STRUCTURAL INTERPRETATION OF THE SOUTHERN HALF OF THE SAWTOOTH SALIENT OF THE MONTANA DISTURBED BELT

By
Stephen P. Gardner
and
Jonathan M. Achuff
Texaco U.S.A.
P.O. Box 2100
Denver, CO 80201

ABSTRACT

The Sawtooth salient is an assemblage of interlocking arcuate thrusts and associated folds. Subsurface and surface data show a transition from the northerly strike of the thrust faults of the Sawtooth salient to a northwesterly strike in the Sun River reentrant to the south. Two zones of thrust faulting have been mapped in the subsurface using 500 miles of seismic reflection data. The western zone consists of five major thrust faults dipping 25-30 degrees westward with 1-7 miles of displacement. The eastern zone consists of thrust faults with similar dips but an order of magnitude less displacement. Some of these thrusts can be traced directly to surface exposures to the north. Surface mapping and data from 20 boreholes in the area provided control for the seismic interpretation. Forward and inverse seismic modeling and formulation of regionally consistent structural and tectonic models provided further constraints for processing and interpreting the seismic data. Displacements and fault angles were determined from geologic cross-sections generated via an analytical raytracing inversion of selected seismic lines. Surface exposures, well data and seismic data reveal that Paleozoic units in thrust plates dip nearly vertically toward the truncation by the underlying thrust fault.

Displacement transfer patterns mapped in the adjacent Sawtooth Range are similar to patterns interpreted from the seismic data and provide detailed examples to aid seismic interpretation. The ability to accurately map strike closure for structural hydrocarbon traps is dependent on understanding the structure within the transfer zones. Geometric and kinematic analysis of the fault transfer zones indicates that displacement on adjacent faults occurred contemporaneously.

INTRODUCTION

The disturbed belt lies along the front of the Rocky Mountains from Montana northwestward through western Canada (Stebinger, 1916; Bevan, 1929). Although recent workers have used disturbed belt to refer more broadly to various portions of the fold and thrust belt, in this paper the term remains consistent with the older use. We use the term to refer only to the disturbed belt of rocks extending from the easternmost thrust-imbricated pre-Mesozoic outcrops along the mountain front eastward to the limit of subsurface thrusting and folding. The Sawtooth salient bulges eastward between Glacier National Park and the South Fork of the Sun River. The southern half of the salient lies along the eastern side of the Sawtooth Range from the Teton River area southward to the Scapegoat-Bannatyne trend (Fig. 1).

The structural interpretation presented in this paper resulted from the development and application of models of displacement transfer and the style and nature of deformation observed within the study area. These concepts were applied together with inverse seismic modeling techniques to produce the geologic maps and cross-sections from available surface and subsurface data. Synthetic seismograms produced from forward seismic models of these cross-sections show good correlation with actual seismic data from the study area.

STRUCTURAL TRENDS

The Sawtooth salient consists of an assemblage of overlapping arcuate thrusts and associated hanging wall folds. Fault and fold systems throughout the central portion of the study area generally trend north-northwestward (Fig. 2). Major faults dip west-southwestward toward the adjacent Sawtooth Range at 25-30 degrees. Folds plunge gently southward (Fig. 2b).

In the northern portion of the study area the structural trend curves more northwesterly. In the Sun River reentrant to the south...
Figure 2. Structure of the top of the Sun River Member of the Castle Reef Dolomite; a) map of thrust fault traces in the hanging wall; b) map of fold axes showing plunge direction.
Figure 3. Caption on Following Page
Figure 3. (Preceding Page) Stratigraphic column and seismic velocity units for the southern portion of the Sawtooth salient. Compiled from surface reconnaissance, well data and published descriptions (Balster, 1971; Cobban, 1945; Cobban, Erdmann, Lemke and Maughan, 1959, 1976; Mudge, Sando and Dutro, 1962; Mudge, 1965, 1967, 1968, 1972a, 1972b; Mudge and Earhart, 1983).

(Fig. 1), the structural pattern undergoes a transition to northwest-trending thrust faults and folds which overlie the southward plunging features of the salient (Fig. 2). This change in structural trends coincides with the transfer of displacement from the thrusts and folds of the Sawtooth Range to the Eldorado-Steinbach thrust system.

