ADVANCED RESOURCES INTERNATIONAL

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Naturally Fractured Tight Gas Reservoir Detection Optimization

Prepared for:

U.S. Department of Energy
Federal Energy Technology Center

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Quarterly Status Report

Period of Performance: April 1, 1998 – June 30, 1998

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Quarterly Status Report

CONTRACT NO.:

DE-AC21-93MC30086

CONTRACTOR:

Advanced Resources International, Inc.
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CONTRACT NAME:

Naturally Fractured
Tight Gas Reservoir
Detection Optimization

CONTRACT PERIOD:

4/01/98 – 6/30/98

CONTRACT OBJECTIVE: No change.

TECHNICAL APPROACH CHANGES: No change.

FIELD PERFORMANCE TEST PLAN:

The primary goal of this work is to focus in on the Table Rock field area in the northern Washakie basin of the Greater Green River basin in support of Union Pacific Resources and DOE planned horizontal drilling efforts. The work plan for the quarter of April 1, 1998 – June 30, 1998 consisted of three tasks:

1. Acquire necessary seismic data and depth-convert,
2. Map major fault geometry and analyze displacement vectors,
3. Develop and initiate a natural fracture prediction study.

The three tasks were completed during this reporting period.

Introduction

During this quarter, work focused on a local structural analysis of the Table Rock field, greater Green River basin (GGRB) in southwestern Wyoming. The ultimate objective of the local analysis is to apply the techniques developed and demonstrated during earlier phases of the project in the Rulison Field area of the Piceance basin for sweet-spot delineation. This effort parallels the regional analysis, of GGRB

The following sections describe the tasks performed during this quarter as part of the Table Rock local fracture prediction analysis.

Task 1. Data Acquisition/Processing

This task involves acquiring 3-D seismic data from Western Geophysical with UPR's support. Two pre-existing seismic surveys were combined, the Table Rock and Continental Divide II. Thirty-two 2-D lines were extracted from the 3-D data for post-stack depth conversion. These lines were then imported into the SeisVision interpretation platform for analysis.

Aeromagnetic data was purchased over the Table Rock area for mapping out basement trends. This will provide information on possible basement control on the larger structures and to determine the depth-extent of structure, beyond the limit of seismic imaging.

Task 2. Structural Analysis

Two major fault systems were mapped, the Table Rock thrust fault and a related northeast-trending strike-slip fault. It was determined from analysis of displacement vectors that the Table Rock thrust fault formed before the strike-slip fault. It was only after a critical amount of deformation occurred along the thrust fault that the strike-slip fault develop to accommodate the shortening strain. The strike-slip fault occurred along a pre-existing basement feature, as determined from the aeromag data, and is slightly oblique to the strain direction. This obliquity causes the strike-slip fault to have a reverse component in its displacement.

Task 3. Natural Fracture Prediction

Using the geometry of the couple thrust-strike-slip fault system, we predicted a region of potential increased shear fracturing using a boundary-element program. Using the displacement amounts across the faults, a stress concentration is formed near the upward termination of the fault system. This stress information was then used to determine the area of fracture generation based on a Coulomb failure for shear fractures. The analysis shows an eight township areas in the Table Roc region were it can be expected that well on average will be better producers than well drilled outside this region.

Appendix

Table Rock Horizontal Drilling Project: Results of Regional Structural Analysis (Task 1)

"Developing and demonstrating high value E&P technology for unlocking natural gas resources in low permeability basins."

A Presentation to DOE/FETC
by
Advanced Resources International, Inc.

June 8, 1998

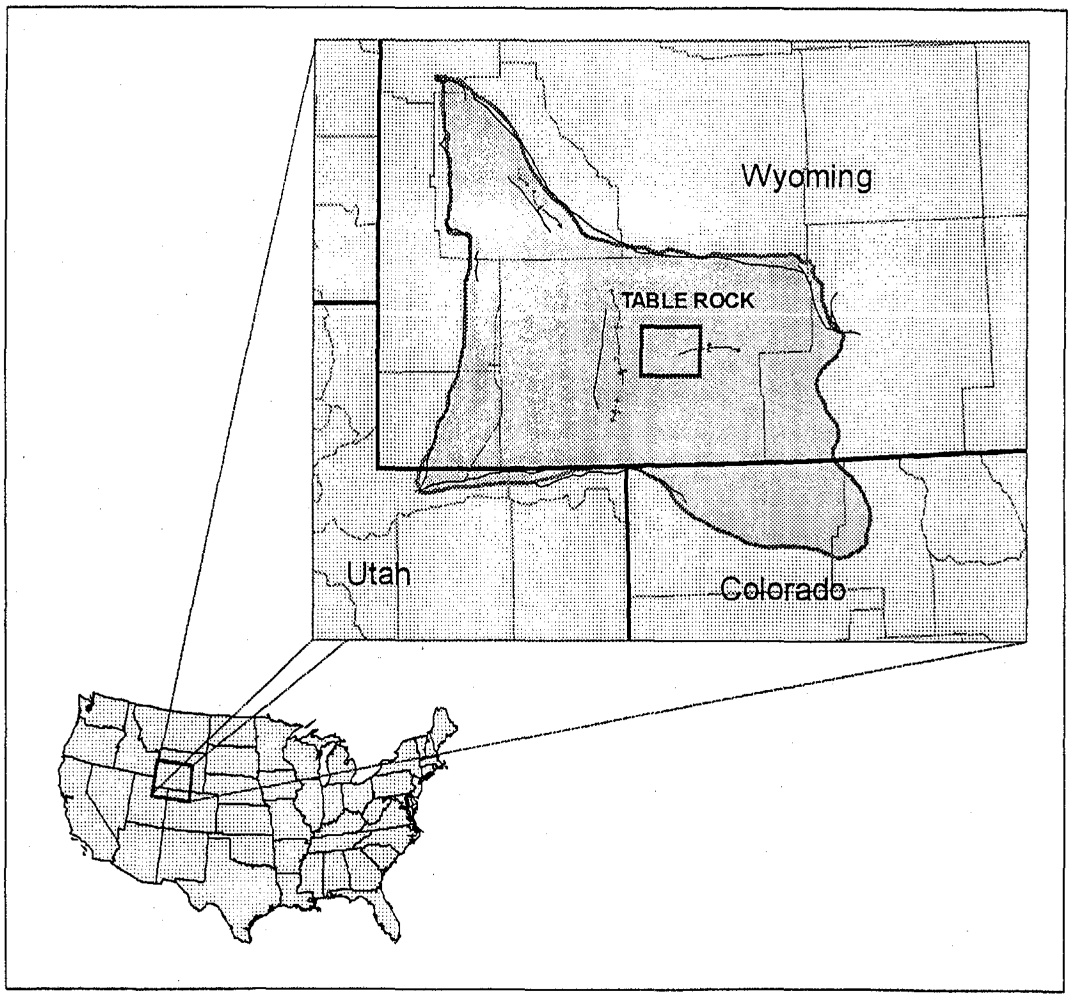
Project Objectives

1. ***Corroborate geologic rational of drilling location and horizontal drilling orientation for UPR/DOE Table Rock Frontier test.***

2. ***Determine local natural fracture clusters from detailed fault mapping that may impact the horizontal leg of the test well.***

