Chapter 20

Exploring for Structural Traps

by

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and

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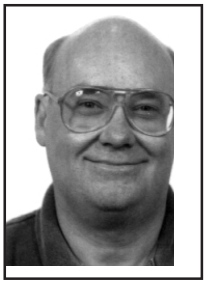

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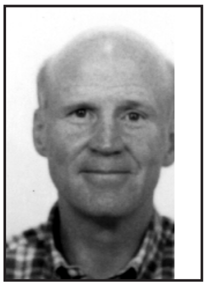

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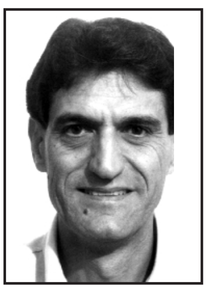

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Overview

Introduction

Structural traps are the most prolific and varied of all trap types; they account for most of the world's hydrocarbon reserves. They range from very large [e.g., Ghawar, Saudi Arabia (560,000 ac)] to small [Major County, Oklahoma, U.S.A. (160 ac or less)]. (J. Coughlon, personal communication, 1996). To effectively prospect at all scales in this size continuum, we must apply a wide variety of techniques, tools, and approaches.

Deformation, including sedimentary (diagenetic) processes of compaction, creates folds and faults, which can result in structural traps, anticlines, and fault closures. This chapter discusses how to predict these by applying structural geology principles to find and develop oil and gas traps.

In this chapter

This chapter contains the following sections.

Section A

Basic Structural Approach

What is a structural trap?

In a structural trap, closure of the reservoir rock and seal are defined entirely by various structural or deformational elements, such as folds or faults. In Chapter 4, a structural trap is defined as a "hydrocarbon accumulation in which the trapping element is post- or syndepositional deformation displacement of reservoir and/or sealing units."

Structural maps and sections

The structural maps and structural cross sections we create are more than just 2-D spatial representations of subsurface data. They are shorthand visual depictions of our views of geological history as well. Structural maps and sections display our understanding of the geology, showing the known facts as well as the implied sequence of events within the context of current geoscience paradigms and approaches. The more thorough our knowledge of the geology of a structural play or prospect, the easier it is to evaluate.

In this section

This section covers the following topics.

Structural Maps and Cross Sections

Basic tools of a structural play

Four basic tools must be put together in a structural play or prospect, regardless of local structural style, level of structural complexity, or exploration maturity:

- A structure contour map on top of the reservoir.
- An isopach map of the target reservoir—especially important if the reservoir displays significant stratigraphic thickness variation or has behaved in a ductile or compactive manner during deformation.
- Two or more structural cross sections incorporating all surface and subsurface control (wells and seismic) projected into the line of section in both the strike and dip directions.
- Fault-surface maps (structural contours on the fault plane), made for all faults critical to closure at the top of the reservoir.

Guidelines for making maps and sections

Follow these guidelines when making maps and cross sections of a structural play.

- Construct maps using interpretive, not mechanical, mapping techniques.
- Make maps and sections at the same scale—in depth, not seismic time (if possible)—and internally consistent to one another.
- Use a 1:1 vertical to horizontal scale for sections. If this is impractical, construct sections with as little vertical exaggeration as possible to minimize distorting the true shape of the structures.
- For control, project wells into sections parallel to the structural contours.
- Check sections for geometric feasibility (i.e., balanced or restored) where appropriate.
- Integrate the contours of reservoir tops and fault surfaces to honor vertical separation along faults.
- Depict "known" vs. "inferred" or interpreted geometry on sections and maps. Display the relative subjective quality of interpreted geometry (low, medium, high). As shown in Figure 19–1, displaying the data in this manner allows the viewer to know where it is well and poorly constrained.

Integrating maps and sections

The schematic figure below represents how to integrate different maps and cross sections in a structural geology play. It also shows how to display levels of confidence of interpretation. (More control points are depicted than would normally be present in a prospect.)

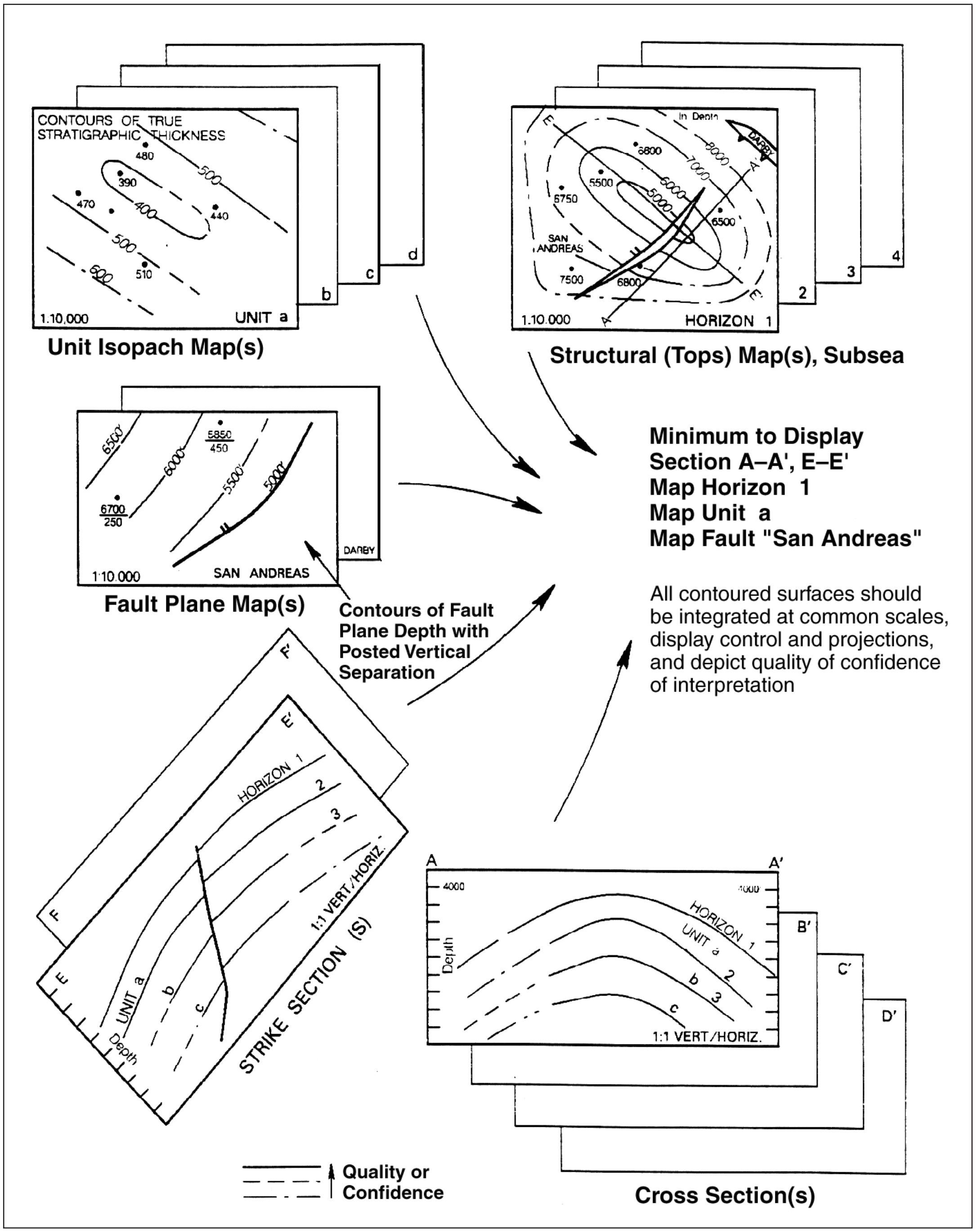

Figure 20–1.

Understanding the Geology of a Structural Play

Structural elements

To build a structural play and create the necessary factual/interpretive displays, we must analyze four structural elements of the play:

- The structural geometry of the play in three dimensions, including relative attitudes of formation and fault surfaces
- Deformation or physical diagenesis of reservoirs and seals (trap integrity)
- Timing of structural development and trap formation, and its relation to important petroleum system events
- Trap genesis in terms of structural process and/or tectonic context

Too often we focus only on structural geometry and ignore the other three elements. Timing, seal, reservoir, and process are what relate structural geometry to the petroleum system.

Unraveling structural geometry

To describe adequately the structural geometry of the subsurface trap, we must integrate subsurface data into a cohesive whole. Data include well logs, 2-D and 3-D seismic images (in both time and depth), gravity surveys, magnetics, and surface geology. These data are integrated with our understanding of the geometric possibilities for the structural style expected or demonstrated to exist in the area.

A structural style is a group of structures that often occur together in a particular tectonic setting. The following table from Harding and Lowell (1983) lists the characteristics of the primary structural styles. Figure 20–2 illustrates schematic cross sections of hydrocarbon traps (black areas) most commonly associated with the major structural styles.

Structural Style	Dominant Deformational Force	Typical Transport Mode	Plate-Tectonic Habitats: Primary	Plate-Tectonic Habitats: Secondary
BASEMENT INVOLVED				
Wrench-fault assemblages	Couple	Strike slip of subregional to regional plates	Transform boundaries	Convergent boundaries: 1. Foreland basins 2. Orogenic belts 3. Arc massif Divergent boundaries: 1. Offset spreading centers
Compressive fault blocks and basement thrusts	Compression	High to low-angle convergent dip slip of blocks, slabs, and sheets	Convergent boundaries: 1. Foreland basins 2. Orogenic belt cores 3. Trench inner slopes and outer highs	Transform boundaries (with component of convergence)
Extensional fault blocks	Extension	High to low-angle divergent dip slip of blocks and slabs	Divergent boundaries: 1. Completed rifts 2. Aborted rifts; aulacogens Intraplate rifts	Convergent boundaries: 1. Trench outer slope 2. Arc massif 3. Stable flank of foreland and fore-arc basins 4. Back-arc marginal seas (with spreading) Transform boundaries: 1. With component of divergence 2. Stable flank of wrench basins
Basement warps: arches, domes, sags	Multiple deep-seated processes (thermal events, flowage, isostacy, etc.)	Subvertical uplift and subsidence of solitary undulations	Plate interiors	Divergent, convergent, and transform boundaries Passive boundaries
DETACHED				
Decollement thrust-fold assemblages	Compression	Subhorizontal to high-angle convergent dip slip of sedimentary cover in sheets and slabs	Convergent boundaries: 1. Mobile flank (orogenic belt) of forelands 2. Trench inner slopes and outer highs	Transform boundaries (with component of convergence)
Detached normal fault assemblages (“growth faults” and others)	Extension	Subhorizontal to high-angle divergent dip slip of sedimentary cover in sheets, wedges, and lobes	Passive boundaries (details)	
Salt structures	Density contrast Differential loading	Vertical and horizontal flow of mobile evaporites with arching and/or piercement of sedimentary cover	Divergent boundaries: 1. Completed rifts and their passive margin sags 2. Aborted rifts; aulacogens	Regions of intense deformation containing mobile evaporite sequence
Shale structures	Density contrast Differential loading	Dominantly vertical flow of mobile shales with arching and/or piercement of sedimentary cover	Passive boundaries (deltas)	Regions of intense deformation containing mobile shale sequence

Understanding the Geology of a Structural Play, continued

Unraveling structural geometry (continued)

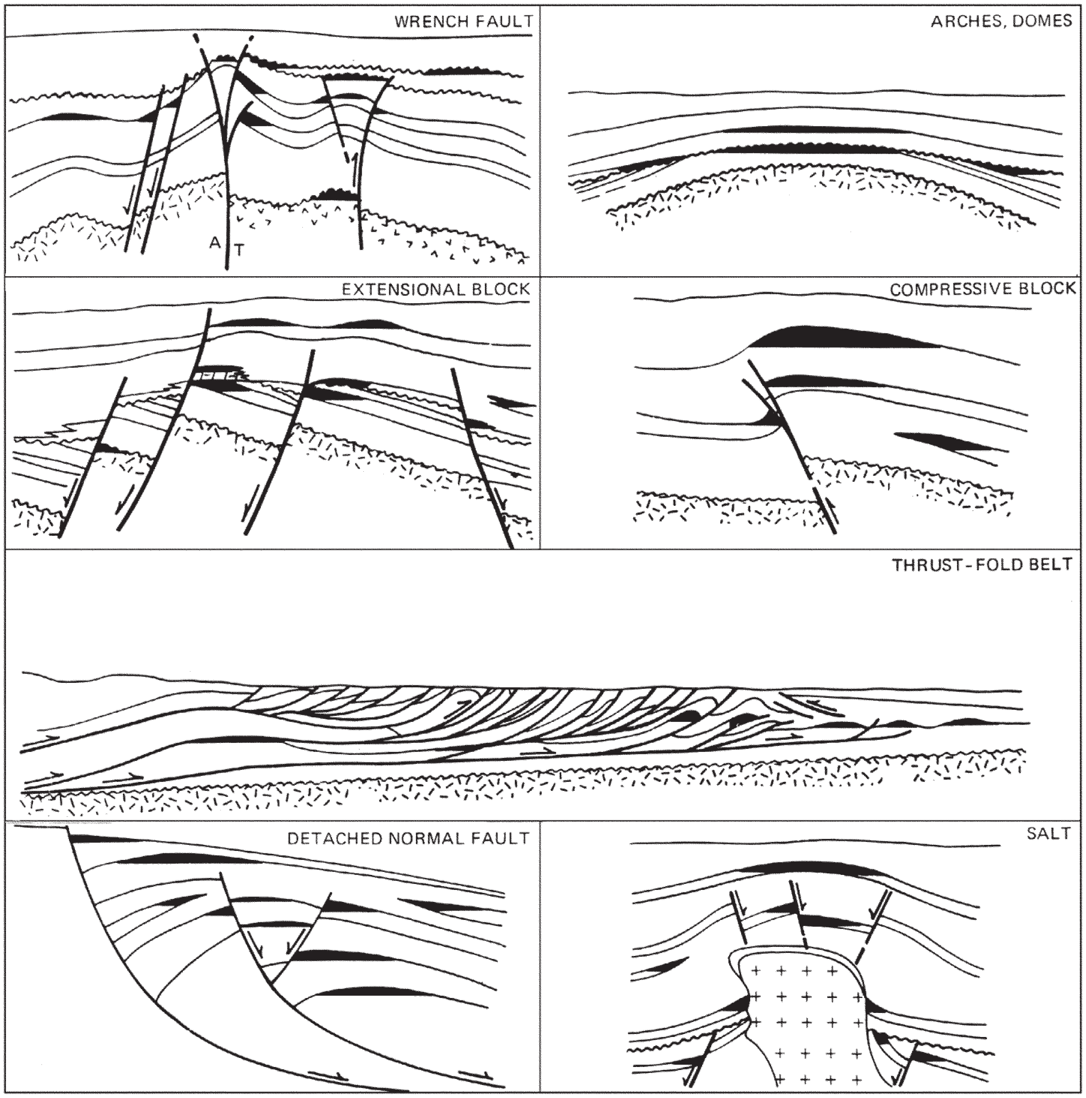

Figure 20–2. After Harding and Lowell, 1983; courtesy AAPG.

