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AREA BALANCE AND STRAIN IN AN EXTENSIONAL FAULT SYSTEM: STRATEGIES FOR IMPROVED OIL RECOVERY IN FRACTURED CHALK, GILBERTOWN FIELD, SOUTHWESTERN ALABAMA

Annual Report
March 1996 to March 1997

By
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Geological Survey of Alabama
Tuscaloosa, Alabama

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EXECUTIVE SUMMARY

Gilbertown Field, established in 1944, is the oldest oil field in Alabama and produces oil from fractured chalk of the Cretaceous Selma Group and sandstone of the Eutaw Formation. Nearly all of Gilbertown Field is still in primary recovery, although operators are considering a redevelopment program that includes waterflooding. The objective of this project is to analyze the geologic structure and burial history of Mesozoic and Tertiary strata in Gilbertown Field and adjacent areas in order to suggest ways in which oil recovery can be improved. The decline of oil production to marginally economic levels in recent years has made this type of analysis timely and practical. Key technical advancements being sought include understanding the relationship of strain to production in Gilbertown reservoirs, incorporation of synsedimentary growth factors into models of area balance, quantification of the relationship between requisite strain and bed curvature, determination of the timing of hydrocarbon generation, and identification of the avenues and mechanisms of fluid transport.

Structural maps and cross sections establish that the Gilbertown fault system defines part of a full graben and an associated horst that are interpreted to be detached at the base of the Jurassic Louann Salt. Sequential restoration of cross sections suggests that the fault system began forming as a half graben during the Jurassic. The Early Cretaceous was the major episode of structural growth and subsidence of the half graben. By the end of Early Cretaceous time, the growth rate of antithetic faults became effectively equal to that of synthetic faults. Thus, the half graben began collapsing, and the overall structural geometry of Upper Cretaceous and younger strata is that of a full graben. Cross sections and isopach maps of selected intervals demonstrate significant growth of the graben during Cretaceous time but do not show growth of mid-Tertiary strata. However, offset of Tertiary strata indicates late reactivation.

Analysis of burial history indicates that the subsidence history of Jurassic and Tertiary strata in the Gilbertown area is typical of extensional basins. Factoring out the tectonic component of subsidence suggests that more than half of the total effective subsidence in the Gilbertown area can be accounted for by sediment loading and compaction.

Geologic mapping of formations and fracture systems is adding significantly to knowledge of the geology of the Gilbertown area. Faults offset strata as young as Miocene, whereas Quaternary alluvial deposits cut across structures in the area. Fault gouge with Riedel shears was observed locally. Tertiary strata are jointed, and the joints tend to parallel straight river segments. Preliminary assessment of joint patterns reveals little relationship to fold and fault patterns, suggesting that the joints formed in a different stress field than the folds and faults. One possibility is that joints represent unloading structures that began forming after fault movement ceased.

Eutaw and Selma reservoirs are internally heterogeneous. The Eutaw Formation was divided into seven intervals that could be mapped throughout the Gilbertown area. Thickness of the intervals is fairly uniform, and facies changes within the intervals are expressed by variation of sandstone content. Stratigraphic and paleontologic evidence suggests that the Eutaw accumulated in transgressive shoreface and shelf environments. The Selma Group was divided into eight mappable intervals that were instrumental for locating faults. The Selma chalk is interpreted as a regionally extensive shelf deposit.

Conventional trapping mechanisms are effective in the Eutaw Formation, and oil is trapped in faulted anticlines and the horst. Core analyses and production data, however, indicate that the distribution of oil and water within the Eutaw is extremely heterogeneous, and in some wells, as many as seven pay zones are developed. Oil is produced in the Selma Group from faults and fractures constituting the Gilbertown fault system. Comparison of production patterns in the Eutaw Formation and Selma Group indicate that oil may have accumulated in the faults by leakage from the Eutaw Formation.

Three-dimensional computer visualization of the Gilbertown fault system and associated structures helps in the formulation of structural models and provides the straight-line cross sections required for area balancing. Preliminary balanced models have elucidated complications related to offset of regional elevations by salt withdrawal, as well as synsedimentary growth of fault systems. Area-depth plots indicate that synsedimentary growth is the most important variable affecting construction of balanced structural models. The basic equations of area balance have been modified to account for growth, and future efforts will include incorporation of growth factors to derive new equations for requisite strain.

Personnel at the Geological Survey of Alabama are developing an aggressive technology transfer program through contact with industry and researchers and through professional presentations. These contacts have proven valuable for data exchange and for ensuring continued development in Gilbertown Field. A focused-technology workshop is being planned that will be conducted at the Eastern Gulf Coast Regional Resource Center of the Petroleum Technology Transfer Council in Tuscaloosa. The Gilbertown project continues to move forward according to schedule. Efforts this coming quarter will focus on Surface Geology (Task 2), Petrology and Log Analysis (Task 3), Structural Modeling (Task 4), and Burial and Thermal Modeling (Task 5).

ABSTRACT

Gilbertown Field is the oldest oil field in Alabama and produces oil from chalk of the Upper Cretaceous Selma Group and from sandstone of the Eutaw Formation along the southern margin of the Gilbertown fault system. Most of the field has been in primary recovery since establishment, but production has declined to marginally economic levels. This investigation applies advanced geologic concepts designed to aid implementation of improved recovery programs.

The Gilbertown fault system is detached at the base of Jurassic salt. The fault system began forming as a half graben and evolved in to a full graben by the Late Cretaceous. Conventional trapping mechanisms are effective in Eutaw sandstone, whereas oil in Selma chalk is trapped in faults and fault-related fractures. Burial modeling establishes that the subsidence history of the Gilbertown area is typical of extensional basins and includes a major component of sediment loading and compaction. Surface mapping and fracture analysis indicate that faults offset strata as young as Miocene and that joints may be related to regional uplift postdating fault movement. Preliminary balanced structural models of the Gilbertown fault system indicate that synsedimentary growth factors need to be incorporated into the basic equations of area balance to model strain and predict fractures in Selma and Eutaw reservoirs.

INTRODUCTION

The first commercial production of oil in Alabama was from naturally fractured chalk of the Upper Cretaceous Selma Group in Gilbertown Field. Oil production has been reported from fractured chalk in the Gulf Coast basin since the 1920's, and Gilbertown Field was discovered in 1944. Many of the original fields, including Gilbertown, are still producing oil, although production has declined greatly (Scholle, 1977; Lowe and Carington, 1990). Even though production from Gilbertown has declined, the field is still largely in primary recovery, and the applicability of improved recovery strategies to the field has not been considered fully.

Virtually all oil production from chalk in the United States is from extensional faults associated with salt domes and the peripheral faults defining the margin of the Mississippi interior salt basin. Similarly, the major oil production from chalk in the North Sea basin of Europe is from extensional fault and fracture systems related to salt movement (Brown, 1987; Meling, 1993). Many fields in the eastern part of the Gulf Coast basin produce from multiple pools in sandstone and carbonate of Jurassic to Tertiary age and, in most of those fields, fractured chalk is considered a reservoir of secondary importance. As a result, natural fracturing has received only passing consideration in field management plans, which have focused mainly on production from the conventional sandstone and carbonate reservoirs. This is unfortunate, because much additional oil may be produced from untapped fractured chalk in existing fields. Furthermore, fracturing may have a strong influence on the distribution and producibility of oil in traditional sandstone and carbonate reservoirs and should thus be considered when implementing plans for improved oil recovery. Indeed, as production from domestic oil fields continues to decline, it is imperative that recovery efficiency be optimized and that unconventional opportunities be pursued to avoid premature abandonment of existing fields.

For this reason, the Geological Survey of Alabama has undertaken an intensive multidisciplinary investigation of the impact of fracturing on the distribution and producibility of oil from extensional fault systems in Gilbertown Field and adjacent areas. This research project focuses on natural fracturing in the Selma chalk as well as in conventional sandstone reservoirs of the underlying Eutaw Formation. This is a 3-year project that is designed to develop and apply advanced technical concepts in coordinated geoscience and engineering research.

Central to this research is the refinement and application of area balancing techniques to extensional structures in the Gilbertown area. These emerging, innovative techniques have the potential to constrain structural geometry and kinematics, quantify layer-parallel strain, and predict the distribution of fractures (Epard and Groshong, 1993; Groshong, 1994). As such, area balancing has immediate applications to developing strategies to improve oil recovery from fractured reservoirs. However, these techniques are still largely in the theoretical and experimental domains and therefore have yet to be applied rigorously to natural and practical settings. Our goal is to demonstrate comprehensively the utility of area balancing techniques in designing improved recovery programs for fractured oil reservoirs. In order to attain this goal, a coordinated multidisciplinary approach is required that synthesizes geologic, geophysical, and engineering data.

Gilbertown Field

Gilbertown Field occupies approximately 18 square miles in southern Choctaw County and extends along the length of the Gilbertown fault system (fig. 1). In the early days of Gilbertown, Hunt Oil Company owned the western part of the field, and Carter Oil Company owned the eastern part. The discovery well, drilled by Hunt Oil Company, is the A. R. Jackson no. 1 well. It was the first commercial oil well drilled in Alabama and initially produced approximately 30 barrels of 19.6° gravity oil per day at a depth of 2,575 to 2,585 feet from fractured chalk of the Selma Group. According to Toulmin and others (1951), the well was drilled on the basis of seismic surveying. The first well drilled by Carter Oil Company was the Sam Alman no. 1, which was completed in sandstone of the Eutaw Formation at a depth of 3,336 to 3,348 feet in 1945. The Alman well was reportedly sited on the basis of surface investigations (Toulmin and others, 1951). Most recent development in Gilbertown Field was carried out by Belden and Blake Corporation, who operated the field from 1976 to 1991. Since 1991, wells in Gilbertown have changed hands several times, and Union Pacific Resources, Incorporated is now principal operator. Union Pacific is considering the possibility of waterflooding in the Eutaw Formation, and other operators are considering drilling new wells in the Eutaw Formation and in the Selma Group.

To date, 212 wells have been drilled in Gilbertown Field. Of these, 101 wells have been completed in the Eutaw Formation, and 40 have been completed in the Selma Group. Fifty dry wells have been drilled, and 21 wells are used for disposal of salt water, which is produced in volume. Most of the salt water disposal wells were originally completed as oil wells in the Eutaw Formation and have since been recompleted for deep injection of produced formation water into the Tuscaloosa Group. Only six Selma wells have been converted for disposal of produced water.

The dominant hydrocarbon trapping mechanism in Gilbertown Field is fault closure, and normal faults with variable displacement are distributed sporadically in Eutaw and Selma reservoirs throughout the field (Bolin and others, 1989). Selma chalk is productive only in the western part of the field, whereas production from the Eutaw Formation is dispersed throughout the field (fig. 2). Early investigators identified three pools in Gilbertown Field: the lower Eutaw, upper Eutaw, and the Selma (Braunstein, 1953). The lower Eutaw pool is in a series of quartzose sandstone units with high resistivity and strongly negative spontaneous potential. The upper Eutaw, by comparison, is developed in glauconitic sandstone with low resistivity and weakly negative spontaneous potential. During the 1970's, producers recognized that the Eutaw comprises a multitude of low-resistivity, low-contrast sandstone lenses and may produce from as many as seven pools (Charles Haynes, personal communication, 1996). Porosity in Eutaw sandstone is typically 15 to 33 percent, and permeability ranges from 1 to 500 millidarcies; the pay column is generally less than 25 feet thick, and oil saturation is commonly 10 to 30 percent.

Selma production is strictly from faulted and fractured chalk, and productive intervals can be distinguished in many well logs by high resistivity and negative spontaneous potential (fig. 3). Productive zones in the Selma are as much as 150 feet thick and have exceptional effective fracture porosity, which is locally as high as 30 percent (Braunstein, 1953); estimates of permeability, oil saturation, and water saturation are not available. In most wells productive zones in the Selma are 400 to 700 feet above the Eutaw Formation. Even so, Selma and Eutaw production are mutually exclusive. Only one well has ever been completed in both formations.

Production in Gilbertown Field is by primary water drive, and waterflooding has been attempted only in the East Gilbertown Eutaw Unit and in the Gilbertown (Eutaw Sand) Unit (fig. 2). Oil and water are the principal fluids produced from the three pools in Gilbertown Field, and gas production is minimal. Cumulative oil production is now approaching 14 million barrels; 11.7 million have been produced from the Eutaw, and 2.1 million have been produced from the Selma. Oil production in Gilbertown reached a peak of 864,000 barrels in 1951 and has since declined markedly (fig. 4). In 1994, total oil production was 64,000 barrels and, of that, less than 1,000 barrels were from the Selma. In 1995 and 1996, total oil production was 36,000 and 29,000 barrels, respectively, and no oil was produced from the Selma. Gas production from Gilbertown Field is minimal and has never exceeded 700 thousand cubic feet in a single year. By contrast, a large amount of water is produced from the field, but data are not available from the first few decades of production. Peak recorded water production was in 1985 when 10.3 million barrels were produced.

The decline of oil production to marginally economic levels in Gilbertown Field makes assessment of improved recovery operations timely and practical. Detailed structural modeling is necessary to determine the nature and distribution of faults and fractures and, hence, what methods can be applied most effectively to Selma and Eutaw reservoirs. The following sections describe the concepts of area balance and strain in extensional structures and discuss how these concepts can be used to help design improved oil recovery strategies for Gilbertown and beyond.

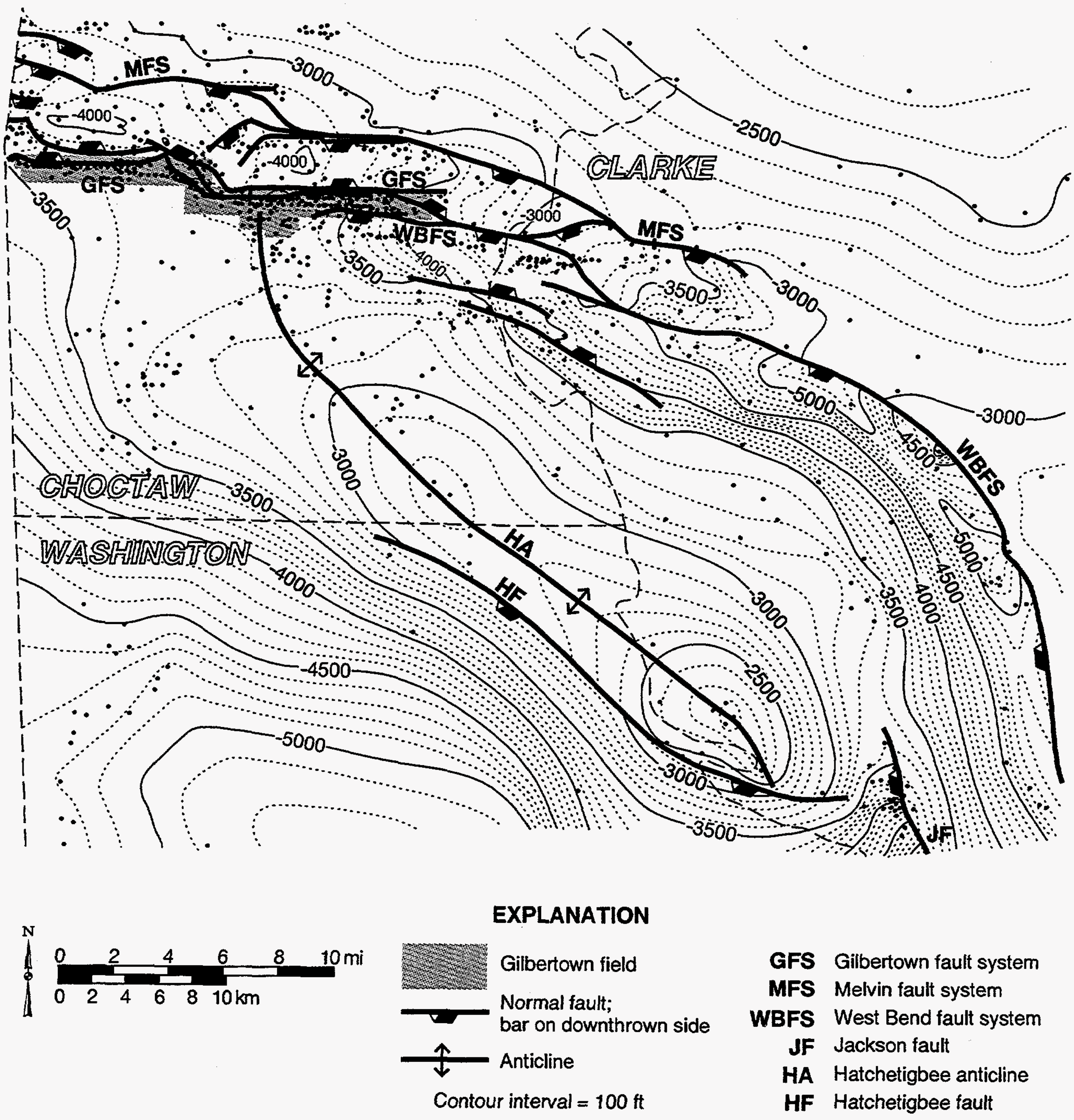

Figure 1.--Structural contour map of the top of the Eutaw Formation showing the relationship of Gilbertown Field to the Gilbertown, Melvin, and West Bend fault systems and the Hatchetigbee anticline.

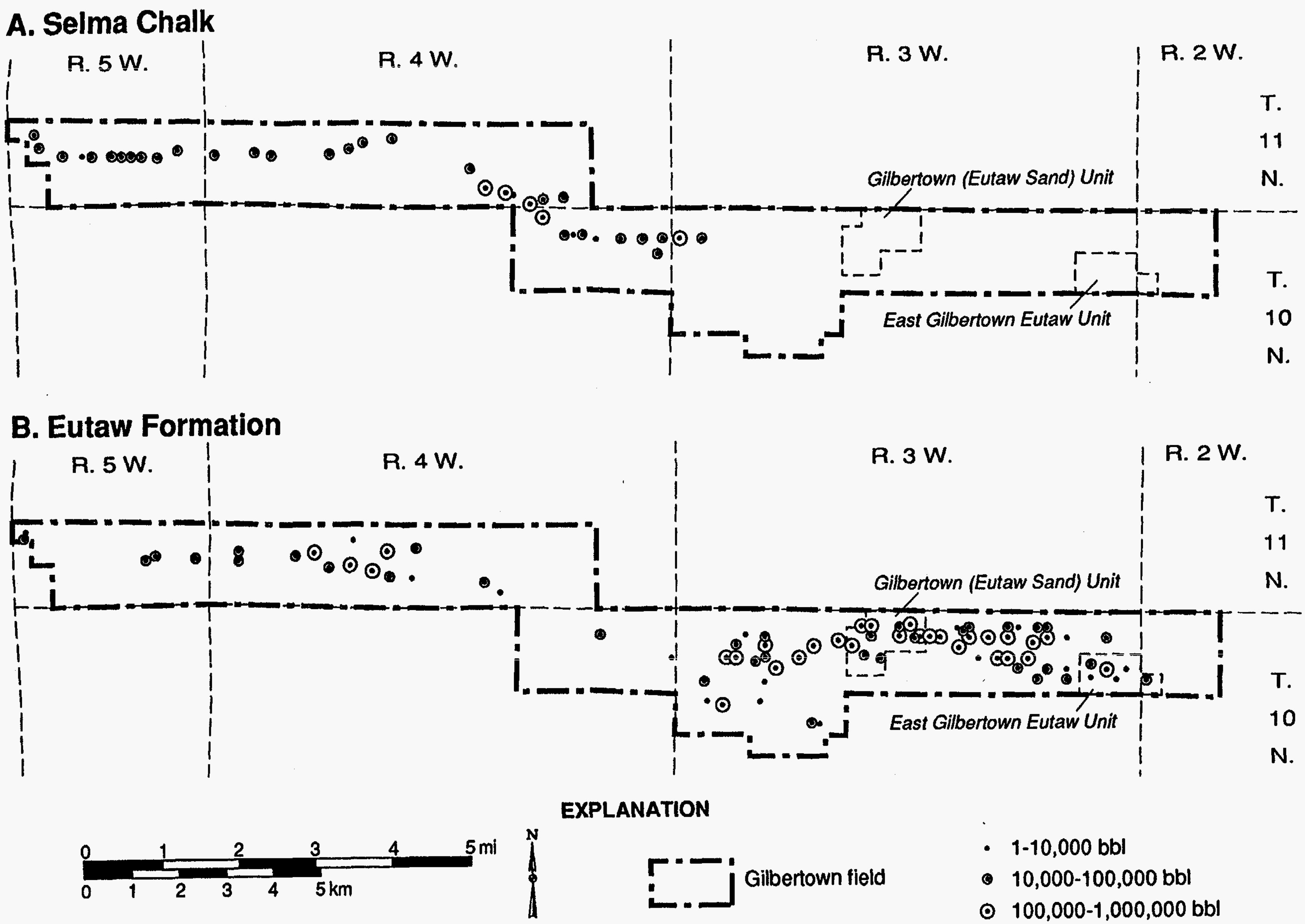

Figure 2.--Map of cumulative oil production of wells producing from the Selma chalk and Eutaw Formation, Gilbertown Field.

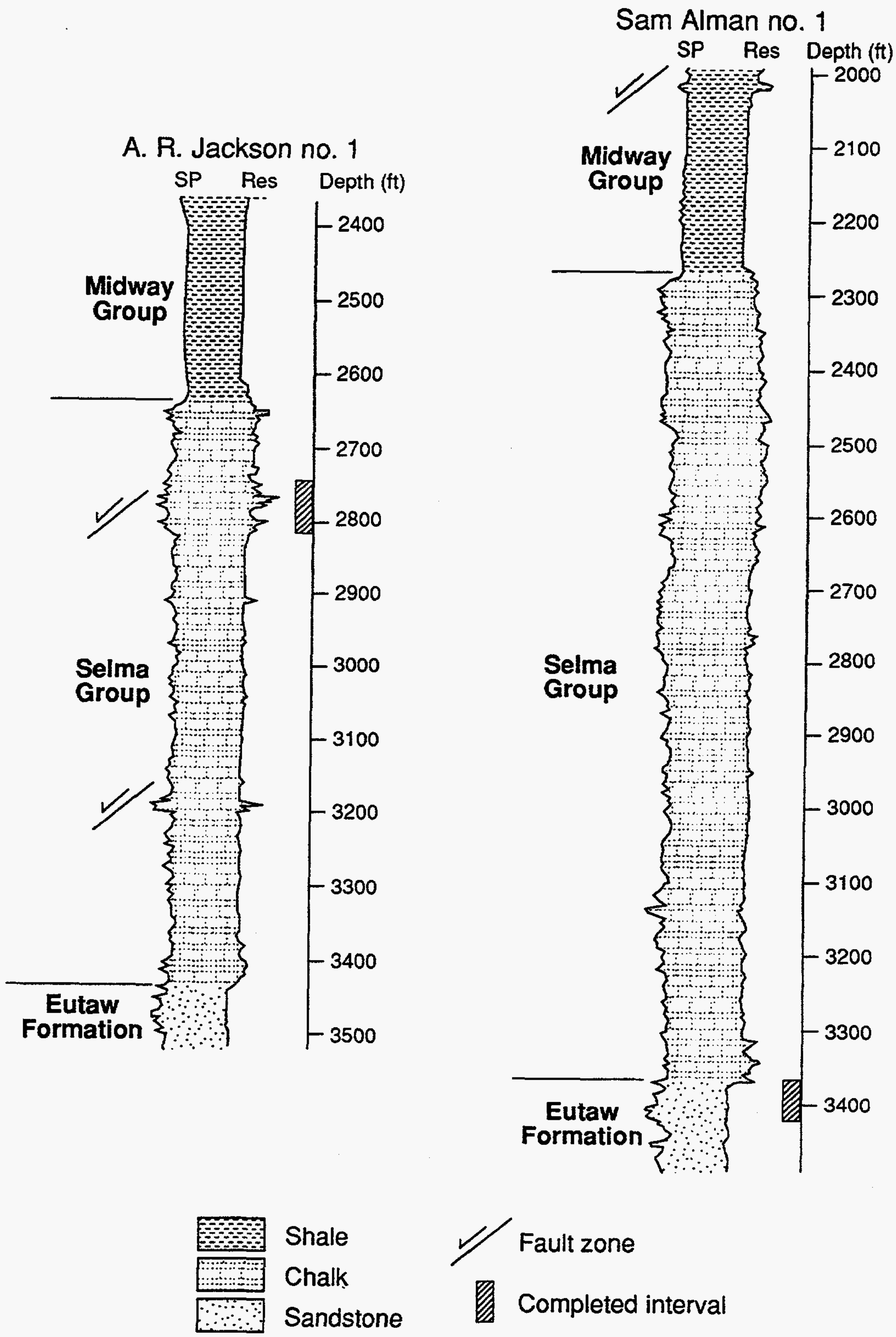

Figure 3.--Selected well logs showing characteristics of Selma and Eutaw reservoirs in Gilbertown field (modified from Braunstein, 1953).

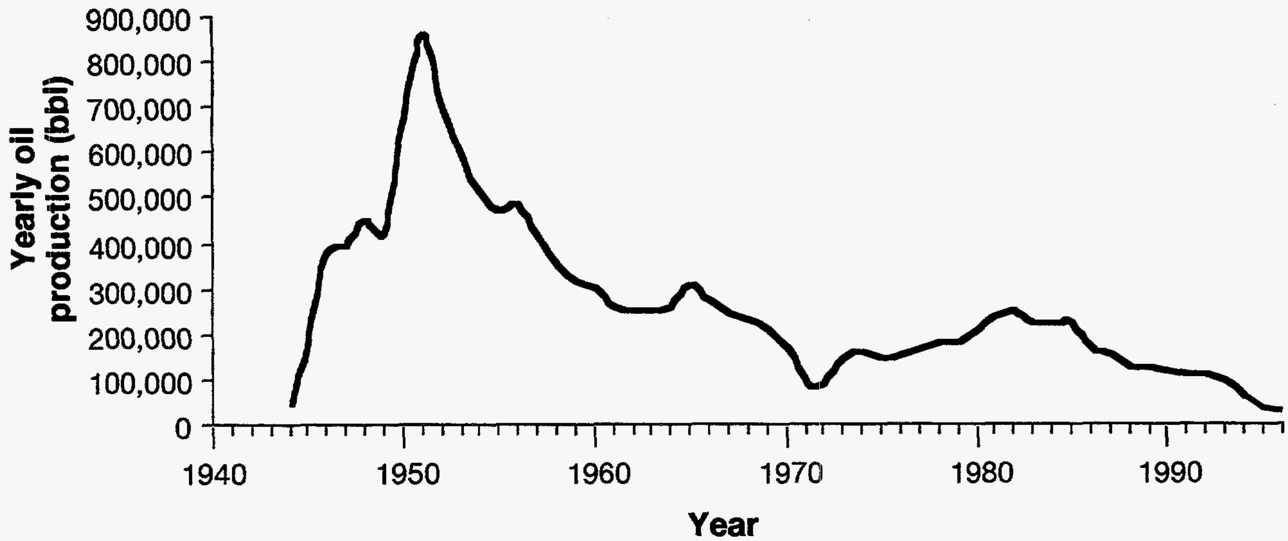

Figure 4.--Production history of Gilbertown Field showing major decline of oil production.

Area Balance and Strain in Extensional Structures

The geometry of extensional and compressional detachment structures can be quantified using area balancing techniques (fig. 5). Area balancing provides a means of constraining structural cross sections, because layer-parallel transport and the position of the basal detachment can be calculated (Groshong, 1990, 1994; Epard and Groshong, 1993). Area balancing is, moreover, superior to commonly used length balancing techniques (Dahlstrom, 1969; Davison, 1986; Keller, 1990) because layer-parallel strain can be quantified (Groshong, 1994; Groshong and Epard, 1994). To employ these techniques, only basic stratigraphic data are required, preferably from several marker beds.

Area-depth relationships were first proposed for compressional structures by Chamberlin (1910) but were not applied to extensional structures until the study of Hansen (1965). Area-strain relationships have been developed more recently and have been considered mainly in the context of sedimentary basin modeling (de Charpal and others, 1978; McKenzie, 1978). Until recently, however, area-depth-strain relationships were applied only to specific structural models that require basic assumptions about kinematic and rheological behavior that may be untestable or even erroneous when applied to a given set of structures (Groshong, 1994). Thus, the newly developed area balancing techniques developed by Groshong and Epard (1994) and Groshong (1994) offer a great advantage when analyzing area-depth-strain relationships, because they make no assumptions about rheology and kinematics and can be applied readily using basic measurements from geologic cross sections.

Two fundamental assumptions are used when area balancing cross sections. The first is that the cross-sectional area of a body of rock remains constant during deformation; this is the primary tenet of area balance originally put forth by Chamberlin (1910). The second assumption, which applies specifically to detached structures like those in the Gilbertown area, is that the structure must terminate downward at a basal detachment.

If the cross-sectional area of a structure is constant, then the area displaced above the basal detachment is equal to the area uplifted or downdropped relative to the original level, termed regional, so that:

$$S = DH, \qquad (1)$$

where S is displaced area, D is displacement distance of the block on the lower detachment, and H is depth to detachment. The area downdropped below regional in extensional structures is termed lost area. The sign convention is that displacement distance and the displaced area are negative in extensional structures and are positive in compressional structures. The cross section must obey the area-depth relationship at every structural level given by the depth, h, to a common reference level. Plotted on an area-depth graph (fig. 5), the relationship between structural levels is the straight line,

$$S = Dh + S_a, \qquad (2)$$

where S_a is the area intercept of the line. The slope of this line is the displacement distance on the lower

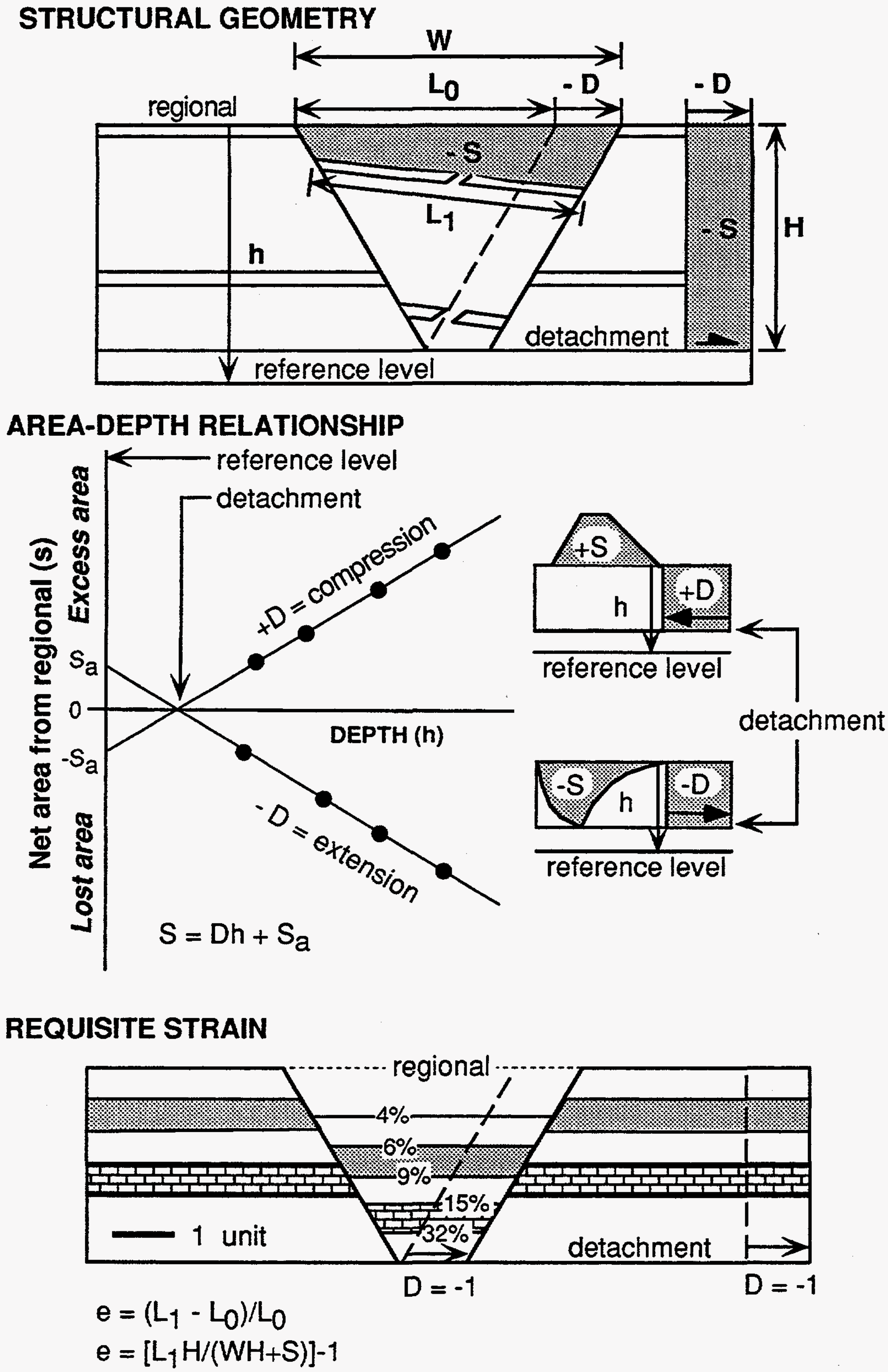

Figure 5.--Structural diagrams showing area-depth-strain relationships in extensional structures (modified from Groshong, 1994; Pashin and others, 1995).

detachment, and the detachment itself is located where lost or excess area projects to zero; the detachment may be above or below the arbitrary reference level. In a typical example, the displaced areas from multiple stratigraphic markers are plotted to define the area-depth line from which the displacement and depth to detachment are determined (fig. 5).