3. ***Evaluate play extent and assess resource in place.***

Project Location in the Greater Green River Basin, Wyoming



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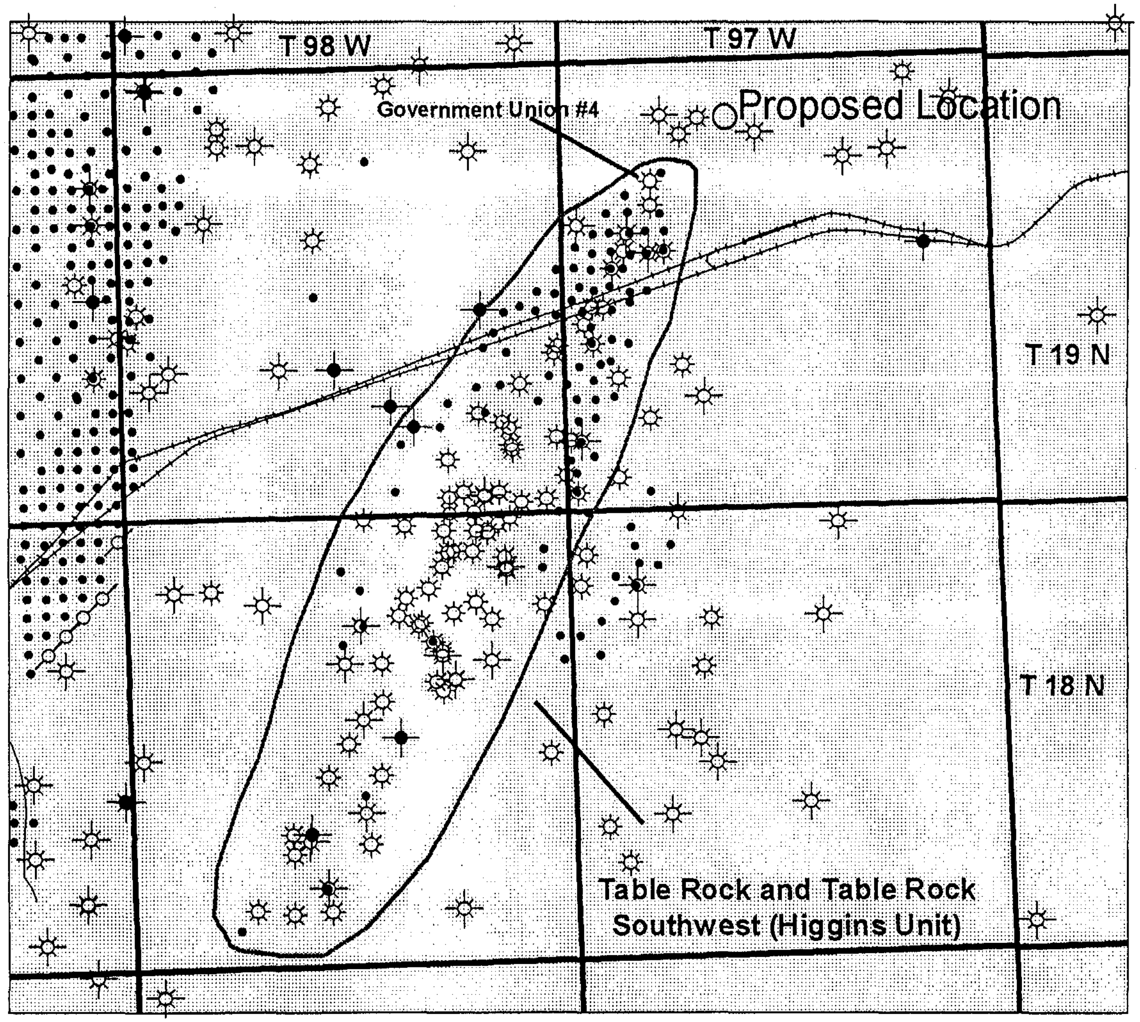
Proposed Location of Frontier Test



The Technical Program

The program is divided into three tasks:

1. Preliminary Assessment of Proposed Location
   - *A. Regional Structural Analysis*
   - *B. Regional Natural Fracture Assessment*
2. Detailed Structural Study for Horizontal Drilling Plan
   - *A. Detail Fault Mapping*
   - *B. Predict Local Natural Fracture Characteristics*
3. Regional Geologic Assessment of Play Economics
   - *A. Play Extent*
   - *B. Gas-in-Place*
   - *C. Economic Assessment*

Task 1. Preliminary Analysis

The first task involves a preliminary structural analysis that will provide the appropriate structural framework for more detailed study of the proposed drilling location and plan.

This will be accomplished by utilizing a fracture detection methodology, examination of the Govt. Union #4 core, and a preliminary stress model of a regional fault geometry of the Table Rock thrust system.

Task 1. Preliminary Analysis

1a. Characterize Natural Fractures in the Frontier Fm.

Examine Govt. Union #4 core.
Review existing publications.

1b. Analyze Imagery and Aeromagnetic Data

Integrate surface and basement structural analyses to map regional basement-involved fault trends and relate to natural fractures.

1c. Regional Mapping of 3D Seismic Data

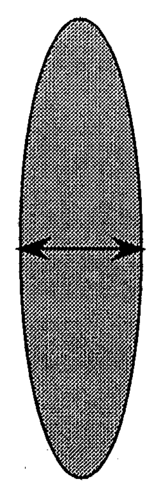
Post-stack depth convert selected lines
Map horizons and develop structure and isopach maps
Map fault geometry for input to stress model.

1d. Perform Regional Stress Model

Using regional fault geometry, determine area(s) of enhanced natural fracturing based on stress calculations.

Natural Fractures Observed In Cores

There are three modes of fracture origin; Mode 1 is extensional and Modes 2&3 are shear. Technically shear fractures are faults as there is displacement along plane of the fracture.

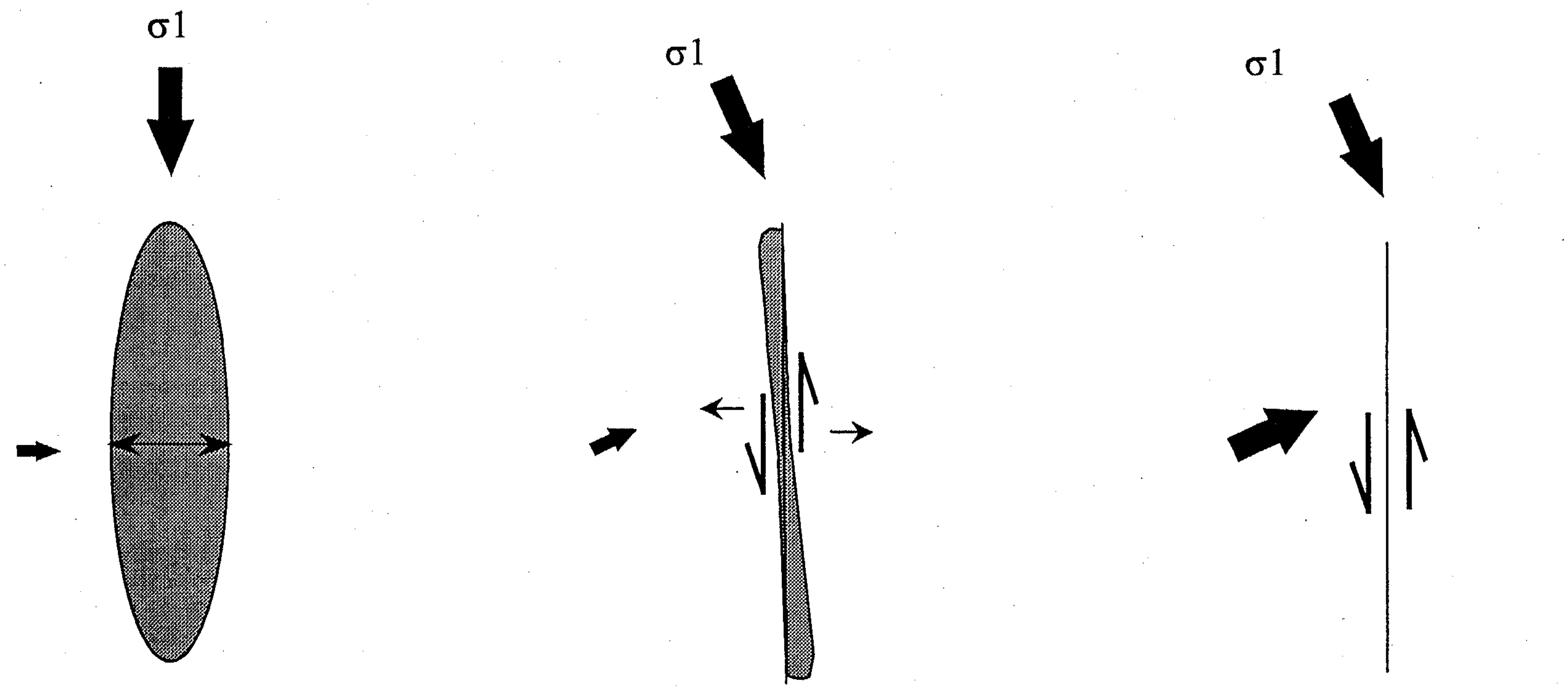


Extensional Fracture

Shear Fracture

Natural Fractures Observed In Cores

The type of natural fracture observed in core is important information that will help determine the method of quantitative stress modeling.



