold system appearing in Figure 5. These faults were mapped from a recent detailed aeromagnetic study of the Wind River Basin that shows they are members of an evenly spaced series of pre-existing parallel basement faults (shear zones) most of which show no reactivation (basement fault characteristics and basement mapping techniques are discussed in detail in Gay, 1995).



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Barlow & Haun, Inc., 1992, 1998: Structure Contour Map of the West Wind River Basin. Contours are on top of Lower Cretaceous Dakota fm. (500 ft. interval)

Figure 8. West Wind River Basin fold and thrust system with causative basement faults marked. This system follows 4 “main” NW trending basement faults and 3 cross-faults and exhibits other interesting characteristics (see text).

The faults in Figure 8 are quite revealing in helping us understand the kinematics of fault reactivation. It is seen that the thrust-fold system follows four separate northwest trending primary basement faults and three secondary, or cross-cutting, northeast basement faults. In the southeasternmost cross-trend, the thrust cuts across it without being greatly affected. However, on the other two cross-trends, the folds terminate (Sage Creek Anticline and Winkleman Dome). Possibly these cross-trends were characterized by up-to-the-west normal faults that acted as barriers to longitudinal movement, thus resulting in accentuation of the folds and/or increased fracturing of the strata in the folds. Winkleman Dome is the most prolific oil producer in this whole chain of fields, perhaps due to such fracturing. A hidden northeast-trending cross-fault just northwest of Winkleman Dome was actually proposed by Keefer (1970) to explain the structural relations he observed in outcrop. Sage Creek Anticline is the highest of the structures, but is non-producing, apparently due to erosional breaching of the productive and/or sealing strata.

Other Examples and Conclusions

The phenomenon of end-to-end anticlines formed along regional thrusts having lateral movement appears to be common in the Rockies. Figure 9 shows such a thrust-fold system controlled by basement faults in the Powder River Basin, Figure 10 shows another in the Big Horn Basin, and Figure 11 is a structure map of the Western U.S. overthrust belt where three or more such systems are present in a thin-skinned environment. A similar strike-slip fold and thrust system in the Midcontinent is the Nemaha Ridge in Kansas and Oklahoma where strike-slip (longitudinal) movement may equal, or nearly equal, thrust (transverse) movement (Gay, 1999).

Knowing the general structural characteristics of compressional systems as set forth herein, including the locations of controlling basement faults and their orientations relative to regional stress, should enable explorationists to find new oil and gas-bearing structures in the Rockies and

