United States
Environmental Protection
Agency

Robert S. Kerr Environmental
Research Laboratory
Ada, OK 74820

EPA/600/2-89/038
July 1989

Research and Development

EPA

Development of a Methodology for Regional Evaluation of Confining Bed Integrity

EPA/600/2-89/038
July 1989

DEVELOPMENT OF A METHODOLOGY FOR REGIONAL EVALUATION OF CONFINING BED INTEGRITY

by

Gary F. Stewart
Wayne A. Pettyjohn
Oklahoma State University
Stillwater, Oklahoma 74078

Cooperative Agreement CR-814061

Project Officer

Jerry Thornhill
Applications and Assistance Branch
Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma 74820

ROBERT S. KERR ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
ADA, OKLAHOMA 74820

DISCLAIMER

FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of the facilities, the Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the laboratory are responsible for management of research programs to; (a) determine the fate, transport and transformation rates of pollutants in the soil, the unsaturated zone and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

This report contributes to that knowledge which is essential in order for EPA to establish and enforce pollution control standards which are reasonable, cost effective and provide adequate environmental protection for the American public.

Clinton W. Hall

Clinton W. Hall, Director
Robert S. Kerr Environmental
Research Laboratory

ABSTRACT

For safe underground injection of liquid waste, confining formations must be thick, extensive, and have low permeability. Recognition of faults that extend from the potential injection zone to underground sources of drinking water is critical for evaluation of confining-bed integrity.

Nonproprietary geologic information from ordinary sources can be used to map localities suspected to be injection-sensitive. Materials include remote-sensing imagery, aerial photographs, surface-geologic maps, and subsurface-geologic maps; structural geologic maps, thickness maps and initial-production maps are useful. Persons with limited experience can use data bases and computer mapping to generate well-suited information, but input by experienced geologists is necessary.

In the Southwest Enid Area and West Edmond Field, Oklahoma, rocks at the surface reveal little evidence of subsurface faulting. Oil reservoirs are "tight", fractured limestones. Cumulative-production mapping (Southwest Enid), initial-production mapping (West Edmond), structural contour mapping, and analysis of lineaments from stream patterns (Southwest Enid) and Landsat imagery (West Edmond) were combined. Production at Southwest Enid Area seems to be correlated with intersections of lineaments. At West Edmond Field, lineaments suggested penetrative fractures; an injection-sensitivity map was based on inferences from lineaments and subsurface mapping.

The sandstone reservoir at Burbank Field, Oklahoma, almost certainly is jointed systematically. Structural contour maps and initial-production maps do not show the fracture system. Faults are few or are of little displacement; geometry of the channel-fill reservoir influences production more so than natural fractures. Fitts Pool, Oklahoma, is in a complexly faulted graben. Areas near bounding faults were interpreted as injection-sensitive. Faults in thick shales that seal Fitts Pool are suggested by the many lineaments shown on satellite imagery; the faults are believed to be closed. Confining beds probably would be effective if fluid injected did not exceed volumes withdrawn, and injection pressures were below original formation pressure.

Injection-sensitivity maps are for precautionary purposes. They are designed to protect underground drinking water, not to obstruct responsible and conscientious production of oil and gas.

This report was submitted in fulfillment of Cooperative Agreement No. CR-814061 by Oklahoma State University under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from July 1, 1987 to February 28, 1989.

CONTENTS

FIGURES

TABLES

SECTION 1

INTRODUCTION

The Underground Injection Control (UIC) program of the U.S. Environmental Protection Agency (EPA) is involved with the safe emplacement of liquid wastes in subsurface geologic formations. Of particular concern are hazardous toxic wastes injected in Class I wells and the vast quantity of oil-field brine injected in Class II wells. EPA is required by the Hazardous and Solid Waste Amendment of 1984 to assess the environmental suitability of well injection. Presently the Agency's paramount interest and effort lie in (1) evaluation of well construction, (2) reactions among injected waste, formation fluids, and the geologic framework, and (3) relation of the injection interval to the confining beds.

A major part of environmental suitability for underground injection is tied to the integrity of confining beds. That is, confining units must be of areal extent, thickness and low permeability sufficient to prohibit the upward migration of injected fluids or displaced formation fluids into underground sources of drinking water.

A major concern in confining-unit integrity is the presence of abandoned wells, either unplugged or inadequately plugged. An equally important concern and one that is rarely considered, particularly for Class II wells, is the potential for upward migration of waste substances or formation fluids along faults or other fractures. Additionally, at a few places operational experience clearly has indicated a relationship between deep-well injection and increasing occurrences of earthquakes, as exemplified by the former operation of a deep injection well at the Rocky Mountain Arsenal near Denver, Colorado (Evans, 1966). In Ohio, reactivation of stabilized faults by deep-well injection may have been the primary cause of one or more earthquakes in recent years.

In a major oil field in the southwestern part of the United States, brines have been injected through several wells for more than 30 years. It was recently discovered that several shallow cathodic-protection wells in this field, all located along a nearly straight line, contain brine with total dissolved solids that exceed 100,000 mg/l. This explanation seems to be warranted: The brine originates from fluids injected at depths as great as 8,000 ft (2400 m). Under pressure of injection and of differential formation pressures, the brine migrated to shallower units -- including sources of underground drinking water -- along a fault or a set of faults.

Investigations of shale-gas production in West Virginia during the late 1970's indicated that wells drilled within 350 ft (100 m) of a fracture or linear feature mapped from aerial photographs or satellite imagery produced substantially more gas than did wells at greater distances. This implies that the linear features, which in this case probably are fractures, are indicative of zones of substantial permeability.

Geologists have long recognized systems of joints and fractures, in the field and on aerial photographs. However, after the Earth Resources Technology Satellite 1 (ERTS-1) was launched in July, 1972, linear features were discovered to be far more abundant and extensive than previously considered. Satellite imagery, which is available for the entire Earth, can be readily used to map regional linear features. These linears represent both faults and joint systems.

Presently, siting procedures for Class I hazardous-waste wells call for an extensive examination of subsurface conditions within 2 mi (3.2 km) of the proposed well. Of major concern in this case is the location of abandoned wells within the area of influence and the description of primary hydraulic characteristics of confining units. However, pressure build-up brought about by injection can extend outward for miles, even from a single injection well. The pressure increase could cause formation fluids to migrate upward through fractures to impact underground sources of drinking water located much farther away than the 2-mi (3.2-km) radius from an injection site. Thomas (1986) provided descriptions of the long distances across which injected fluids could migrate through fractures.

Regulatory controls on Class II wells are far less stringent, with most of these wells situated at points of convenience. Throughout decades of use, Class II wells have led to a variety of problems; some severe problems are related to lack of integrity of confining units. The integrity of confining units can be compromised by abandoned wells and open fractures, which are potential avenues for upward migration of formation fluids into underground sources of drinking water.

INJECTION WELLS

In 1983, 195 hazardous-waste injection wells were in operation in the United States (Brazier, 1987); currently 245 such wells exist. In addition, about 120,000 enhanced-recovery wells are in use (J. Lynn, Underground Injection

Practices Council, personal communication, 1989). In the latter, water is injected into oil-producing zones to maintain formation pressure as an aid to oil recovery. Finally, Clark (1983) estimated that 20,000 wells were used strictly for disposal of oil-field brine; about 38,000 wells of this type are in operation now (J. Lynn, UIPC, personal communication).

Underground injection presently is the least expensive method of waste management. EPA estimated that for hazardous waste, disposal by deep-well injection costs roughly $8 per ton, ($8.80 per metric ton) disposal in a surface impoundment about $28 per ton ($31 per metric ton), and disposal in a landfill about $50 per ton ($55 per metric ton), assuming full compliance with federal regulations. In contrast, resource recovery, treatment, and incineration can cost as much as $718 per ton ($791 per metric ton)(Gordon and Bloom, 1987).

Because underground injection is the least expensive, and in some cases, the only practical option available for liquid-waste disposal, there is a trend toward greater reliance on deep-well injection. Generators of waste probably will rely even more heavily on deep-well injection.

In approximately 95 percent of all Class-I wells, wastes are injected into zones that lie below usable water resources. Brasier (1987) determined that the average depth of hazardous-waste injection wells is 4,000 ft (1200 m). Typically, 2,800 ft (850 m) of strata separate the injection zone from shallower aquifers that contain water with dissolved-solids concentrations of 10,000 mg/l (10,000 ppm) or less.

Injection wells for commercial purposes originated in the oil and gas industry. Beginning in the middle 1930's, injection wells were used instead of open evaporation pits, which had been employed to dispose of highly corrosive, commonly chemical-laden brines and drilling fluids; injection wells also were used to enhance oil recovery. Injection of toxic and hazardous chemical waste from the steel and chemical industries began in the 1950's. The practice of injection came into favor following the enactment of environmental laws designed to protect surface waters from pollution (Gordon and Bloom, 1987).

The objective of deep-well injection is the disposal of liquid wastes into a suitably porous and permeable formation, in such a fashion that it does not impinge upon the human health and safety or the environment. To that end, several geologic and engineering-design criteria must be taken into account in planning a deep-injection well.

Engineering concerns typically center on well design and operations. Many methods have been developed or adapted to insure the mechanical integrity of an injection well, including cement-bond logging and pressure testing.

Geologic standards of concern are much less precise than criteria of engineering design. A typical geologic assessment of a potential injection-well site should include (1) the geologic-hydrologic environment, (2) structural geology, (3) physical and chemical properties of rocks, and (4) chemical characteristics of fluids in the subsurface.

A potential injection formation must be evaluated for suitability. To be viable as an injection zone, the formation must (1) have no value as a resource, (2) have sufficient porosity, areal extent, and thickness to accept the anticipated volume of liquids, (3) be located in a seismically inactive area, and (4) contain water that is compatible chemically with wastes to be injected. Furthermore, it should be sealed above and below by confining beds with strength, thickness, and low permeability, altogether sufficient to prevent vertical migration of injected fluids or formation fluids from the disposal zone.

Information concerning the general lithology, distribution, and structural configuration of a rock unit potentially capable of accepting wastes generally can be obtained. However, collection of geologic information typically depends upon rock cores, records of nearby wells, logs of nearby open holes, and seismic surveys. Information may be detailed but, at best, at one locality it provides little more than a one-dimensional sample of subsurface characteristics. Extrapolation and assumptions about homogeneity or the lack of it are used to infer formation qualities between data points.

FAULTS, JOINTS, LINEAMENTS AND FRACTURE TRACES

A critical geologic factor is recognition of penetrative faults -- that is, delineation of faults that extend from the potential injection zone to the surface, or to an underground source of drinking water. Such faults may breach confining beds and may be passageways for migration of wastes into shallow ground-water supplies.

Although delineation of faults is difficult, with adequate subsurface data the presence and configuration of some deep faults can be discerned. Geologic study of the subsurface herein called "subsurface studies") in the detail necessary is expensive, tedious, time-consuming, and commonly inadequate to determine the full scope and magnitude of faulting. In addition, to determine localities where a fault intersects the surface is critical; this is an objective that subsurface studies normally cannot produce.

Close inspection of aerial photographs, satellite imagery, surface-geologic maps and topographic maps ordinarily reveals numerous alignments in landforms, streams and vegetation. The longer of such straight features have been called "lineaments," a useful concept of which is encompassed in the definition set out by Lattman (1958, p. 569): "A photogeologic lineament is a natural linear feature consisting of topographic (including straight stream segments) vegetation, or soil tonal alignments, visible primarily on aerial photographs or mosaics, and expressed continuously for at least one mile, but which may be expressed continuously or discontinuously for many miles."

The shorter of such aligned fractures have been called "fracture traces," as described by Lattman (1958, p. 569): "A photogeologic fracture trace is a natural linear feature consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs or mosaics, and expressed continuously for less than one mile. Only natural linear features not obviously related to outcrop pattern of tilted beds, lineation and foliation, and stratigraphic contacts are classified as fracture traces. Included in this term are joints mapped on aerial photographs where bare rock is observed."

Although the definitions shown above make reference only to mapping on aerial photographs, the criteria can be applied to mapping of lineaments and fracture traces on satellite imagery, topographic maps, and surface-geologic maps.

Evaluation of remotely sensed data provides an attractive alternative to subsurface investigations. Many faults or fracture traces can be located by study of linear features on aerial photographs or satellite images. Fracture-trace analysis using remote sensing has many advantages. The technique provides an inexpensive, simple, and speedy method of analysis of large geographic regions.

Unfortunately, fracture-trace analysis is decidedly subjective. In some instances, interpretations vary significantly from person to person. Some mapped features are discovered to be results of human activity, or otherwise to be nongeological. Many such errors can be isolated and corrected through geologic field work.

Assuming that all anthropomorphic features have been eliminated from the set of lineaments and fracture traces mapped, the interpreter must determine which of these linear features correspond to shallow joints and fractures and which could represent significant deep-seated faults. Shallow fractures and joints are much more numerous at the surface of the earth than faults. Therefore, it is logical to assume that many lineaments and fracture traces are results of surficial fractures or joints.

Such discontinuities commonly do not extend to significant depths, and therefore do not necessarily threaten confining-layer integrity. On the other hand, faults significantly disrupt confining layers and unsealed faults can be conduits for fluid migration.

Mapping of regional lineaments by means of satellite imagery, in conjunction with aerial-photographic interpretation, geologic field work, and study of history of injection and production in oil fields, provide a means to develop maps of lineaments, joints, and faults. The maps can be used to delineate areas where the integrity of confining units potentially is disrupted. In turn, this information can be used in regulatory procedures involved in the permitting of Class I and Class II wells. That is, the methodology can lead to a fundamental, scientifically based approach to estimate whether pressure in an injection zone is sufficient to cause migration of injected or formation fluids into underground sources of drinking water. Lineament maps, when combined with geologic maps and subsurface data, can be used to develop "sensitivity maps." Sensitivity maps indicate those areas where there is significant probability of poor or questionable confining-unit integrity and, therefore, the possibility of unacceptable contamination of an underground source of drinking water. State or federal regulatory personnel could use sensitivity maps to suggest or require further subsurface investigation to establish safety of injection, or (in clear-cut exceptional cases) to forestall or prohibit the installation of an injection well.

SCOPE AND APPROACH OF STUDY

The objective of this research is to define methods to develop deep-well injection-sensitivity maps. The principal working hypotheses are as follows:

(1) Synthesis of data about areal geology, lineaments and fracture traces permits the mapping and isolation of localities that would be suitable or unsuitable for Class I or Class II injection wells.

(2) A body of information that can be used reliably to infer likelihood of fractured and permeable confining beds exists in the form of remotely sensed data -- linear features

manifest on earth-satellite imagery, aerial photographs, surface-geologic maps, and topographic maps. A component hypothesis is that numerous linear features can be mapped in the field and shown to be images of fractured bedrock; therefore, the linear features mapped remotely can be dealt with on the warranted assumption that they represent lineaments and fracture traces.

(3) Lineaments and fracture traces are evidence of zones of weakness in bedrock and indicate permeability distributions that are likely to be greater than that of the adjacent bedrock. Fractures presumed to underlie them are judged to have originated in crystalline basement rocks and to have propagated toward or to the surface. They would be paths along which fluids could migrate if pressure distributions are modified by injection of wastes.

Basic premises on which this research is based are as follows:

(1) Fracture traces and lineaments are correlated with joints, faults or directional zones of weakness in reservoirs of selected oil and gas fields.

(2) Correlation of fracture traces, lineaments and fractured reservoir rock justifies the working assumption that discontinuities have been translated vertically, and that all strata above the reservoir are disrupted locally, or might have been disrupted locally.

Substantial amounts of published information suggest that the fundamental working hypotheses are stable. Reliability of the premises described above seems to be justified by the work of Alpay (1973), Trantham and others (1980), Rausch and Beaver (1964), Schridder and others (1970), Brown and Forgotson (1980), Komar and others (1973), and Feder (1984).

Effectively, the research cited above has shown substantial evidence of correlation between strikes of joints, faults, fracture traces or lineaments at the surface and fractures in reservoirs. The correlation is not one-to-one of course, but relations are shown to be strong enough to justify the assumption that fracture traces and lineaments imply similarly oriented fractures in the subsurface -- despite geologic and geographic differences in the areas investigated.

METHODS OF INVESTIGATION

Research proceeded along these lines:

(1) Selection of (a) oil and gas fields to serve as models and (b) reservoirs known to be fractured systematically or strongly suspected to be fractured systematically.

(2) Documentation of orientations of fracture-systems and

abundances of fractures, insofar as was practical.

(3) Documentation of fractures and fracture traces above and around the oil and gas fields by analysis of remotely sensed imagery, including data from earth-orbiting satellites and standard aerial photographs.

(4) Testing of validity of fractures in bedrock and fracture traces mapped as described above, by methods of standard geologic field mapping.

(5) Comparison of orientations of fractures and fracture-traces at the ground surface with trends of fractures documented in oil and gas reservoirs described above, to the level of documentation that data permitted.

Oil fields selected are judged to have analogs at numerous localities elsewhere in the United States. Geology of these areas generally conforms with that of other injection regions in the United States, specifically those in so-called "hard-rock" terrain, onshore and inland from Tertiary-Pleistocene fields of the Gulf Coast.

Study areas selected included the Sooner Trend, the West Edmond Field, the Burbank Field, and the Fitts Pool (Figure 1), all of which are in Oklahoma. The Sooner Trend, West Edmond Field, and Fitts Pool produce from carbonate rocks; fractures have strongly influenced the locations and rates of production in the Sooner Trend and West Edmond Field, and they are suspected to have had marked effect upon reservoir performance in the Fitts Pool. The major reasons for specifying these four fields were their proximity, the large data base available, and knowledge of and experience with the sites. Despite the fact that all the fields are in Oklahoma, the methodology should be transferable readily because structural geologic controls and stratigraphy are similar to a large percentage of oil fields elsewhere in the United States.

The products described herein evolved from a mix of published work and original work (for example, mapping of fracture traces, geologic field mapping, subsurface mapping, and analysis of commonly available data about production from oil and gas reservoirs). If methods and products discussed here are practical, and in application elsewhere are robust (that is, economically and temporally feasible, and applicable under a large range of conditions) then it is because the methods were developed under conditions that are general. The data were of common sorts and they were nonproprietary. Under such constraints some operating assumptions necessarily are regarded as general geologic truths, verifiable by reference to the literature. These are the premises described above by reference to published work.

Figure 1. Locations of study areas: Burbank Field in Osage County, Southwest Enid Area in Garfield and Major Counties, West Edmond Field in Oklahoma and Logan Counties, and Fitts Pool in Pontotoc County, Oklahoma.

Under the overall advisement of Gary F. Stewart and Wayne A. Pettyjohn, experienced graduate students were assigned to evaluate the four study areas. Evaluation of the Fitts Pool and the Pontotoc County mapping project were conducted by James O. Puckette and Michael R. Thornhill, the West Edmond Field by Lonnie G. Kennedy, the Sooner Trend by Lyle G. Bruce, and the Burbank Field by Kevin D. Flanagan and James O. Puckette. Although the general approaches to evaluation were similar, each investigator emphasized slightly different techniques, and some differences in methods evolved as a function of differences in local geologic conditions. This report was integrated by Stewart and Pettyjohn.

Separate accounts of work in the Southwest Enid Area, the West Edmond Field, Burbank Field, and Pontotoc County are set out by Bruce (1989), Kennedy (1989), Flanagan (1989) and Thornhill (1989).

SECTION 2

CONCLUSIONS

1. In the Southwest Enid Area of the Sooner Trend, the soft sedimentary bedrock and widespread cover of unconsolidated materials tend to minimize direct surface-geologic evidence of faults. The concentrated area of exceptionally productive oil and gas wells seems to be positively but generally correlated with areal density of stream-lineament intersections. This relation suggests that fracture-enhanced permeability in the "tight" Mississippian carbonate-rock reservoir is shown to some degree by stream-lineaments, particularly by the intersections of lineaments. Therefore, in terrain where surface- and subsurface-geologic conditions are similar, working hypotheses about injection sensitivity should be concentrated on areas where stream-lineaments intersect.

2. Initial-production trends in West Edmond Oil Field indicate that in reservoir rocks of the Hunton Group permeability is strongly fracture-influenced. Faults in West Edmond Field dip almost vertically. In similar reservoirs, valid interpretation of faulting can be based on initial-production trends, conspicuous and linear deviations in strike or dip of mapping datums, and repeated or missing rock-stratigraphic units.

3. At Burbank Oil Field, trends of lineaments mapped from satellite imagery are correlated closely with orientations of fractures described in published accounts of detailed study of the reservoir. Fractures at the surface and in the reservoir are similar in trend.

4. At Burbank Oil Field, initial-potential and initial-production maps are of little use in detection of fracture-trends in the reservoir. The Burbank Sandstone is multistoried, multilateral, channel-fill sandstone; abrupt variations in porosity and permeability are governed more by internal geometry of the sandstone than by fracturing. Large production units are common; therefore oil-production records combine the yields of more than one well, and individual-well performance is obscured. For this reason, initial-production maps are marginally informative.

5. In Pontotoc County, numerous faults delineated by subsurface geologic mapping were not shown by lineaments. Many of these faults seem to have formed before Middle Pennsylvanian time; presumedly, in structural movements that

took place after the Middle Pennsylvanian they were not rejuvenated enough to affect overlying strata detectably. However, the extensive Ahloso, Franks, and Stonewall Faults, and a large fault in northern Pontotoc County are partly manifest as lineaments.

6. Aerial photographs and satellite imagery are quite useful for mapping of lineaments. Most lineaments mapped from aerial photographs correspond to linear transitions in topography or to stream-drainage patterns. Lineaments mapped from satellite imagery tend to be the larger in extent, and in general seem to match better with faults mapped by standard field-geologic methods. Major lineaments mapped from aerial photographs correlate well with lineaments mapped from satellite imagery. Aerial photographs are better for small areas and detailed work.

7. Judicious constructive-bias mapping allows projection of some faults from petroleum reservoirs to shallow marker beds. Trends of faults in shallow beds can be evaluated in conjunction with lineaments mapped from stream trends, aerial photographs, Landsat imagery, color-infrared imagery and topographic maps. Convergence of evidence permits the assessment of terrain for injection sensitivity. Zones of sensitivity accent localities within which underground injection of fluid would be advisable only after careful study demonstrated acceptable levels of risk.

8. Confining-potential is an important counterpart to assessment of injection sensitivity. Documentation of thickness and extent of storage formations and confining beds should be included in mapping for injection sensitivity. In most instances, formation-thickness maps would meet basic needs for information.

9. A computer data base allows quick generation of maps, including structural contour maps, interval-thickness maps, and cumulative-thickness maps of confining beds and storage formations. Routine use of data bases would allow geologists with limited experience in subsurface geology to generate several kinds of maps. Experienced geologists could synthesize the information and construct injection-sensitivity maps.

10. Integration of geologic material from sources diverse in nature and quality may produce interpretations that are strongly inferential but nevertheless close to the truth. Under some kinds of review, such interpretations may be regarded as being unacceptably subjective. Structural geologic maps and formation-thickness maps constructed by

computers -- where algorithms are conventional, have been tested repeatedly, and are of third-party origin -- are likely to be regarded as "unbiased". They may provide interpretations of structural geology and thicknesses of beds that would be acceptable to persons with vested interests and opinions that are quite different. Computer-based maps should provide minimally controversial baseline interpretations, and thereby should reduce the probability of conflict between regulating agency and producer.