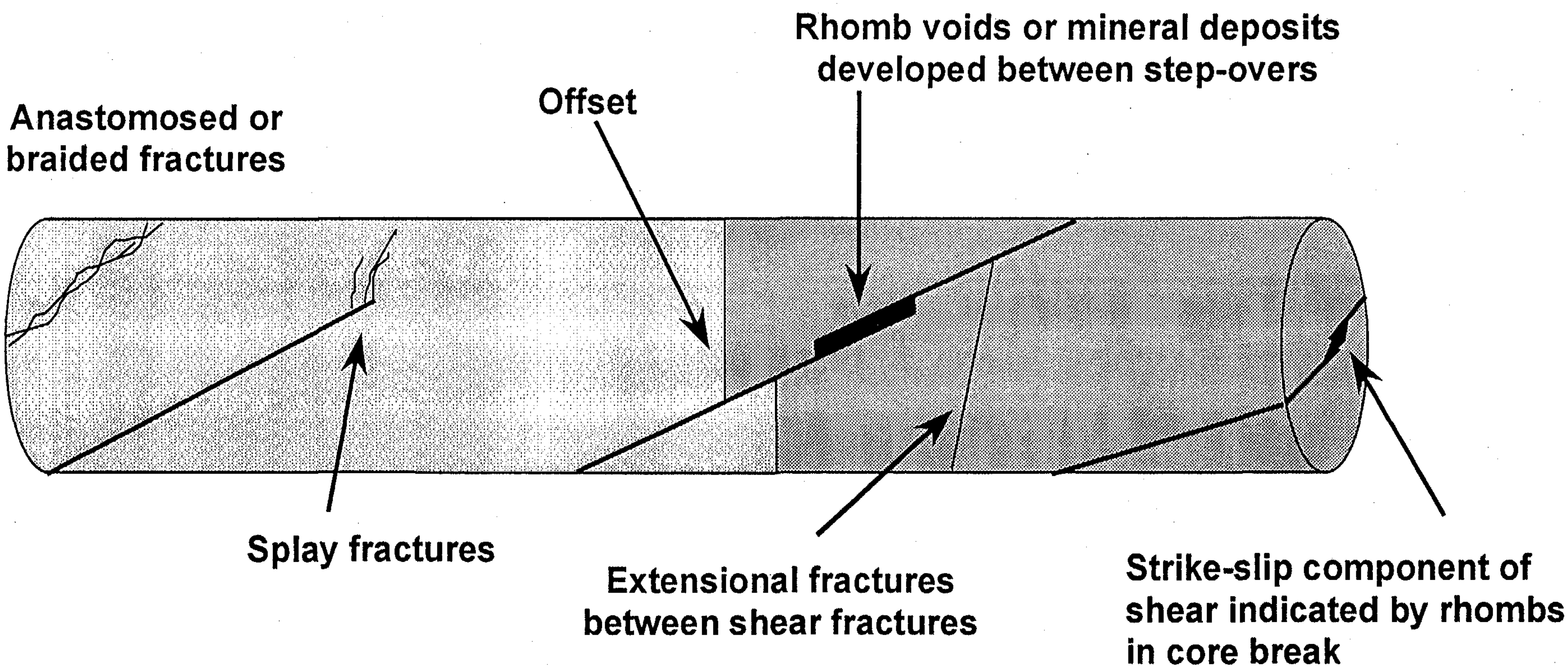
extension fracture

shear fracture with extensional component (mixed mode)

shear fracture

Natural Fractures Observed In Cores

Shear(ed) fractures are identified in core by:



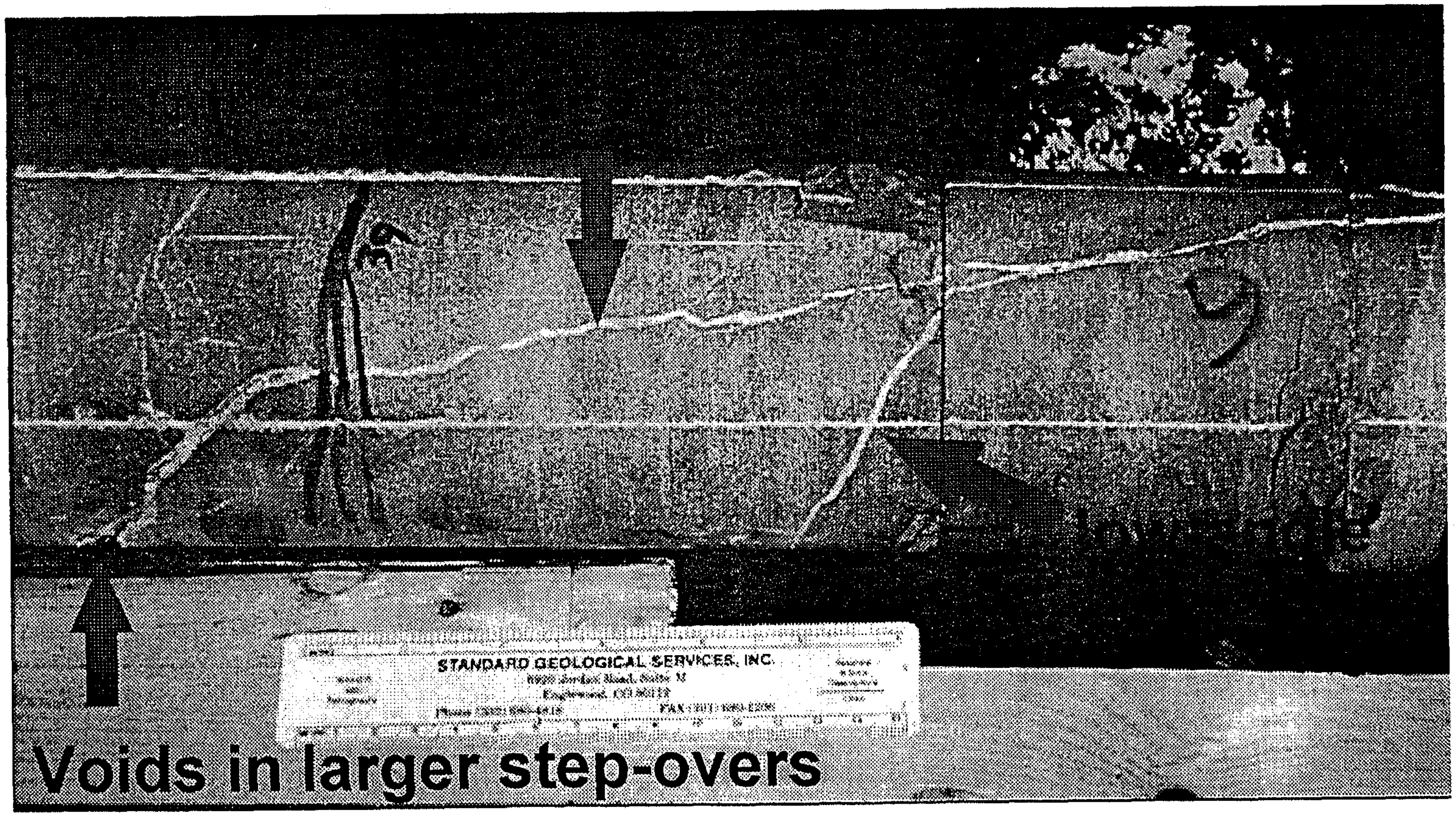
Natural Fractures Observed In Frontier Fm. Cores

The Govt. Union #4 core was examined to ascertain fracture character.

Types of fractures identified in the Govt. Union #4 core include:

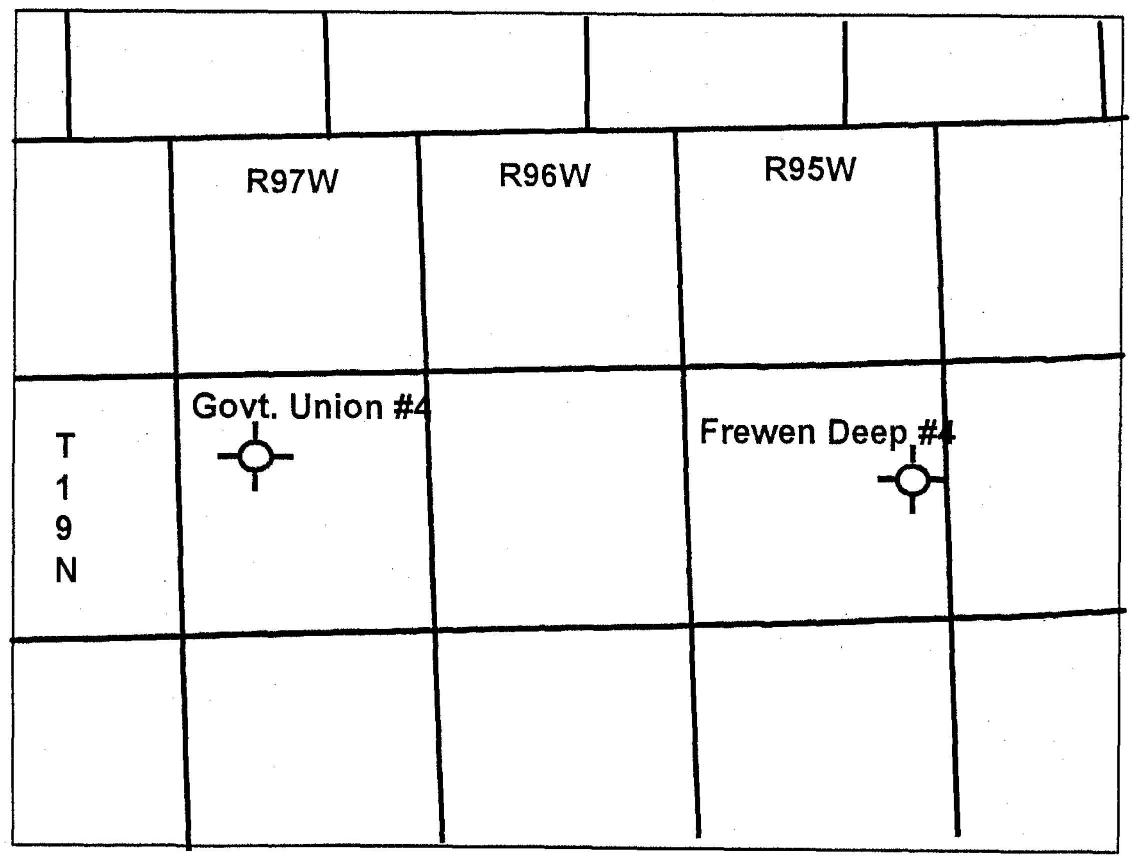
- Shear fractures with an extensional component exhibiting oblique-reverse slip
- Bitumen-filled splay fractures
- Bedding plane fractures
- Minor extensional fractures

Govt. Union #4 Core



Frewen Deep #4 Core

17 miles East of the Govt. Union #4, Amoco's Frewen Deep #4 cored and tested the Frontier Fm.



