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STRESSES AND FRACTURES IN THE FRONTIER FORMATION, GREEN RIVER BASIN, PREDICTED FROM BASIN-MARGIN TECTONIC ELEMENT INTERACTIONS*

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ABSTRACT

Thrust faults are capable of affecting the stress magnitudes and orientations in little-deformed strata several hundreds of kilometers in front of a thrust front. A conceptual model based on this mechanism suggests that regional fractures and the maximum horizontal compressive stress trajectories in the Frontier Formation in the central Green River basin trend approximately north-south. This regional pattern results from the imposition of stresses onto basin-fill strata by Sevier and Laramide thrusting at the edges of the basin. The Sevier thrust belt on the western margin of the basin was active for 100 million years, but had relatively little permanent

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influence on stresses and fracturing in the Frontier Formation within the basin because stresses from this system were self-limiting. The east-west horizontal stress trajectories from this system were overwhelmed by north-south compression during the Laramide orogeny. Stress and fracture orientations deviate from the general north-south trend at the basin margins, in the corners of the basin, and in association with local structures. Stress-orientation data, from a limited number of oriented caliper logs, support the conceptual stress trajectories.

INTRODUCTION

Rationale

Natural fractures and in situ stresses commonly dictate subsurface reservoir permeability and permeability anisotropy, as well as the effectiveness of stimulation techniques in low-permeability, natural gas reservoirs. This paper offers an initial prediction for the orientations of the fracture and stress systems in the tight gas reservoirs of the Frontier Formation, in the Green River basin of southwestern Wyoming (**Fig. 1**). It builds on a previous report that addressed fractures and stresses in the western part of the basin (Laubach and Lorenz, 1992), and on ideas developed for the rest of the basin (Lorenz, 1993), using the principle that thrust faults are capable of affecting the stress magnitudes and orientations in little-deformed strata several hundreds of kilometers in front of a thrust (Lorenz et al., 1993).

The prediction of subsurface stresses and natural fracture orientations is an undertaking that requires the willingness to revise models as definitive data are acquired during drilling. The predictions made in this paper are offered with the caveat that geology in the subsurface is always full of surprises.

Approach

A semi-quantatative conceptual geologic model of the fracture/stress system in the Green River basin is offered as the principal result of this study. The key elements of this model are (1) stratigraphy: the age, burial history, and rock properties of the strata in which the reservoirs occur, and (2) tectonics: the location, geometry, and timing/direction/magnitude of motion of the structural features comprising the basin. Since rock properties are in large part dependent on changes in pore pressure, an estimate of the pore pressure history of the strata is also necessary.

The nature of most of these elements will vary across the basin, with depth, and through time. Thus this is a four-dimensional problem with the complications of a cumulative history. The goal is to reconstruct the geologic history closely enough to duplicate the conditions under which fracturing occurred (thus to reconstruct fracture characteristics and patterns), and to correctly "predict" the present stress orientations and magnitudes.

Zoback and Zoback (1989) map current in situ stress domains as almost continental-scale features, and global tectonism is certainly the ultimate source of local geologic structure. However, reconstructions and predictions of the locally variable basin-scale stresses and fracturing, especially at the relatively shallow depths of interest to the hydrocarbon industry, are likely to be more accurate if modelled at the scales of basins and structures, and if vertical variations are allowed for.

Geologic Setting

The Green River basin is the western sub-basin within the amalgamated Greater Green River basin. It lies between the Wind River and Uinta Mountains to the north and south, and the Rock Springs Uplift and Sevier Thrust Belt to the east and west respectively (**Figs. 1,2**). The Moxa Arch trends north-south across the western part of the basin.

The Frontier Formation, early Late Cretaceous in age, is the focus of this paper. The low-permeability, gasbearing sandstones of this unit were deposited in a variety of marine and non-marine environments during several regressive phases in the infilling of the Western Interior Cretaceous Seaway (e.g., Dutton, 1993; Winn et al., 1984; Moslow and Tillman, 1989; Merewether, 1984; Cobban and Reeside, 1952). Numerous channel and shoreline sandbodies are interbedded with shales, mudstones, and local coals and conglomerates (De Chadenedes, 1975; Myers, 1977; Hamlin, 1991). The clastic sediments that comprise the Frontier Formation were derived from erosion of highlands elevated by tectonic activity to the west along the Paris-Willard thrust fault in the Sevier thrust belt (Schmitt et al., 1981).

If the stresses and fractures in the Frontier Formation can be predicted, recovery of the natural gas from the formation can be facilitated. Moreover, the stresses and fractures in the Frontier may be relevant to understanding these parameters in younger formations.

STRATIGRAPHY

Age and Thickness

The Frontier Formation was deposited during the Cenomanian and Turonian stages of early Late Cretaceous time, between about 96 and 89 m.y. (Merewether, 1984). The associated tectonic events are less precisely dated (**Fig. 3**), but are reasonably well known (e.g., Wiltschko and Dorr, 1983). The influx of Frontier sediment left a layer of relatively sandy strata between 150 ft (50 m) and 900 ft (300 m) thick (Merewether, 1983) within the Cretaceous marine shales filling what would become the Greater Green River basin. The strata thicken westward as a result of rapid foredeep subsidence in front of the thrust belt.

Burial History

Rock properties change with depth of burial, since compaction changes bulk density and since diagenetic changes (cementation, leaching, mineral alteration, etc.) effect strength and mechanical properties. The rates of the mineralogic changes are not well known, but compaction-depth curves have been published for different types of sediments in various basins (e.g., Tertiary sediments in the Gulf of Mexico; Nettleton, 1934).

From these curves, it has been assumed that most of the Frontier sediments were reasonably well lithified by the time they were buried to about 3000 ft (1000 m). Most of the Frontier Formation was buried to at least this depth by the end of Cretaceous time, about 24 m.y. after final Frontier deposition. Thicker Frontier strata at the western margin of the basin, however, were deposited in the Cretaceous foredeep and buried relatively rapidly, and may have resembled the poorly consolidated Tertiary strata in the Gulf of Mexico for some time after Frontier lithification elsewhere in the basin.

The west- and northwest-ward thickening trend in the western part of the basin is typical of the post-Frontier, Upper Cretaceous formations west of the Moxa Arch, where nearly 19,000 ft (6000 m) of Upper Cretaceous strata were deposited over the Frontier Formation (Weimer and Haun, 1960; Weimer, 1961). This compares to a 3000 ft (1000 m) thickness for the same strata over the crest of the adjacent Moxa Arch. Over and east of the Moxa Arch, average Cretaceous sedimentation rates were a factor of 3 to 4 slower than in the foredeep. Although the sediments were less deeply buried, dewatering, compaction, and diagenesis may have proceeded at a more normal rate over the arch, allowing early lithification and a susceptibility to fracturing during some of the earlier tectonic stress events described below.

Erosional remnants of Paleogene strata suggest thickening southward along the Moxa Arch as a result of subsidence against the Uinta Mountains. The structure-contour map of the Green River basin (Lickus and Law, 1988) shows a similar basin-margin thickening of post Cretaceous strata against the Wind River Mountains. Most of this thickening occurred after lithification of the Frontier Formation, and thus its effects were to enhance fracture susceptibility (due to increased pore pressures associated with thermal maturation at deeper burial), rather than to delay it as in the Cretaceous foredeep.

Pore Pressure

Pore pressure counteracts the strengthening effects that confining stresses have on a rock, and weaker rock fractures more readily. Due to overpressuring, deeply buried strata are often under low effective confining stresses despite burial, and are therefore relatively weak and susceptible to fracture. However, a differential stress is required to fracture rocks, and the differences between the principal stresses diminishes as pore pressure increases (e.g., Lorenz et al, 1991; Yassir and Bell, 1994). Thus optimum conditions for fracturing of strata occur at pore pressures elevated above the hydrostatic gradient but less than the lithostatic value.

Pore pressures throughout the Green River basin, but especially in the more deeply buried strata, have been enhanced during gas generation associated with organic maturation (Law et al., 1980; Law, 1984; McPeek, 1981). Pore pressures near the tectonically active margins of the Green River basin have been further elevated, probably by compression associated with thrusting and/or rapid sedimentation. Rathbun and Dickey (1969) report pore pressure gradients as high as 0.91 psi/ft (2.03 MPa/100 m) adjacent to the Wind River thrust, and up to 0.66 psi/ft (1.47 MPa/100 m) just east of the Sevier thrust belt. Subsequent studies (Law, 1984) found that significantly overpressured strata are rare above the depth at which formation temperatures equal 190-200 degrees F (88-93 degrees C) in the central parts of the basin, but are common below this level. This temperature horizon is presently relatively uniform across the basin at about -11,500 ft (-3500 m), deepening to about -15,500 ft (-4700 m) against the Uinta thrust front (Law and Smith, 1983).

Strata below this horizon should be, at least at the present time, susceptible to fracturing due to the low effective confining stresses related to elevated pore pressures. However, in the absence of active tectonic compression, stress magnitudes and differentials should be low, and the probability of active natural fracturing in these rocks is low despite their susceptibility.

Nevertheless, these strata are the most likely to have been fractured under earlier tectonic stresses. The deepest horizons, and those at the tectonically active margins of the basin, commonly are the most overpressured and therefore most susceptible. Tertiary uplift and erosion of the strata within the basin should have caused cooling and a downward migration of the 190-200 degree F (88-93 degrees C) horizon; strata several hundreds of meters above this present-day temperature level may have been overpressured and susceptible to fracturing during tectonism, prior to and immediately after mid-Tertiary uplift.

The relatively uniform depth-to-temperature horizon crosses formation boundaries. Associated vertically stratified fracture domains would thus be only loosely related to stratigraphy. Moreover, the uniformity of this temperature horizon is perturbed near the basin margins: a cross section across the northwestern corner of the basin suggests that the overpressured horizon was displaced upward by Laramide thrust faulting and has not yet regained equilibrium (Law, 1984). Conversely, rapid subsidence of the strata in front of the Uinta thrust caused steepening of the thermal gradient in this area, and thus the zone of likely fracturing is also deeper.

A coal-rank map (Scott, 1994) also shows changes in the thermal regime near the basin margins. Top-of-Cretaceous coals increase in rank within 12 mi (20 km) of the Wind River Mountain front, and decrease in rank adjacent to the Rock Springs Uplift. Much of this is related to maximum depth of burial. Although strata associated with these coals are typically fractured in outcrop (Grout and Verbeek, 1992), they were not as susceptible to fracturing for as extended an interval, or as early in their history, as strata at the northern margin of the basin.

Intermediate Summary

The conceptual model being developed suggests that the Frontier sandstones were probably lithified and capable of fracturing after being buried to about 3000 ft (1000 m) by about 65 m.y., except at the western edge of the basin where high subsidence rates led to overpressured, unconsolidated strata. Once lithified, and as burial continued, brittle rock properties were imparted to these sandstones by elevated pore pressures (1) near the active margins of the basin by compression related to thrust faulting, and (2) below burial depths of 11,500 ft (3500 m) by gas generation associated with organic maturation. This top-of-overpressuring horizon crosses formation boundaries. It is probably several hundreds of meters lower in the section than it was initially (due to cooling during uplift and erosion), and it has been depressed by foredeep subsidence at the north and south basin margins. It has also locally been elevated by thrusting at these same margins.

TECTONICS

Introduction

With the qualitative picture of the fracture susceptibility of strata as assembled above, the tectonic setting must now be considered. Strata will not fracture just because they are weak; there must also be a differential stress imposed on the rocks. The timing and magnitudes of motion of the structures associated with the basin must be reconstructed, since lateral (thrust) motion of the structures created stress in the adjacent strata due to volume constraints.