**STRATIGRAPHIC AND VELOCITY UNITS**

Geophysical well logs and velocity surveys provided velocity data used to analyze reflection character and to select velocity units for seismic modeling. The resolution of detailed stratigraphy used in geologic surface mapping and lithologic well logs reduces to a far simpler set of velocity units for seismic interpretation. The velocity units correlate closely with the gross lithologic changes and consequently with significant lithostratigraphic boundaries (Fig. 3).

Velocity contrasts exceeding 5000 feet per second (1.52 km/sec) occur at the top and base of the Madison Group, the top of the Jefferson Group, the top and base of the Switchback Shale and the top of the Gordon Shale. The largest contrasts occur at contacts between carbonate and shale units and produce large-amplitude seismic reflections.

In addition, signal interference associated with thin high-velocity sandstones interbedded with low-velocity mudstones in the Kootenai and Blackleaf formations produce characteristic reflection patterns. Interbedded carbonates and shales throughout the Cambrian section also produce consistent and recognizable reflection patterns. The general lack of velocity contrast and consequent lack of recognizable reflections characterizes much of the Mississippian and Devonian section. The seismic character produced by this entire stratigraphic package is generally consistent throughout the salient.

We have found no evidence for the existence of any rocks of the Belt Supergroup in the subsurface within the study area. The position of the eastern edge of the Belt Supergroup is constrained only by its existence above the Eldorado thrust to the west of the Sawtooth Range and its absence in the few boreholes east of the range which have reached crystalline basement. Throughout known parts of the Belt Supergroup sediments produce clear, identifiable reflections in seismic data. We have not been able to identify any similar reflections in any of the seismic data through the disturbed belt and eastern portion of the Sawtooth Range.

**SEISMIC MODELING AND INTERPRETATION**

Interpretation of 550 miles of 1- to 24-fold common depth point seismic data acquired from 1960 through 1987 provided the basic framework for construction of structural cross-sections and maps. Additional control included surface mapping (Mudge, 1965, 1967, 1968; Mudge and Earhart, 1983) and geological and geophysical data from 20 boreholes.

A series of analytical modeling techniques were used to correlate seismic responses with geologic features. An iterative process using both forward and inverse modeling methods was used in formulating and testing structural hypotheses to explain the observed seismic response. Regionally consistent structural and tectonic models provided first-order constraints for the hypotheses.

**Forward Seismic Modeling**

Forward modeling involved calculating the theoretical zero-offset seismic response from a two-dimensional geologic model using a 45-degree approximation to the acoustic wave equation. The results of the forward modeling, displayed as synthetic seismograms, comprise a catalog of theoretical responses to observed and hypothesized structural geometries. The modeled responses contrast simple geometries with more complex geometries (Figs. 4 and 5). The use of realistic geometries and velocities based on observed structure and stratigraphy in the study area allowed the resulting synthetic seismograms to be used as quantitative as well as qualitative interpretive tools.

The forward models demonstrated several key seismic responses which are characteristic of high velocity Paleozoic carbonates thrust over lower velocity Mesozoic clastics. The high velocity contrast between the two units produces a strong reflection from this segment of the fault plane. This feature commonly occurs as a discordant, isolated reflection. Diffractions emanate from fault edges and crests of tightly-folded, hanging wall anticlines. Velocity pull-ups disturb the reflections emanating from beneath the high-velocity units and the edges of the high-velocity units produce diffracted reflections. Reflections from steeply-dipping units and refraction of ray paths through shallow interfaces cause reflec-

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**Figure 4.** Examples of geologic input to wave equation forward model program. Synthetic seismic responses are shown in Figure 5. K-Cretaceous event, M-Mississippian event, C-Cambrian event, FLT-thrust fault.
Figure 5. Wave equation forward modeled seismic responses to respective geologic models in Figure 4. K-Cretaceous event, M-Mississippian event, C-Cambrian event, FLT-thrust fault. PULL UP refers to the time anomaly caused by a lateral change to higher velocities in overlying units.

These anomalies migrate systematically. Gray zones, commonly referred to as no-data zones or noise, occur in areas of steep dips and extensive small-scale faulting and folding.

Large fault offsets within the Cambrian section produce a subtle yet recognizable seismic response in the forward models. This response also occurs in the seismic data. Complex velocity pull-up patterns and diffractions often overprint this response, making it difficult to interpret directly without forward modeling.

The results of the forward models show that most of these features can be recognized and rationally interpreted. Addition-
ally, the modeling confirms the potential misinterpretation which may result from the common practice of treating the seismic time section as an approximation to a depth section. Finally, the models indicate that the quality of the data in this area and other areas of structural complexity cannot be judged purely on the basis of continuity and clarity of obvious reflections.