Frewen Deep #4 Core

The fractures reported in this core (Lorenz and Billingsley, 1996) include:

- Mineralized natural fractures (quartz and calcite) with large isolated apertures connected by thin calcite-filled fractures oriented EW (““wide fractures...change abruptly into local zones of thin...fractures”).
- “Irregular anastamosed fracture strands.”
- Bitumen-filled splay fractures (“wispy, multistranded “mares tails”).

The description of these natural fractures indicate that they are shear fractures, very similar to those observed in the Govt. Union #4.

Natural Fractures in Frontier Fm. Cores

Summary

- The natural fractures present are dominantly oblique-reverse shear fractures with an extensional component.
- Open isolated voids in core result from step-overs in shear fractures.
- The voids are connected by single fractures that are typically filled with mineral deposits.
- Open voids represent storage for gas whereas the connecting shear fractures provide the deliverability (i.e., the controlling factor in permeability).

High-Resolution Imagery and Aeromagnetic Data

High-resolution imagery and aeromagnetic data were examined to:

- Map regional basement-related structural trends
- Delineate local patterns of surface fractures
- Identify structural partitions and any control over fracture trends.

Imagery and Aeromagnetic Analysis

Summary

- Regional NE-SW strike-slip fault systems are basement controlled.
- NNE trending thrust faults show subtle or no correlation with basement structure.
- Surface geomorphology indicate the natural fracture pattern near the proposed location is dominated by N60W orientations - similar to the present-day orientation of maximum horizontal stress.

Table Rock and Continental Divide 3-D Seismic Surveys

Analysis objectives:

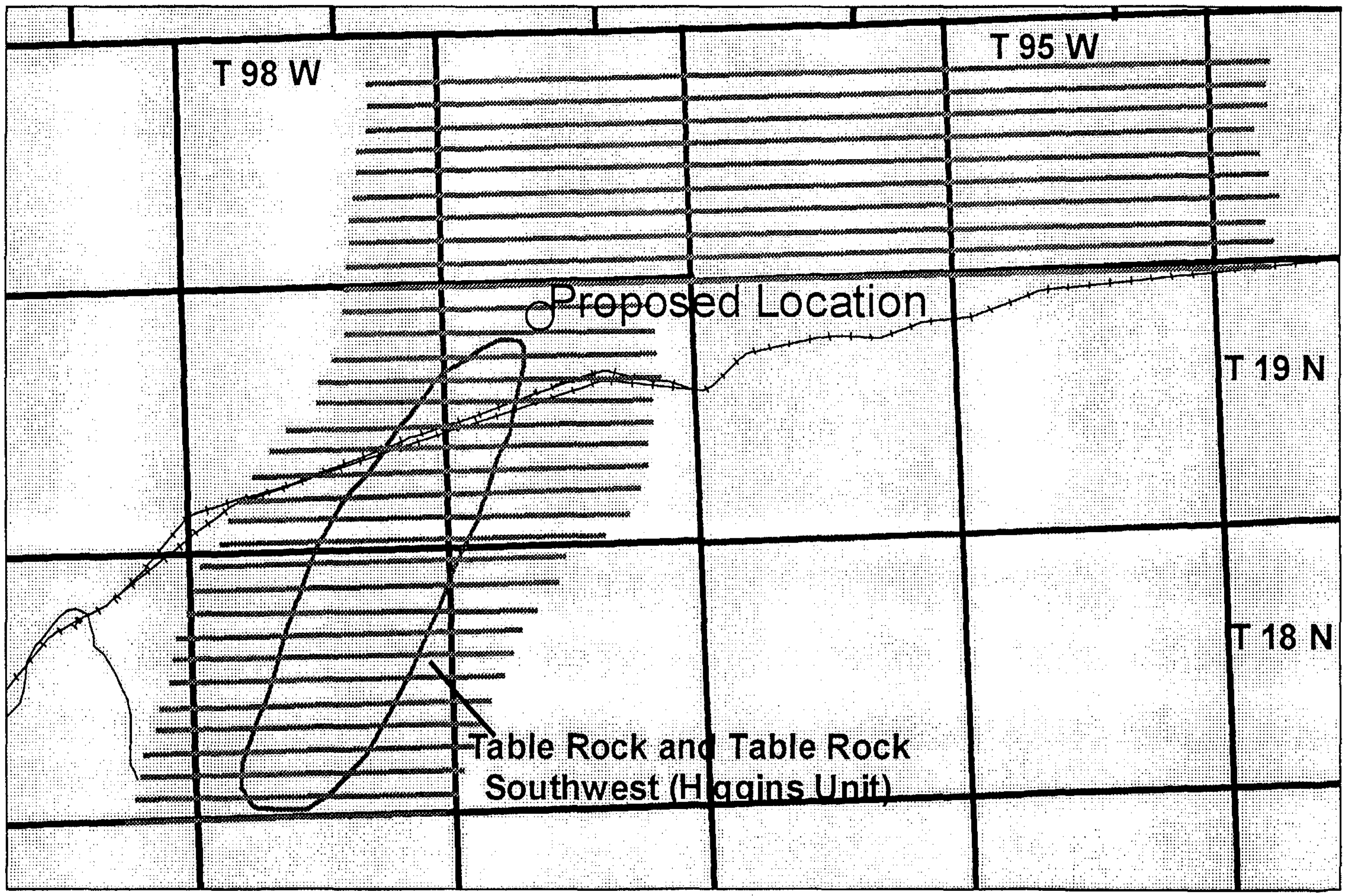
1) To examine history of deformation associated with fault systems and,

2) To provide accurate fault geometry in spatial coordinates for use in stress model.

Selected lines in the Table Rock and Continental Divide Phase II surveys at 1/2 mile spacing were post-stack depth converted and mapped.