11. Nonproprietary geologic information from ordinary sources can be used under general methods to produce maps showing localities that are suspected to be injection-sensitive. The necessary materials generally are inexpensive and readily accessible.

12. Deliberations based on mapped zones of injection sensitivity should include consideration of the likelihood that (suspected) faults are sealed. If faults penetrative from oil reservoir to the surface were unsealed, the trap should be emptied of petroleum, seepage should be evident at the surface, or seepage should have been evident (and perhaps recorded) before the oil field was developed.

13. Interpretation of surface and subsurface geology for injection-sensitivity mapping, including study of remote-sensing imagery, aerial photographs and geologic maps would be done best by experienced geologists who are trained empirically for pattern recognition. Synthesis of geologic information commonly results in significantly different interpretations among geologists. Mapping for injection sensitivity inevitably will generate adversarial positions between regulating agencies and producers. Therefore, both parties must bear in mind the fact that injection-sensitivity maps are precautionary devices. They are designed to protect underground supplies of drinking water, and not to obstruct the responsible and conscientious producers of oil and gas.

SECTION 3

RECOMMENDATIONS

Methods described in this report are believed to be simple and robust enough to be applicable in many parts of the United States, under a wide range of geologic conditions. Nevertheless, trial elsewhere should be illuminating, especially if carried out under operational conditions. Certainly the probability exists that partly different approaches would be necessary outside the Midcontinent; for example, some of the structural geologic conditions and circumstances of confining beds in Mesozoic, Tertiary and Quaternary formations of the Gulf Coast are markedly different from the Midcontinent.

Mapping of injection-sensitive areas could benefit from compilation of historical data. In some areas of the United States oil and gas seeps were numerous long ago. Because of nearby production and consequent pressure depletion, the large majority no longer are active. Such possible conduits from subsurface to surface should be evaluated, especially if injection of fluid under high pressure is planned. Clearly, oil and gas traps exist because the reservoir is sealed completely, or is so nearly sealed that migrating petroleum can be regarded as having been arrested -- in the short-term perspective of geologic time. In either case, integrity of the seal is relative to pressure in the reservoir. Put simply, confining beds seal a trap if pressure in the reservoir is not sufficient to force oil and gas across the barrier. The conclusion follows that fluids injected into a reservoir under pressures less than or equal to the original reservoir pressure should not breach the confining beds.

Records of brine intrusion into fresh-water aquifers might permit detection of contamination that is not related to leaking wells. Sampling of streams during base-flow conditions might indicate localities where water from the deep subsurface emerges.

In the instances where methods and maps of the kinds described herein are applied, we hope that a spirit of cordial and cooperative interest in protection of underground sources of drinking water can be maintained by regulator and producer alike. The intent of this endeavor was to contribute information that in the long run would tend to maximize the benefits of all subsurface resources.

SECTION 4

SOUTHWEST ENID AREA, SOONER TREND

INTRODUCTION

In the attempt to correlate fractures in rocks of the subsurface with geologic data from the surface, to study an area with abundant oil and gas wells and fractured reservoir rocks is necessary. The westerly dipping carbonate-rock strata of the Mississippian Meramecian and Osagean Series in the Sooner Trend of Oklahoma (Figure 2) compose a fractured reservoir (Nelson, 1985). The trend is about 20 mi (30 km) wide; it extends for approximately 60 mi (100 km) on a homocline on the northeastern shelf of the Anadarko Basin. The trap developed where a system of fractures penetrates a thick section of limestones and dolomites with low matrix porosity. According to Harris (1975), the limits of commercial production of oil and gas are a function of fracture-controlled permeability. Cumulative production from the Sooner Trend is more than 270 million barrels of oil and 650 billion cubic feet of gas from more than 4,900 wells (Petroleum Information, 1982).

The study area is in the central part of the Sooner Trend; it is referred to herein as the Southwest Enid Area. It includes 324 sq mi (839 sq km) in parts of Major and Garfield Counties, and a small area in Kingfisher County, Oklahoma (Figure 3). The area is farmland with a few small towns; in the northeastern part are the city of Enid and Vance Air Force Base (Figure 4).

The terrain is of very gentle relief; most of it is cultivated in wheat. Bedrock is eroded easily, and outcrops are rather sparse. Topography evolved by differential stream erosion of the comparatively soft bedrock and overlying Quaternary materials. In general, bedrock stratigraphy and structural geology influenced the overall development of the gentle hills only slightly. Development of stream valleys seems to have involved the partial adjustment of streams to subtle stratigraphic and structural variations in bedrock.

The northeastern two-thirds of the study area is underlain by sandstones, siltstones and shales of the Permian Salt Plains Formation, Bison Formation, Cedar Hills Sandstone, and Flowerpot Shale, and by Quaternary terrace alluvium (Figure 5). The southwestern one-third of the area is underlain mostly by Quaternary terrace alluvium, alluvium, and eolian deposits;

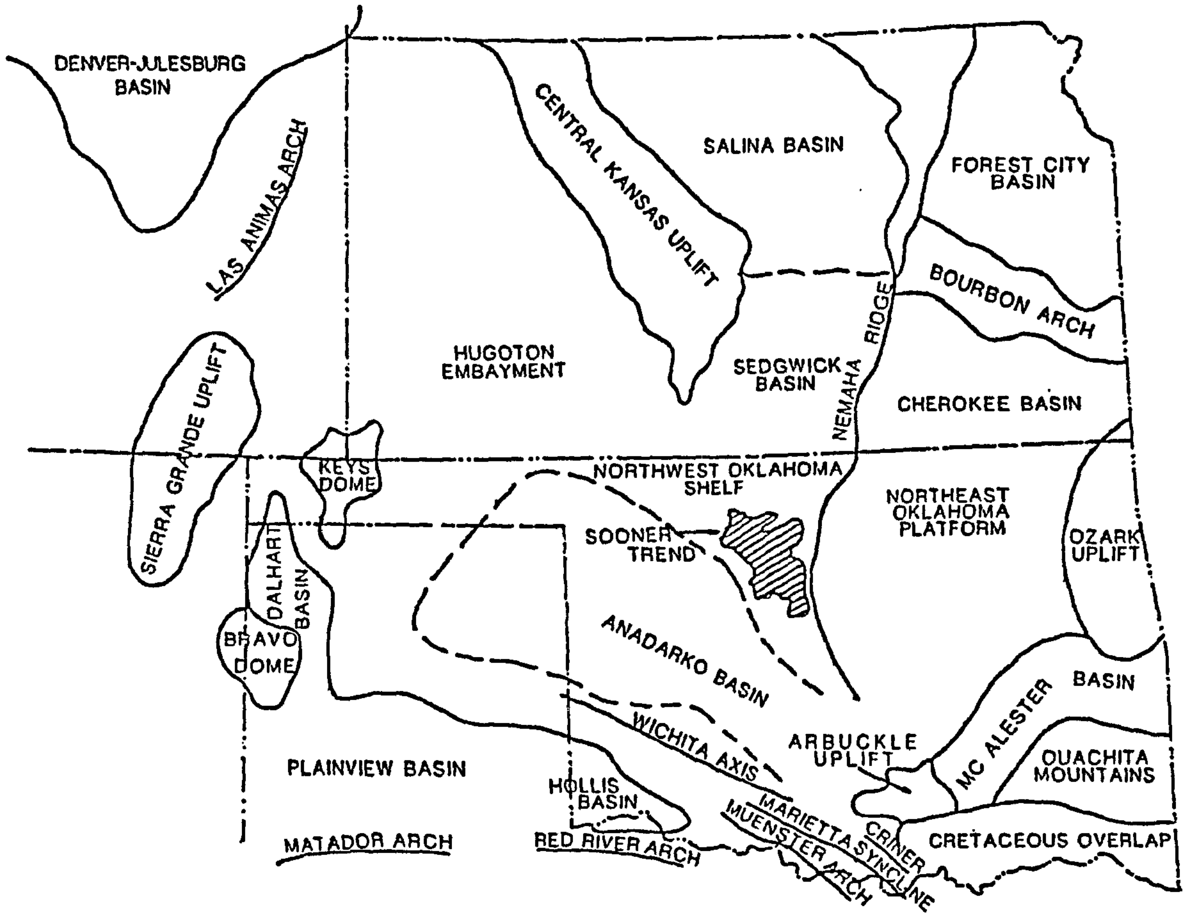

Figure 2. Generalized tectonic map of Midcontinent region, showing location of Sooner Trend, on northeastern shelf of Anadarko Basin. (After Huffman, 1959.)

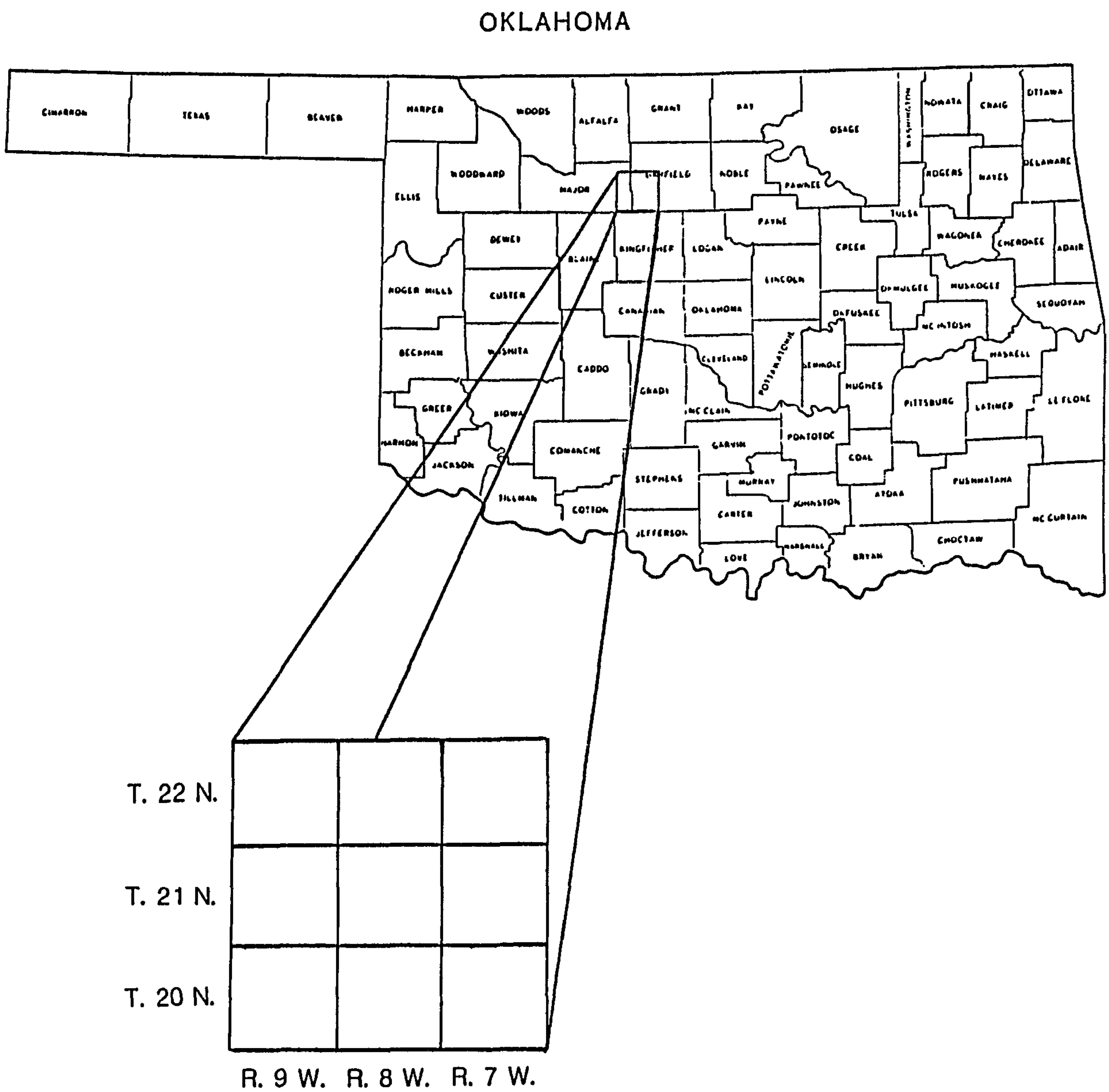

Figure 3. Location of 9-township Southwest Enid Area, Garfield, Major and Kingfisher Counties, Oklahoma.

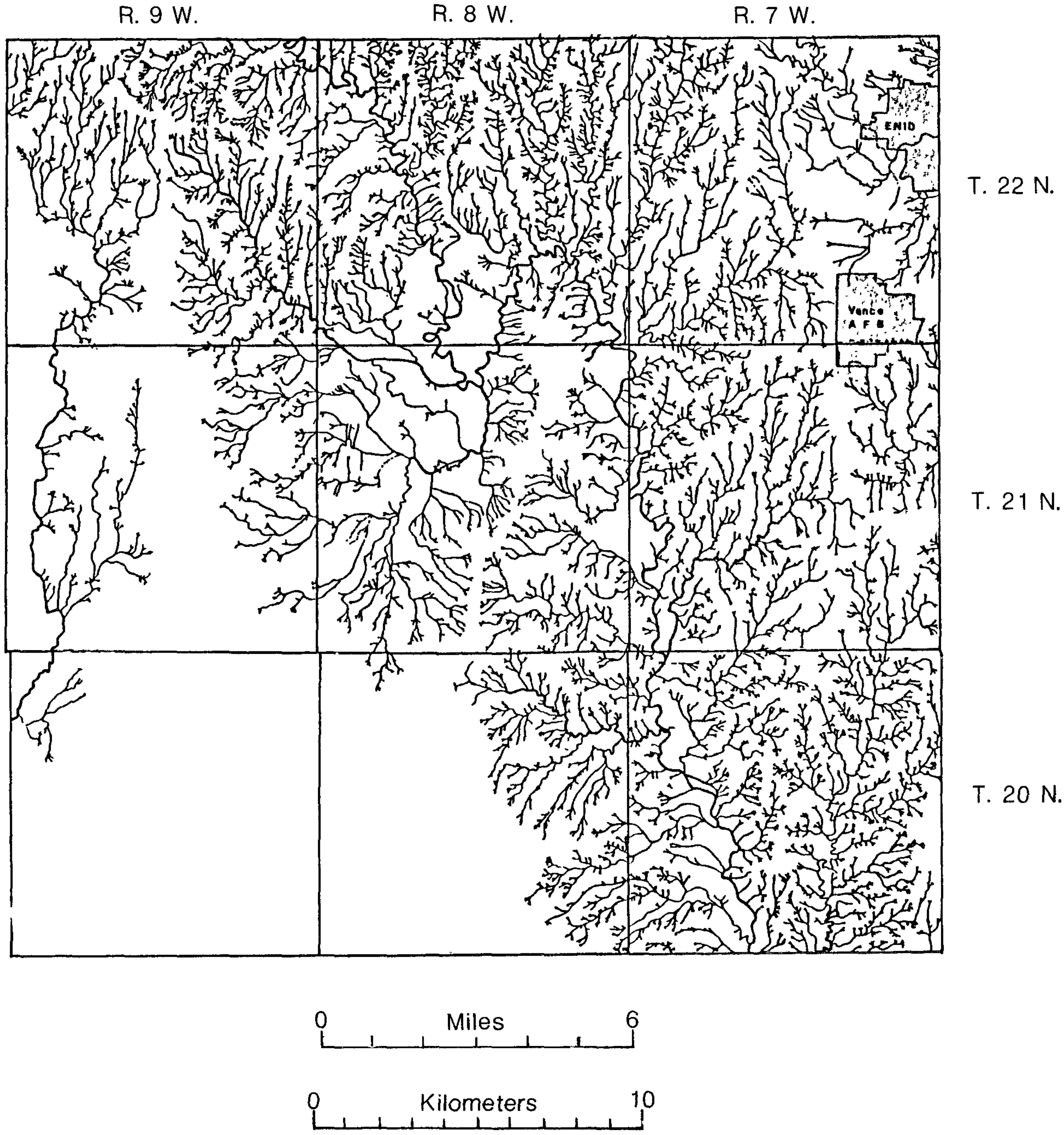

Figure 4. Stream network, Southwest Enid area. Drainage pattern traced from topographic maps. Southwestern part of area is underlain by young, unconsolidated geologic materials, and drainage network is not integrated.

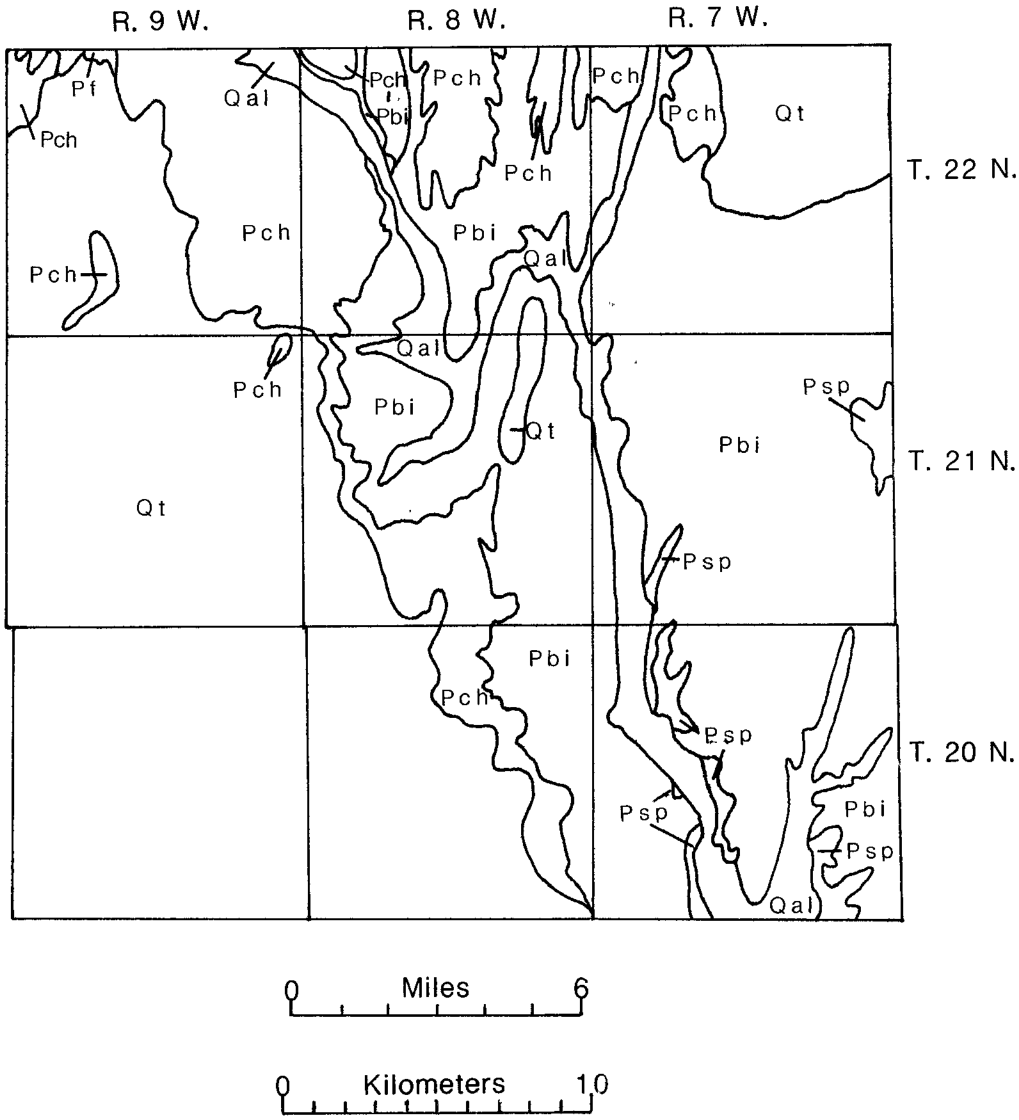

Figure 5. Surface geologic map, Southwest Enid Area. In ascending stratigraphic order, bedrock is Permian Salt Plains Formation (Psp), Bison Formation (Pbi), Cedar Hills Sandstone (Pch), and Flowerpot Shale (Pf). Quaternary terrace alluvium (Qt) and alluvium (Qal) cover Permian strata in extensive areas. (After Bingham and Bergman, 1980.)

in this locality stream drainage has not evolved to an integrated system (Figure 5).

Oil and gas are the most valuable mineral resources in the area. Average density of oil and gas wells is 5.2 per sq mi (2 per sq km); approximately 1700 wells have been drilled (Figure 6). As of January, 1987, more than 52 million bbl of oil and 475 billion cu ft of gas have been produced the nine townships of the Southwest Enid Area (Petroleum Information oil data and Dwight's Energy Data). Almost 90 percent of the wells were completed in Mississippian carbonate rocks.

Wells completed after 1976 were "infill" wells, most of which were drilled in a partially depleted reservoir. The post-1976 wells yield production data that are not compatible with records of wells drilled in the few years after the field was discovered. For this reason, production data used were from wells completed before 1977.

As described above, carbonate rocks of the Mississippian System in the Sooner Trend are a fractured reservoir. Therefore, a map of cumulative production from wells drilled into the reservoir before its significant depletion should be indicative of relative fracture density.

At many localities outside the study area, faults in rocks of the deep subsurface extend through rocks at the surface. At other localities faults and joints of the subsurface are expressed indirectly at the earth's surface or are manifest not at all. Close inspection of aerial photographs, satellite imagery, areal geologic maps and topographic maps ordinarily reveals numerous alignments in landforms, streams and vegetation -- the fracture traces and lineaments discussed previously. Although definitions of the terms "fracture trace" and "lineament", as set out by Lattman (1958), make reference only to mapping on aerial photographs, the criteria can be applied to mapping of lineaments and fracture traces on satellite imagery, topographic maps, and standard geologic maps of the surface.