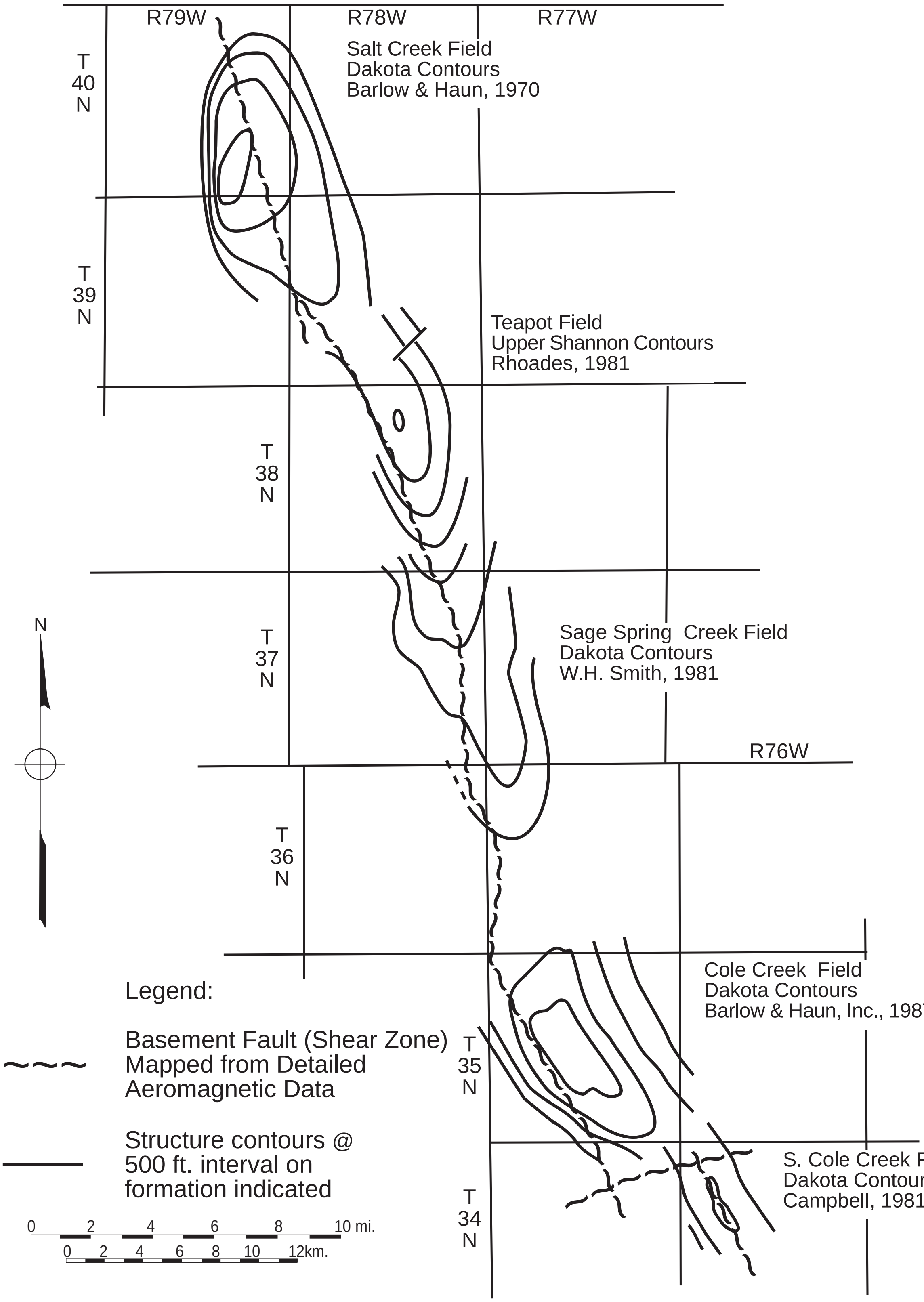