Seismic Survey Lines

32 seismic lines were extracted from the 3-D data for depth conversion



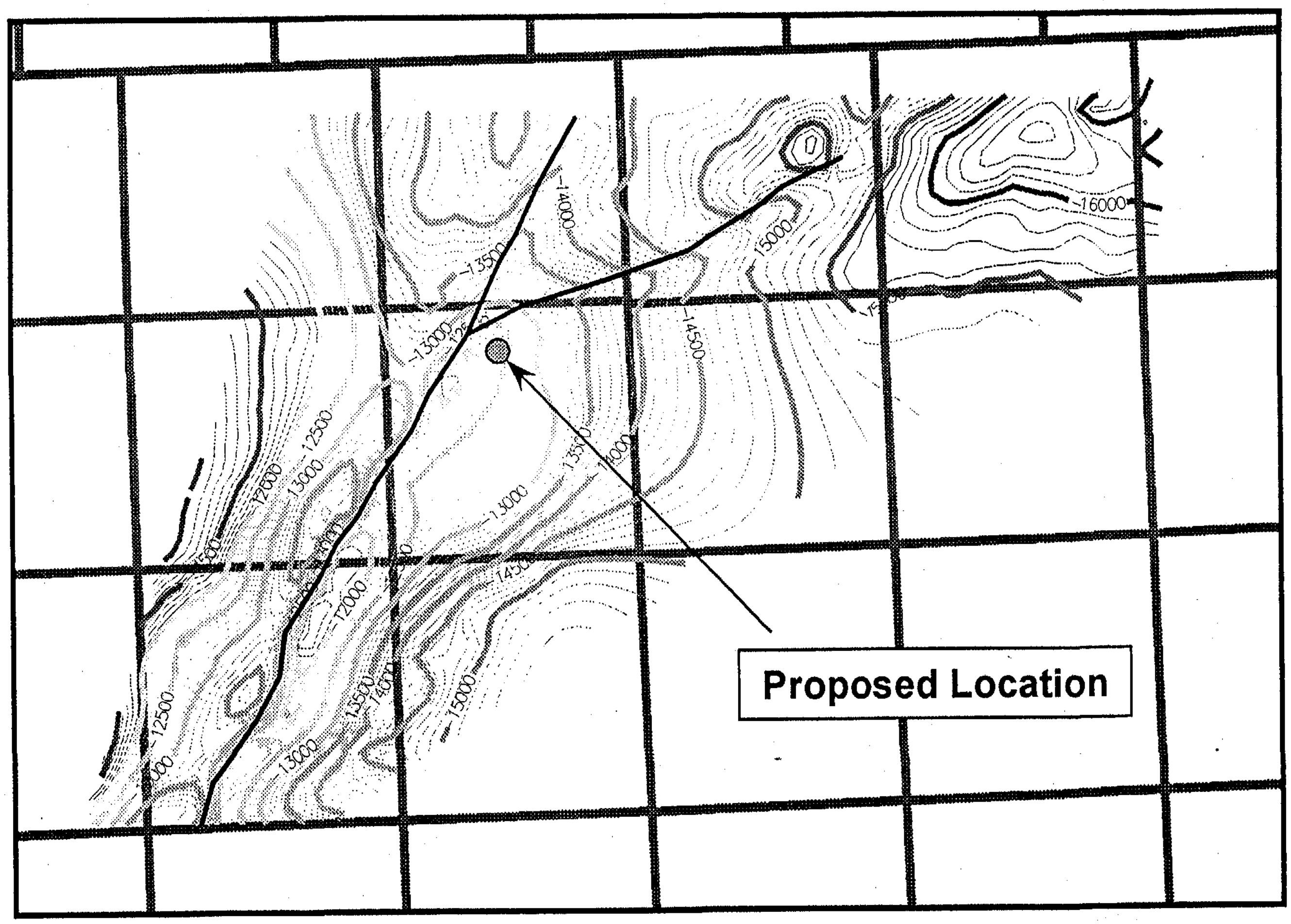
3-D Seismic: Fault Mapping

The major fault systems were mapped from the basement break to the up section terminus.

The Table Rock thrust system is comprised of two major faults, a thrust fault that trends N30E and a oblique reverse-strike-slip fault that trends approximately N60E.

3-D Seismic: Fault Mapping

At the Madison level, the two faults are distinct and intersect just North of the proposed location.

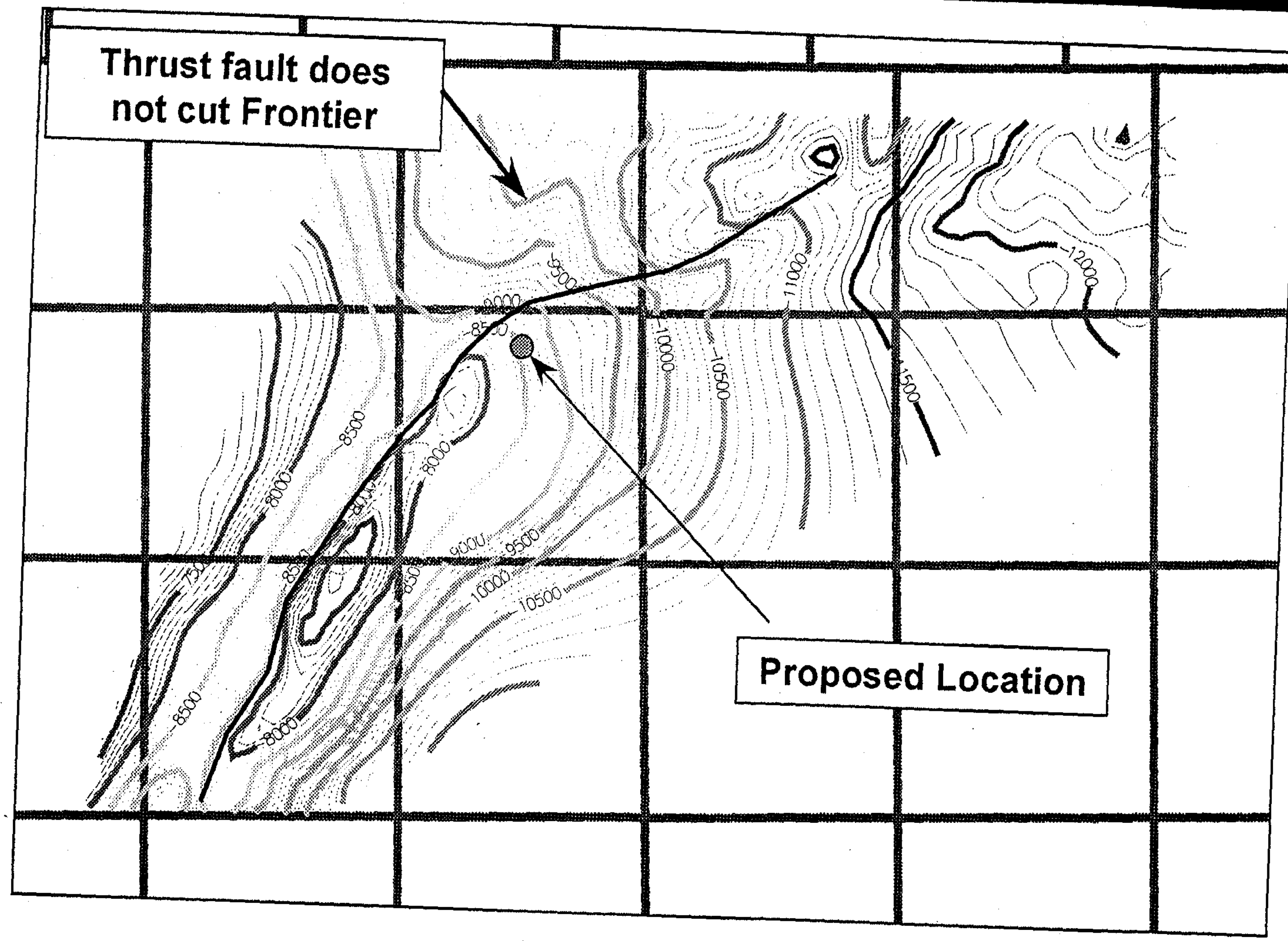


Subsea structure of the Madison Fm.

3-D Seismic: Fault Mapping

At the Frontier level, the northward extension of the thrust system terminates below the Frontier Fm.

The strike-slip fault acts as an oblique tear fault accommodating strain on the thrust.