**Inverse Seismic Modeling**

Inverse modeling was used to build a geologic interpretation from seismic time sections. The method used an inverse ray-tracing technique to migrate key seismic events into appropriate spatial positions. This two-dimensional analytical method converts a seismic time event to an interface in depth by constructing normal

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**Figure 6.** Illustration of ray paths, ray terminations and location of velocity interfaces determined by analytical time-to-depth ray-tracing technique performed on Crab Butte thrust, cross-section E-E' (Fig. 11). a) Rays converge to a line describing the fault and to a diffracting point at the updip termination of the fault. b) Ray terminations describe an interface too complex to be geologically reasonable, hence subtle changes in attitude of shallower interfaces are warranted.
incident ray paths from a datum through intervening refracting interfaces to the seismic event being modeled (Fig. 6). The geometry of this modeled interface is determined by the collective positions of the ray path terminations. Ray-tracing is used to determine the locations of individual interface segments identified from linear and curved features in the seismic sections. Ideally, the ray path terminations in the model should form a line in the case of a reflection or converge to a point in the case of a diffraction (Fig. 6a). Deviations from these patterns usually suggest geologically unreasonable interpretations (Fig. 6b) and may warrant changes in the model velocities or modification of the shallower interfaces of the model.

Figure 7. Cross-section A'-A'; a) seismic section; b) synthetic seismogram; c) geologic cross-section. CBT-Crab Butte thrust, CTT-Cowtrack thrust, PT-Pamburn thrust, Msr-Sun River event, E-Cambrian event.
An interactive computer program provided a rapid means for entering and editing key seismic horizons and building a geologic interpretation directly from the seismic sections. The speed of the modeling process allowed many iterations for testing multiple hypotheses. The identities of isolated reflections were verified by comparing migrated positions and attitudes with other controlling

Figure 8. Cross-section B-B': a) seismic section; b) synthetic seismogram; c) geologic cross-section. CBT- Crab Butte thrust, CTT-Cowtrack thrust, PT-Pamburn thrust, Mst- Sun River event, C Cambrian event.
The limited range of realistic geometries and velocities observed in the area constrained the modeled locations of velocity unit boundaries.

The migrated seismic features provide a structural framework with which other data were incorporated to produce structural cross-sections (Figs. 7-13). Forward modeling of the integrated

Figure 9. Cross-section C-C'; a) seismic section; b) synthetic seismogram; c) geologic cross-section. CBT-Crab Butte thrust, CTT-Cowtrack thrust, PT-Pamburn thrust, Ms-Sun River event, £-Cambrian event.
structural cross-section produced a synthetic seismic response for direct comparison with the seismic section. Differences between the seismic section and synthetic seismogram provided semi-quantitative input for further iterations.

Subsurface Structural Mapping

The subsurface structural map (Plate I) was produced by migrating mapped times to selected seismic horizons into three-dimensional positions. This map migration requires a realistic three-dimensional model of the velocity gradient above the horizon. This model was obtained from the two-dimensional velocity models generated through the inverse modeling procedure. The map migration was constrained through correlation with the cross-sections produced by the inverse modeling technique.

Absolute elevations and map positions may be affected by errors

Figure 10. Cross-section D-D'; a) seismic section; b) synthetic seismogram; c) geologic cross-section. CBT-Crab Butte thrust, TLT-Twin Lakes thrust, CTT-Cowtrack thrust, Mrw-Sun River event, C-Cambrian event.
Figure 11. Cross-section E-E'; a) seismic section; b) synthetic seismogram; c) geologic cross-section. TRT-Teton River thrust, WCT-Willow Creek thrust, CBT-Crab Butte thrust, CTT-Cowtrack thrust, Msr-Sun River event, E-Cambrian event.
incurred through simplification of velocity fields, insufficient seismic resolution and two-dimensional approximations to three-dimensional features. However, these errors are too small to affect the gross geometry summed up as structural style.

DISPLACEMENT TRANSFER
Displacement transfer is the strain relationship between genetically-related faults and folds. Within transfer zones, thrust faults lose displacement to adjacent folds which then transfer displacement on to adjacent faults. Faults and folds differ in their spatial and temporal patterns of strain distribution.