This principal operating assumption is considered to hold true and to be justified or justifiable by repeated observation: In places where faulting and folding have affected the evolution of landforms not at all or only to a small extent, landforms are curvilinear in overall form or in general outline. This working assumption is useful through contradiction. In some regions, straight-line topographic features contrast strongly with the predominant curvilinear forms. The straightness of these landforms is such an uncommon attribute that a sense of empirical and intuitive probability

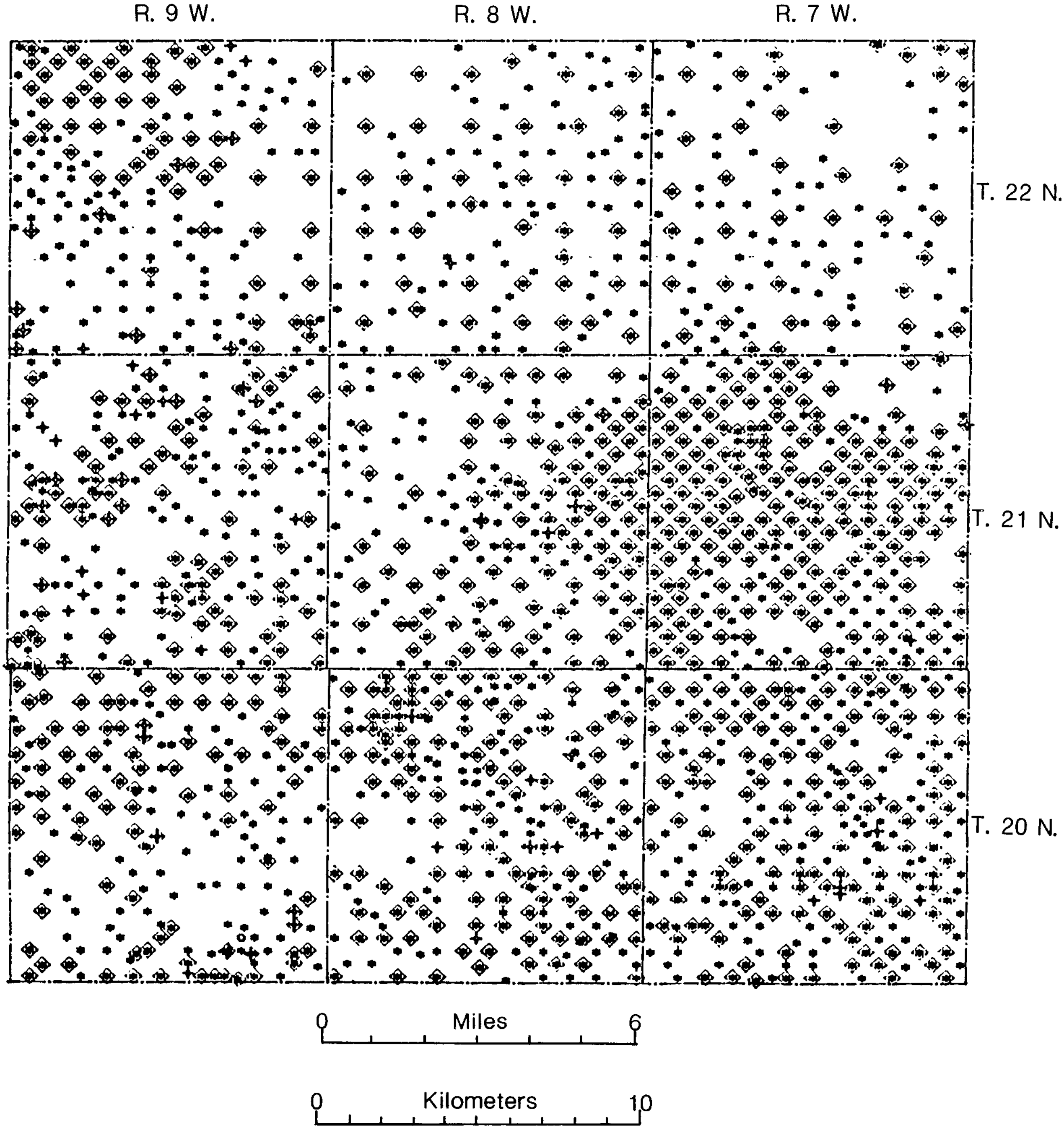

Figure 6. Locations of oil and gas wells drilled before 1977 (simple asterisk within diamond), dry holes drilled before 1977 (cross with open circle, within diamond), oil and gas wells drilled after 1977 (simple asterisk), and dry holes drilled after 1977 (simple cross with open circle).

leads to the inference that folds, faults or joints in bedrock have influenced evolution of the landforms.

The terms "empirical" and "intuitive" are evidence of subjectivity inherent in mapping of lineaments and fracture traces. Because areal geology is so variable from region to region, the mapper or mappers must establish the limits of features that are more-or-less linear but judged to be random and therefore not the results of structural discontinuities in bedrock. This limit necessarily is set by experience -- by study of the local terrain and by empirical definition of two general kinds of landforms: (a) Those that are rectilinear but nevertheless reasonably probable to have developed without strong influence of joints, faults or folds, and (b) those that are so rectilinear as to be improbable in the absence of influence or control of joints, faults or folds.

MAPPING OF LINEAMENTS

A detailed map of stream drainage (Figure 4) was made on topographic maps. Streams were traced as far headward as possible. Because quadrangles at the scale 1:125,000 were not available for coverage of the entire area, quadrangles at the scale of 1:62,500 (approximately 1 in. per mi (1.6 cm per km)) were used.

Each stream pattern was examined; straight-line segments and angular reaches of channels were marked, if they were judged to be anomalous. Changes in directions of channels on the order of 90 deg., or of an acute angle were regarded as being particularly suggestive. (Compare Figures 4 and 7.) Four general orientations of lineaments are apparent (Figure 7): Northward, eastward, northwestward, and northeastward.

The map of lineaments was generalized (Figure 8), in the expectation of usefulness of such a map for comparison with maps related to subsurface geology. Numerous short lineaments arranged end-to-end were considered to be evidence of a larger lineament that by ordinary inspection was not mappable in its entirety; therefore, the short lineaments were combined. A pattern of high- and low-density areas was revealed (Figure 8), but the lineaments were so abundant that reduction of the data was required. Intersections of lineaments were mapped (Figure 9).

SUBSURFACE GEOLOGY

From public records available at Oklahoma Well Log

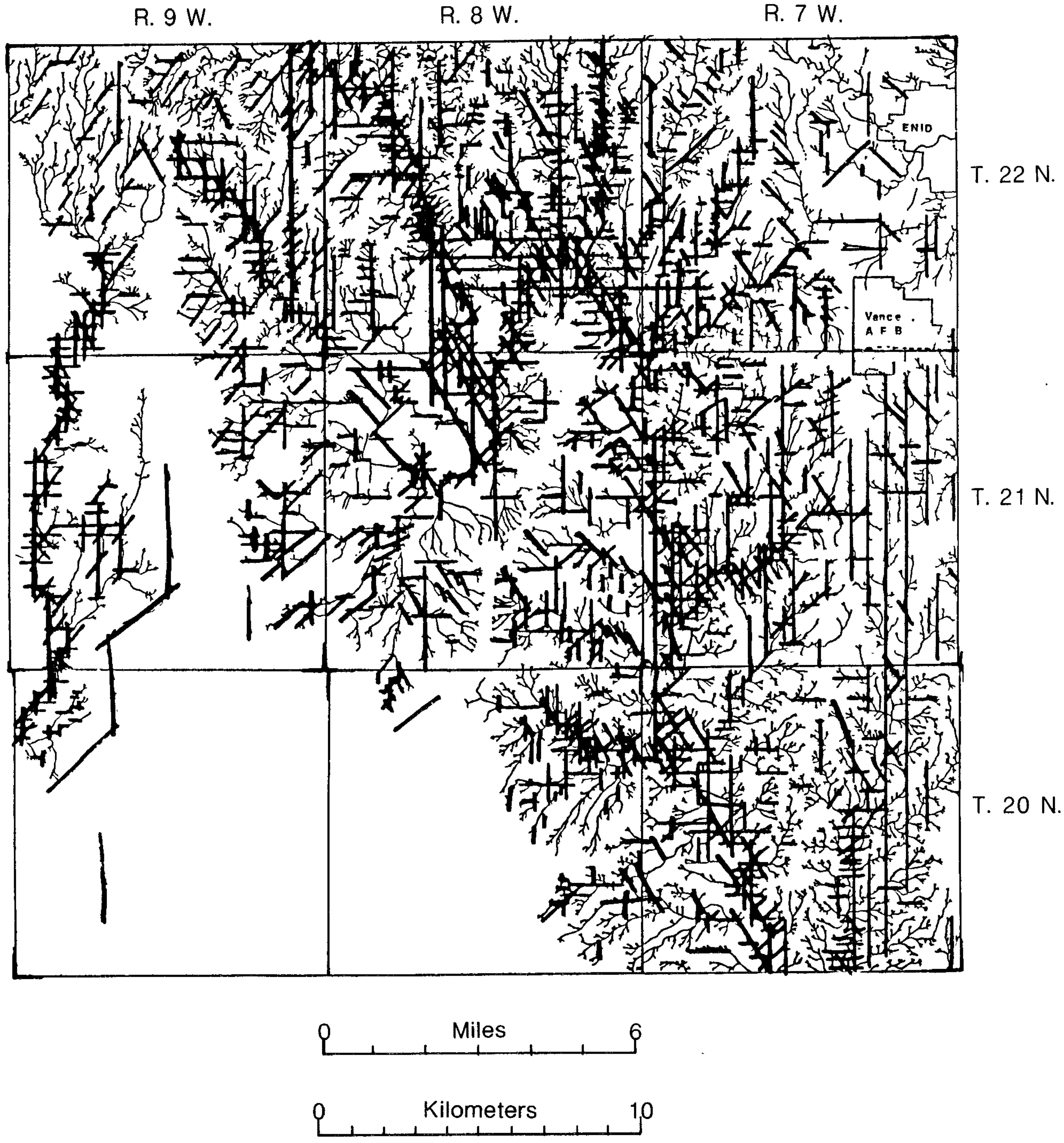

Figure 7. Stream network, Southwest Enid Area, with segments marked that were judged to show anomalous straightness, anomalous intersections with other streams, or both.

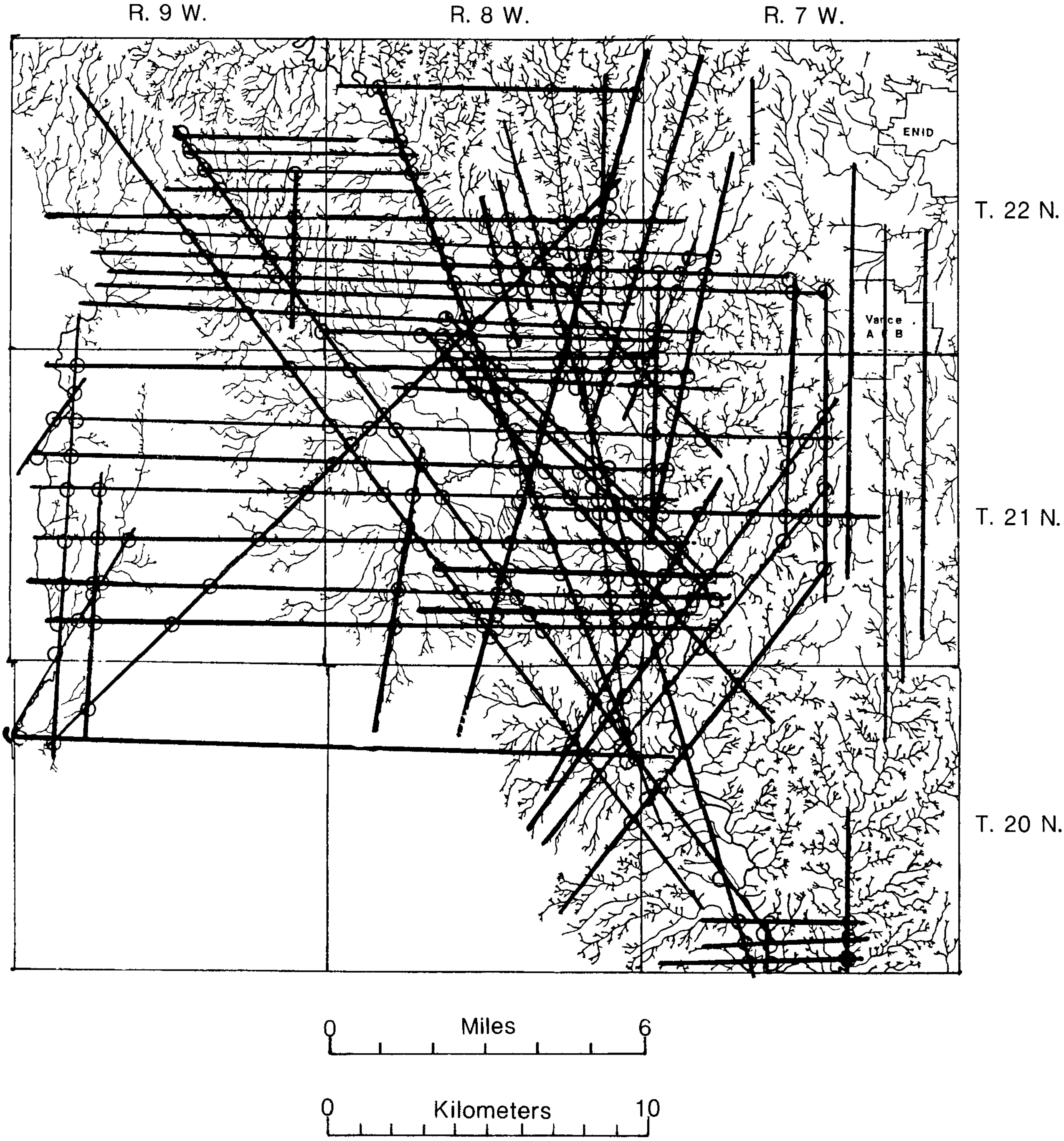

Figure 8. Stream network, Southwest Enid Area, with stream-lineaments extended and intersections marked by circles.

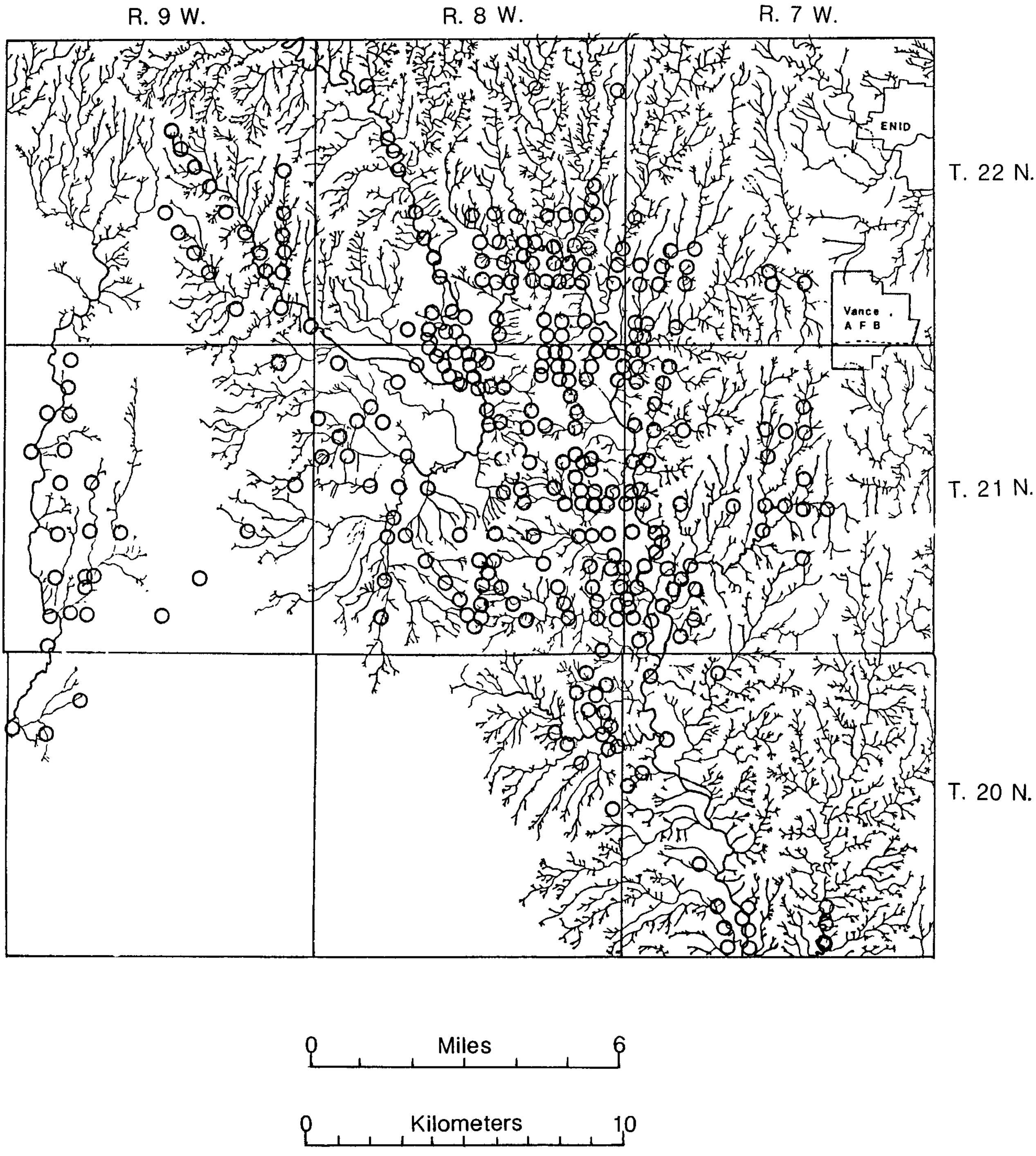

Figure 9. Southwest Enid Area. Circles show locations of intersection of generalized stream-lineaments.

Library, Tulsa, Oklahoma, data on each of the 1,688 oil and gas wells in the Southwest Enid Area were studied, including:

Location, accuracy of 2.5 acres (1 hectare).
Well status (i.e., oil well, gas well, or dry hole).
Year completed.
Datum elevation (ordinarily the kelly-bushing elevation).
Availability of wireline logs.
Depth to top of Meramecian Series of Mississippian System.
Depth to base of Mississippian System.
Cumulative oil production to January 1, 1987.
Cumulative gas production to January 1, 1987.
Fracture-treatment of the well.
Pay zone or zones.

Wireline logs were reviewed; kelly-bushing elevations and depths of the top of Meramecian strata and the base of the Mississippian System were recorded. Only data from such sources were used for construction of thickness maps and structural geologic maps. Scout-ticket tops were considered not to be reliable. Of 1,688 wells in the study area, logs of 813 were available. These 813 wells were distributed in such a manner that the entire area can be considered to have been sampled adequately.

Data were entered into a spread-sheet program; thickness of the Meramecian-Osagean stratigraphic section was calculated for each well. Cumulative production was estimated for each well, as an oil-equivalent quantity. Added to oil production (in thousands of barrels) was a number calculated by conversion of gas production to oil production. One billion cubic feet of gas was estimated to be equal to 75 thousand barrels of oil.

Data from the spread-sheet were entered into the Jupiter Mapping Program, the principal algorithm of which is "neighborhood-based" (Watson and Philip, 1987). Data calculated for each intersection of a generated grid are based on a weighted well-value; data at each well-location and distances from the grid intersection to nearby wells are taken into account. Each well-value also is honored, as long as density of wells is not more than one well per grid unit. The grid size was defined so that each well-value was integrated in contour mapping.

Structural contour maps were made of the top of Meramecian strata and the base of Mississippian rocks (top of underlying Woodford Shale) (Figures 10 and 11). The working hypothesis tested was that faults in Mississippian rocks would be shown or indicated at places where configurations of datums are anomalous -- where changes in dip are uncommonly abrupt, where dip is reversed in short distances, or where the structural

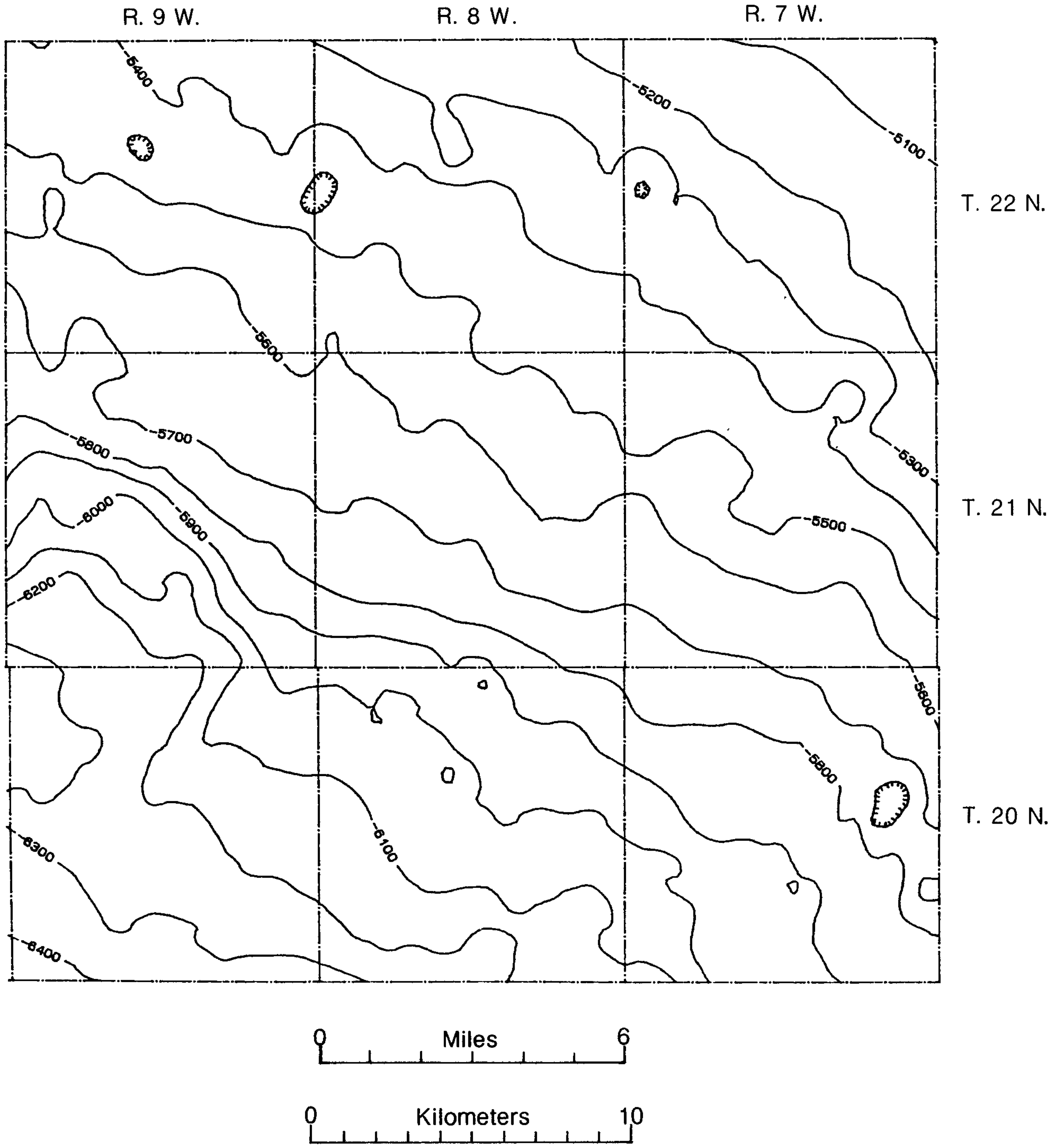

Figure 10. Southwest Enid Area. Structural contour map, top of Meramecian strata. Contour interval 100 ft.

