A SEISMIC INVESTIGATION OF THE
NORTH GOLDEN AREA, JEFFERSON COUNTY, COLORADO

by
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A Thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science in Geophysical Engineering.

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ABSTRACT

Two and one-half miles of continuous east-west 12-fold seismic data were obtained across the zone of flank deformation two miles north of Golden. The seismic section was correlated with single-fold seismic data obtained from Shell Oil Co. and to the formation-depth information from the No. 1 Farmers Highline and Canal Reservoir well (7-3S-69W). The data indicate that over 8,000 ft. of vertical Laramide uplift has occurred along the four fault planes within the survey area. All four faults trend north-south, with down-to-the-east relative movement. In general, the fault throw increases from fault-to-fault in a westerly direction.

The two westernmost faults detailed in this investigation comprise the Golden fault zone. Major flank deformation occurs in this zone, with a total vertical displacement of about 3,000 ft. These high-angle reverse faults are dominantly vertical and probably join at depth. Near the surface the fault planes curve convex-upward, dipping west, causing vertical and overturned dips on surface outcrops. Basin sedimentary units are flat-lying or slightly tilted at depth. To the north the Golden fault zone widens and the faults are separated at depth. South of the thesis survey the faults converge.
Two vertical basin-margin faults are located 1,500 and 4,500 ft. east of the Golden fault zone. The faults down-drop Denver basin sedimentary rocks to the east. Fault displacement is not observed at the surface but increases to nearly 200 ft. at the Precambrian basement. Displacement is greater across the western basin-margin fault. Between the abrupt fault boundaries there is a rotation of basin rocks controlled by differential basement uplift. This evidence supports the idea of growth or intermittent movement of the basement-controlled faults.
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ACKNOWLEDGMENTS

I wish to thank Dr. Thomas L. Davis for suggesting the subject matter of this thesis and for his patient help and encouragement throughout. In addition, he made available to me seismic data released to him by Shell Oil Co. To George Beggs, much appreciation for his continuing help with operation of equipment, especially processing problems on the Phoenix computer. Also, I would like to acknowledge the cooperation of Ms. Gladys Ramstetter, Ms. Lida Ann Ramstetter, and Mr. Herbert T. Young, manager of Table Mtn. Corp., for allowing me to conduct this survey across their land.
INTRODUCTION

The Front Range bounds the western margin of the Denver basin, upturning the oldest basin sedimentary rocks to form a prominent hogback paralleling the Front Range (Fig. 1). The Denver basin is an asymmetric basin composed of sedimentary rocks ranging in age from Recent to Pennsylvanian, lying unconformably upon a Precambrian basement. The axis of the Denver basin is approximately six miles from the surface exposure of the Precambrian (Haun, 1968). West of the basin axis sedimentary rocks dip eastward while to the east there is a very gentle westward dip. A zone of flank deformation extends from the mountain front several miles into the Denver basin. Flank deformation began in the Late Cretaceous with the onset of the Laramide orogeny. Compensation for vertical uplift results in monoclinical folding and high-angle reverse and normal faulting of sedimentary rocks (Boos and Boos, 1957). The Golden fault zone is associated with the vertical and overturned hogback features in the thesis area. Basin-margin faults, postulated by Weimer (1973), are also related to Laramide tectonic forces.
Figure 1. Location map of thesis area.
To delineate the zone of flank deformation the VIBROSEIS® method of reflection seismic data acquisition was chosen. The resulting 12-fold common-depth-point (CDP) seismic line was correlated with single-fold seismic data from Shell Oil Co. Formation-depth information from the No. 1 Farmers High-line and Canal Reservoir well (7-3S-69W) coupled with formation travel time and velocities led to several conclusions about flank deformation structures and fault history.

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PURPOSE AND SCOPE OF INVESTIGATION

Objectives

Previous methods of investigation of the Golden fault zone have been limited to surface observation with the exception of Stommel's (1951) research. That data consisted of seismic refraction and jump-correlation reflection work in Jefferson County, but the results were inconclusive due to two factors:

a) one-mile shot-point intervals prevent detection of small displacement basin-margin faults;

b) data quality especially near the Front Range is poor, so correlation of particular reflectors is difficult.

This thesis involves the acquisition, processing, and interpretation of a 12-fold seismic line (Golden Line 1). The data were obtained using the VIBROSEIS method. Golden Line 1 is located in the northwest sector of T3S R70W (Fig. 2). The westernmost survey station is situated on the Lykins Formation (Fig. 17). Golden Line 1 trends eastward for two and one-half miles, extending stratigraphically
EXPLANATION

SCALE:

0 5 10

CONTOUR INTERVAL:
100 feet

DATUM: MEAN SEA LEVEL

Figure 2. Location map of thesis area.
up-section onto the Denver Formation. Two and one-half miles northeast of Golden Line 1 is located the No. 1 Farmers Highline and Canal Reservoir well (SE SE NW 7-3S-69W). Depths to key formation tops have been obtained from the Schlumberger electric log from the well (Table 1). Additional seismic data used in the construction of the geologic cross section (Plate 2) across the zone of flank deformation is Line 54-6; shot point (SP)-188. The data is single-fold seismic data obtained by Shell Oil Co. in 1953 using a dynamite source. SP-188 allows correlation of the stratigraphic thicknesses taken from the electric log with interval times.