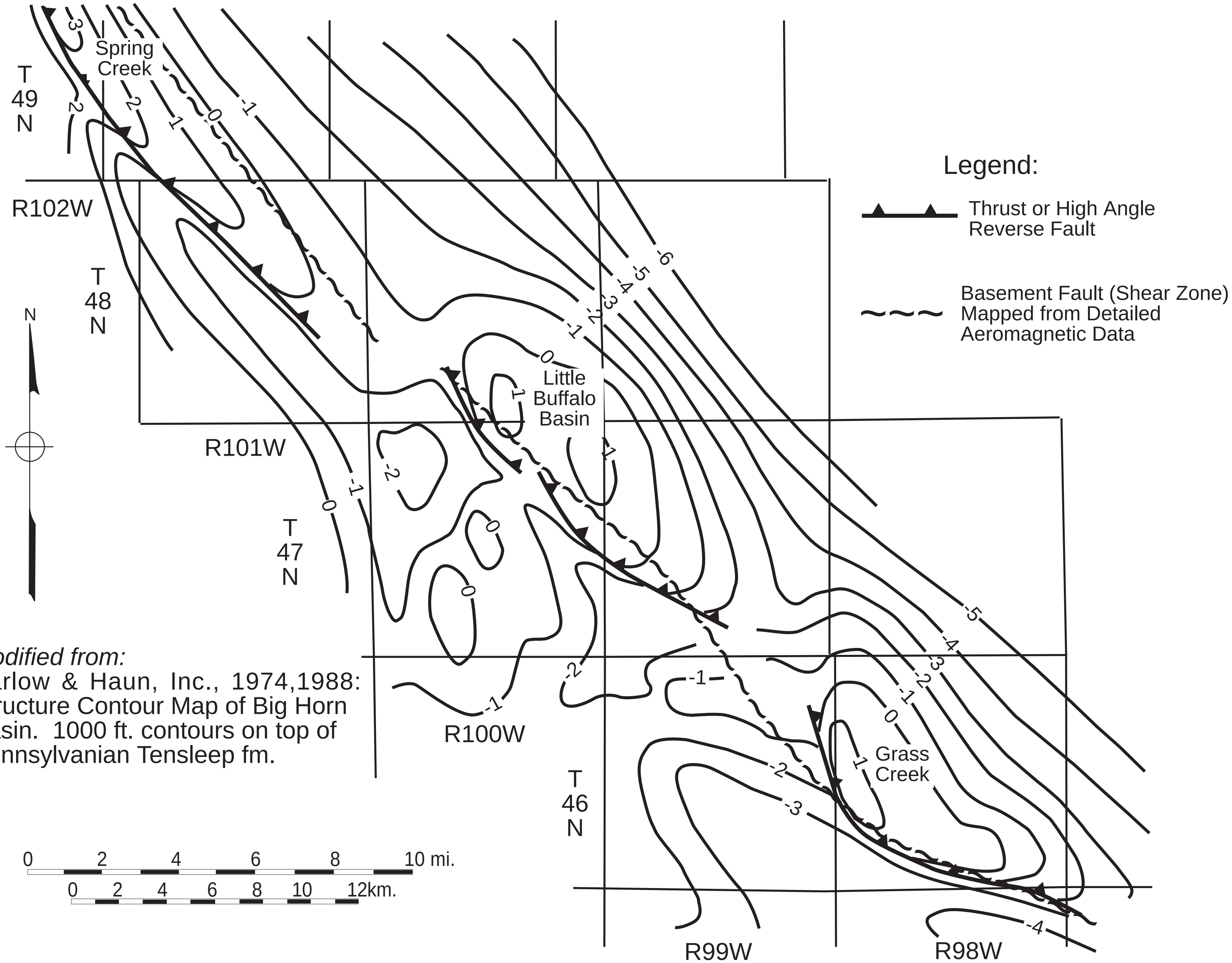