Understanding the Geology of a Structural Play, continued

Creating a concept

Using these data, we create a concept of the structural geometry of the play, following the steps in the table below.

Step	Task	Why
1	Through stratigraphic correlation, determine/delineate “structural tops” for several mappable horizons from well and/or seismic data. The number of horizons depends on the quality of the data and the complexity of the structural style.	Changes in structural form with depth vary with structural style, mode of origin, and the operative deformational mechanisms.
2	Determine the relative attitude and thickness of units on fold limbs (dip panels) and/or units within fault blocks.	Given a deformational style, limb angles and thicknesses can be used to estimate fault and axial plane dip, and vice versa.
3	Determine the tightness of fold hinges with depth and the 3-D orientation of axial surfaces.	These features vary substantially with fold origin and are critical to predicting well paths.
4	Determine the position and offsets (throw, heave, separation, etc.) on faults and map their variation along the fault surface(s) (contour integration).	In any structural trap where faults play an important part in closure, the fault surface(s) must be contoured in order to accurately contour the top of the reservoir near the fault trace on that reservoir.
5	Determine closure (dip and/or fault) in all 2-D map directions.	Closure is the key element in all structural plays and must be evaluated at all appropriate horizons to look for vertical continuity and variation.

Timing structural development

In the petroleum systems approach to exploration, the relative timing of major events, such as trap formation, is critical. Timing of structural trap development is difficult to determine and usually must be inferred. The techniques for determining timing are often integrated with one another using sequential restored sections (by hand or computer) that either back-strip the sedimentary layers by “flattening” to their depositional surface or palinspastically restore them to predeformational geometries by removing displacement on the faults and unfolding the folds (Nelson et al., 1996). In simplified structural settings, isopach maps of successive stratigraphic units may be regarded as paleostructural maps.

Determining timing

Following are tables of primary, secondary, and tertiary techniques that can be applied to determine structural trap timing, with primary techniques being the most useful.

Understanding the Geology of a Structural Play, continued

Primary techniques

The following techniques are the most useful in determining structural trap timing.

Technique	Function
Isopachs of time-specific intervals	Isopach maps are a basic subsurface tool. Thicks and thins displayed in those maps are assumed to be depositional variations related to vertical components of structural relief and/or movement.
Unconformity studies • Missing time/section • Relations to eustacy • Sequence stratigraphy • Angular discontinuities	The ages of surfaces of erosion, nondeposition, condensed section, or angular discordance can be used to time the structural motion that caused them.
Facies/isolith distributions	Often structural motion or relief does not cause interval isopaching but does cause facies or environment of deposition changes due to subsidence rate differences or sediment pathways.
Fault terminations • Up-section termination horizons • Lower detachment planes	Consistent vertical termination of faults within the section can help us bracket timing relative to the ages of the section they cut and do not cut.
Relative crosscutting relations of faults	The crosscutting nature of discrete fault sets can help us infer the relative timing of motion of those sets.
Subsidence profiles	Changes in subsidence rate as shown in time/thickness profiles imply times of uplift and subsidence.
Thermal maturity profiles	Inflections in curves of maturity vs. depth depict burial/uplift history and can help us model structural development.

Secondary techniques

The following techniques are useful in determining structural trap timing.

Technique	Function
Vertical and lateral distribution of depositional environments to document uplift and subsidence	Tectonic activity can cause changes in sediment source terrances, bathymetry, and depositional environment, resulting in structurally controlled facies variations.
Radiometric dates of crosscutting intrusives and capping volcanics	Absolute age dating of these units can help to constraint the age of deformation of the host sedimentary rocks.
Unroofing sequences/ clastic lithology studies	The age of deposits shed off erosional highs relative to the age of the rock(s) being eroded implies the time of uplift.
Outcrop studies of kinematic indicators	Tectonic fabrics showing crosscutting or overprinting relationships suggest the sequence of deformation events.

Understanding the Geology of a Structural Play, continued

Tertiary techniques

The following techniques are the least useful in determining structural trap timing.

Technique	Function
Fission-track thermal history modeling	These data help us model the temperature history of a rock from the time it cooled below a threshold temperature, thereby helping to date uplift and erosional events.
Inflections in shale compaction curves and velocity profiles	Vertical changes in percent compaction in shales inferred from logs can document changes in depth and/or rate of burial.
Paleoseismic indicators due to fault motion	The presence of synsedimentary or soft sediment deformation may indicate paleoseismic activity and date the tectonic motions responsible, in a relative sense.
Geochemical and geophysical investigations of fault zones • Rb-Sr, Ar-Ar, and K-Ar dating of fault zone material • Electron spin resonance techniques • Fracture fabric sequencing in fault zones	Fabric analysis and relative dating of fault zone diagenesis can be used in some cases to date periods of fault motion.

Understanding the Geology of a Structural Play, continued

Reservoir and seal deformation

The table below describes the procedure for determining the relative deformation of seals and reservoirs in a structural trap.

Step	Task	Explanation
1	Based on outcrop studies and subsurface data, subdivide the stratigraphic section according to the relative mechanical strength of the units.	In all structural styles, the mechanical makeup of the stratigraphic package has a strong and often predictable effect on structure geometry.
2	Determine the mechanical properties (brittle vs. ductile) of the individual reservoir and seal rocks using the following: • Mechanical tests • Resistivity logs (in shales) • Composition–porosity–grain size predictions	These properties help predict the deformation mechanisms activated during deformation. In siliciclastic reservoirs, these mechanisms may result in deformation-induced dilatant or compactive changes which in turn may have a large impact on reservoir quality.
3	Interpret equivalent strain maps derived from curvature analysis, such as Gaussian curvature.	These maps determine possible compactive zones and predict fractured reservoir properties, such as fracture permeability.
4	Define deformation mechanisms (fracture, cataclasis, intracrystalline flow, pressure solution, etc.) in seal and reservoir rocks at appropriate depths, and relate them to capillary pressure for sealing capabilities.	These mechanisms help us predict deformation-related changes in seal and reservoir rock properties.
5	If needed, create equivalent plastic strain maps or sections (numerical mechanical modeling, e.g., boundary value problems and finite element modeling).	Numerical mechanical modeling can predict and map (1) deformation mechanisms and (2) reservoir and seal property changes related to deformation

Reservoir and seal changes

Structural deformation changes the petrophysical properties of the reservoir and seal facies. This physical diagenesis of reservoirs and seals in structural traps can take the form of compaction (reduction in porosity, permeability, and/or pore size) or dilatancy (increase in permeability by fracturing). These deformation-related changes should be either documented or predicted to estimate and risk reservoir and seal properties accurately in a structural trap.

Selling a Structural Play

Explaining the concept

For a structural play to be accepted, we must construct a coherent explanation of the mechanics or tectonics responsible for creating the play. Such explanations can be any of the following:

- The sequential development of the structure
- How the structure fits spatially and temporally within the regional tectonic fabric
- Appropriate physical and/or mechanical models that clarify the structure's development

Once constructed, these explanations give us greater confidence in our interpretations and a higher level of predictability in poorly constrained areas.

The table below describes the procedure for constructing such an explanation.

Step	Task	Explanation
1	Relate the play to published or in-house regional tectonic reconstructions and paleogeographic maps of the time periods over which the play's structural movement(s) occurred. Determine if your concept of the structural genesis of the play on the local scale is consistent with these regional scale models. Also consider whether to modify the local structural model or the tectonic model.	Provides a context in which to place the deformation that is consistent with regional data.
2	Determine whether results from considering structural timing and reservoir and seal quality are consistent with current mechanical models of fold and fault generation or with current knowledge of structural styles.	Provides a check with respect to the rules of mechanics and our knowledge of general structural form.
3	If the structural prospect is either quite complicated or ill constrained by the data, consider physical or numerical modeling to help define geometry and probable mode of origin.	Modeling provides a heuristic approach to predicting type and position of deformational features that can then be tested in outcrop or with subsurface data.

Selling a Structural Play, continued

Testing the play

If we have created the minimum play requirements, then we must convince someone—either management or investors—to test the play concept. Gaining consensus from peer review bodies, risk panels, management committees, and financial advisors can require a variety of presentation formats. Whereas the presentations all share some common aspects, differences exist because of the varied focus of these groups in today's exploration environment. The table below lists suggestions for the style of presentation appropriate for various groups.

Target Group	Style of Presentation
All groups	Control quality of all displays. This includes proper position of control and interpretive "picks" and consistency of dipping fault plane and axial surfaces between mapped horizons. One mistake can destroy the reviewer's faith in the entire project. Openly discuss strengths and weaknesses of the play. And be enthusiastic without equating approval to your own emotional well-being.
Peer review	Lead a discussion rather than make a presentation. Present negatives of the play up front to draw out helpful suggestions. Discuss detailed technical approaches and arguments early in the presentation. The goal is to solicit help solving problems.
Risk review panel (major company)	Emphasize the technical details. Present the positive and negative aspects in a more balanced manner than in the peer "problem-solving" review. Use all supportive illustrations and approaches to make a fair and accurate depiction of technical risk. The goal is technical calibration with other prospects within the exploration portfolio.
Management committee	Focus on technical conclusions and implications of the play to company exploration strategy. Emphasize the advantages of the play, but also disclose any technical details that increase the play's risk over other plays. The goal is to illustrate the strategic fit or importance of the play in the company's exploration portfolio.
Outside investors	Focus on generalities and play concepts. Check all data for accuracy. The goal is to gain commitment of capital early in the exploration process.

Section B

Structural Interpretation Techniques and Tools

Introduction

A variety of techniques and tools are available to explorationists for analyzing various aspects of a structural play. These cover a broad range, both in scale and type, from plate tectonic studies to microscopic examination of grain-scale structures and from outcrop studies to computer-intensive numerical modeling.

In this section, each technique or tool is discussed, emphasizing the following:

- The information it provides
- How to get that information
- When, where, or how to use the information
- Examples in the literature

In this section

This section contains two subsections:

Subsection B1

Scoping Techniques and Tools

In this subsection

This subsection discusses techniques that are primarily scoping in character and are frequently applied to large geographical areas. They often require little in monetary expenditure and are most appropriate for frontier basins. However, they can also be useful to companies seeking an entry position in a basin with established production and a competitive business environment.

Plate Tectonic Studies

Information provided

Plate tectonic studies provide the following kinds of information:

- Regional geologic framework
- Types of major structures expected in the play
- Whether the area may have been affected by more than one deformation event and/or more than one deformational style
- Age and relative timing of deformation
- Relation between structural trap development and other hydrocarbon systems events, such as source, seal, and reservoir deposition

When to use it

Always use plate tectonics. Although it is most useful in frontier basins, it is helpful even in mature basins. Knowing how a structural play fits into the regional tectonic picture may yield new ideas and approaches to exploration.

How to use it

This inexpensive technique is applied directly from the following:

- Regional literature in professional journals
- Interactive computer programs showing plate positions and configurations during geologic history
- Independent or "spec" regional studies integrating all aspects of the petroleum geology of a large region

Examples of use

Beydoun, Z.R., 1991, Arabian Plate Hydrocarbon Geology and Potential—A Plate Tectonic Approach: AAPG Studies in Geology 33, 77 p.

Busby, C.J., and R.V. Ingersoll, eds., 1995, Tectonics of SedimentaryBasins: Cambridge, Mass., Blackwell Scientific, 570 p.

Dickinson, W.R., and H. Yarborough, 1978, Plate Tectonics and Hydrocarbon Accumulation: AAPG Continuing Education Series 1, 148 p.

Harding, T.P., and J.D. Lowell, 1979, Structural styles, their plate-tectonic habitats and hydrocarbon traps in petroleum provinces: AAPG Bulletin, vol. 63, p. 1016–1058.

Pindell, J.L., and S.F. Barrett, 1990, Geological evolution of the Caribbean region: a plate-tectonic perspective, *in* G. Dengo and J.E. Case, eds., The Caribbean Region (vol. H of the Geology of North America series): Boulder, Colorado, Geological Society of America, p. 405–432.

Redfern, P., and J.A. Jones, 1995, The interior rifts of Yemen-analysis of basin structure and stratigraphy in a regional plate tectonic context: Basin Research, v. 7, p. 337–356.

Watson, M.P., A.B. Hayward, D.N. Parkinson, and Z.M. Zhang, 1987, Plate tectonic history, basin development and petroleum source rock deposition onshore China: Marine and Petroleum Geology, vol. 4, p. 205–225.

Yin, A., and S. Nie, 1996, A Phanerozoic palinspastic reconstruction of China and its neighboring regions, *in* A. Yin and T.M. Harrison, eds., The Tectonic Evolution of Asia: Cambridge, Mass., Cambridge University Press, p. 442–485.

Potential Fields

Information provided

The following table indicates the information provided by the three kinds of potential fields.