The main objective of this seismic investigation is to detail structurally the transition zone between the central Front Range and the Denver basin. The multiplicity of stacked data increases the signal-to-noise ratio allowing recovery of good data even in structurally complex areas. The seismic survey was carried out perpendicular to structural strike eliminating the interference of reflections coming in from out of the plane of the section. This thesis attempts to resolve the controversy of the attitude and structural style of the zone of flank deformation.

**Previous Work**

Ziegler (1917) described much of the early field geology of the foothills area west of Denver. He was the first to
interpret high-angle reverse faulting in the Golden area, resulting from nearly vertical forces. Wahlstrom (1947) discussed the Front Range structure as a result of intermittent Laramide uplift with complex faulting and folding. He noted the dominant fault trend as northwest. From relationships between faults and Tertiary intrusives Wahlstrom has shown repeated movement along faults.

Stommel (1951) and Stewart (1951) combined efforts between the geology and geophysics departments of the Colorado School of Mines. Stommel was in charge of a spot-correlation seismic survey. Stewart mapped the field geology defining a 20 mile minimum length for the Golden thrust fault. The seismic survey consisted of six reflection profiles with shot-points every mile to determine the attitude of subsurface reflectors. A refraction line was conducted across the fault trace to locate points on the fault plane. They concluded that the Golden Fault was a single thrust dipping 4°W in the present area of study.

The Front Range was mapped by Boos and Boos (1957). Over a 30-year study was conducted on the foothills structure. They describe a Golden thrust-fault belt comprised of under-thrusts in which the footwall, or Denver-basin block was the active element of faulting.
Osterwald (1961) analyzed the Front Range and bordering plains as a part of the Cordilleran foreland. He suggested that the tectonic framework is controlled by basement structure yielding block-shaped mountains and asymmetric basins. He mapped the Golden fault zone south of Golden as two high-angle reverse faults with small-scale imbricate structures. At depth these faults converge, originating from dominantly vertical uplift between basement blocks.

Berg (1962) concluded that the structure at Golden was initiated by vertical uplift which resulted in a thrust-overturned fold. He drew his conclusions from the geologic information of two wells in the Soda Lakes area 10 miles south of Golden. He states that at Golden, thrust faulting is more prominent than at Soda Lakes. He assigns characteristics to fold-thrust zones:

1. multiple faults, usually two;
2. fault zones consisting of overturned Paleozoics and early Mesozoics, only the most competent rocks, are 500 to several thousand feet thick;
3. dip varies, very steep to vertical at depth to only a few degrees along the middle portion of the overturned limb.

Harms (1965) studied Laramide faulting and the associated stresses. He confirmed by analysis of sandstone dikes south
of Denver that the necessary mechanism of injection is dip-slip movement of steep west-dipping convex-up reverse faults. The same theory is applied for the area near Golden.
GEOLOGY OF THE GOLDEN AREA

Stratigraphy

The Front Range of Colorado extends for 180 miles north-south and 40 miles east-west across the center of the state. Highly metamorphosed crystalline rocks with numerous igneous intrusives compose the core of this dominantly "Laramide" generated feature. Near the area of investigation Boos and Boos (1957) describe the Precambrian as a biotite-sillimanite schist, injection gneiss, and quartzite. Curtis (1960) believes these gneisses and schists to have developed from sediments and lavas.

There is no Paleozoic section earlier than Pennsylvanian present in the Denver basin. Berg (1960) describes the Siouxsia uplift as a broad gently undulating platform. Early Paleozoics were believed to have been of intermittent shelf deposition (Gilluly, 1963) which were eroded during regional epeirogeny of Early and Middle Paleozoic time.

During Pennsylvanian time the Ancestral Rockies were characterized by a major uplift which exposed huge expanses of Precambrian basement. This ancient mountain chain was
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Figure 3. Generalized stratigraphic column of thesis area. After LeRoy (1955).
uplifted on an axis 30°NW to the present Front Range axis (Harms, 1965). Rapid erosion of terrigenous sediments led to fluvial deposition of the Fountain Formation upon the Precambrian erosional surface. Red arkosic conglomerates and sandstones were laid down as a series of coalescing alluvial fans or on an alluvial plain. A variety of depositional environments are represented: stream channels, flood plains, near-beach and near-shore marine.