Figure 9. A chain of anticlinal thrust-fold fields on the Casper Arch in the Powder River Basin, WY. None of the published maps show an underlying thrust, but basement faults occur in precisely the right locations for giving rise to blind thrusts or reverse faults that create the asymmetric folds. The northernmost of these fields, Salt Creek, has produced over 680 million barrels of oil and appears to result from left-lateral movement on the underlying thrust. The “tri-shear” model of fault propagation folding (Erslev, 1991) may apply to these structures.



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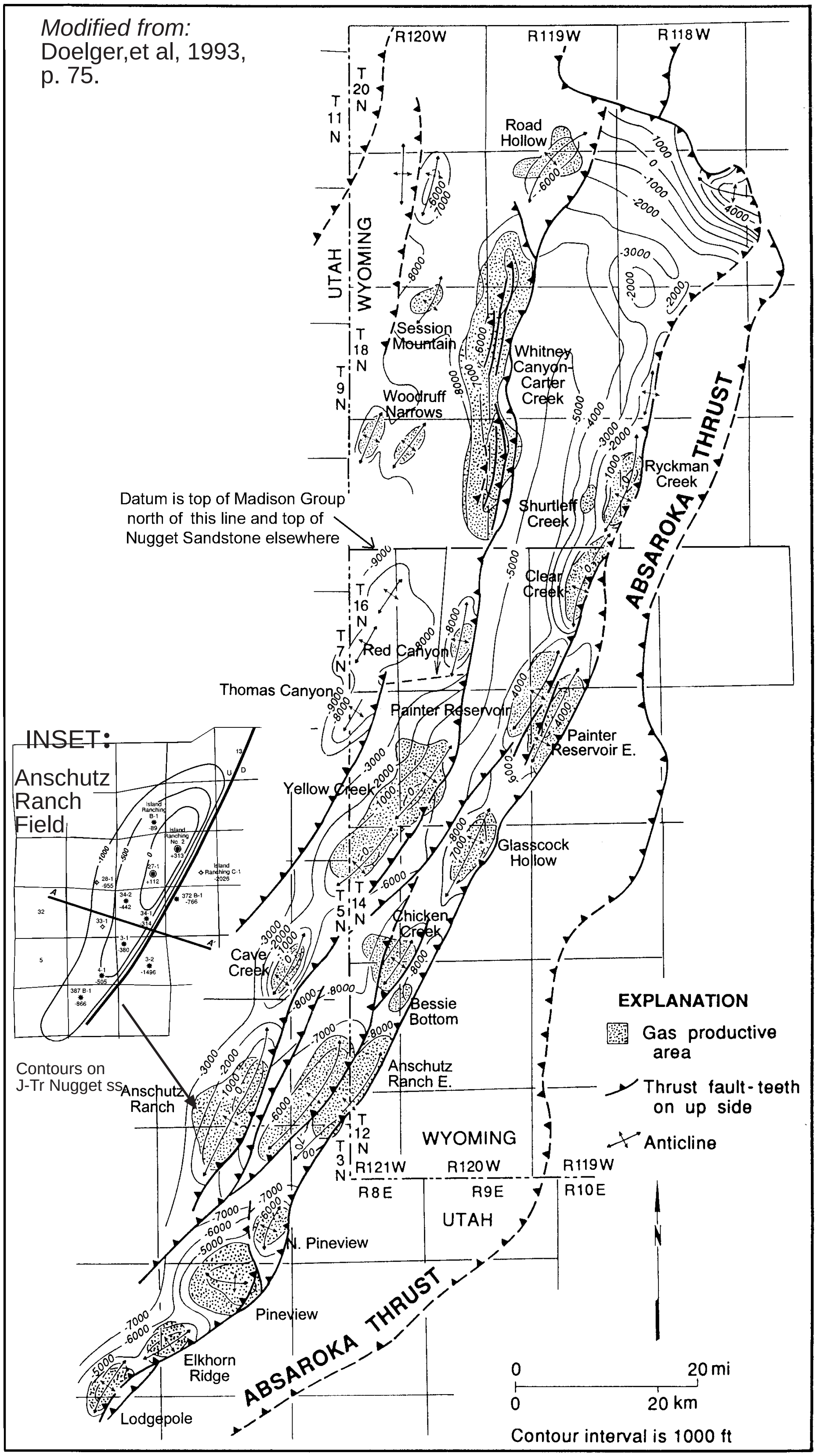
Barlow & Haun, Inc., 1974,1988: Structure Contour Map of Big Horn Basin. 1000 ft. contours on top of Pennsylvanian Tensleep fm.

Figure 10. A thrust-fold system in the SW part of the Big Horn Basin. The increasing distance between the basement fault trace and the thrust fault trace toward the northwest indicates a flattening of dip of the thrust to the northwest.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Doelger,et al, 1993, p. 75.

Datum is top of Madison Group north of this line and top of Nugget Sandstone elsewhere

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Figure 11. The western U.S. overthrust belt in Utah and Wyoming. These structures formed during the early stages of the Laramide orogeny and show three or more classic chains of end-to-end thrust-fold anticlines in a thin-skinned environment. Horizontal movement appears to be right-lateral because of steeper longitudinal dip on the north ends of the folds.

in similar structural settings worldwide. It should also contribute to a better understanding of the kinematics of thrust systems in general.

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References

Anderson, E.M., 1951, Dynamics of faulting and dyke formation, 2nd edition, 206 pp., Oliver and Boyd, Edinburgh.

Bates, R.L. and J.A. Jackson, 1980, Glossary of Geology, 2nd Edition: American Geological Institute, p. 661.

Barlow, J.A. and J.D. Haun, 1970, Regional stratigraphy of Frontier formation and relation to Salt Creek Field, Wyoming, in M.T. Halbouty, editor, Geology of Giant Petroleum Fields: AAPG, Tulsa, pp. 147-157.

Bayley, R.W. and W.R. Muehlberger, 1968, Basement Rock Map of the United States, U.S. Geological Survey.

Berg, R.R., 1962, Mountain flank thrusting in Rocky Mountain foreland, Wyoming and Colorado: American Association of Petroleum Geologists Bulletin, v. 46, pp. 2019-2032.

Billings, M.P., 1972, Structural geology, 3rd Edition: Prentice Hall, 606 p.

Campbell, D., 1981, South Cole Creek Field, in Powder River Basin Oil and Gas Fields Case Histories Volume: Wyoming Geological Association, Casper, pp. 94-97.

Cohee, G.V., et al, 1962, Tectonic Map of the United States: American Association of Petroleum Geologists.