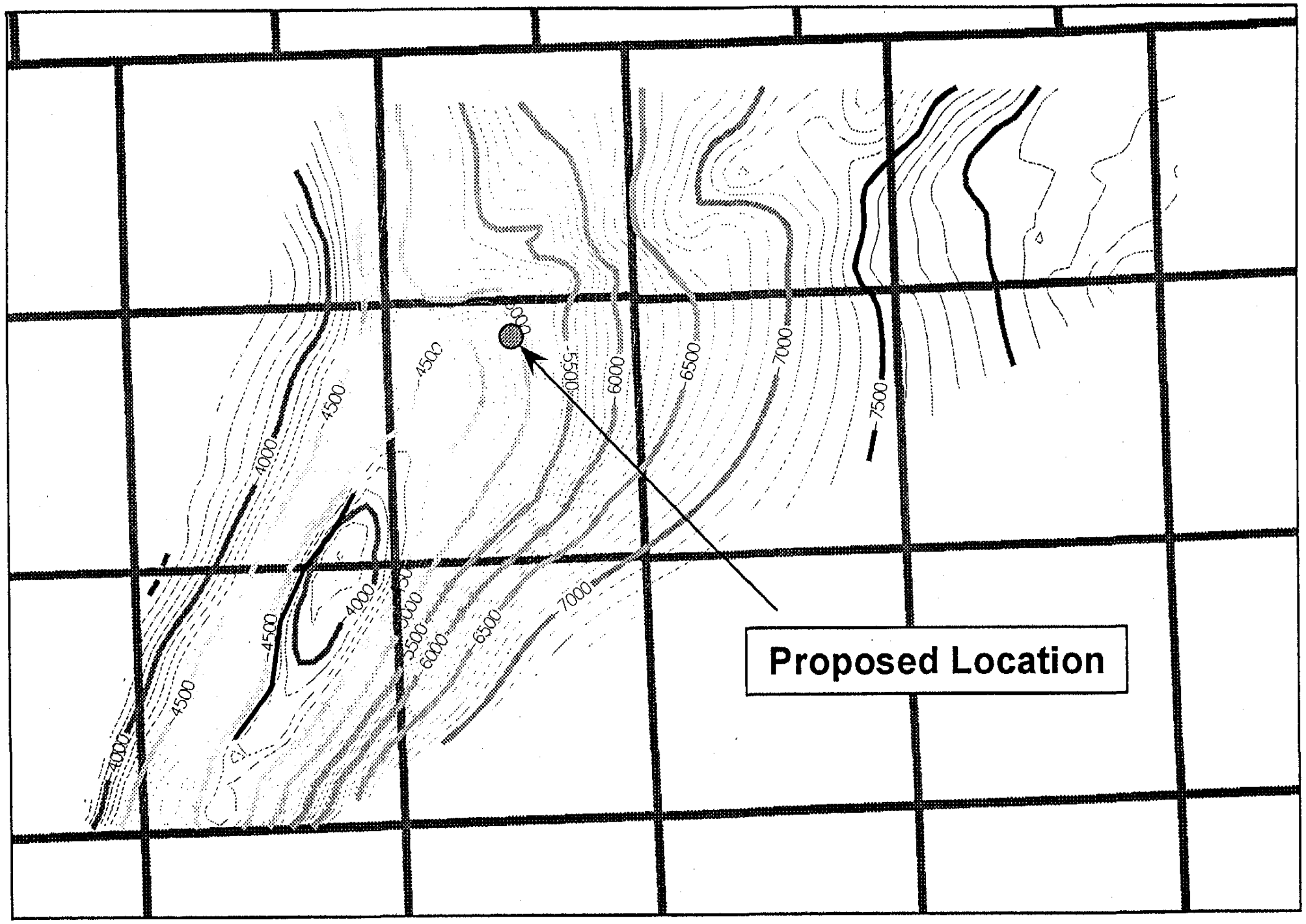


Subsea structure of the Frontier Fm.

3-D Seismic: Fault Mapping

The thrust fault only reaches the Baxter Shale level at the center of the Table Rock anticline.

The thrust system is represented by folding elsewhere.

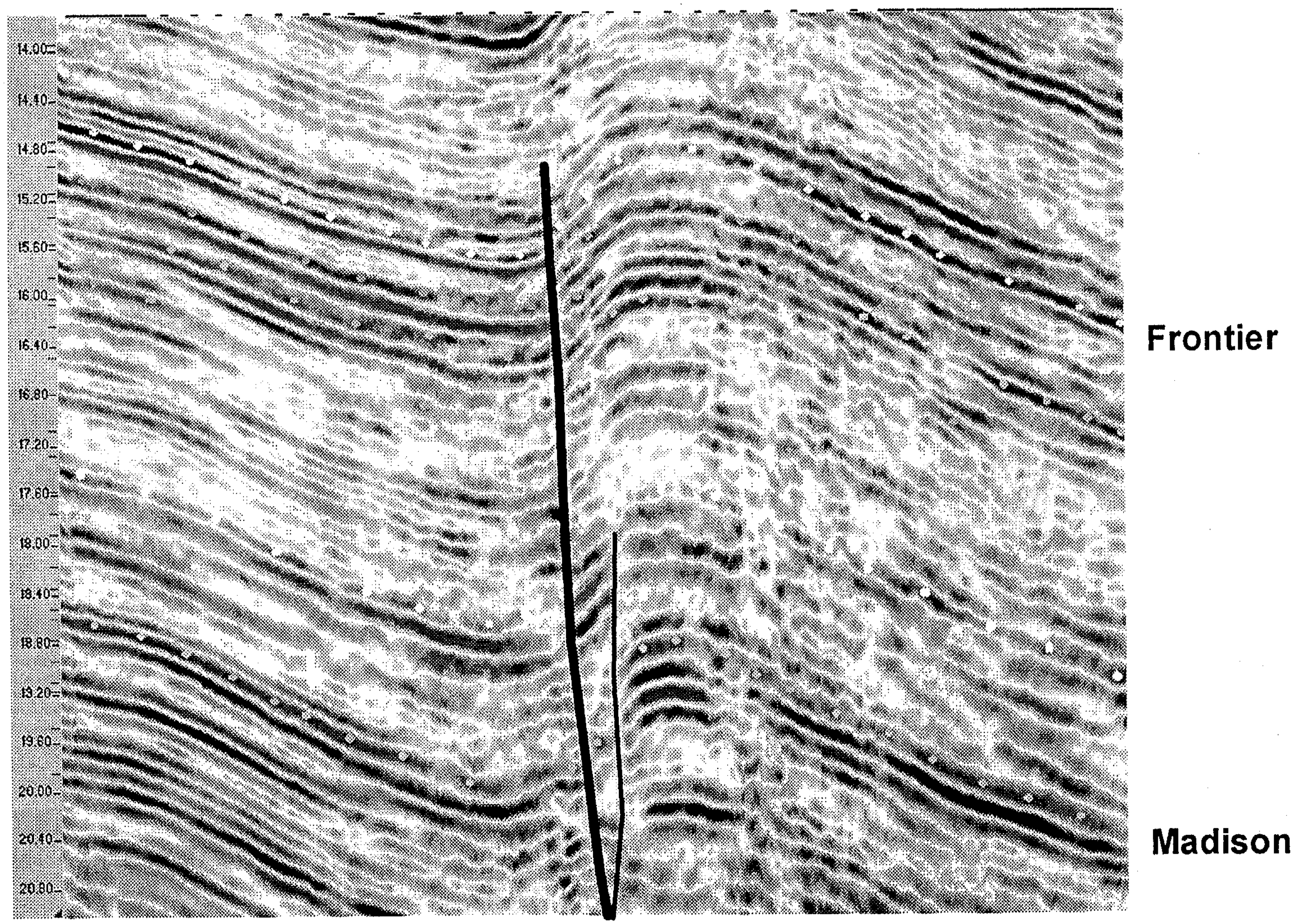


Subsea structure of the Baxter Shale.

3-D Seismic: Fault Mapping

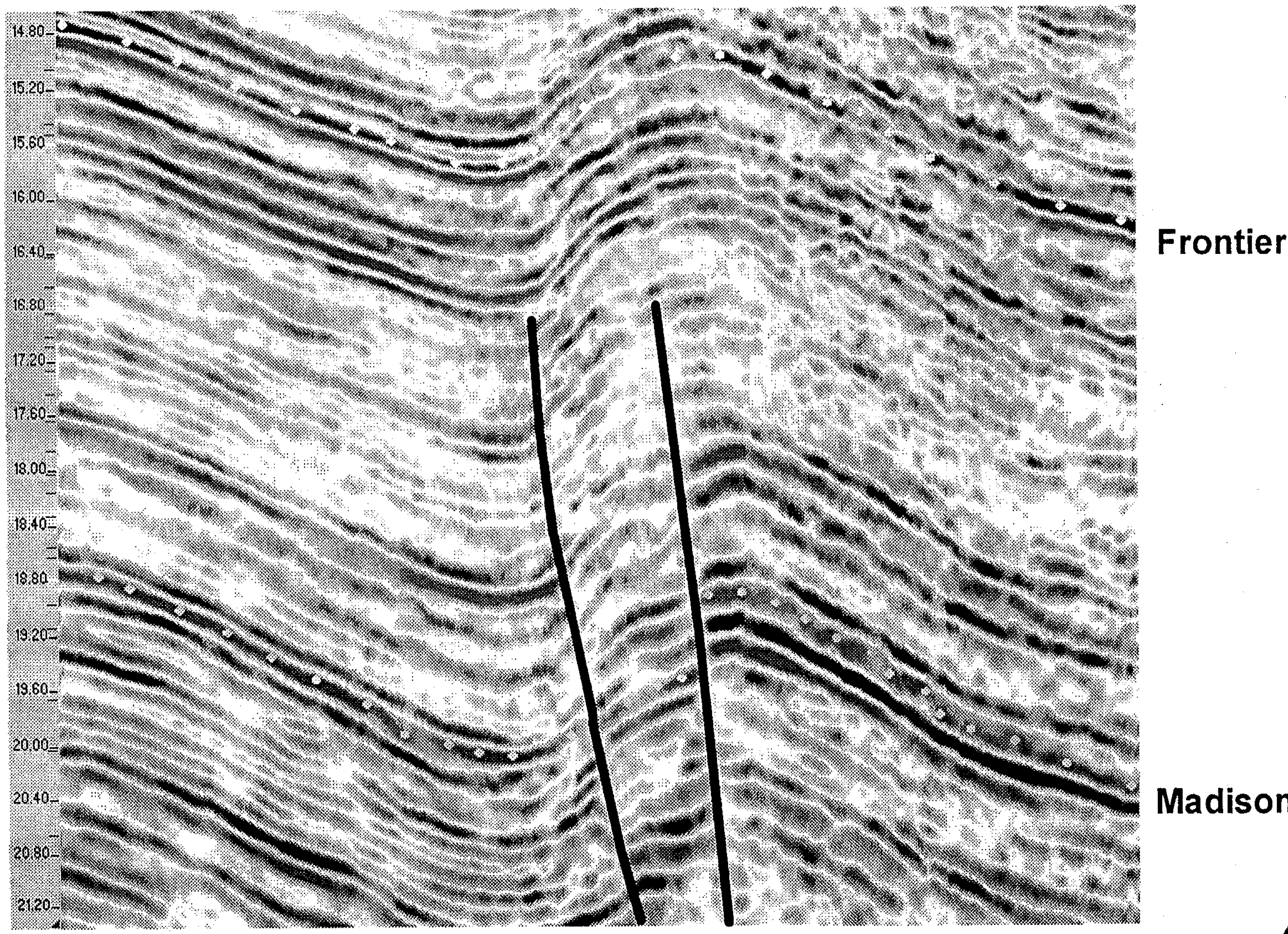
Profile view of Table Rock thrust fault near Govt. Union #4.