The Lyons Formation overlies the Fountain Formation. The Permian Lyons was deposited as beach sands and dunes adjacent to beaches (Maughan and Wilson, 1960). It is a tan fine-to-medium grained well-sorted sandstone with conspicuous cross-bedding.

Transgression continued with shallow-sea deposition of siltstones and mudstones, with the inclusion of two limestone members. Age of the Lykins Formation spans the boundary between the Permian and Triassic Periods. LeRoy (1955) has placed this boundary at the top of the Glennon limestone member. The Ancestral Rockies continued to be a dominant positive feature which influenced sedimentation during the Early Mesozoic, even though they were eroded and modified.

The Ralston Creek Formation is the result of non-marine deposition in an area of poorly-drained lakes and marshes.
The Morrison Formation was deposited over the Ralston Creek Formation and is characterized by gypsum beds with dense limestones and occasional claystones. Sediments were entirely of continental origin; aggrading streams and lakes on a relatively featureless surface.

The Denver basin is predominantly composed of Cretaceous sedimentary rocks. Between deposition of Jurassic and Cretaceous sediments is an unconformity. Cretaceous sediments are almost exclusively clastics derived from western sources. During the Early Cretaceous sediments came from an eastern source as well (Haun and Weimer, 1960).

The Dakota group is composed of marine sandstones and shales that interfinger with non-marine sands and shales. This unit is a transgressive sequence covering huge Precambrian remnants and basins. Strandlines trend northwest; marine waters transgressed southwest and regressed northeastward.

Overlying the Dakota Formation is the dark fine-grained Benton shale, a neritic sequence. The Benton Formation has been subdivided into the Carlile, Greenhorn limestone, and the Graneros shale.

The Niobrara Formation is mainly a dark-gray thin-bedded calcareous shale of marine origin. At the base of the Niobrara is a thin-bedded limestone. The Niobrara is a key
horizon in the correlation of seismic data used in this thesis. Due to the fact that the Niobrara is overlain by relatively low-velocity shales and siltstones the seismic signature of the Niobrara is readily identifiable.

The most dominant formation in the Denver basin is the Pierre shale (Fig. 4). The Pierre is composed of 6,000 to 8,000 ft. of uniform clastics. There are four zones (Davis, 1974) within the Pierre: the Transition zone, the Hygiene zone, the Rusty zone, and the Sharon Springs zone. The latter two make up only one-fourth of the total Pierre thickness. These are siltstones and shales providing a velocity contrast with the underlying Niobrara. The Middle Pierre is composed of the Hygiene zone. Within this unit are the Terry and Hygiene sandstone members which yield identifiable seismic events. The Hygiene member is a gradational siltstone grading upward to a clean sandstone of shelf, bar margin, and central bar facies (Porter, 1976). The Terry member is a 300 ft. sequence of interbedded siltstones, shales, and thick fine-grained sandstones deposited in a near-shore environment (Moredock and Williams, 1976). The Upper Pierre is composed of the Transition zone. This zone has been interpreted as a high-constructive deltaic sequence (Weimer, 1976). There are cycles of pro-delta shales which are thought to indicate an unstable tectonic environment. Davis (1974) has labeled two distinctive seismic markers
Figure 4. Stratigraphy of the Pierre Formation. 
(After Davis, 1974)
in the Transition zone: TZ1 and TZ2. Final regression of the Cretaceous Sea ended Pierre deposition. The transition between marine and continental deposition is represented by the Laramie and Fox Hills Formations. The Fox Hills is a delta-front sandstone. The Laramie is a thick sequence of coals, sands, shales, and clays. The old environment of deposition was a delta plain (Weimer, 1976).

The Denver-Arapahoe Formation is composed of conglomerates, sandstones, and claystones. These continental clastics were deposited in alluvial valleys and plains. In the Cenozoic, there was continued rapid deposition of poorly sorted alluvium, the Green Mountain Formation.

**Structure**

Front Range morphology is primarily the result of mountain building and erosional action associated with the Laramide orogeny. Two structural provinces abut, forming a complex boundary between a large uplifted block of Precambrian metasedimentary rocks and the down-dropped asymmetric Denver-basin block. Sedimentary rocks has been faulted up from the bottom of the basin to form a prominent hogback paralleling the Front Range. Within six miles of the hogback these same rocks are buried as deep as 13,000 feet.
Uplift during the Cretaceous continued from evidence of uninterrupted deposition in the stratigraphic record. Pleistocene terrace development supports the idea of intermittent of the Front Range (Wahlstrom, 1947).

The Front Range is a large elongate block of uplifted Precambrian rocks oriented approximately north-south. Associated structures strike northwest to northeast. Analysis of joint-failure patterns (Badgley, 1960) shows the major direction of stress to be N 80°E. Paralleling the east flank of the Front Range is a zone of flank deformation. Included in this structural complex are the Golden fault zone and two basin-margin faults (Weimer, 1973).
SEISMIC INVESTIGATION

Field Equipment

All the equipment used in the organization and processing of data is the property of the Colorado School of Mines. The recording truck was equipped with a Texas Instruments 10,000 Digital Field System, recording 24 data traces on one-inch magnetic tape. The seismic source was a single 15-ton vibrator (Fig. 5). The cable and geophones are the standard type used in industry. Geophones strings contain 14 Geopsace geophones stretched over a 200 ft. spacing.