Beds within graben and half-graben systems typically undergo layer-parallel stretching strain, e, which can be quantified using area balancing techniques. Although some layer parallel strain can be ductile, the greatest proportion of the strain is by brittle faulting and associated fracturing. The layer-parallel strain is defined by the equation,

$$e = (L_1 - L_0)/L_0, \qquad (3)$$

where the original bed length is L_0 and the observed bed length is L_1. The original bed length can be determined from area-depth relationships by

$$L_0 = W + D, \qquad (4)$$

where W is the width of the graben at regional and D is extensional displacement which, according to the sign convention, is expressed as a negative value. A strain equation that can be used with measurements from geologic cross sections can be derived by solving (1) for D and substituting the result into (4) and then into (3). This transformation gives

$$e = [L_1H/(WH+S)]-1 \qquad (5)$$

and is termed the requisite strain (Groshong and Epard, 1994). The term requisite strain is used because the derived value is the homogeneous strain required for the observed structural geometry to be area balanced.

Area balancing techniques have yet to be applied rigorously to hydrocarbon reservoirs. Thus far, these methods have been applied to well-constrained structures to validate the basic concepts (Groshong, 1994). Preliminary tests of the methodology in producing reservoirs have been made for coalbed methane fields in northern Alabama (Wang and others, 1993; Pashin and others, 1995). However, these tests have focused more on structural geometry than on the distribution of strain.

The fractured chalk of Gilbertown Field is an ideal place to test the importance of area-depth-strain relationships in the development and implementation of strategies for improved oil recovery from chalk and associated sandstone reservoirs. Abundant subsurface control provided by more than 50 years of drilling and seismic exploration enables tight constraint of reservoir geometry as well as reservoir properties. Additionally, the long production history of Gilbertown Field enables a thorough understanding of the relationship of oil and water production to structure and will aid greatly in predicting the effects of improved recovery strategies, such as infill drilling, horizontal drilling, waterflooding, and gas injection.

Determination and validation of extensional structural geometry through area balancing has broad application to fractured chalk and associated sandstone reservoirs. Indeed, all major chalk reservoirs in the United States and Europe are developed in extensional salt basins (Scholle, 1977). Furthermore, understanding detachment geometry is critical, because fracturing and second-order faulting in detached extensional structures is developed in large part by transport of the hanging-wall block through buried fault bends (McClay and Scott, 1991; Withjack and others, 1995). Structural analysis of Eutaw reservoirs will also be valuable because, although considerable research has been perfomed on reservoir heterogeneity in sandstone (Sharma and others, 1990a, b; Pashin and others, 1991; Kugler and others, 1994), investigators have not fully considered the effect of natural fractures on reservoir performance.

To balance structures in the Gulf Coast basin, however, the basic methodology requires further development. Area balancing techniques have yet to be applied to natural salt structures, which may present complications due to the typical regional elevation changes caused by salt movement. Furthermore, synsedimentary growth affects the slope of the line represented by equation (1), so a growth factor needs to be incorporated into the equation to derive accurate values of D.

Several investigators have considered the effect of stress in fractured chalk on fracturing and fluid flow (Teufel and Farrell, 1990; Teufel and Warpinski, 1990; Peterson and others, 1992), but the distribution of strain has yet to be examined. Examining strain will be a significant contribution, because natural fractures are a direct expression of strain and can indicate ancient and modern stress fields (Griggs and Handin, 1960; Stearns and Friedman, 1972; Watts, 1983). An important aspect of area balancing is that requisite strain can be calculated at multiple stratigraphic levels. Furthermore, if a dense network of cross sections is constructed, the distribution of strain can be mapped at each level. As stated, the requisite strain calculation (equations 4 and 5) models only homogeneous strain between fault planes (fig. 5). However, curvature of beds between the fault planes can be calculated to determine how strain is distributed between faults (Narr, 1991; Lisle, 1994). If the relative distribution of strain is known, then requisite strain can be quantified precisely.

An enhanced knowledge of fracture architecture and strain distribution has immediate applications to the development and execution of improved oil recovery programs. For example, sites of exceptional strain can be identified that may contain untapped oil and can thus be prospective for infill drilling and horizontal drilling. Indeed, horizontal drilling has exceptional potential to increase oil recovery from fractured reservoirs (Selvig, 1991; McDonald, 1993). Additionally, understanding structural geometry and the distribution of strain can provide important information regarding the feasibility of infill, waterflood, and gas injection efforts. This is particularly critical in fractured chalk, where primary production and waterflooding can induce formation damage (Hermansson, 1990; Teufel, 1991, 1992). Recompleting wells in chalk may also present difficulties. For example, Simon and others (1982) indicated that oil-based drilling mud and fracture fluids help ensure integrity of fractured chalk reservoirs in the North Sea basin.

METHODS

This project employs an interdisciplinary approach that combines basic geologic methods, petrologic and geophysical methods, advanced structural modeling, subsidence and thermal modeling, and production analysis. This approach is establishing the importance of area balancing for understanding the distribution of strain, stress, and fractures in extensional fault systems and is further establishing how these factors determine the distribution and producibility of oil and associated fluids. With this increased understanding, the best decisions can be made regarding which technologies, such as waterflooding, gas injection, recompletion, infill drilling, and horizontal drilling, can be applied to improve oil recovery in fractured reservoirs in extensional terranes, thereby facilitating efficient management of oil fields in an economically sound and environmentally prudent manner.

Task 1: Subsurface Geology

More than 700 geophysical logs from the Gilbertown area were correlated to identify structurally significant stratigraphic markers and to identify faults. Markers in Jurassic through Tertiary strata were picked using resistivity and spontaneous potential logs. Faults were identified and vertical separations were quantified on the basis of missing section. Well locations, kelly bushings, depths of log picks, and vertical separations of faults were tabulated in a spreadsheet that was used to calculate the elevation of each marker and fault and the thickness of stratigraphic intervals between markers.

After logs were picked and elevations were calculated, a series of seven structural cross sections traversing the Gilbertown fault system and adjacent parts of the Hatchetigbee anticline was constructed. These cross sections are all perpendicular to the major fault traces and are designed to provide the best possible structural interpretation that can be used for area balancing. Well data were projected to straight lines of cross section by simple distance-depth interpolation. Detailed stratigraphic cross sections were also made to determine the internal stratigraphy of the Selma Group and the Eutaw Formation. A localized structural cross section showing geophysical log signatures was made in the western part of Gilbertown Field that demonstrates the diagnosis of faults in the Selma Group, as well as the effect of faulting on well-log properties. Three stratigraphic well-log cross sections were also made of the Eutaw Formation in the eastern part of the field. These cross sections not only establish correlations and the distribution of productive pools, but demonstrate the extreme depositional heterogeneity of Eutaw reservoirs.

Structural contour maps were made showing the elevation of various stratigraphic markers. One regional map was made of the top of the Eutaw Formation. In addition, maps were made showing the configuration of all Jurassic through Tertiary stratigraphic markers in Gilbertown field and in adjacent areas; selected maps are included in this report. Using fault-cut information, faults were correlated among wells, and contour maps of fault surfaces were made. These maps aided greatly in constraining the structural contour maps because they show precisely the attitude, geometry, and horizontal separation of the faults in the reservoir intervals. In all, development of structural cross sections and maps was an iterative process in which each step of construction led to refinements.

In addition to structural contour maps, isopach maps were made of key marker-bound intervals in the Gilbertown area. These maps show the thickness of units ranging in age from Jurassic to Tertiary. Only thickness calculations from intervals lacking faults were used to generate these maps. The isopach maps help verify and quantify syndepositional growth of the Gilbertown fault system and the Hatchetigbee anticline and show how subsidence was distributed through time in plan view. After the maps were completed, rigid-body restorations were made of selected cross sections to characterize the structural evolution of the Gilbertown area.

To study stratigraphy and facies variations in the Eutaw Formation of Gilbertown Field, wells were correlated and five geologic cross sections were constructed using SP logs and a datum at the top of the Eutaw. This part of the investigation focused on the eastern half of Gilbertown field, where waterflooding of the Eutaw Formation is being considered. Two cross sections extend west to east, and three extend north to south. Perforated and producing zones were marked on a set of cross sections to indicate productive intervals in the Eutaw and thus to determine their distribution within the formation. Results of core analyses and core descriptions also were plotted on cross sections.

Cores from 22 wells in Gilbertown Field were suitable for study of the Eutaw Formation and the Selma Group. Each core was described with the aid of a binocular microscope. No continuous core is available. Only representative core samples from 1- or 10-foot intervals or sidewall cores could be used. Lithologic core logs were drawn for wells with samples representing a significant part of the Eutaw Formation. These core logs were then compared with a complete electric log of the Eutaw Formation to provide a composite core description.

Task 2: Surface Geology

The Gilbertown fault system has been mapped at the surface by several investigators (MacNeil, 1946; Toulmin and others, 1951; Szabo and others, 1988), but these maps are generalized and reveal little about the distribution of fractures and other strain indicators. For this reason, an intensive investigation of the Gilbertown fault system and associated structures is being conducted using standard field techniques.

Before field work began, the published literature and unpublished field notes were scanned for evidence of faulting at the surface in the Gilbertown area. A database of paleontologic field sites proved extremely useful, because the largest and freshest exposures in the field area are also classic fossil localities. Surface geologic methods in Gilbertown Field and vicinity include (1) observing the characteristics and measuring the orientation of faults and joints in outcrop, and (2) precise mapping of formations and members near faults.

For mapping and fracture analysis, every public road and quarry is being examined, with a stop made at every fresh or large outcrop. Road-accessible river bluffs were examined in fall 1996, and suitable creek exposures were selected for study in winter 1997. River bluffs are the largest and freshest exposures and thus yield the most valuable and cost-effective results. Creek beds and banks are less extensive, but can be just as fresh as river bluffs; however, they are not readily accessible and can consume an inordinate amount of time. Roadcuts and small quarries are readily accessible, but most are deeply weathered.

Outcrops were examined closely to determine the presence of faults, joints, and contacts. The orientations of faults and fractures were measured with a Brunton compass, and the elevation of contacts was measured by altimeter or by reference to topographic maps. Outcrops were located on 7.5-minute topographic quadrangles, and data were recorded in level books. Photographs are taken to illustrate pertinent features. A detailed geologic map of the fault system and associated structures is being compiled that shows the distribution and elevation of all exposed formations and members. The distribution and orientation of all types of fractures observed in the study area are also being mapped and analyzed statistically.

Task 3: Petrology and Log Analysis

Petrologic analysis of Selma and Eutaw reservoirs is being performed to understand diagenesis and porosity. Thin sections are being made and will be analyzed to determine primary rock composition and the composition and distribution of authigenic minerals, which have a strong impact on reservoir properties and well-log response. Also, samples of carbonate cement and fracture fillings from the Eutaw Formation and the Selma chalk are being sampled to be analyzed for oxygen and strontium isotopes. This last analysis provides critical information about formational fluids and thermal conditions during diagenesis and hydrocarbon generation, which may greatly affect the basic reservoir properties of chalk (Jensenius and Munksgaard, 1989).

Well logs of reservoir intervals in Gilbertown field are being digitized using Geographix/Schlumberger QLA-2 software. Data from the well logs will be used to calculate porosity, oil saturation, water saturation, gas saturation, and net pay. Logs to be digitized include spontaneous potential, resistivity, caliper, gamma ray, bulk density, density porosity, and neutron porosity. Calculations of basic reservoir parameters will be made using QLA-2 software.

Task 4: Structural Modeling

A three-dimensional model of the Gilbertown structure is being developed using GeoSec3D software. This model is helping with visualization and the construction of straight-line cross sections required for area balancing. The GeoSec3D computer program has been provided to this project through a DOE EPSCoR grant to the Department of Geology at the University of Alabama. It runs on a Silicon Graphics Indigo workstation that is available at the University of Alabama site of the Alabama Supercomputer Network. Input to the program is through GeoSec2D, kindly donated to the Department of Geology by CogniSeis, Incorporated. GeoSec2D runs on a Sun workstation that is in the Department of Geology computer laboratory.

The structural cross sections made under Task 1 were used to make a preliminary determination of detachment depth and structural geometry using the lost-area method (fig. 5). This was done to test the applicability of area balancing to the Gilbertown fault system and to identify and characterize potential problems related to salt movement, basement faulting, and synsedimentary growth. Once these problems were identified, the theory of area balance was modified to account for these variables.

Task 5: Burial and Thermal Modeling

To establish the burial history of Jurassic through Tertiary strata in the Gilbertown area, subsidence curves were generated using BasinMod-2D, an advanced basin modeling computer program that runs on an IBM PC-compatible computer. The burial curves made during this study incorporate standard compaction constants and backstripping techniques (Sclater and Christie, 1980; Angevine and others, 1990) and were used to distinguish tectonic and compactional components of subsidence. Well cuttings are being sampled and prepared to be analyzed for vitrinite reflectance. Reflectance data will be used to develop Lopatin models (Waples, 1980) and kinetic models of hydrocarbon generation (Burnham and Sweeney, 1989; Sweeney and Burnham, 1990).

REGIONAL GEOLOGIC SETTING

This study focuses on southern Choctaw County, Alabama, and adjacent areas in the vicinity of the Gilbertown fault system (fig. 6). The Gilbertown fault system is one of many extensional structures in the eastern part of the Gulf Coast basin, a Mesozoic-Cenozoic rifted basin formed during the opening of the Gulf of Mexico (Salvador, 1987; Worrall and Snelson, 1989). Evaporite sedimentation associated with early rifting had a profound impact on the structural and sedimentologic evolution of the region and ultimately affected the generation and entrapment of hydrocarbons.

Stratigraphy and Sedimentation

Rifting commenced with extensional collapse of the Appalachian-Ouachita orogen near the start of the Mesozoic Era (Horton and others, 1984). Initially, coarse-grained, arkosic clastics of the Eagle Mills Formation were deposited in deep half grabens and grabens and are associated with basaltic dikes, sills, and flows (Guthrie and Raymond, 1992). As rifting continued, magmatism waned, and evaporite sedimentation prevailed until near the end of Jurassic time (fig. 7). Evaporite sedimentation marks initial opening of the Gulf of Mexico and began with deposition of the Werner Formation, which is a dominantly anhydritic unit with some coarse-grained clastics (Tolson and others, 1983). Above the Werner Formation is the Louann Salt, which contains mainly massive halite intercalated with a lesser amount of anhydrite (Oxley and Minihan, 1969; Mink and others, 1985).

Above the Louann Salt are the Norphlet Sandstone and limestone and dolomite of the Smackover Formation (fig. 7), which are of Late Jurassic age and are among the most important hydrocarbon reservoirs in the eastern Gulf Coast basin. In the Gilbertown area, Upper Jurassic and Lower Cretaceous units have a cumulative thickness of approximately 9,000 feet. The Norphlet is dominantly an eolian unit and contains associated alluvial fan, wadi, and playa deposits (Mancini and others, 1985). The Smackover, by comparison, represents development of an extensive carbonate ramp above the Norphlet Formation (Ahr, 1973) and was deposited in a spectrum of intertidal, oolite-bank, and open-marine environments (Mancini and Benson, 1980; Benson, 1988). Following Smackover deposition, widespread intertidal to shallow marine evaporite deposition resumed, as represented by the Haynesville Formation (Harris and Dodman, 1982; Mann, 1988). The Haynesville Formation is transitional from the evaporite and carbonate sedimentation that dominated the Late Jurassic to the siliciclastic sedimentation that dominated much of Cretaceous time in southwest Alabama. The Cotton Valley Group spans the Jurassic-Cretaceous boundary and contains mainly coarse-grained arkosic clastics of alluvial origin in southwest Alabama (Tolson and others, 1983). Above the Cotton Valley, Lower Cretaceous strata are dominantly siliciclastic deposits that accumulated in coastal and shallow shelf environments and contain numerous oil reservoirs south of the Gilbertown area (Eaves, 1976).

Upper Cretaceous strata are subdivided into the Tuscaloosa Group, the Eutaw Formation, and the Selma Group (fig. 7). The Tuscaloosa Group contains marginal to open-marine siliciclastics and produces oil southeast of the Gilbertown area (Mancini and Payton, 1981; Mancini and others, 1987). In the Gilbertown area, the Tuscaloosa Group is approximately 600 feet thick. The Eutaw Formation is composed of sandstone and a lesser amount of mudstone and accumulated in beach-barrier and inner-shelf environments (Frazier and Taylor, 1980; Cook, 1993); the Eutaw is approximately 300 feet thick in the Gilbertown area. The Selma Group is composed of chalk and marl and is locally thicker than 1,300 feet near Gilbertown. The Selma signals regional inundation of the Eutaw barrier shoreline and establishment of an extremely widespread, muddy carbonate shelf that persisted for

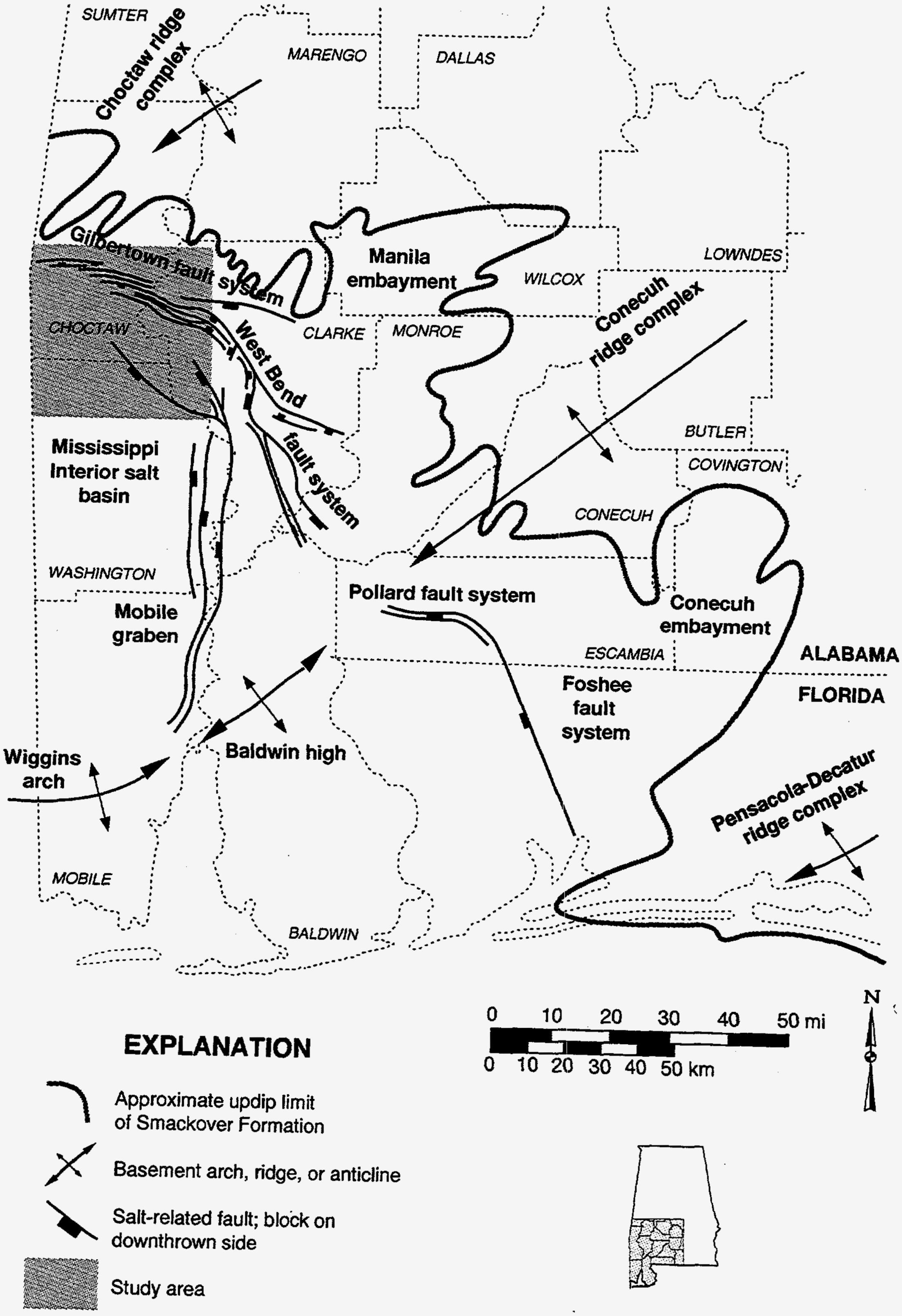

Figure 6.--Relationship of study area to structural features in the Gulf Coast basin of southwest Alabama (modified from Mancini and others, 1991).

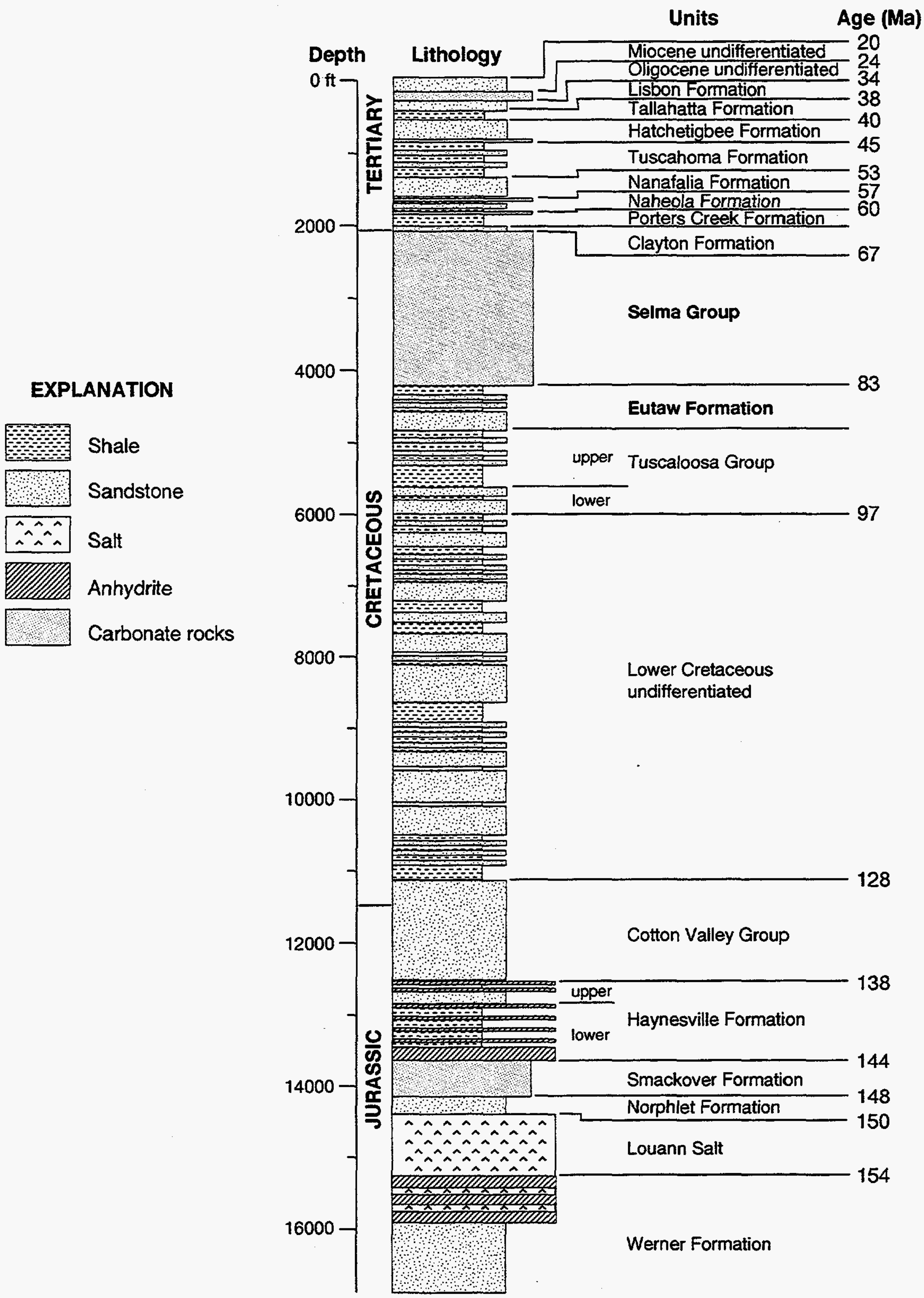

Figure 7.--Generalized stratigraphic section showing Jurassic through Tertiary stratigraphy and ages of marker beds in Gilbertown Field and adjacent areas.

the remainder of Cretaceous time (Russell and others, 1983; Puckett, 1992).

Tertiary strata ranging from Paleocene to Miocene in age are the youngest deposits preserved in the Gilbertown area and locally have cumulative thickness in excess of 2,000 feet (fig. 7). Paleocene and Eocene strata include the Clayton through Lisbon Formations, which contain a cyclic succession of coastal-plain and shallow-marine siliciclastics, lignite, and marl (Gibson and others, 1982; Mancini and Tew, 1993). Oligocene strata are composed mainly of shallow-marine carbonate rocks (Tew, 1992), and Miocene strata contain mainly unconsolidated sand and gravel (Szabo and others, 1988), which appear to be of fluvial origin.

Structure and Tectonics

Southwest Alabama contains a diversity of basement and salt structures (fig. 6). Deep tests penetrate the Eagle Mills Formation and crystalline basement mainly northeast of the Mississippi Interior salt basin and in the general area of the Wiggins arch (Horton and others, 1984; Mink and others, 1985; Guthrie and Raymond, 1992). Basement structures define a series of ridge complexes, such as the Choctaw and Conecuh ridge complexes. These ridge complexes separate embayments, such as the Manila and Conecuh embayments. In general, early rift clastics of the Eagle Mills Formation are present near the axes of the embayments and are absent on the basement ridges. Although the details of basement structure are obscured by sparse well control and the thick sedimentary cover, the ridges and embayments appear to define a series of horsts and grabens that began forming during extensional collapse of the Appalachian-Ouachita orogen and have been modified by deep erosion.

Among the most conspicuous structural features in southwest Alabama are the peripheral normal faults (fig. 6). The peripheral fault trend in Alabama contains four major fault systems, which are the Gilbertown, West Bend, and Pollard fault systems and the Mobile graben. These fault systems define a series of arcuate half grabens with southwestward to westward polarity. The Gilbertown and West Bend fault systems are closely related and can be considered together as a single half graben system. Using the terminology of Rosendahl (1987) and Scott and Rosendahl (1989), the Gilbertown-West Bend system, the Mobile graben, and Pollard fault systems can be classified as overlapping half grabens with similar polarity.

The peripheral faults mark the northeast margin of the Mississippi Interior salt basin and have therefore long been considered salt structures (Murray, 1961). Indeed, salt seeps have been observed along some of the faults (Copeland and others, 1976). The overall configuration of the faults, however, suggests some influence of fault geometry by basement. For example, the major fault bend where the Gilbertown fault system connects with the West Bend fault system corresponds with the boundary between the Choctaw ridge complex and the Manila embayment (fig. 6). Moreover, the discontinuity between the West Bend and Pollard fault systems corresponds with the crest of the Conecuh ridge complex, and the southern terminus of the Mobile graben is near the Wiggins arch. A common interpretation is that basement influenced the original distribution of Louann Salt and influenced where the salt could flow, but basinward withdrawal of the salt was the ultimate determinant of structural style in the overlying part of the sedimentary cover (Rosenkrans and Marr, 1967; Martin, 1978).

Numerous salt-cored anticlines are associated with extensional faulting in southwest Alabama. Most of the anticlines contain concordant salt pillows in the cores, and only one salt dome within the Mobile graben can be classified as a true piercement structure (Joiner and Moore, 1966). One of the most prominent folds in southwest Alabama is the Hatchetigbee anticline (Hopkins, 1917; Moore, 1971). The axial trace of the anticline strikes northwest, crudely parallel to the West Bend fault system, and intersects the Gilbertown fault system at nearly a right angle (fig. 1). The petroleum potential of the Hatchetigbee anticline was recognized long ago (Hopkins, 1917), but to date, only dry wells have been drilled in the crestal region of the structure.

Subsurface mapping reveals the extreme complexity of the Gilbertown fault system (fig. 1). The fault system contains numerous normal faults and is part of a full graben that is in places wider than 5 miles. The Gilbertown fault system forms the south side of the graben, and the Melvin fault system forms the north side. The pattern of fault traces in the Gilbertown area is evidence for complex structural relay between the full graben comprising the Gilbertown and Melvin fault systems and the half graben comprising the West Bend fault system.

Vertical separation of the top of the Eutaw Formation across the Gilbertown fault system is approximately 400 feet (fig. 1). Displacement apparently increases with depth and, along parts of the fault system, vertical separation of the Smackover Formation exceeds 1,500 feet (Wilson and others, 1976). Increasing displacement with depth has been noted by several workers, all of whom have suggested that the peripheral faults and associated salt-cored anticlines in Alabama are synsedimentary growth structures (Current, 1948; Copeland and others, 1976; Wilson and others, 1976) similar to the well-known examples in the western part of the Gulf Coast basin (Wilhelm and Ewing, 1972; Galloway, 1986).

STRUCTURE OF GILBERTOWN FIELD

Considerable progress has been made in the past year toward understanding the structural geology of Gilbertown Field. This section begins with a discussion of maker beds and fault cuts that highlights some of the limitations of using geophysical well logs for characterizing faulted regions in the Gulf Coast basin. The main part of the section presents, describes, and interprets the numerous structural cross sections and structure contour maps made under Task 1. The section concludes by presenting and discussing isopach maps of key units that help elucidate the role of synsedimentary structural growth in the development of the Gilbertown fault system.

Marker Beds and Fault Cuts

Correlation of 725 geophysical well logs revealed numerous stratigraphic markers that could be used to characterize structure in Gilbertown Field and adjacent areas (fig. 7). Wells were drilled in search of shallow Cretaceous and deep Jurassic reservoirs, and the stratigraphic and structural data reflect these disparate drilling targets. Wells drilled before 1970, including most wells in Gilbertown Field, record Tertiary and Cretaceous strata from depths of 200 feet to 5,000 feet. Of these logs, 332 begin in the Hatchetigbee through Lisbon Formations, which are of Tertiary age, and end in the Eutaw Formation, which is of Late Cretaceous age. Three hundred ninety three (393) wells were drilled in search of deep reservoirs in the Jurassic Smackover Limestone and record strata from the Upper Cretaceous Selma Group at a depth of 2,000 to 5,000 feet to the Jurassic Smackover Limestone at more than 12,000 feet. Only eight wells penetrate crystalline basement north of the Melvin fault system, and six wells penetrate the Jurassic Louann Salt and deeper strata south of the fault system.