Field	Information Provided
Gravity	• Basin shape and depth • Constraints on diapiric origin of modeling structural geometry and depth structures
Magnetic	• Depth to basement • Basement fault trends and fault block boundaries
Magnetotelluric	• Thick-skinned vs. thin-skinned deformation • Amount of section below regional decollement

How to get it

Various scale regional gravity and magnetic surveys can be obtained from the following sources:

- Existing surveys (both ground and airborne acquired) from contractors
- Contractor-acquired data along seismic lines during seismic surveys
- Purchased surveys from government sources in the U.S. and overseas

Where to use it

Such data are extremely useful in extensional and rift terranes and as a guide in planning subsequent seismic surveys.

Examples of use

Billings, A.J., and J.H. Thomas, 1990, The use and limitations of non-seismic geophysics in the Papuan thrust belt, *in* G.J. Carman and Z. Carman, eds., Petroleum Exploration in Papua New Guinea: Proceedings of the First Papua New Guinea Petroleum Convention, Port Moresby, p. 51–62.

Christopherson, K.R., 1990, Applications of magnetotellurics to petroleum exploration in Papua New Guinea, *in* G.J. Carman and Z. Carman, eds., Petroleum exploration in Papua New Guinea: Proceedings of the First Papua New Guinea Petroleum Convention, Port Moresby, p. 63–71.

Nettleton, L.L., 1971, Elementary gravity and magnetics for geologists and seismologists: Society of Exploration Geophysicists Monograph Series 1, 121 p.

Remote Sensing

Information provided

Remote sensing data such as satellite imagery can help us examine regional structural fabrics, patterns, and contacts. Detailed mapping can be done using high-resolution satellite imagery and both high-altitude and low-level photography. The infrared bands on satellite imagery minimize the blurring effects of haze. Radar imagery removes the effects of haze and clouds.

Types

There are four types of remote sensing imagery used when exploring for structural traps:

- Satellite imagery
- High-altitude photography
- Low-level aerial photographs
- Side-looking airborne radar (SLAR) and/or sonar

The following table indicates the coverage and resolution of the various types of satellite imagery.

Type	Single Scene Coverage (km)	Resolution (m)
Landsat MSS	185 × 170	80
Landsat TM	185 × 170	30
SPOT	60 x 60	20 (color), 10 (b&w)
Soyuz	40 × 40	2

How to get it

Remote sensing imagery can be obtained from the following sources:

- Directly from vendors or foreign governments for satellite or high-altitude data or by using a contractor as an intermediary for obtaining and/or processing the imagery
- From published sources such as the proceedings from conferences and topical meetings
- Directly contracting low-altitude aerial photography or, in the U.S., obtaining existing surveys from the Department of Interior or Department of Agriculture (In foreign locations, such surveys often require local government approval and involvement.)

U.S. sources for high-altitude photography, low-level aerial photography, and SLAR are listed in the table below.

Type of Imagery	Sources
High-altitude photography	• Manned space mission photographs • U-2 photographs • National High Altitude Photography (NHAP)
Low-level aerial photographs	• Black and white or color, vertical or oblique photographs • Infrared (IR) photographs
Side Looking Airborne Radar (SLAR)	• Aircraft-based, low-level radar imagery • Satellite or shuttle-based radar imagery

Remote Sensing, continued

Where to use it

Remote sensing data are useful in all structural terranes but are especially important in remote areas where local topographic and geological control is absent or unobtainable.

In hydrocarbon exploration, remote sensing data is primarily used to (1) examine and map the surface geology in and around a concession area and (2) check terrain conditions and access routes for geologic fieldwork, seismic surveys, well locations, pipeline routes, and environmental hazards

Examples of use

Allenby, R.J., 1987, Origin of the Bolivian Andean orocline: a geologic study utilizing Landsat and Shuttle Imaging Radar: Tectonophysics, vol. 142, p. 137–154.

Beauchamp, W., M. Barazangi, A. Demnati, and M. El Alji, 1996, Intracontinental rifting and inversion: Missour Basin and Atlas Mountains, Morocco: AAPG Bulletin, vol. 80, p. 1459–1482.

Foster, N.H., and E.A. Beaumont, eds., 1992, Photogeology and photogeomorphology: AAPG Treatise of Petroleum Geology Reprint Series 18, 555 p.

Halbouty, M.T., 1980, Geologic significance of Landsat data for 15 giant oil and gas fields: AAPG Bulletin, vol. 64, p. 8–36.

Insley, M.W., F.X. Murphy, D. Naylor, and M. Critchley, 1996, The use of satellite imagery in the validation and verification of structural interpretations for hydrocarbon exploration in Pakistan and Yemen, *in* P.G. Buchanan and D.A. Nieuwland, eds., Modern Developments in Structural Interpretation, Validation and Modeling: Geological Society of London Special Publication 99, p. 321–343.

Prost, G.L., 1994, Remote Sensing for Geologists: A Guide to Image Interpretation: Gordon and Breach Science Publishers, 326 p.

Sabins, F.F., Jr., 1987, Remote Sensing, Principles and Interpretation: New York, W.H. Freeman Company, 449 p.

_____, 1998a, Remote sensing for petroleum exploration, part 1: overview of imaging systems: The Leading Edge, vol. 17, p. 467–470.

_____, 1998b, Remote sensing for petroleum exploration, part 2: case histories: The Leading Edge, vol. 17, p. 623–626.

Sosromihardjo, S.P.C., 1988, Structural analysis of the north Sumatra Basin with emphasis on synthetic aperture radar data: Proceedings of the Indonesian Petroleum Association, p. 187–209.

Regional Maps and Cross Sections

Information provided

Maps and cross sections provide the following kinds of information:

- Documentation/determination of structural style(s)
- Size, distribution, and spatial and age relationships of structures
- Spatial and age relationships of rock units

Types

Among the various types of maps are ...

- Maps of structural patterns and trends (fold, faults, lineaments)
- Structure contour/isopach maps
- General geological and tectonic maps

We should always compile/construct maps and cross sections using all available surface, well log, and seismic data.

How to get it

Such maps and sections can be obtained from the following sources:

- Local geological surveys and international societies
- National oil companies as part of data packages for concession offerings
- Independent regional studies within companies or by service companies on a "spec" or contract basis

Where to use it

Such data are mandatory for structural background in all structural terranes, especially in less mature basins.

Examples of use

Bally, A.W., P.L. Gordy, and G.A. Stewart, 1966, Structure, seismic data and orogenic evolution of southern Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, vol. 4, p. 337–381.

_____, L. Burbi, C. Cooper, and R. Ghelardoni, 1986, Balanced sections and seismic reflection profiles across the central Apennines: Memorie della Societa Geologica Italiana, vol. 35, p. 257–310.

Dixon, J.S., 1982, Regional structural synthesis, Wyoming salient of the Western overthrust belt: AAPG Bulletin, vol. 66, p. 1560–1580.

Dunn, J.F., K.G. Hartshorn, and P.W. Hartshorn, 1995, Structural styles and hydrocarbon potential of the Sub-Andean thrust belt of southern Bolivia, *in* A.J. Tankard, R.S. Suarez, and H.J. Welsink, eds., Petroleum Basins of South America: AAPG Memoir 62, p. 523–543.

Dutton, S.P., A.G. Goldstein, and S.C. Ruppel, 1982, Petroleum Potential of the Palo Duro basin, Texas Panhandle: University of Texas at Austin Bureau of Economic Geology Report of Investigations 123, 87 p.

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Fieldwork

Information provided

Reconnaissance fieldwork can be used to familiarize the explorationist quickly with regional structural patterns, stratigraphy, and the distribution of rock types. It can also highlight areas where more detailed work is necessary. Existing maps should be spot-checked to determine if they can be confidently used for interpretation and as a base for additional work. In areas where geologic maps at the required scale are not available, detailed mapping and traversing may be required. Fieldwork can also be targeted to investigate specific topics such as fracture morphology and distribution, detailed fold geometry, and timing of structures.

The various types of fieldwork include the following:

- Regional reconnaissance
- Spot checks of existing maps
- Detailed mapping, traversing
- Targeted studies

When to use it

Structural fieldwork can be useful throughout an exploration program. If it is done prior to or in conjunction with the interpretation of seismic data in the area, it can help guide the interpretation. Structural fieldwork is most effective when done in conjunction with other stratigraphic and petrologic studies.

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Natural Analogs

How to use it

Well-documented surface or subsurface structures can be used as analogs to help constrain other structural interpretations based on sparse data. For example, if the regional tectonic setting indicates that our exploration area is in a thrust belt, but local outcrop/subsurface data do not accurately define the shape of individual structures, then we can use well-documented examples of structures from other thrust belts *with similar stratigraphy* as analogs to constrain our interpretation. However, correlation to producing structures is most valued.

Where to get it

Because one of the strongest arguments that can be used to “sell” a play in the industry is a producing analogy, such structural analogs are an important part of every structural play. These can be found in such sources as:

- Field catalogs within major companies
- Published regional field atlases from oil-producing states like California, Texas, and Louisiana
- The AAPG Treatise of Petroleum Geology, Atlas of Giant Fields, volumes on structural traps

Examples of use

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Natural Analogs, continued

Examples of use (continued)

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Subsection B2

Prospect Delineation Techniques and Tools

In this subsection

In this subsection, we discuss techniques that refine our understanding of individual structural traps, both prior to and subsequent to drilling. The techniques may require significant monetary expenditure and are applied in smaller, more well-defined geographical areas (i.e., structural fairways) than the techniques discussed in Subsection B1.

Seismic Data

Information provided

Seismic data provide a “time picture” of subsurface structure. For accurate structural analysis, an effort should be made to convert the time data to depth.

There are three types of seismic data:

- Reflection (including 2-D and 3-D)
- Shear wave
- Refraction

2-D reflection seismic data provide cross-sectional views in both the dip and strike directions. Data on the lines are a mixture of both in-plane and out-of-plane reflectors. 2-D reflection seismic data are most important in the earlier stages of an exploration program, especially in frontier basins.

3-D reflection seismic data provide resolved cross-sectional views along any azimuth within the survey area. Time “slices” (maps) on any horizon can also be generated. The nature and location of out-of-plane features can be more accurately determined. Because of the high acquisition costs, 3-D seismic techniques normally are used only to more accurately define individual prospects.

Shear wave data, in combination with conventional compressional wave data, can provide information on lithology, fractures, and the presence of hydrocarbons.

Refraction seismic data provide a deep crustal view of gross structure (basin scale to lithosphere–upper mantle scale), which is useful when trying to understand regional tectonics.

How to use it

Although structural interpretation from seismic data is indeed a difficult endeavor and a detailed discussion is beyond the scope of this chapter, the following are hints for effective interpretation procedures.

- Interpretation on each line should proceed from well-imaged, well-constrained portions of the line toward areas of poorer constraint. Use symbols for varying quality of interpretation.
- Map multiple horizons.
- Map and contour fault surfaces critical to closure.
- Integrate fault and horizon contours.
- In thrust, rift, and extensional terranes, emphasize dip line interpretation; in foreland and wrench terranes, equally emphasize strike line interpretation.
- Generate depth conversions during iterative interpretations.

Examples of use

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Modeling

Information provided

Models are representations of natural structures. They are used when direct analysis of various aspects of natural structures is either difficult or impossible.

There are two types of models:

- Physical (including rock mechanics models, photoelastic models, and geometry models)
- Mathematical (including mechanics models and geometry models)

Physical models

Physical models are constructed from rocks or a variety of materials including clay, sand, and putty.

- **Rock mechanics models** are designed and run to gain information on the strength and deformation mechanisms of rocks when subjected to various loads and displacements under controlled conditions of pressure, temperature, strain rate, and pore fluid pressure and chemistry. The starting configuration of these models is usually a right circular cylinder composed of the rock(s) being studied.
- **Photoelastic models** provide information on stress magnitude and orientation. They are made of transparent materials such as clear plastics or gelatins. When deformed and examined in polarized light, these materials exhibit color fringes and alternating light and dark bands. From these, we can determine the stress intensity and the orientation of the principal stresses at any point in the model.
- **Geometric models** reproduce the shape of naturally occurring structures. The starting configuration is usually a layered rectangular block or some variation thereof. Displacements are imposed at the boundaries of the block to create the desired deformation. The hope is that if we can create a good geometric analog of a natural structure under conditions we specify and control, then we will gain a better understanding of the conditions that influence the development of the natural structure. This highlights an important role of these models: they generate hypotheses or ideas regarding the development and final shape of natural structures—ideas that may not occur to us even after careful study of structures in the field.

Mathematical models

Mathematical models consist of equations that describe the interrelationship of parameters thought to be important in the development of natural structures.

- **Mechanics models** use various analytic and numerical techniques (finite element, distinct element, finite difference) to simulate deformation. Input parameters are undeformed shape, mechanical properties of the model materials, displacements, and displacement rate. The models yield information on deformed shape, displacement trajectories, and the orientation and magnitude of stress and strain in the model at various stages of displacement.
- **Geometry models** examine the development of structures, mainly in 2-D, by applying various simplified kinematic or displacement rules. These models do not provide direct information on the structural effects of environmental parameters during deformation (e.g., rock strength, overburden pressure, temperature, strain rate).

How to use it

Models offer insight into how natural structures may have developed. For structures where geometry is poorly constrained by outcrop, seismic data, or well data, models may suggest reasonable options for completing the structural interpretation.

Modeling, continued

How to use it (continued)

Quantitative data derived from a model can be confidently applied to natural structures only if the model has been accurately and completely scaled with respect to the natural counterpart. In practice, this degree of scaling may be achieved in numerical models and mechanical physical models. It is often difficult to achieve in geometrical physical models. Nevertheless, partially scaled and even nonscaled models can still help generate ideas on structure development.

"No absolute or final decision can be made about the admissibility of a given modeling technique; the decision must always depend on the interest of the experimenter, the accuracy and urgency of the required prediction, and the availability of other techniques. Often the modeling technique which most flagrantly flouts the similarity [scaling] rules is the most useful one in practice" (Spalding, 1962).

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Geometry models

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Mechanics models

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Balanced Cross Sections

Definition

Balanced cross sections honor all available data and are constructed and analyzed to ensure they are geometrically possible and geologically admissible, given reasonable assumptions about the predeformation setting of rocks and how rocks behave during deformation in a particular tectonic environment. "Balanced" refers to the basic assumption made in constructing these sections—that rock area (rock volume) does not change substantially as a result of deformation. Balanced cross sections are restorable. This means that, while maintaining constant area, the deformation displayed in a balanced cross section can be incrementally removed to yield a geologically plausible predeformation configuration.