Strain Distribution and Fault Movement
Many materials demonstrate a brittle or elastic response to high strain rates and a ductile or inelastic response to lower strain rates under otherwise identical conditions. Folds commonly result from relatively low-velocity dissipation of pressures under low local strain rates, while faults result from higher strain rates in the same materials. Strain along a fault is concentrated within the fault

Figure 12. Cross-section F-F'; a) seismic section; b) synthetic seismogram; c) geologic cross-section. WCT-Willow Creek thrust, CBT-Crab Butte thrust, SdT-Salmond thrust, Mr-Sun River event, E-Cambrian event.
Figure 13. Cross-section G-G': a) seismic section; b) synthetic seismogram; c) geologic cross-section. ST-Sawtooth thrust, CRT-Cutrock thrust, FCT-Ford Creek thrust, BBT-Black Butte thrust, LT-Long thrust, CT-Cobb thrust, SDT-Salmond thrust, Mr- Sun River event, E- Cambrian event.
plane. Strain within a fold, however, is more widely distributed throughout some notable volume of rock. The terms fault and fold form the end-members of a continuum between concentrated and distributed strain.

Displacement transfer results from local variations in the spatial and temporal distribution of strain. A given amount of strain is more broadly distributed throughout the transfer zone than it is in adjacent areas. Consequently, differences in strain distribution may result in faulting in one area and folding in surrounding rocks or complex combinations of both responses. It may also result in faulting in a given area at one time and folding at another time during on-going deformation.

Studies of recent fault movements demonstrate that only a portion of a fault, limited spatially in both the strike and dip directions, slips during an individual earthquake (Stacey, 1977, p. 119-127; Price, 1988). Movement on a fault segment during a measurable earthquake occurs as a high velocity propagation of a series of movements on even smaller segments. The spatial and temporal distribution of these incremental movements is complex.

At map scale, a recognizable fault plane is the composite result of many discrete, incremental dislocations which are not individually distinguishable. Each dislocation occurs over only a relatively small portion of the fault plane (Price, 1988; Gretener, 1972). Incremental movement occurs at an extremely high rate when compared with the average rate of motion for the total displacement across the entire fault. Each dislocation releases pressure along the fault, resulting in the redistribution of this pressure throughout the adjacent rock. The rate and direction of dissipation of pressure away from the activated fault segment varies as a function of the strength parameters of the rock. Consequently the surrounding rocks produce a variety of rheologic responses which may produce folds, faults and fractures at several scales either concurrently or sequentially. Within transfer zones, the overall displacement is taken up primarily by folds or by faults with significantly less individual displacement than in adjacent areas.

In displacement transfer zones, the continuity of overall shortening indicates that movements on adjacent faults and folds occurred penecontemporaneously in response to a common cause. In the broader reference frame of geologic time these movements appear to be simultaneous (Goldberg, 1984). The interlocking relationship of adjacent faults throughout the Sawtooth salient indicates overall penecontemporaneous movement on the entire assemblage of thrust faults within the study area.

Observations of Displacement Transfer

Goldberg (1984) described and discussed displacement transfer within the Sawtooth Range along part of the western margin of the study area. Structural patterns observed both in outcrop and in the subsurface correlate well with key characteristics of physical models of displacement transfer produced by Gardner and Spang (1973). Dahlstrom (1970) previously described similar displacement transfer zones in Canada. Similar features also occur within the disturbed belt.

Figure 14 shows the ideal map pattern and predicted displacement for a theoretical displacement transfer model of a thrust-to-fold and thrust-to-thrust displacement transfer. Figure 15 shows how the measured displacements for the individual thrusts identified in this study vary. Due to displacement transfer, however, the total displacement across the thrust system remains relatively constant.

Displacement transfer occurs at a variety of scales. For example, at their southern limits, the Pamburn and Cowtrack thrusts (Fig. 2 and Plate 1) lose displacement to adjacent folds, just south of the Cowtrack thrust terminus, the displacement transfers from these folds to the Salmon thrust. At a larger scale, the overall displacement across the structurally lower, westward dipping Black Butte, Long, Cobb and Salmon thrust system decreases southward while the adjacent structurally higher, southerly dipping French, Sawtooth, Cutrock and Ford Creek thrust system shows a corresponding increase in displacement (Figures 13 and 15). On an even larger scale, the cumulative displacement of the many faults and folds of the southern Sawtooth Range transfers to the Eldorado-Steinbach thrust system to the south. At the northern end of the Sawtooth Range near the southern margin of Glacier National Park, the displacement transfers to the Lewis thrust.