Thrust fault is steeply dipping and an asymmetrical fold is well developed on the hanging wall.



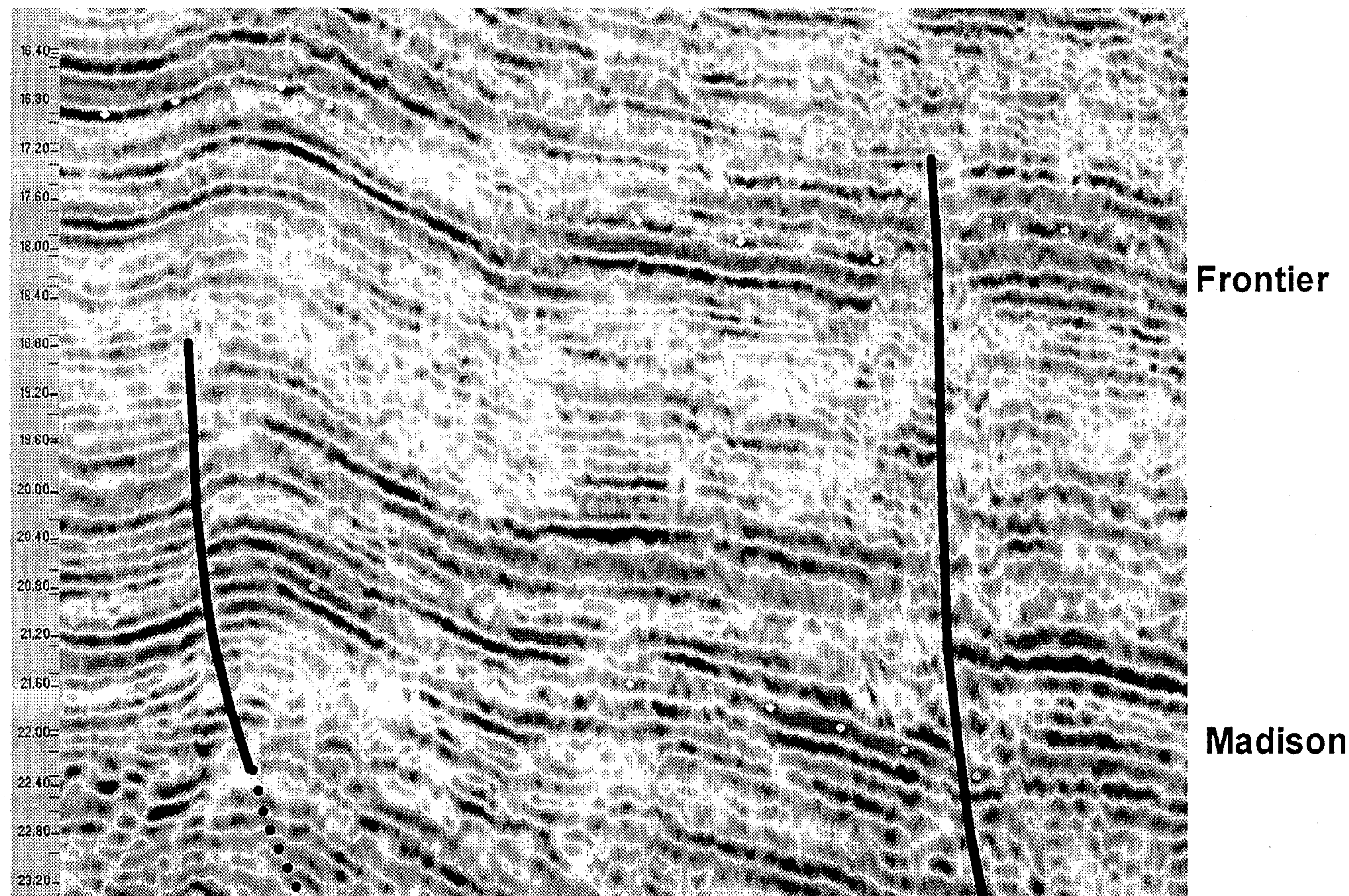
3-D Seismic: Fault Mapping

Profile near the intersection of the Table Rock thrust and the NE trending strike-slip fault just north of proposed location.



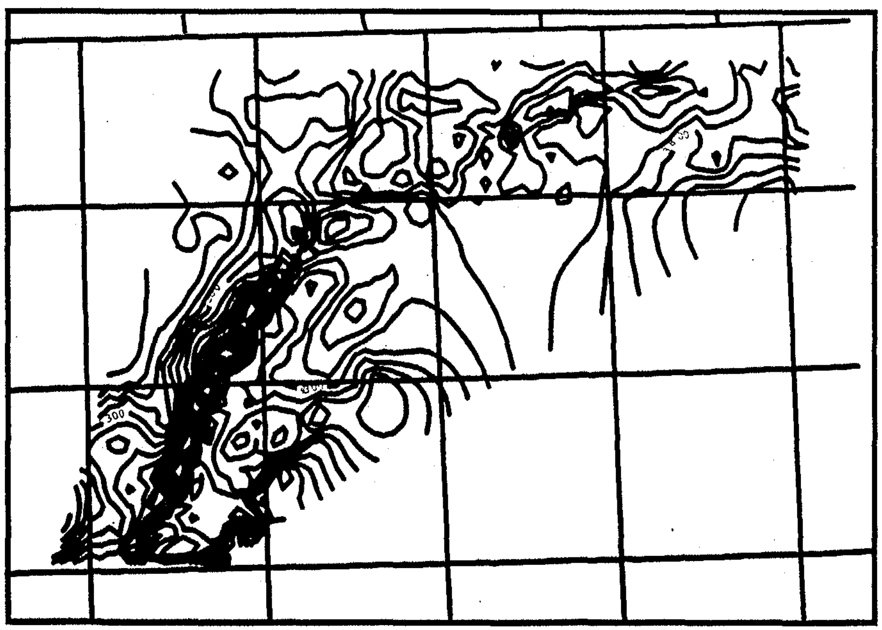
3-D Seismic: Fault Mapping

The thrust and the NE trending strike-slip fault (to the right in this profile) are separated as one moves North in the seismic data.

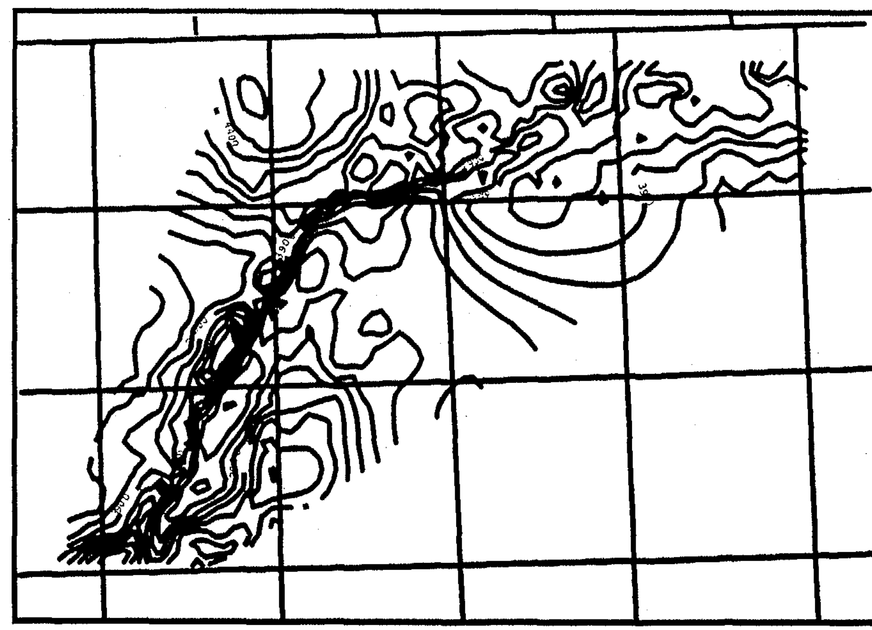


3-D Seismic: Fault Mapping

Isopach maps suggest that most of the deformation associated with the thrust-strike-slip coupled system occurred post-Frontier. There may have been an earlier period of deformation in the thrust system without strike-slip movement.