The constant area (constant volume) assumption is generally valid for deformation that has occurred in upper crustal, nonmetamorphic settings, but there are important exceptions. For example, in some settings syntectonic deposition and compaction can result in substantial rock volume changes throughout the course of deformation. In these cases, approximations of the volume changes must be incorporated in the balancing process.

Balancing is an interative, trial-and-error process. If done manually, it is tedious and very time consuming. Computer programs greatly simplify the measurement and drafting aspects of cross section balancing. Some of these programs also incorporate functions and algorithms that permit some rudimentary 3-D balancing of structures.

Value of Balancing

Balanced cross sections are not necessarily correct. However, the methodical scrutiny imposed by the balancing process highlights discrepancies in interpretations, points to the types of data or alternative schemes needed to resolve the discrepancies, and generally results in more carefully constructed, defensible, and explainable cross sections.

Examples of use

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Balanced Cross Sections, continued

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Dipmeter Analysis

Information provided

Dipmeter logs provide data on the dip magnitude and azimuth of planar features in the well bore. These features commonly include primary bedding, cross-bedding, and faults. High-resolution dipmeters can also yield information on fractures and lithologic textural variations. Analysis of dipmeter data using statistical curvature analysis techniques (SCAT) let us more confidently extrapolate structural data away from the well bore.

Where to get it

Dipmeter and borehole imaging logs like the formation microscanner (FMS) or FMI are useful in analyzing all subsurface structural plays, regardless of origin or style.

Interpretations can be obtained from the following:

- Logging service companies as a consulting service
- SCAT-type analysis from commercially available programs and consultants.
- Independent analysis of tadpole logs via pattern recognition or by standard stereographic projections and rose diagrams from FMS workstations

Examples of use

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Nurmi, R. D., 1984, Geological evaluation of high resolution dipmeter data: Society of Professional Well Log Analysts' 25th Annual Logging Symposium, vol. 2, paper YY, 24 p.

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Fault Seal–Conduit Studies

Introduction

These studies try to determine if faults in a particular tectonic setting have acted as conduits or seals with respect to the migration of subsurface fluids. They use a variety of techniques, including outcrop studies of fault zones, core analysis and laboratory testing, thin-section analysis, and construction of fault-plane maps to determine the juxtaposition of rock types along faults.

Information provided

Fault seal–conduit studies predict fault seal–conduit behavior and potential hydrocarbon column height, based on fault morphology and gouge composition, lithology juxtapositions along faults, hydrocarbon type, and reservoir pressure.

How to use them

These data are important in traps where faults play an important role in the critical seal. The analysis involves blending data on fault deformation mechanisms and kinematics with petrophysics and hydrodynamics. Historical analysis of fault sealing capacity in an area is also extremely useful.

Examples of use

Alexander, L.L., and J.W. Handschy, 1998, Fluid flow in a faulted reservoir system: fault trap analysis for the Block 330 field in Eugene Island, South Addition, offshore Louisiana: AAPG Bulletin, vol. 82, p. 387–411.

Allan, U.S., 1989, Model for hydrocarbon migration and entrapment within faulted structures: AAPG Bulletin, vol. 73, p. 803–811.

Antonellini, M., and A. Aydin, 1995, Effect of faulting on fluid flow in porous sandstones: geometry and spatial distribution: AAPG Bulletin, vol. 79, p. 642–671.

Brenneke, J.C., 1995, Analysis of fault traps: World Oil, vol. 217, p. 63–71.

Finkbeiner, T., C.A. Barton, and M.D. Zoback, 1997, Relationships among in-situ stress, fractures and faults, and fluid flow: Monterey Formation, Santa Maria basin, California: AAPG Bulletin, vol. 81, p. 1975–1999.

Gibson, R.G., 1994, Fault-zone seals in siliciclastic strata of the Columbus basin, offshore Trinidad: AAPG Bulletin, vol. 78, p. 1372–1385.

Hooper, E.C.D., 1991, Fluid migration along growth faults in compacting sediments: Journal of Petroleum Geology, vol. 14, p. 161–180.

Jev, B.I., C.H. Kaars-Slijpesteijn, M.P.A.M. Peters, M.L. Watts, and J.T. Wilkie, 1993, Akaso field, Nigeria: use of integrated 3-D seismic, fault slicing, clay smearing and RFT pressure data on fault trapping and dynamic leakage: AAPG Bulletin, vol. 77, p. 1389–1404.

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Nybakken, S., 1991, Sealing fault traps—an exploration concept in a mature petroleum province: Tampen Spur, northern North Sea: First Break, vol. 9, p. 209–222.

Smith, D.A., 1980, Sealing and non-sealing faults in Louisiana Gulf Coast salt basin: AAPG Bulletin, vol. 64., p. 145–172.

Petrofabrics

Information provided

Petrofabrics is the study of deformation features in rocks, usually at the grain scale. The most commonly studied features are fractures (distribution, morphology, and orientation), twinning, pressure solution, and recrystallization fabrics.

Petrofabrics provides information on the following:

- Mechanisms of deformation
- Orientation and magnitude of principal stresses
- Deformation effects on porosity/permeability

How to use it

Structural petrofabric analysis is important in a relatively limited number of special situations. It requires oriented subsurface or surface samples and is performed only by a relatively limited number of specialists, usually at universities.

Examples of use

Allmendinger, R.W., 1982, Analysis of microstructures in the Meade plate of the Idaho–Wyoming foreland thrustbelt, U.S.A.: Tectonophysics, vol. 85, p. 221–251.

Burger, H.R., and M. Hamill, 1976, Petrofabric analysis of the Dry Creek Ridge anticline, Montana: Geological Society of America Bulletin, vol. 87, p. 555–566.

Burkhard, M., 1993, Calcite twins, their geometry, appearance and significance as stress-strain markers and indicators of tectonic regime: a review: Journal of Structural Geology, vol. 15, p. 351–368.

Friedman, M., 1964, Petrofabric techniques for the determination of principal stress directions in rocks, *in* W.R. Judd, ed., State of Stress in the Earth's Crust: New York, Elsevier, p. 451–552.

_____ and G.M. Sowers, 1970, Petrofabrics: a critical review: Canadian Journal of Earth Sciences, vol. 7, p. 477–497.

_____ and D.W. Stearns, 1971, Relations between stresses inferred from calcite twin lamellae and macrofractures, Teton anticline, Montana: Geological Society of America Bulletin, vol. 82, p. 3151–3162.

Onasch, C.M., 1990, Microfractures and their role in deformation of a quartz arenite from the central Appalachian foreland: Journal of Structural Geology, vol. 12, p. 883–894.

Fracture Analysis

Information provided

Five types of fracture analysis provide the following types of information:

Outcrop studies
- Regional-scale to prospect-scale fracture orientation, distribution, width, and spacing
- Fracture size and morphology

Curvature analysis
- Strain distribution prediction based on geometry from structural mapping (fold shape and location on fold)
- Natural fracture intensity prediction and, to a limited extent, fracture porosity, given assumptions regarding rock behavior and strain partitioning

Core analysis
- Downhole fracture distribution, orientation, size, width, spacing, and morphology
- Relationship between petrophysical properties of fractures and matrix

Log analysis
- Detection of fractures in a nonquantitative manner
- Orientation of a selected fracture population
- In some cases, determination of the fluid or mineral filling in fractures

Mathematical models
- Prediction of compactive vs. dilatant rock behavior
- Maps of fracture zones and variations in fracture intensity
- Prediction of fracture porosity, given assumptions regarding relationships between stress and strain and the fracture response of the rock

How to use it

Fracture analysis can help us define structural axes and trends or fracture-related reservoir properties. It can be applied in a variety of structural terranes and rock types, but it is especially important in brittle rock packages. To determine reservoir-property requires integrating geology, petrophysics, and reservoir engineering, and it is most often done by experienced specialists.

Examples of use

Aguilera, R., 1980, Naturally Fractured Reservoirs: Tulsa, PennWell, 703 p. Coward, M.P., T.S. Daltaban, and H. Johnson, eds., Structural Geology in Reservoir Characterization: Geological Society of London Special Publication 127, 266 p.

Jamison, W.R., 1997, Quantitative evaluation of fractures on Monkshood anticline, a detachment fold in the foothills of western Canada: AAPG Bulletin, vol. 81, 1110–1132.

Kulander, B.R., S.L. Dean, and B.J. Ward, Jr., 1990, Fractured Core Analysis: Interpretation, Logging, and Use of Natural and Induced Fractures in Core: AAPG Methods in Exploration 8, 88 p.

Laubach, S.E., 1989, Fracture Analysis of the Travis Peak Formation, Western Flank of the Sabine Arch, East Texas: University of Texas at Austin Bureau of Economic Geology Report of Investigations 185, 55 p.

_____, 1997, A method to detect natural fracture strike in sandstones: AAPG Bulletin, vol. 81, p. 604–623.

Examples of use (continued)

Narr, W., 1996, Estimating average fracture spacing in subsurface rock: AAPG Bulletin, vol. 80, p. 1565–1586.

Nelson, R.A., 1985, Geologic Analysis of Naturally Fractured Reservoirs: Houston, Gulf Publishing Co., 320 p.

_____ and S. Serra, 1995, Vertical and lateral variations in fracture spacing in folded carbonate sections and its relation to locating horizontal wells: Journal of Canadian Petroleum Technology, vol. 34, p. 51–56.

U.S. National Committee for Rock Mechanics, 1996, Rock Fractures and Fluid Flow: Washington, D.C., National Academy Press, 551 p.

Wiltschko, D.V., K.P. Corbett, M. Friedman, and J-H. Hung, 1991, Predicting fracture connectivity and intensity within the Austin Chalk from outcrop fracture maps and scanline data: Transactions of the Gulf Coast Association of Geological Societies, vol. 41, p. 702–718.

Section C

Workflow to Find a Prospect

Introduction

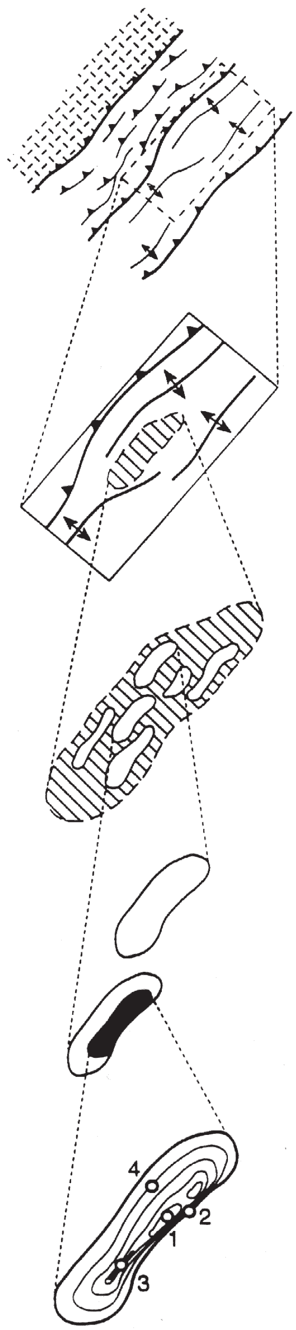
This section suggests a flow of tasks to help explorationists define a drill location, moving from the regional scale to the drill site. The discussion is from the perspective of a full-cycle exploration play, where we have a play concept and are looking for a drill location to test it.

In this section

This section contains the following topics.

Schematic Overview

The workflow We begin by envisioning a structural play concept based on the thrust belt play of the U.S. Rocky Mountain area. The following workflow discussion tracks this play concept from inception to drill location through a “normal” structural exploration process, as shown in the figure below.



A **TECTONIC SETTING (1000s – 100s km)**
A convergent tectonic setting has been targeted for exploration. Preliminary assessment identifies three structural domains bounded by major thrust faults: a basement-involved thrust sheet, thrust faulted and folded sedimentary-cover thrust sheet, and a detached, fold-dominated sheet.

B **STRUCTURAL DOMAIN (100s – 10s km)**
The structural domain targeted for exploration to the most foreland thrust sheet. Its internal structural style is characterized by unfaulted detachment folds developed above a regional decollement.

C **PROSPECTIVE STRUCTURAL FAIRWAY (100s – 10s km)**
That portion of the structural domain in which elements of the hydrocarbon system have had a significant chance of being active or present is defined as the prospective fairway. It may encompass the entire structural domain or only a small portion of it.

D **STRUCTURAL LEAD**
Potentially attractive structural anomalies within the prospective fairway form structural leads.

E **PROSPECT (10s – 1s km)**
A structural lead becomes a prospect when the major components of the hydrocarbon system demonstrate sufficient probabilities of success in contributing to an economic accumulation of hydrocarbons in the structure.

F **LOCATION (1s – 0.1s km)**
A variety of locations may be considered for drilling: 1) crestal location 2) steep forelimb location 3) maximum curvature location or 4) least deformed (minimal structural damage) reservoir location or hydrocarbon-water contact confirmation location.

Figure 20–3.

Effects of scale

The technical tasks we identify are often related to the scale of our observation, from regional to microscopic. The following figure summarizes where the different techniques and tools described in section B can be applied. This sequence of tasks, in varying degrees, applies to any structural play.