The deepest stratigraphic marker that has been drilled in enough places to make structural cross sections is the top of the Smackover Formation, which is readily identified below the basal anhydrite (Buckner Member) of the Haynesville Formation (fig. 7). Interbedded anhydrite and shale provide numerous stratigraphic markers that are useful for correlation in the Haynesville, and a widespread sandstone unit was used to divide the formation into upper and lower parts. By comparison, the Cotton Valley Group is composed almost entirely of sandstone and thus lacks significant stratigraphic markers. The top of the Cotton Valley Group is marked by exceptionally resistive sandstone with shale partings in some areas, and careful correlation was required to ensure consistent log picks.

Lower Cretaceous strata contain mainly interbedded sandstone and shale with some redbeds and can be subdivided crudely on the basis of shale and sandstone content. However, no regionally extensive marker beds were identified that could be used reliably to make structural cross sections and maps. This lack of markers is a significant obstacle for making structural interpretations, considering that the Lower Cretaceous is thicker than 5,000 feet in the Gilbertown area. Even so, recognition of shaly and sandy units was useful for identifying missing section and estimating vertical separations in faulted wells.

Upper Cretaceous strata, by comparison, contain numerous widespread stratigraphic markers (fig. 7). A massive sandstone unit was identified as the base of the Tuscaloosa Group, although correlation was difficult where sandstone of the Tuscaloosa Group is in contact with that of the Lower Cretaceous. The base of the so-called marine Tuscaloosa shale is a distinctive marker that was used to subdivide the Tuscaloosa Group into upper and lower parts. Stratigraphic relationships are difficult to decipher in the upper part of the Tuscaloosa Group and in the Eutaw Formation, so the safest approach was to combine the two units for the structural parts of this investigation. The upper contacts of the Eutaw Formation and the Selma chalk are readily identified in well logs and are thus among the most reliable markers for making structural maps and cross sections. Indeed, nearly all wells penetrate the top of the Eutaw Formation, making it the best controlled surface in the stratigraphic section.

Interbedded sandstone, shale, and marl in the Tertiary section comprise a multitude of stratigraphic units that can be correlated throughout the study area (fig. 7). Thin, resistive marl markers (Matthews Landing and Coal Bluff Members, respectively) mark the top of the Porters Creek and Naheola Formations. The top of a sandstone unit in upper part of the Nanafalia Formation (Gravel Creek Member) is a useful marker throughout the northern part of the study area; the top of a correlative marl unit was used in the southern part. The Tuscahoma Formation contains many shale, sandstone, and marl units, but these units are too discontinuous to be reliable markers. The top of the Tuscahoma Formation is marked by the base of the Bashi Marl Member of the Hatchetigbee Formation and is an extremely reliable marker. The upper contact of the Hatchetigbee Formation, which is marked by the resistive, siliceous shale of the overlying Tallahatta Formation, is the youngest marker used for subsurface investigation.

A total of 428 wells (59 percent of those analyzed) intersect faults with vertical separation exceeding 50 feet. As many as six faults were identified in a single well, and the vertical separation of some faults exceeds 3,000 feet. Faults can be identified readily by recognizing missing section, but the precision with which faults can be located varies depending on the internal stratigraphy of the faulted units. The numerous markers in pre-Cotton Valley units makes faults simple to locate. By contrast, the great thickness of homogeneous sandstone within the Cotton Valley Group is a source of considerable uncertainty when trying to locate faults in shortened sections. This uncertainty is greatest in the Lower Cretaceous, where no reliable marker beds can be used as a point of reference. Considering the great thickness of the Lower Cretaceous, moreover, only faults with vertical separations greater than 300 feet can be identified with any degree of confidence. In most younger units, however, abundant marker beds make it possible to identify faults with minimal displacement and to locate faults to the nearest 100 feet.

Structure

Numerous faults compose the Melvin, Gilbertown, and West Bend fault systems, and individual faults were labeled so they could be identified consistently (fig. 8). The Melvin fault system contains three major faults labeled A, B, and C. The Gilbertown fault system was subdivided into West Gilbertown faults A and B and East Gilbertown faults A and B. By comparison, the West Bend fault could be mapped as a single fault.

Maps and cross sections establish that the Gilbertown and Melvin fault systems form a full graben extending the length of the map area, whereas the Gilbertown and West Bend fault systems form a horst that is restricted to the eastern end of the map area (fig. 8). The full graben contains most of the faults in the map area and consists of two major segments containing faults that generally strike east. The western segment comprises Melvin fault A and the West Gilbertown faults, whereas the eastern segment contains Melvin faults B and C and the East Gilbertown faults. A structurally complex relay zone is present at the intersection of the two graben segments. The relay zone marks a lateral offset of the axis of the graben and is defined by faults striking southeast and northwest. The horst in the eastern part of the Gilbertown Field is formed principally by East Gilbertown fault A and the West Bend fault. The horst is an arcuate structure in which East Gilbertown fault A intersects the West Bend fault just beyond the eastern margin of Gilbertown Field.

Cross Sections

Cross sections establish that structural relationships change considerably with depth and along strike (figs. 9-17). For example, dip of the faults changes with depth. Interestingly, this change corresponds approximately with the base of the Selma Group. Below the Selma Group, faults generally dip 60°. In the Selma Group and younger units, by comparison, faults dip as gently as 45°. In some of the eastern cross sections, moreover, faults of opposite polarity nearly intersect at the level of the Smackover Formation. The cross sections also show evidence of considerable growth in the Cretaceous section and little or no growth in the Tertiary section. Because of insufficient data, however, evidence for growth in the Jurassic section is incomplete.

A key problem encountered when making cross sections is that direct control of the elevation of Jurassic stratigraphic units is limited along the axis of the graben. This is because Smackover reservoirs in the map area are primarily in footwall uplifts, so the major faults are typically penetrated no deeper than the Cotton Valley Group. To compensate for this problem, maps and cross sections were drawn by using vertical separations of fault cuts to estimate the elevation of the Jurassic units. Considering the probability of synsedimentary growth of the faults, however, Jurassic units may be slightly deeper than shown in cross section.

Each cross section reveals different nuances of structural style in the Gilbertown area. In cross section A-A', the westernmost cross section in the map area (figs. 9, 10), Jurassic strata thicken southward and appear to roll over into West Gilbertown fault A. A significant footwall uplift in the Smackover and Haynesville Formations is apparent below the fault. Cretaceous strata roll over more strongly into West Gilbertown fault B than into fault A. These relationships suggest that, in this line of cross section, the West Gilbertown faults are the synthetic structures. Melvin fault A and West Gilbertown fault B apparently intersect in the Jurassic section, and the top of the Cotton Valley Group is anomalously deep.

Cross section B-B' traverses the center of the western graben segment but, unfortunately, is one of the least constrained cross sections (figs. 9, 11). Vertical fault separations suggest that Jurassic strata are nearly horizontal in the graben, and the overall geometry of the structure suggests that these strata roll over into the Melvin fault. Similar relationships are apparent in the Cretaceous section, and comparison of cross sections A-A' and B-B' indicate transfer of dominant fault slip from the West Gilbertown faults to Melvin fault A.

Cross section C-C' is better constrained than B-B' and is the only cross section that shows the Louann Salt, which is only 868 feet thick at the south end of the cross section (fig. 12). Structural relationships in cross section C-C' are similar to those in B-B'. However, the graben is significantly narrower than in the cross sections to the west, and Cretaceous strata clearly roll over into Melvin fault A. One significant feature in cross section C-C' is a second-order fault in the central part of the graben that intersects West Gilbertown fault B. The fault has a vertical separation exceeding 300 feet in the Eutaw Formation, but no evidence for offset

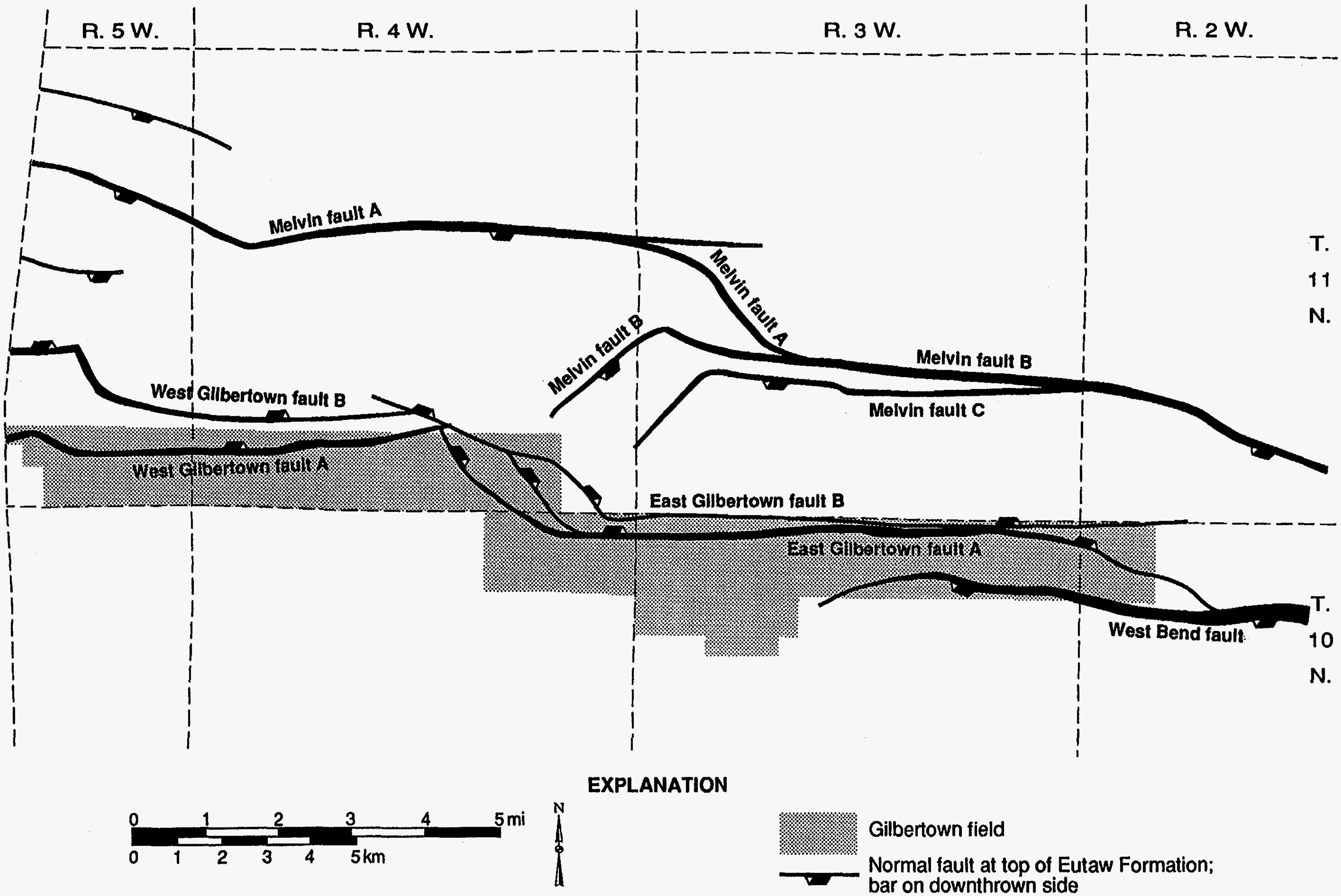

Figure 8.--Index map showing distribution and names of major faults, Gilbertown Field and adjacent areas.

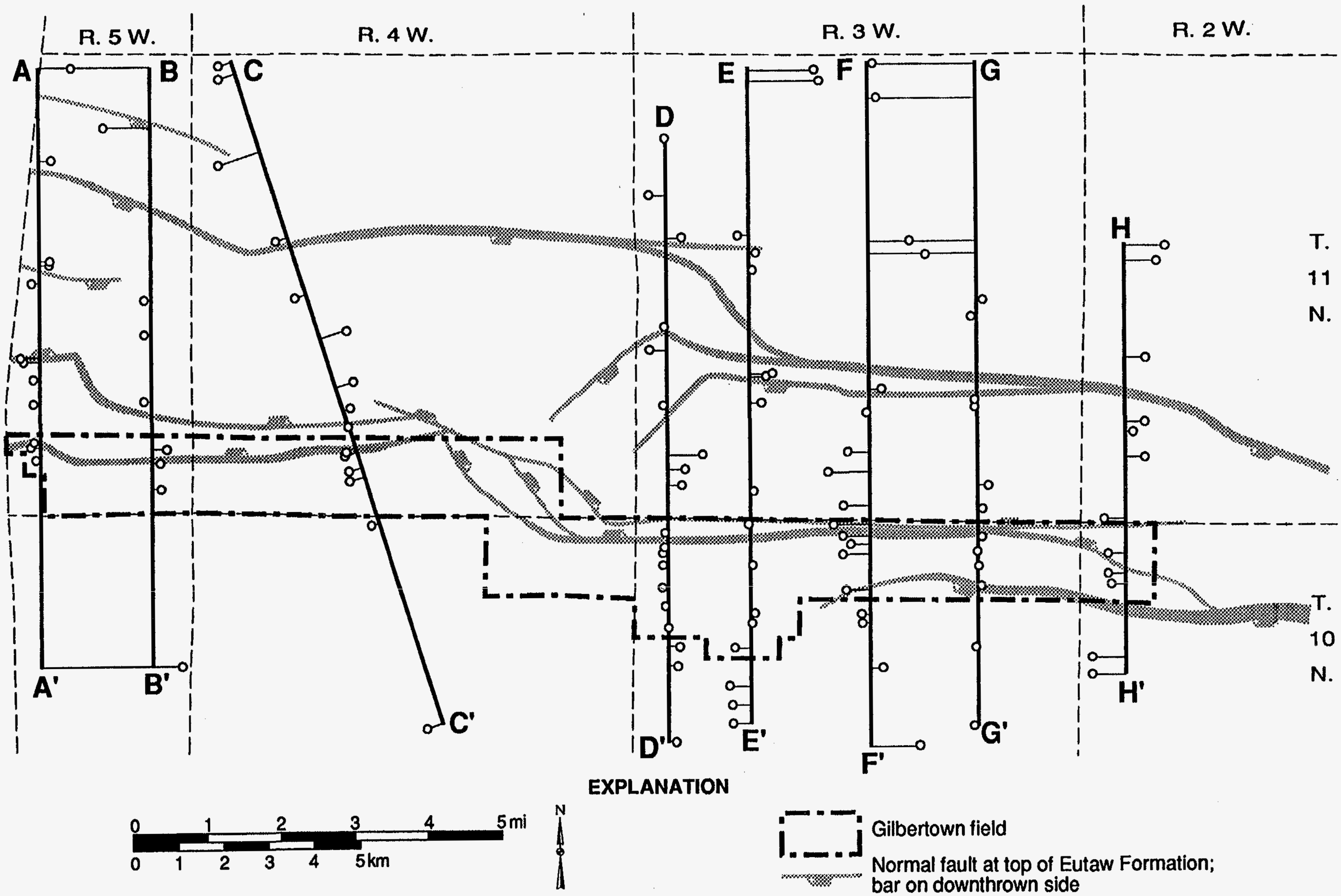

Figure 9.--Index map showing location of structural cross sections, Gilbertown Field and adjacent areas.

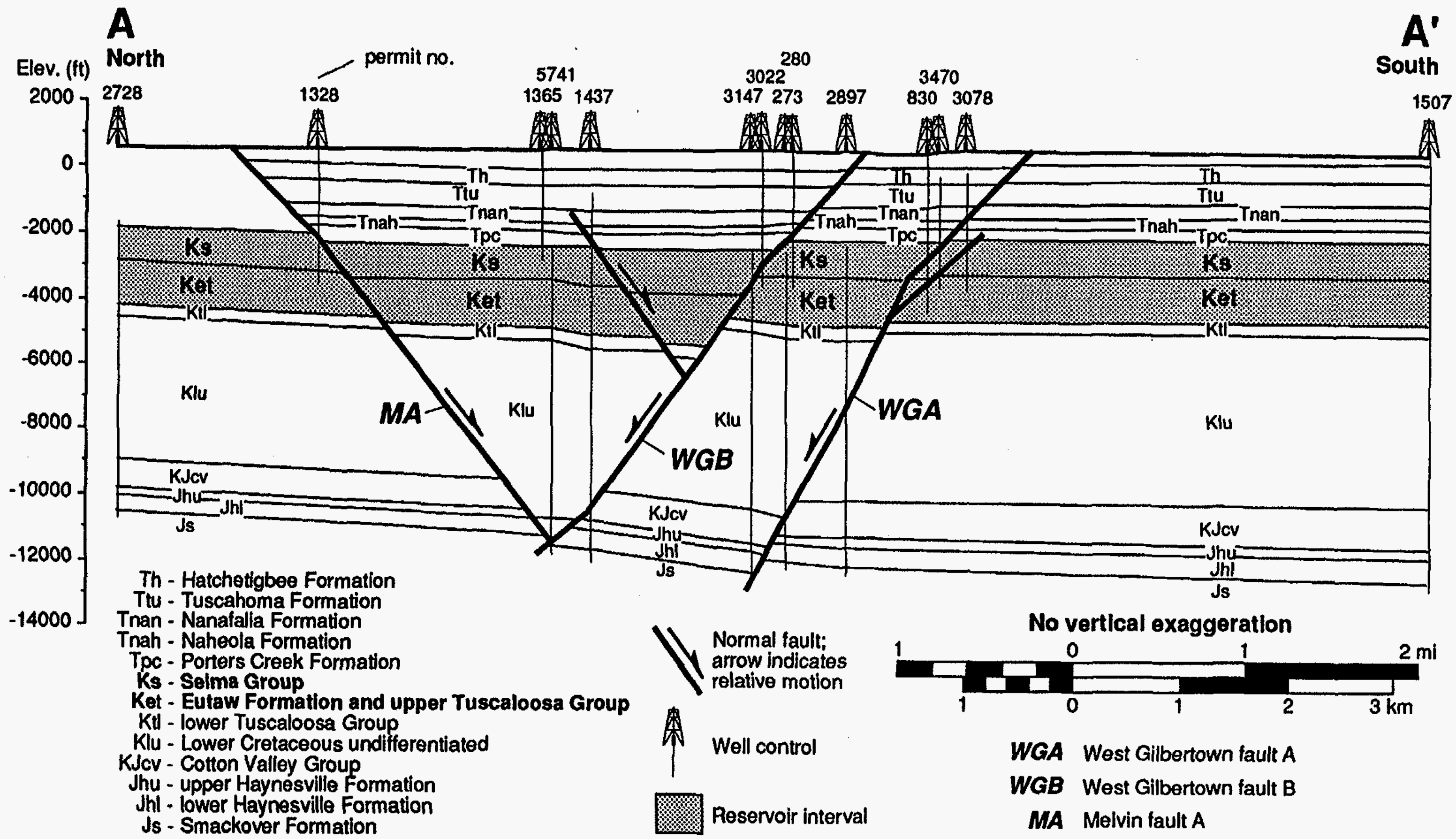

Figure 10.--Structural cross section A-A'. See figure 9 for location.

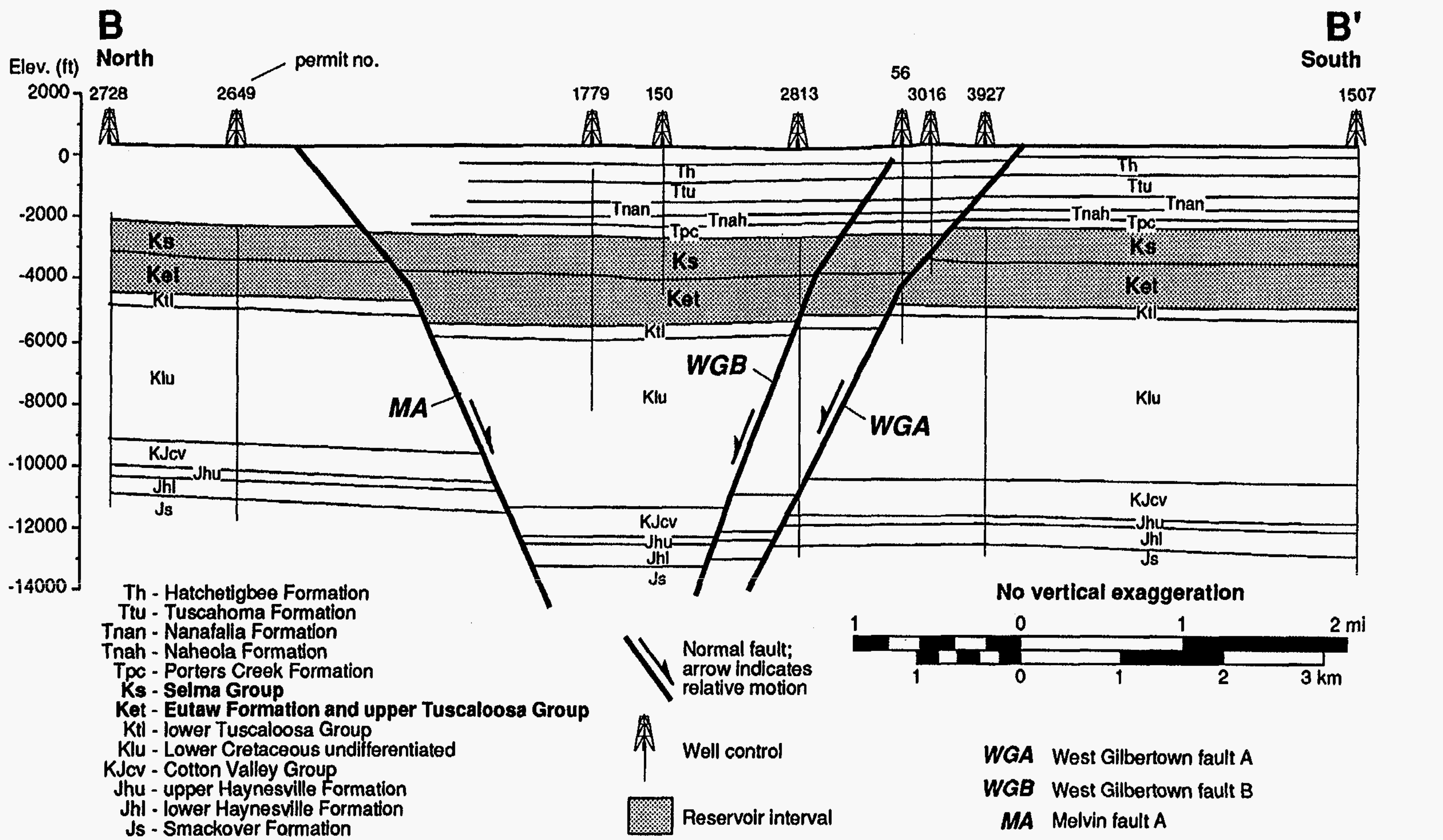

Figure 11.--Structural cross section B-B'. See figure 9 for location.

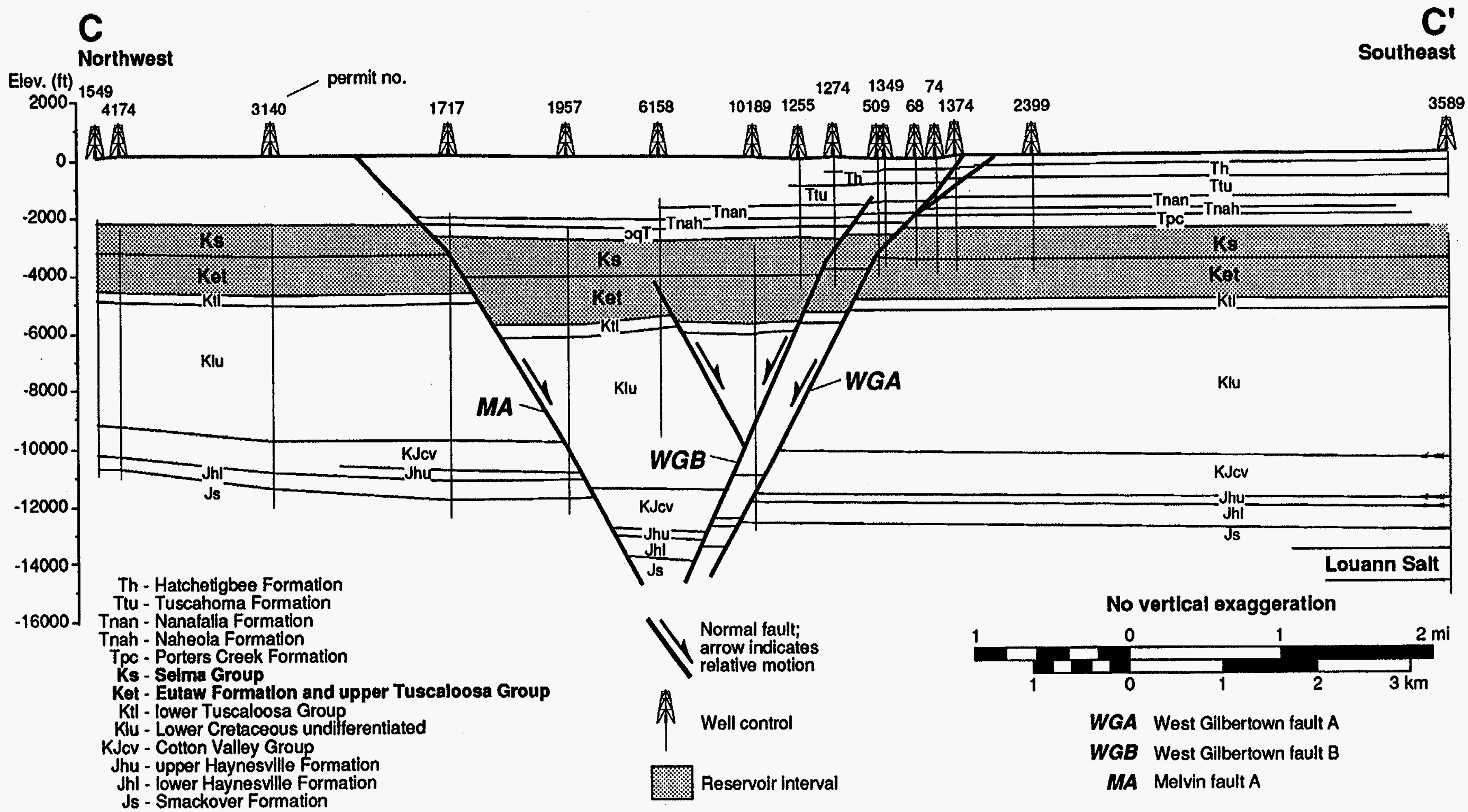

Figure 12.--Structural cross section C-C'. See figure 9 for location.

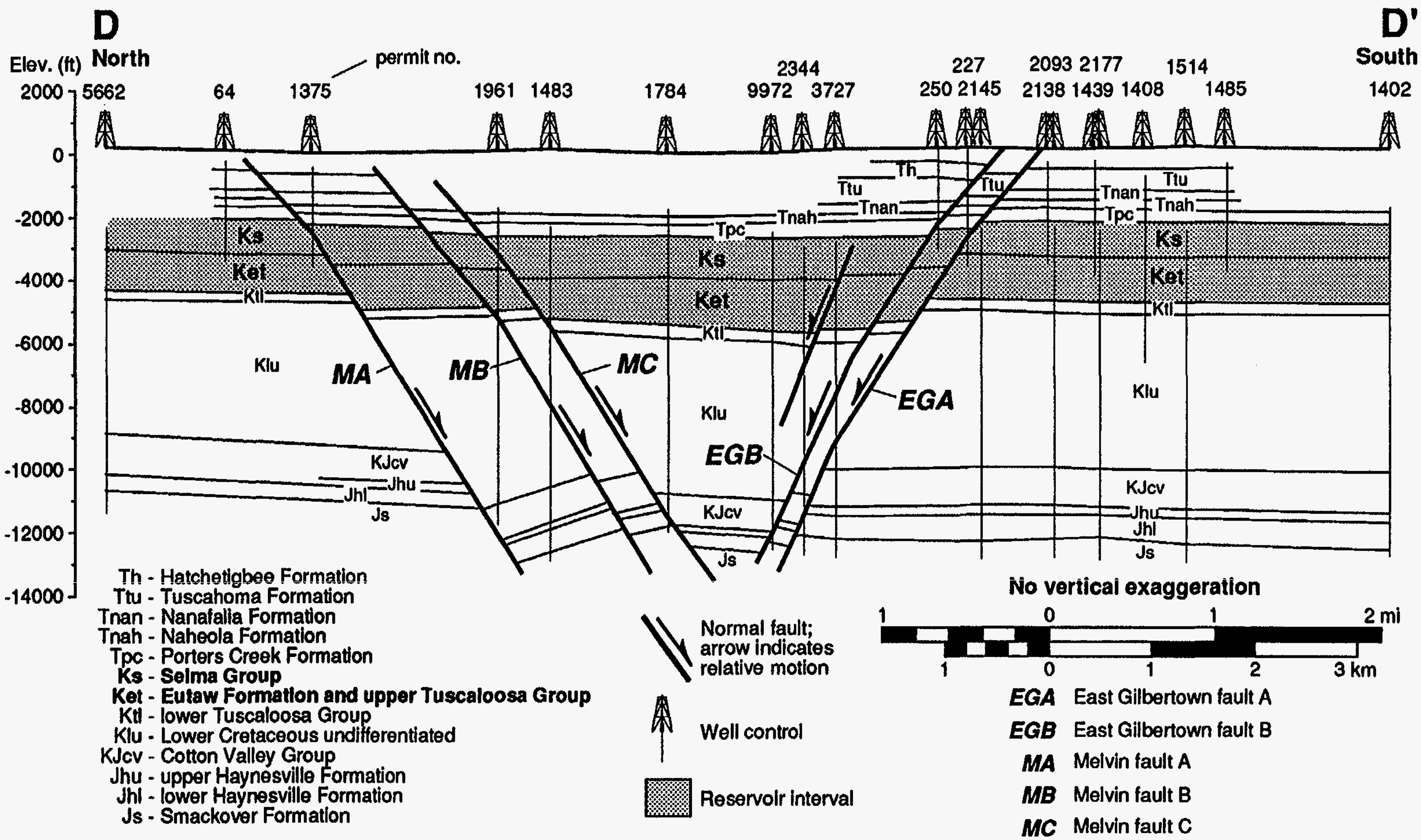

Figure 13.--Structural cross section D-D'. See figure 9 for location.