Fig. 5. Field operations in progress.
Field Procedure

The cable was laid out from west to east with a geophone-group station spacing of 300 ft. Geophones were planted in-line with the cable over a 200 ft. interval at each station. The vibrator sent 28 sweeps into the ground for each vibrator point (VP). The vibrator pattern was in-line over a 300 ft. spacing (Fig. 6). The VP's were 600 ft. apart. The sweep used was an eight-second 48-to-8 Hz downsweep. The recording time was 11 seconds; sweep length plus a three second listening time. The sampling rate was two milliseconds.

Field parameters were selected on a trial and error basis. A noise spread was conducted in the area (Shuck, 1976). Analysis of the noise spread showed that a geophone array spacing of 200 ft. would cancel the low frequency ground roll. Field experimentation, however, proved that 300 ft. group spacings obtained much better data quality.

Data was collected in two groups; east and west of Highway 93. Twenty stations were laid out west of the road. With the recording equipment stationary, the VIBROSEIS vibrated through the twenty stations continuing across Highway 93 to obtain subsurface coverage across the road. The recording equipment was relocated east of Highway 93, using a full spread of 24 stations. The vibrator was able to complete five VP's before terrain conditions became impassable.
Seismic Method

The seismic reflection technique was chosen for this investigation for the following reasons:

a) except for Stommel's research, only surface geology mapping had been done in the area;

b) due to the complexity of faulting as well as the Quaternary cover of alluvium over bedrock, complete detailing of the subsurface geology is impossible with only outcrop information;

c) modern multifold seismic data are a good presentation of subsurface geologic structure.

The sound waves sent into the earth by the VIBROSEIS technique are partially reflected back to the surface by each acoustic impedance boundary which is usually synonymous with a lithologic interface. The reflected energy, or signal, from each sweep is weak so 28 sweeps were used at each VP and later summed in the processing to increase the signal-to-noise ratio. The data were recorded, processed, and displayed. Interpretation of this seismic section provides a structural insight to the subsurface configuration in the zone of flank deformation, especially the Golden fault zone.

Processing

The Phoenix mini-computer was used to process the field data. The data were recorded on 1-inch 21-track magnetic
field tape. To process the field data on the Phoenix, the field-tape data format was changed to a trace-sequential Phoenix format in the DEMULT program. Poor quality records were also dropped in this process. Records were resampled from 2 to 4 milliseconds and transferred onto half-inch 9-track magnetic tape. Digital trim was applied to increase the amplitude of attenuated signal near the end of the record. The processing steps from field data to final section are outlines in Fig. 7.

After DEMULT, the SUM program summed the 28 records from one VP into a single record; digital trim was applied. FDXCOR crosscorrelated the summed record with the field sweep. At this point the record length is cut from 11 seconds to 3 seconds. Crosscorrelation acts as a filter to random noise. During data recording gravel trucks traveling along the line introduced more ground motion than the vibrator. That noise was effectively eliminated by the crosscorrelation process.

A stacking table was constructed from spread configuration and VP locations. This table served as a check on the output of SSORT which also constructed a stacking table and calculated static corrections of each trace to a datum of 5800 ft. above sea level. The inputs were station elevation, station and shot location numbers, and datum elevation. Once the SSORT parameters were checked, SSORTCO collected the data into common-depth-point groups or gathers.
FIELD DATA
COLLECTION

DEMULT
Transfer and Reformat to Phoenix format

SUM
Summing of 28 Sweeps into a single Record

PDXCOR
Crosscorrelation of Raw Data with Sweep

SSORT
Sorting of Traces into Common Depth Points

100% STACK
Single Fold Record to Pick Proper Mute Zones

PREVIEW
Constant Velocity Stacks to Determine Proper Velocity Functions

SEISPAK
Brute Stack with NMO and Velocity Functions

CSTAT
Automatic Statics Program to align Reflectors

PRELAN
Frequency Content Analysis

FINAL SECTION

Figure 7. Flow diagram of processing steps
Stacking velocities were picked from constant velocity stacks output by PREVIEW. This program applied a set of specified velocities to the section. Three separate velocity functions were chosen across Golden Line 1 to accommodate for structural and stratigraphic changes (Fig. 8). Velocities in the western portion of Golden Line 1 were higher to accommodate for the higher-velocity older sedimentary rocks brought to the surface by faulting. Velocities increase with depth; a result of compaction and cementation.