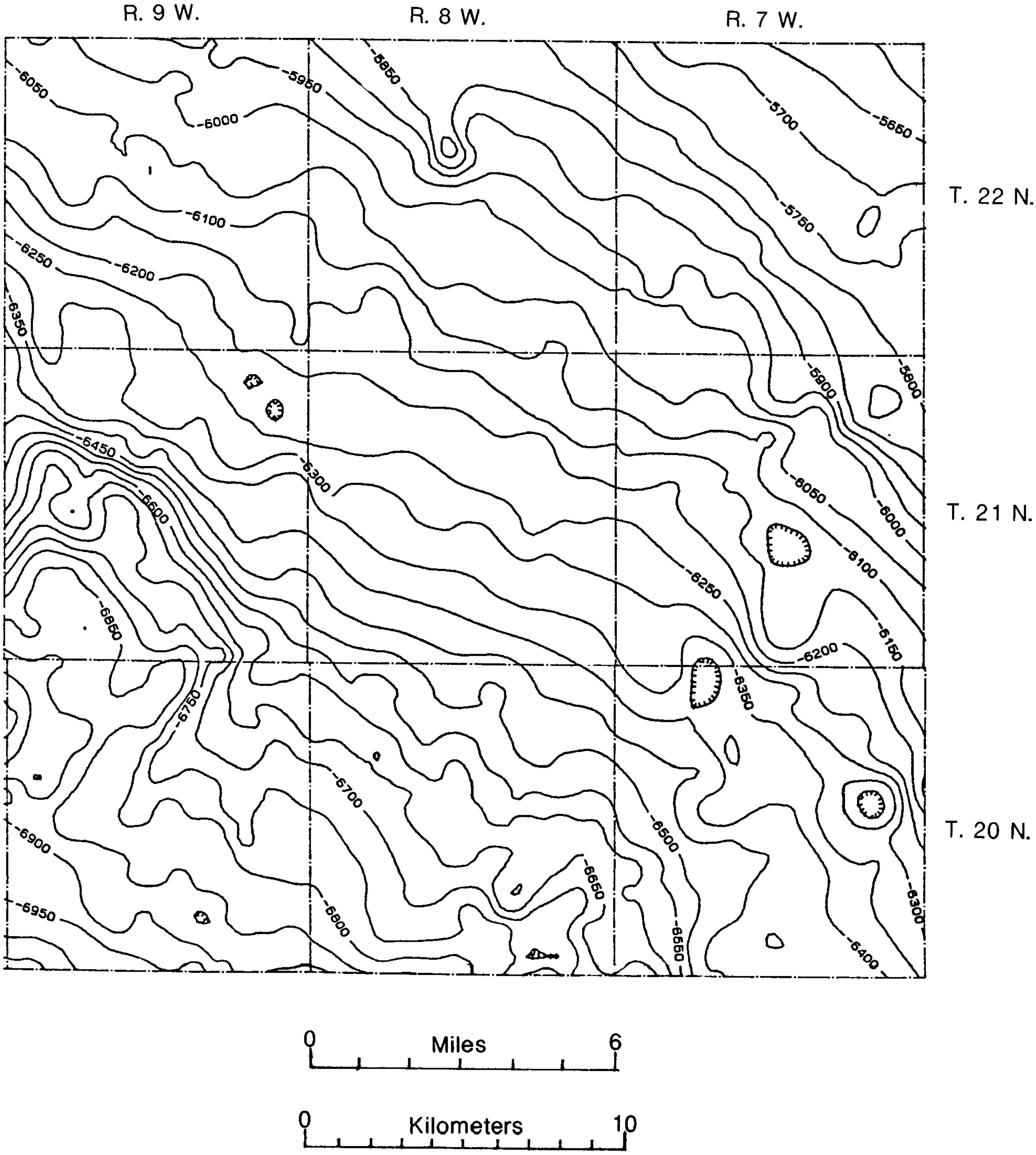

Figure 11. Southwest Enid Area. Structural contour map, base of Mississippian System (top of Devonian Woodford Shale). Contour interval 50 ft. Observe increase in detail, most of which is due to smaller contour interval.

fabric seems to show alignments. A first-order trend surface of the top of Meramecian rocks (a best-fit planar surface) shows that regional dip is south-southwestward at less than 1 degree.

Several small anomalous areas of closed contour lines are shown in Figures 10 and 11. A fault was interpreted by Harris (1975) on the eastern side of the syncline that trends through the northwestern part of T. 20 N., R. 9 W. (arrows, Figure 11). The syncline is uncommonly large and asymmetrical; by comparison to other folds in the study area, its size and shape were taken as justification for the inference of a normal fault that strikes northeastward, downthrown to the west.

Figure 12 shows thickness of rocks between the top of the Meramecian Series and the base of the Mississippian System. In the Southwest Enid Area, the post-Mississippian, pre-Pennsylvanian unconformity is on Chesteran strata; the Meramecian-Osagean strata probably were shallow beneath the surface, and could have been part of a fresh-water aquifer. Numerous areas in Figure 12 are mapped as localities where the reservoir is thin; these circular, ovate and elliptical patterns are suggestive of terrain where rock has been eroded locally by dissolution. If these features are interpreted correctly, their distribution may have been influenced by systematic fractures in the rock, a relation that is well documented (for example, see Thornbury, 1956, p. 337; also Jennings, 1985; Bogli, 1980). Otherwise, Figures 10, 11 and 12 show no evidence that is firmly indicative of the abundance and orientations of fractures in the reservoir rock; the maps show no conclusive evidence about fracturing of the reservoir.

In the Southwest Enid Area oil and gas have been produced from rocks as old as Ordovician and as young as Pennsylvanian. However, 88 percent of the wells were completed in Meramecian-Osagean rocks, and about 90 percent of the petroleum has been produced from these Mississippian strata.

The statement that the Mississippian reservoir of the study area is permeable mostly because of systematic fractures (Nelson, 1985; Harris, 1975) seems to provide a stable premise. Accordingly, this inference would seem to follow: If permeability in the reservoir is correlated directly with abundance of fractures, with lengths, heights and openness of fractures, then relative density of fracturing in the reservoir should be manifest in a general way by volumes of oil and gas produced from place to place. (The qualifying phrases "relative density" and "general way" take into consideration lithic variation in the reservoir, perforated intervals of different lengths, fracture-treatments of different types,

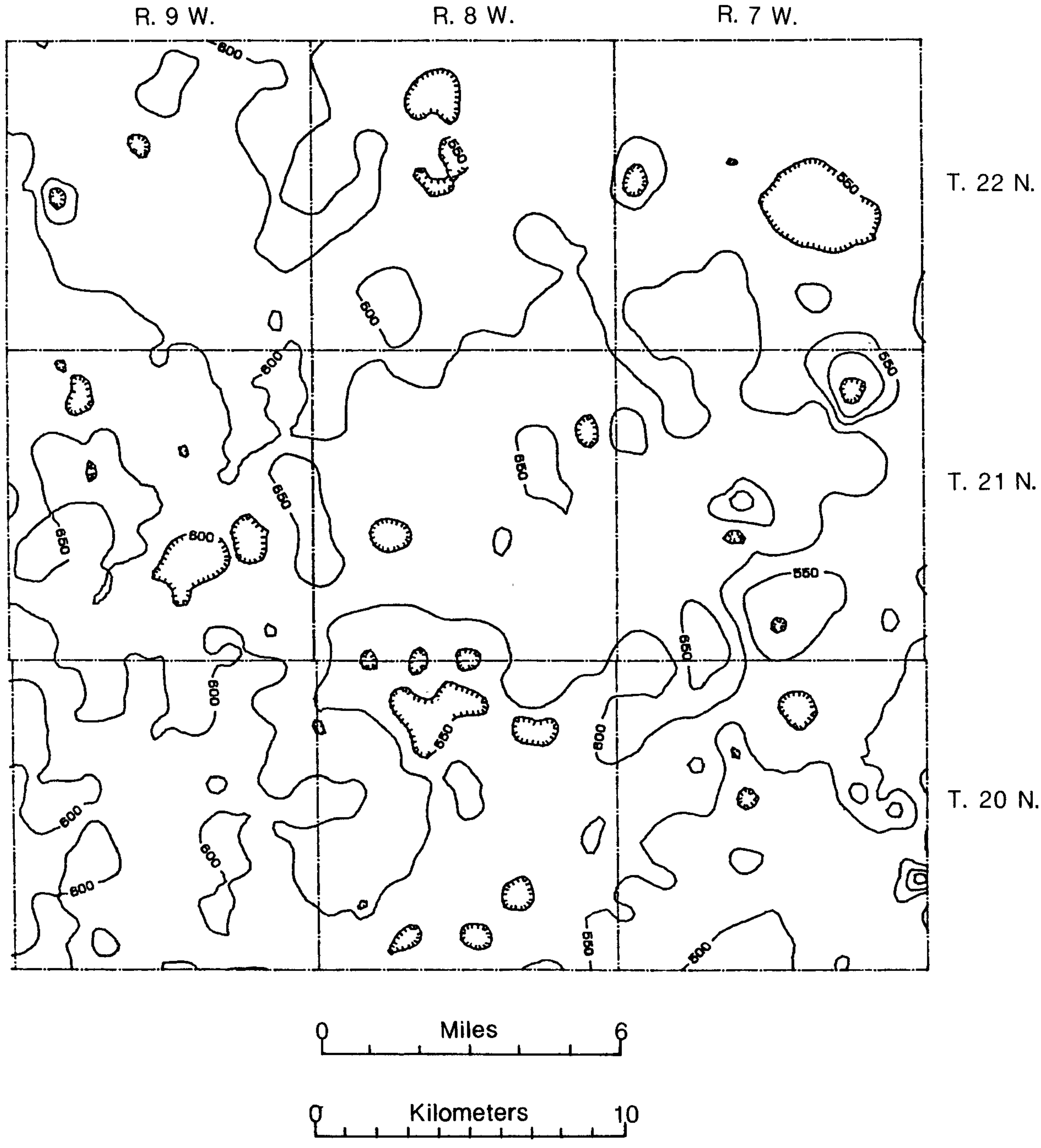

Figure 12. Southwest Enid Area. Thickness of strata between top of Meramecian Series and base of Mississippian System. Contour interval 50 ft. Hachured closed lines show areas where the stratigraphic sequence is thin.

operators with different practices, and other variables that are exceedingly difficult to document in systematic fashion.)

Figure 13 shows cumulative oil-equivalent production from wells completed before 1977. (Production from wells drilled thereafter probably was reduced by overall depletion of the reservoir.) If production of oil and gas is related directly to systematic, closely spaced fractures in the reservoir, then patterns of contour lines suggest that fractures are concentrated in T. 21 and 22 N., R. 7 and 8 W. If indeed such a relation exists, then fractures seem to trend eastward, northeastward, and northwestward (see arrows, Figure 13).

At several places in T. 20 N., R. 8 and 9 W., and T. 21 N., R. 9 W., large cumulative production per well is owing to commingling of petroleum from Mississippian rocks and strata of the deeper Silurian-Devonian Hunton Group (Figure 13). In Figure 14 these localities are not shown, and terrain where exceptionally large amounts of production from Mississippian rocks is outlined. Figure 15 shows areas of large cumulative production per well, and the outlines of areas where fractures are judged to be uncommonly numerous.

In general, the patterns seem to be positively and generally correlated. Two areas in which the patterns seem definitely not to match are (a) the northeastern part of the study area, where the city of Enid and Vance Air Force Base diminished the effect of analysis of stream patterns, and (b) the northwestern part of T. 21 N., R. 8 W. If only the region where cumulative production of more than 250,000 bbl per well is considered, correlation of cumulative production and abundance of (inferred) fractures seems to be significantly greater (Figure 15).

CONCLUSIONS

In the Southwest Enid study area, tracts of exceptionally productive oil and gas wells seem to be positively but only generally correlated with areal density of intersecting lineaments. This general observation could be the basis for a deductive argument that where cumulative production of wells is uncommonly large and no fundamental change in matrix porosity and permeability of the reservoir is evident, the reservoir is more fractured than elsewhere. Accordingly, if confining beds are cut by throughgoing fractures, then the penetration is more probable in terrain where lineament intersections are abundant.

In terrain geologically similar to this part of the Sooner Trend, where structural geology is simple and bedrock at the

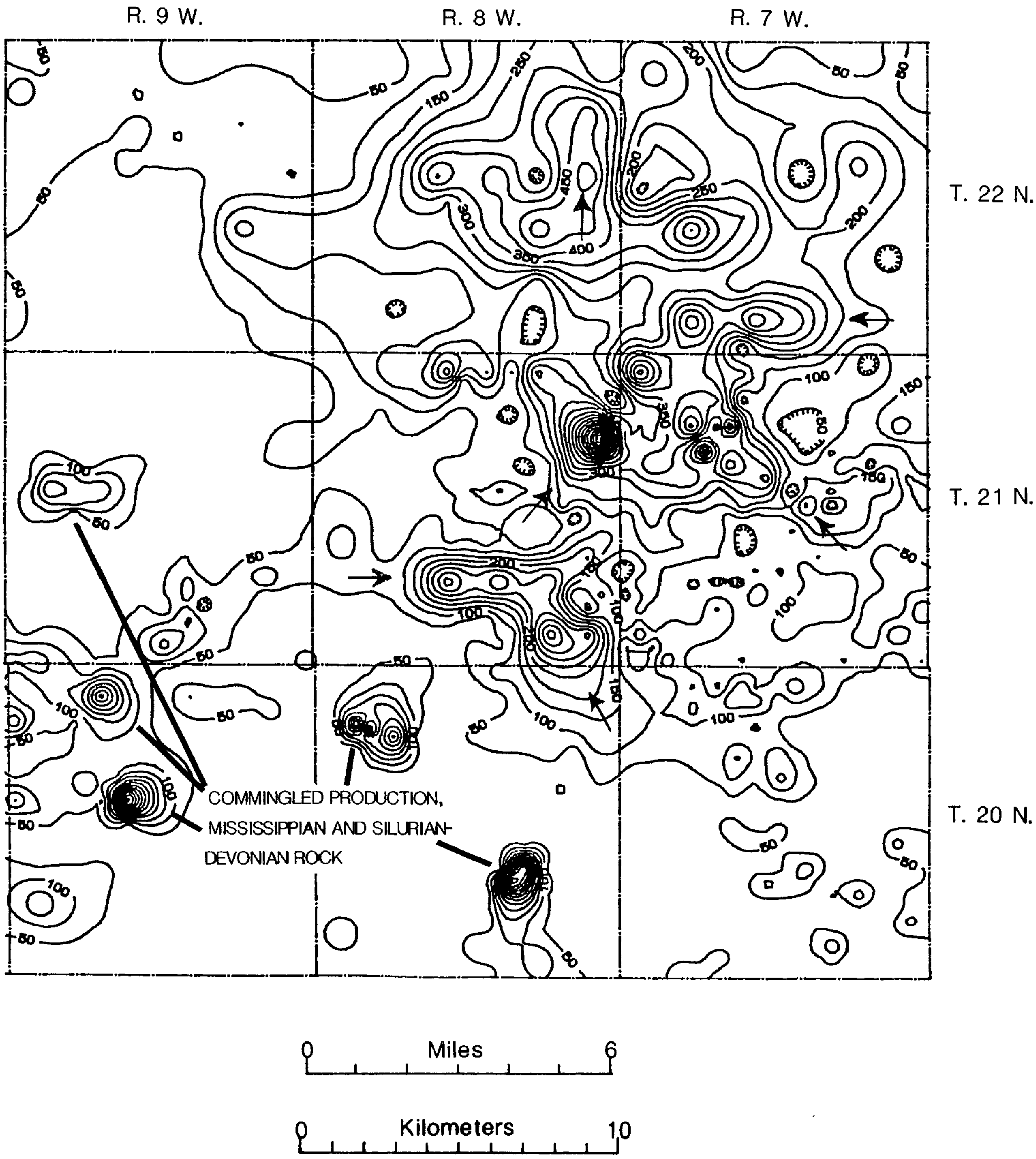

Figure 13. Southwest Enid Area. Contour lines show cumulative production from Mississippian rocks, and locally from Mississippian and Silurian-Devonian rocks. Contour interval, 50,000 barrels of oil-equivalent production.

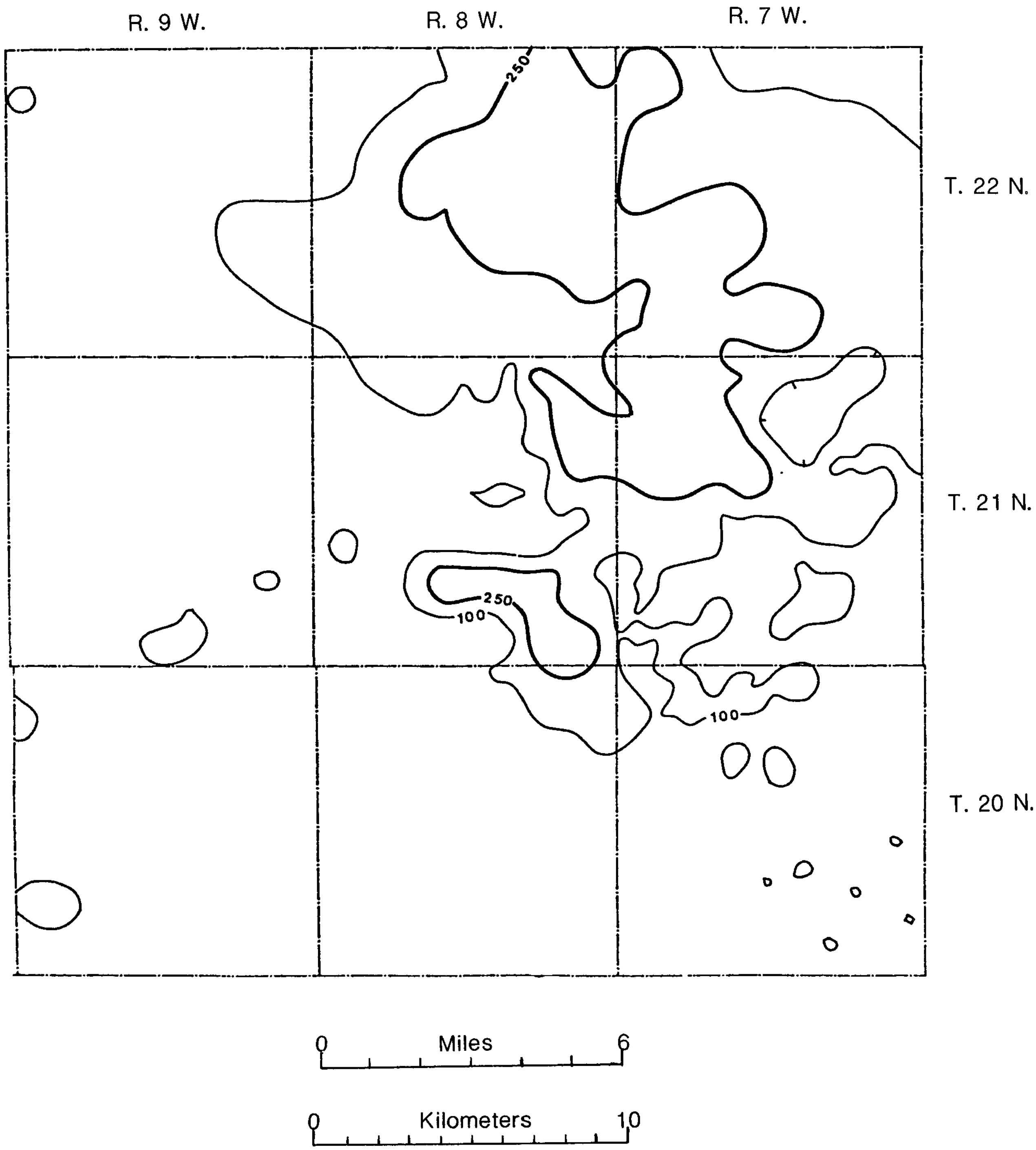

Figure 14. Southwest Enid Area. Contour lines show cumulative production from Mississippian rocks. Contour lines scaled as 100,000 and 250,000 barrels of oil-equivalent production.

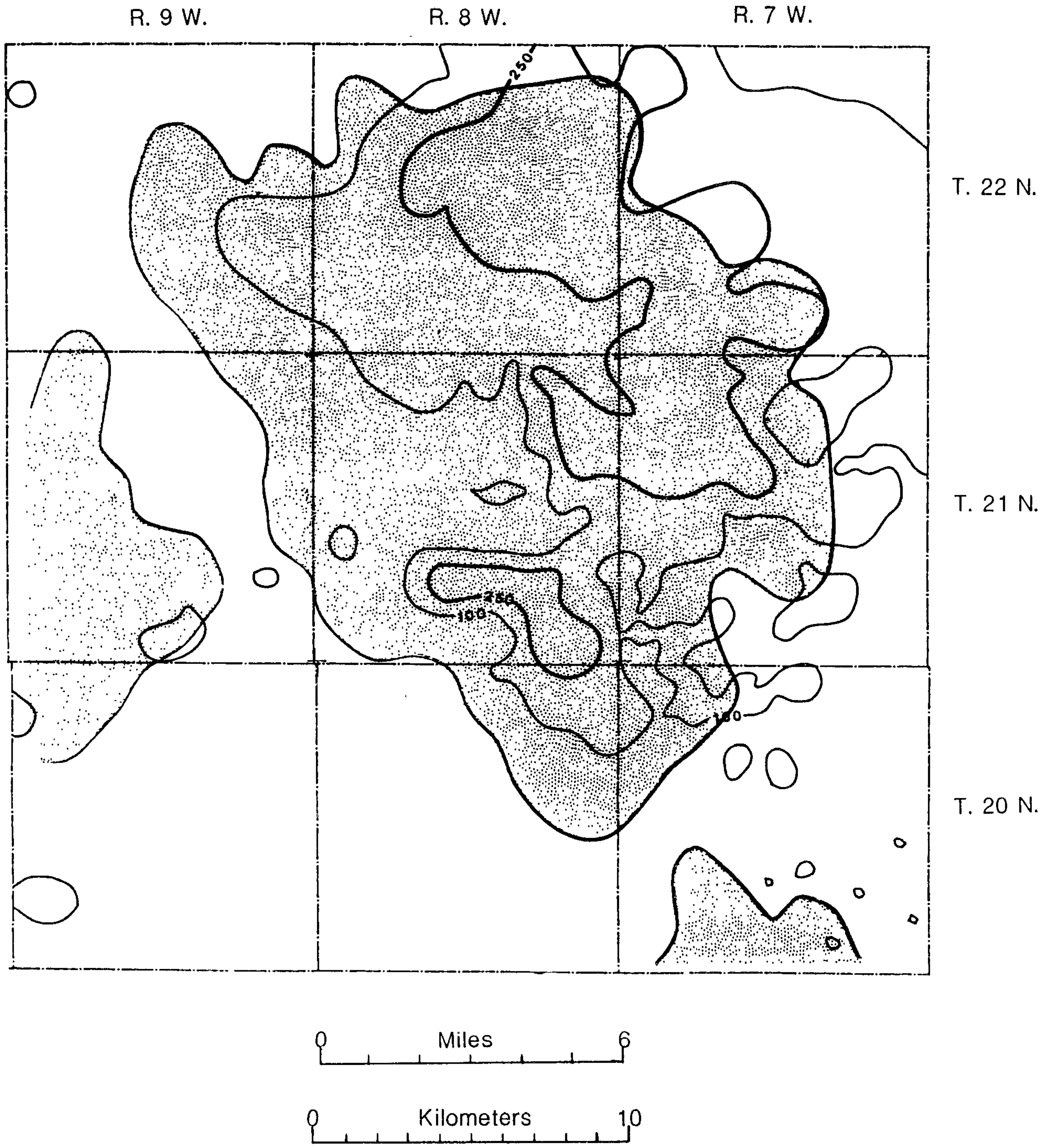

Figure 15. Southwest Enid area. Stippling shows where intersections of stream-lineaments are numerous. Oil-equivalent production of more than 250,000 bbl per well is near up-dip limit of area of abundant lineament intersections.

surface is weakly resistant to erosion and almost undeformed, maps designed to show areas of possible injection-sensitivity should show localities where intersections of lineaments are closely spaced. In combination with computer-contoured structural-geologic and unit-thickness maps, the injection-sensitivity maps could indicate areas in which cautious assessment of local geology should precede disposal of fluids by underground injection -- especially if injection pressures are designed to exceed original formation pressures.