Large thrust faults define the present margins of the Green River basin, and several structural elements occur within its confines (**Fig. 2**). There are three questions to be answered for each structural element of the basin in order to determine how much stress it imparted to the adjacent basin-fill strata: (1) how much motion of the element took place, (2) in what direction(s) was the motion, and (3) when did motion occur? The thick-skinned, Laramide Wind River and Uinta Mountains thrust blocks impinge on the northern and southern basin margins respectively. The western edge of the basin is presently defined by the Sevier thrust belt, a complex, longer-lived thrust system with considerably more lateral displacement of thinner thrust sheets. The Rock Springs Uplift, a smaller fault-bounded Laramide uplift, defines the eastern edge of the Green River basin. The Moxa Arch is the principle structural feature within the basin.

Sevier Thrust Belt

Timing: The Sevier thrust belt was active for nearly

100 m.y., between Late Jurassic and Early Eocene time (Wiltschko and Dorr, 1983). The Frontier Formation was deposited near the middle of this interval (**Fig. 3**). Frontier strata could have been stressed by any or all of the eight, separate, post-Frontier thrust events, although compressional stresses from the earliest of these were probably dissipated into poorly consolidated Frontier sediment.

Stress Magnitude: This report assumes that the stresses in the foreland strata in front of the thin-skinned thrust sheets were derived primarily from impingement of thrusts, rather than from the overall regional stresses that initiated thrusting or from the drag of subcrustal convection currents.

Approximately 60 mi (100 km) of east-west shortening was accommodated during compression of the Sevier thrust belt to 50% of its original width (Royse et al., 1975). Individual thrusts have displacements of up to 30 mi (50 km) (Dixon, 1982). The large displacements and the lateral compressive forces necessary to initiate and propagate them suggest that the system probably imparted stress eastward into the adjacent basin. Measurements have been made of the strains resulting from compressive horizontal paleostresses in front of the similar Appalachian and Ouachita thrust systems (Craddock et al., 1993), confirming that such a transmission of stress from thrust belt to basin-fill strata can take place in these systems.

However, this was thin-skinned thrusting: stress in the undeformed foreland strata should never have exceeded that level needed to initiate a new thrust. Once this stress level was exceeded, a new thrust formed and compression of the strata beyond it was temporarily relieved (Bombalakis, 1986). A crude estimate of the stress needed to initiate a new thrust, and therefore of the maximum stress imparted to adjacent undeformed strata, can be made by adapting the arguments of Goff and Wiltschko (1992) and Bombalakis (1986) to the problem.

The horizontal force required to initiate a new thrust is approximately equivalent to the breaking strength of the strata (negligible on a geologic time scale), plus the weight of the strata that is lifted up the thrust ramp incline, as modified by the tangent of the incline angle. **(Figs, 4,5)**. This force can be estimated for the Hogsback thrust using geometries from published cross sections (Lamerson, 1982), which show the ramp angle (30 degrees), the depth to the basal decollement (23,000 ft/7000 m), and the horizontal dimension of the wedge of rock lifted (35,000 ft10,700 m).

A one-ft (0.3-m) thick vertical slice through this triangular wedge of rock, using a standard density of 2.4 and the formula for the area of a triangle, should weigh about 6 X 10^{10} lb (2700 metric tons). It would take a lateral compressive force of about 10,500 psi (71 MPa) to push a wedge of this weight up a 30-degree incline. Cello and Nur (1988) suggest that frictional resistance along the shear plane of the thrust decollement would add only 150-750 psi (1-5 MPa) to such a calculation, and thus shear stress is ignored.

This calculation is simplistic, and the resulting value of stress may be more useful for comparison with similarly derived estimates for stresses from other structures than as an absolute number. However, it gives some feel for the magnitudes of stresses involved in this system. Moreover, this value is not significantly different from the stress estimates calculated from calcite twin lamellae in carbonate formations in foreland strata adjacent to the Appalachian and Ouachita thrust systems: Craddock et al. (1993) and Craddock and van der Pluijm, (1989) suggest that the maximum horizontal compressive stress differential directly adjacent to these thrust systems were on the order of 12,000-14,500 psi (81-99 MPa).

The weight of the block being forced up the ramp increased gradually as the thrust grew because the strata thicken toward the hinterland. Therefore the force required to move the thrust increased with distance travelled. Increases in bending resistance and shear stress along the lengthening decollement surface enhanced this effect. When the growing force required to propagate a thrust met or exceeded the threshold of stress required to create a thrust in undeformed foreland strata, a new thrust formed and the old thrust became inactive.

Because the stress system at the toe of the thrust belt is self-limiting, stresses in the undeformed strata in the foreland basin should never have exceeded the level required to form a thrust fault, estimated here to be on the order of 10,000 psi. The maximum stress imparted to the adjacent strata should have occurred just prior to rupture along the new thrust plane. In fact, cross-cutting relationships commonly indicate that the Paleozoic strata within the Idaho-Wyoming thrust belt fractured prior to becoming incorporated into the thrust system (Mitra et al., 1984; Mitra, 1994), and Craddock (1992) inferred thrust-related, layer-parallel stresses of the same order (14,500 psi/99 MPa) for fractured carbonates <u>within</u> the Sevier thrust sheets, suggesting that the fractures formed early, under the high differential stresses present prior to thrust-plane rupture.

A stress on the order of 10,000 psi (68 MPa) is only half to a quarter of that required to break Frontier-type sandstones under laboratory conditions of high confining stress, zero pore pressure, and rapid loading. It would be entirely adequate, however, to fracture such sandstones under geologic conditions where loading took place over millions of years, and where the rock-strengthening effect of confining stress was largely negated by formation pore pressures (Lorenz et al., 1991).

In fact, east-west, thrust-normal fracturing is a strong component of the fracture system present in Frontier sandstone outcrops on the western edge of the basin (Lorenz and Laubach, 1993), and it is inferred that these fractures formed in response to thrust-derived stresses. However, these "thrust-dilatancy" fractures did not form until late in the tectonic history of the strata, post-dating a set of north-south fractures which developed under east-west extension (see below). The absence of early thrust-dilatancy fractures, despite the ongoing nature of the thrusting, may be attributed to (1) non-fracture of poorly consolidated strata near the surface and which, due to rapid burial, remained unlithified to significant depths, (2) rapid burial to depths below the horizons that were most effected by thrust stresses, and/or (3) rapid stress dissipation in front of the thrusts.

<u>Stress Dissipation</u>: Stress magnitude and differential in the foreland strata would have been at their maximum immediately in front of a thrust, and would have decreased with distance from the source. Timoshenko and Goodier (1951) suggest that stress dissipation in a laterally unconstrained elastic medium in front of an isolated indenter occurs at a rate that is dependent on the area

over which the force is applied. Thus a force applied over the 150-mile (250-km) length of the Sevier thrust belt bounding the basin would be decreased to half its original magnitude at twice that distance, 300 mi (500 km), out into the basin. However, measurements of stress dissipation in front of the Appalachian/Ouachita system (Craddock et al., 1993) suggest that a significantly more rapid rate of dissipation takes place in actual geologic systems: i.e., the magnitude of the compressive stress differential inferred from measured strains apparently decayed exponentially to the 50% stress level about 120 mi (200 km) out from the orogenic front, or 2/5 of the theoretical distance (**Fig. 6**).

This would suggest that significant east-west compressive stresses were present across the entire 60 mi (100 km) wide Green River basin. Since stress trajectories would have radiated from the curved thrust front (**Fig. 7**), stress dissipation would probably have been more rapid than observed in the Appalachians by Craddock. Moreover, not all rocks behave elastically, and the thick interbedded Cretaceous shale formations common in the basin (especially those over- and underlying the Frontier Formation) must have accommodated much of the stress as ductile strain.

No quantatative method for estimating this effect has been published. It is suggested here, based on the observation that east-west thrust-dilatancy fracturing in

Frontier sandstones in the Hogsback thrust is a relatively late occurrence (Lorenz and Laubach, 1994), that the east-west differential stress magnitude decayed by 50%, or to about 5,000 psi (34 MPa), as close as 15 mi (25 km) east of the thrust front.

Fracture of the Frontier sandstones is not predicted to have occurred in the mid-basin regions of deep burial under this stress system. Moreover, as will be shown below, significantly larger, north-south trending compressive stresses were superimposed on the strata during Laramide time.

Stress Orientation: As noted, stress trajectories from this system would have been oriented normal to the thrust front. For an arcuate, convex-into-the-basin thrust front such as the Sevier system in Idaho and Wyoming, the trajectories radiate from the curved front (**Fig. 7**). Stress trajectory orientations would become complex where they interact with other structures, but during most of the Late Cretaceous other structures and stresses were not present to interrupt the pattern. The trajectories became more complex once the Uinta and Wind River thrusts became active.

Uinta and Wind River Mountains Uplifts

Timing: The Uinta Mountains which form the southern limit of the basin, and the Wind River Mountains along the northwest-southeast trending northern margin, had initial phases of uplift in latest Cretaceous to Paleocene time (Hansen, 1965; Hansen and Bonilla, 1954; Wiltschko and Dorr, 1983; Perry et al., 1992). These early uplifts were coincident with maximum burial of the Frontier Formation (**Fig. 3**). However, the stratigraphy around these features suggests that the most significant phase of uplift took place along deep-seated thrust faults during classical Laramide (Eocene) time (Crewes and Ethridge, 1993; Steidtmann and Middleton, 1991).

Stress Magnitude: A first-cut estimate of the force required for uplift (similar to the calculation made for the Sevier thrust above) can be made for the Uinta Mountains. A 36,000 ft (11,900 m) vertical offset of the Precambrian basement is depicted on cross sections across the northern margin of the Uinta Mountains (**Fig. 8**), but, due to erosion, that is only the distance lifted, not the initial thickness of the strata lifted. The restored thickness is estimated to have been on the order of 60,000 ft (18,000 m). The ramp angle is about 35 degrees, and the length of the wedge is about 55,000 ft (17,000 m). The horizontal force required to lift this weight up a frictionless incline is about 22,000 psi (150 MPa), about twice that derived above for the thin-skinned Sevier thrust system. Brewer and Turcott (1980), using the Anderson theory of faulting, derived a conveniently similar value of 26,000 psi (177 MPa) for the force required to lift the Wind River Mountains.

The important differences between the Sevier and Laramide systems are that:

(1) The Laramide thrusts are opposite-verging, thick-skinned thrusts on opposing edges of the basin, doubling the stress effect in the north-south direction within the basin-fill strata.

(2) These thrust fronts acted like bulldozers, crumpling strata before them during the formation of overhangs of up to 15 mi (25 km) rather than riding up and over the adjacent strata. Because they did not ride up and over, these thrust/stress systems were not self-limiting as was the Sevier system: significantly more of the stress that went into creating the uplifts could be, and probably was, imparted to the adjacent strata. A 6-mi (10-km) indentation at both edges of a 120 mi (200-km) wide basin would equal a 10% strain that would have created enormous stresses, although local folding, peeling back, and uplifting of the immediately adjacent strata would reduce this.

(3) Thrusting occurred over a relatively short time, intensifying the differential stress by limiting the time-dependent, stress-mitigating ductility effects of interbedded shales. Warpinski, 1989, suggests that a reasonable relaxation time constant for Cretaceous shales

in the Piceance basin is on the order of 5 m.y.

Thus the magnitude of compressive stress derived from the Uinta-Wind River systems was probably at least twice that derived from the Sevier system, and the maximum horizontal compressive stress in the basin immediately adjacent to the thrusts could have been in excess of 22,000 psi (150 MPa).