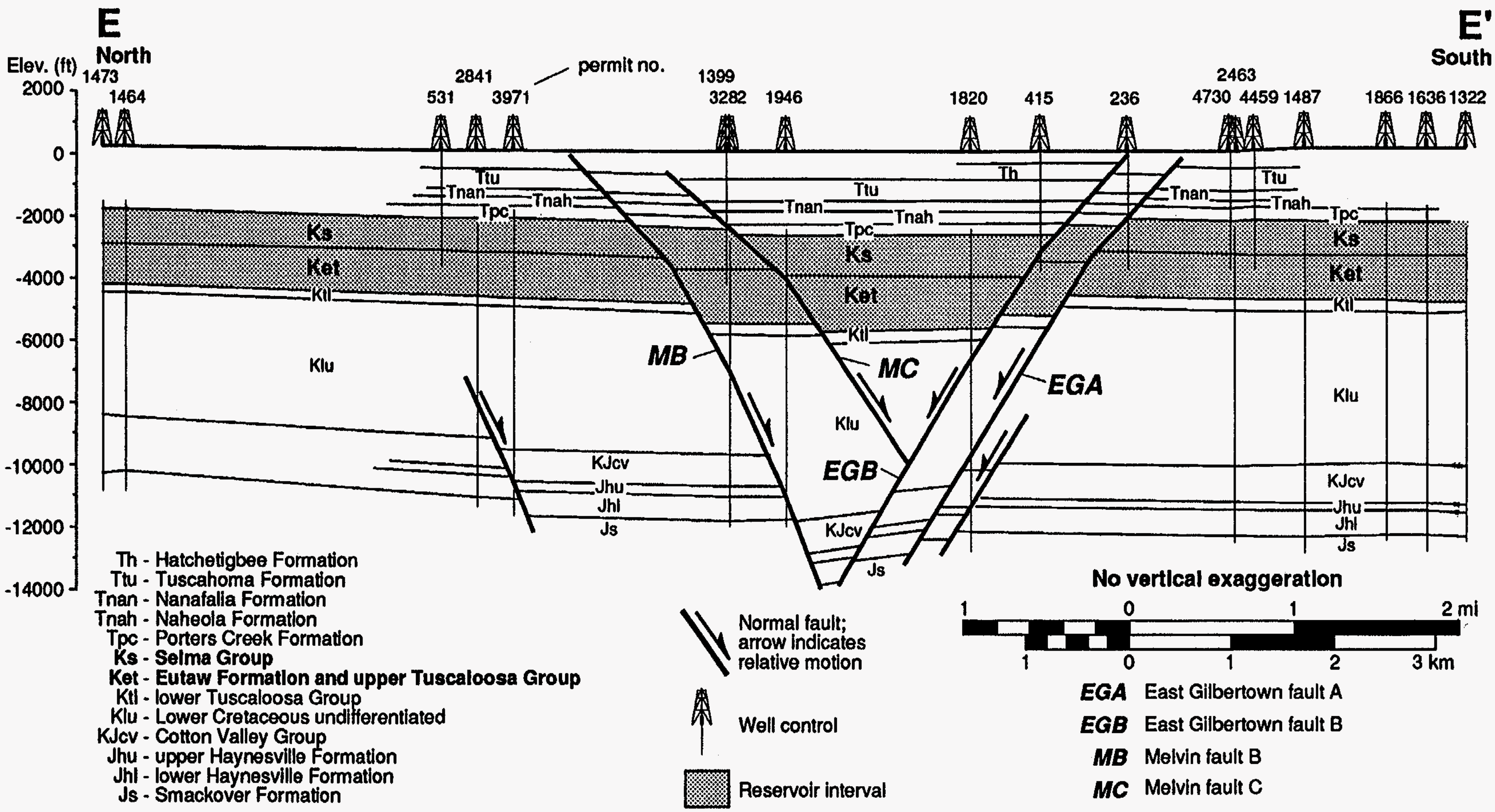

Figure 14.--Structural cross section E-E'. See figure 9 for location.

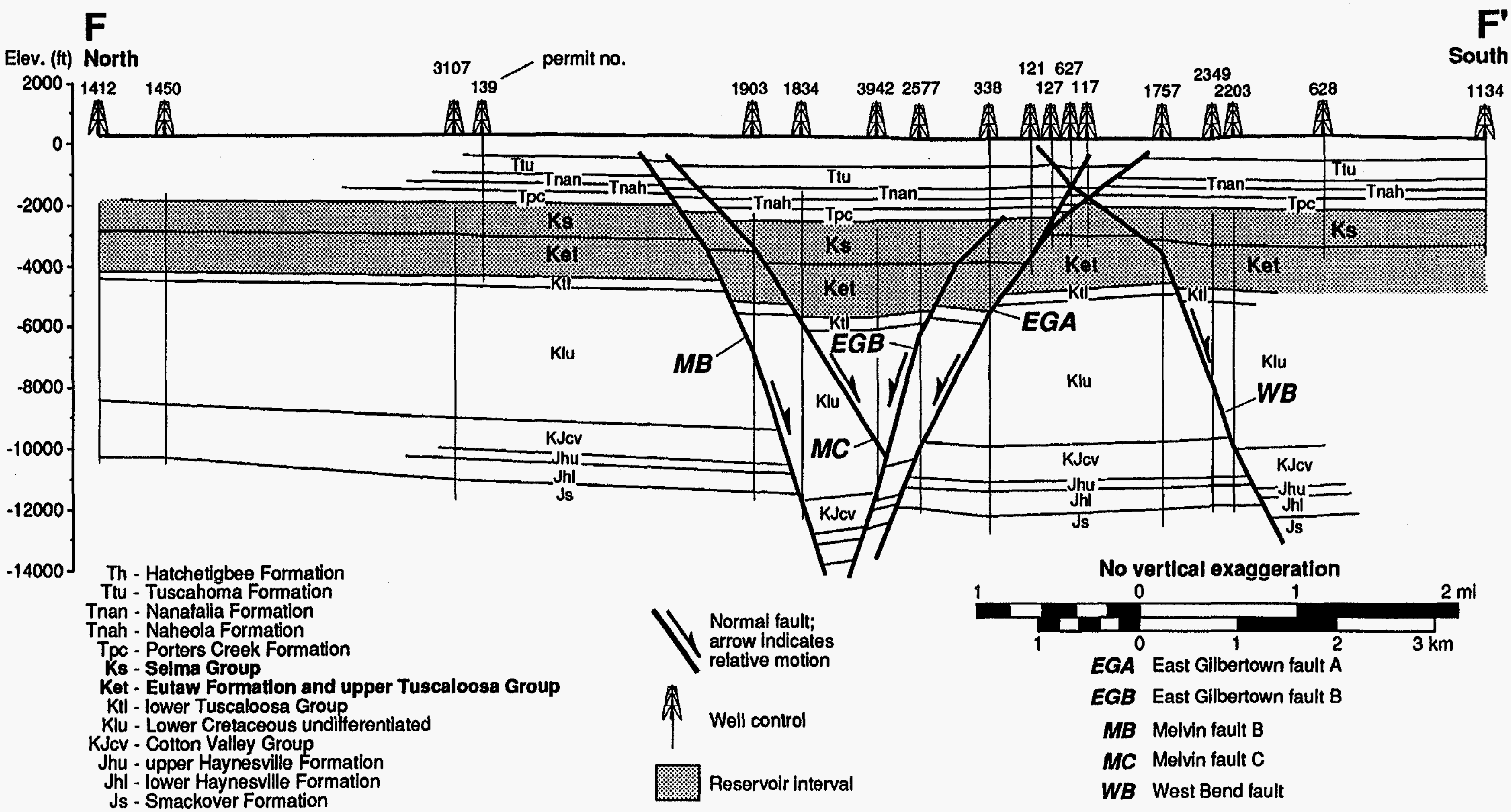

Figure 15.--Structural cross section F-F'. See figure 9 for location.

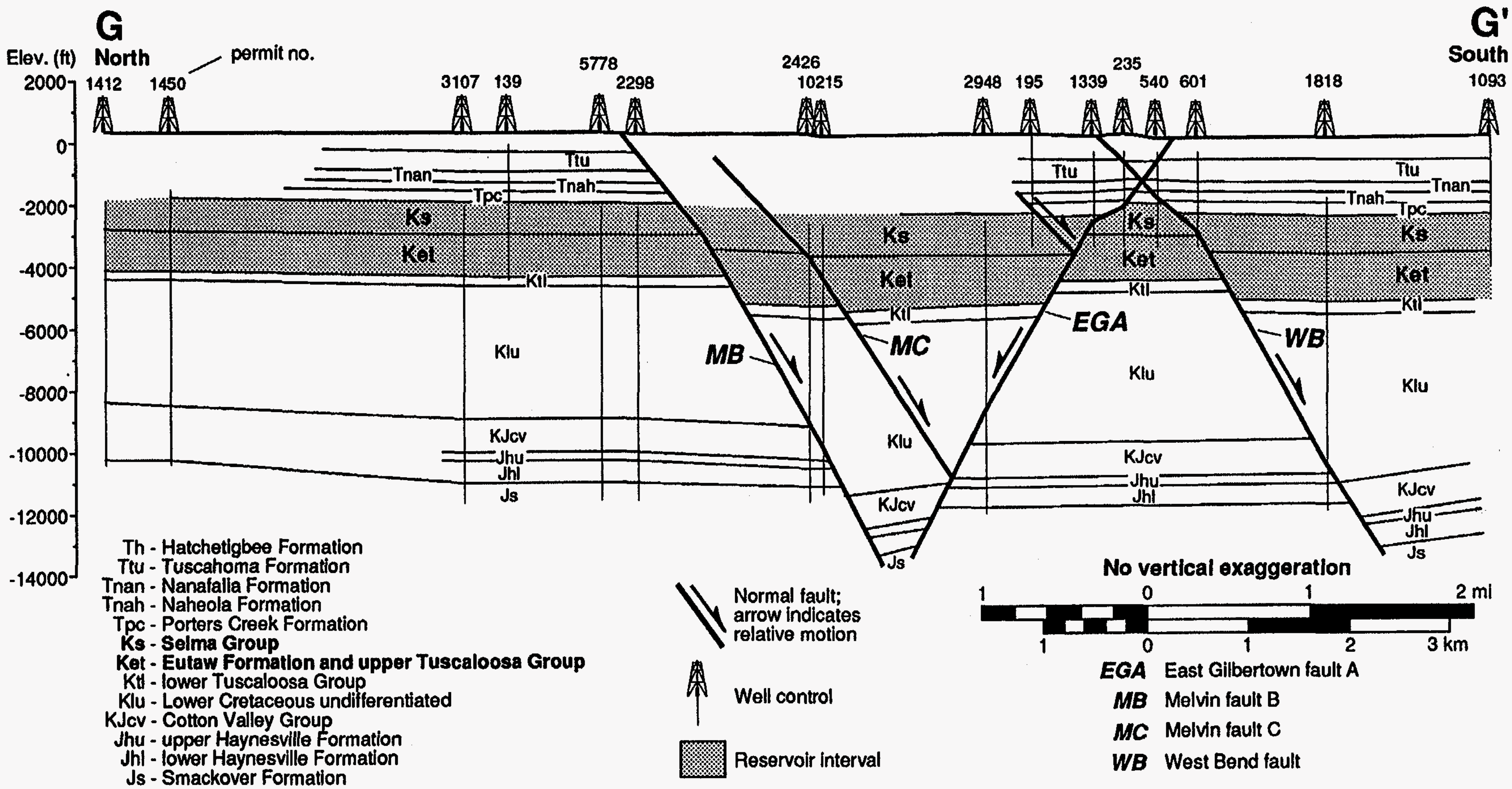

Figure 16.--Structural cross section G-G'. See figure 9 for location.

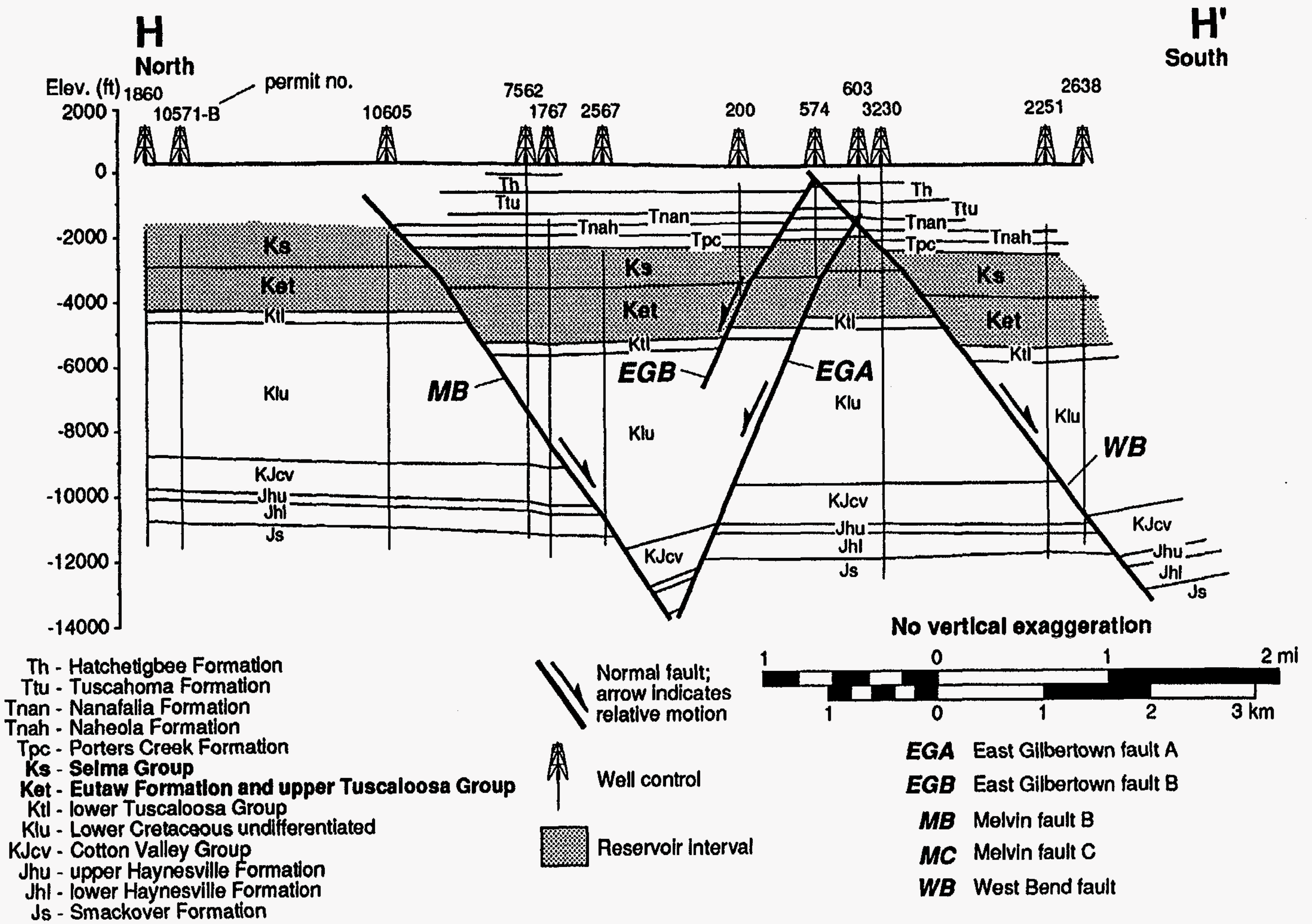

Figure 17.--Structural cross section H-H'. See figure 9 for location.

exists above the Eutaw, suggesting that the fault was a short-lived structure.

The only cross section traversing the relay zone connecting the two major graben segments is D-D', which contains all the major faults comprising the Melvin and East Gilbertown fault systems (figs. 9, 13). South of the graben, a localized anticline and footwall uplift are developed in the Smackover and Haynesville formations but are not apparent in Cotton Valley and younger strata. Structure is very complex within the graben, and some strata dip as steeply as 17°. Jurassic strata roll over toward both sides of the graben, but roll much more strongly into Melvin fault A than into East Gilbertown fault A. Conversely, Cretaceous strata roll more strongly into East Gilbertown fault A than into Melvin fault A, suggesting transfer of dominant slip from the north side of the graben toward the south side during growth.

The western portion of the eastern graben segment is well shown in cross section E-E' (fig. 14). South of the graben, strata dip gently southward, and oil has been produced from a small anticline in the Jurassic section. In the graben, Melvin fault B nearly intersects East Gilbertown fault B at the level of the Smackover Formation, and Melvin fault C is interpreted to intersect East Gilbertown fault B in the Lower Cretaceous section. Jurassic strata clearly roll over into Melvin fault B, and the southernmost fault in the rollover system apparently penetrates strata no younger than Lower Cretaceous. Rollover folding is at best indistinct in the Cretaceous section. A fault with a vertical separation of 400 feet was identified in Lower Cretaceous and older strata north of the graben.

Cross section F-F' is the westernmost cross section showing the relationship between the horst and graben (fig. 15). Control on the orientation of Jurassic strata in the hanging wall of the West Bend fault does not exist. However, Cretaceous and Tertiary strata in the hanging wall dip southward, away from the fault, and no rollover fold is apparent. This configuration may reflect movement of strata above the shallow fault bend where dip of the fault increases from approximately 45° to more than 60°. Jurassic strata in the horst block are gently folded, and fault separations suggest that the lower Tuscaloosa Group dips significantly toward the north. Faults defining the horst block intersect just above the Selma chalk. The faults apparently cross, forming a conjugate pair. Tertiary strata between the faults, moreover, are preserved in a complementary graben. The main graben is narrower than it is in cross section E-E', but otherwise, structural relationships are essentially the same.

Structural relationships in cross section G-G' resemble those in F-F', although some differences are worthy of mention (fig. 16). The shallow bend in the West Bend fault is less pronounced than in cross section F-F', and Cretaceous and Tertiary strata in the hanging wall dip away from the fault more gently. Control on the geometry of Jurassic strata in the horst block is minimal. As in cross section F-F', the West Bend fault and East Gilbertown fault A intersect to form a conjugate pair with a complementary graben, and the overall structural geometry is simpler in cross section G-G'. In the graben, East Gilbertown fault B is absent or has merged with East Gilbertown fault A. Another significant difference is that Jurassic and Cretaceous strata roll over, albeit weakly, into Melvin faults B and C.

H-H' is the easternmost cross section of the network (figs. 9, 17). The most notable difference between cross section H-H' and the previous two cross sections is the relationship between the West Bend fault and East Gilbertown fault A. In cross section H-H', the West Bend fault appears to be continuous, whereas the East Gilbertown fault is interpreted to terminate near or even abut the West Bend fault. No control exists on the position of the East Gilbertown faults in the deep subsurface. On the opposite side of the graben, Melvin fault C is absent or has merged with Melvin fault B. Additionally, Melvin fault B dips more gently in cross section H-H' than in other nearby cross sections.

Structural Contour Maps

A series of structure maps shows distinctive changes of the structural plan at different stratigraphic intervals. The deepest stratigraphic surface that could be mapped in the Gilbertown area is the top of the Cotton Valley Group (fig. 18). Most of the major faults composing the Gilbertown, Melvin, and West Bend fault systems are readily recognized (compare figs. 8 and 18). At the top of the Cotton Valley, however, the graben formed by the Melvin and Gilbertown fault systems is wider than 2 miles only in a few places. Conversely, the horst is locally wider than 3 miles. Indeed, the only major fault that is absent is Melvin fault C, which is interpreted to intersect East Gilbertown fault B above the Cotton Valley Group.

Widely spaced contours in the western graben segment reflect the gentle dip of Jurassic strata in this area (fig. 18). In the relay zone and the eastern part of the graben, by contrast, the top of the Cotton Valley Group dips markedly toward the north as the Jurassic section rolls over into the Melvin fault system. The top of the Cotton Valley Group is essentially horizontal in the northwestern part of the horst and dips south-southeast in the eastern part. West of the horst, and immediately south of the relay zone, is a fault-bound anticline that has been drilled extensively in search of Smackover reservoirs.

A map of the top of the lower Tuscaloosa Group differs considerably from the Cotton Valley map (fig. 19). Throughout the map area, the graben is 2 to 3 miles wide, and the horst is only 1 mile wide. In

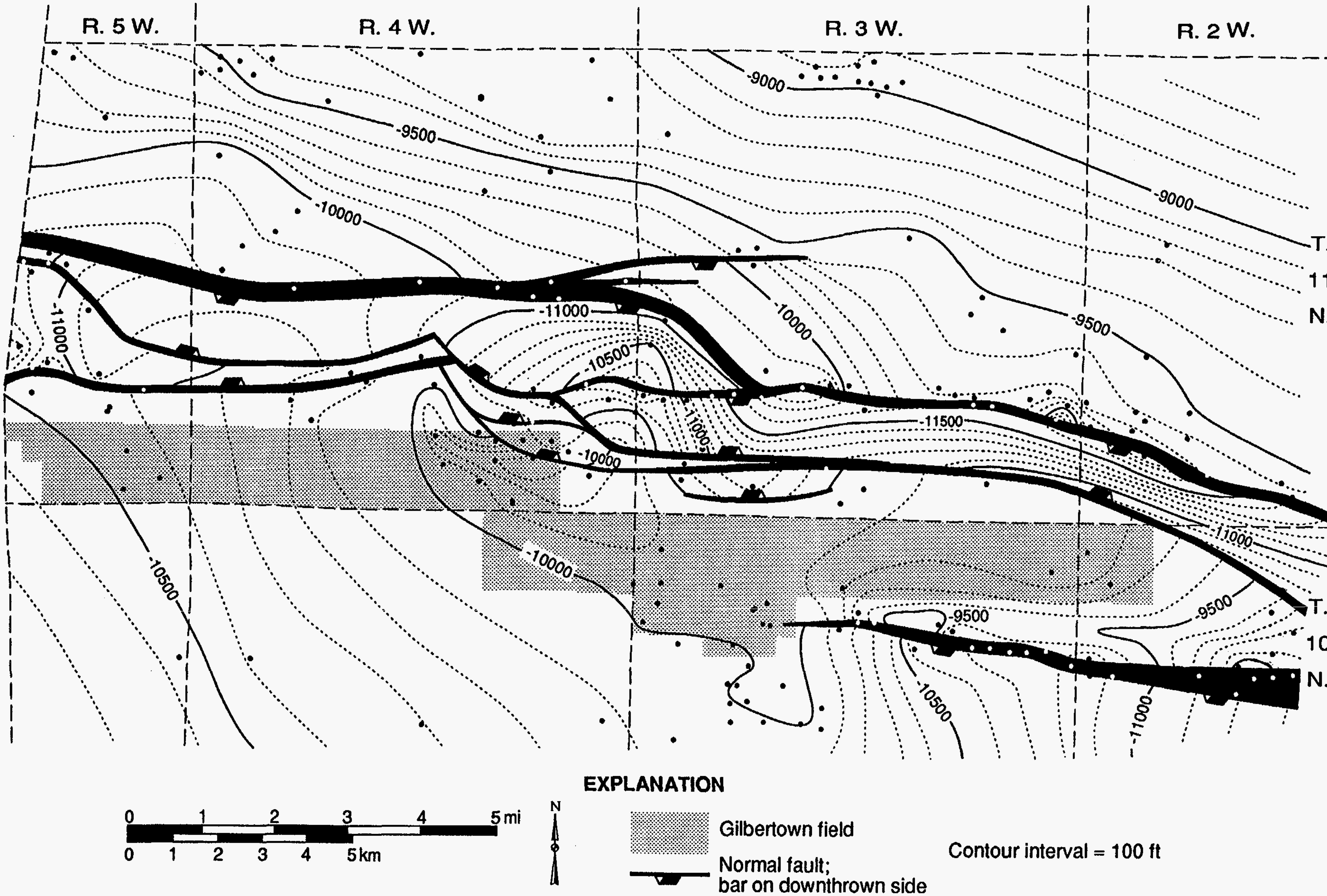

Figure 18.--Structural contour map of the top of the Cotton Valley Group, Gilbertown Field and adjacent areas.

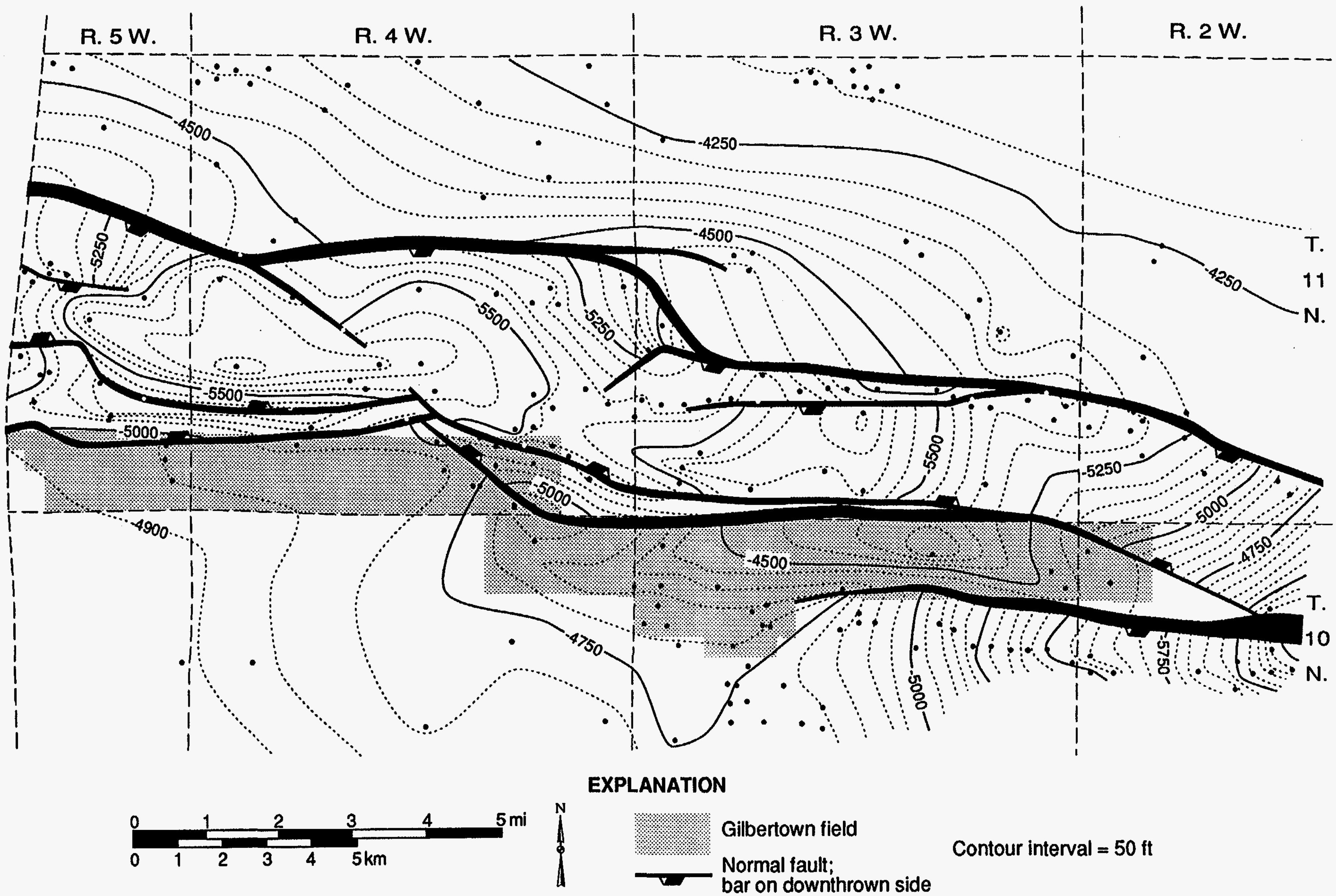

Figure 19.--Structural contour map of the top of the lower Tuscaloosa Group, Gilbertown Field and adjacent areas.

contrast to the top of the Cotton Valley, the top of the lower Tuscaloosa appears to sag between the faults making up the western graben segment. The top of the lower Tuscaloosa sags less distinctly in the eastern segment, and rollover into the Melvin fault is not readily apparent. South of East Gilbertown fault A and in the horst, the top of the lower Tuscaloosa Group forms a simple fault-bound anticline. West of the horst, moreover, the fault-bound anticline that was drilled in search of Smackover reservoirs is absent.

The structural contour map of the top of the Eutaw Formation contains the tightest well control of any map presented in this study and provides a clear picture of the structural configuration of Eutaw sandstone reservoirs in Gilbertown Field (fig. 20). As with the top of the lower Tuscaloosa, the top of the Eutaw Formation sags between the faults defining the western graben segment. However, sagging at the top of the Eutaw is considerably less pronounced than at the top of the lower Tuscaloosa. The fault-bound anticline south of East Gilbertown fault A and in the horst has a configuration similar to that at the top of the lower Tuscaloosa Group. Immediately south of West Gilbertown fault A is a minor footwall uplift.

Structure at the top of the Selma Group differs from that at the top of the Eutaw Formation in some distinct ways (fig. 21). In the western part of the graben, widely spaced contours indicate that sagging is much less pronounced than in the Eutaw Formation and the Tuscaloosa Group. Structure is also subdued in the relay area and in the eastern graben segment. The most conspicuous difference is that the horst is extremely narrow, reflecting the near intersection of the West Bend fault and East Gilbertown fault A.

The top of the Nanafalia Formation was the youngest surface mapped (fig. 22). Structure in most of the map area resembles that at the top of the Selma Group, although Nanafalia structure is even more subdued. However, intersection of the West Bend fault and East Gilbertown fault A has resulted in markedly different structural patterns in the eastern part of Gilbertown Field. The West Bend fault appears to connect with East Gilbertown fault A, and the small graben formed by conjugate faults is mapped in the east-central part of the field.

Isopach Maps

Isopach maps comparing the thickness of successive stratigraphic intervals to fault patterns were made to assess the distribution and timing of synsedimentary fault growth. The deepest unit mapped is the Lower Cretaceous section (fig. 23). In parts of the map area where the Lower Cretaceous is unfaulted, interval thickness was read directly from well logs. In the graben and the hanging wall of the West Bend fault, however, direct control on interval thickness is largely lacking, so thickness was measured from the cross sections (figs. 10-17). North of the graben, the Lower Cretaceous section is generally thinner than 4,400 feet, whereas south of the graben and in the horst, the Lower Cretaceous is approximately 5,000 feet thick (fig. 23). Growth was apparently minimal in the western segment of the graben where the Lower Cretaceous is only 5,400 feet thick. By contrast, up to 1,800 feet of growth is evident in the relay zone and in the eastern graben segment where Lower Cretaceous strata are locally thicker than 6,200 feet.

The map of the combined upper Tuscaloosa Group and Eutaw Formation shows marked thickening of sediment in the graben and in the hanging wall of the West Bend fault (fig. 24). North of the graben, this interval is less than 1,350 feet thick. The interval is approximately 100 feet thicker south of the graben and is just under 1,400 feet thick in most of the horst. The section typically expands across the faults by 300 feet, and in the deepest parts of the graben, the upper Tuscaloosa Group and Eutaw Formation locally have a combined thickness exceeding 1,700 feet. Growth across the West Bend fault is even more pronounced, with a maximum hanging-wall thickness greater than 1,800 feet.

The isopach pattern of the Selma Group closely resembles that of the combined upper Tuscaloosa Group and Eutaw Formation (fig. 25). Outside the graben, the Selma Group is generally thinner than 1,100 feet. The Selma Group is locally thicker than 1,350 feet in the western graben segment and reaches a maximum thickness of 1,400 feet in the eastern segment. Interval thickness is locally less than 1,050 feet in the horst and reaches a maximum of 1,550 feet in the hanging wall of the West Bend fault.

Whereas thickness patterns are similar from the upper Tuscaloosa Group through the Selma Group, the isopach map of the Tuscahoma Formation shows a very different pattern that may not be related to faulting (fig. 26). The Tuscahoma thickens southward from approximately 600 feet to 700 feet in the general area of the Melvin fault system and is locally thicker than 750 feet in the western part of the graben. An elliptical area where the Tuscahoma Formation is locally thinner than 650 feet is centered above the West Gilbertown faults and the area where the East Gilbertown faults turn northwest into the relay zone. Perhaps the only convincing evidence for fault control of sediment thickness is in the graben formed by conjugation of East Gilbertown fault A and the West Bend fault.