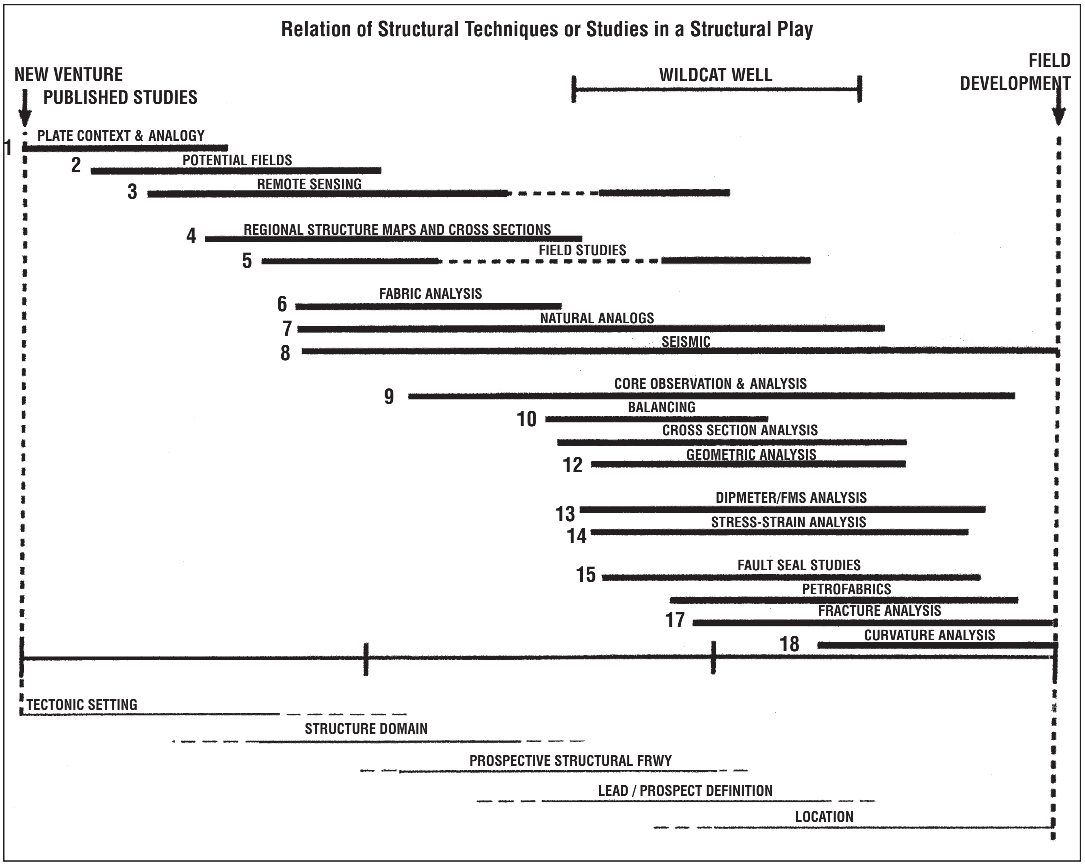


Figure 20–4.

Tectonic Setting

Determining the tectonic setting

The play concept envisioned is determined by the tectonic setting(s) in which the play can be pursued, from a structural as well as source and reservoir perspective. We identify regions with the correct tectonic setting by using the following data sources:

- Published geological studies
- Plate reconstructions and motions
- Tectonic maps
- Paleomagnetic data
- Satellite images

Assessing the area

Once regions with the appropriate tectonic setting are identified, we determine if these areas have the appropriate components to satisfy the requirements established for the play concept. Examples of issues of structure and tectonics which might be addressed include the following:

- Kinematics (e.g., oblique vs. orthogonal convergence)
- Significant changes in kinematics with time (e.g., episodic vs. continuous tectonic events)
- Duration of tectonism
- Major tectonostratigraphic terranes
- Overall complexity of the deformed belt
- Igneous activity

We then examine more closely those regions that meet the play concept criteria to determine if specific structural domains exist within these settings where we can pursue the structural play concept.

Structural Domains

Definition

A structural domain is an areally distinct region or subregion with similar structural properties (e.g., similar fold vergence or style, shortening, uplift, faulting style, etc.).

Identifying structural domains

Once a prospective tectonic setting is identified, we can determine where to focus exploration within that setting. This can be done most effectively by defining the boundaries and internal structural character of the different structural domains within the tectonic setting.

Among different tectonic settings, the number and complexity of the structural domains can vary significantly. For example, the number and character of the structural domains defined in a basin forming in the cratonic interior in a relatively quiet but long-lived tectonic setting contrast significantly to those defined in a short-lived but intense rifting event.

Tools to define structural domains

Within a particular tectonic setting, a significant number of markedly different domains may exist. Our ability to define the domains depends on the data available and the scale of observation. The following data sources can help define the boundaries and describe the internal complexity of structural domains:

- Potential fields
- Satellite imagery and/or aerial photography
- Regional surface and subsurface geologic data
- Exploration seismic data
- Deep crustal seismic data
- Reconnaissance outcrop studies

Assessing potential

Once the structural domain is defined and described, we must assess its potential to satisfy the play concept criteria. Some of the more obvious issues center around structural style:

- Fold styles
- Fault–fold relationships
- Fault spacing and interaction
- Fault fabrics
- Fault scaling
- Shortening–uplift ratios

Characterizing the structural domains lets us look at specific domains relative to the hydrocarbon system and thereby identify prospective structural fairways.

Prospective Structural Fairways

Definition

Certain structural domains or specific portions of those domains provide the greatest opportunities for exploration success. Those areas are called **prospective structural fairways.** In a prospective structural fairway, the structural history, trap configuration, and major elements of the hydrocarbon system combine to present a likely scenario for an economic accumulation of hydrocarbons.

Important considerations in identifying a prospective structural fairway are as follows:

- Structural style
- Tectonic overburden or denudation
- Trap evolution and timing
- Presence of source and reservoir facies
- Timing of hydrocarbon generation and migration

Assessing fairway prospectivity

The above considerations and their interdependencies, along with the following data sources, help us assess which structural fairways might be prospective:

- Regional geologic data (tops, sections, maps)
- Natural and productive analogs of structures
- Reconnaissance seismic data
- Potential fields
- Remote sensing data (satellite and air photo)
- Surface geologic data
- Fabric analysis
- Tectonic subsidence analysis
- Surveys for remote detection of hydrocarbons

If the structural fairway has most, if not all, of the major components needed for a viable hydrocarbon system, the next step is to identify structural leads and convert these to prospects.

Lead/Prospect Delineation

Prospect identification

A structural lead becomes a prospect once we determine that the major components of the hydrocarbon system have sufficient probabilities of success in contributing to an economic accumulation of hydrocarbons in the structure. In the table below are examples of some structural technical issues to consider when assessing the petroleum system relative to a structural lead. Many companies use a mixture of these issues to assess exploration risk, employing various numerical approaches.

Element	Factors Defining the Structural Prospect
Trap	• Trap integrity (certainty of dip closure; integrity of the closure throughout the evolution of the structure) • Area/volume under closure (present closure; structural closure during migration)
Seal	• Integrity of seals (continuity and integrity of top seal; integrity and capacity of fault seals)
Reservoir	• Storage capacity (structural degradation or enhancement effects) • Deliverability (structurally induced enhancement or degradation of permeability) • Anisotropy (flow anisotropy due to faults, folds, or fracture facies variability) • Heterogeneity (local enhancement or degradation; fault isolation or compartmentalization) • Pressures (structurally induced overpressures)
Source facies	• Maturation (structural overburden considerations; tectonic subsidence and uplift effects considered)
Expulsion/ migration	• Structural pathways (charge areas have been in effective communication with prospects) • Structural gathering areas (sufficient volumes of migrating hydrocarbons captured and diverted into appropriate pathways) • Timing (structural pathways effective throughout generation/migration event)

Assessing technical issues

The following data sources and techniques can help us assess some of these technical issues:

- Outcrop studies (interpretive analogs)
- Structure section balancing (structural geometry)
- Palinspastic restoration (migration pathways; paleostructure)
- Dipmeter and FMS analysis (structural geometry)
- Detailed seismic, 2-D and 3-D (structural geometry)
- Modeling studies (seismic; theoretical; physical; interpretive analogs)
- Hydrocarbon migration pathway analysis
- Fault-seal studies (trap integrity)
- Core analysis (fracture potential)
- Mechanical testing of rock (fracture potential)
- Petrofabric analysis
- Fracture analysis
- Curvature analysis (fracture potential)
- Mechanical testing (fracture potential)
- Special seismic processing and velocity analysis (e.g., prestack migration; amplitude vs. offset)

When a lead becomes a prospect

Once we determine that the risk in drilling for hydrocarbons on the structural anomaly is acceptable, the lead qualifies as a prospect. The next problem confronting the explorationist is picking an appropriate location on the prospect.

Location Selection

Crestal locations

Because the most important goal of exploration is economic success, locations are often chosen to provide maximum information on the economic viability of the prospect. Therefore, locations that assess the structurally highest point (crest) at the primary reservoir appear, at first, to be most attractive. However, other criteria in structural plays need to be recognized when determining prospect-assessing locations. This approach becomes critical as the structural complexity increases or the structural play concept becomes more sophisticated.

Off-crestal locations

Circumstances may occur in which it is more appropriate to select a location based on technical needs or data quality rather than optimizing the economic success of the first well. Generally, these locations provide greater certainty in evaluating data (e.g., clearly defined seismic reflectors to help define a crestal position). Other structural play concepts may require off-crestal positions to be viable.

Examples of circumstances in which it is desirable to drill a location other than the crest include the following:

- Certain fracture plays in the Rocky Mountain thrust belts of the U.S. and Canada may be sensitive to fore limb or back limb locations to provide the flow rates necessary to establish economic success.
- Tests in the offshore Netherlands have been drilled off crest and away from hinges to obtain an early assessment of matrix porosity in the reservoir.
- The position of the oil–water contact may be critical in defining the volume of hydrocarbons necessary for economic success.
- A nonoptimal acreage position may preclude access to the crestal location.
- Logistics problems (e.g., topography, environmental sensitivities) may preclude access to the crestal location.

Multiple-well locations

Well locations may be selected solely to provide information to support a second location. Such locations may be entirely off structure.

Well data programs and contingencies

There is often a tendency to plan well programs with economic success in mind. Unfortunately, an economic or technical failure is more likely, and we need to design data acquisition programs with options for that eventuality. In choosing a location and designing a well data program, we need to plan for possible failure by asking the following questions:

- Can this play be tested effectively with one well?
- What data do we need to establish a second location?
- What data do we need to determine whether to continue evaluating this play concept on this prospect?

Thrust Belt Example

Introduction

This example of structural exploration in the Laramide western Wyoming thrust belt in the late 1970s and early 1980s illustrates how the preceding tasks flow together and applies the techniques and approaches in Figure 20–4. The exploration process begins with an examination of the regional tectonic setting of the Wyoming thrust belt and gradually narrows to a study of structural features at the prospect level.

Tectonic setting

The figure below depicts the tectonic setting for the western U.S. relevant to Laramide plate tectonics. It shows where overthrusting took place, its overall geometry and vergence direction, and the interference with foreland deformation.

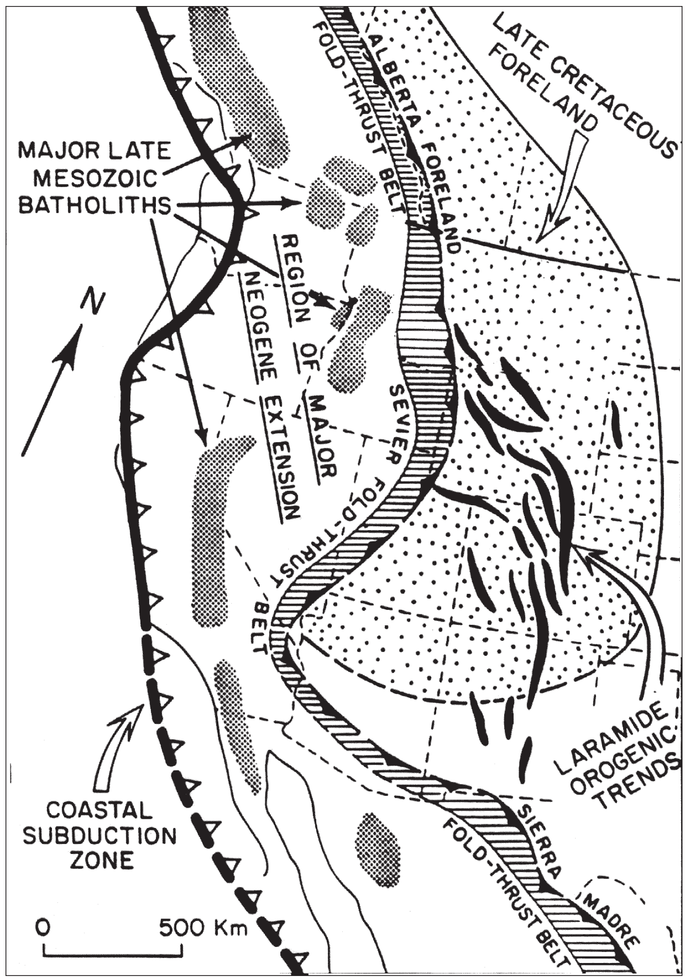


Figure 20–5. From Schwartz, 1982; courtesy Rocky Mountain Assoc. of Geologists.

Thrust Belt Example, continued

Structural domains

Structural domains within the Wyoming thrust belt were defined by the regional mapping of the U.S. Geological Survey (Rubey, 1973) and by interpreting satellite images such as the one shown in the figure below. Individual major thrust sheets were defined across the belt as well as their change in character along strike, thus defining domains on a large scale. Note that the small white rectangle in the center of the satellite image is the approximate area seen in the oblique aerial photograph in Figure 20–12.