Conventional contouring of structural geologic maps with unit-thickness data and lineaments taken into account can produce an integrated interpretation of subsurface structural geology. An experienced and creative mapper may present interpretations that in fact are closer to the truth than mapping with somewhat less license. However, under some circumstances the interpretation probably would be regarded as being unacceptably more subjective than the computer-contoured maps set out here. Computer-contoured maps seem to be regarded as being "unbiased"; for this reason they may provide interpretations of structural geology that are rather likely to be acceptable to persons with central interests and derivative opinions that are quite different. In regions with geologic similarities to the Southwest Enid Area (and indeed to the Sooner Trend), computer-generated structural geologic maps and thickness maps, and conventionally prepared lineament-intersection maps should provide a basis from which regulatory personnel and petroleum companies could begin to decide whether underground injection of liquid waste is prudent.

SECTION 5

WEST EDMOND OIL FIELD

INTRODUCTION

West Edmond Oil Field includes about 160 sq mi (420 sq km), located mainly in Oklahoma County, Oklahoma (Figure 1). The field was developed in the early 1940's. The principal reservoir is the "Hunton Lime" -- strata of the Silurian-Devonian Hunton Group (Figure 16). The field is on the northern part of the plunging Oklahoma City Anticline. The trap in West Edmond Field is developed chiefly where a large salient of the upper part of the Hunton Group extends eastward past the general erosional limit and up-dip onto the flank of the Oklahoma City Anticline (Figures 17 and 18). About 1,400 wells were completed in the Hunton, at depths averaging about 6,800 ft (2100 m). Hundreds of wells have been drilled near the periphery but outside West Edmond Field; collectively, wells in the field and in the surrounding area provide excellent basic data about the subsurface geology.

Excellent accounts of the early history of West Edmond Field were provided by McGee and Jenkins (1946) and Swesnik (1948). Four months after the discovery well was drilled only 10 or so drilling rigs were in operation; by the end of 1944, 120 rigs were drilling, and by the end of 1946, development of the Hunton reservoir was nearly finished; more than 1300 wells had been completed. In the period between the discovery well in April, 1943 and the end of 1945, the field had produced more than 32 million barrels of oil and 46 billion cubic feet of gas (McGee and Jenkins, 1946). In July, 1947 the field was unitized by order of the Oklahoma Corporation Commission; at this time 65 million barrels of oil had been produced. As of 1989, total production of oil exceeds 160 million barrels.

In the western, down-dip part of the field, many wells penetrated only the upper part of the Hunton Group, chiefly in the Bois d'Arc Limestone (Figure 18). Although the Haragan and Henryhouse Formations and the Chimneyhill Subgroup are less porous and permeable than the Bois d'Arc, the strata are fractured and the formations are productive near the eastern limit of the field.

In the early development of the field, most wells initially were allowed to flow at relatively high rates, in order to "clean up" the reservoir near the borehole. In this process the 24-hr production rate was measured. Most wells in the field were drilled on 40-acre (16-hectare) spacing. Oil-

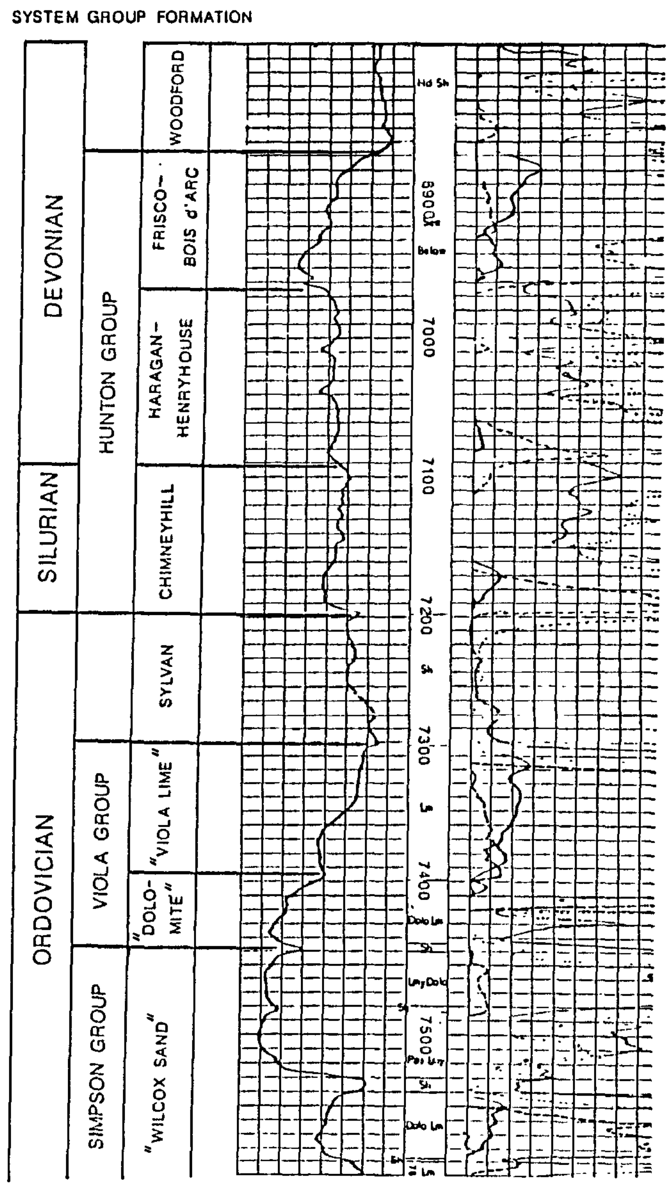

Figure 16. Type electric log, West Edmond field, showing rock-stratigraphic units from Woodford Shale to Simpson Group.

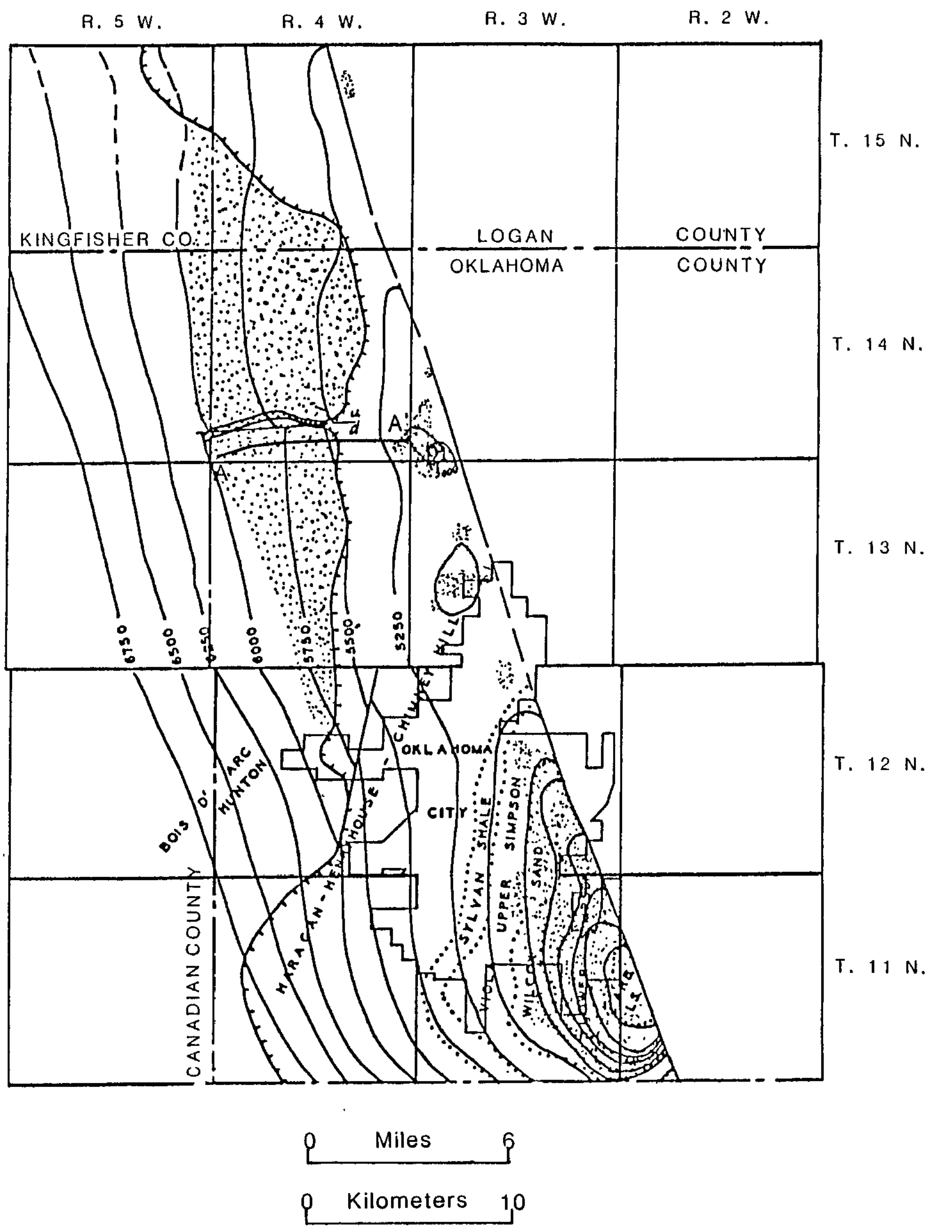

Figure 17. Paleogeologic-structural geologic map, Oklahoma City Anticline and West Edmond Field, showing paleogeology of the time after deposition of Hunton Group and before deposition of Woodford Shale. The trap was formed where salient of upper part of Hunton Group extends up-dip onto flank of northward-plunging Oklahoma City Anticline. Contour lines indexed in feet below mean sea level; contour interval 250 ft (76 m). Modified from McGee and Jenkins, 1946, p. 1805.)

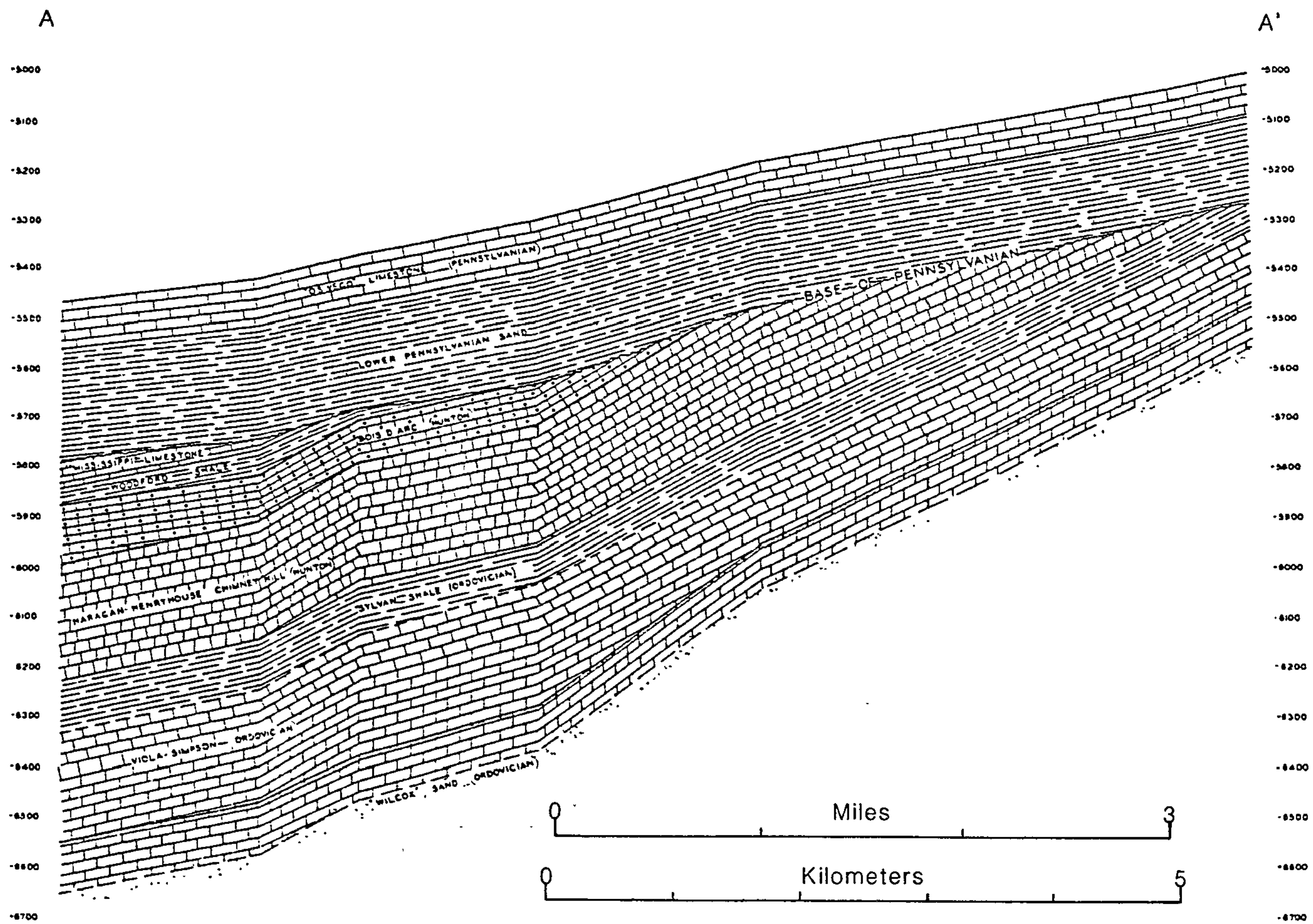

Figure 18. Cross-section, central part, West Edmond Field, showing truncation of Hunton Group and sealing of trap by Woodford Shale and Pennsylvanian strata. Line of cross-section shown in Figure 16. Bois d'Arc Limestone is principal reservoir in central part of field. (Modified from McGee and Jenkins, 1946, p. 1804.)

production quotas were established in the year of discovery, in order to maximize long-range production of oil; to forestall decline of reservoir pressure, quotas were placed on gas as well. In 1947, the Hunton Group in the West Edmond Field was unitized. Field-wide reservoir-pressure maintenance was based on injection of water or gas. As a consequence of this history, only the gross field production is reported to the State of Oklahoma; single-well production data are not available for the period from date of unitization to the present.

SURFACE GEOLOGY

The West Edmond Field is on the northwestern flank of the Oklahoma City Anticline (Figure 19). The anticline is near the southern end of the Nemaha Range, a complex of faulted anticlines that extends from southeastern Nebraska into south-central Oklahoma. The eastern margin of the range is faulted (Figure 19).

Generalized surficial geology of the study area is shown in Figure 20. The Hennessey Shale, which crops out over most of the area, dips southwestward at about 90 ft per mi (17 m per km). In the northeastern part of the area Garber Sandstone is exposed, whereas in the southwestern part the El Reno Group crops out. Quaternary sand, silt, clay and gravel are distributed along the North Canadian River (southern part, Figure 20) and all major tributaries. To the southeast Quaternary dune sands and alluvial terrace deposits conceal bedrock.

SUBSURFACE GEOLOGY

STRATIGRAPHY

In Oklahoma, stratigraphic nomenclature of sedimentary rock units exposed at the surface ordinarily differs considerably from nomenclature of strata concealed in the subsurface. In this report nomenclature used in exploration of the subsurface takes precedence. Additionally, several stratigraphically successive rock units are lithically so similar that they cannot be discriminated on wireline logs that date from the 1940's and 1950's. Therefore such formations were combined into units that have distinctive characteristics on wireline logs, and that can be correlated from well to well. The following terminology was used:

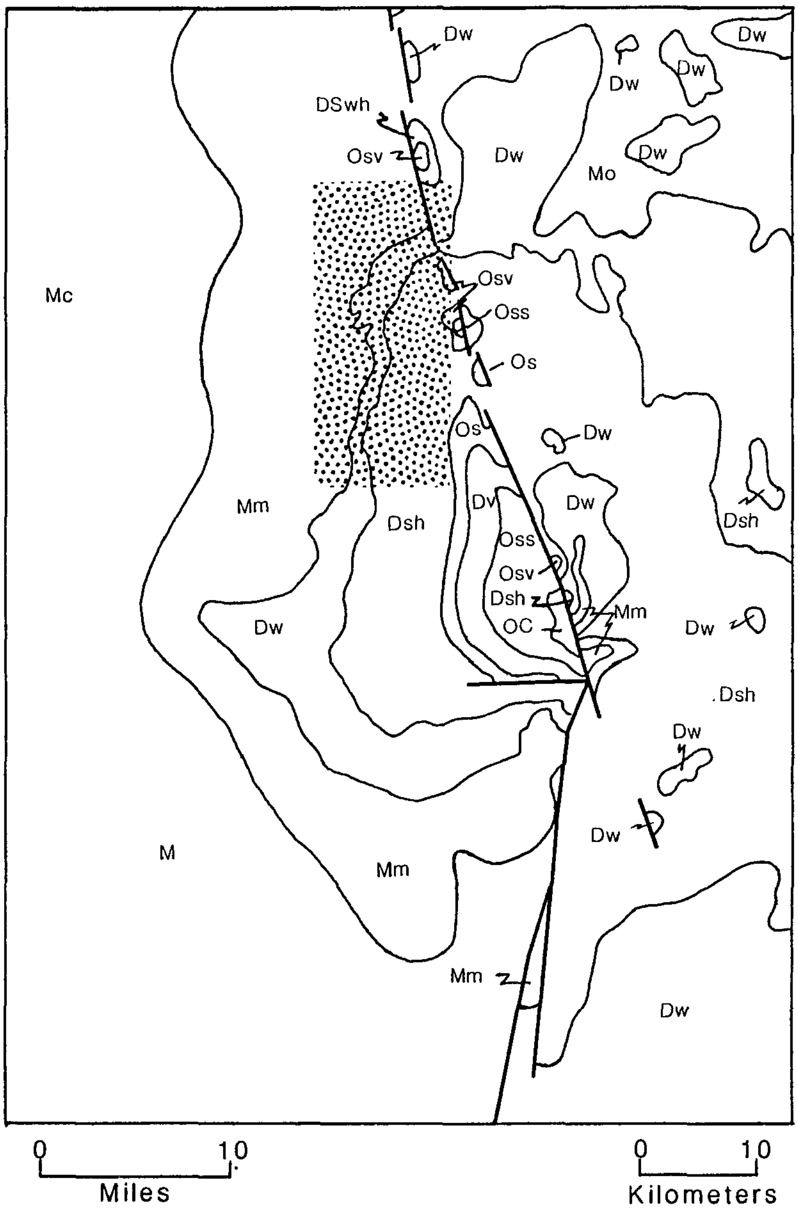

Figure 19. Pre-Pennsylvanian paleogeologic map of central Oklahoma, showing location of West Edmond Field relative to Oklahoma City Anticline. (Modified from Jordan, 1962.) Symbols: OC - Cambrian-Ordovician Arbuckle Group. Oss - Ordovician Simpson Group. Ov - Ordovician Viola Group. Os - Sylvan Shale. Osv - Viola Group and Sylvan Shale. Dsh - Silurian-Devonian Hunton Group. Dw - Devonian Woodford Shale. DSws - Hunton Group and Woodford Shale. M - Mississippian rocks, undifferentiated. Mn - Mississippi Lime. Mc - Mississippian Chester Group.

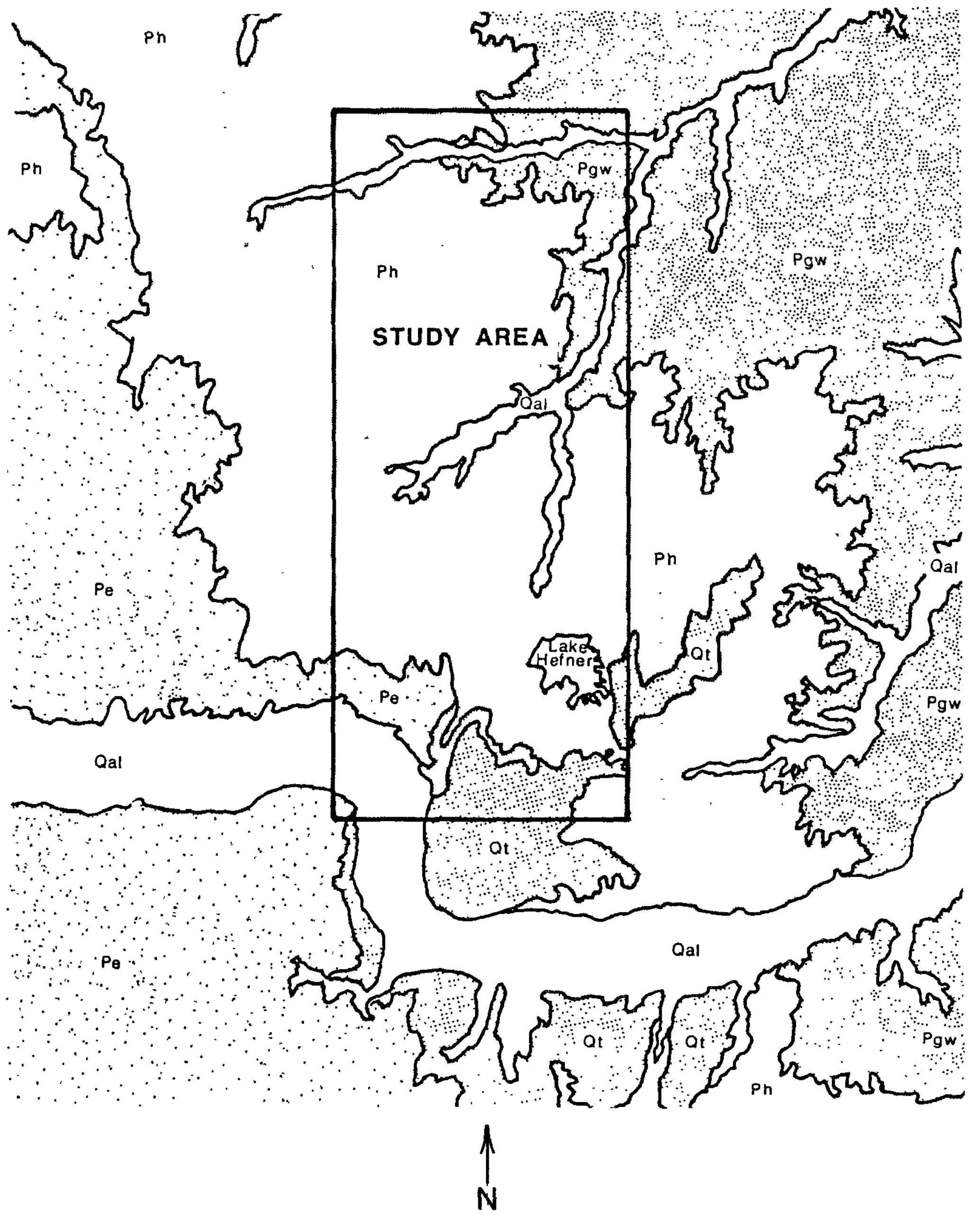

Figure 20. Generalized surface geology, West Edmond Field and nearby areas. Symbols: Pgw - Garber-Wellington Formations. Ph - Hennessey Group. Pe - El Reno Group. Qt - Pleistocene terrace alluvium. Qal - Quaternary alluvium. (After Bingham and Moore, 1975.)