Stress Dissipation and Orientation: The Wind River thrust front is approximately 90 mi (150 km) long, and the Uinta thrust front is 75 mi (125 km) long. Combining these lengths and using the Timoshenko and Goodier (1951) elastic criteria, stress values would not have decreasedto the fifty-percent level until a distance of over 300 mi (500 km), well beyond the basin margins. However, applying the empirical:theoretical ratio of 2:5 noted for the thin-skinned thrusting above, the 50% stress level would occur at a distance of about 120 mi (200 km). Further adjusting the predicted stress levels qualitatively for shale ductility by a somewhat lesser effect than for the Sevier system--since it would be largely offset by rapid loading--the north-south horizontal compressive stress component within the basin is suggested to have been reduced to the 50% level (11,000 psi/75 MPa) within 30 mi (50 km) of the thrust front, and probably remained above 5,000 psi (34 MPa) throughout the basin during Laramide tectonism.

The thick-skinned, Laramide uplift events overlapped physically and chronologically with episodes of thrusting in the Sevier thrust belt. Both Crittenden (1976) and Hansen and Bonilla (1954) noted evidence for repeated changes in stress orientations (superimposed fold axes, cross-cutting thrusts, and folds with opposed orientations), at the southern margin of the basin, especially in the southwestern corner.

There is also evidence for east-west left-lateral shear motion along the thrust fault system at the north edge of the Uinta Mountains (e.g., Hansen and Bonilla, 1954). It could be argued that friction or stresses associated with sheared asperities along the wrench fault might skew the local stress trajectories caused by indentation into the basin to the north. However, it is suggested rather that such shear stress was minimal, behaving similarly to shear stress along the modern San Andreas fault, which is an order of magnitude less than the maximum horizontal compressive stress. The compressive stress along the fault maintains an orientation that is normal to the fault despite changes in fault strike (Mount and Suppe, 1987, 1992; Castillo and Zoback, 1994).

The northwest-southeast trend of the Wind River thrust front has been treated simplistically here, idealized as an east-west thrust front opposite the Uinta Mountains. The proximity of the Sevier thrusts to the

Wind River thrust front in the northwestern narrow panhandle of the basin suggests stress trajectories that trend northeast, nearly straight across between the two structures. South of the dogleg in the Sevier thrust front northwest of LaBarge, however, and away from the immediate vicinity of the Sevier thrust front, a roughly north-south maximum horizontal paleo-stress is expected to have dominated the central parts of the basin in the absence of local structural complexities.

A free-surface or buttressing effect may have been caused by the Rock Springs Uplift (note the abrupt rise of the basement shown on the the seismic line published by Stearns et al., 1975). Edge-normal, east-west stress trajectories would be expected within a few km of this structure.

Thrust-Front Foredeeps

Price (1974) suggested that stresses could be induced in strata during subsidence and uplift by changes in their lateral dimensions due to volume constraints on the curved surface of the earth. A similar mechanism is inferred to have created stresses in the Frontier Formation where it was deposited in the foredeep adjacent to the Sevier thrust belt. This 40-mi (65-km) wide foredeep accommodated nearly 19,000 ft (5800 m) of Upper Cretaceous strata (Weimer, 1961). The Frontier Formation, deposited "horizontally" at the earth's surface, was buried to 19,000 ft (5800 m) within the foredeep by the end of Cretaceous time, but was buried to only 5500 ft (1680 m) over the Moxa Arch.

The difference can be visualized as the base leg of a right triangle, the other being the original 40 mi (65 km) length of the strata at the earth's surface. As the strata were buried, the surface leg would have been stretched to the length of the hypotenuse of the triangle, producing slightly more than 0.2% strain. The hypotenuse was not straight, however: an elastic lithosphere commonly bows upward in front of thrust sheet loads, in this case with about 3000 ft (1000 m) of departure from a straight line. This adds about 0.06% strain to the system, for a total of 0.26% (Laubach and Lorenz, 1992). Sandstones similar to those of the Frontier Formation (i.e., the Mesaverde Formation) have been tested to fracture in laboratory conditions at about 0.3% strain, thus the 0.26% strain due to this mechanism is suggested to have been more than sufficient to create fractures in Frontier sandstones under geologic conditions, where less strain is required for failure at geologic strain rates and over geologic times.

Fractures would have been most likely to form at the time of maximum extension, i.e., at maximum burial, at the end of the Cretaceous, and would be oriented normal to maximum extension, parallel to the north-south axis of the basin. Coincidentally, this is also the time when north-south compressive stresses were first being imposed on the basin from the Laramide Wind River and Uinta thrusts, enhancing the probability of fracture. North-south fractures are, in fact, the earliest-formed and dominant fractures present in outcrops of the Frontier Formation on the western edge of the basin (Lorenz and Laubach, 1993).

The same mechanism may have assisted in fracturing of strata in the deep part of the basin east of the Moxa Arch. Strains would not have been as high because burial depths were not as great nor was the basin as narrow. However they would have been oriented properly to augment the effects of the north-south compressive stresses derived from the Uinta Mountain thrust.

Analogous, younger (Paleogene), foredeeps are present in front of the Wind River and Uinta Mountains thrusts (e.g., Hagen et al., 1985; Schuster and Steidtmann, 1988). These basins are not as deep or as narrow as the Cretaceous foredeep, and strains sufficient to cause fracturing may not have been obtained. Moreover, thrust-normal compression due to thrust indentation into these developing basins would probably have negated any extension normal to the long axis of the basin caused by subsidence, and thus the latter is not considered further here.

The Moxa Arch

The Moxa Arch is the largest structure within the basin, dividing the Cretaceous foredeep from the central basin. The western flank of the arch has been suggested to be faulted at deeper stratigraphic levels (Kraig and Wiltschko, 1988; Wiltschko and Eastman, 1983), although published seismic lines (Stearns et al., 1975), do not support this.

The arch may have initially acted as a buttress to stresses derived from the Sevier thrust belt, reinforcing an east-west orientation for the local compressive stress trajectories. However, local thrust faults, anticlines, and other structural complications are present over much of the arch, especially at its northern end (**Fig. 9**). These have resulted in a complex and difficult to interpret suite of local subsurface stress orientations, stress profiles, and natural fractures in the only part of the basin where any significant number of such measurements have been made (Laubach et al., 1992; Cipolla et al., 1993).

Normal Faulting and the Present Stress Regime

Steidtmann and Middleton (1991) suggest that regional, continental-scale, compression held up the major

Laramide thrust blocks (Wind River and Uinta Mountains) dynamically. Tectonic rearrangement during Oligocene time led to local collapse of the thrust-block toes that had impinged on the basin-fill strata, and therefore local compression due to basin-margin indentation was eliminated.

Pliocene and younger north-striking younger faults are present in the northwest corner of the basin. Some of these faults are still active (Sylvester et al., 1990). Active normal faulting suggests east-west extension, at least locally. On the other hand, a tenuous fault-plane focal mechanism solution for a February, 1995, earthquake centered just east of the Rock Springs Uplift suggests an east-west compressive stress, acting along a fault that parallels the northeast-striking faults mapped across the adjacent uplift (John Minsch, National Earthquake Information Center; personnel communication, February, 1995).

The general stress setting of the basin thus has changed from being dominated by basin-margin compression, to relaxation of the regional compression and local extension in the east-west to southeast-northwest direction. However, it is entirely unlikely that the strata within the basin are under true tension. Although Laramide basin-margin compression has been released, all stresses in the deeply buried strata at the center of the basin are still compressive. Compressive stress magnitudes have undoubtedly diminished with the collapse of the basin-margin indenters, but it is probable that some proportion of the Laramide compressive stress was locked into the strata during lithification, especially of the sandstones.

Presently measured stresses in Frontier sandstones and shales over the Moxa Arch are less than the lithostatic overburden stress but greater than the hydrostatic stress (Cipolla et al., 1993). The shale stresses exceed those in the sandstones, suggesting that the shales are relaxing toward overburden values whereas the sandstones have retained some strength over time. Less-than-lithostatic values might also be expected if a tensile subsurface stress regime were possible, but the ductile matrix shales would be expected to have stresses **less** than the stiffer sandstone inclusions during such stretching. Since this is not the measured condition, a tensile condition is not the preferred interpretation.

Intermediate Summary

Trajectories of the maximum horizontal compressive stresses in the basin radiated out from the Sevier thrust front with a generally east-west orientation during the first two-thirds of the 100 m.y. long episode of Sevier thrusting. The Frontier Formation was deposited near the middle of the time of Sevier thrusting, but the formation was not initially fractured by the thrust-related stresses.

North-south trending compressive stresses of significantly higher magnitude were created in latest Cretaceous to Paleocene time with the onset of thick-skinned Laramide thrusting. These stresses are suggested to have overwhelmed the earlier Sevier compression, reorienting the mid-basin maximum horizontal compressive stress by 90 degrees and enhancing the horizontal stress anisotropy.

Deeply buried Frontier strata in the foredeep at the western margin of the basin fractured initially under the influence of the north-south maximum horizontal compressive stress system, except, perhaps, immediately adjacent to the Sevier thrust front. North-south fracturing was facilitated by stress anisotropy created during subsidence. Subsequent east-west, thrust-related dilatancy fracturing occurred as the Sevier thrust belt advanced eastward.

SYNTHESIS AND COMPARISON WITH SUBSURFACE CONTROL

The compendium of data, correlations, modelling, and inferences offered above can be synthesized into a conceptual model leading to a preliminary prediction of the present fracture and stress orientations in the subsurface Frontier Formation in the central Green River basin. This reconstruction is testable using measurements of the present in situ maximum horizontal compressive stress. The working hypothesis presented here is intended for preliminary use in exploratory or development drilling until more definative data are obtained.

Sevier Stress and Fracture System

The maximum horizontal compressive stress orientation in Frontier strata within the basin was controlled for approximately 25 m.y., until the onset of Laramide thrusting, by the Sevier thrust system. Seven post-Frontier Sevier thrust sheets have been identified (**Fig. 3**), and four of them were active during the post-Cretaceous time when Frontier sediments in most of the basin are inferred to have been buried deeply enough to have been lithified and susceptible to fracture.

The thrust-related maximum horizontal compressive stress was oriented generally east-west, radiating out from the convex thrust front. It was of significant magnitude within a few tens of kilometers of the thrust front, decreasing exponentially to half it's original magnitude within 15 mi (25 km). However, the Frontier Formation in this area of high stress west of the Moxa Arch was probably not susceptible to fracturing during this time. Outcrop data at the western edge of the basin (Lorenz and Laubach, 1993) corroborate this interpretation, showing that east-west thrust-dilatancy fractures related to Sevier thrusting did not in fact form until late in Sevier time, and post-date north-south fractures of Laramide age.

However, the great depth of the narrow foredeep was an important factor, since a small but significant amount of east-west extension of the Frontier strata was incurred by geometric constraints during subsidence. This extension may have initiated the north-south fracturing noted above during the later stages of subsidence, and certainly it enhanced fracture susceptibility during subsequent active compression related to Laramide thrusting from the south.

East-west compression was probably of insufficient magnitude east of the foredeep (and east of the Moxa Arch) to cause regional fracturing at this time.

Laramide Stress and Fracture System

Stress orientations changed and horizontal stress anisotropy increased significantly with the onset of Laramide thick-skinned thrusting at the north and south margins of the basin. Preliminary calculations suggest that the Laramide-related horizontal compressive stress was a minimum of twice as much as that created by the

Sevier thrust system. Moreover, the region affected by this stress was significantly larger, with an estimated horizontal stress differential of 5000 psi (35 MPa) possible throughout the basin.

Laramide horizontal compressive stress trajectories would have radiated normal to the Laramide thrust fronts at the northern and southern margins of the basin. They are inferred to have overwhelmed the contemporaneous east-west Sevier stress trajectories in the central parts of the basin, leaving a dominantly north-south regional stress trajectory. Free-edge effects caused by faults along the Rock Springs Uplift to the east, and compression from the Sevier thrust system to the west, would have caused perturbations of the trajectories at the edges of the basin. The basin-wide stress pattern is inferred to have been similar to that portrayed in **Figure 10**. Unmapped structures within the basin would cause local deflections of the trajectories, and the vertical distributions of the stresses are not well constrained at this point in the development of the model.