SEISPAK incorporated previously computed parameters: static corrections, normal move out (NMO), velocity functions, CDP groups, and mute patterns. A mute pattern was determined by first separating NMO-corrected traces into 100 percent groups. Early portions of these groups which were dominated by refraction arrivals or "stretched" by NMO were excluded, or muted. A BRUTE STACK was displayed after mute zones and velocity functions were chosen.

Several computer techniques were subsequently employed to enhance the section. The appearance of the BRUTE STACK was ragged because no weathering corrections were applied in processing the VIBROSEIS data. An automatic statics program, CSTAT, was used. The application of CSTAT improved the data quality of Golden Line 1 significantly.
Figure 8. Velocity functions used in processing.
A frequency analysis was performed upon the data. The frequency spectra indicated that the data contained frequencies in the rage of 9 to 48 Hz. The option for additional filtering of the data was not chosen. The final non-migrated seismic section is shown in Fig. 9.

Golden Line 1 was migrated. This program shifted dipping events into their true spatial position. Diffractions were migrated to their point of origin. The final migrated section is shown in Fig. 10.
Figure 9. Golden Line 1, uninterpreted, non-migrated
Figure 10. Golden Line 1, uninterpreted, migrated
INTERPRETATION

Interpretation of two and one-half miles of seismic data across the zone of flank deformation north of Golden required an integration of geophysical and geological knowledge. Golden Line 1 was tied to other regional seismic surveys on the basis of seismic character. Surface geology and well-log data provided stratigraphic correlations and velocity information.

Stratigraphic Correlation

In the Golden area, seismic character and time intervals are used to correlate seismic sections. From the seismic work done in the area (Davis, 1974; Shuck, 1976) the following stratigraphic units have been correlated:

a) Precambrian;
b) Niobrara;
c) Pierre Hygiene zone, Hygiene sandstone;
d) Pierre Hygiene zone, Terry sandstone;
e) Pierre Transition zone, marker 2 (TZ2);
f) Pierre Transition zone, marker 1 (TZ1);
g) Pierre.
The Niobrara shows the most character on the seismic section. This strong amplitude seismic marker event was used as the key tie from Golden Line 1 to other seismic lines. Once the Niobrara correlation was defined, time intervals and seismic character were used to identify the remaining seismic marker horizons. Surface geology was tied to Golden Line 1. Seismic character of reflectors in the western portion of the line is poor due to steep dip and interference from diffractions, so geologic control is the only correlation used in this zone.

Analysis of Line 54-6, recorded by Shell in 1953, provided an extension of seismic data into the Denver basin. Seismic character of the Niobrara enabled a correlation across the two and one-half mile interval between Golden Line 1 and SP-188 (Plate 1). A single record, SP-188, was used for two reasons:

1) data quality was exceptional;

2) SP-188 is located three-quarters of a mile from the No. 1 Farmers Highline and Canal Reservoir well.

The stratigraphic correlations made between SP-188 and Golden Line 1 are shown in Plate 1. The zero time line is referenced to a datum of 5800 ft. above sea level. Both Golden Line 1 and SP-188 are displayed at the same time scale. The horizontal distance across Golden Line 1 is about
two miles, while the distance across SP-188 is only about 2,000 ft. The upheole method was used to correct SP-188 to datum.

**Velocity Determination**

Velocity control is needed for complete interpretation of a seismic time section. To realize the magnitude of structure the two-way time interval must be converted to depth. The velocity function used in processing the seismic section was selected on the criterion of the "best stack" of data. These stacking velocity values are too high for use in converting time to depth, but provide a guide in selecting proper values for average and interval velocity.

To obtain reliable velocity information the reflecting horizons of SP-188 were tied to formation tops from the Schlumberger electric log of the No. 1 Farmers Highline and Canal Reservoir well (7-3S-69W). Assuming that there were no significant interval thickness or velocity changes within the three-quarters of a mile distance separating SP-188 from the well, interval velocities (Table 1) were calculated from the time-thickness relationship:

\[ V_i = 2 \frac{T_i}{\text{time}} \]
TABLE 1
Formation depths and calculated velocities from electric log of No. 1 Farmers Highline and Canal Reservoir well and Shot Point 188 from Line 54-6.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Well Depth (ft.)</th>
<th>Elevation (ft.)</th>
<th>Thickness (ft.)</th>
<th>Interval Velocity (FPS)</th>
<th>Average Velocity (FPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laramie</td>
<td>190</td>
<td>+5363</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fox Hills</td>
<td>1160</td>
<td>+4393</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pierre</td>
<td>1250</td>
<td>+4303</td>
<td>90</td>
<td>7,500</td>
<td>7,500</td>
</tr>
<tr>
<td>TZ1</td>
<td>2530</td>
<td>+3023</td>
<td>1280</td>
<td>8,000</td>
<td>7,700</td>
</tr>
<tr>
<td>TZ2</td>
<td>3780</td>
<td>+1773</td>
<td>1250</td>
<td>11,000</td>
<td>9,400</td>
</tr>
<tr>
<td>Terry Sand</td>
<td>5390</td>
<td>+163</td>
<td>1000</td>
<td>9,500</td>
<td>9,400</td>
</tr>
<tr>
<td>Hygiene Sand</td>
<td>6390</td>
<td>-837</td>
<td>2110</td>
<td>10,000</td>
<td>9,500</td>
</tr>
<tr>
<td>Niobrara</td>
<td>8500</td>
<td>-2947</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benton</td>
<td>8790</td>
<td>-3237</td>
<td></td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>Dakota</td>
<td>9170</td>
<td>-3622</td>
<td></td>
<td>11,500</td>
<td>10,000</td>
</tr>
<tr>
<td>Morrison</td>
<td>9450</td>
<td>-3897</td>
<td></td>
<td>280</td>
<td></td>
</tr>
<tr>
<td>Lykins</td>
<td>9650</td>
<td>-4097</td>
<td></td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Lyons</td>
<td>10259</td>
<td>-4706</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
where
\[ V_i = \text{interval velocity} \]
\[ T_i = \text{formation thickness} \]
\[ \text{time} = \text{formation two-way time interval.} \]

From these interval velocities, average velocities to the top of each mapped reflector were determined from the equation:

\[
V_{\text{avg}} = \frac{\sum_{i=1}^{N} V_i T_i}{\sum_{i=1}^{N} T_i}
\]

where
\[ V_{\text{avg}} = \text{average velocity;} \]
\[ N = \text{total number of intervals (i).} \]

In conjunction, a sonic log from the Tom Jordan No. 1 Sam Rudd well (22-1S-70W) in the vicinity of Marshall Lake ten miles north of the thesis area was used to check the calculated interval velocities. The interval velocities were found to be reasonable.

**Structural Interpretation**

The interpreted non-migrated display of Golden Line 1 (Fig. 11) depicts four faults labeled 1 to 4, west to east. The faults exhibit several significant structural characteristics.

a) all strike nearly north-south;

b) all have down-to-the-east relative movement, generally decreasing in displacement to the east;

c) the fault planes are near-vertical.
Figure 11. Golden Line 1, interpreted, non-migrated.
The zone of flank deformation contains two tectonically related fault systems; the Golden fault zone and a basin-margin fault set. The two fault systems are distinguished on the basis of fault plane behavior near the surface and magnitude of displacement.

Golden Fault Zone

The Golden fault zone contains two high-angle reverse faults which have a combined throw of at least 8,000 ft. Fault 2 has approximately 7,000 ft. of displacement. Both faults 1 and 2 are near vertical and probably join at depth. The fault planes diverge and become convex-up near the surface. At the surface the fault traces are about 2,000 ft. apart. The curvature of these faults can be seen more clearly on the interpreted migrated section (Fig. 12). Diffractions have been migrated to the apex of diffraction. Dipping reflectors have been shifted up-dip to the proper spatial position. With the elimination of diffractions, coherency of reflectors was improved.

Looking at the geologic map (Fig. 17) the character of the Golden fault zone changes. One mile north of the thesis line, Shuck (1976) has mapped these same faults. Fault 1 veers to the northwest while Fault 2 continues on a northward trend. Shuck has also found these faults to be vertical at depth becoming convex-up near the surface. The faults have separated at depth by 1,000 ft. From the geology as mapped by Scott and Cobban (1965) and Van Horn (1972) the
LINE 1 - MIGRATED

Figure 12. Golden Line 1, interpreted, migrated.
Golden fault zone curves west a mile south of Golden Line 1 to account for the disappearance of the Dakota hogback. Faults 1 and 2 converge into a narrow zone of imbricate faulting.

Displacement of fault 2 is about 7,000 ft. as compared to 1,000 ft. across fault 1. Shuck measured displacements of 6,000 and 2,000 ft. respectively. The separation of the faults has affected the relative displacements but not significantly. Further north, however, the degree of vertical compensation for uplift of the Front Range by fault 2 could be taken up solely by fault 1.

**Basin Margin Fault Set**

Two basin-margin faults are located a mile eastward of the Golden fault zone. These faults are vertical as characterized by very distinct breaks across seismic reflectors. Fault displacement increases with depth, downdropping basin blocks to the east. A similar fault has been documented by Weimer (1973) in the Leyden mine and was interpreted as a basin-margin fault by him.

Figure 13 is a graph of the relative movements of the two basin-margin faults. Amount of displacement is plotted against geologic time. Time shifts of marker events were measured across the fault plane and converted to displacement with interval velocities. The displacement curves are parallel
Figure 13. Relative displacement of basin margin faults. Not to scale.
indicating that fault movements were concurrent and result from the same tectonic episodes of deformation.