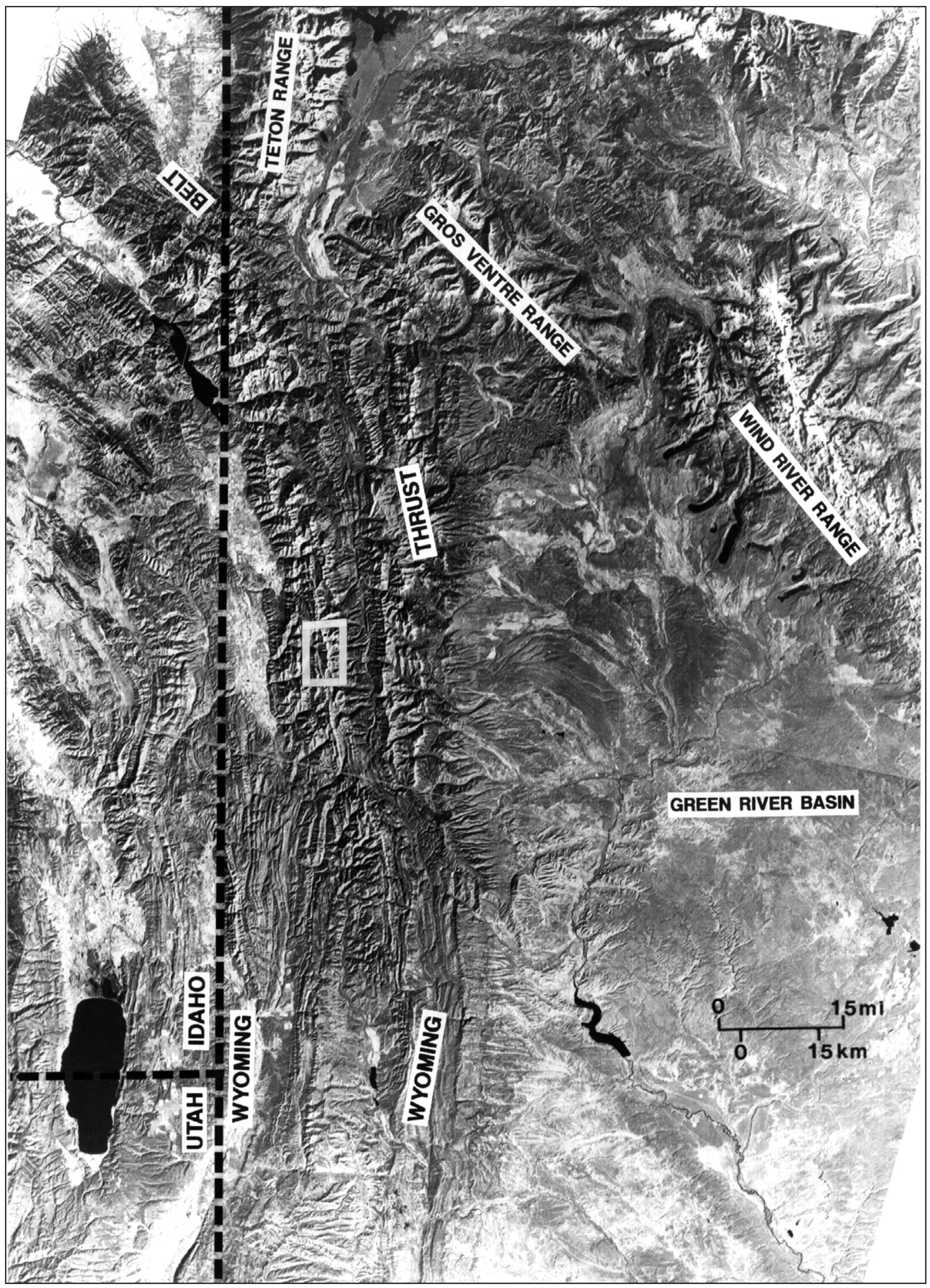


Figure 20–6.

Thrust Belt Example, continued

Prospective structural fairways

Within the structural domains, regional analysis of structural style and timing were integrated with other elements of the hydrocarbon system to define prospective fairways. The figure below covers approximately the same area as the preceding satellite image and shows the location of the major thrust sheets in the Wyoming thrust belt. Note that most of the oil and gas fields occur in the southern half of the Absaroka thrust sheet.

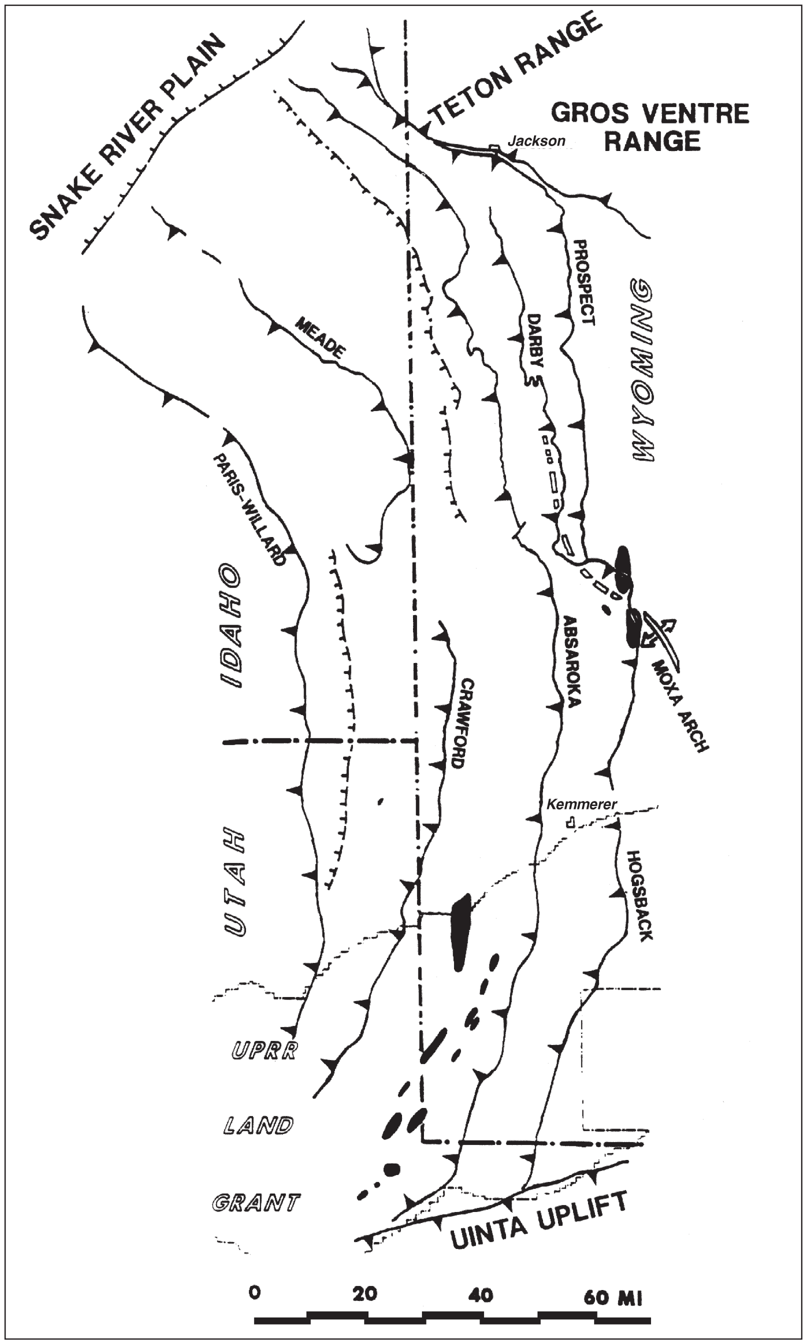


Figure 20–7. From Dixon, 1982; courtesy AAPG.

Thrust Belt Example, continued

Prospective structural fairways (continued)

The figure below is a contoured fault-plane map at two different scales for the Absaroka thrust, the major thrust that contains the producing fairway.

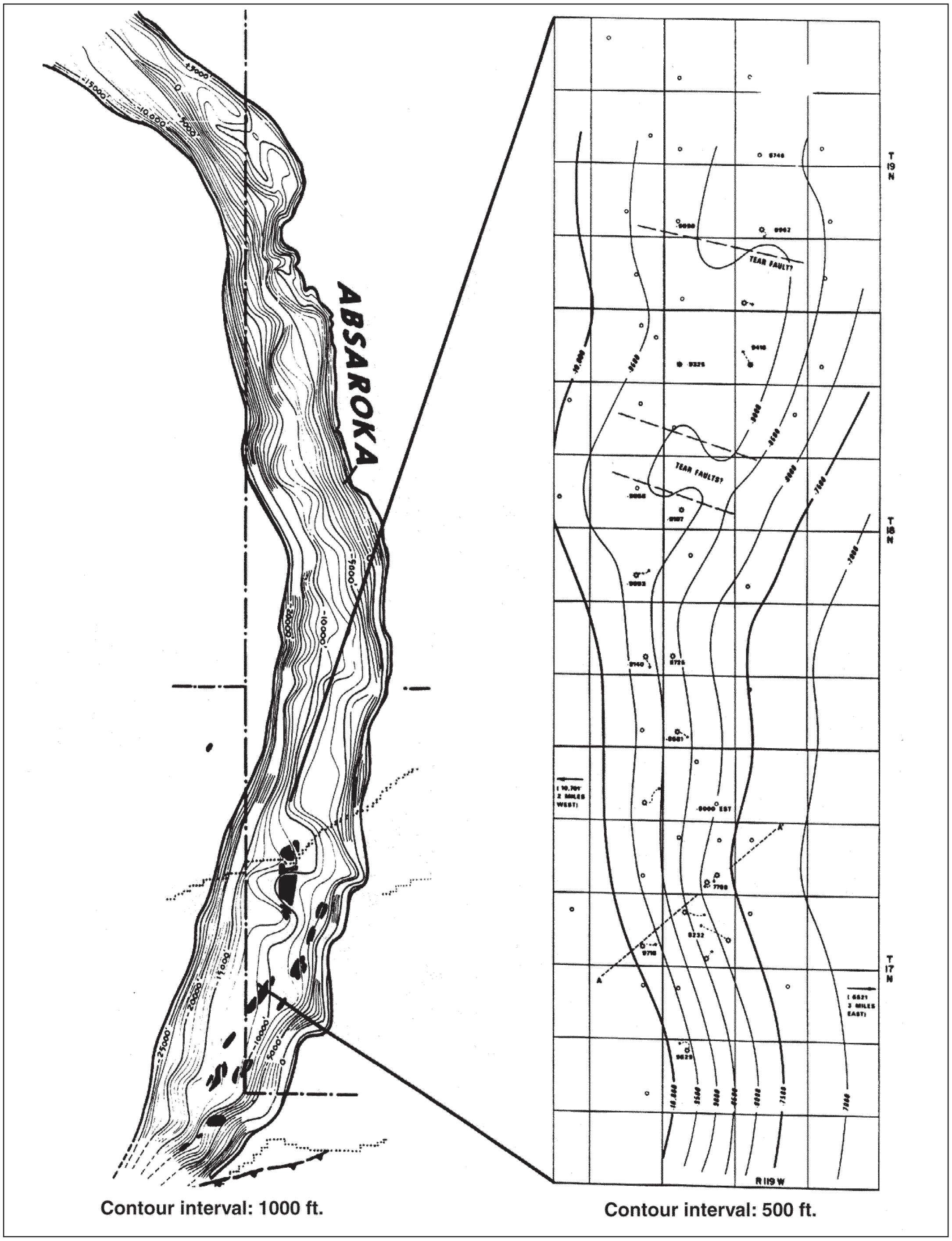


Figure 20–8. From Dixon, 1982, and Bishop, 1982; courtesy AAPG and Rocky Mountain Assoc. of Geologists, respectively.

Thrust Belt Example, continued

Structural lead

Detailed analysis of the fairway proceeded using surface and subsurface data. Examples of the data used are shown below and on the next few pages.

Figure 20–11 on the opposite page shows a cross section across the Whitney Canyon and Ryckman Creek producing structures in the upper plate of the Absaroka thrust.

The figure below shows an interpreted seismic line in the approximate location of Figure 20–11.

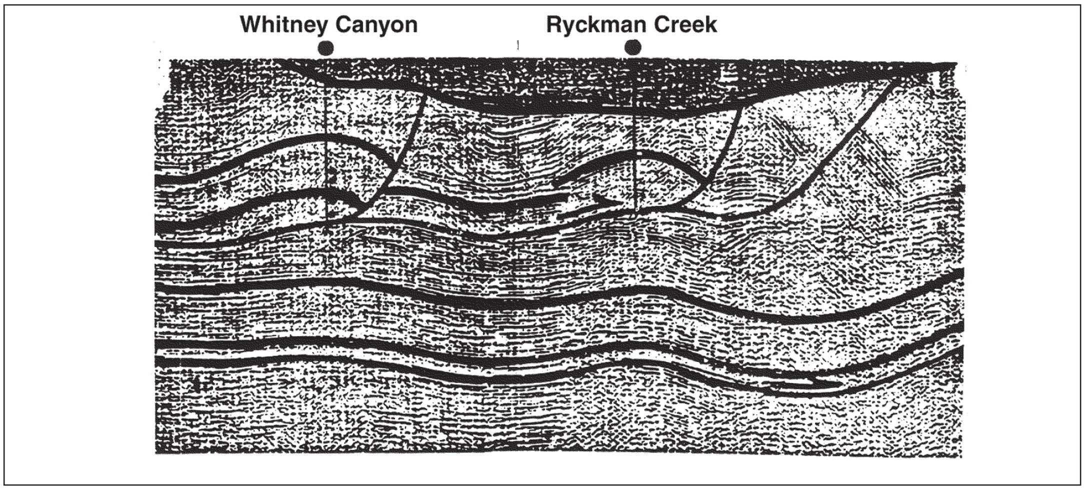


Figure 20–9.

The figure below shows restoration and balancing of a cross section through the Whitney Canyon and Ryckman Creek fields. Restoration and balancing help ensure that structures shown on cross sections are geometrically possible and geologically plausible.