Thrust Plates and Thrust Plate Boundaries

The idealized transfer model predicts equal transfer of displacement to faults and folds both above and below a given fault (Fig. 14). In exposures in the Sawtooth Range, however, most of the displacement has commonly transferred to only one of these faults, either above or below. This preference results in a continuous zone

Figure 14. Hypothesized ideal map patterns of thrust-to-thrust and thrust-to-fold displacement transfer as inferred from results of this study and models by Gardner and Spang (1973).
of deformation consisting of a series of interconnected folds and faults which maintain nearly constant composite displacement along strike. In the simplest cases, this zone may consist of a single fault surface or fold. In more complex cases, the zone of deformation may consist of disharmonic folds, breccia or duplex stacks. The zone of deformation thins where strain is concentrated as along a single fault and thickens where strain is more widely distributed through folding and complex faulting. The less-deformed rocks between these zones correspond with what have commonly been called thrust plates by other defining criteria (Dahlstrom, 1970). For the purpose of relating thrust plates to hydrocarbon traps, the zone of deformation is commonly included as a part of the upper thrust plate. We have identified five of these plates through subsurface mapping of the top of the Castle Reef Dolomite. These are the Pamburn plate, Cowtrack-Salmon plate, Crab Butte-Twin Lakes plate, Willow Creek-Teton River-Cobb plate and the Long-Black Butte plate (Fig. 2).

The geologic cross-sections (Figs. 7-13) show thrust faults near the eastern edge of the disturbed belt displacing crystalline basement. These thrust faults extend upward through the Phanerozoic section at 25-30 degrees toward the surface. At the easternmost edge of the disturbed belt these thrusts die upward into folds before reaching the surface. The amount of displacement across each of the faults decreases northward along strike to the thrust culmination, then decreases as the displacement transfers to an adjacent thrust which continues to the north. The total amount of displacement across each zone of deformation increases northward toward the axis of the salient. The general elevation of the plate also increases northward along strike as the vertical component of displacement increases in proportion to the total displacement. In this fashion, cumulative displacement within the disturbed belt also increases systematically from zero at the eastern limit to a few miles at the front of the Sawtooth Range.

The increase in displacement toward the central portion of each fault results in fault lines having an arcuate shape at individual stratigraphic levels in the hanging wall (Fig. 2). In map view, the fault lines of adjacent fault planes consequently often converge or cross at high angles in transfer zones.

Thrust faults having displacements of greater than 2 miles (3 km), have flattened in the upper portion of the Cretaceous section. This appears to have occurred as a series of imbrications breaking forward in the footwall through units from the Marias River Shale upward in the section. The Crab Butte thrust (Fig. 11) imbricated in this manner, carrying previous imbrications in the hanging wall as each new imbricate formed in the footwall. The footwall also broke into several horsts which have been simplified in Figures 7, 8 and 9 to appear as a single horse beneath the roof and floor thrusts of the Twin Lakes thrust complex.

In addition, this flattening produced back-limb imbricate thrusts in the hanging wall. The Crab Butte and Twin Lakes thrusts diverge upward from a single root thrust (Figs. 7, 9 and 10). Due to a greater proportion of throw along the inclined fault segment relative to the flattened segment, the rearward portion of the hanging wall (Crab Butte plate) moved upward over the flattened portion (Twin Lakes plate) of the hanging wall. These back-limb imbricate faults typically have a few hundred to a few thousand feet of displacement. In the Cretaceous section, much of the displacement transferred into numerous small-scale faults, too small to be reliably mapped in this study. The cumulative displacement on the imbricate stack and associated folds equals the displacement on the main fault rearward of the imbricate fan. As displacement increases northward along strike, these imbrications increase in number and cumulative displacement, eventually cropping out northward within the Sawtooth Range.

The topographic expression of the Sawtooth Range is due to the higher resistance to erosion of the exposed Paleozoic section relative to the Mesozoic section exposed throughout the disturbed belt. The amount of fault displacement required to lift Mississippian rocks from the elevations observed in the subsurface at the eastern edge of the disturbed belt to the elevations at which they first crop out along the front of the Sawtooth Range is primarily a function of the effective dip on the intervening thrust faults and the thickness of overlying sections. The thickness varies from approximately 6,000’ (1830 m) in the northern portion of the area to as much as 10,000’ (3050 m) in the Sun River re-entrant. For thrust faults dipping 25-30 degrees, the minimum predicted cumulative displacement at the Mississippian outcrop would be 2.7 miles (4.3 km) for the northern portion of the area and 4.5 miles (7.2 km) for the southern portion. The lower fault angle observed for part of the Twin Lakes thrust (Figures 7, 8, 9 & 10) requires additional displacement to uplift the Mississippian section to current outcrop levels. Consequently, the boundary between the disturbed belt and the Sawtooth Range occurs where cumulative displacement relative to the undeformed rocks to the east is approximately 5 miles (8 km).