The Fountain-Precambrian contact is an erosional surface; a very poor seismic reflector throughout the Denver basin. Displacement at the Precambrian level could not be reliably picked and herein has been assumed equal to the Niobrara offset. The displacement curves for faults 3 and 4 are both level from Precambrian through Hygiene time. At this point there is a rapid decrease in displacement in the Hygiene-TZ2 time interval. The displacement gradient shows a maximum about TZ2 time and decreases in both curves after TZ2 time.

The S-shaped curves show a non-linear relationship between displacement and geologic time. Faulting presumably began in the Hygiene-Terry time interval. There is decreasing displacement in younger sedimentary rocks indicating growth along the basin-margin faults with time. Fault 3, which is closer to the Front Range uplift, shows more displacement than fault 4. Fault 3 has been tied to Shuck's (1976) seismic line. He estimates 200 ft. of displacement which is greater than the displacement observed on Golden Line 1. Fault 4 seems to die out to the north, but has been documented by Young (personal communication) on seismic data across North Table Mountain.

The basin-margin fault set could be tectonically related to the initial uplift of the Front Range and influenced by local deformation. These faults once activated by Laramide
orogenic forces act as a compensation mechanism for sediment loading and areas of differential uplift.

**Shot Point 188**

Golden Line 1 has been tied to the 100 percent seismic data of Line 54-6. These data covered the same ground as Golden Line 1 as well as continuing several miles eastward into the Denver basin. The data quality was poor throughout the line. SP-188 was selected as the only tie. There is an indication of minor faulting on this record by the offset of the Niobrara reflector. The geophone array was oriented NW-SE. Displacement is up to the northwest. Such a fault may be analogous to a fault system northeast of Boulder. Davis (1974) has mapped these northeast trending faults associated with Late Cretaceous growth faulting. Young (personal communication) has documented similar fault displacement on Young Line 3 across South Table Mountain.

**Geologic Model**

During the Late Cretaceous there were at least three delta complexes in northern Colorado contributing large amounts of clastics to the epeiric sea covering Colorado (Weimer, 1970). At this time the sea was regressing in response to initial stages of Laramide uplift beginning in the southwest. Regressive shorelines were pushed to the
northeast. The structural compensation to this early mountain building or epeirogenic uplift may have been the origin of vertical basement faults. Figure 14A represents the tectonic beginning of such basement-controlled faults during deposition of the Middle Pierre.

Once tectonically activated, these faults may have reacted to sediment loading. A western thickening in the Terry-TZ2 time interval can be seen between Golden Line 1 and SP-188. This 60 millisecond time thickening could be explained by a regressing shoreline. Depositional rates in the shoreline zone are much higher than out in the basin (Weimer, 1970).

The Front Range became a positive tectonic element within the Pierre seaway at this time. The localization of this element presumably was controlled by the fault initiation and growth described herein within the Pierre seaway. This local Front Range uplift returned substantial amounts of sediments back into the seaway which in turn resulted in the loading of fault blocks.

Growth of the basin-margin faults occurred throughout the remainder of deposition of the Pierre Formation. The relative displacement of faults 3 and 4 became less in younger sedimentary rocks. Less displacement occurs across the easternmost basin-margin fault. Fault displacement cannot
Figure 14a. Fault initiation in Late Cretaceous.
be measured above the Pierre seismic marker due to the low
frequency range obtained with the VIBROSEIS method and the
spread configuration. The amount of resolution is limited
to measuring displacements greater than five milliseconds.
Work by Weimer (1973) supports the hypothesis of recurrent
movement or growth of basin-margin faults. Uplift continued
on a gradual scale as evidenced by deposition of the Fox
Hills and Laramie Formations. Figure 14B represents differ-
ential Front Range uplift and rotation of basement blocks.
Block faulting similar to that shown by Stearns (1971) is
the dominant style of structural deformation. Sedimentary
rocks directly overlying the Precambrian basement are competent
and are therefore modeled as acting in the same manner.
Vertical forces are progressively stronger to the west
causing a tilting or rotation of fault blocks.

In the lower Paleocene there was a great amount of in-
trusive and extrusive volcanic activity associated with the
major uplift of the present Front Range. The time of this
greatest vertical uplift would presumably be during deposi-
tion of the conglomeratic Green Mountain Formation. The
character of faulting remains vertical at depth. Near the
surface fault planes curve convex-upward, possibly a reaction
to tilting of fault blocks and gravity effects. The tectonic
vertical uplift was largely concentrated over faults 1 and 2,
Figure 14b. Differential uplift and block rotation, Late Cretaceous to Early Tertiary.
which possibly join at depth. The tilted blocks between all the faults result from differing amounts of uplift west to east. Figure 14C portrays this maximum uplift of the Front Range from late Paleocene to Eocene time. There is drape-folding of the Laramie and Fox Hills Formations. The Pierre shale acts as the incompetent mass in the Stearns (1971) drape-fold model.