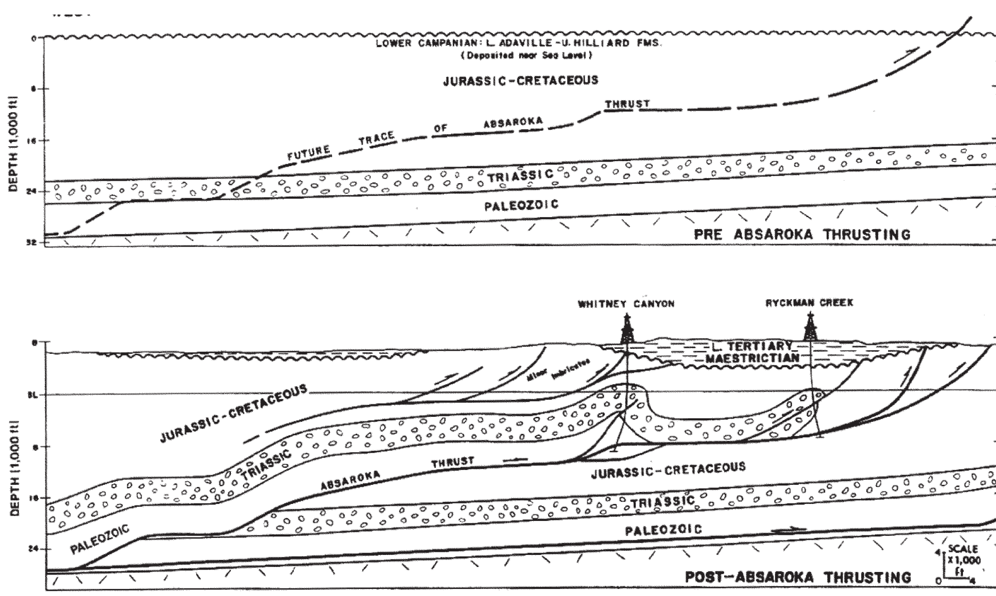


Figure 20–10. From Sieverding and Royse, 1993; courtesy AAPG.

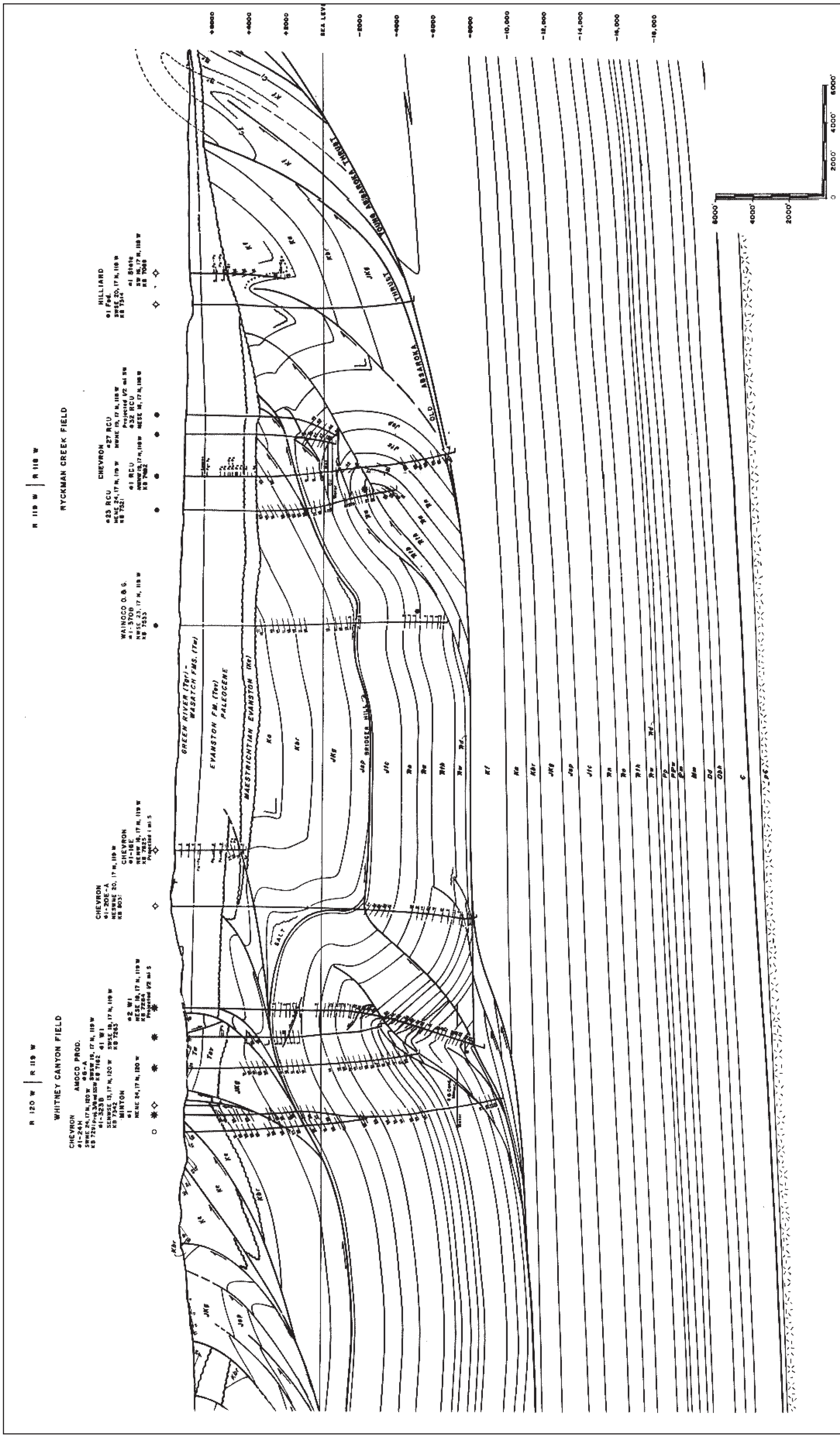


Figure 20–11. From Lamerson, 1982; courtesy Rocky Mountain Assoc. of Geologists.

Thrust Belt Example, continued

Structural lead (continued)

The oblique aerial photograph below shows structures in the upper plate of the Absaroka thrust in the central Wyoming thrust belt, updip and along strike of the producing structures in the same thrust sheet to the south. (See Figure 20–6 for the location.)

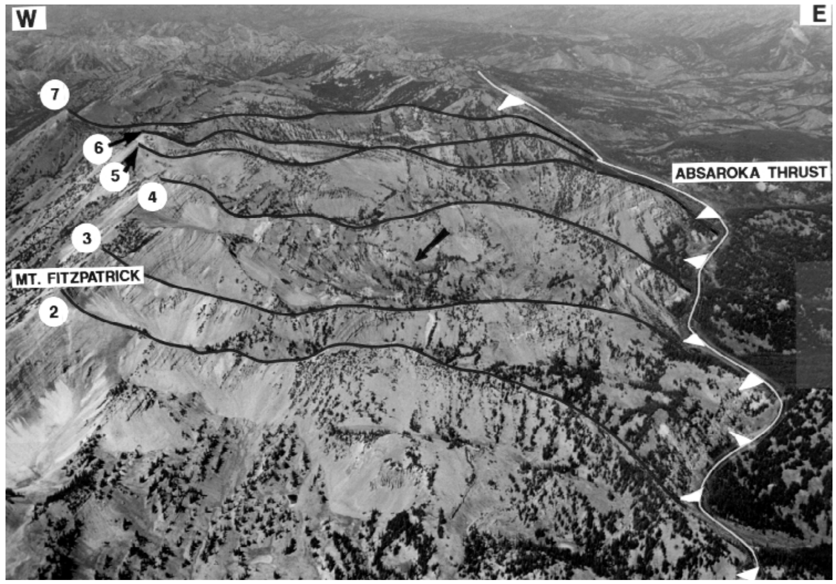


Figure 20–12.

The tectonic setting and stratigraphic section are similar to the producing trend; therefore, the deformation features of the exposed structures can be used as analogs for producing structures to the south. The numbered ridge lines in the photo provide a set of natural serial cross sections through the structures, detailed below.

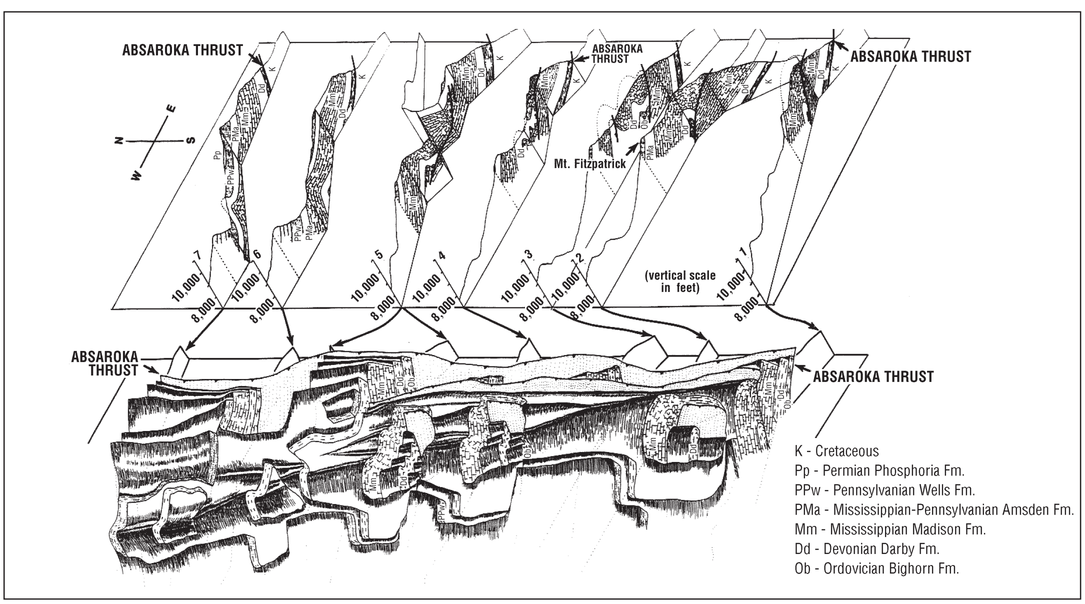


Figure 20–13.

Thrust Belt Example, continued

Structural lead (continued)

The photograph below shows structures in the upper plate of the Absaroka thrust fault on the south side of ridge line 4 in Figure 20–12. The white outcrops in the valley in the left foreground are tightly folded Ordovician Bighorn dolomite.

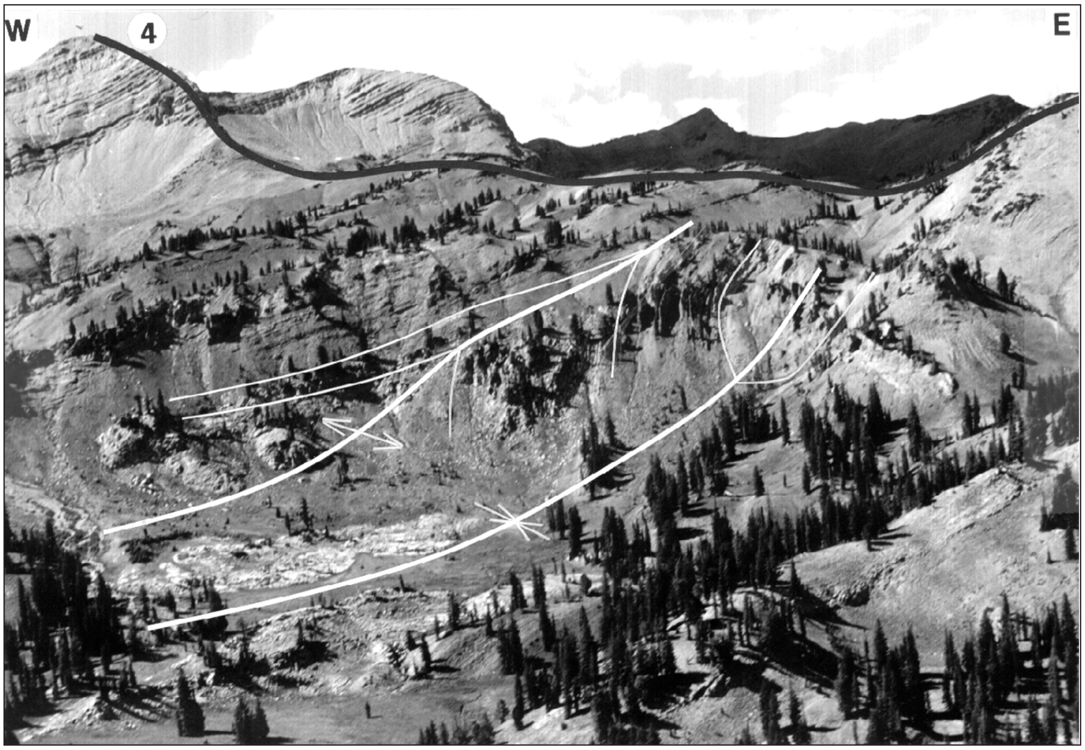


Figure 20–14.

Prospect and location

Once leads have been defined, detailed analyses of individual well locations must take place. The figure below shows an example of detailed structural mapping at the prospect level. It is a structural map on top of the Upper Triassic Nugget Sandstone, Ryckman Creek field area, Uinta County, Wyoming. Contour interval varies from 100 ft (30 m) near the crest of the structure to 500 ft (150 m) on the flanks. The dashed contours are the oil/water and gas/oil contacts.