Formations that compose the Hennessey Group are referred to as the "Hennessey Shale".

The Garber Sandstone and Wellington Formation are called the "Garber-Wellington Formations".

The Frisco and Bois d'Arc Limestones of the Hunton Group are called the "Frisco-Bois d'Arc Limestones".

The Haragan and Henryhouse Formations of the Hunton Group are called "Haragan-Henryhouse Formations."

The Chimneyhill Subgroup of the Hunton, composed of the Clarita, Cochrane, and Keel Formations, is dealt with as one rock-stratigraphic unit.

Stratigraphy of rocks ranging in age from Permian through Cenozoic, including the Garber and Wellington Formations, is derived from Christenson and Parkhurst (1987) and Wood and Burton (1968). The Desmoinesian Series of the Pennsylvanian System was described by Benoit (1957). Much of the stratigraphy of Ordovician and Silurian strata was taken from Swesnik (1948). Nomenclature of the Hunton Group was described by Amsden and Rowland (1967).

Permian System

In the study area, the boundary between the Permian and Pennsylvanian Systems is open to question. A set of thin, extensive limestone marker beds at about 1,500 ft (460 m) below the surface is near the base of the Permian; the provisional base-of-Permian was mapped close beneath the base of the lowermost bed in the set (Figure 21).

Hennessey Shale--

Thickness of the Hennessey Shale is 600 to 650 ft (180 to 200 m). The Hennessey is dominantly reddish brown shale that includes siltstone and fine grained sandstone.

Garber-Wellington Formations--

In the subsurface the boundary of the Garber Sandstone and the underlying Wellington Formation is not detectable at most places (Carr and Havens, 1976). The two are undifferentiated in this report (Figure 21). Aggregate thickness of the Garber and Wellington ranges from 800 to 1000 ft (250 to 300 m). The sequence is composed of red to maroon, lenticular strata of fine grained cross-bedded sandstone, interbedded irregularly with sandy, silty shale.

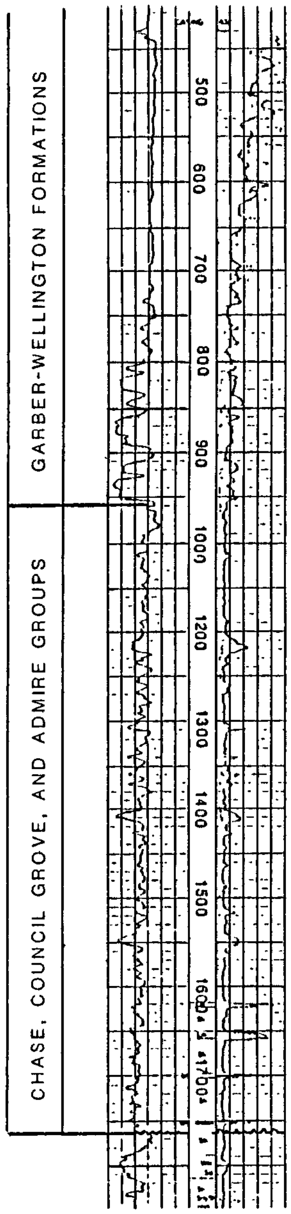

Figure 21. Type electric log, West Edmond Field, showing rock-stratigraphic units from base of surface casing to uppermost part of Pennsylvanian System. Pennsylvanian rocks are below wavy line at 1760 ft.

Chase, Council Grove, and Admire Groups--

Approximately 750 ft (230 m) of red to maroon, fine grained, cross-bedded sandstone and shale compose the Chase, Council Grove and Admire Groups; the strata are similar to the Garber and Wellington Formations.

Pennsylvanian System

The Pennsylvanian System is composed predominantly of gray shale interbedded with sandstone and thin limestones. The Pennsylvanian unconformably overlies older Paleozoic rocks, ranging from the Mississippian System in the western part of the study area to Ordovician and Silurian-Devonian rocks in the eastern part (Figures 19 and 22).

Mississippian System

In central Oklahoma, Mississippian rocks compose the "Mississippi Lime" (Figure 22), a section of gray to brown limestone and cherty limestone. In the northwestern part of study area Mississippian rocks are as thick as 270 ft (80 m); in the eastern part of the study area the Mississippian is absent because of post-Mississippian, pre-Middle Pennsylvanian erosion on the Oklahoma City Anticline (Figure 19).

Devonian and Silurian Systems

The Woodford Shale, Frisco, Bois d'Arc, and Haragan Formations of the Hunton Group (the principal reservoir in the West Edmond Field) are classified as Devonian (Figure 18). The lower rock-stratigraphic units of the Hunton, the Henryhouse and Chimneyhill, are Silurian (Amsden and Rowland, 1967). (In Figure 22 the Henryhouse is shown as being Devonian, because on ordinary wireline logs the Henryhouse and Haragan cannot be differentiated sufficiently for consistent well-to-well correlation.)

Frisco and Bois d'Arc Formations--

The Friso Limestone (Figure 18) is maximally 40 ft (12 m) thick. The underlying Bois d'Arc is made up of four lithologic units, all limestone. The boundary between the Frisco and Bois d'Arc and the internal carbonate-rock stratigraphy of the two formations is discernible in bit cuttings and cores, but is not consistently mappable on ordinary wireline logs. Therefore the Frisco and Bois d'Arc were treated as one mapping-unit.

Haragan and Henryhouse Formations--

The Haragan-Henryhouse stratigraphic sequence (Figure 22) is approximately 180 ft (55 m) thick. The Haragan overlies the Henryhouse unconformably, but in study of subsurface geology,

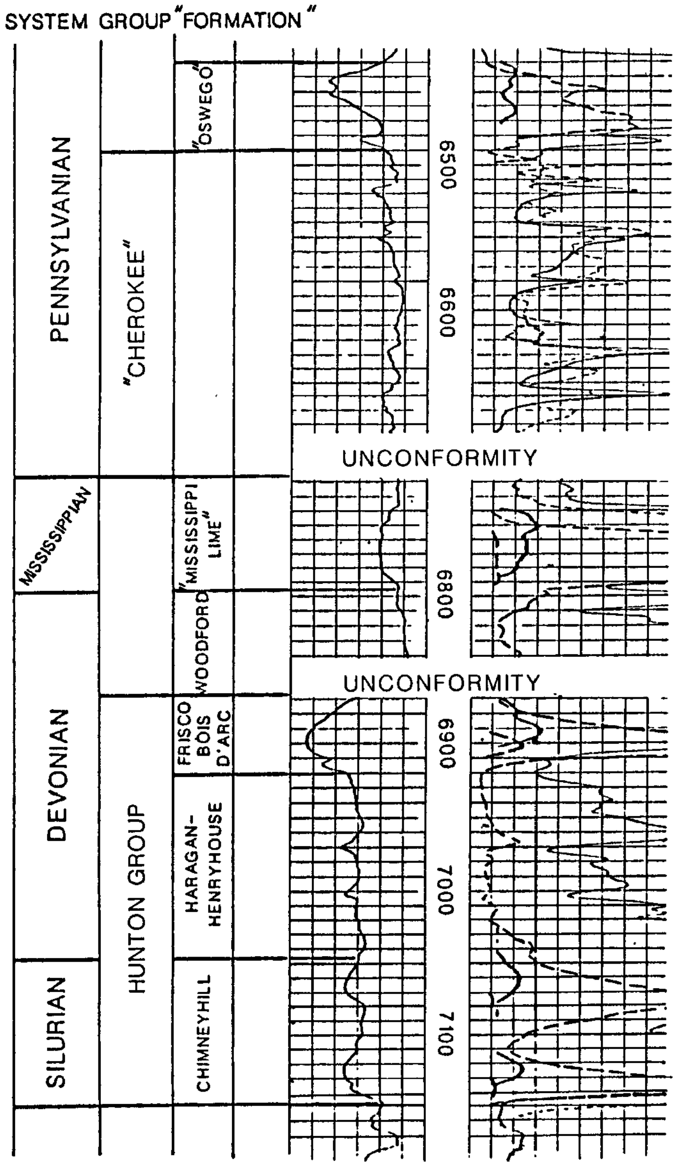

Figure 22. Type electric log, West Edmond Field, showing rock-stratigraphic units from "Oswego Lime" (Middle Pennsylvanian) to Chimneyhill Subgroup (Silurian).

the distinction is exceedingly difficult without careful examination of cores. The sequence is composed of limestones and dolomitic limestones.

Chimneyhill Subgroup--

The Chimneyhill Subgroup (Figure 22) is about 40 to 50 ft (12 to 15 m) thick and is composed of limestone. Formations that compose the group are poorly documented in the West Edmond Field. The Chimneyhill conformably underlies the Henryhouse Formation and conformably overlies the Sylvan Shale.

Ordovician System

The Sylvan Shale is the uppermost rock-stratigraphic unit of the set of Ordovician rocks (Figure 18). The greenish gray shale is approximately 100 ft (30 m) thick throughout the study area. The underlying Viola "Lime" is compact, clean limestone, about 100 ft (30 m) thick. The Viola overlies the Simpson Group, which is composed of interbedded dolomitic clean quartzitic sandstones, dolomite, limestone and shale.

ABBREVIATED STRUCTURAL-GEOLOGIC HISTORY

During the early part of the Paleozoic Era, Oklahoma was within a broad sedimentary basin. After deposition of the Hunton Group regional uplift was accompanied by widespread erosion, especially in the more extensively folded and elevated regions. Subsidence during the Mississippian Period and covering of the post-Devonian regional unconformity by carbonate rocks was followed during the early part of the Pennsylvanian Period by general exposure of terrain, except in the deeper basinal areas, and by extensive removal of Mississippian and older rocks from the crests of uplifts.

The Oklahoma City Anticline is located near the southern end of the Nemaha Range (Figure 2), an extensive tectonic element that is bounded on the east by a down-to-the-east normal fault. Entrapment of petroleum in the West Edmond Field is associated with up-dip wedge-out of the Hunton Group, on the northwestern flank of the Oklahoma City Anticline. Here the porous, permeable, fractured carbonate rocks of the Hunton are sealed by overlying Pennsylvanian strata, chiefly shale.

INTERPRETATION OF SUBSURFACE GEOLOGY

Subsurface geology was mapped using data from wireline geophysical logs, scout cards, and Forms 1002A of the Oklahoma Corporation Commission. The Forms 1002A document the methods of completion of wells and the rates of initial production.

Wireline logs are available for most wells; electric logs are the only logs generally available for wells drilled during the 1940's. Most of the wells drilled in the 1950's and 1960's are documented by electric logs and microresistivity logs. Induction-electric logs with combinations of microresistivity logs, gamma-ray logs, compensated density-neutron logs and sonic logs commonly are available for wells drilled after the 1960's.

Production data were compiled for each well in the field; data were drawn from scout cards and Forms 1002A. Data compiled included name of operator, date of completion, completion-zones, methods of completion, initial oil production, initial water production, and duration of initial-production tests. Lease boundaries and cumulative production were recorded. From this information-base wells that produced exclusively from the Hunton Group could be identified. Records from these wells were used to make a production-trend map (Figure 23).

Production-trend Mapping

Initial-potential oil production was reported in several manners. The most reliable data were obtained when wells were allowed to produce for a full 24-hr period. Wells tested in this fashion are coded by the letter "a" in Figure 23, an isopotential map. Some wells were tested over a period of a few to several hours, typically in the range of 6 to 10 hr; production was recorded hour-by-hour. Data from these wells were extrapolated to estimates of 24-hr-equivalent production. In Figure 23, wells with initial potential estimated in this fashion are coded by the letter "b". Production from other wells was reported as increments of a few hours; for example, 200 bbl produced during the first 4 hr, 160 bbl during the next 6 hr, and so on. Duration of the total test generally was less than 24 hr. Such data were extended to estimates of 24-hr production. Data of this sort are coded as "c" in Figure 23. In some instances a single production-value was reported for an initial test of less than 24 hr. The average hourly production rate was determined and multiplied by 24 to estimate the daily production rate. Estimates of this sort are shown in Figure 23 by the code "d". This method produced 24-hr rates that probably were somewhat larger than the true rates. To minimize the likelihood of serious error in interpretation, no data of this type were used if the duration of the test was less than 18 hr.

Contour interval of Figure 23 is 500 bbl per day, which tends to smooth the error inherent in estimates of initial 24-hr production rates. The isopotential map shows somewhat linear patterns of large or small production. The basic

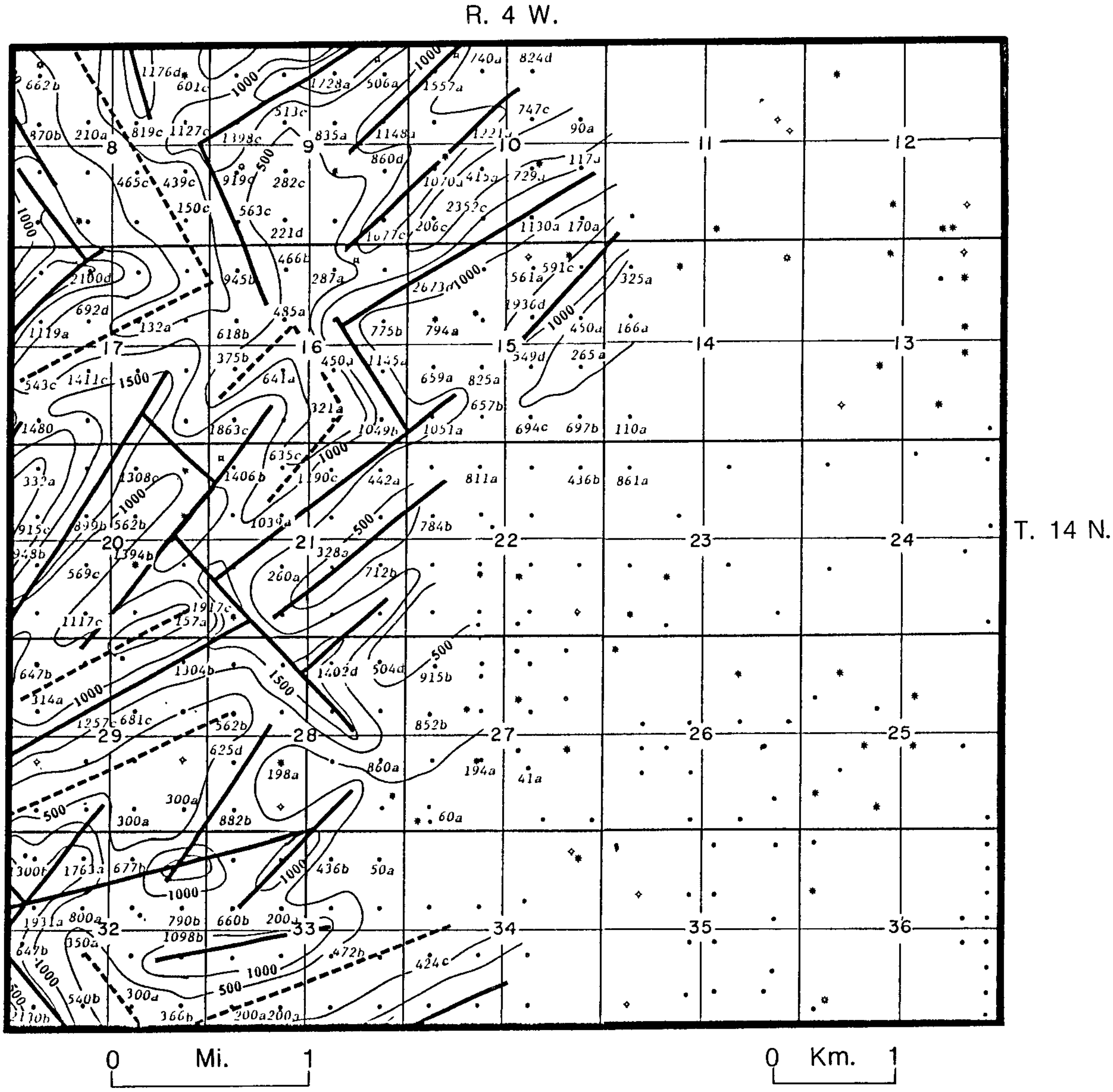

Figure 23. Production-trend map, central part, West Edmond Field, showing initial-production potential in barrels of oil per day. Contour interval 500 bbl per day. Unbroken wide straight lines show trends of areas of large production. Dashed straight lines show trends of areas of low production. Subscripts: a - Full 24-hr production test. b - Hour-by-hour tests extrapolated to 24-hr equivalent production. c - Serial tests of a few hours' duration, extrapolated to 24-hr equivalent production. d - Single-stage test of less than 24 hr. Average hourly production extrapolated to 24-hr equivalent production.

pattern shown in Figure 23 extends throughout the field. Lineations of production trends are oriented generally in northeast- and northwest-trending sets. Average orientation of large initial-production lineations is N. 48 deg. E. and N. 36 deg. W. Basic configuration of the production-trend map (Figure 23) suggests initial rates of production. Systematic fracturing of the Hunton Group in West Edmond Field has been described previously (see Swesnik (1948), and Elkins (1969), for example).

Structural Contour Mapping

Figures 24 and 25 show structural configuration of the top and base of the Hunton Group, respectively. The upper surface of the Hunton was eroded during the regional post-Devonian, pre-Mississippian hiatus, and during the post-Mississippian, pre-Pennsylvanian hiatus. Therefore some of the variation in shape of the upper surface of the Hunton can be attributed to gentle erosional relief. Consequently, structure of the base of the Hunton is the more reliable estimator of general deformation of the reservoir, especially in the eastern, up-dip part of the field, where wells that penetrated the entire reservoir are more abundant.

Final interpretation of faults in West Edmond Field was based on three general lines of evidence: (1) Repeated or omitted rock-stratigraphic units were bases for interpretation of reverse and normal faulting respectively. (Evidence of this kind was sparse.) (2) Abrupt differences in elevation between or among close-by wells were regarded as being indicative of anomalous changes in strike or dip. Faulting seemed to be the more probable interpretation at localities where contour lines indicated large changes in strike in short distances, where dip changed in an extraordinary amount, or both. (3) The previously mentioned linear trends in initial production were considered to be suggestive of faulting.

In the course of normal geologic field mapping where faults are exposed locally in outcrops and concealed in the reaches between, mapping of faults commonly is strongly inferential; interpretations are made on bits of convergent evidence, some of strongly differing kinds. Mapping of faults in the subsurface commonly is more inferential and consequently less definite. The number of faults shown in Figure 25 could have been reduced by simple rearrangement of contour lines; elevations posted to the map could have been explained with fewer faults. But if the object of mapping is to delineate areas in which faults might extend into the sealing beds above oil reservoirs, the mapping could be described as depiction of working hypotheses -- the illustration of localities that might

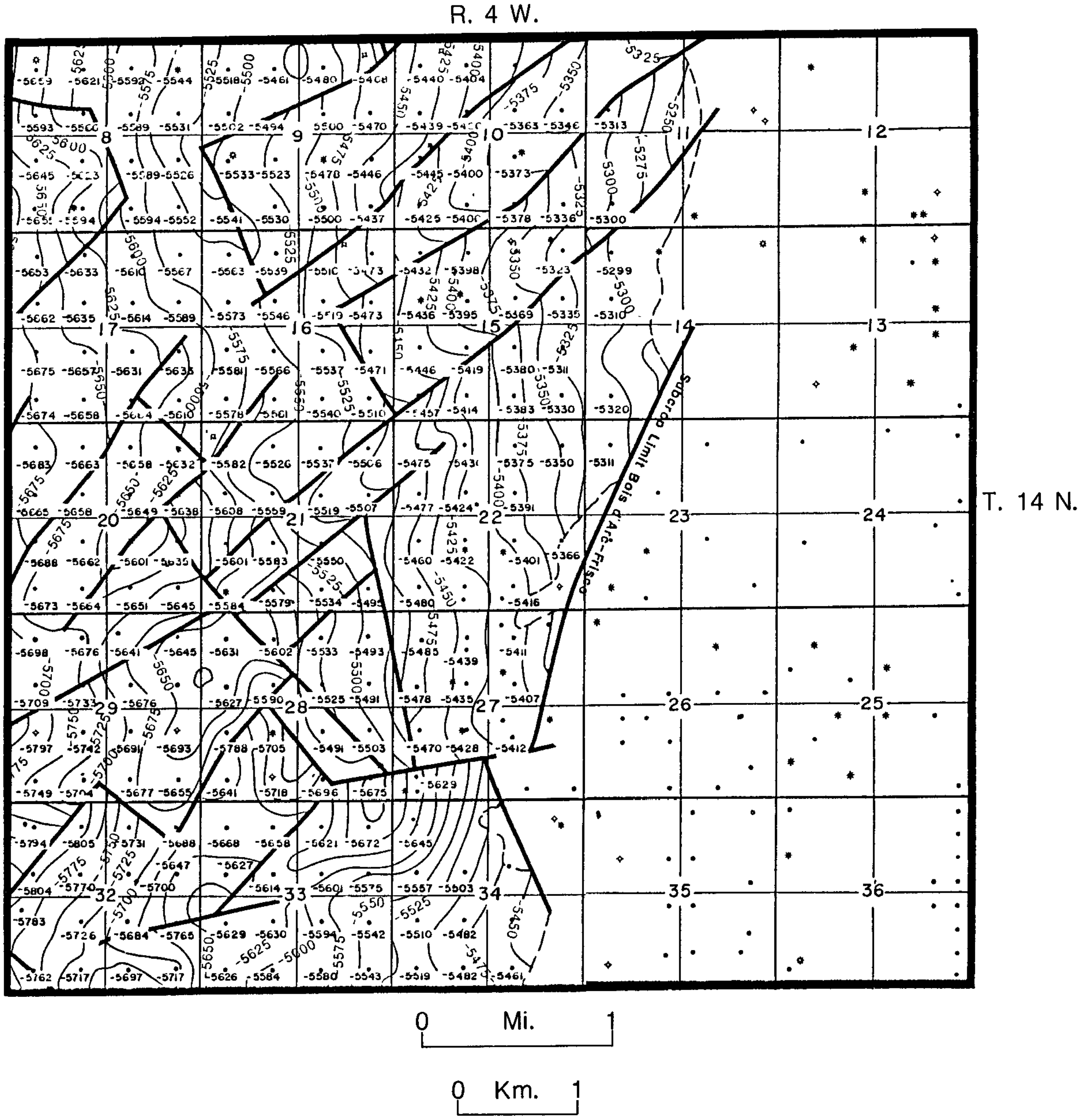

Figure 24. Structural geology, top of Hunton Group, central part, West Edmond Field. Contour interval 25 ft (7.6 m). Elevations relative to mean sea level. Broad "straight" lines: Inferred faults. Broad dashed lines: Inferred faults with less supportive evidence.