Fracture susceptibility of Frontier strata during this time was enhanced by continued burial leading to increased lithification and elevated temperatures, and by related thermal maturation/gas generation. Important overpressuring occurred at depths of about 11,500 ft (3500 m), causing strata below this depth to become increasingly susceptible to fracturing as the effective confining stresses were lowered.

Pore pressures in strata at the north and south edges of the basin were also probably enhanced by tectonic compression, leaving much of the stratigraphic column, including the Frontier sandstones, susceptible to fracturing in these areas of greatest tectonic stress.

The Frontier Formation in the central Green River basin is most likely to have fractured during the culmination of Laramide tectonism, when maximum stress magnitude, maximum stress anisotropy, and maximum fracture susceptibility occurred. If a regional set of natural fractures actually formed in the Frontier Formation under these optimal fracture conditions, it is suggested to trend primarily north-south except where interrupted by local structures and against the basin margins.

Horizontal stress decollements and related segregation of fracture domains may have also occurred within the thick marine shales common in the basin. Moreover, vertical fracture domains may vary against the northern and southern margins where they have been physically elevated by thrusting or depressed by thrust-related subsidence. Frontier strata near the Rock Springs Uplift were not buried deeply and probably did not fracture at this time. Further complications may occur in the southwest and northwest corners of the basin, as well as over the Moxa Arch.

Post-Laramide Stress and Fracture System

Relaxation of crustal forces and the collapse of the Laramide uplifts during Oligocene time meant the end of active compression of the basin-fill strata by basin-margin indenters. However, a memory of this compression was probably locked into the strata by cementation and diagenesis under compression, and the post-Laramide effective compressive stress anisotropy at depth, while of significantly less magnitude, is interpreted to have maintained a Laramide orientation.

If the conceptual modelling outlined above has validity, the predicted stress and natural fracture orientations should be corroborated by measurements of the modern conditions. Publicly available data on natural fracture occurrence and orientation, primarily oriented core and fracture identification logs, are essentially non-existent in the central parts of the basin in question. However, assessments of present-day in situ maximum horizontal compressive stress orientations can be made from oriented caliper logs.

The publicly available data set of decent caliper logs is unfortunately small (**Fig. 11**), but compares favorably with the interpreted Laramide stress trajectories (**Fig. 10**):

-At the northern and southern ends of the Moxa Arch, the stress orientations trend between the nearby thrust fronts.

-The measurement from within the Sevier fold and thrust belt is sub-parallel to thrust transport direction even though thrusting is inactive, suggesting a stress memory.

-Local structure probably determines the seemingly anomalous stress orientation at the north end of the Rock Springs Uplift.

-The approximately east-west stress measurement at the middle of the western edge of this uplift suggests control of the local trajectory by free-surface effects associated with faulting at the edge of the uplift.

-The caliper log from the southern end of the Rock Springs Uplift indicates two distinct stress orientations at shallow and deep intervals. The deep maximum horizontal compressive stress stress orientation trends north-northeast, suggested to result from interaction between the Rock Springs Uplift and the Uinta Mountains thrust. The shallower horizontal compressive stress trends consistently southeast, possibly for the same unknown reason that the stress at the northwest corner of the Rock Springs Uplift trends northeast.

Thus, despite indications of recent extension in directions east-west (normal faults in the Teton area), north-south (earthquake just east of the Rock Springs Uplift), or northwest-southeast (normal faults over the Rock Springs Uplift), stresses in Paleozoic and Mesozoic strata seem to have retained the signature of Laramide compressive events. The dominant fracture set in the Frontier Formation of the central Green River basin probably formed during this tectonic interval, and is predicted to be aligned north-south with a remnant maximum horizontal compressive stress. Local complications and overprintings of stress records may be expected. Future drilling will offer proof of the model or suggestions for significant modification: publication of this model offers a target in several senses of the word.

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REFERENCES

Bombalakis, E.G., 1986, Thrust-fault mechanics and origin of a frontal ramp: Journal of Structural Geology, v. 8, p. 281290.

Brewer, J.A., and Turcott, D.L., 1980, On the stress system that formed the Laramide Wind River Mountains, Wyoming: Geophysical Research Letters, v. 7, p. 449-452.

Castillo, D.A., and Zoback, M.D., 1994, Systematic variations in stress state in the southern San Joaquin Valley: Inferences based on well-bore data and contemporary seismicity: American Association of Petroleum Geologists Bulletin, v. 78, p. 1257-1275.

Cello, G., and Nur, A., 1988, Emplacement of foreland thrust systems: Tectonics, v. 7, p. 261-271.

Cipolla, C.L., Meehan. D.N., and Stevens, P.L., 1993, Hydraulic fracture performance in the Moxa Arch Frontier Formation: SPE 25918, Society of Petroleum Engineers Rocky Mountain Regional Meeting/Low Permeability Reservoirs Symposium, April 26-28, Denver, CO, 13 p.

Cobban, W.A., and Reeside, J.B. Jr., 1952, Frontier Formation, Wyoming and adjacent areas: American Association of Petroleum Geologists, Bulletin, v. 36, p. 1913-1961.

Craddock J.P., 1992, Transpression during tectonic evolution of the Idaho-Wyoming fold-and-thrust belt; in Link, P.K., Kuntz, M.A., and Platt, L.B., eds, Regional Geology of eastern Idaho and western Wyoming: Geological Society of America Memoir 179, p. 125-139.

Craddock J.P., and van der Pluijm, B.A., 1989, Late Paleozoic deformation of the cratonic carbonate cover of eastern North America: Geology, v. 17, p. 416-419.

Craddock J.P., Jackson, M., and van der Pluijm, B.A., 1993, Regional shortening fabrics in eastern North America: Far-field stress transmission from the Appalachian-Ouachita orogenic belt: Tectonics, v. 12, p. 257-264.

Crewes, S.G., and Ethridge, F.G., 1993, Laramide tectonics and humid alluvial fan sedimentation, NE Uinta Uplift, Utah and Wyoming: Journal of Sedimentary Petrology, v. 63, p. 420-436.

Crittenden, M.D. Jr., 1976, Stratigraphic and structural setting of the Cottonwood area, Utah: Rocky Mountain Association of Geologists 1976 Symposium, p. 363-379.

Davis, D., Suppe, J., and Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153-1172.

De Chadenedes, J.F., 1975, Frontier deltas of the western Green River Basin, Wyoming, in Boyland, D.W. (ed), Deep drilling frontiers of the central Rocky Mountains: Rocky Mountain Association of Geologists 1975 Symposium, p. 149-157.

Dixon, J.S., 1982, Regional structural synthesis, Wyoming salient of western overthrust belt: American Association of Petroleum Geologists Bulletin, v. 66, p. 1560-1580.

Dutton, S.P., 1993, Influence of provenance and burial history on diagenesis of Lower Cretaceous Frontier Formation sandstones, Green River Basin, Wyoming: Journal of Sedimentary Petrology, v. 63, p. 665-677.

Goff, D., and Wiltschko, D.V., 1992, Stresses beneath a ramping thrust sheet: Journal of Structural Geology, v. 14, p. 437-449.

Grout, M.A., and Verbeek, E.R., 1992, Joint-history summary and orientation data for Upper Cretaceous sandstones, Rawlins and Rock Springs uplifts, Washakie basin, southern Wyoming: U.S. Geological Survey Open File Report 92-388, 30 p.

Hagen, E.S., Schuster, M.W., and Furlong, K.P., 1985, Tectonic loading and subsidence of intermontane basins: Wyoming foreland province: Geology, v. 13, p. 585-588.

Hamlin, H.S., 1991, Stratigraphy and depositional systems of the Frontier Formation and their controls on reservoir development, Moxa Arch, southwest Wyoming: Texas Bureau of Economic Geology Topical Report GRI-91/0128, 45 p.

Hansen, W.R., 1965, Geology of the Flaming Gorge area, Utah-Colorado-Wyoming: U.S. Geological Survey Professional Paper 490. 196 p.

Hansen, W.R., and Bonilla, M.G., 1954, Laramide faulting and orogeny on the north flank of the Uinta Mountains in eastern Daggett county, Utah: Proceedings of the Colorado Scientific Society, v. 17, p. 1-29.

Kraig, D.H., Wiltschko, D.V., and Spang, J.H., 1988, The interaction of the Moxa Arch (La Barge Platform) with the Cordilleran thrust belt, south of Snider Basin, southwestern Wyoming; in Schmidt, D.J., and Perry, W.J Jr. (eds), Interaction of the Rocky Mountain Foreland and the Cordilleran Thrust Belt: Geological Society of America Memoir 171, p. 395-410.

Lamerson, P.R. 1982, The fossil basin and its relationship to the Absaroka thrust system, Wyoming and Utah, <u>in</u> Powers, R.B. (ed.), Geologic studies of the Cordilleran thrust belt: Rocky Mountain Association of Geologists, p. 279-340, 12 plates.

Laubach, S.E., and Lorenz, J.C., 1992, Preliminary assessment of natural fracture patterns in Frontier Formation sandstones, southwestern Wyoming: Wyoming Geological Association Guidebook, 43rd Field Conference, p. 87-96.

Laubach, S.E., Clift, S.J., Hill, R.E., and Fix, J, 1992, Stress directions in Cretaceous Frontier Formation, Green River Basin, Wyoming, <u>in</u> Mullen, C.E. (ed), Rediscover the Rockies: Wyoming Geological Association 43rd Field Conference Guidebook, p. 75-86.

Law, B.E., 1984, Relationships of source-rock, thermal maturity, and overpressuring to gas generation and occurrence in low-permeability Upper Cretaceous and Lower Tertiary rocks, greater Green River Basin, Wyoming, Colorado, and Utah, in Woodward, J., Meissner, F.F., and Clayton, J.L., (eds), Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists, p. 469-490.

Law, B.E., Spencer, C.W., and Bostick, N.H., 1980, Evaluation of organic matter, subsurface temperature and pressure with regard to gas generation in low-permeability Upper Cretaceous and Lower Tertiary sandstones in Pacific Creek area, Sublette and Sweetwater counties, Wyoming: The Mountain Geologist, v. 17, p. 23-35.

Law, B.E. and Smith, C.R., 1983, Subsurface temperature map showing depth to 180 degree Fahrenheit in the greater Green River Basin of Wyoming, Colorado, and Utah: U.S. Geological Survey Miscellaneous Field Studies Map MF-1504.

Greater Green River Basin, Wyoming, Colorado, and Utah; in Eisert, J.L. (ed.), Wyoming Geological Association 40th field Conference Guidebook, p. 39-61

Lickus, M.R., and Law, B.E., 1988, Structure contour map of the greater Green River Basin, Wyoming, Colorado, and Utah: U.S. Geological Survey Map.

Lorenz, J.C., 1993, Reservoir fracture and permeability trends inferred from reconstructions of tectonic stress orientations: Example from the Green River Basin, Wyoming (abs): American Association of Petroleum Geologists, Annual Convention, abstracts volume, p. 141.

Lorenz, J.C., Warpinski, N.R., and Teufel, L.W., 1991, Regional fractures I: A mechanism for the formation of regional fractures at depth in flat-lying reservoirs: American Association of Petroleum Geologists Bulletin, v. 75, p. 1714-1737.

Lorenz, J.C., Warpinski, N.R., and Teufel, L.W., 1993, Rationale for finding and exploiting fractured reservoirs, based on the MWX/SHCT-Piceance Basin Experience: Sandia National Laboratories Report SAND93-1342, 147 p.

Lorenz, J.C., and Laubach, S.E., 1994, Description and interpretation of natural fracture patterns in sandstones of the Frontier Formation along the Hogsback, southwestern Wyoming: Gas Research Institute Topical Report GRI-94/0020, 89 p.