Structural Evolution

The structural cross sections, structural contour maps, and isopach maps provide evidence for a long and complex structural history in the Gilbertown area (fig. 27). Development of small anticlines and footwall

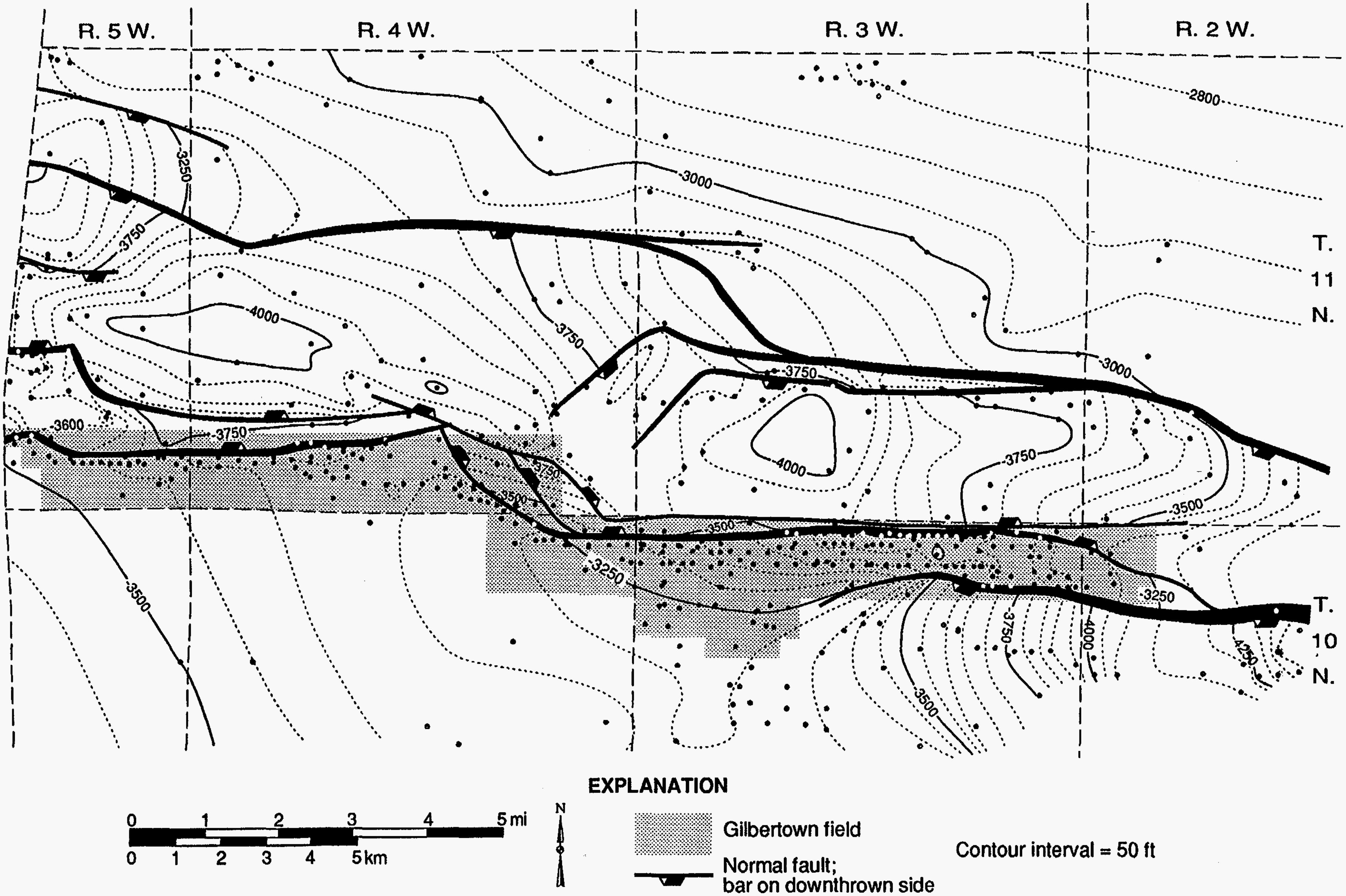

Figure 20.--Structural contour map of the top of the Eutaw Formation, Gilbertown Field and adjacent areas.

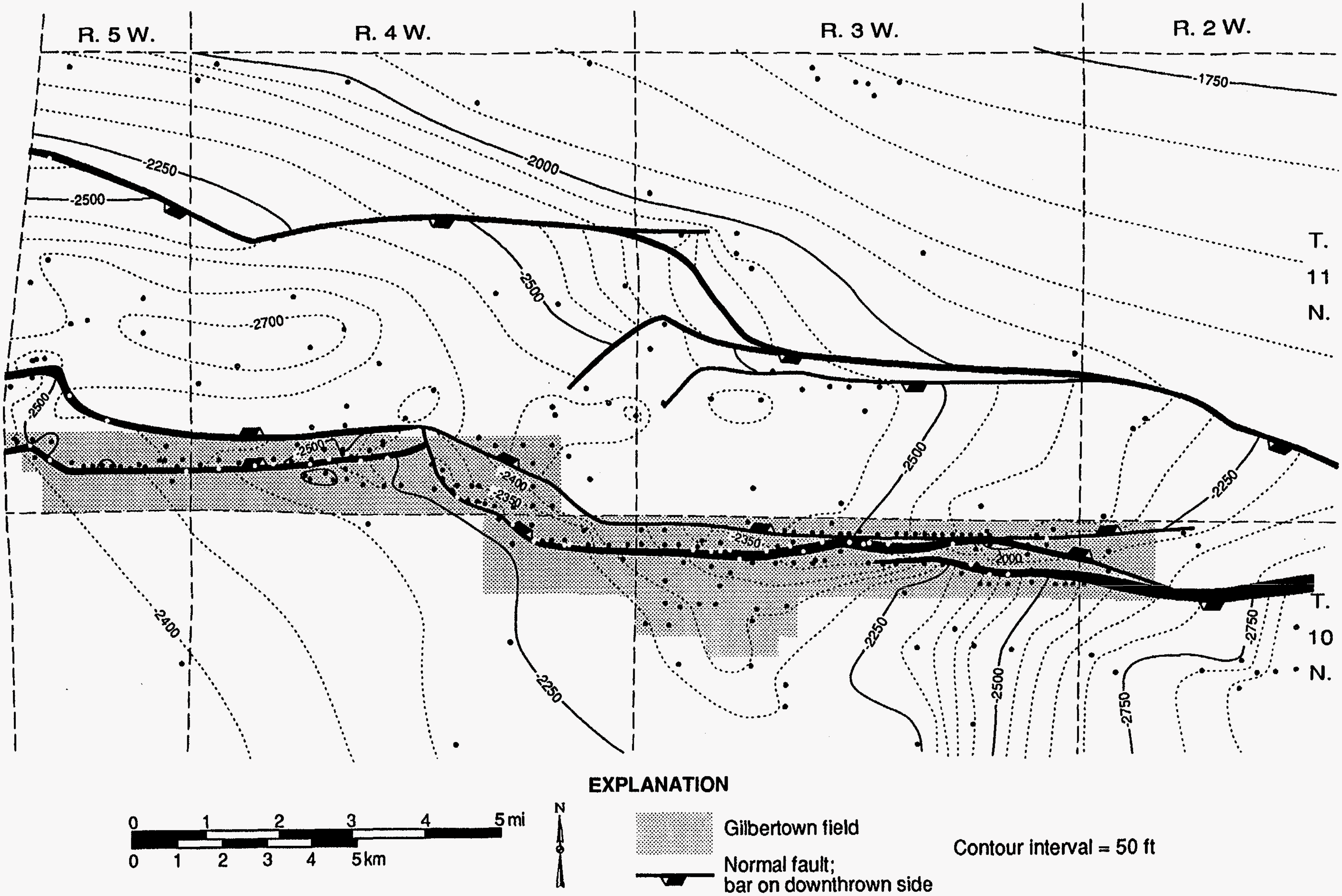

Figure 21.--Structural contour map of the top of the Selma Group, Gilbertown Field and adjacent areas.

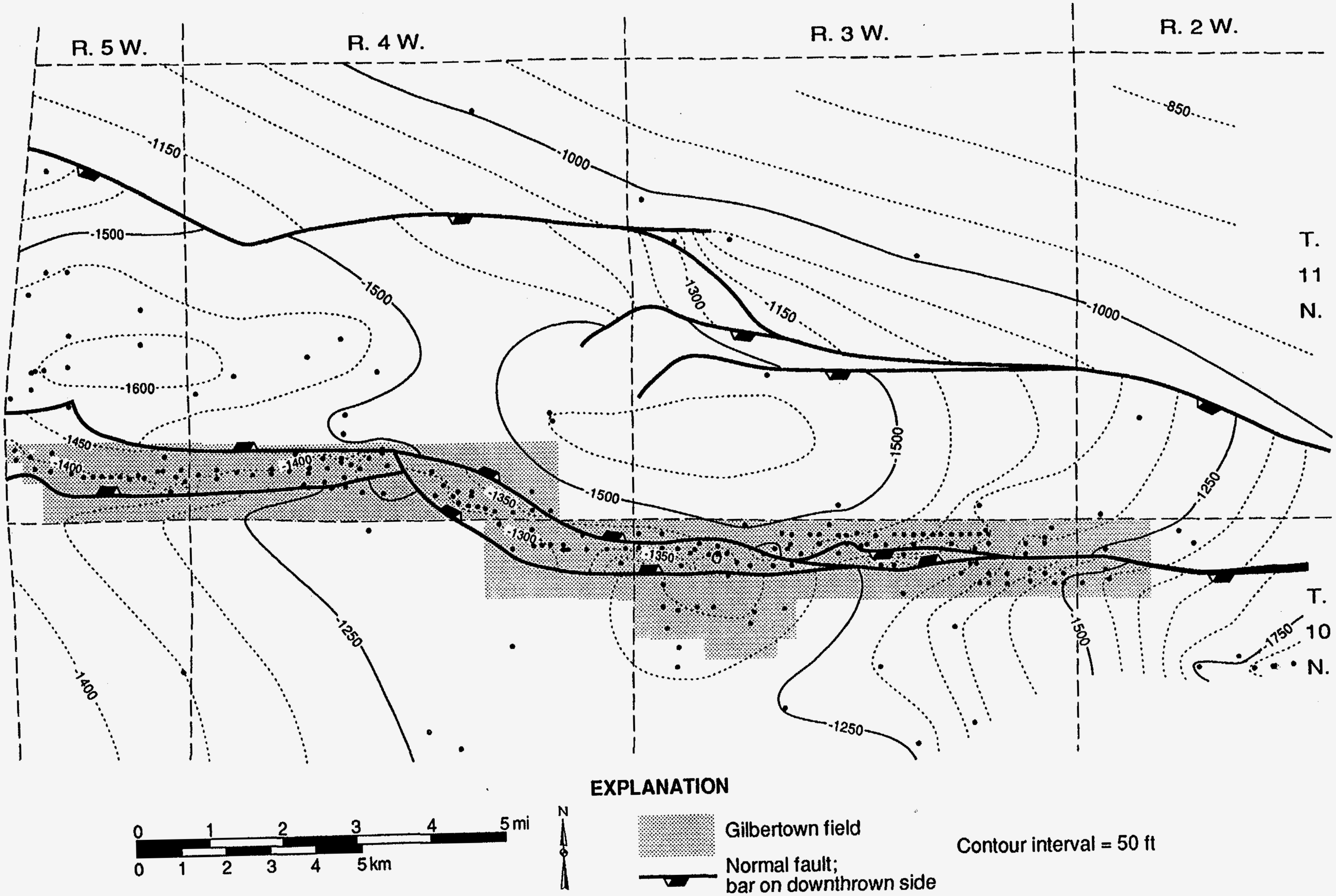

Figure 22.--Structural contour map of the top of the Nanafalia Formation, Gilbertown Field and adjacent areas.

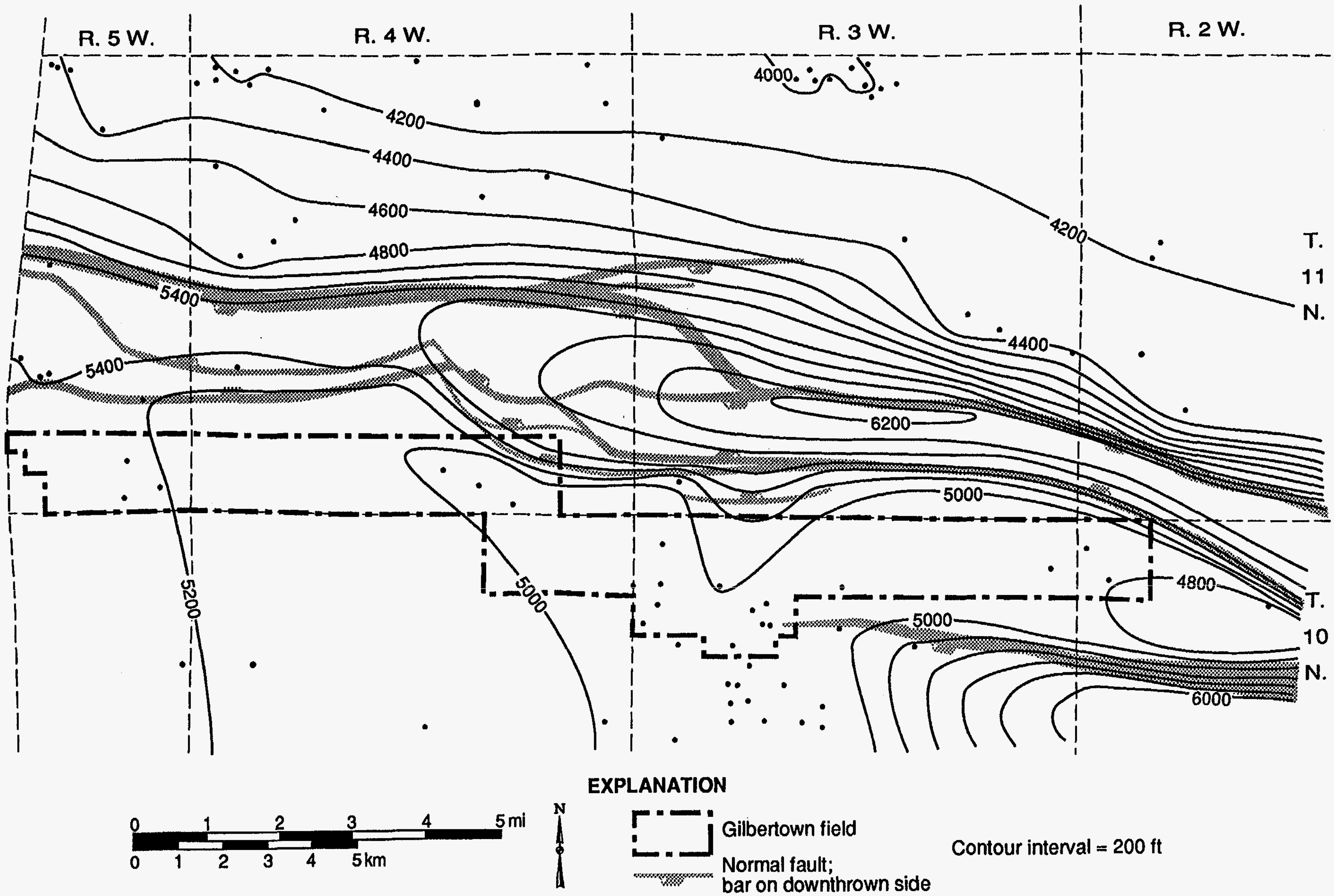

Figure 23.--Isopach map of the Lower Cretaceous section, Gilbertown Field and adjacent areas.

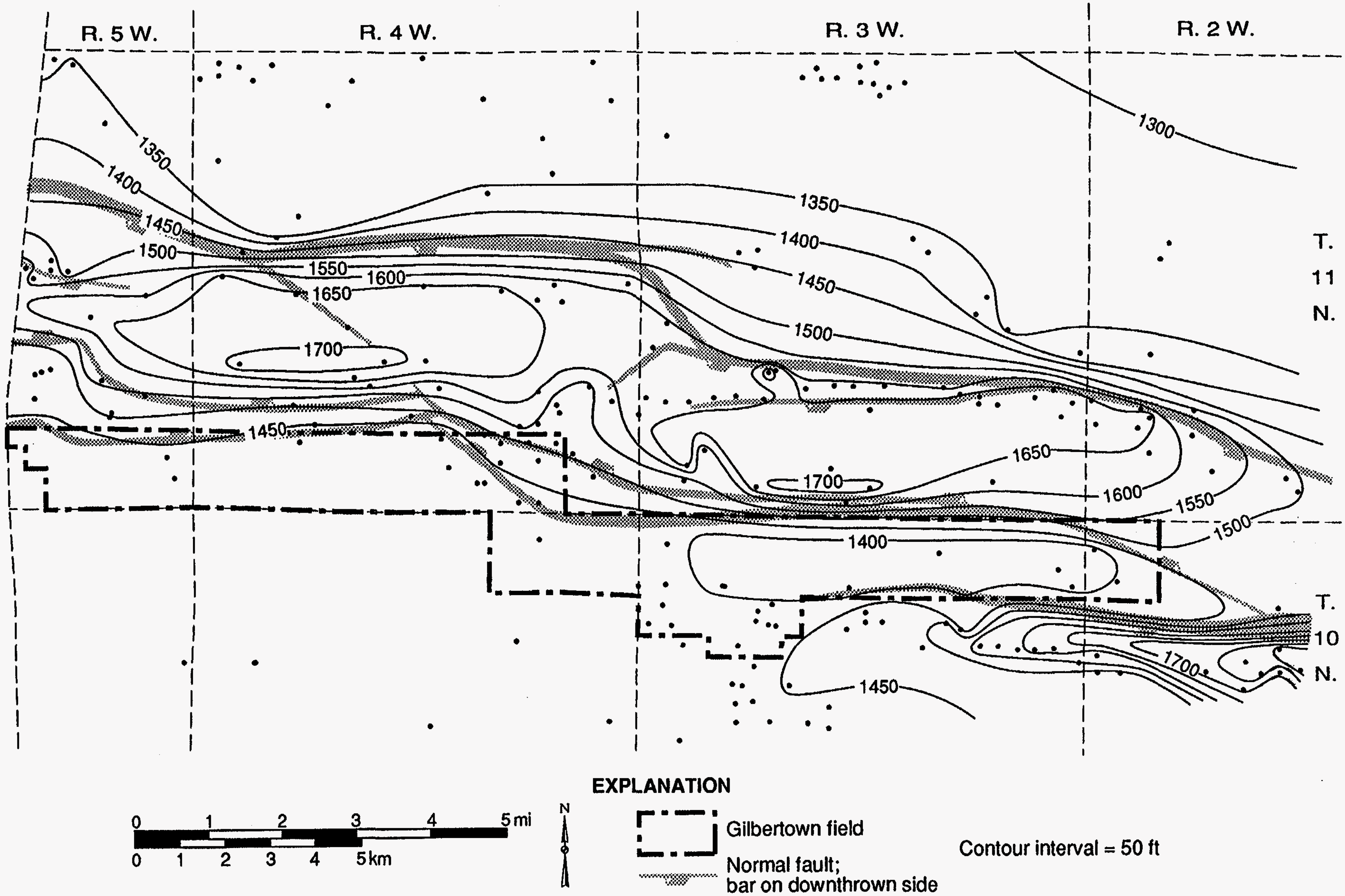

Figure 24.--Isopach map of the combined Upper Tuscaloosa Group and Eutaw Formation, Gilbertown Field and adjacent areas.

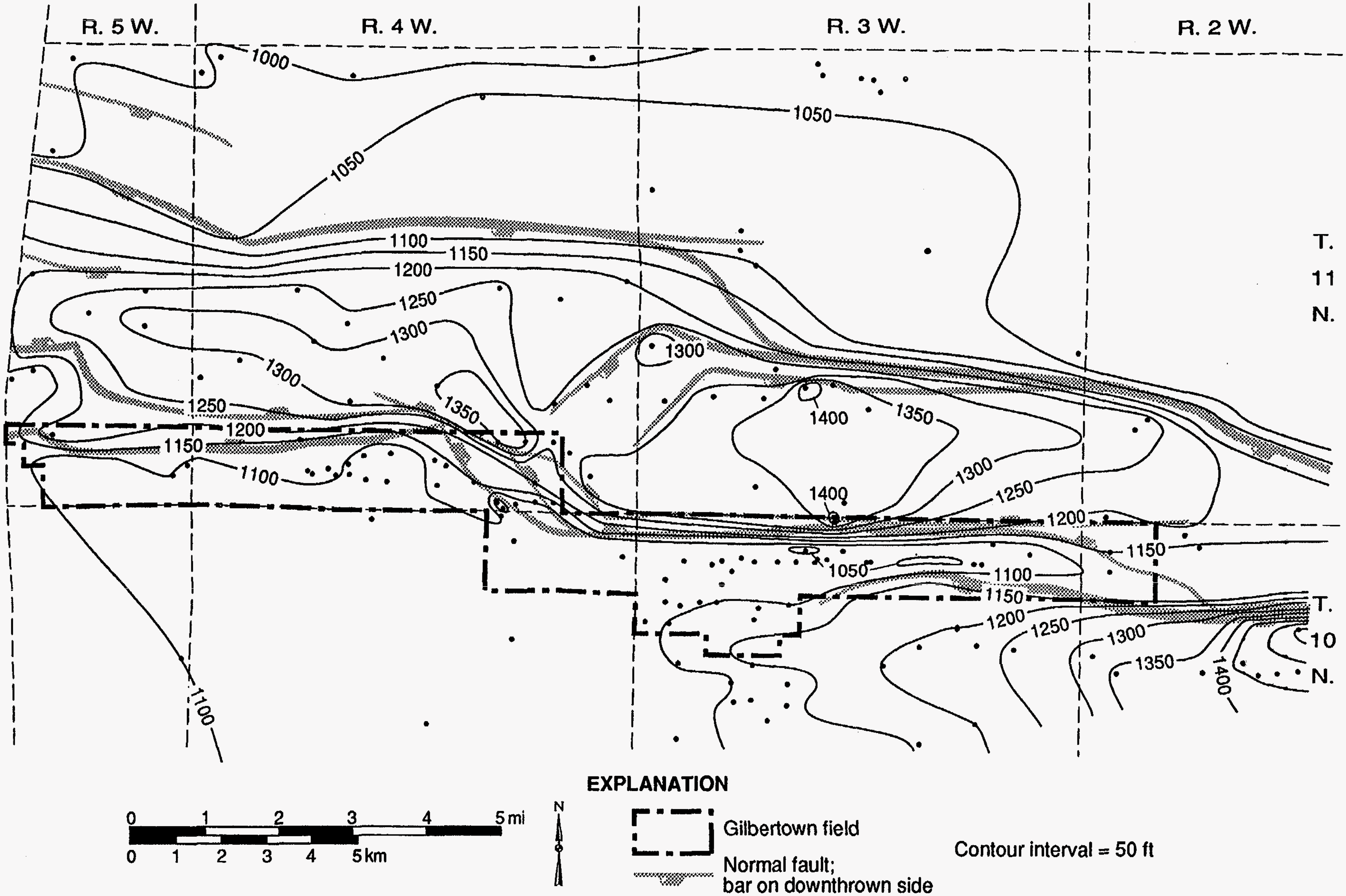

Figure 25.--Isopach map of the Selma Group, Gilbertown Field and adjacent areas.

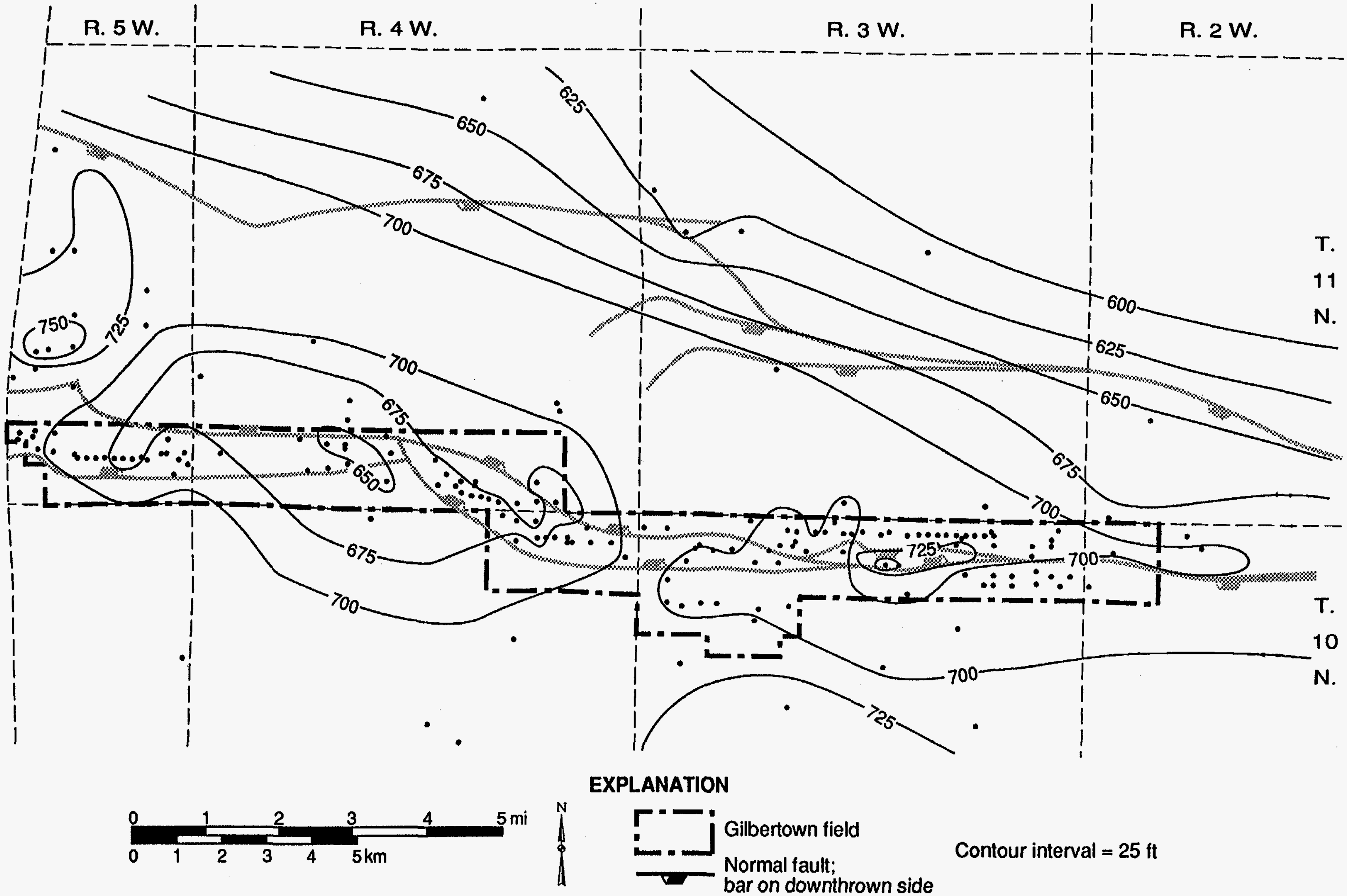

Figure 26.--Isopach map of the Tuscahoma Formation, Gilbertown Field and adjacent areas.

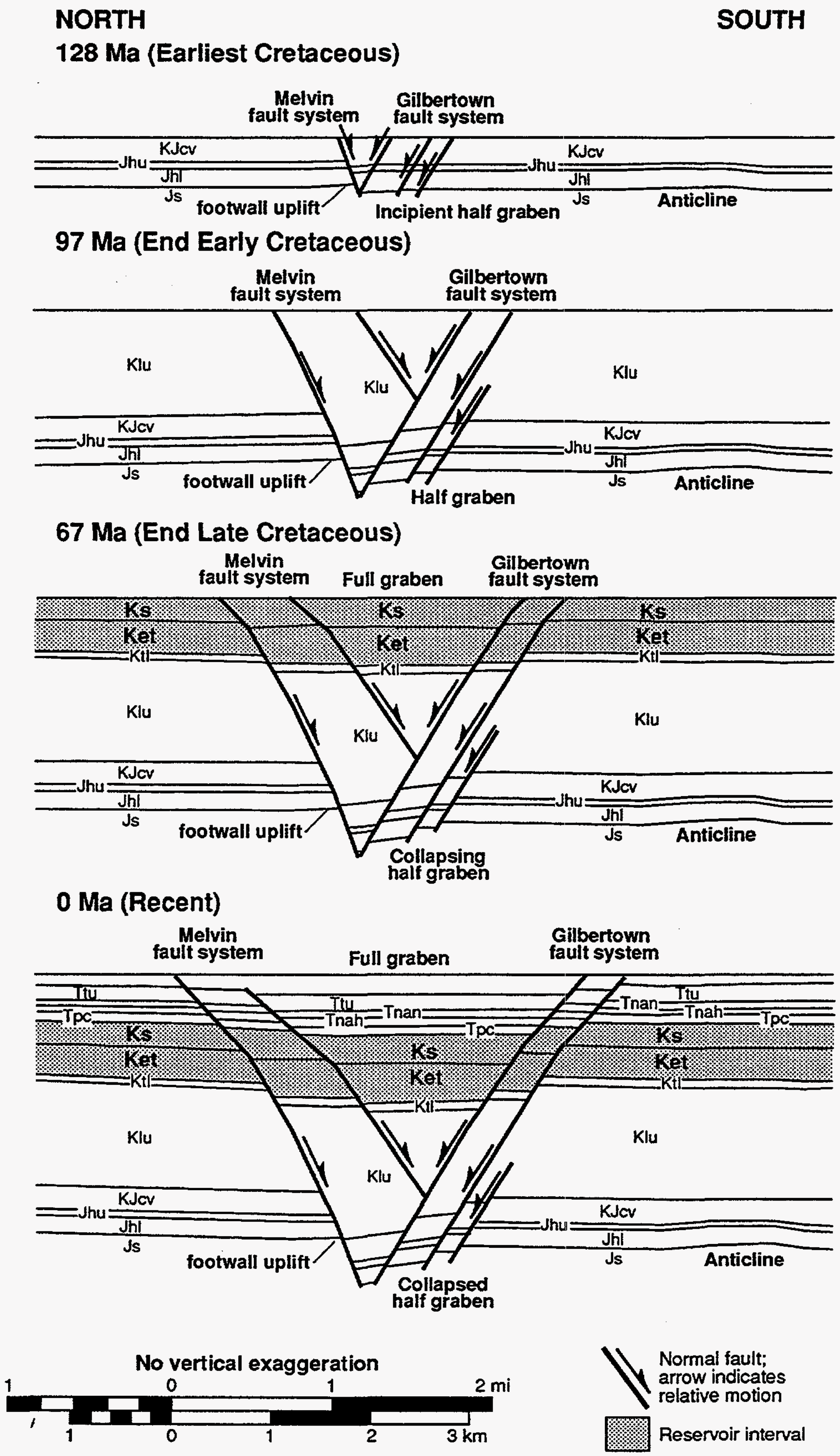

Figure 27.--Sequential restoration showing evolution of the graben formed by the Gilbertown and Melvin fault systems. Restoration based mainly on cross section E-E' (fig. 14).

uplifts in the Jurassic section indicate that the structures began developing early as sediment accumulated above the Louann Salt. Most of the anticlines finished forming prior to deposition of the Lower Cretaceous section. Although these structures were active only for a short time they form significant traps for oil in the Smackover Formation. Footwall uplifts commonly form by accumulation of salt that has withdrawn from below the hanging wall (Hughes, 1968; Jenyon, 1986). Accordingly, the footwall uplifts provide the best evidence that the faults began forming during Jurassic time, because well control in the deepest parts of the graben is sparse. A lesser indication that faults began growing during the Jurassic is that the section is consistently thicker on the south side of the graben than on the north side (figs. 10-17).

Restoration of cross sections indicates that most of the deep structure that is present today had developed by the end of the Early Cretaceous (fig. 27). In the eastern graben segment and the relay zone, the deep structure is that of a half graben in which strata roll over into the Melvin fault system (figs. 13-17). In the western part, alternatively, Jurassic strata roll over into the Gilbertown fault system (fig. 10), indicating development of a half graben of opposite polarity, or are essentially flat-lying (figs. 11, 12), indicating early development of a full graben. The horst appears to have been an essentially stationary structure during this time with only minor deformation of the Jurassic section (figs. 15-17).

Half-graben development dominated the early structural history of the Gilbertown area, but restoration to the top of the Cretaceous reveals a change in overall structural style (fig. 27). In many parts of the graben where Jurassic strata roll over into the Melvin fault system, Upper Cretaceous strata do not exhibit rollover, suggesting that the half graben evolved into a nearly symmetrical full graben. This means that the half-graben rollover began collapsing as the rate of displacement on synthetic and antithetic faults became equal. Locally, however, half-graben formation continued through the Cretaceous. In cross section A-A', for example, Jurassic and Cretaceous strata roll over into the Gilbertown fault system (fig. 10). In the relay zone, by contrast, Jurassic strata roll over into the Melvin fault system, whereas Cretaceous strata roll over into the Gilbertown fault system, thus providing evidence for local reversal of structural polarity during the Cretaceous (fig. 13).