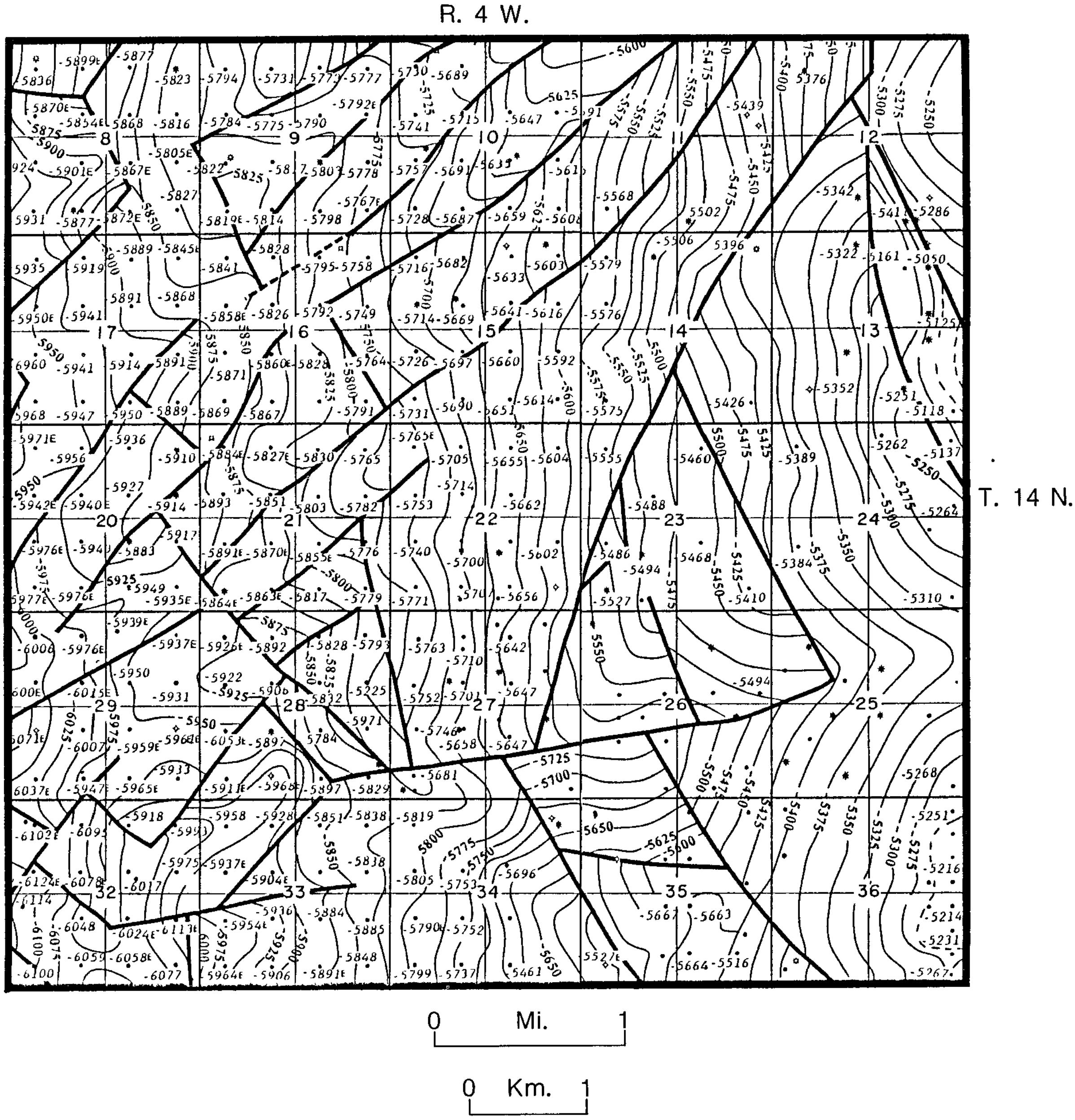

Figure 25. Structural geology, base of Hunton Group, central part, West Edmond Field. Contour interval 25 ft (7.6 m). Elevations relative to mean sea level. Subscript "e" signifies estimated elevation. Broad "straight" lines: Inferred faults. Broad dashed lines: Inferred faults with less supportive evidence.

be tested for penetrative fractures, if and when the means of testing becomes available.

In the case at hand, the hypothesis that some faults might penetrate confining beds to or near the level of underground drinking water was tested by mapping the structural geology of shallow marker beds. The mapping datum was the provisional base-of-Permian marker bed (Figure 26), which is about 1500 ft (450 m) below the surface. The general pattern of folding at this datum is similar to that of the base of the Hunton Group, but appreciably gentler (compare Figures 25 and 26). Throughout the West Edmond Field, faults interpreted at the level of the "base-of-Permian" marker were about one-half as abundant as those interpreted in the Hunton Group (Kennedy, 1989).

MAPPING OF LINEAMENTS

Formations that crop out in the study area are composed mostly of soft sandstones and shales and surficial deposits. In general they are weakly resistant to erosion and uplands evolve to terrain made up of low hills where sandstone is bedrock and gently sloping open lands where shale is bedrock. Because extensive, resistant tabular beds are few, distinctive and easily correlated strata are not abundant, and the bedrock tends not to erode in a strongly differential fashion, mapping of faults at the surface by ordinary field-geologic methods is quite difficult and time-consuming. The working hypothesis that faults penetrate rocks at the surface, and that they are manifest on Landsat imagery and color-infrared imagery was tested by mapping of lineaments.

Landsat imagery at the scale of 1:12,000 and high-altitude, near-infrared photographs at the scale of 1:60,000 were examined. Care was given to exclude man-made features. Figures 27 and 28 show lineaments interpreted from Landsat imagery and color-infrared imagery, respectively. Most of the lineaments mapped are associated with uncommonly straight segments of streams, but a few simply are linear parts of stream-valley walls or linear tonal anomalies in upland terrain (see Figure 27, lineament in extreme southeastern part of Section 28, T. 14 N., R. 4 E., and eastward-trending lineament in Section 20, T. 14 N., R. 4 E., respectively). The interpretations from Landsat imagery and from infrared imagery are different in some localities (for example, compare Sections 15, 16, 20, and 28, T. 14 N., R. 4 W.) and similar in others (for example, compare Sections 2, 10, 35, and 28, T. 14 N., R. 4 W.).

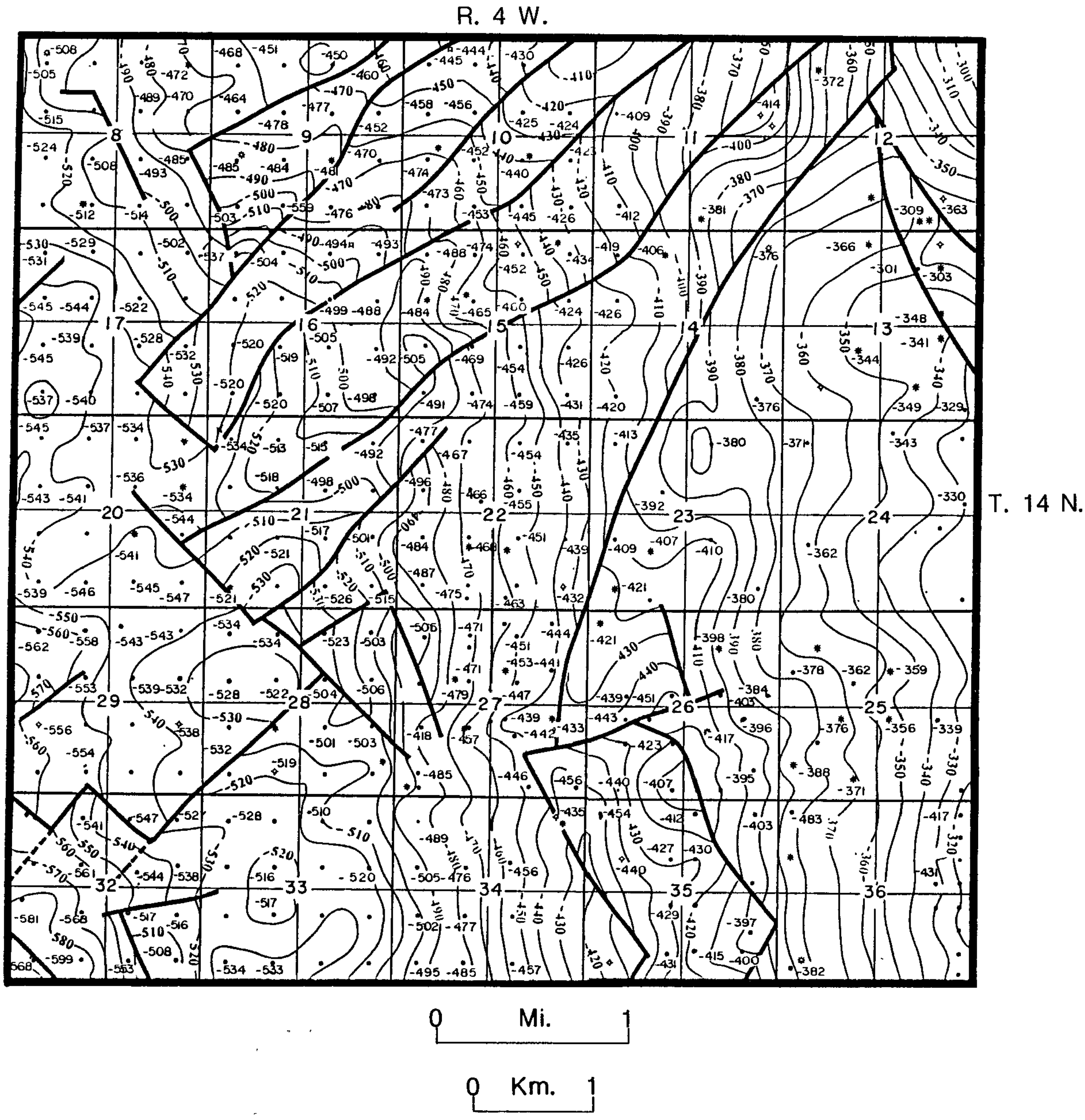

Figure 26. Structural geology, "base-of-Permian" marker bed, central part, West Edmond Field. Elevations relative to mean sea level. Contour interval 10 ft (3 m). Broad "straight" lines: Inferred faults.

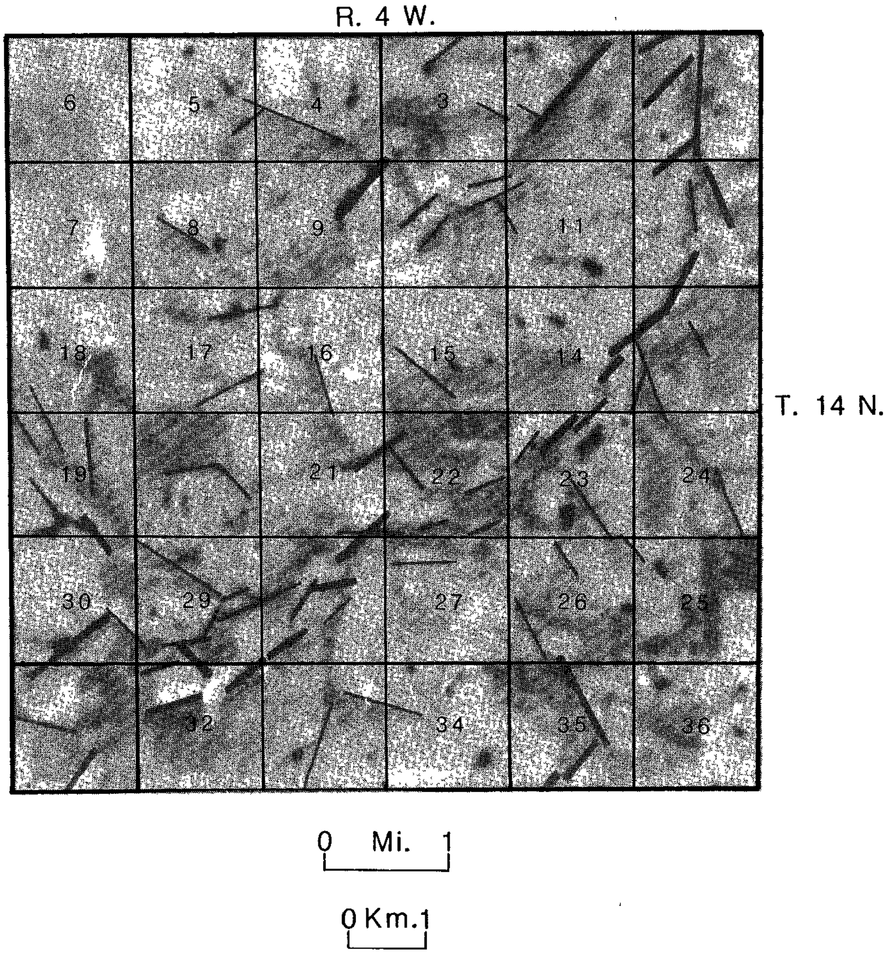

Figure 27. Lineaments interpreted from Landsat imagery, central part, West Edmond Field. Broad, dark, straight lines: Lineaments in approximate positions of faults mapped by Kennedy (1989). Narrow, dark, straight lines: Lineaments not in approximate positions of faults mapped by Kennedy (1989).

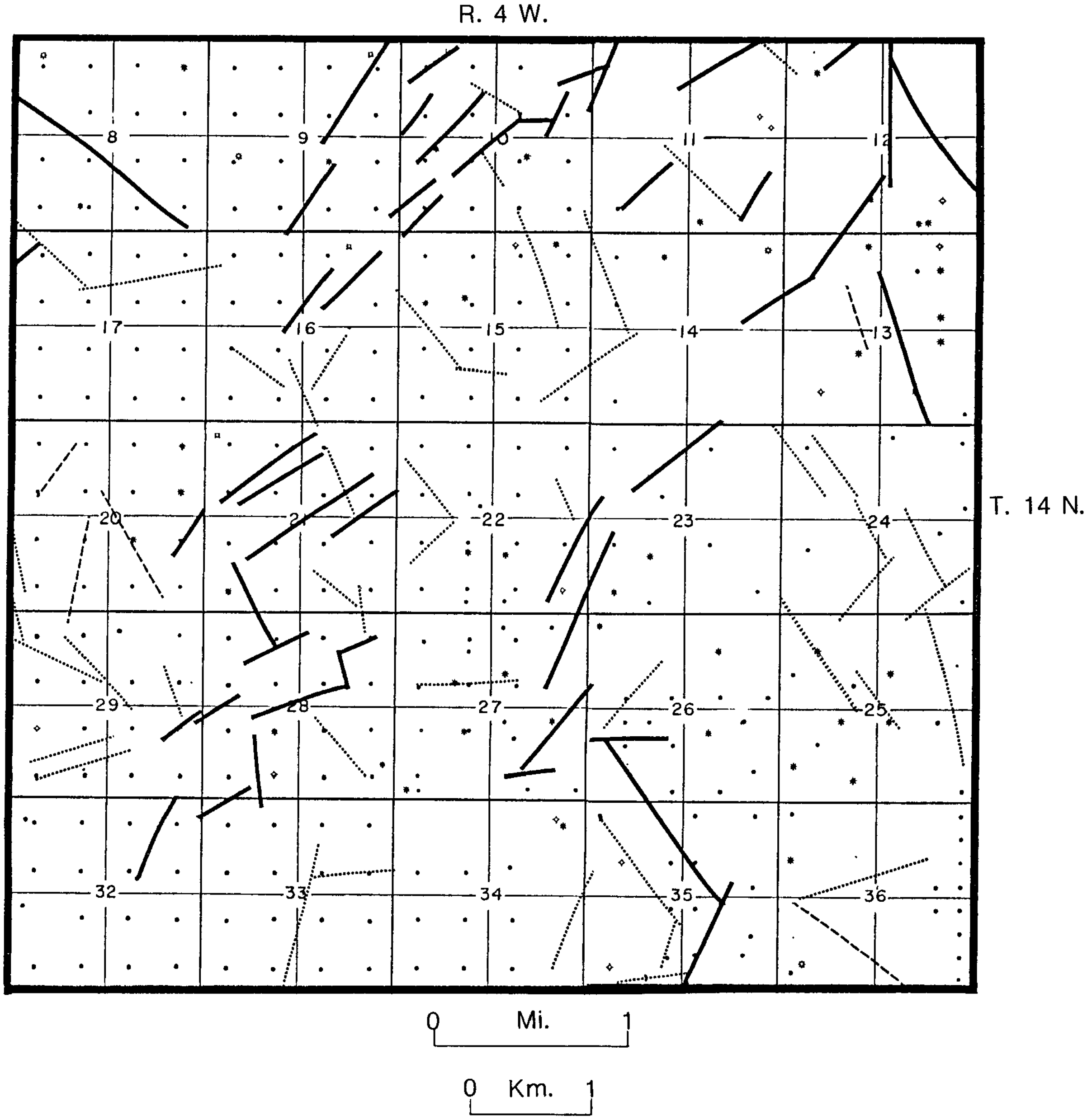

Figure 28. Lineaments interpreted from color-infrared imagery, central part, West Edmond Field. Broad, dark, straight lines: Lineaments in approximate positions of faults mapped by Kennedy (1989). Narrow, dark, straight lines: Lineaments not in approximate positions of faults mapped by Kennedy (1989).

If, for the sake of logical argument, one assumes that structural configuration of the base-of-Permian is virtually correct as mapped, and that all faults identified at the base-of-Permian marker penetrate to the surface, then approximately 50 percent of the lineaments interpreted from Landsat imagery seem to correlate to faults at the base-of-Permian marker (Kennedy, 1989). If fewer than all the faults mapped at the base-of-Permian marker extend to the surface, then detection of them by mapping lineaments on Landsat imagery is somewhat more efficient than 50 percent. The reader will be quick to recognize that reliability of such statements is based on compound probability: (Probability of correct interpretation of configuration of the base-of-Permian marker) X (Probability of correct interpretation of lineaments from Landsat imagery) = Probability of correct correlation of lineaments to through-going faults in the shallow subsurface. In virtually any such interpretive geologic exercise, the probability of correct correlation of lineaments to through-going faults in the subsurface would be less than 100 percent -- and in most such exercises the probability would be much less than 100 percent.

According to Kennedy (1989) about one-half the faults mapped at the level of the Hunton Group are indicated at the level of the base-of-Permian marker. In keeping with the qualitative probability statement above, if faults at the levels of the Hunton and base-of-Permian were mapped correctly and if Landsat imagery were interpreted correctly, then about one in four faults in the Hunton Group could be detectable by Landsat imagery. Because data in subsurface geologic mapping can be interpreted in at least a few different ways, and because no worker is likely to make the indisputably correct detailed interpretation, Kennedy's (1989) observations lead to the conclusion that of faults in the Hunton Group, less (and perhaps much less) than one in four should be detectable on Landsat imagery.

INJECTION-SENSITIVITY MAPS

In the exercise under discussion, the object of endeavor was to isolate parts of the terrain within which upward migration of injected wastes through faulted confining beds is a likelihood that seems to merit close attention -- if in fact such localities were to exist. In subsurface geologic mapping, one source of information -- one kind of document -- rarely is definitive. Stable conclusions, or conclusions that are regarded as likely to be true, commonly are based on convergent evidence. In the ideal, conceptual case, independent sources of evidence are evaluated after the fact of their having taken form. This procedure is meritorious and it tends to minimize the drift toward a favored interpretation. In such a manner of operation the former source of information tends not to bias the shape taken by the latter. (But the interpretation of the latter source may be biased, and constructively so (for a brief example of constructive geologic bias see Low (1957, p. 219-220))). In the practical case, an unpremeditated carry-forward of information that seems to be valid may produce a final interpretation that is quite useful for operational purposes.

In the circumstance at hand, initial-production trends seemed to be in rectilinear patterns, and to be suggestive of fracturing in the reservoir. Fracturing of the Hunton at West Edmond Field and dissolution of reservoir rock have been discussed extensively (McGee and Jenkins, 1946; Swesnik, 1948; Elkins, 1969). The proposition that the fabric of dissolution is strongly influenced by patterns of fractures is supported by rather common geomorphic evidence. The evidence chiefly is joint-controlled differential erosion of carbonate rocks and evaporites, and information compiled from the mapping of caves (for example, see Thornbury (1956, p. 337). Moreover, the initial-production trends are oriented more-or-less in keeping with regional trends of fractures in rocks at the surface (Melton, 1929; Shelton and others, 1985, p. 39). Thus to regard the trends of large production as being reasonable cause for the hypothesis of many small-scale faults seemed reasonable. On structural contour maps, where trends of large production were located at or near places of abrupt change in elevation of the datum, or in strike, or dip, the mapping of a fault seemed to be a respectably probable interpretation. Thus, maps were used as guides from former to latter, with trends of initial production having been regarded as a rather strong initial basis for indication of fracturing in the reservoir.