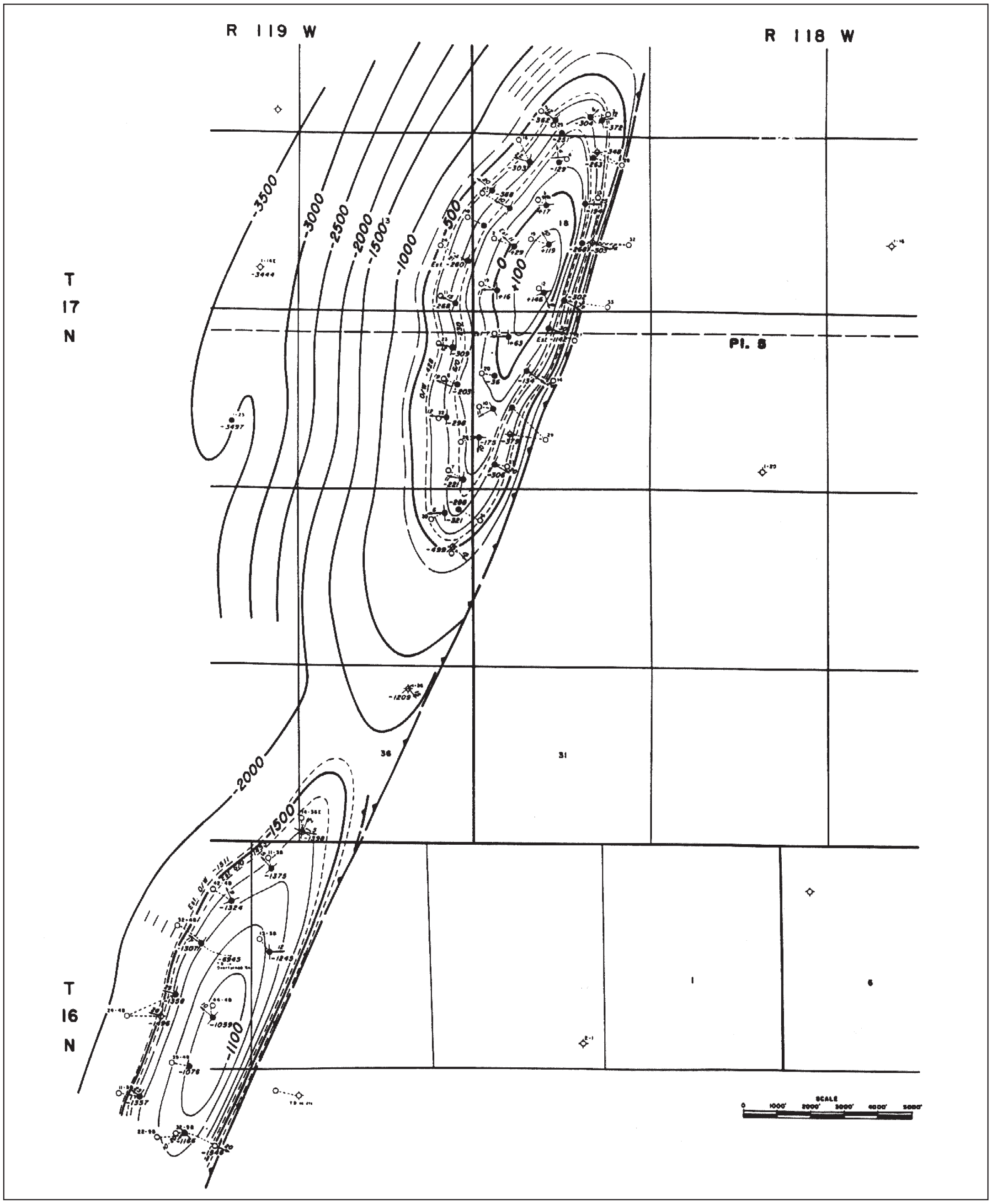


Figure 20–15. From Lamerson, 1982; courtesy Rocky Mountain Assoc. of Geologists.

Prospect and location (continued)

Physical models, such as those shown below, that display structures similar in shape to natural, prospect-scale, thrust-related structures can provide insight on the overall geometry of the prospect and the location of zones of high strain (high fracture density?) within the structure. These insights can be useful in determining optimal well locations.

These models were constructed of originally planar layers of limestone, sandstone, and granite. They were deformed in a pressure vessel at an effective overburden pressure of 15×10^3 psi (1×10^5 kPa). The top view is a photomicrograph of a model that simulates a thrust ramp. The bottom view simulates the hanging-wall geometry produced by movement along a series of bedding-parallel and ramp segments of a thrust fault.

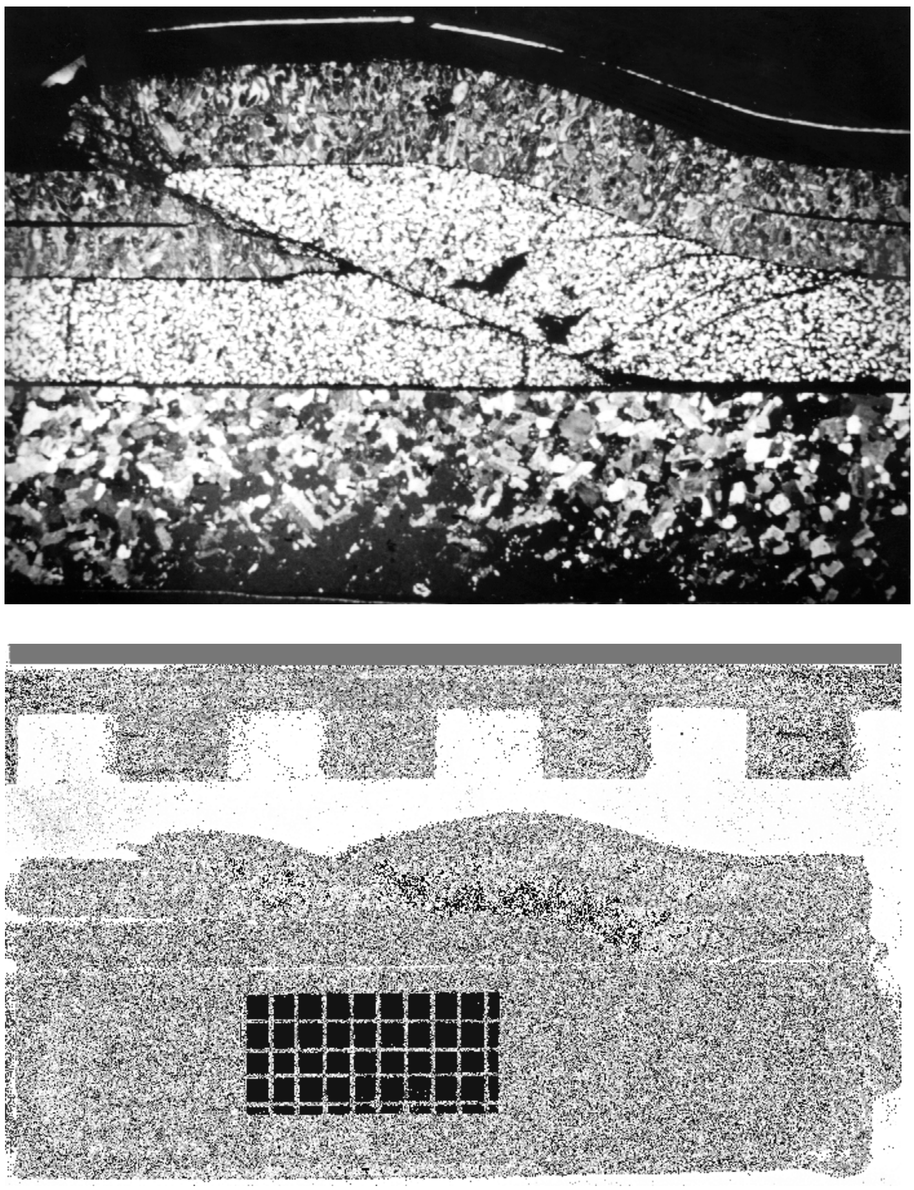


Figure 20–16. Published with permission of James Morse, Computational Geology.

Thrust Belt Example, continued

Prospect and location (continued)

Data on deformation mechanisms, such as fractures and how they affect reservoir properties, are obtained by integrating outcrop fracture data and laboratory estimates of fracture aperture. This integration allows for a direct calculation of fracture porosity and fracture permeability for the reservoir.

Examples of outcrop fracture-spacing data relevant to the carbonate section of Whitney Canyon field are shown below. The photograph shows fractures in the Ordovician Bighorn dolomite in outcrops in the valley seen in Figure 20–14. (Note the inch-scale measuring tape stretched across the center of Figure 20–17.)

Figure 20–17.

Thrust Belt Example, continued

Prospect and location (continued)

The outcrop sketch below is of folds in the Devonian Darby siltstone and Ordovician Bighorn dolomite from the same location as Figure 20–17. The numbers on the sketch represent fracture intensity values expressed as the average number of fractures encountered per foot of scanline measurement at various locations on the folds. All else being equal, higher fracture intensities should be associated with zones of higher fracture porosities and permeabilities. Maps of high fracture intensities can be used to locate optimum well locations and well trajectories in prospects.

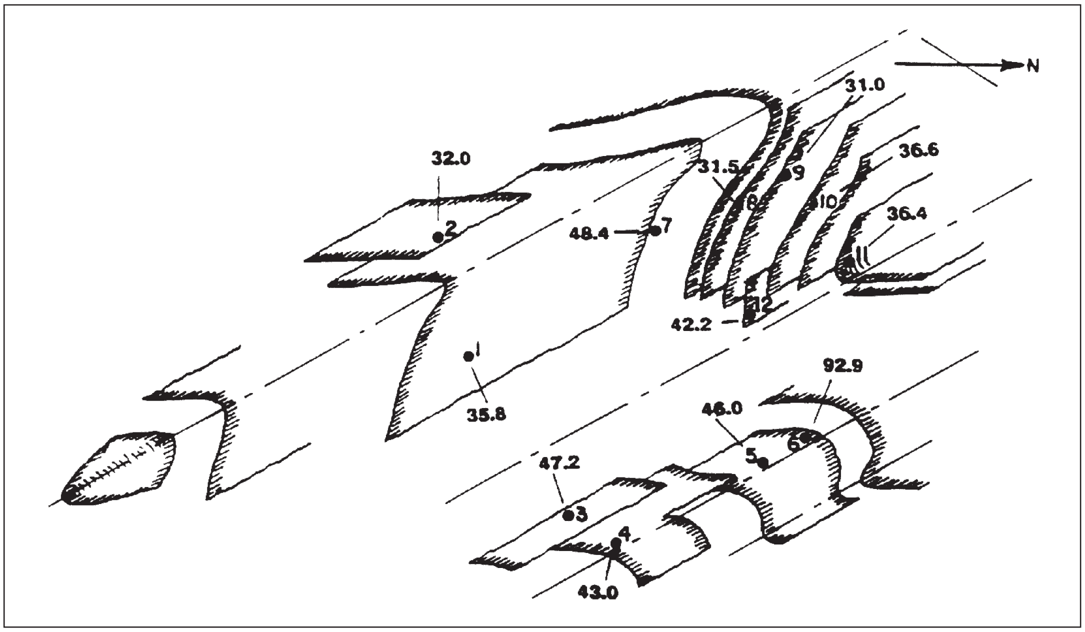


Figure 20–18. From Nelson and Serra, 1995; courtesy Journal of Canadian Petroleum Technology.

Summary

This thrust belt example has shown the structural exloration process and some of the data types, techniques, and approaches that can be used in exploring for a structural trap.

Section D

Project Planning: The One-Minute Structural Play for Managers

Introduction

This section discusses how we might shorten or streamline the general technical application process presented in Figure 20–4 by limiting ourselves to those structural techniques most relevant to the particular project or structural play of interest. This can be done by considering the following:

- The structural style with which we are dealing
- The maturity of the area or play
- The structural philosophy dominant within the exploration team or company

In general, we strive to minimize technical application cycle time to match our original goal as described in section A and thereby maintain our competitive advantage. Increased technical quality and reduced cycle time might require outsourcing and strategic alliances to meet our goals.

In this section

This section contains the following topics.

Data and Techniques That Delineate Structural Styles

What is a structural style?

Structural styles or structural families are associations of structures that often occur together due to a common origin. For example, major foreland thrust belts usually contain a mixture of listric reverse or decollement thrust faults, large asymmetric hangingwall folds, and late listric normal faults. These features are arranged to form an overall arcuate deformed belt. There is little or no involvement of mechanical basement in the deformation. Individual structures generally have good strike continuity and poor depth or dip continuity. Hence, in any newly discovered thrust belt, these same associations (thrust belt structural style) would be anticipated, modified somewhat by local geology. The concept of structural styles and their classification are given in Harding and Lowell (1979) and Lowell (1985).

Choosing techniques

If and when a structural style(s) is ascribed to an area, certain of the structural techniques become more important to perform than others. The list below displays those techniques (keyed to the numbers in Figure 20–4) deemed important for each major structural style.

Style	Very Important*
Thrust belts	5, 8, 10, 12
Wrench systems	1, 3, 11
Rifts and detached normal fault systems	2, 8, 10, 12, 15
Diapiric	2, 12
Foreland block folds	3, 6, 8
Basement warps and sags	2, 6, 8, 11

* Techniques 13–15 are important in all styles but in later stages of exploration.

Data and Techniques to Study Basins of Varying Maturity

Techniques to use

We limit or reduce the number of structural techniques applied by the inherent maturity of the basin or play. In general, those techniques involving data and data generation on a large or reconnaissance scale (left half, Figure 20–4) are most important to perform early in a frontier basin or play. More detailed analyses requiring more detailed data (right half, Figure 20–4) are appropriate only to more mature basins and development studies/plays.

These are depicted in the table below by a common basin/play maturity classification.

Maturity Level	Very Important*
Frontier	1, 2, 3, 7, reconnaisance 5
Emergent	4, 5, 7, 8 stratigraphic, 10
Established	6, 9, 11, 13, 14
Mature	6, 8 (rock properties), 9, 13, 15

*For number reference, see Figure 20–4.

How Different Structural Philosophies Govern Techniques

Introduction

There are several major philosophies or approaches to structural geology, and various university departments and E&P companies favor one or another in their courses and approaches to problem-solving. The major approaches can be grouped into four major categories:

- Global tectonics
- Structural styles
- Detailed geometric and/or kinematic studies
- Mechanical or dynamic approaches

The individual techniques presented in this section and highlighted in Figure 20–4 span the range of these categories. A complete E&P structural study, therefore, includes aspects of all four.

Different organizations; different philosophies

Exploration and production organizations usually display strength or focus in perhaps one or two of the above category areas or focus on different areas of the technologies timeline. For example: organizations that emphasize global tectonics (including basin analysis) and structural styles probably display particular strength in new ventures and effective concession acquisition, whereas those that emphasize mechanical structural approaches probably have great success in development geology. Those emphasizing detailed geometric analyses probably work more in the central portions of Figure 20–4 and effectively pick wildcat and first follow-up well locations.

Matching strength to strategy

Organizations should understand their strengths and areas of focus in their structural plays and supplement them in other areas by judiciously using complementary consultants, strategic alliances, and partnership agreements. Each player, then, brings the strength and focus necessary to conduct the effective structural play.

In this way, Figure 20–4 can be a tool for effective project planning when deciding which studies need to be done in-house, which ones should be done by various support organizations and partners, and when these studies should be initiated and completed.

Section E
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