Structural history during Tertiary time is less clear than that during the Cretaceous. Whereas structural growth is readily apparent in Cretaceous units (figs. 10-17, 23-25), growth of Tertiary units across the faults is at best questionable (figs. 10-17, 26), with the exception of the small graben formed by conjugation of East Gilbertown fault A with the West Bend fault (figs. 15, 26). Thus, two possibilities exist for interpreting Tertiary structural history. The first is that most faults ceased moving some time after Selma deposition and were reactivated after deposition of the Tuscahoma Formation. The second possibility is that, although faults may have moved some during the Tertiary, local depositional variability overwhelmed the effect of synsedimentary growth.

The decrease of fault dip near the start of Selma deposition is perhaps the most enigmatic structural event in the Gilbertown area (fig. 27). One interpretation is that dip decreased by refraction of the faults through the chalk, which is more brittle than the shale and sandstone that predominates in the Lower Cretaceous section through the Eutaw Formation. An alternative cause of low fault dip is compaction of the faults with the surrounding sediment (for example, Skuce, 1996). This may be the more appropriate interpretation, because the faults have not been refracted back to a steep dip in the dominantly siliciclastic Tertiary section.

Conjugation of East Gilbertown fault A with the West Bend fault occurred shortly after Selma deposition (figs. 15, 16). Conjugate fault systems typically develop where the tip regions of opposed normal faults with subequal displacement overlap (Nicol and others, 1995). Growth strata provide evidence for simultaneous movement of opposed faults in conjugate systems (Horsfield, 1980), and simultaneous growth is apparent in cross sections and maps of the Gilbertown area (figs. 15, 16, 24, 25, 26).

Most of the major faults appear to propagate to the surface, suggesting movement that is Miocene or younger. However, the faults appear to be inactive today, because none of the structures are associated with topographic scarps, and streams cut freely across the Gilbertown and West Bend fault systems, as well as the Hatchetigbee anticline (Szabo and others, 1988). However, the distribution of faults at the surface is a matter of continuing debate.

GEOLOGIC MAPPING

Investigation of the surface geology in the area of the Gilbertown fault system and Hatchetigbee anticline is providing new insight into the structural evolution of the eastern Gulf Coast basin. Thus far, field work has proven quite challenging, considering that most strata cropping out in the field area are poorly consolidated. Preliminary work, however, has proven rewarding and is helping define the surface traces of faults and is providing the first analytical glimpse of fracture systems in southwest Alabama.

Major faults are frequently expressed at the surface by minor valleys and dips in the terrain, and are rarely or never exposed. Typically, roads dip and fault traces are covered with road fill. However, roadcuts near faults are common, and they can be used to bracket the fault trace and, occasionally, for fracture analysis. Bracketing faults is especially difficult where the Lisbon Formation, which crops out in much of the field area, is faulted against itself. Where the terrain is deeply dissected, members of the Lisbon can be identified, and differences in elevation across the fault can be compared, but this is not possible everywhere. Remotely sensed imagery, which will be examined later in this project, will provide valuable information that can be used to map fault traces in the field area.

Minor faults and joints are exposed in several river bluffs and roadcuts. Previous literature and unpublished notes proved valuable in locating these outcrops. Several large outcrops of Quaternary alluvium, including river bluffs, were examined to determine whether faulting and jointing are ongoing.

The youngest units offset by faults are of Miocene age, whereas Pleistocene terrace deposits and Quaternary alluvium cut across the faults, as well as the crest of the Hatchetigbee anticline. The Quaternary deposits lack joints, although curved fractures and faults are forming as alluvium slumps along the banks of rivers and creeks. By contrast, all river bluffs composed of Tertiary strata are jointed. The joints are typically subparallel to straight segments of the Tombigbee River. The course of the river, therefore, is interpreted to have been determined in part by jointing patterns. Importantly, preliminary assessment of joint patterns suggests little correlation to fault and fold patterns in the Gilbertown area, suggesting that the joints formed in a different regional stress field than the faults.

Exposure of a fault at Coffeeville landing was especially useful for determining the relationship between normal faults and orthogonal joints. Here, a series of faults which are antithetic to the West Bend fault are developed in the Lisbon Formation. The faults have vertical displacement estimated to be 50 feet or greater and are associated with Riedel shears. Between the faults, however, only orthogonal joints and minor faults with displacement less than 3 inches were observed. The orthogonal joints abut the normal faults, indicating that the joints are younger. One possibility is that joints in the study area are near-surface unloading structures and that deep subsurface strain, which is the principal source of heterogeneity in Selma reservoirs, is expressed mainly as normal faults and associated Riedel shears.

RESERVOIR GEOLOGY

The previous sections provide a robust structural framework for characterizing Eutaw and Selma reservoirs, and this section focuses on internal heterogeneity and trapping mechanisms in these reservoirs. Considering that the Eutaw Formation is a conventional sandstone reservoir and that the Selma chalk is a fault-related fractured reservoir, the contrasts between these units in terms of internal heterogeneity are numerous. However, examination of the structural position of productive wells and the associated trapping mechanisms suggests that Eutaw and Selma reservoirs are more closely related than is commonly acknowledged.

Eutaw Formation

In Gilbertown Field, the Eutaw Formation contains 265 to 290 feet of interbedded sandstone, mudstone, and shale (fig. 28). The sandstone is light-olive-gray to yellowish-gray or dark-yellowish-brown, is in part silty and argillaceous, is generally friable, and is locally stained or even saturated with oil. Some oil-saturated sandstone is so poorly cemented that it crumbles when touched. A few sandstone beds are well-cemented and oil-free. Grain size ranges from very fine to coarse sand, and quartz grains are subangular to subrounded. Quartz is the dominant framework grain, and glauconite and muscovite are abundant in most samples. Minor framework constituents include carbonaceous plant fragments, shell fragments, aragonitic prisms, foraminifera, and phosphatic bone material. Calcite, quartz, and kaolinite are the main cements in the sandstone. Vertical burrows are present in some sandstone beds. Shale and mudstone beds are generally brownish-gray to light-olive-gray, micaceous, carbonaceous, in part glauconitic, in part silty, and locally burrowed.

The Eutaw forms a fining- and thinning-upward succession, and on the basis of SP logs, is subdivided into seven distinct and laterally correlative units designated as E1 through E7 (fig. 28). Intervals E3 through E7 were cored in at least one well. Intervals E1 and E2, however, were not cored except for a small section at the top of E2. Oil has been produced from the top of interval E2 through interval E7. Producers consider the Eutaw Formation as low-resistivity, low-contrast pay, and indeed, resistivity of the sandstone is approximately as low as that of the associated shale. In some intervals, however, oil-saturated sandstone is

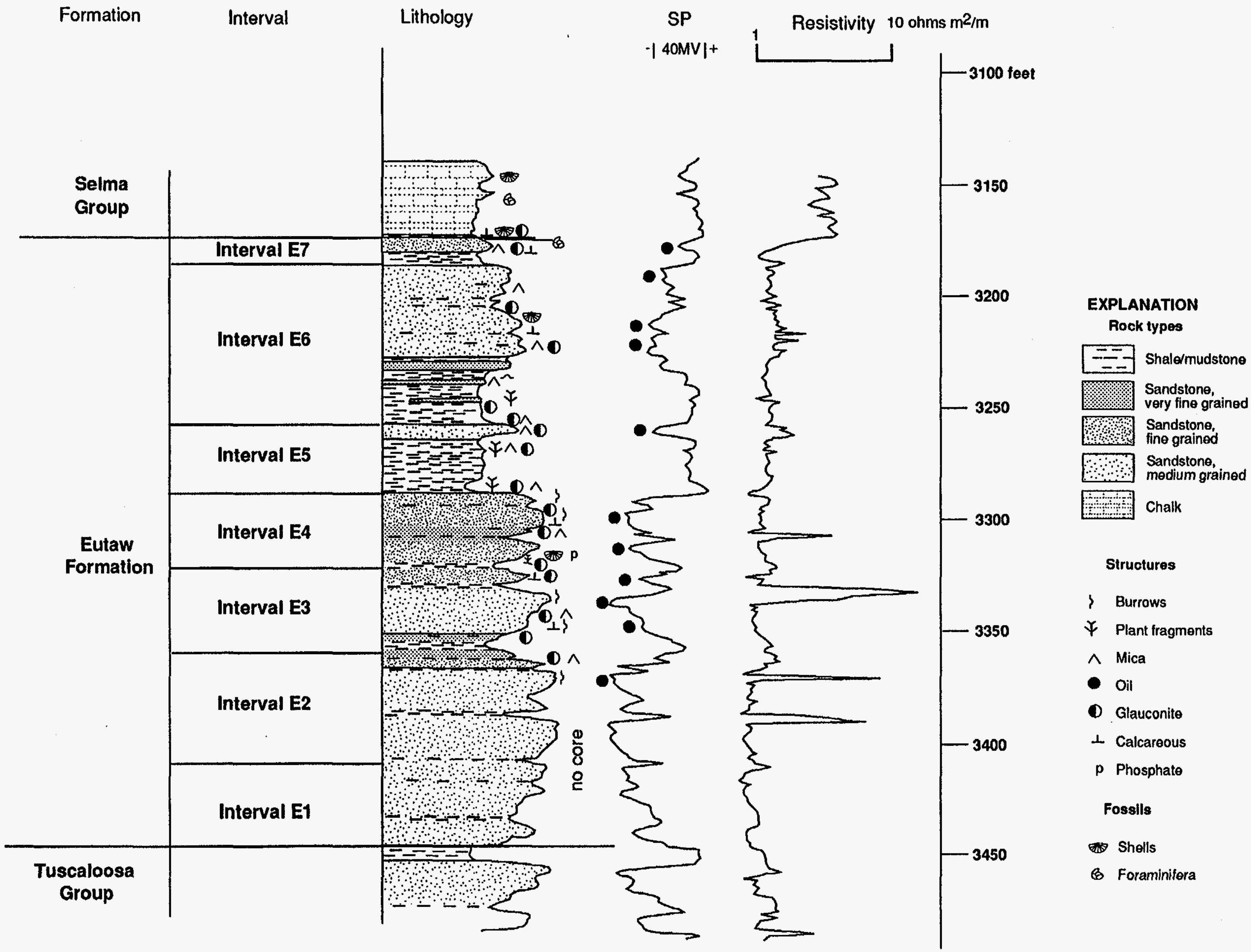

Figure 28.--Composite section and geophysical well log of the Eutaw Formation in Gilbertown Field.

extremely resistive and has a spiked signature in well logs. Even so, productive sand can have very low resistivity, and some calcite-cemented zones and even calcareous shale beds correlate with high-resistivity spikes.

Cross sections demonstrate that the thickness of intervals E1 through E7 is fairly consistent throughout eastern Gilbertown Field (figs. 29-34). However, the cross sections reveal significant facies variations within the intervals. Cross sections V-V' and W-W' indicate that shale content of the Eutaw Formation, especially in intervals E5 through E7, increases from west to east (figs. 30, 31). A similar facies change can be seen from south to north in the field on cross sections X-X', Y-Y', Z-Z' (figs. 32-34).

Well logs indicate that the Eutaw Formation sharply overlies the Tuscaloosa Group. Intervals E1 and E2 consist predominantly of sandstone and are each approximately 80 feet thick (fig. 28). A lack of core in interval E1 and the lower part of interval E2 makes determination of gain size impossible. Burrows are present in the uppermost sandstone of interval E2. Cross section W-W' (fig. 31) indicates that thin shale beds in intervals E1 and E2 pinch out toward the west, thus making the two units indistinguishable. This same type of facies change can be seen on cross section V-V' (fig. 30); however, there is enough shale in the basal section to allow separation of the two intervals.

Sandstone beds in interval E3 are glauconitic and are locally micaceous and calcareous, and vertical burrows are characteristic of the lower sandstone. Interval E3 is approximately 50 feet thick and generally coarsens upward from shale to sandstone (figs. 30-34). Along the northern edge of the field, interval E3 comprises two coarsening-upward couplets of shale and sandstone that total about 40 feet in thickness. Along the most of the southern edge, by comparison, only one coarsening-upward succession can be distinguished from the SP logs (fig. 31).

Interval E4 is about 35 feet thick. Facies within this interval vary considerably across the study area and typically contain a coarsening-upward shale-sandstone succession overlain by two fining-upward sandstone-shale successions that are commonly separated by a shale parting (figs. 30-34). Plant fragments are present in the lower part of the sandstone at the base of interval E4. The lower E4 sandstone locally contains phosphate, shell fragments, and aragonite prisms. Vertical burrows are characteristic of the upper sandstone in interval E4.

Interval E5, the shaliest interval in the Eutaw Formation, is 30 to 35 feet thick. The interval coarsens upward and is composed predominantly of sandy shale overlain by a bed of medium- to very coarse-grained sandstone that is glauconitic and micaceous. Carbonaceous plant fragments, mica, and glauconite are present in the upper and lower parts of the shale interval. The sandstone forming the top of the interval is one of the best stratigraphic markers within the Eutaw Formation but is locally shaly in the east-central part of the field (figs. 30-34).

Interval E6 is about 70 feet thick and is composed of interbedded sandstone and shale. At the base is a shale containing glauconite grains and carbonaceous plant fragments. Horizontal burrows were noted in the upper part of the basal shale. At the top of the interval is medium-grained sandstone containing thin interbeds of shale that give the interval a distinctive, serrate log signature. Phosphate and plant fragments are common in the middle of the interval, and shells were noted in the upper part. The sandstone content of interval E6 generally increases toward the west.

Interval E7, the thinnest interval, is only about 10 feet thick and consists of shale overlain by fine-grained sandstone, which is in turn overlain sharply by the Selma chalk (fig. 28). This sandstone is locally very glauconitic and is probably equivalent to the Tombigbee Sand Member of the Eutaw Formation. The sandstone is locally cemented with calcite and contains foraminifera, mica, and glauconite at the top. The sandstone extends throughout most of Gilbertown Field but passes into shale in the east central part (figs. 30-34).

Little can be said with confidence about the depositional environments of the Eutaw Formation in Gilbertown Field, because a lack of continuous core prevents identification of bedding sequences and sedimentary structures. Investigators in other parts of Alabama have interpreted the Eutaw Formation as transgressive beach and shelf deposits (Frazier and Taylor, 1980; Cook, 1993), and the Eutaw of Gilbertown Field is perhaps best considered in terms of this general framework. The sharp base and thinning- and fining-upward succession of the Eutaw is compatible with a transgressive origin, and presence of shells and foraminiferan tests in the core samples confirms deposition in marine environments (fig. 28). However, abundant plant fragments in some sandstone and in shale indicate input of sediment from terrestrial environments. A distinctive characteristic of the Eutaw Formation in Gilbertown Field is the widespread distribution and uniform thickness of intervals E1 through E7, which suggest deposition of vertically stacked shoreface and shelf sediment, rather than deposition of prograding barrier islands containing tidal inlets and channels.

Oil is produced from the Eutaw Formation mainly in the footwall block of West Gilbertown fault A and in the faulted anticline and horst defined by East Gilbertown fault A and the West Bend fault (fig. 35). Productive wells in the western part of the field are concentrated in a small footwall uplift immediately south of West Gilbertown fault A, and wells that have produced more than 100,000 barrels of oil are in the most elevated part of the footwall uplift (figs. 20, 35). In the eastern part of the field, wells that have produced

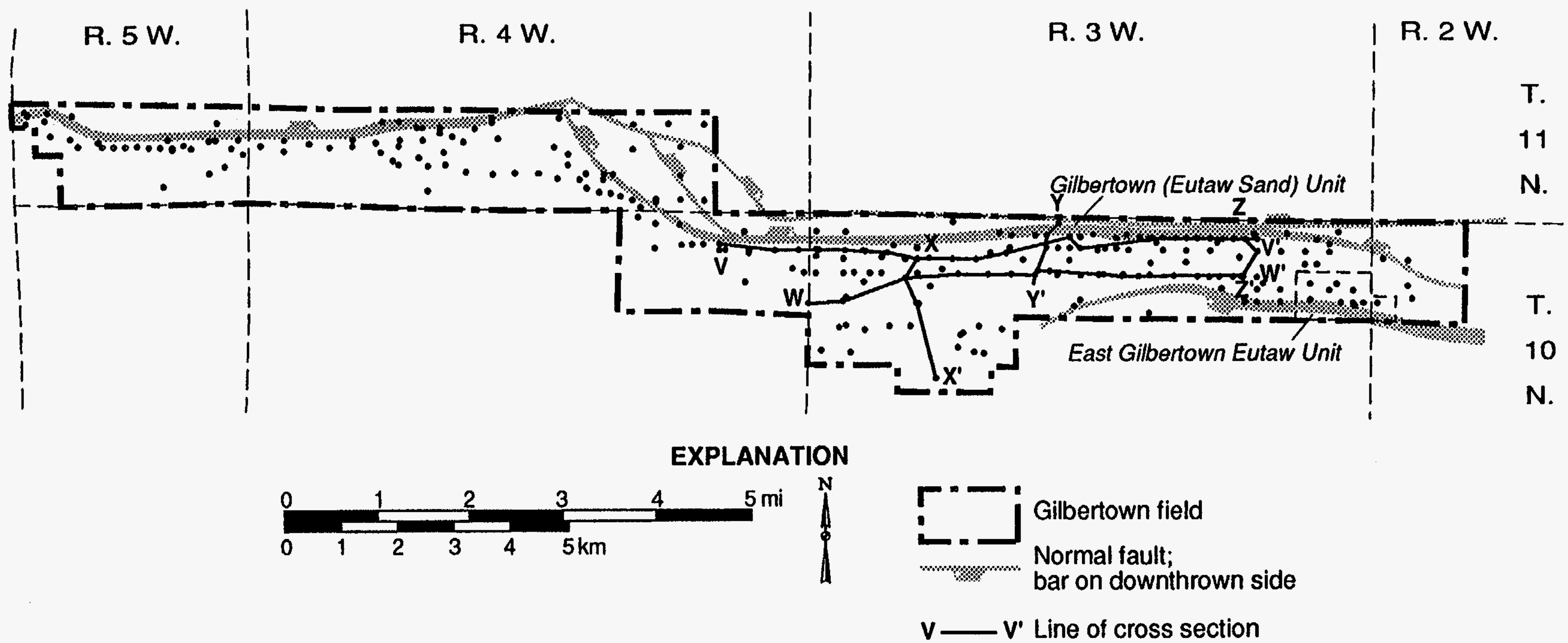

Figure 29.--Index map showing location of stratigraphic cross sections of the Eutaw Formation, eastern Gilbertown Field.

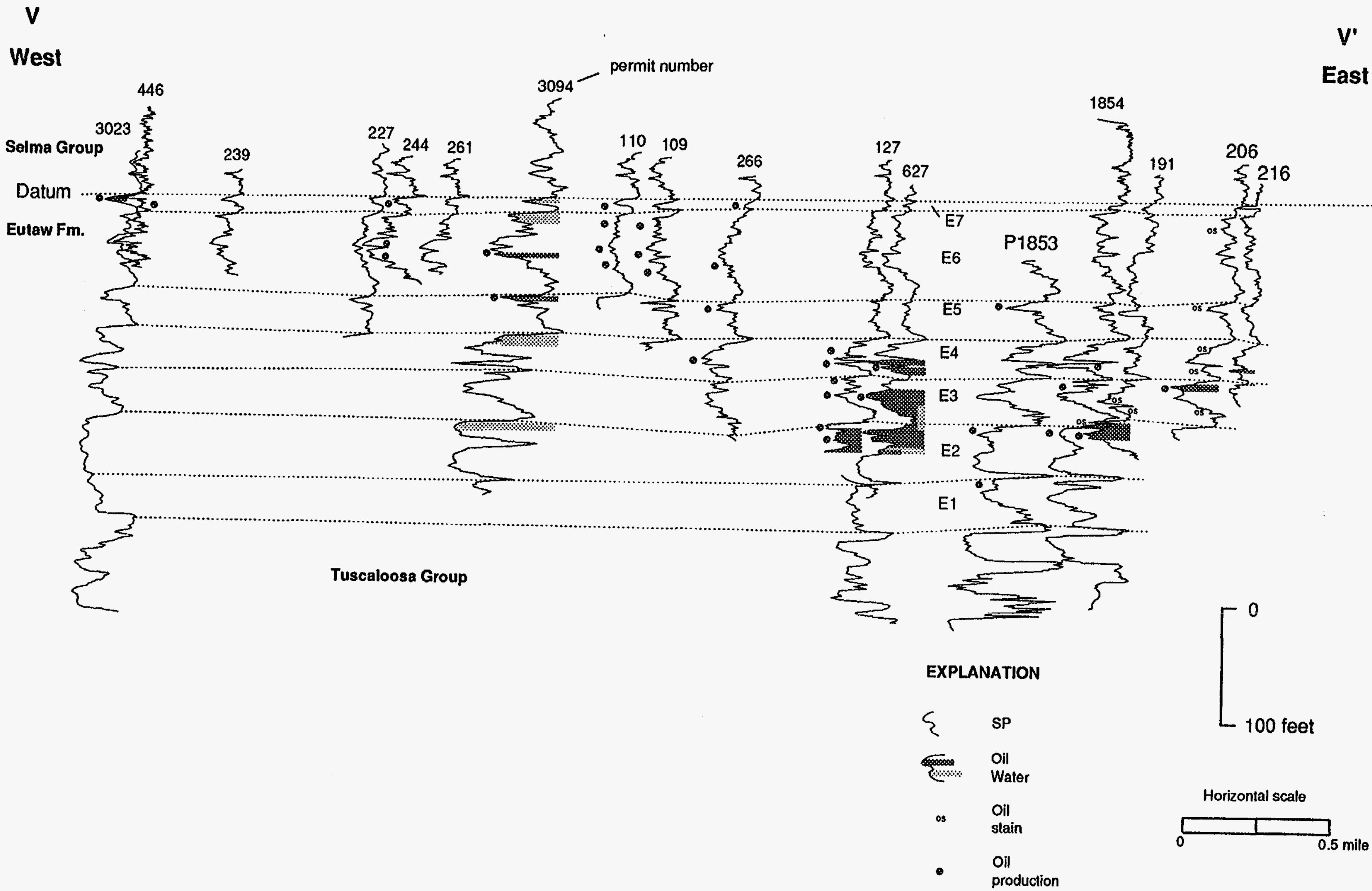

Figure 30.--Stratigraphic cross section V-V' of the Eutaw Formation, eastern Gilbertown Field. See figure 29 for location.

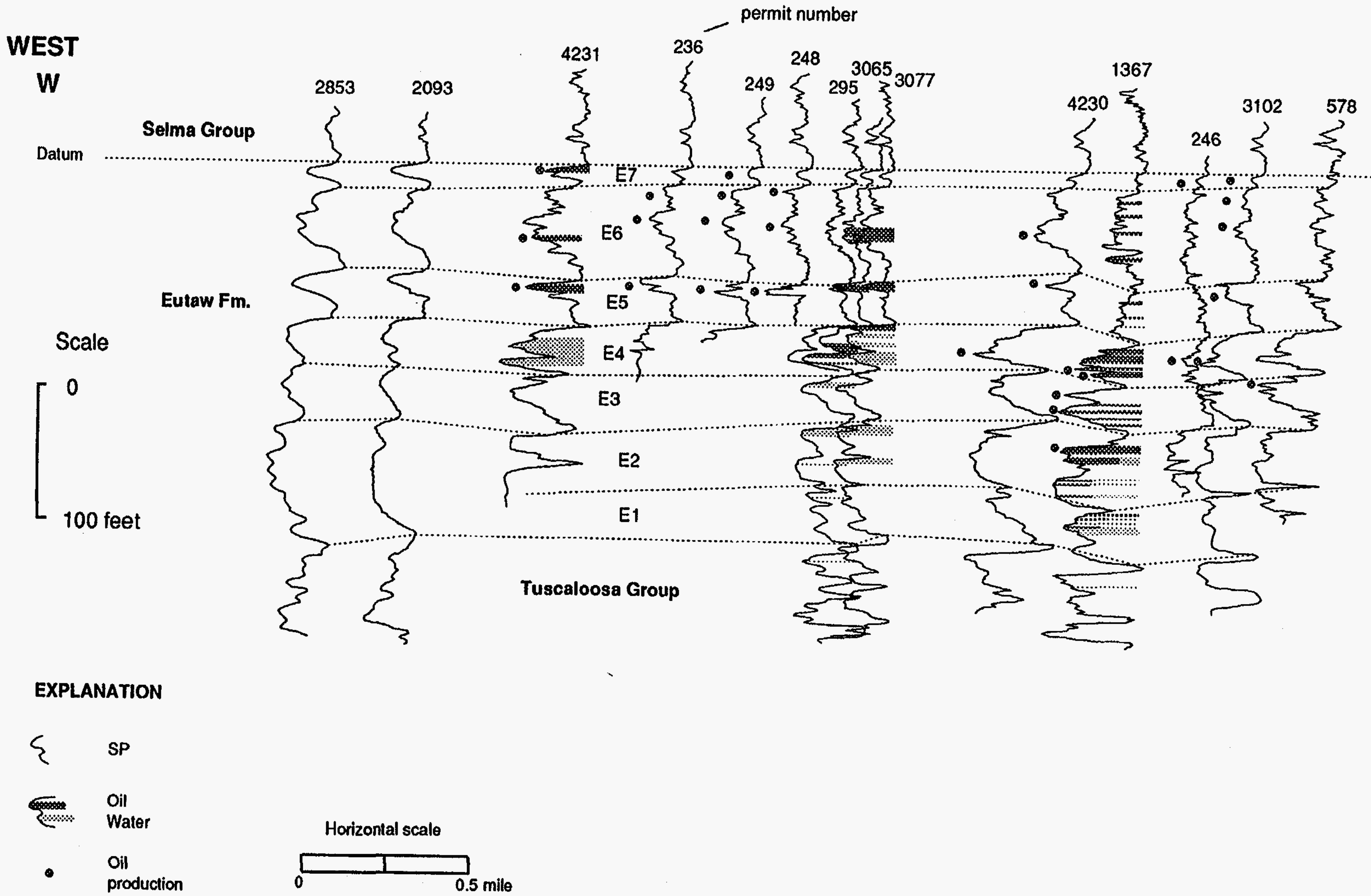

Figure 31.--Stratigraphic cross section W-W' of the Eutaw Formation, eastern Gilbertown Field. See figure 29 for location.

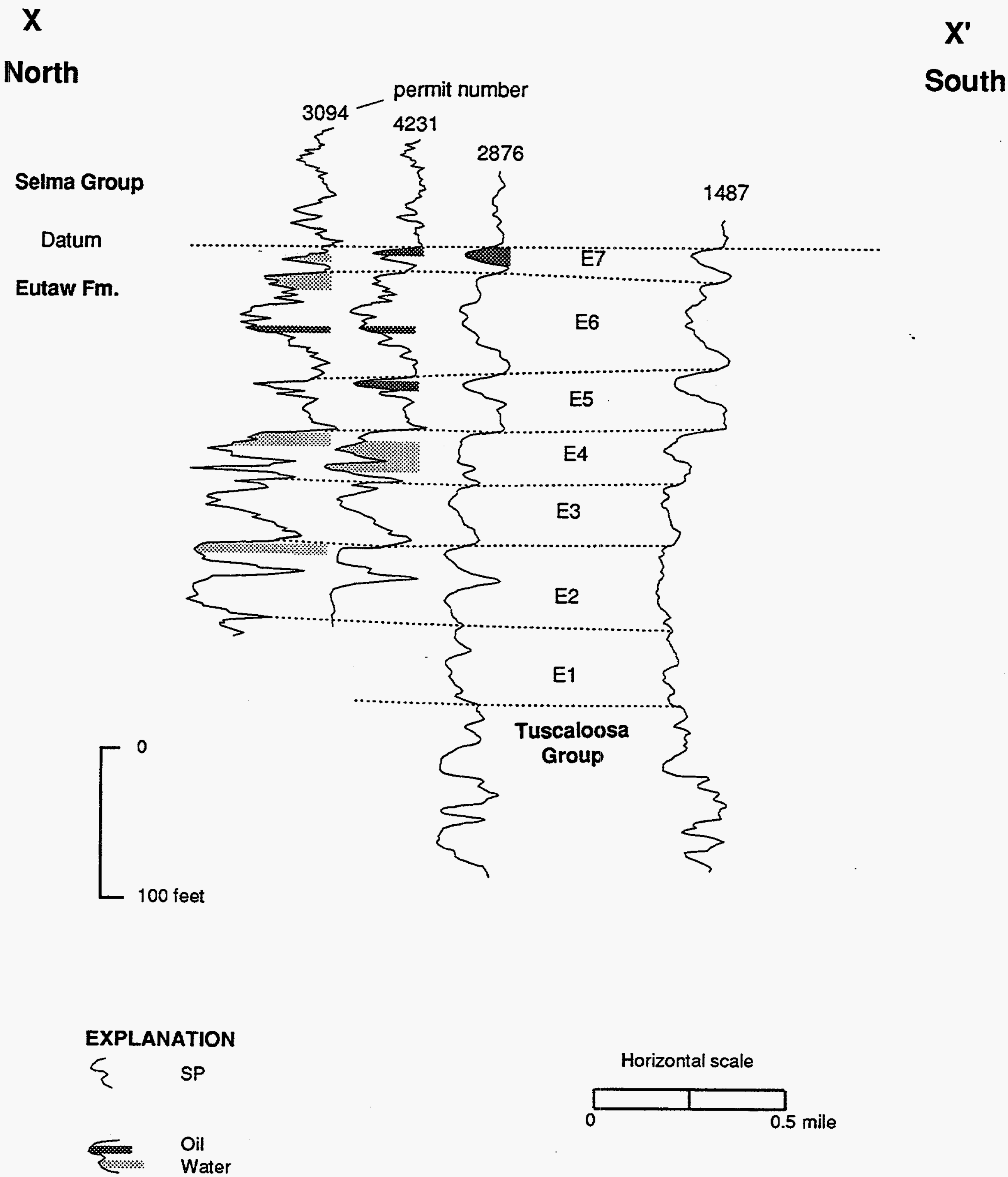

Figure 32.--Stratigraphic cross section X-X' of the Eutaw Formation, eastern Gilbertown Field. See figure 29 for location.