Doelger, J.J., D.M. Mullen, and Barlow and Haun, Inc., 1993, Thrust belt structure plays - overview, in J.M. Robertson, et al, editors, Atlas of Major Rocky Mountain Gas Reservoirs: New Mexico Bureau of Mines and Mineral Resources, Socorro, p. 75.

Erslev, E.A., 1991, Trishear fault-propagation folding: Geology, v. 19, pp. 617-620.

Gay, S.P., Jr., 1995, The basement fault block pattern: its importance in petroleum exploration, and its delineation with residual aeromagnetic techniques, in R.W. Ojakangas, editor, Proceedings of the 10th International Basement Tectonics Conference: Kluwer Academic Publishers, Dordrecht, pp. 159-208.

_____, 1999, The strike-slip, compressional thrust-fold nature of the Nemaha system in eastern Kansas and Oklahoma, in D. Merriam, editor, Transactions of the 1999 AAPG Mid-continent Section Meeting, Wichita.

Gries, R., 1981, Oil and gas prospecting beneath the Precambrian of foreland thrust plates in the Rocky Mountains: Mountain Geologist, v. 18, pp. 1-18.

_____, 1983, Oil and gas prospecting beneath Precambrian of foreland thrust plates in Rocky Mountains: AAPG Bulletin, v. 67, pp. 1-28.

Harding, T.P. and J.D. Lowell, 1983, Structural styles, their plate tectonic habitats and hydrocarbon traps in petroleum provinces, in A.W. Bally, editor, Seismic Expression of Structural Styles, v.1, AAPG, Tulsa, pp. 1-24.

Howell, J.V., 1957, Glossary of Geology and Related Sciences: American Geological Institute, p. 303.

Jacob, A.F., 1983, Mountain front thrust, southeastern Front Range and northeastern Wet Mountains, Colorado, in J.D. Lowell, editor, Rocky Mountain Foreland Basins and Uplifts: Rocky Mountain Association of Geologists, Denver, pp. 229-244.

Jacob, A.F. and R.G. Albertus, 1985, Thrusting, petroleum seeps and seismic exploration, Front Range south of Denver, Colorado, in Rocky Mountain Section (of AAPG) Field Trip Guide: AAPG, Tulsa.

Keefer, W.R., 1970, Structural geology of the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495-D

.

Longwell, C.R., et al, 1944, Tectonic Map of the United States: American Assn. of Petroleum Geologists.

Perry, W.J., D.H. Roeder, and D.R. Lageson, 1984, Introduction, in W.J. Perry, D.H. Roeder and D.R. Lageson, editors, North American thrust-faulted terranes: AAPG, Tulsa, pp. v-xi.

Ray, R.R. and W.R. Keefer, 1985, Wind River Basin, Central Wyoming, in R.R. Gries and R.C. Dyer, editors, Seismic Exploration of the Rocky Mountain Region: Rocky Mountain Association of Geologists, Denver, pp. 201-212.

Rhoades, R.E., 1981, Teapot Field, in Powder River Basin Oil and Gas Fields Case Histories Volume: Wyoming Geological Association, Casper, pp. 413-417.

Smith, W.H., 1981, Sage Spring Creek Field, in Powder River Basin Oil and Gas Fields Case Histories Volume: Wyoming Geological Association, Casper, pp. 356-357.

Stone, D.S., 1983, The Greybull Sandstone pool (Lower Cretaceous) on the Elk Basin thrust-fold complex, Wyoming and Montana, in J.D. Lowell, editor, Rocky Mountain foreland basins and uplifts: Denver, Colorado, Rocky Mountain Association of Geologists, pp. 345-356.

______, 1984, The Rattlesnake Mountain, Wyoming, debate: A review and critique of models: The Mountain Geologist, v. 21, pp. 37-46.

______, 1993, Basement-involved thrust-generated folds as seismically imaged in the subsurface of the central Rocky Mountain foreland, in C.J. Schmidt, R.B. Chase, and E.A. Erslev, editors, Laramide Basement Deformation in the Rocky Mountain Foreland of the Western United States: Boulder, Colorado, Geological Society of America Special Paper 280.

Uemura, T. and S. Mizutani, 1979, Geological Structures: John Wiley, 309 p.