En Echelon Patterns

The divergence of the north-northwestward structural trend from the northward displacement trend results in an en echelon pattern of faults, folds and related topographic features extending through the disturbed belt and the Sawtooth Range. The increase in displacement from east to west across the disturbed belt results in a decrease in structural style from mild folds to simple thrusts to complex imbricate stacks. Consequently, structural features observed in the Sawtooth Range can be traced through a series of transfer zones to related features of predictable structural style in the subsurface of the disturbed belt.
Folds

Subsurface Cambrian and Devonian rocks in the eastern half of the disturbed belt deformed in part as hanging-wall box folds. In seismic data, these folds have the same appearance as back-thrusts. Farther to the west, these folds developed into sharp, commonly overturned chevron folds as interpreted from well log data from the Amoco 1 Cobb (Fig. 13). Due to the similarity in the gross geometry of rocks involved in and adjacent to chevron folds and thrust faults, they both produce a similar seismic response. However, axial planes of hanging-wall folds typically dip approximately 60 degrees westward, diverging from the underlying fault at about 30 degrees.

Hanging wall folds involving Mississippian rocks have typically rotated beds to a vertical or slightly overturned position against the underlying fault. In the Texaco 1 State of Montana "O", dipmeter and borehole survey data reveal that the top of Sun River Member dips approximately 40 degrees toward the east just a few hundred feet east of the crest of the fold. This rate of curvature is similar to that observed in surface exposures in the canyon of the Teton River, as well as other locations within the Sawtooth Range.

The seismic response produced at these steeply-dipping fold margins is a time gap between the migrated position of steep reflections of the Sun River event and the diffractions from the truncation of the Sun River event by the thrust plane. As an example, this amounts to approximately 100 milliseconds along the Crab Butte thrust in Figure 11a. The gap results because the beds at the margin of the fold dip too steeply to reflect seismic waves back to the geophone array. Further evidence for inferring steep dip of the Sun River Member into the thrust fault comes from the abrupt pull-up in the underlying reflections. This indicates an abrupt lateral change from high to low velocity in the overlying velocity field.

Within the thrust plates, numerous observed subsidiary faults and folds may have been caused by movements on structurally lower thrust faults. For example, the development of the fold in the north end of the Cowtrack thrust was probably influenced by movement of the northern subsidiary thrust fault of the Pamburn thrust (Fig. 2, Plate I). Additionally, the broad fold in the north end of the Long thrust probably reflects motion on the underlying Willow Creek thrust where displacement transferred to the Cobb thrust (Fig. 2, Plate I).

HYDROCARBON EXPLORATION

This paper is based on work done in a search for commercial hydrocarbons. The only current production within the U.S. portion of the disturbed belt occurs at Blackleaf Canyon, just north of the study area. In the analogous Canadian foothills, the three nearest fields had combined initial established reserves of 2,785 billion cubic feet of gas (French, 1984).

The Blackleaf Canyon area produces gas from the Sun River Member of the Castle Reef Dolomite just north of the study area (Johnson, 1984). Two wells currently produce gas from a hanging wall anticline east of the imbricate stack (Fig. 16) while two wells drilled into the imbricate stack have proven gas reserves but remain shut-in.

The Sun River Member is the dolomitized upper portion of the Madison Group. It appears to have formed as the result of diagenesis associated with repeated subaerial exposure and erosion (Nichols, 1984). The unconformity between the top of the Madison Group and the overlying Ellis Group represents the entire interval from Late Mississippian to Middle Jurassic time. Studies of Madison Group rocks in adjacent regions indicate a complex diagenetic history throughout the period of time represented by the unconformity (Buda and others, 1987). Sample descriptions of area wells and outcrops of the Sun River Member show intervals of good vuggy porosity. Extensive fracturing within the Sun River Member has enhanced the permeability of the reservoirs, providing good vertical communication within the closure (Johnson, 1984). Fracturing has also allowed lateral migration of hydrocarbons within the fractured unit.
The general southward plunge of large folds in the study area results in general migration of hydrocarbons updip to the north. However, northward dip on folds within the transfer zones provides barriers to migration of hydrocarbons to outcrop northward. Since the reservoir unit is continuous through the folds of transfer zone, the fold geometry within the transfer zone determines the location of the spill point between adjacent thrust-bounded reservoirs. In turn, the location of the spill point determines the amount of vertical closure for the trap to the south of the spill point. Failure to recognize a transfer zone can result in a failure to recognize a potential hydrocarbon trap.