Lorenz, J.C., Argüello, J.G., Stone, C.M., Harstad, H., Teufel, L.W., and Brown, S.R., Predictions of fracture and stress orientations: Subsurface Frontier Formation, Greeen River basin: Gas Research Institute Topical Report GRI95**xxx**

McDonald, R.E., 1976, Big Piney-La Barge producing complex, Sublette and Lincoln counties, Wyoming, in Braunstein, J. (ed), North American oil and gas fields: American Association of Petroleum Geologists Memoir 24, p. 91-120.

McPeek, L.A., 1981, Eastern Green River Basin: A developing giant gas supply from deep, overpressured Upper Cretaceous sandstones: American Association of Petroleum Geologists Bulletin, v. 65, p. 1078-1098.

Merewether, E.A., 1984, The Frontier Formation and mid-Cretaceous orogeny in the foreland of southwestern Wyoming: The Mountain Geologist, v. 20, p. 121-138.

Mitra, G., 1994, Strain variation in thrust sheets across the Sevier fold-and-thrust belt (Idaho-Utah-Wyoming): Implications for section restoration and wedge taper evolution: Journal of Structural Geology, v. 16, p. 585-602.

Mitra, G., Yonkee, W.A., and Gentry, D.J., 1984, Solution cleavage and its relationship to major structures in the Idaho-Utah-Wyoming thrust belt: Geology, v. 12, p. 354-358.

Moslow, T.F., and Tillman, R.W., 1989, Characterization, distribution of Frontier Formation reservoir facies of Wyoming fields: Oil and Gas Journal, May 29, p. 95-104.

Mount, V.S., and Suppe, J., 1992, Present-day stress orientations adjacent to active strike-slip faults: California and Sumatra: Journal of Geophysical Research, v., 97, p. 11,995-12,013.

Mount, V.S., and Suppe, J., 1987, State of stress near the San Andreas fault: Implications for wrench tectonics: Geology, v. 15, p. 1143-1146.

Myers, R.C., 1977, Stratigraphy of the Frontier Formation (Upper Cretaceous), Kemmerer Area, Lincoln county, Wyoming: Wyoming Geological Association, 29th Annual Field Conference Guidebook, p. 271-311.

Nettleton, L.L., 1934, Fluid mechanics of salt domes: American Association of Petroleum Geologists Bulletin, v. 18, p. 1175- 1204.

Price, N.J., 1974, The development of stress systems and fracture patterns in undeformed sediments: Proceeding of the Third Congress of the International Society of Rock Mechanics, v. 1-A, p. 487-496.

Rathbun, F.C., and Dickey, P., 1969, Abnormal pressures and conductivity anomaly, northern Green River Basin, Wyoming: The Log Analyst, v. 10, p. 3-8.

Royse, F., Warner, M.A., and Reese, D.L., 1975, Thrust belt structural geometry and related stratigraphic problems, Wyoming-Idaho-northern Utah, _in_ Boyland, D.W. (ed), Deep drilling frontiers of the central Rocky Mountains: Rocky Mountain Association of Geologists 1975 Symposium, p. 41-54.

Schmitt, J.G., Sippel, K.N., and Wallem, D.B., 1981, Upper Jurassic through lowermost Upper Cretaceous sedimentation in the Wyoming-Idaho-Utah thrust Belt I. Depositional environments and facies distributions, _in_ Sedimentary tectonics: Principles and applications: Wyoming Geological Association; Conference Notes, p. 26-27.

Schuster, M.W., and Steidtmann, J.R., 1988, Tectonics and sedimentary evolution of the northern Green River basin, western Wyoming, in Schmidt, C.J., and Perry., W.J., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America, Memoir 171, p. 515-530.

Scott, A.R., 1994, Coal rank, gas content, and composition, and origin of coalbed gases, in, Tyler, N.R., Kaiser, W.R., Scott, A.R., Hamilton, D.S., McMurry, R.G., and Zhou, N., Geologic and hydrologic assessment of natural gas from coal seams in the Mesaverde Group and Fort Union Formation, Great Green River basin, Wyoming and Colorado: Chicago, Topical Report, Gas Research Institute, GRI-93-0320, p. 69-86.

Steidtmann, J.R., and Middleton, L.T., 1991, Fault chronology and uplift history of the southern Wind River Range, Wyoming: Implications for Laramide and post-Laramide deformation in the Rocky Mountain foreland: Geological Society of America Bulletin, v. 103, p. 472-485.

Stearns, D.W., Sacrison, W.R., and Hanson, R.C., 1975, Structural history of southwestern Wyoming as evidenced from outcrop and seismic; in Bolyard, D.W. (ed.), Deep drilling frontiers of the central Rocky Mountains: Rocky Mountain Association of Geologists, p. 9-20 plus 2 plates.

Sylvester, A.G., Byrd. J.O.D., and Smith, R.B., 1990, Aseismic(?) reverse creep across the Teton fault, Wyoming, with implications for interseismic strain (abs): Geological Society of America Abstracts with Programs, v. 22, no.3., p. 88.

Thomaidis, N.D., 1973, Church Buttes Arch, Wyoming and Utah: Wyoming Geological Association Guidebook, 25th Field Conference, p. 35-39.

Timoshenko, S., and Goodier, J.N., 1951, Theory of Elasticity: McGraw-Hill, New York.

Warpinski, N.R., 1989, Elastic and viscoelastic calculations of stresses in sedimentary basins: SPE Formation Evaluation, v. 4, p. 522-530.

Weimer, R.J., 1961, Uppermost Cretaceous rocks in central and southern Wyoming, and northwest Colorado: in Wiloth, G.J. (ed), Late Cretaceous rocks of Wyoming and adjacent areas: Wyoming Geological Association 16th Annual Field Conference Guidebook, p. 17-28.

Weimer, R.J., and Haun, J.D., 1960, Cretaceous stratigraphy, rocky Mountain region, U.S.A.: International Geological Congress, Copenhagen, section 12, p. 178-184.

Wiltschko, D.V., and Dorr, J.A., 1983, Timing of deformation in overthrust belt and foreland of Idaho, Wyoming, and Utah: American Association of Petroleum Geologists Bulletin, v. 67, p. 1304-1322.

Wiltschko, D.V., and Eastman, D., 1983, Role of basement warps and faults in localizing thrust fault ramps: Geological Society of America Memoir 158, p. 177-190.

Winn, R.D., Stonecipher, S.A., and Bishop, M.G., 1984, Sorting and wave abrasion: Controls on composition and diagenesis in lower Frontier sandstones, southwestern Wyoming: American Association of Petroleum Geologists Bulletin, v. 68, p. 268-274.

Yassir, N.A., and Bell, J.S., 1994, Relationship between pore pressure, stresses, and present-day geodynamics in the Scotian Shelf, offshore eastern Canada:American Association of Petroleum Geologists Bulletin, v. 78, p. 1863-1880.

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Zoback, M.L., and Zoback, M.D., 1989, Tectonic stress field of the continental United States, in Pakiser, L.C., and Mooney, W.D. (eds), Geophysical framework of the United States: Geological Society of America Memoir 172, p. 523539.

FIGURE CAPTIONS

Figure 1. Location map of the Green River basin in southwestern Wyoming

Figure 2. Schematic showing the configuration of the Green River basin with the basin-fill strata removed, to illustrate the impingement of the basin-margin structures

Figure 3. Relative timing of the deposition of the Frontier Formation, thin-skinned thrusting in the Sevier thrust belt, and thick-skinned thrusts of the Laramide Uinta and Wind River mountains. Timing of the Sevier Thrusts taken from Wiltschko and Dorr (1983).

Figure 4. The force required to initiate a new thrust is equal to 1) the force necessary to move the wedge of rock up the inclined thrust-fault ramp, plus 2) the breaking strength of the strata. The latter component is negligible. A ballpark estimate for the the first factor, applied to the Hogsback thrust, is 10,500 psi (71 MPa); see text. Friction along the thrust plane becomes a minor component as the thrust is propagated.

Figure 5. As the thrust propagates, the westward-thickening section requires that progressively more force is needed to push a sections of increasing weight up the thrust ramp. This is added to increases in the shear stress (friction) along the lengthening decollement surface. When the force required to propagate the active thrust sheet meets or exceeds the force required to initiate a new thrust (see previous figure), the first thrust becomes inactive and a new thrust forms.

Figure 6. Paleostresses inferred from measurements of calcite twin strain lamellae, in platform carbonates at variable distances from the Appalachian and Ouachita thrust systems (from Craddock et al., 1993, figure 3).

Figure 7. Inferred maximum horizontal compressive stress trajectories in basin-fill strata east of the Sevier thrust belt, prior to complications imposed on the system by activity of the Wind River and Uinta Laramide thrusts.

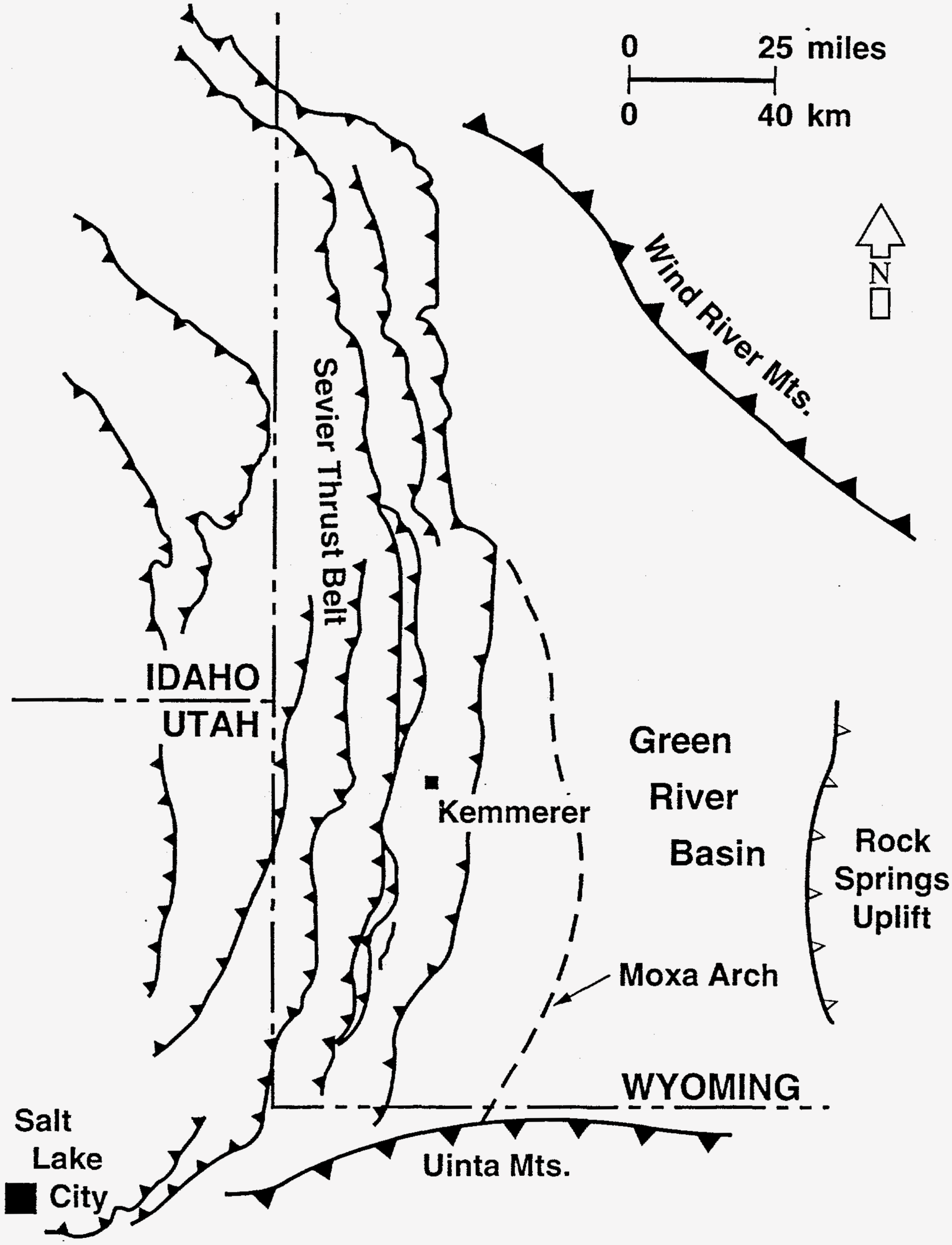
Figure 8. Cross section through the western part of the Uinta Mountains thrust, near the southwestern corner of the basin (from Lamerson, 1982, plate 12).