Shuck (1976) has constructed a similar model (Fig. 15) for flank deformation one mile north of Golden Line 1. He depicts drape folding of the Laramie and Fox Hills Formations. He times the occurrence of the Golden fault zone after the intrusion of the Ralston sill sometime in the early Paleocene. Shuck accounts for the presence of a slump or landslide feature composed of Pierre shale by the weight of the intruded volcanics and the possible existence of overpressured shale in the Upper Pierre shale.

Berg (1962) has depicted the subsurface (Fig. 16) of the Soda Lakes area. He has indicated the complex faulting from the Golden fault zone to die-out within the Pierre shale. Berg also implies one movement or episode of faulting. He has shown a sharp fold in the competent sedimentary rocks beneath the Pierre Formation. This structure is not seen on Golden Line 1. Berg interpreted the anticline from dip-meter information from the Johnson No. 1 well (7-5S-69W) and from relative elongation of stratigraphic intervals from the Great
Figure 15. Golden Fault zone, Ralston area, Jefferson Co., Colorado. (After Shuck, 1976).
Basins No. 1 well (6-5S-69W). He had no seismic control for his interpretation.

**Geologic Cross Section**

Incorporating all the seismic data geologic cross section A-A' (Plate 2) was constructed to show flank deformation structure. The migrated seismic section (Fig. 12) with average and interval velocities (Table 1) were used to plot depths to formation tops and locations of faults. Electric log data from the No. 1 Farmers Highline and Canal Reservoir well was used as the eastern tie. A fault has been dashed in to represent possible faulting seen on SP-188.

**Alternate Interpretation**

Uplift of the Front Range may have occurred in a single major episode of faulting. Previous authors cited in this thesis have advocated the idea of a single period of uplift in the Early Tertiary. The evidence suggesting growth or recurrent movement is the change in displacement along basin-margin faults with time. These faults may have been formed in a single period of movement with the fault displacement dying out near the surface.

The Green Mountain Formation is a conglomerate indicating the age of maximum uplift of the Front Range. The intense vertical uplift of the Front Range was distributed almost completely over faults 1 and 2 of the Golden Fault zone. Lateral
compensation by the basement and overlying competent sedi-
mentary rocks resulted in the brittle vertical faulting through
the Denver basin rocks. The Pierre Formation behaved as a
ductile material compared to the underlying competent sand-
stones. Throughout the 6,000 to 8,000 ft. of Pierre shale
much of the displacement could possibly be absorbed by the
ductile shale. A rock-mechanics type model would be required
to substantiate either interpretation of fault history pre-
sented in this thesis.

There are facts to support the hypothesis of growth of
these faults rather than as a single-stage Laramide event:

a) surface indications documented by Weimer (1973)
at the Leyden mine;
b) basin-margin faults are vertical;
c) basin-margin fault planes are very abrupt with
little evidence of drag by sedimentary rocks;
d) increasing displacement along basin-margin faults
with depth.
e) the displacement varies in a non-linear fashion,
i.e. displacement changes occur only in the Upper
Pierre section and above.
Figure 17. Geologic map of the thesis area. (After Van Horn, 1972; Shuck, 1976).
CONCLUSIONS

From the analysis of data presented in this thesis the following conclusions can be drawn:

a) North of Golden there exists a two mile wide zone of flank deformation between the Front Range and the Denver basin. The Golden fault zone and a basin-margin fault set compose the zone of flank deformation.

b) The Golden Fault zone is a complex of high angle reverse faulting. This faulting is the result of intense local vertical uplift of the Front Range. Faults 1 and 2 (Fig. 14C) compensate for that amount of uplift in a narrow zone between the Front Range and Denver basin blocks. These faults are separate at the surface but seem to join at depth. They are vertical at depth, becoming convex-up near the surface. The Golden fault zone appears to converge to the south and diverge to the north.

c) A basin-margin fault set parallels the Golden fault zone. The displacement ranges from 100 to 200 feet at depth to approximately 15 feet at the surface. These are growth faults, vertical, controlled by deep Precambrian basement block faulting.
d) Faulting within the zone of flank deformation is the result of Late Cretaceous uplift extending through the Early Cenozoic. The Laramide orogeny probably began in the Late Cretaceous with an epeirogenic type of uplift continuing until the Late Paleocene with a major tectonic upthrust of the Front Range. The vertical forces associated with uplift of the Front Range were acting very intensely west of the zone of flank deformation. Across the two mile wide zone of deformation, there is no evidence of vertical uplift, but rather downdropping of Denver basin sedimentary rocks.

e) Faulting may be more prominent within the Denver basin than suspected. Near the axis of the Denver basin, possible faulting has been noted on SP-188. This faulting could be similar to a northeast trending fault system east of Boulder.
REFERENCES


CORRELATION BETWEEN LINE 1
AND
SHOTPOINT 188 OF LINE 54-6