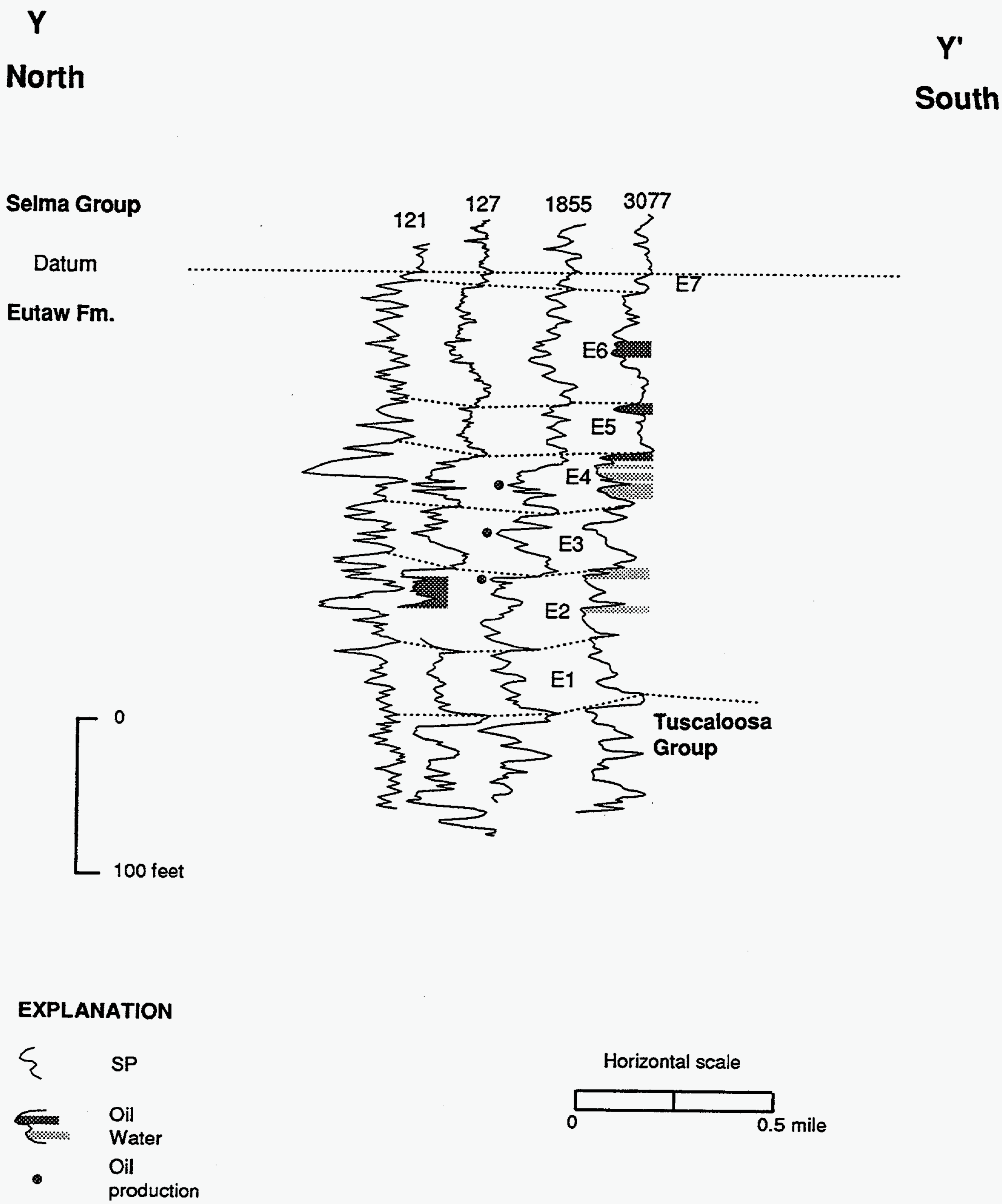

Figure 33.--Stratigraphic cross section Y-Y' of the Eutaw Formation, eastern Gilbertown Field. See figure 29 for location.

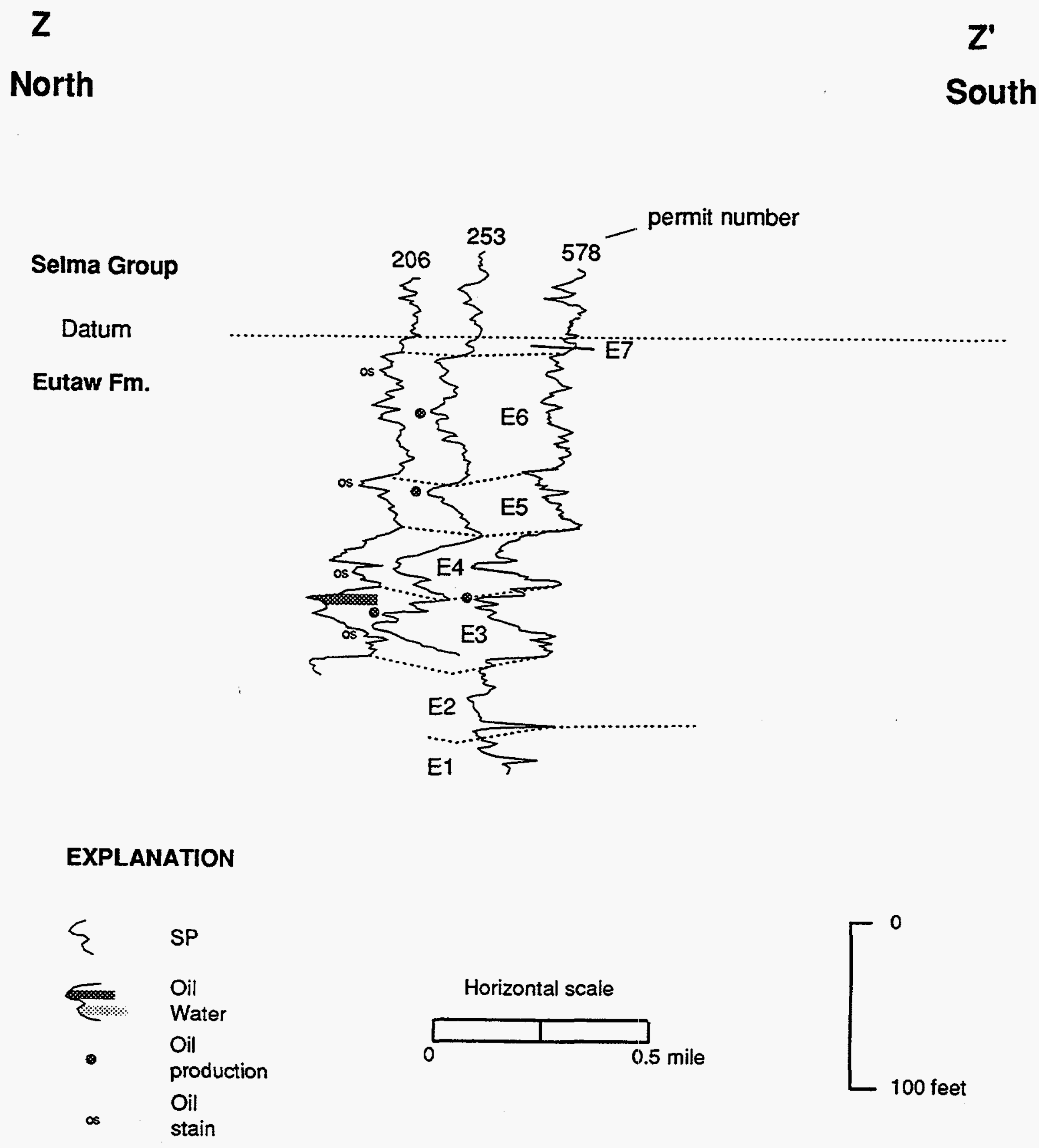

Figure 34.--Stratigraphic cross section Z-Z' of the Eutaw Formation, eastern Gilbertown Field. See figure 29 for location.

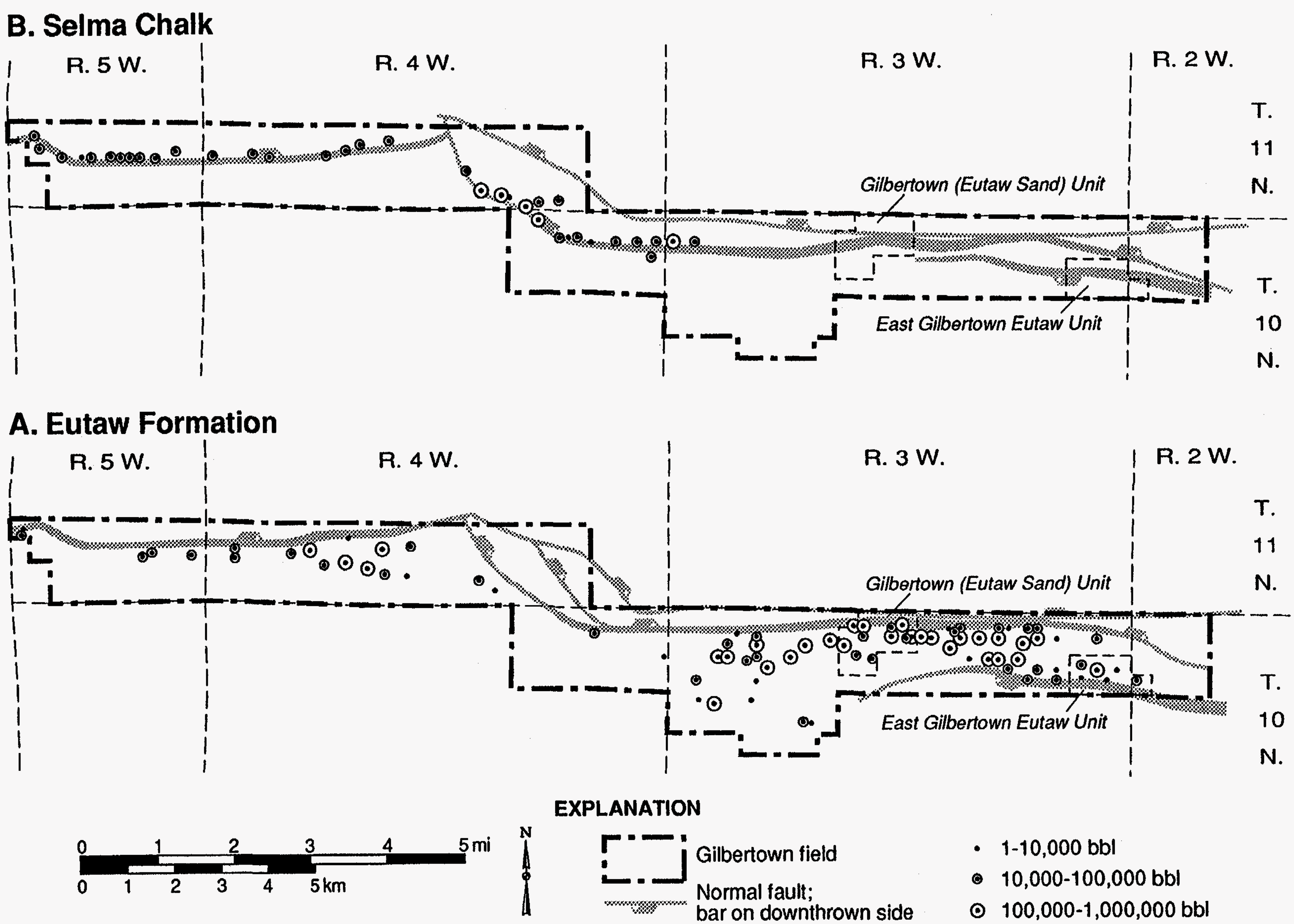

Figure 35.--Relationship of oil production to fault patterns in the Eutaw Formation and Selma Group, Gilbertown Field.

more than 100,000 barrels are distributed throughout the horst and faulted anticline.

Localization of productive wells in structural highs indicates that conventional trapping mechanisms are effective, but comparison of well logs, core analyses, and completed zones in the eastern part of the field reveals considerable internal heterogeneity (figs. 30, 31). Core analyses indicate that oil-wet sandstone is concentrated in numerous thin zones in the upper part of the Eutaw, whereas water-wet sandstone is most common in the lower part. In the western part of cross section V-V', the Eutaw produces oil mainly from intervals E4 through E7 (fig. 30). In the eastern part of the cross section, which is in the structurally highest part of the horst, oil is produced mainly from intervals E2 through E4. A similar trend is apparent in cross section W-W', although intervals E5 through E7 are productive along the length of the cross section (fig. 31).

Selma Chalk

Chalk is effectively impermeable to oil and water, thus all production from the Selma Group in Gilbertown field is from faults and fractures. Identifying faults and quantifying fault displacement in the Selma requires detailed correlation of well logs. As will become apparent in the following discussion, however, determining the extent of fault-related fractures and productive reservoir in the Selma Group is extremely difficult.

Correlating well logs reveals a distinctive internal stratigraphy within the Selma Group that can be recognized throughout the Gilbertown area (fig. 36). Eight intervals, labeled S1 through S8, could be identified in Selma Group. Interval S1 sharply overlies Eutaw Sandstone and is distinguished by higher resistivity than other parts of the Selma Group. The other intervals can be distinguished by changes in spontaneous potential (SP). Intervals with negative deflection on the SP curve tend to have lower resistivity than those with a positive deflection. Examination of well samples indicates that, despite significant variation of geophysical log properties, lithologic variation within the chalk is minimal. In general, intervals with a negative SP deflection are slightly darker and more micaceous than other intervals.

A calcisphere packstone corresponding to the Arcola Member of the Mooreville Chalk was identified at the depth of a thin, negative-SP marker near the middle of the Selma Group (fig. 36). The Arcola Member marks the top of the Mooreville Formation. In the upper part of the Selma Group, intervals with a negative SP deflection correlate provisionally with the Bluffport Member of the Demopolis Chalk (interval S6) and the Prairie Bluff and Ripley Formations (interval S8). The Selma Group is overlain by the Clayton Formation, which is a sandy limestone thinner than 20 feet. The Clayton Formation has high resistivity similar to the Selma Group and positive SP similar to that of the shale of the overlying Porters Creek Formation.

Each Selma Group interval can be correlated throughout the Gilbertown area, and missing intervals can be used to identify faults and, hence, areas of historic, ongoing, and potential oil production (fig. 37). Oil-bearing fluids in the fault zones commonly form zones of exceptional resistivity, such as in permit 97, thus making identification of the faults and the main pay zones simple. In other wells, like permits 2984 and 73, the fault zones have no distinctive signature and can thus be located only by recognizing missing stratigraphy. This variability of log response in wells that have produced oil makes evaluation of productive intervals extremely difficult.

The Selma Group has produced oil only from faults in the western part of Gilbertown field, and comparison of Eutaw and Selma production patterns suggests that oil was trapped in the faults by leakage from the Eutaw (fig. 35). Oil production is associated with only two faults, namely West Gilbertown fault A and East Gilbertown fault A. Oil has been produced nearly along the full length of West Gilbertown fault A, whereas Selma production is restricted to the western part of East Gilbertown fault A. Completed zones are generally in the upper 500 feet of the chalk, and the seal for Selma reservoirs appears to be shale of the Porters Creek Formation. Cumulative oil production from wells that have produced from West Gilbertown fault A are relatively consistent, typically on the order of 10,000 barrels. Cumulative production is more variable along East Gilbertown fault A, especially in the relay zone where four wells have produced more than 100,000 barrels.

Vertical separation of the faults appears to have little to do with oil production from Selma chalk in most areas. Along East Gilbertown fault A, vertical separation at the top of the Selma Group only locally exceeds 150 feet (fig. 21). Similarly, vertical separation at the top of the Selma Group along East Gilbertown fault A in the relay zone is typically less than 100 feet. Absence of oil along East Gilbertown fault A east of the relay zone is difficult to explain, but local contact of the Selma Group with the Naheola Formation (fig. 15), suggests that the seal formed by the Porters Creek Formation is broken in the horst and that some oil has leaked to younger strata.

Completion of successful wells as much as 500 feet below the top of the chalk indicates development of a tall oil column extending along the full length of West Gilbertown fault A. Along East Gilbertown fault A, by contrast, successful wells are typically completed in the upper 200 feet of the chalk. Productive wells are concentrated where the top of the Selma Group in the

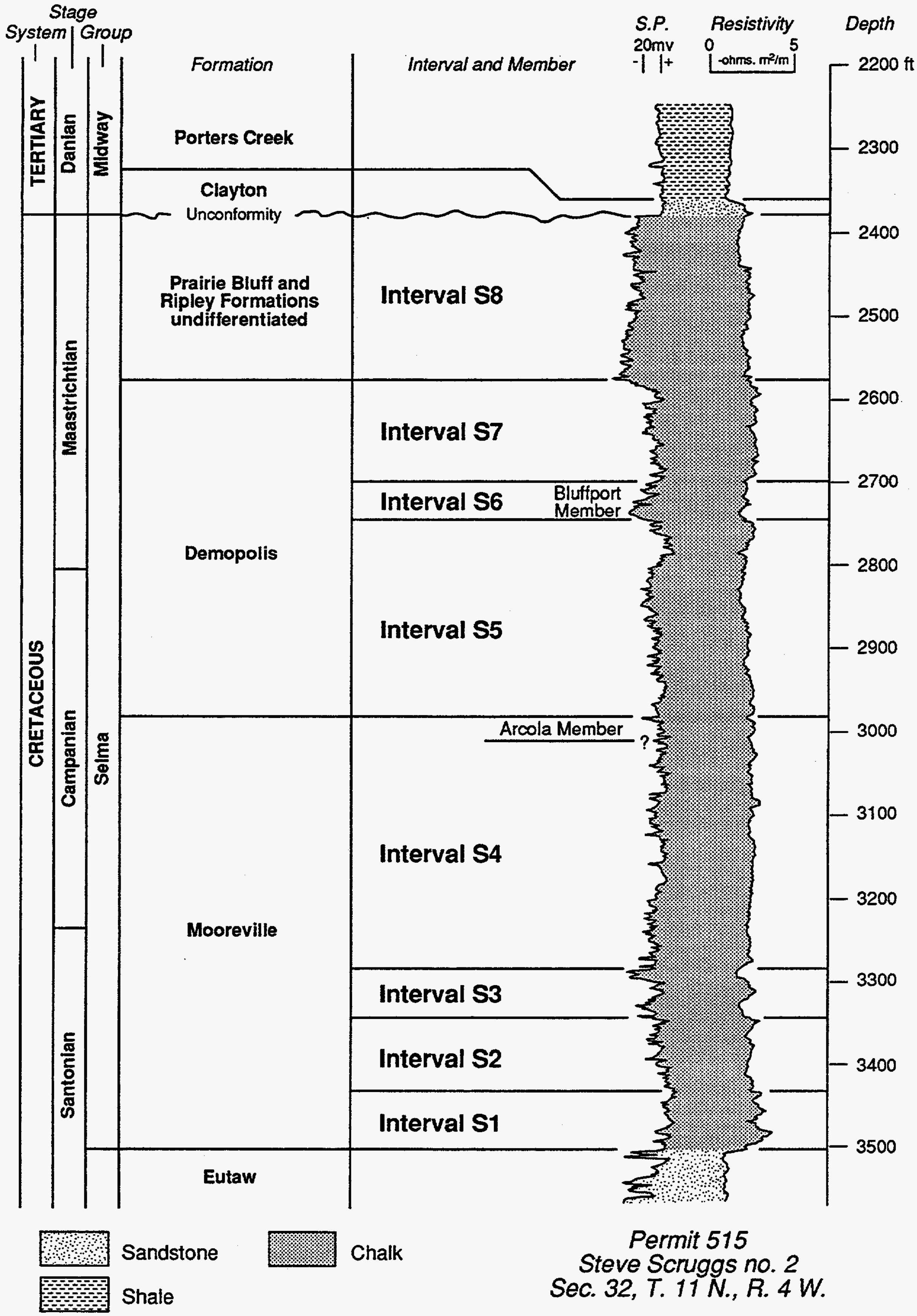

Figure 36.--Stratigraphy of the Selma Group, Gilbertown Field and adjacent areas.

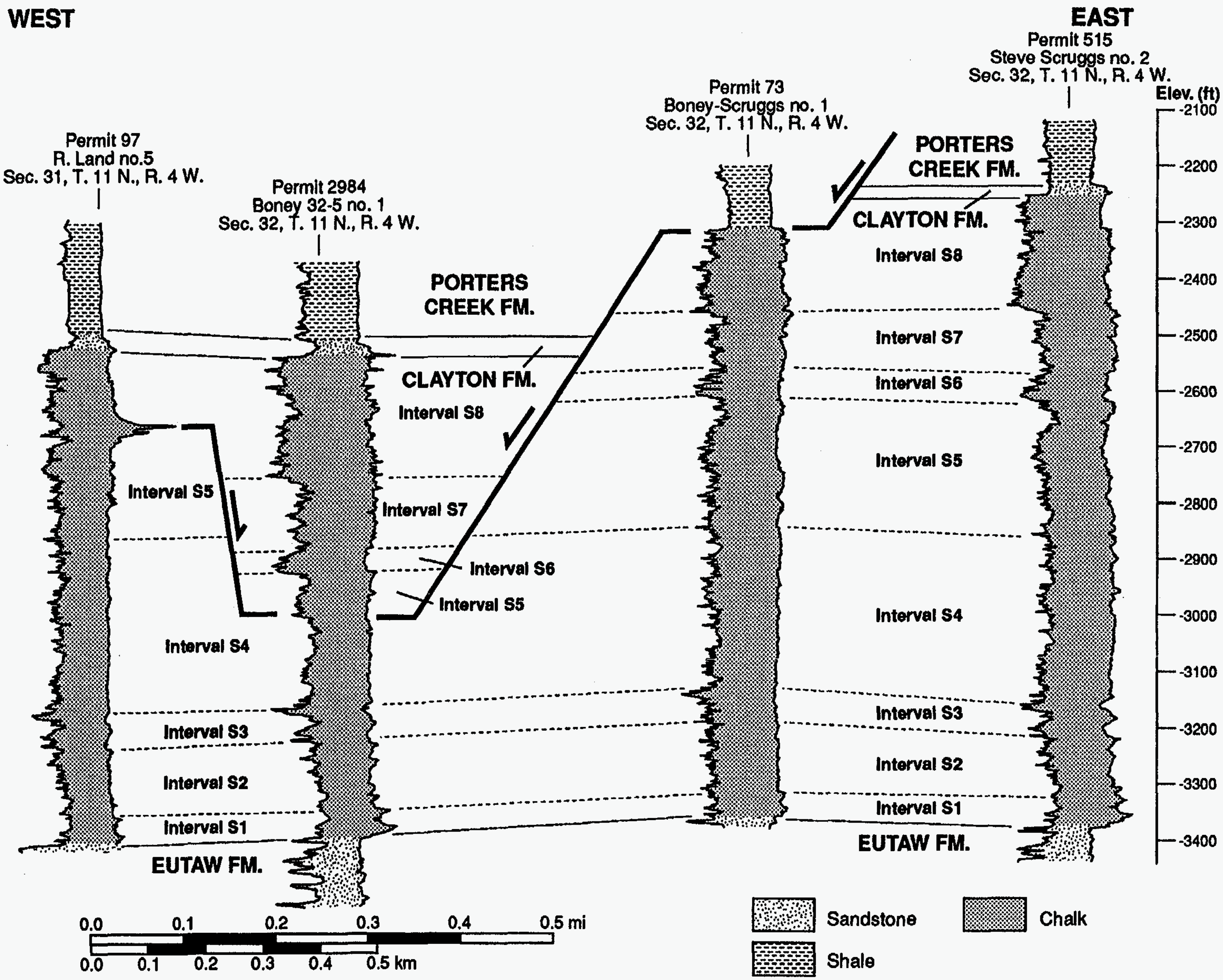

Figure 37.--Correlation of selected well logs penetrating West Gilbertown fault A, Gilbertown field.

hanging wall is higher than 2,350 feet below sea level, suggesting that oil has accumulated conventionally where the fault seal is most elevated.

STRUCTURAL MODELING

Structural modeling of the Gilbertown area began last quarter, and significant progress has been made. Three-dimensional modeling of structures in Gilbertown Field and adjacent areas is underway and is playing a critical role in visualizing the structural complexities of Eutaw and Selma reservoirs. Other efforts have centered on balancing cross sections of the Gilbertown fault system. Preliminary results indicate that salt motion and synsedimentary growth are important variables that need to be accounted for before requisite strain can be calculated.

Three-Dimensional Structural Modeling

A three-dimensional model of structure in the Gilbertown area is being developed using the GeoSec3D computer program (fig. 38). The resulting three-dimensional solid model of the structure is critical for visualization and area balancing because the cross sections to be interpreted must be straight and represent the best possible projections of the data onto the line of section. Incorrect projections (or crooked-line sections between wells) contain distortions that will significantly affect the area balance (Groshong and Epard, 1996). The best projection method for a data set derived from wells is based on structure contouring every marker bed and every fault and requiring that the fault maps be compatible with the basic data derived from well logs. At the level of precision that can be obtained from area balancing and required for fracture prediction, small differences of interpretation are potentially important. Once the three-dimensional model is complete, the computer program will produce the straight-line cross sections required for the final interpretation. Correlated marker beds and fault surfaces can be mapped within the program or can be output to other programs like Geographix for other analytical procedures, such as curvature mapping, which will be performed later in this project.

After the data are input to GeoSec3D, three-dimensional modeling requires defining the nearest-neighbor connections between all data points for all marker beds and faults. Once the nearest neighbors are defined, the surfaces can be contoured. The process of neighbor identification and contouring is iterative and is designed to resolve data conflicts. A typical problem is that a fault surface does not contour smoothly, indicating that two or more fault cuts have been assigned erroneously to the same fault surface. Bed surfaces must be truncated at the faults so that the beds are contoured correctly. Step offsets in the marker bed maps are a good indication of the presence of faults. Determination of the best fault correlations depends on the determination of the fault offsets of all marker beds on both sides of the fault up, down and along the fault surface. This form of interpretation is virtually impossible using structure-contour maps developed independently for each bed and fault. Although difficult and time-consuming, three-dimensional computer visualization enables simultaneous treatment of beds and faults.

Area Balancing

Key problems in balancing cross sections of the Gilbertown area include salt movement and synsedimentary growth. The possibility of salt withdrawal is recognized from a vertical shift of the regional surface at the top of the Cotton Valley Group across Melvin fault A in cross section C-C' (fig. 39). In area-constant structures not associated with salt withdrawal, by contrast, the regional surface should be continuous across a graben for all beds. The dip of the regional is about the same on both sides of the graben from the top of the Selma Group to the top of the Haynesville Formation, which indicates that the graben developed above a planar lower detachment.

Above the top of the Cotton Valley Group, the regional continues without offset across the graben from the hanging wall to the footwall (for example, the regional of the top Selma Group) (fig. 39). This indicates that displacement or withdrawal of salt above a dipping lower detachment ceased by this time. Extension and graben formation continued during deposition of the Cretaceous units, but on a lower detachment that was parallel to regional dip. Layer-parallel sliding on the remaining salt is the probable cause.

Area-depth measurements for cross section C-C' (fig. 39) are given in table 1. Lost area measurements for all marker beds from the top of the Cotton Valley Group and lower are made from the hanging-wall regional for reasons explained below. The reference level for depth measurements is arbitrary as long as it is the same for all marker beds. The level selected is the base of the Louann Salt, which was projected along regional dip to the center of the graben. The regional surface for measurement of the Lower Cretaceous and

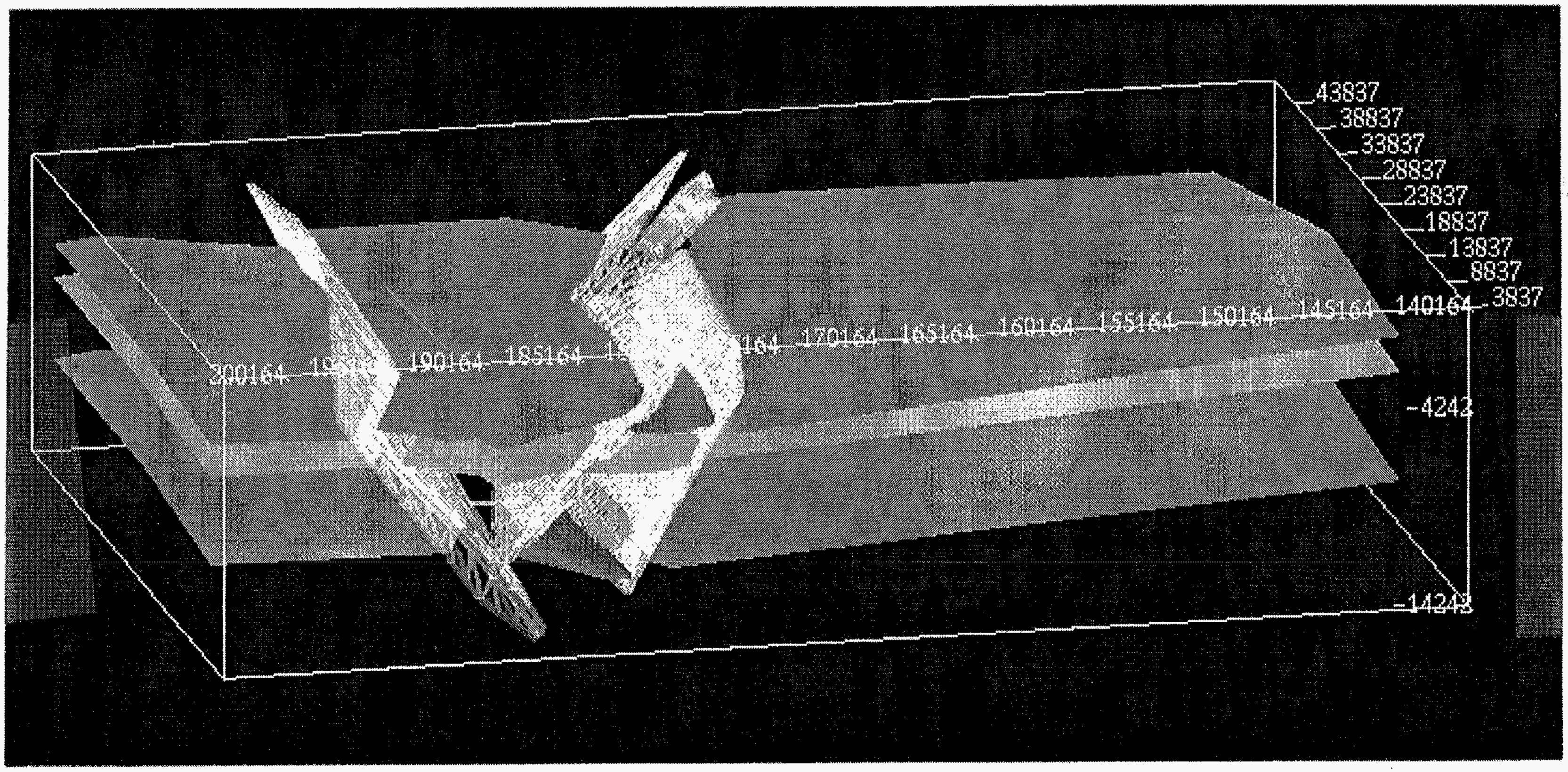

Figure 38.--Three-dimensional computer model of the Gilbertown and Melvin fault systems, western Gilbertown Field. North is to the left.

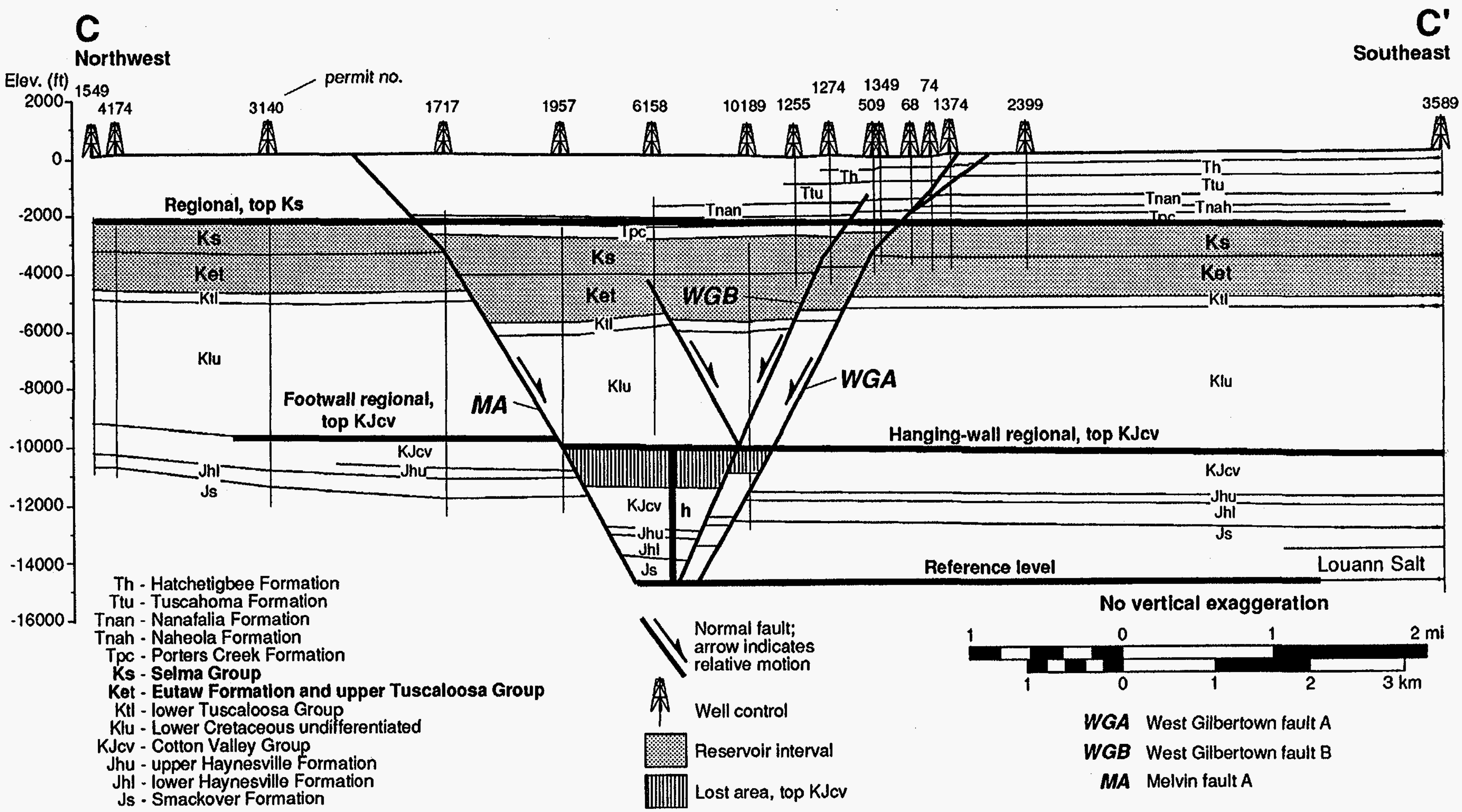

Figure 39.--Interpretation of cross section C-C' showing reference level at base of salt, offset regional surface at the top of the Cotton Valley Group, and uniform regional surface at the top of the Selma Group. See Figure 9 for location of cross section.