Figure 9. Structural complexities over the north end of the Moxa Arch (from McDonald, 1975, figure 15). Regional stress trajectories are commonly deflected or refracted at local structures, which may account for the seemingly erratic stress orientation measurements reported from wells over the north end of the Moxa Arch by Laubach et al. (1992).

Figure 10. Inferred Laramide stress trajectories across the Green River basin. This conceptual, non-quantatative model is preliminary: it does not provide for changes in stress orientation with time, with trajectory interference by local structural features, or trajectory changes with depth and differing formation rock properties. It represents a snapshot of the trajectories as they might have appeared in a homogeneous basin-fill medium at that instant in time when all three basin-margin thrust systems were active.

Figure 11. Six measurements of the orientations of the maximum in situ horizontal compressive stress at depth from caliper logs and borehole ellipticity. At the southern end of the Rock Springs uplift, the Exxon #1 Red Creek wellbore suggests two distinct stress orientations at shallow and deep intervals: the maximum compressive stress below 13,500 ft trends north-northeast, suggestive

of interaction between the Rock Springs Uplift and the Uinta Mountains thrust, whereas the shallower horizontal compressive stress trends consistently southeast.



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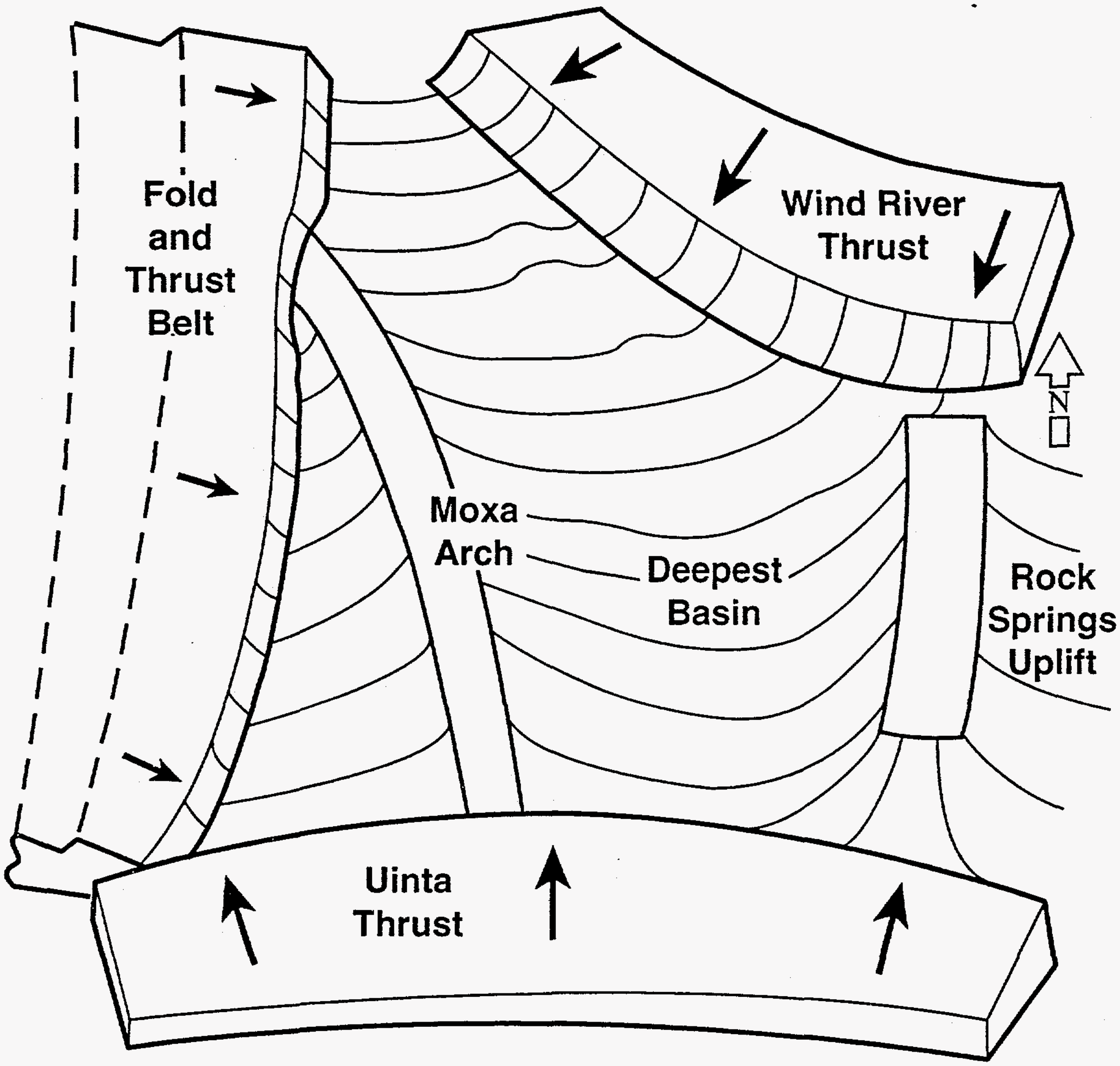

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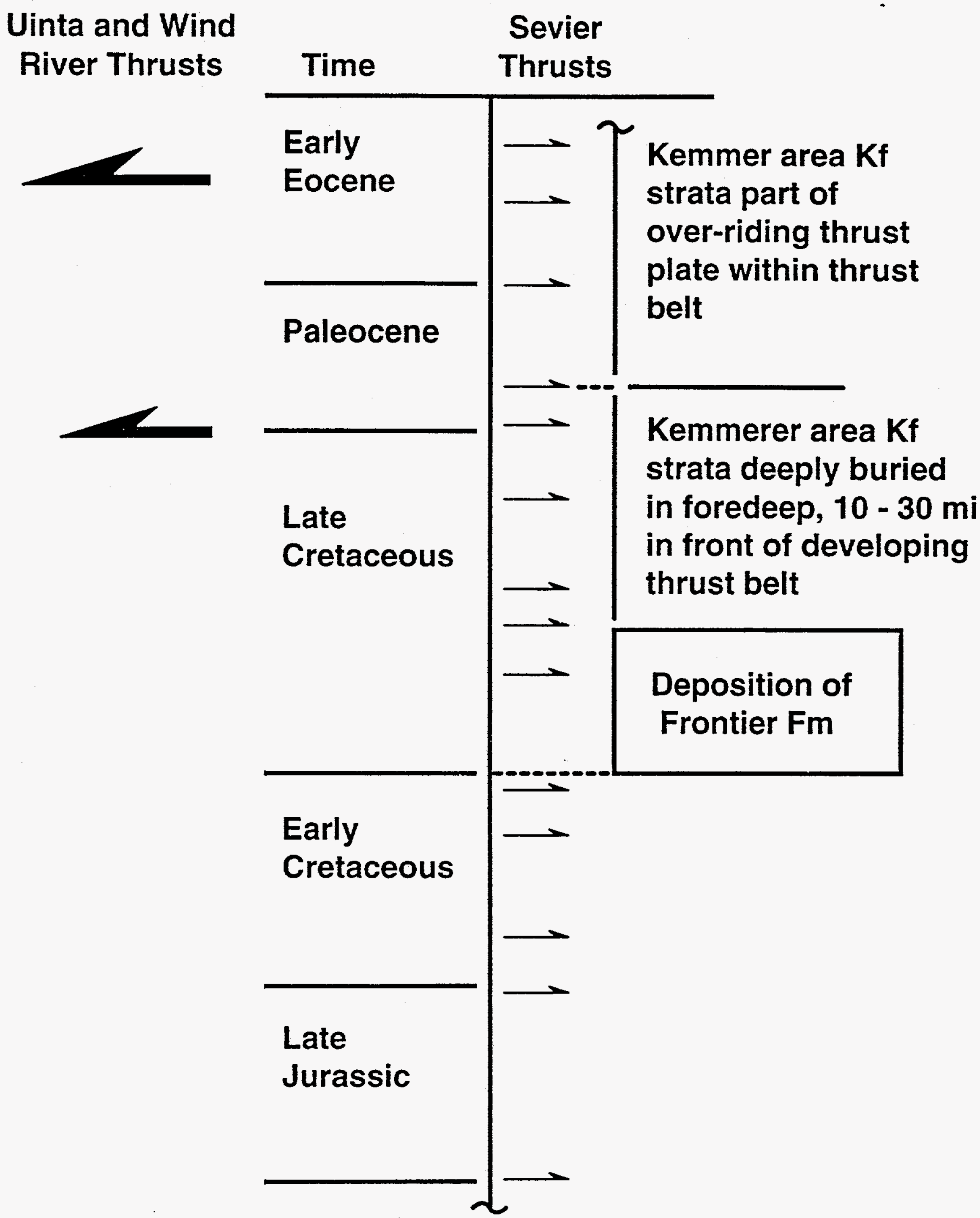

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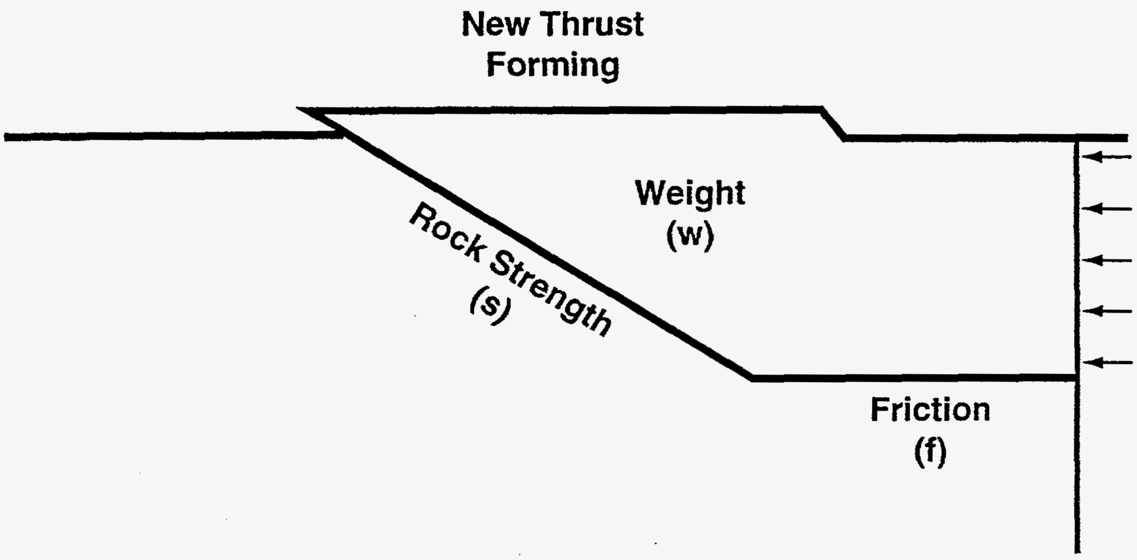