The hydrocarbon traps at Blackleaf Canyon Field appear to be filled to the spill point, and may rely in part on fault closure. Structural closure appears to be a key factor in defining a commercial reservoir in this area.

**Texaco 1 State of Montana “O”**

During the summer of 1988, Texaco drilled the 1 State of Montana “O” (Plate I) located in Teton County (SW SW NE Section 7, Township 22 North, Range 8 West, PMMI). This well drilled a prospective pair of stacked hanging-wall anticlines selected for their similarity in structural style and stratigraphy to Blackleaf Canyon Field.

Due to drilling problems, the initial hole was plugged back from a depth of 3378’ (1030 m) to 1150′ (350 m). Further drilling problems were averted by drilling a sidetrack hole with a steerable bit to a final drilling depth 5972′ (1820 m). Three drill stem tests run through seven zones of casing perforations in the upper section of the Sun River Member of the Castle Reef Dolomite yielded no shows of oil or gas.

Porosity within the Sun River Member range from 4.5% to 11% based on well log calculations. Micrographs taken with a scanning electron microscope reveal abundant vugs and fractures (L.H. Taylor, personal communication). For comparison, porosity in correllative units in several major Canadian gas fields in the disturbed belt range from 4.1% to 6.5% (French, 1984). Throughout the study area porosity in the upper 100 feet (30 m) of the Sun River Member is consistently lower than in the lower portion. This division is also evident around Blackleaf Canyon field.

The lack of hydrocarbons in this well is probably due to a lack of closure northward from the well (Plate I). Displacement on the Willow Creek thrust transfers northward to a structurally higher thrust. Further north, displacement transfers again to a structurally higher thrust. Additional transfers to structurally higher plates may continue northward, eventually reaching the surface. Fractures may also have provided conduits to the surface, allowing gas to escape. Similar circumstances may explain the lack of commercial hydrocarbons in other boreholes in the area. The subsurface map (Plate I) shows numerous other possibilities for closures analogous to Blackleaf Canyon with potential for economic hydrocarbon production.

**SUMMARY**

The en echelon thrust faults and folds of the southern portion of the Sawtooth salient of the disturbed belt show a systematic pattern of change in structural style resulting from increasing displacement westward. Subsurface fault and fold patterns predicted from surface information correspond with patterns deciphered from the observed seismic response. Folds along the eastern margin of the disturbed belt transfer into thrust faults along strike. These thrusts dip 25-30 degrees westward through Phanerozoic sediments and into crystalline basement. Displacement along thrust faults has transferred both in dip and strike directions to other faults, forming an interlocking en echelon pattern. Where displacement on an individual thrust fault has exceeded 2 miles (3 km), the thrust has flattened into the upper Cretaceous section. This has produced an imbricate fan and duplex in the footwall and a back-limb imbricate stack in the hanging wall. Erosionally resistant Mississippian rocks within the back-limb imbricate stack form the eastern margin of the Sawtooth Range. Individual thrust fault displacements within the disturbed belt are commonly less than 2 miles (3 km), with a maximum displacement of about 4 miles (6.5 km). Cumulative displacement across mapped thrusts decreases to the south within the Sawtooth salient of the disturbed belt as displacement transfers to the faults beneath the Eldorado-Stinbach thrust system.

In spite of the complexity of the seismic response, useful information has been deciphered from seismic data through the use of forward and inverse modeling techniques. Specific interpretation techniques locate faults, folds and lithostratigraphic units by analyzing response patterns from known geologic relationships.

Displacement transfer zones provide a strain continuum between adjacent thrusts. Observations of recent fault movements suggest that movement on adjacent thrusts and intervening folds occurred pencontemporaneously. Laterally continuous plates are formed by component thrust faults connected along strike by transfer zones. Numerous possibilities for hydrocarbon traps occur within these component plates.

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**REFERENCES CITED**