Table 1.--Area-depth data derived from cross section C-C'. HW = hanging wall used as reference level for area measurement, FW = footwall. The reference level is the projected base of Louann Salt at the center of the Gilbertown graben.

Unit Top	Graben Area (kft^2)	FW uplift (kft^2)	Net Area (kft^2)	Depth to Reference (kft)
Ks	-7.52	-	-7.52	12.37
Ket	-9.54	-	-9.54	11.24
Ktl	-10.94	+0.19	-10.75	9.87
Klu	-11.00	+0.31	-10.69	9.45
KJcv HW	-8.47	-	-8.47	4.44
Jhu HW	-6.25	-	-6.25	2.93
Jhl HW	-5.75	-	-5.75	2.57
Js HW	-4.48	-	-4.48	1.83

younger units is a line connecting regional dip on both sides of the graben. Lower Cretaceous strata and the lower Tuscaloosa Group contain small footwall uplifts above the regional on the northeast side of the graben.

The data are plotted on an area-depth diagram (fig. 40). Where footwall uplifts are developed, the correct method for area balancing is to measure the net area (algebraic sum) of the hanging wall and footwall combined (Groshong, 1994), which is the value plotted. The lower four marker beds fall on the least-squares regression line, $S = -1.51\ h - 1.78$, which has a coefficient of determination of 1.0, indicating a very good fit. However, this line is simply a product of the way the cross section was constructed, because only the vertical separation of fault cuts can be used to estimate the elevation of Cotton Valley and older markers in the graben. Regardless, the depth to detachment predicted using the Jurassic markers is 1.18 kilofeet below the reference level. The upper four marker beds clearly do not fall on this line and show a trend of upward-decreasing lost area. As discussed in the next sections, the reasons for the shift of regional and upward-decreasing lost area are salt movement and synsedimentary fault growth.

The downward shift of the regional in the Cotton Valley Group has two possible causes. The first is salt withdrawal from the lower side (fig. 41), and the second is displacement on a dipping lower detachment (fig. 42). Extrusion of salt along with the extensional displacement results in an area-depth diagram in which most of the units record the correct displacement but project to a shallower detachment (fig. 41). The shallow predicted detachment is at the original level of the top of salt. The lower units record more displacement and define a portion of the area-depth line that gradually curves to predict the correct deformed-state detachment level. Displacement on a dipping lower detachment results in a downward shift of the regional (fig. 42). The area-depth relationship derived from the false regional is linear. However, this relationship predicts a displacement that is too small and a detachment location that is too shallow.

In addition to shifting regional related to salt withdrawal, synsedimentary growth is the other variable that may significantly affect area-depth relationships in the Gilbertown area. Within growth structures, younger units are not displaced as far as the older units. Moreover, growth structures have a boundary displacement that decreases upward to zero at the cessation of growth. An area-depth diagram can be constructed if deposition occurs completely across and outside the structure such that the regional for each younger unit is always farther above the lower detachment than the regional of the previous unit (fig. 43). For a constant displacement rate, the boundary line is inclined an angle α from the vertical in the growth beds. The area-depth curve has two segments. In the pre-growth units the relationship is the straight line given by equation 2. In growth units, however, the relationship is a curve:

$$S = Dh - h(h - h_u) \tan \alpha + S_a \qquad (6)$$

where h is a depth to the reference level for horizons in the growth sequence, h_u = elevation of the top of the pre-growth units above the reference level, and α = angle of tilt of the pin line caused by growth.

The modeled area-depth plot closely resembles that derived for cross section C-C' (figs. 40, 43). This suggests strongly that structural growth is the main factor contributing to non-linearity of the area-depth plot (fig. 40). The true detachment for the Gilbertown and Melvin fault systems is probably the base of the Louann Salt, but the area-depth plot predicts a deeper detachment. One explanation for this is associated basement faulting, but considering that basement faults typically extend down to mid-crustal detachments or deeper, a better explanation may be that the predicted detachment is simply the product of a linear projection based on growth strata. Thus, a more reasonable area-depth plot would be a curve connecting the data points to the true detachment (fig. 40). Another result of this exercise, moreover, is that false hanging-wall regional has less of an impact on detachment prediction than synsedimentary growth in the Gilbertown area. If false regional were a dominant factor, the detachment would have been predicted above the reference level rather than below. This result suggests that growth is the critical factor that must be incorporated into the basic theory of area balance to develop methodology for calculating requisite strain in Gilbertown Field.

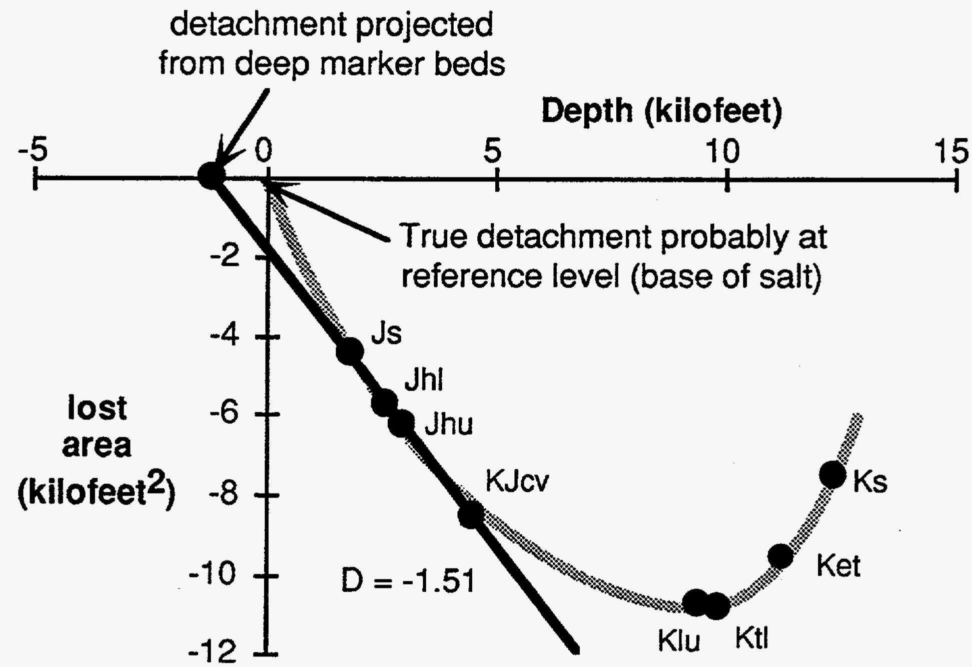

Figure 40.--Area-depth plot of cross section C-C' (fig. 39).

BURIAL HISTORY

The distribution of hydrocarbons in the Gilbertown area raises questions about the burial and thermal history of the eastern Gulf Coast basin. The only field producing hydrocarbons from post-Jurassic strata in this area is Gilbertown; all other fields in the area produce from the Norphlet and Smackover Formations. Importantly, geochemical data establish that oil in Gilbertown Field has a strong affinity with source rocks in the Smackover Formation, suggesting migration of hydrocarbons into submature Cretaceous reservoirs from deep sources (Claypool and Mancini, 1989). Thus, a close association exists between extensional faulting, burial, and the generation and migration of hydrocarbons in the Gilbertown area, and this association merits detailed investigation to understand the origin and distribution of oil in fractured chalk reservoirs.

Analysis of burial history and hydrocarbon generation in the Gilbertown area is in an early stage, and work to date has focused on analyzing basin subsidence history based on a well (permit 3589) that penetrates the Louann Salt (fig. 44). To analyze the complete subsidence history of the region, the Oligocene-Miocene section, which is preserved in parts of the study area but is not logged in wells, was added to the section. The total effective subsidence curve shows decelerating subsidence from the Jurassic into the Miocene, followed by a brief episode of unroofing that continues today.

Decelerating subsidence curves are typical of successions deposited in extensional basins and reflect lithospheric contraction as the crust cools during the late stages of rifting (Sclater and Christie, 1980). Factoring out the tectonic component of subsidence reveals some key characteristics of basin formation in southwestern Alabama (fig. 44). Tectonic subsidence was apparently a significant component of total subsidence during the Jurassic and Early Cretaceous. However, the curve flattens significantly during the Cretaceous, indicating that the crust was effectively

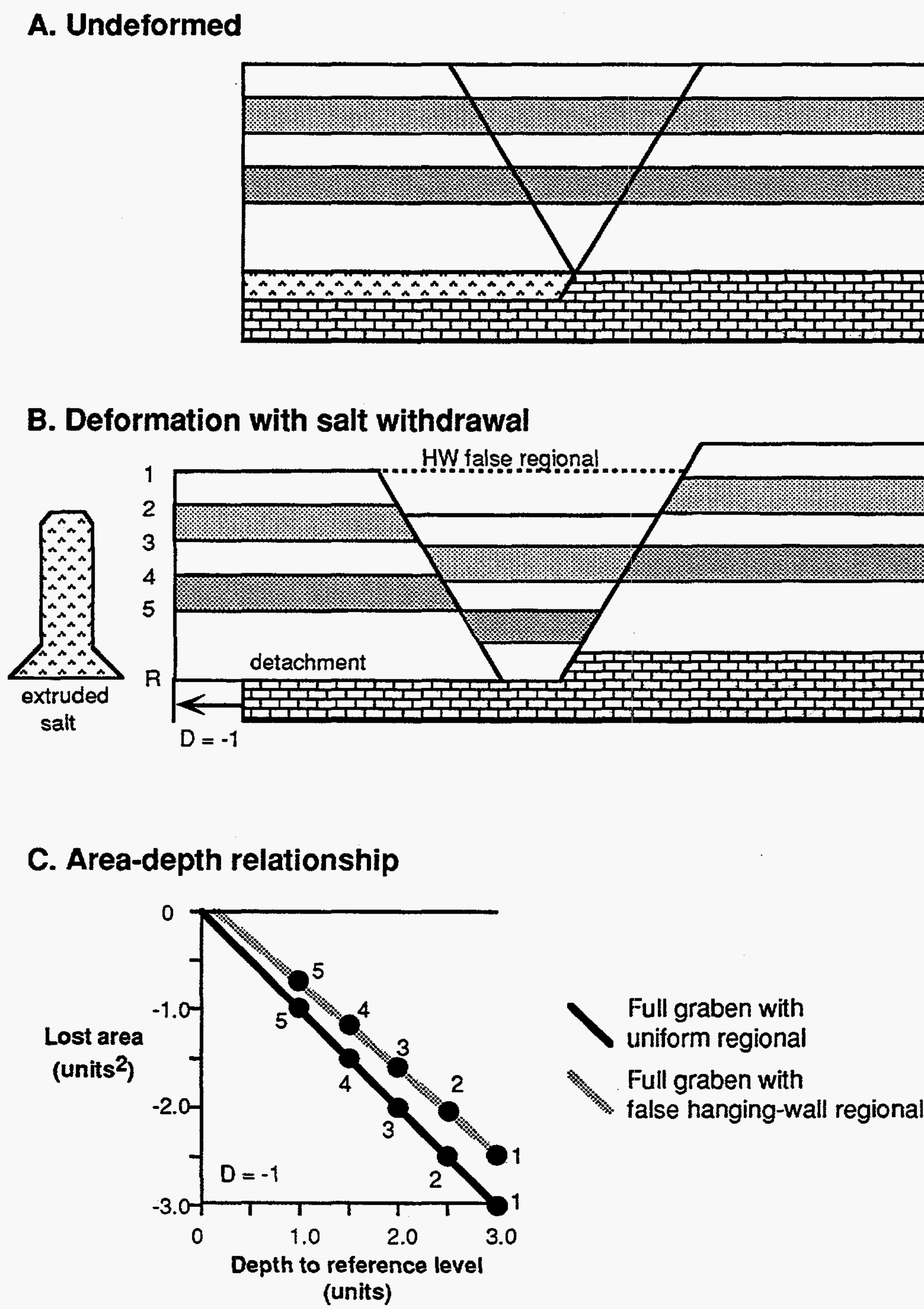

Figure 41.--Area-depth model of full graben formed above laterally migrating salt.

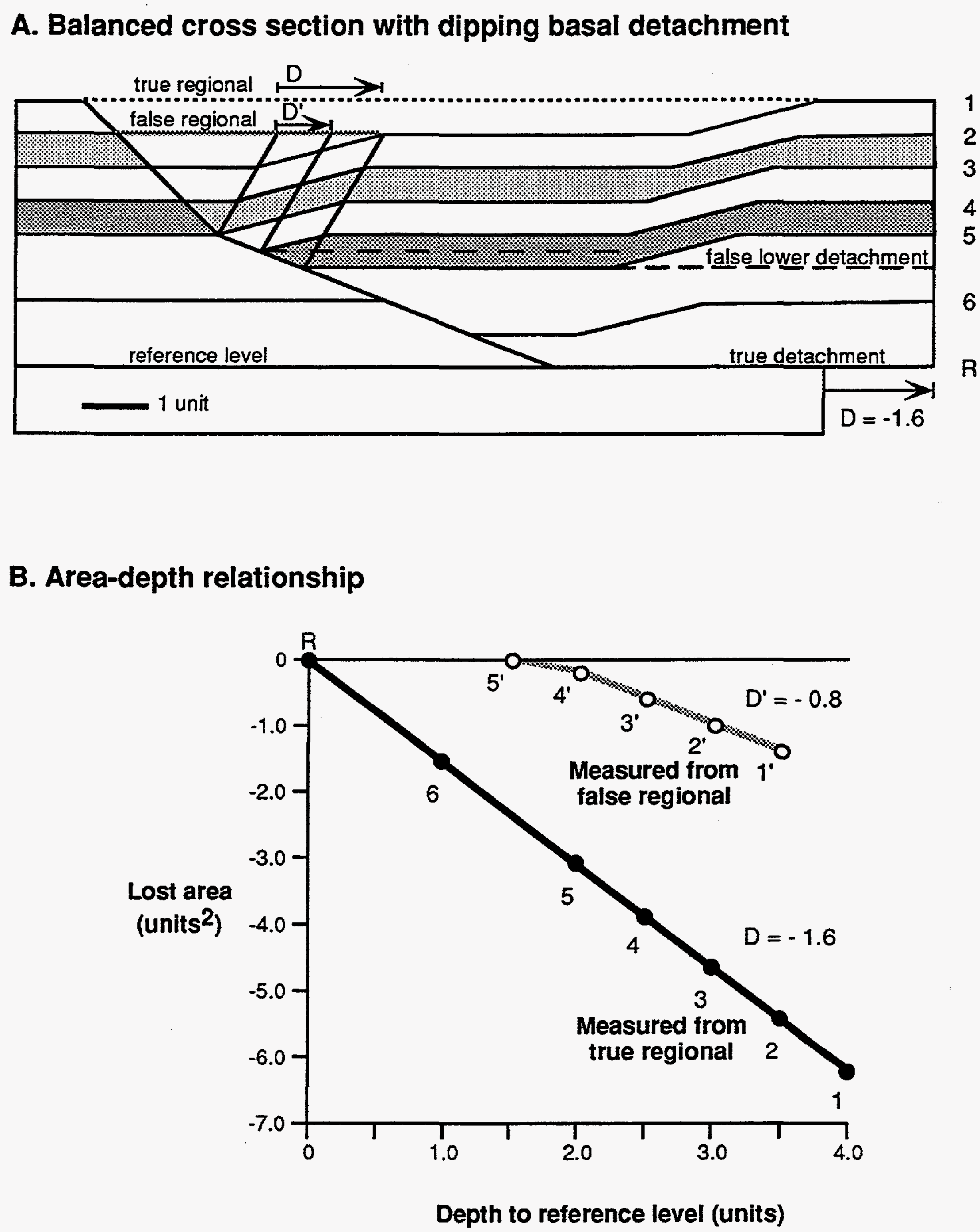

Figure 42.--Area-depth model of half graben formed above a dipping detachment.

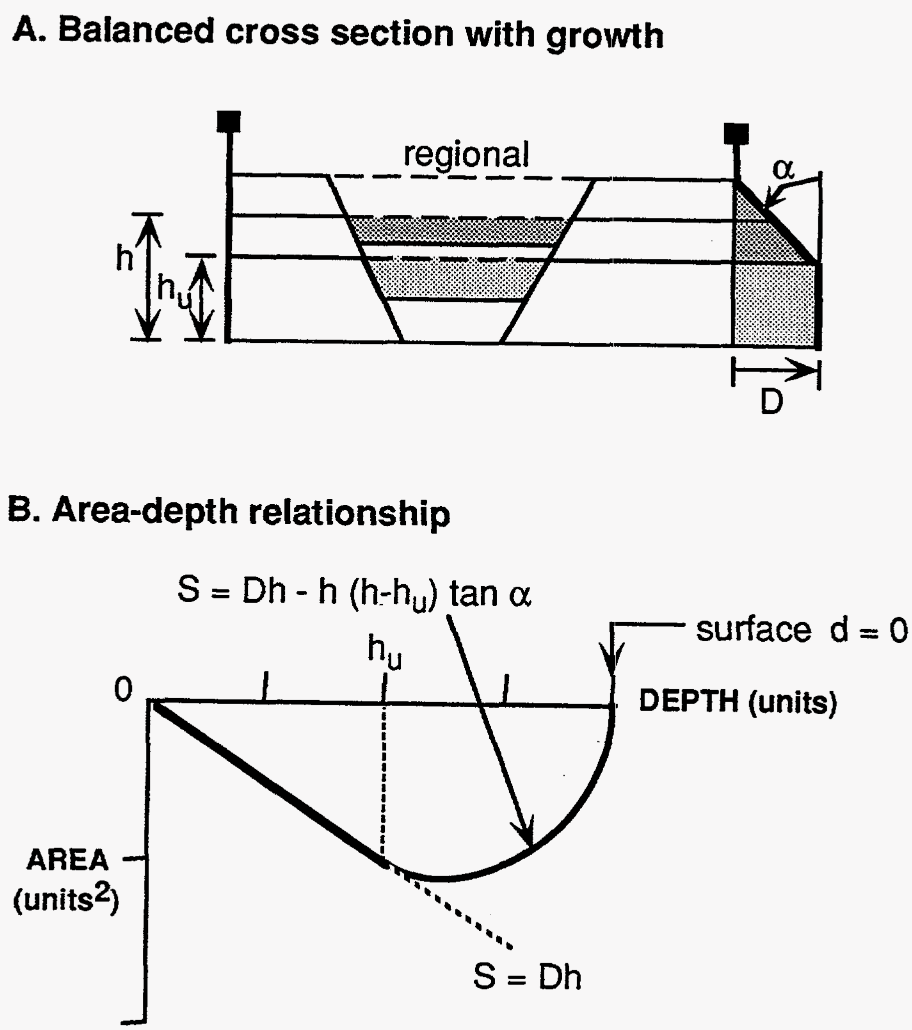

Figure 43.--Area-depth model of full graben formed with synsedimentary growth.

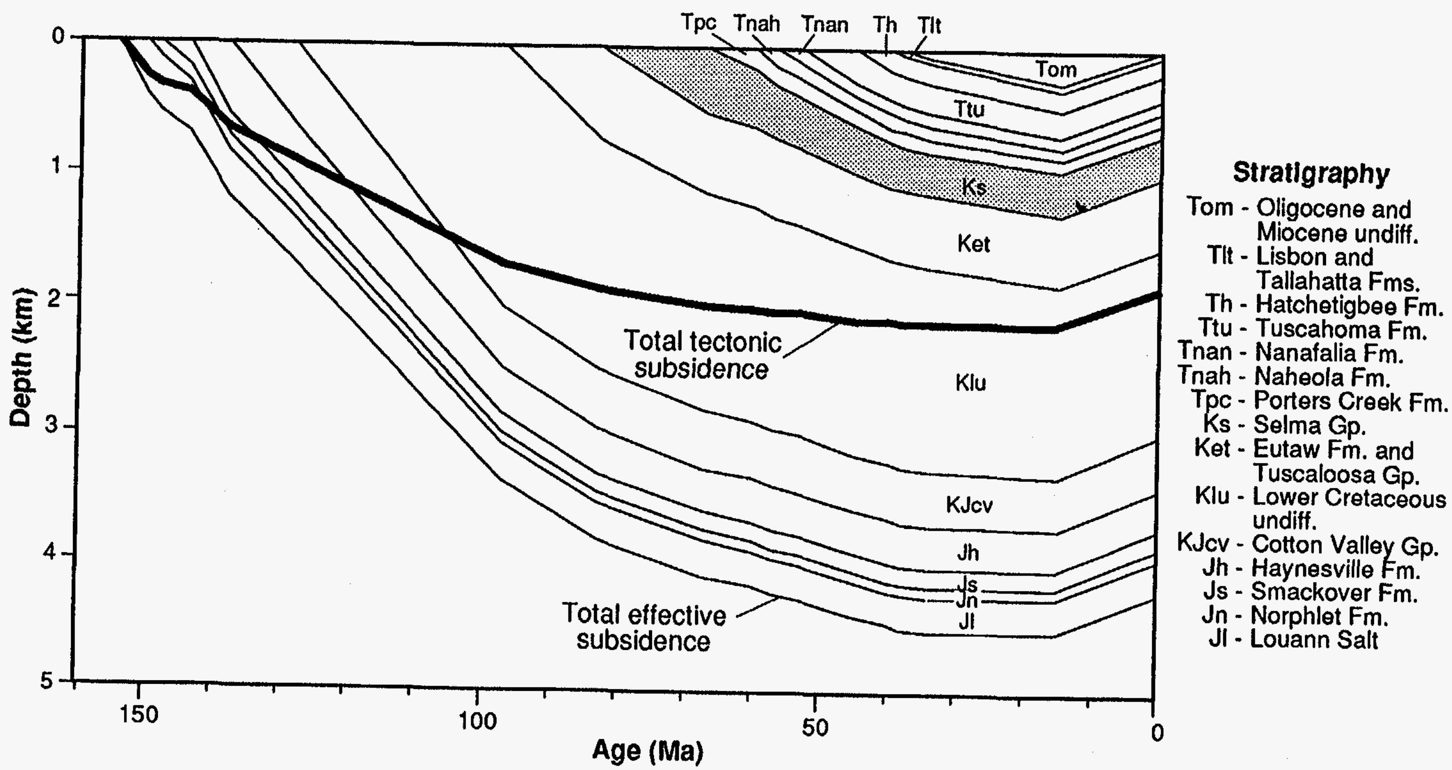

Figure 44.--Plot showing subsidence history of Jurassic through Tertiary strata, Gilbertown Field and adjacent areas.

cool and that no external tectonic forces were required to drive subsidence and fault growth by the time the Eutaw Formation and Selma Group were deposited. Comparison of the total tectonic subsidence curve with the total effective subsidence curve suggests that more than 50 percent of the basin fill is the product of sediment loading and compaction. The effect of compaction is especially apparent from 40 to 15 million years ago. During this time, Jurassic strata are interpreted to have ceased subsiding, but compaction of Lower Cretaceous and younger strata provided sufficient accommodation space for Eocene through Miocene sediment to accumulate.

TECHNOLOGY TRANSFER

Contact was made with producers in the Gilbertown area early in the project and has been maintained since that time. Producers have been supportive of the Gilbertown project and are facilitating our efforts by supplying structural, geophysical, and reservoir data. Many of the well files from when Belden and Blake, Incorporated, operated Gilbertown Field have been donated to the Geological Survey of Alabama and have been an excellent source of reservoir data. We are engaged in active discussions with producers who are exploring in the Gilbertown area. For example, industry personnel have inquired about prospects in the Hatchetigbee anticline and about the possibility of drilling new wells in the Selma Group and the Eutaw Formation as part of a redevelopment effort in Gilbertown Field.

Presentations were made at meetings attended by industry personnel in October and November. At the Eastern Section Meeting of the American Association of Petroleum Geologists in Charleston, West Virginia, and at the Annual Meeting of the Geological Society of America in Denver, Colorado, Jack Pashin presented models of area balance and strain in coalbed methane reservoirs. He further discussed how efforts to refine the basic theories and methodologies in Gilbertown field will facilitate effective management of conventional and unconventional reservoirs in a variety of tectonic and depositional settings.

In April, Jack Pashin and Rick Groshong will be going to the annual meeting of the American Association of Petroleum Geologists to discuss with producers our research efforts in Gilbertown field and to procure additional geophysical data that will help image the Louann Salt, thus providing critical information on the position and geometry of the basal detachment. In June, Drs. Pashin and Groshong will attend a Hedberg Conference at Bryce Canyon, Utah, that is sponsored by the American Association of Petroleum Geologists and is entitled, "Reservoir-Scale Deformation—Characterization and Prediction." At this meeting, Drs. Pashin and Groshong will present the results of structural modeling in the Gilbertown area and the implications of the models for field development.

Personnel at the Geological Survey of Alabama and the University of Alabama are beginning to plan a focused-technology workshop that will be held at the Eastern Gulf Regional Resource Center of the Petroleum Technology Transfer Council in Tuscaloosa, Alabama. The workshop will focus on results of the Gilbertown project and will be geared toward producers. Topics to be covered include structural characterization of faulted and fractured reservoirs, three-dimensional computer visualization, area balance and strain, and implications for field development.

FUTURE EFFORTS

The Gilbertown project is moving ahead according to the schedule outlined in the program plan. Task 1, subsurface geology, is complete, and work this coming quarter will focus on Tasks 2 through 5, which include Surface Geology (Task 2), Petrology and Log Analysis (Task 3) Structural Modeling (Task 4), and Burial and Thermal Modeling (Task 5).

The geologic map and fracture analyses to be performed under Task 2 will be completed during this coming quarter. Under Task 3, thin sections of the Eutaw Formation will be analyzed for framework composition and diagenetic factors, and samples of fracture fills from the Selma Group will be sent out for isotopic analysis. Geophysical well logs of Eutaw and Selma reservoirs will continue to be digitized, and analysis of log parameters will begin to quantify porosity, oil saturation, and water saturation.

Structural modeling (Task 4) will be a primary focus during the upcoming quarter. Efforts will include continued incorporation of variables associated with salt movement and synsedimentary growth into the theory of area balance. A key objective of these efforts will be to develop an equation that can be used to calculate requisite strain in growth structures. Work will continue on three-dimensional visualization in GeoSec3D software. Also, structural contour maps will be transformed into second-order derivative maps to show bed curvature using the Geographix Exploration System.

Analysis of burial and thermal history (Task 5) will also be a primary focus. Samples will be analyzed for vitrinite reflectance, and reflectance profiles will be made for several wells in the Gilbertown area. When reflectance profiles are complete, the data will be used to make Lopatin models for selected wells. These models will help determine if source rocks for the oil in Gilbertown Field are present in the study area and to identify probable avenues of hydrocarbon migration.

SUMMARY AND CONCLUSIONS

Gilbertown field, established in 1944, is the oldest oil field in Alabama and produces oil from fractured chalk of the Cretaceous Selma Group and sandstone of the Eutaw Formation. Nearly all of Gilbertown field is still in primary recovery, although operators are now considering major waterflood operations. The objective of this project is to analyze the geologic structure and burial history of Mesozoic and Tertiary strata in Gilbertown Field and adjacent areas in order to suggest ways in which oil recovery can be improved. Indeed, the decline of oil production to marginally economic levels in recent years has made this type of analysis timely and practical. Key technical advancements being sought include understanding the relationship of requisite strain to production in Gilbertown reservoirs, incorporation of synsedimentary growth factors into models of area balance, quantification of the relationship between requisite strain and bed curvature, determination of the timing of hydrocarbon generation, and identification of the avenues and mechanisms of fluid transport.

Structural maps and cross sections establish that the Gilbertown fault system defines part of a full graben and an associated horst that are interpreted to be detached at the base of the Louann Salt. Sequential restoration of cross sections suggests that the fault system began forming as a half graben during the Jurassic. The Early Cretaceous was the major episode of structural growth and subsidence of the half graben. By the end of the Early Cretaceous, however, the growth rate of antithetic faults became effectively equal to that of synthetic faults. Thus, the half graben began collapsing, and the overall structural geometry of Cretaceous and younger strata is that of a full graben. Cross sections and isopach maps of selected intervals demonstrate significant growth of the graben during Cretaceous time, but do not show growth of mid-Tertiary strata. However, offset of Tertiary strata indicates reactivation late in the structural history of the region.

Analysis of burial history indicates that the subsidence history of Jurassic and Tertiary strata in the Gilbertown area is typical of extensional basins. Factoring out the tectonic component of subsidence suggests that more than half of the total effective subsidence in the Gilbertown area can be accounted for by sediment loading and compaction.

Geologic mapping of formations and fracture systems is adding significantly to knowledge of the geology of the Gilbertown area. Faults offset strata as young as Miocene, whereas Quaternary alluvial deposits cut across structures in the area. Fault gouge with Riedel shears was observed locally. Most Tertiary strata are jointed, and the joints tend to parallel straight river segments. Preliminary assessment of joint patterns reveals little relationship to fold and fault patterns, suggesting that the joints formed in a different stress field than the folds and faults. One possibility is that joints represent unloading structures that began forming after fault movement ceased.

Eutaw and Selma reservoirs are internally heterogeneous. The Eutaw Formation was divided into seven intervals that could be mapped throughout the Gilbertown area. Thickness of the intervals is fairly uniform, although facies changes are expressed through variation of sandstone content. Stratigraphic and paleontologic evidence suggests that the Eutaw accumulated in vertically stacked, transgressive shoreface and shelf environments. The Selma Group was divided into eight mappable intervals that were instrumental for locating faults. The Selma Group is interpreted as a regionally extensive shelf deposit.

Conventional trapping mechanisms are effective in the Eutaw Formation, and oil is trapped in faulted anticlines and the horst. Core analyses and production data, however, indicate that the distribution of oil and water within the Eutaw is extremely heterogeneous, and in some wells, as many as seven pay zones are developed. Oil is produced in the Selma Group from faults and fractures constituting the Gilbertown fault system. Comparison of production patterns in the Eutaw Formation and Selma Group indicate that oil may have accumulated in the faults by leakage from the Eutaw Formation.

Three-dimensional computer visualization of the Gilbertown fault system and associated structures is helping develop structural models and is providing the straight-line cross sections required for area balancing. Preliminary balanced models have elucidated complications related to offset of regional elevations by salt withdrawal, as well as synsedimentary growth of fault systems. Area-depth plots indicate that synsedimentary growth is the most important variable affecting construction of balanced structural models.

The basic equations of area balance have been modified to account for growth, and future efforts will include incorporation of growth factors to derive new equations for requisite strain.

ACKNOWLEDGMENTS

We would like to thank the many producers of oil and gas in south Alabama. This project would not be possible without their interest. Special acknowledgment goes to Professor Charles D. Haynes of the University of Alabama, who donated a wealth of reservoir data that are vital to this project.

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