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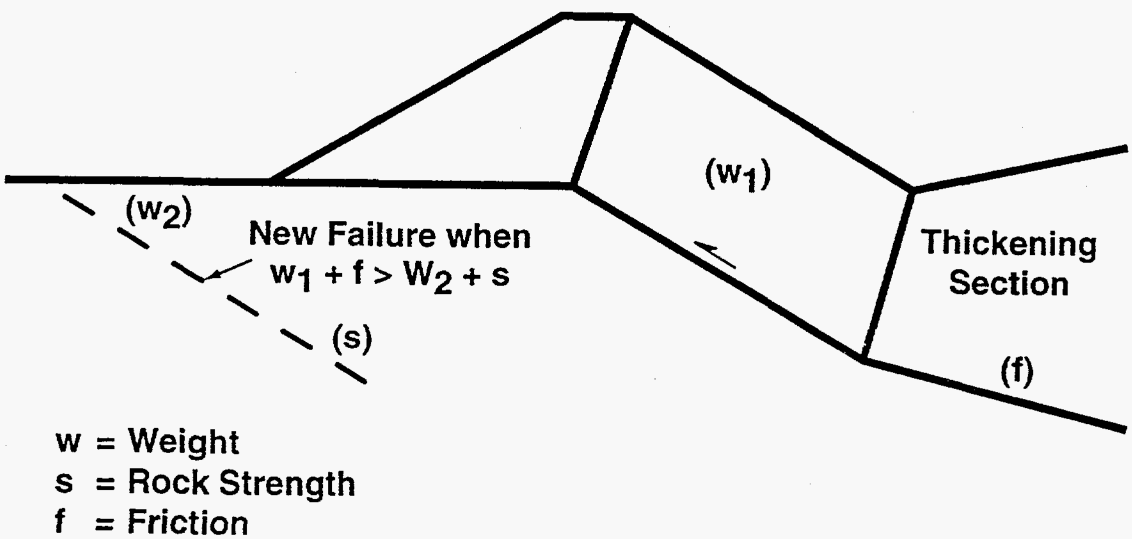

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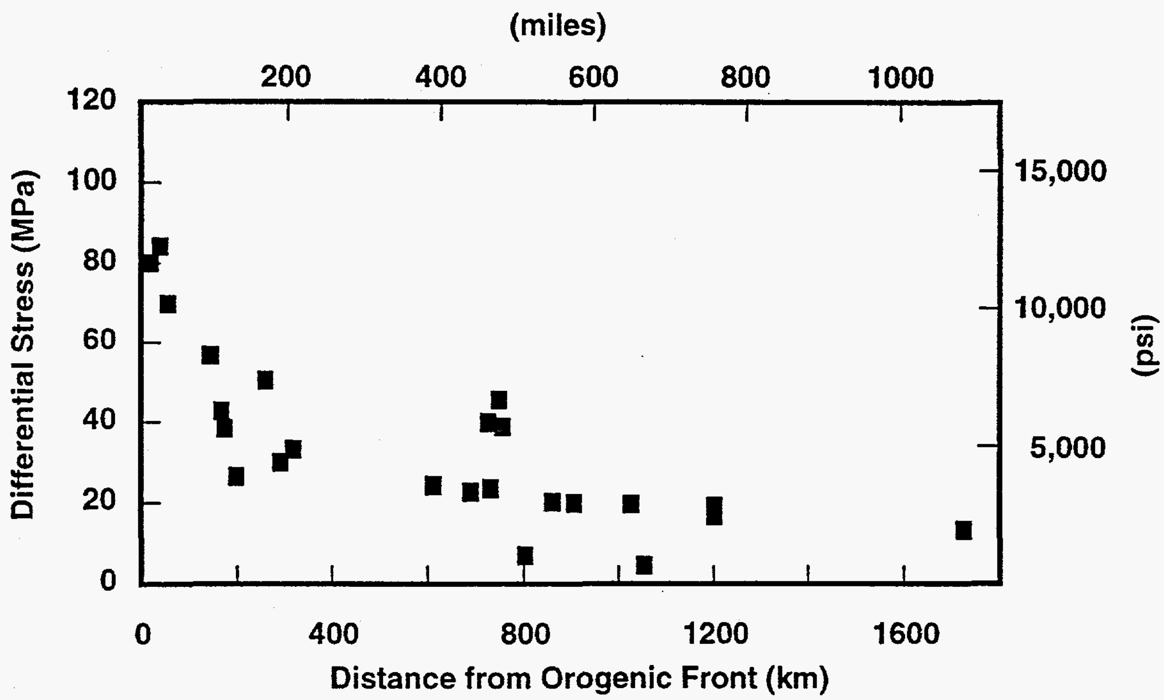

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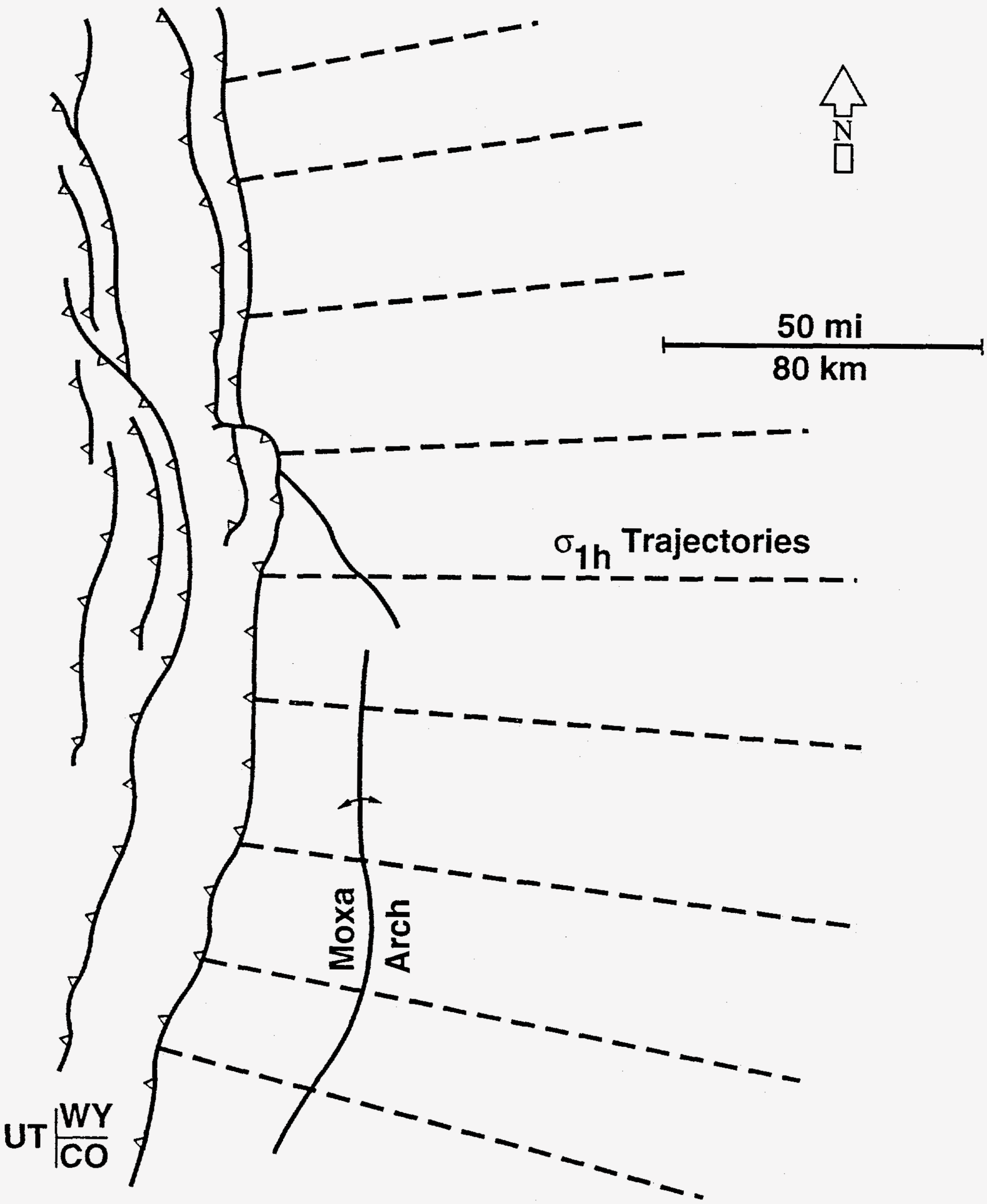
Early Stress Trajectories