Frontier to Madison Isopach



Baxter to Frontier Isopach

3-D Seismic: Fault Mapping

Summary

The deformation pattern suggests a two-stage deformation where the strike-slip fault moved once the level of contractional strain needed accommodating.

The accommodation occurred on a pre-existing basement shear zone causing the strike-slip tear to be slightly oblique to the thrust fault.

Only the connected geometry of the thrust and strike-slip faults were used in the stress model and the northern continuation of the thrust ignored.

3-D Stress Model: Objectives & Methods

Objectives : To predict location and orientations of shear fractures secondary to the Table Rock thrust system.

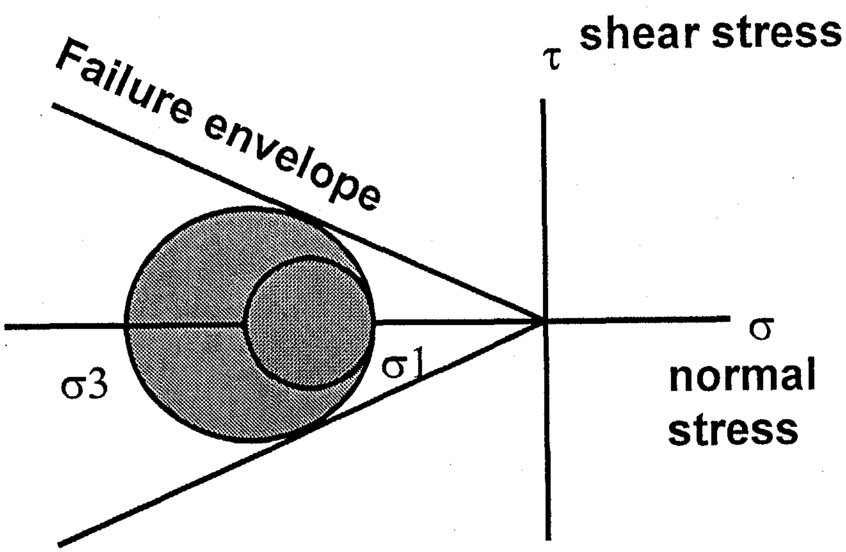
Methods: Numerical model is a 3-D BEM code that solves elastostatic equations for stress and displacement.

This method is limited to modeling failure due to displacement and stress perturbations along a discontinuity (fault, fracture). To capture effects of folding, one would need to include other methods such as a Finite Element Model.

3-D Stress Model: Failure Criterion

To evaluate the mechanical genesis of secondary shear fractures, the maximum Coulomb shear stress (Sc) is used as an indicator of failure.

$$Sc = ((\sigma 1 - \sigma 3)/2) * (1+\mu^2)^{1/2}) + \mu * \{(\sigma 1 + \sigma 3)/2\}$$



As compression (negative sign convention) increases from tectonic forces, the rock will fail in shear. The failure envelope is influenced by frictional forces, μ.

3-D Stress Model: Input Criteria

Inputs into model include: XYZ coordinates of fault geometry, orientation of remote stresses deduced from displacement geometry, and material properties (Poisson's ratio & shear modulus).

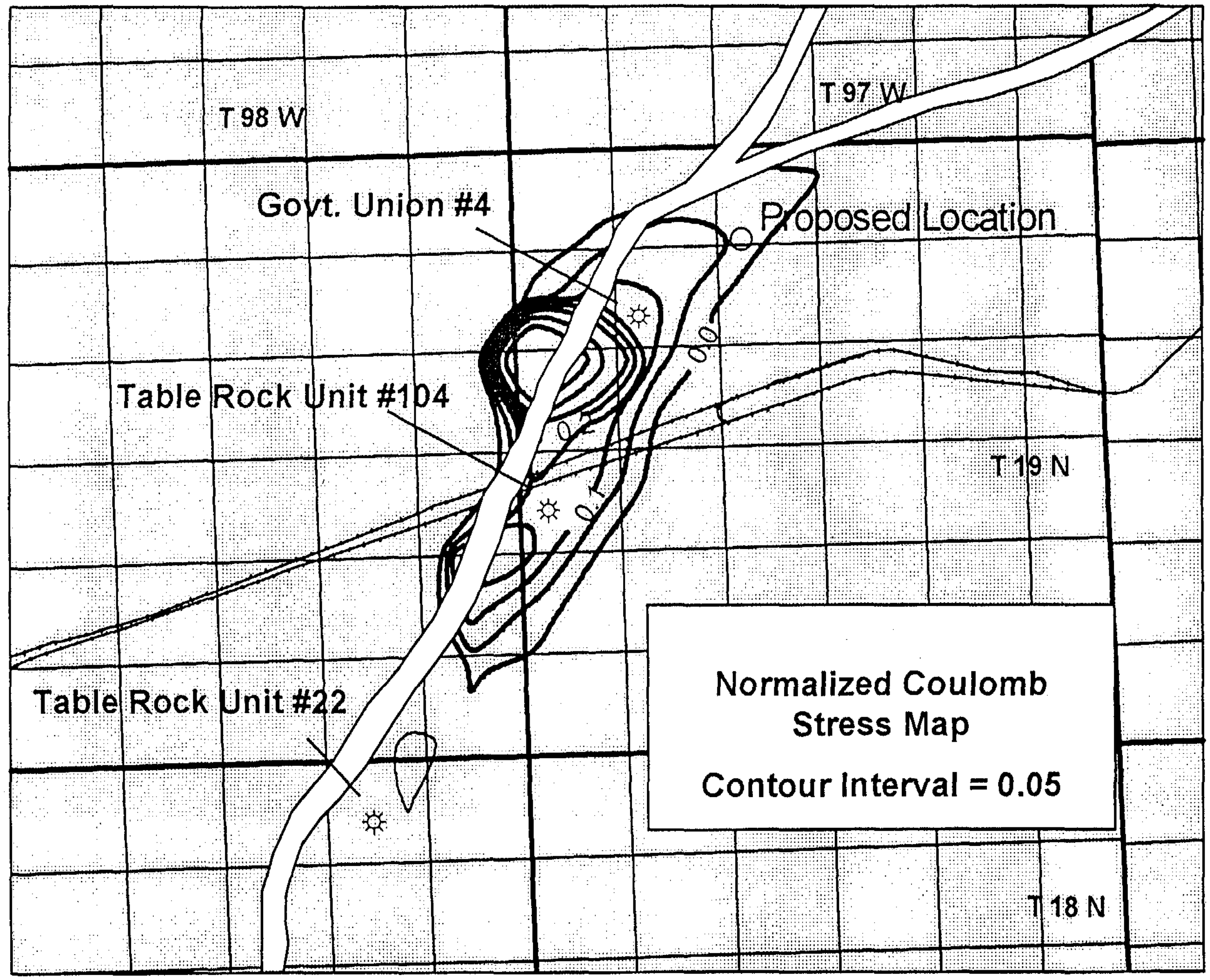
Remote stress orientations were calculated based on displacement amounts of the fault system. The greatest compression stress is N30W, nearly perpendicular to the thrust fault, and given a relative value of twice the other applied stresses.

Frictional component, μ, was assigned 0.6, typical of sandstones.

3-D Stress Model: Results

The proposed location is located at the northeastern extreme of the predicted shear fracture occurrence.

Predicted orientations of shear fractures is 153° (N27W) and 93° (N87W). These are nearly the same orientations found in the Govt. Union #4 core, 141°-161° and 71°-91°.



Predicted Shear Fracture Occurrence Map

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Summary

- Fault mapping of post-stack, depth-converted, Table Rock and Continental Divide Phase II 3-D seismic surveys show a connected thrust and strike-slip fault system.
- Preliminary regional analysis of stress perturbations associated with fault geometry indicate that the proposed location is at the northeastern extent of the perturbation.
- Predicted shear fracture orientations are N27W and N87W.

Implications

- Using the situation at Govt. Union #4 as an analog and the geometry of the major fault systems, the regional extent of shear fracture occurrence is limited to approximately 8 sections. This is probably the worst-case scenario.
- From core observations, the open voids are connected by low permeability mineralized shear fractures.
- The NW trending shear fractures, however, have the greatest chance of being open due to present day stress.

Recommendations for Task 2

Stress model must address a more local occurrence of shear fractures due to interactions of small faults near the major thrust-strike-slip system. We recommend:

- A local area of study (one township) around proposed location.
- Depth-migrate the corresponding 3-D seismic data volume for better definition of structure.
- Map all small faults using continuity filter to enhance identification.
- Rerun stress model to capture small perturbations and identify local areas of shear fracture occurrence that may impact horizontal leg of proposed well.