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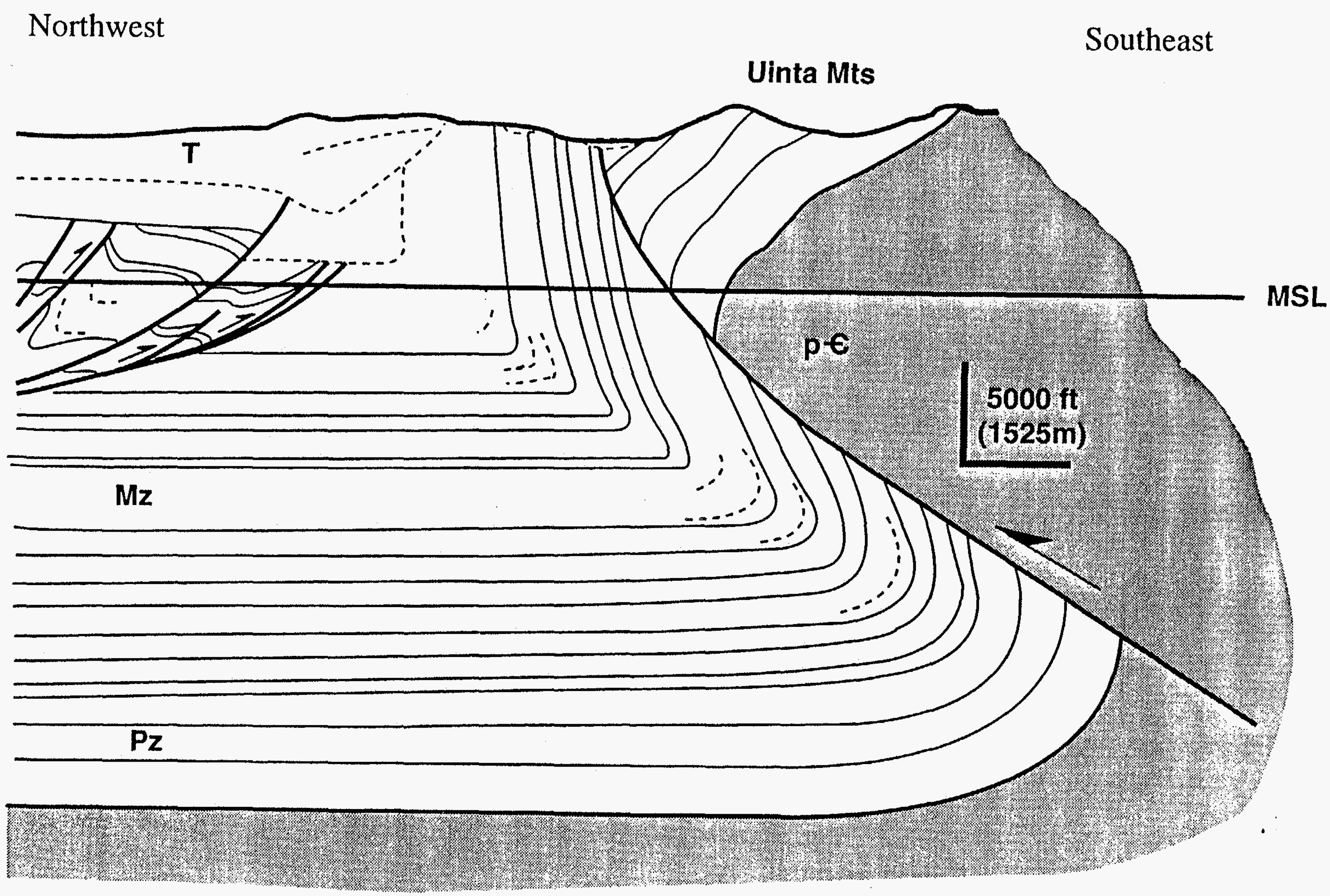
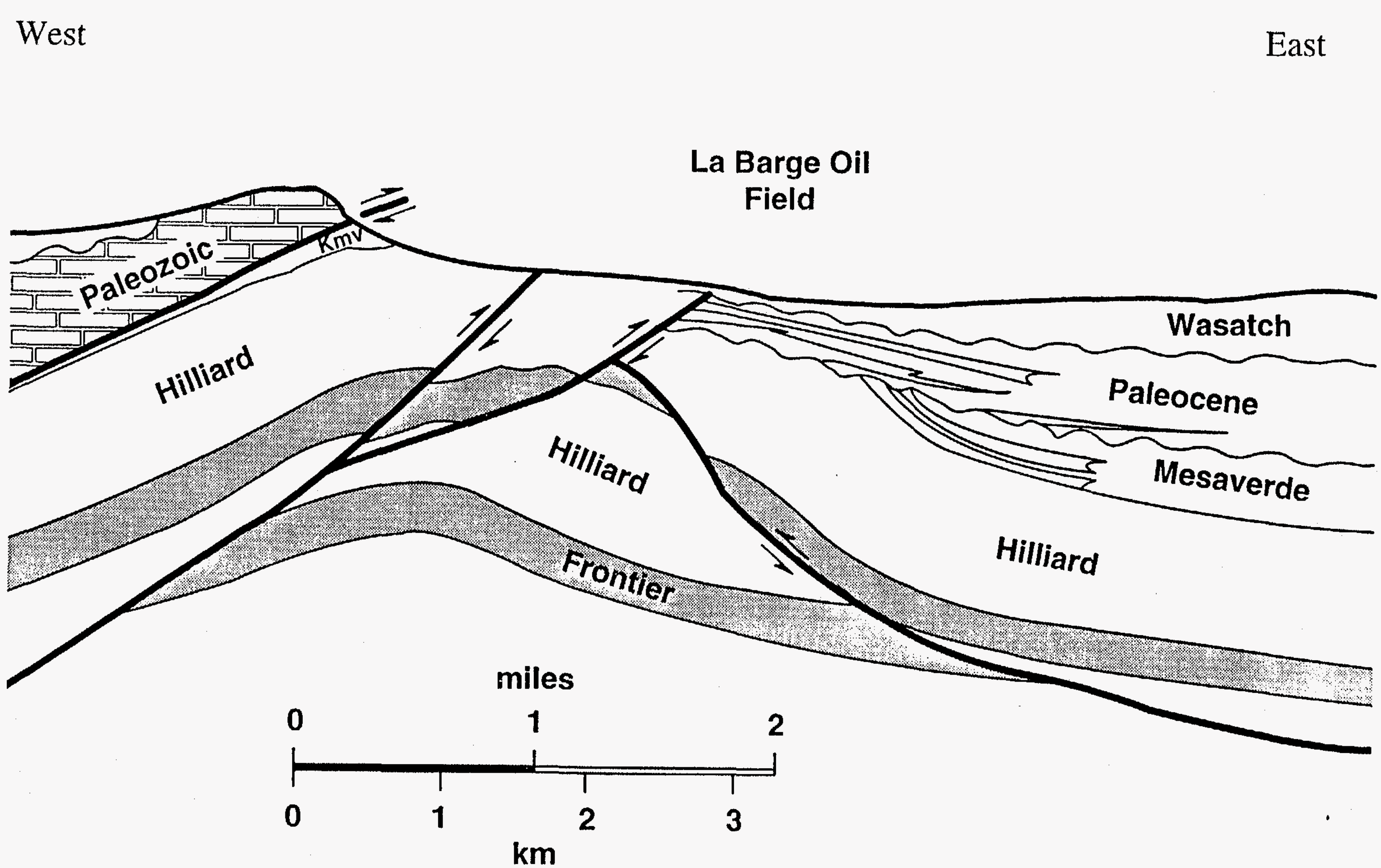


T371K CH7149.08



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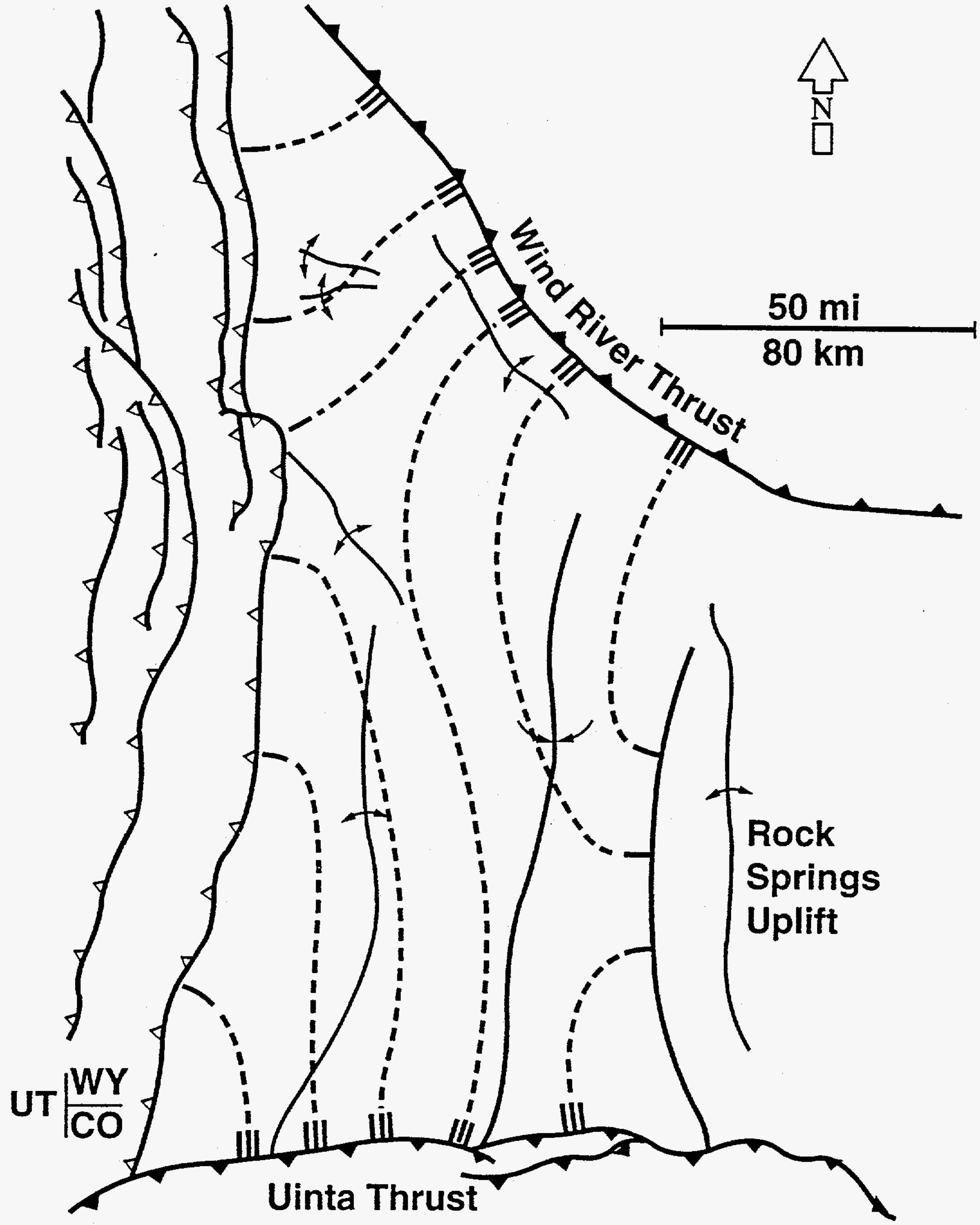

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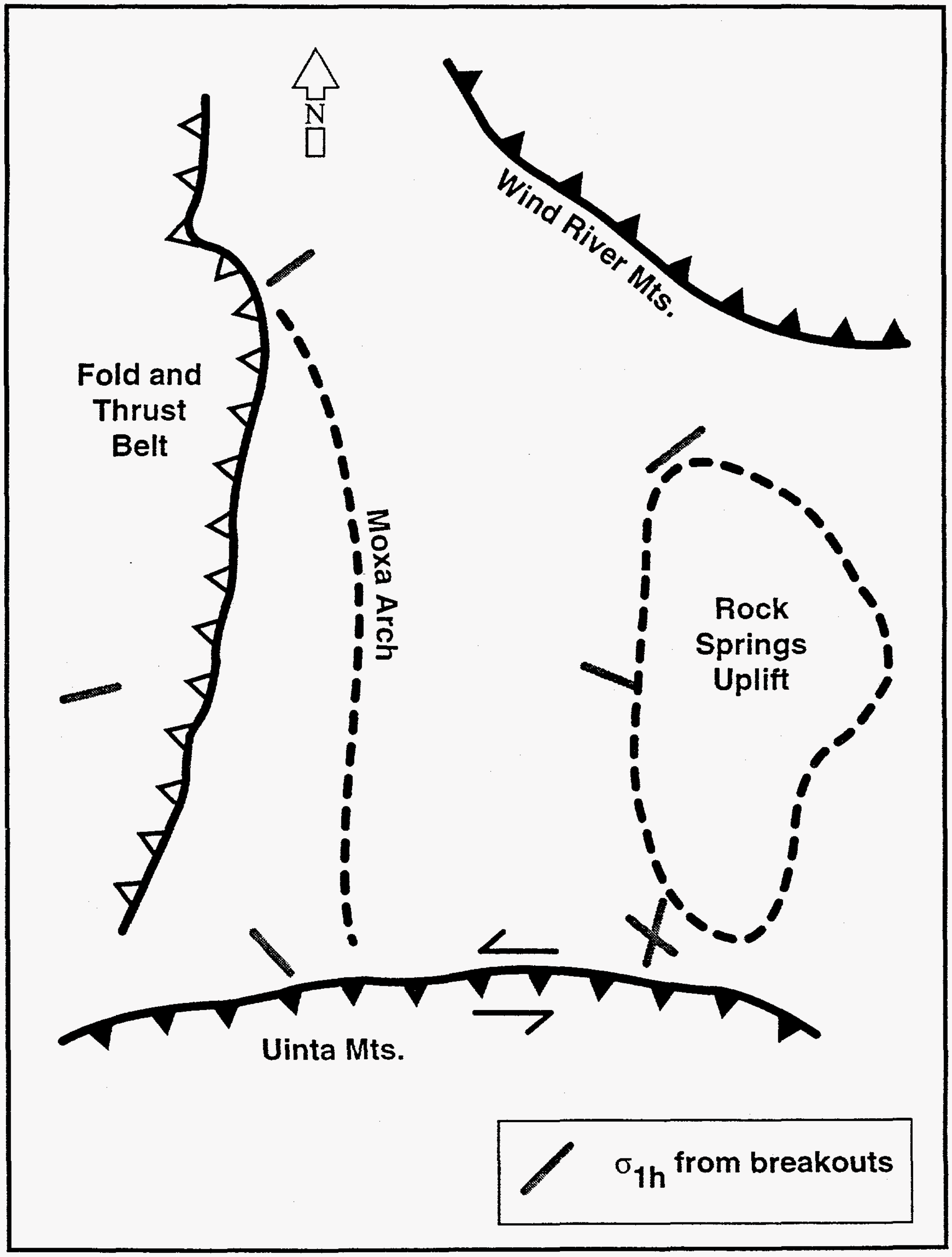
Western Green River Basin



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