The interpretation of Landsat and color-infrared imagery (Figures 27 and 28) did not involve transfer of information from maps of the subsurface. Table 1 shows examples of grading of evidence and convergence of evidence. Configuration of structural contour maps of the base and top of the Hunton Group (Figures 24 and 25) was influenced but not controlled by the map of initial-production potential (Figure 23). Thickness maps of the Hunton Group (Figures 29 and 30) were influenced by structural contour maps of the Hunton. The base-of-Permian structural contour map (Figure 26) was made with consideration of the structural geologic maps of the Hunton Group. Of the nine sources of information, infrared imagery, Landsat imagery, thickness of Woodford Shale (Figure 31) and initial-production potential effectively are independent. The Woodford Shale (Figure 31) was mapped independently, to test the proposition that faults mapped in Sections 10 and 16 and in Sections 11,

TABLE 1. EXAMPLE, CONVERGENT EVIDENCE OF FAULTING, SELECTED LOCALITIES, T. 14 N., R. 4 W., WEST EDMOND FIELD

Locations of Inferred Faults	Trend	GENERAL QUALITY OF EVIDENCE, AS INDICATOR OF FAULTED TERRAIN									
		I.R. IMAGERY (FIG. 28)	LANDSAT IMAGERY (FIG. 27)	STRUCTURE BASE PERMIAN (FIG. 26)	THICKNESS, WOODFORD (FIG.31)	STRUCTURE, FRISCO-BOIS D'ARC (FIG.24)	THICKNESS, FRISCO-BOIS D'ARC (FIG.29)	STRUCTURE, BASE HUNTON (FIG.25)	THICKNESS, HUNTON (FIG.30)	INITIAL-PRODUCTION POTENTIAL (FIG.23)	JUDGMENT OF CONVERGENCE
SEC.10 & 16	NE	GOOD	ABSENT	FAIR	FAIR	FAIR	GOOD	FAIR	POOR	GOOD	FAIR
SEC. 11, 15, 21, 29	NE	FAIR	POOR	FAIR TO GOOD	FAIR TO GOOD	FAIR TO GOOD	FAIR	FAIR	POOR	GOOD	FAIR
SEC. 12, 14, 23, 27	NE	GOOD	GOOD (12,14, 23)	FAIR	NOT APPLICABLE	FAIR	POOR TO NOT APPLICABLE	GOOD	POOR	NOT APPLICABLE	FAIR
SEC. 35	NE, NW	GOOD	GOOD	POOR	NOT APPLICABLE	NOT APPLICABLE	NOT APPLICABLE	FAIR TO GOOD	UNCERTAIN	NOT APPLICABLE	FAIR TO GOOD

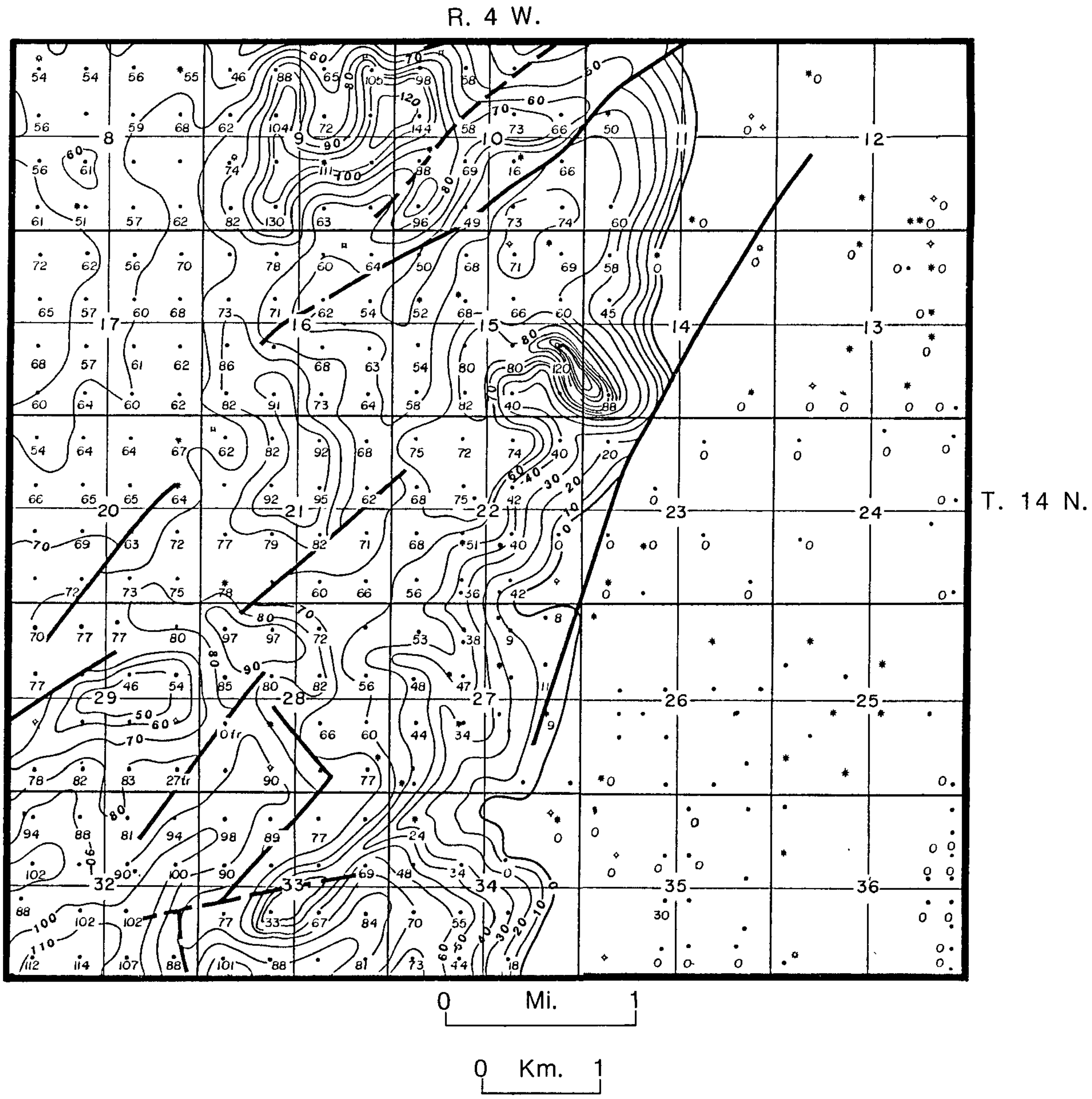

Figure 29. Thickness of Frisco-Bois d'Arc Formations, central part, West Edmond field. Contour interval 10 ft. (3 m). At some localities, map contoured as if thickness varies in direct relation to faulting.

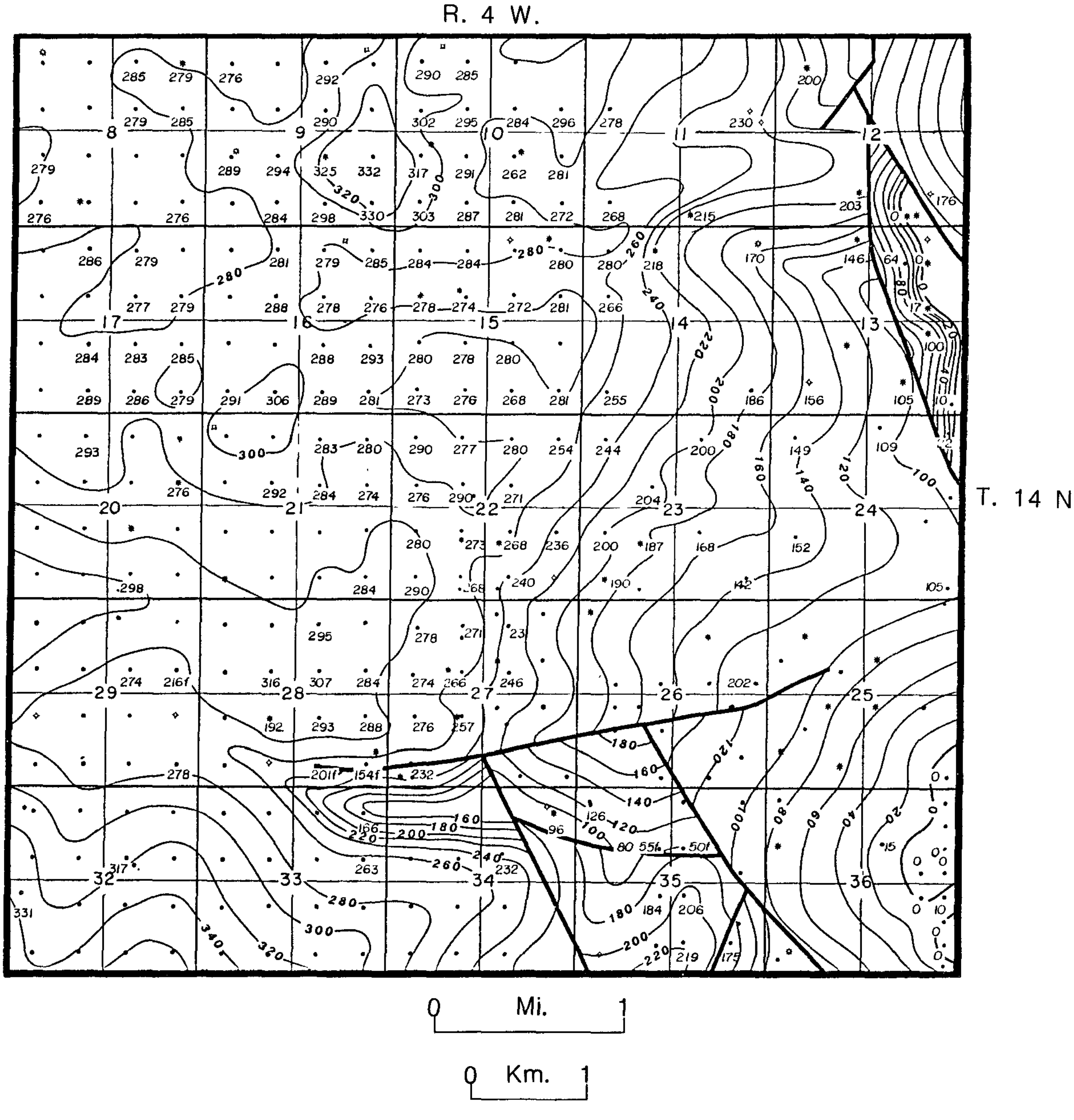

Figure 30. Thickness of total Hunton Group, central part, West Edmond Field. Contour interval 20 ft (6.1 m). At some localities, map contoured as if thickness varies in direct relation to faulting.

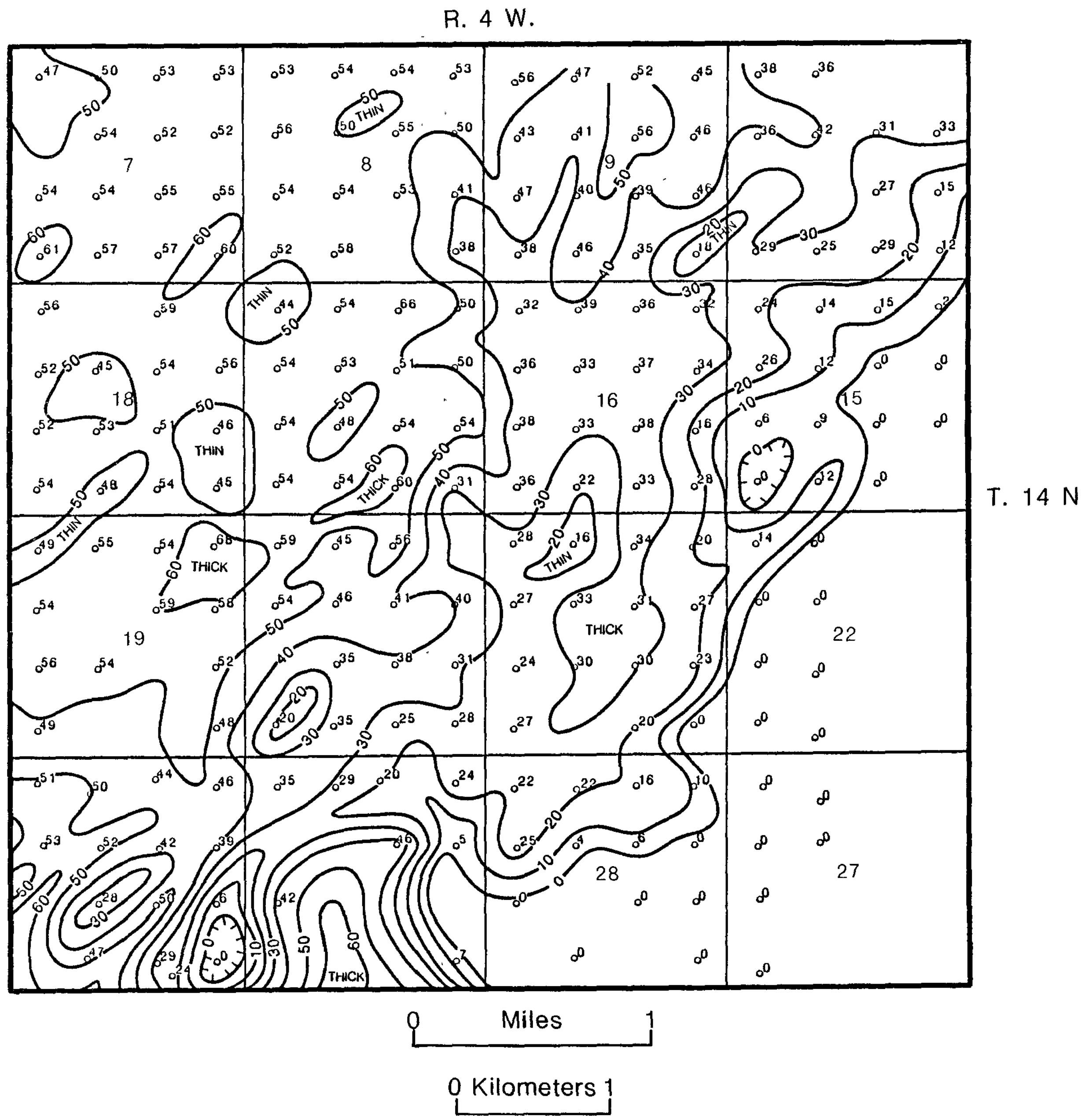

Figure 31. Thickness of Woodford Shale, central part, West Edmond Field. Contour interval 10 ft (3 m).

15, 21 and 29, T. 14 N., R. 4 W. would be indicated by variation in thickness. Figure 31 tends to support the interpretations of faulting. In general, evidence from color-infrared imagery and Landsat imagery is supportive (Table 1).

Kennedy (1989) did not presume that the mapping of faults was to be maximized, nor did he stress the data to project faults to the base-of-Permian marker and to argue thereby for penetration of confining beds. The constructive-bias method was used with strong geologic inference, with the underlying intention of showing localities where evidence raised the suspicion that confining beds might have been breached. The working hypothesis of faulting would serve as a guide for description of areas of suspected injection-sensitivity.

Figure 32 is an injection-sensitivity map of much of T. 14 N., R. 4 W. The purpose of the map is to show a method of illustrating areas in which faults might be suspected to penetrate high into the stratigraphic section -- areas where injected fluids might migrate to fault planes and upward to shallow formations. Convergent evidence and mapping of the kinds described in reference to Table 1 were the basis for inference. Faults in West Edmond Field seem to be almost vertical (Kennedy, 1989); Figure 32 is based partly on the assumption that faults would be within 6 deg. of vertical. At the outer border of the Zone of Sensitivity a fault inclined from vertical by as much as 6 deg. would be encountered at about 5000 ft (1500 m). If the injection zone were at about 3000 ft (900 m), fluid in such a well would be injected about 200 ft (60 m) from the fault zone.

Within the localities shown as Zones of Sensitivity, plans for disposal of fluids by injection should include very close study of surface-geologic evidence and subsurface-geologic evidence from surface casing downward, in order to estimate better the probability of faulting in confining beds. Within a Zone of Sensitivity, disposal by injection could follow assembly of new information and persuasive demonstration that the likelihood of faulting is acceptably low. New information might include seismic or other geophysical surveys, production histories of oil and gas wells, histories of injection wells already in place, and so on. (The reader will recall that by intent, the work reported here involved interpretation of data taken from ordinary sources, the mapping was planned to be of standard kinds, and the purpose was to accent localities in which underground injection could be unwise.)

At the outer border of the Zone of Caution (Figure 32), injection at about 3000 (900 m) would be at a point about 1000 ft (300 m) from a fault plane inclined from the vertical by 6

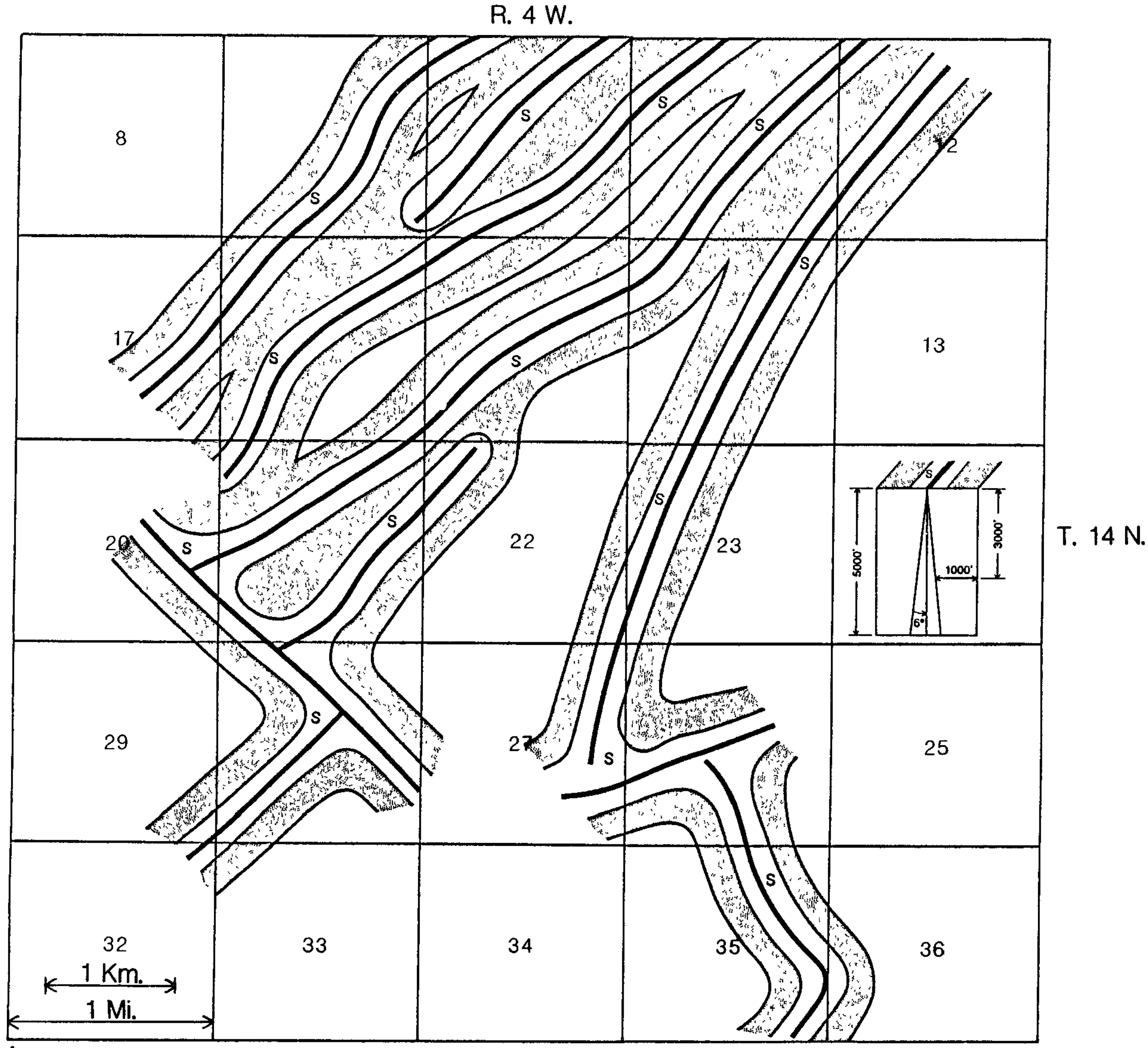

Figure 32. Central part of West Edmond Field: Example of injection-sensitivity map. Broad, gently curved lines show positions of inferred faults. Bounding patterns show Zone of Sensitivity (nonstippled) and Zone of Caution (stippled). Here underground injection would be advisable if closer study generated evidence to show that (a) faults are absent, or (b) convincingly improbable, or (c) fault planes are sealed, or (d) some combination of b and c. Example, use of inset figure: At outer boundary of Zone of Sensitivity, a well about 5000 ft (1500 m) deep would penetrate a fault plane dipping 6 deg. At outer boundary of Zone of Caution, injection at about 3000 ft (900 m) would be about 1000 ft (300 m) from fault plane dipping at 6 deg.

deg. toward the injection well (see inset, Figure 32). Assuming that disposal would be at about this depth or shallower and that the working hypothesis of faulting is not rejected, then special new evidence may lead to the consensus that underground disposal could take place with defined precautions (for example, certain volumes, pressures, and methods of monitoring).

Throughout deliberations about Zones of Sensitivity and Caution, full consideration should be given to the proposition that the (suspected) faults are sealed. If unsealed faults were penetrative from the reservoir rocks to the surface, petroleum should have migrated from the trap long ago. Or, if the trap were young and migration were in progress, unsealed faults should be detectable by oil or gas seeps. Injection in the Zones of Sensitivity and Caution may be harmless if penetrative faults are sealed, if injection is into the petroleum reservoir, if pressures do not exceed original formation pressure, and if volume of fluid injected does not exceed the volume of petroleum and salt water withdrawn in the past.

CONCLUSIONS

Initial-production trends in West Edmond Field indicate that permeability in the Hunton Group is strongly fracture-influenced. Initial-production trends, conspicuous deviations in strike or dip along linear trends and repeated or missing stratigraphic sections combine to permit valid interpretation of faulting in the Hunton Group.

Prudently used constructive-bias methods of mapping allow projection of some of the faults mapped in the Hunton Group to a provisional base-of-Permian marker. Some lineaments mapped from Landsat imagery and color-infrared imagery seem to correlate in position and trend to faults mapped in the Hunton Group. Convergence of information from surface and subsurface geologic mapping permits the assessment of terrain for injection-sensitivity. Zones of Sensitivity and Zones of Caution accent localities within which underground injection would be recommended only after conscientious study, which perhaps would require special sources of information.

The general techniques of subsurface-geologic mapping described in reference to the West Edmond Field contrast severely with methods of computer mapping described in Section 4. Personnel who set out to make injection-sensitivity maps can choose among the relative merits of computer mapping and the more subjective constructive-bias mapping. The fragmentary nature of subsurface geologic data allows multiple detailed interpretations. Geologists with strong empirical backgrounds for pattern-recognition probably would choose to make injection-sensitivity maps by constructive-bias mapping. Computer mapping could be taken into account as a matter of policy, to provide baseline interpretations that are likely to minimize controversy between producers and regulating agencies.

SECTION 4

BURBANK OIL FIELD

INTRODUCTION

The Burbank Oil Field in Kay and Osage Counties, Oklahoma (Figures 1 and 33), is a large stratigraphic trap. The Pennsylvanian Desmoinesian "Burbank Sandstone" reservoir (Figure 34) is encased in shale with oil and gas trapped against the up-dip limit of the reservoir rock (Figure 33). Discovered in 1920, Burbank Field has undergone several stages of development, including secondary and tertiary enhanced-oil-recovery projects.

Hagen (1972) studied trends of subsurface fractures and of joints in bedrock at the surface. The research produced strong evidence of systematic fractures within the Burbank Sandstone and in strata immediately above the reservoir. When the formation was pressured by water-flooding, these fractures were opened to migration of fluids from well to well. Hagen indicated that primarily, overpressuring during secondary recovery was the cause of opened fractures in and above the Burbank reservoir.

MAPPING OF SUBSURFACE GEOLOGY BY COMPUTER

A data base was compiled from wireline logs of 934 wells (Figure 35). Data pertained to the Cottage Grove Sandstone (Figure 34), a potential storage formation, and confining beds within and above the Cottage Grove. Maps used to evaluate confining-bed integrity in the Burbank Field included: (a) Structural geology of two rock-stratigraphic units (Figures 36 and 37), (b) thickness of the interval between the Cottage Grove Sandstone and the Pink Limestone (Figures 34 and 38), (c) thicknesses of rock units and percentage of shale in the Cottage Grove (Figures 39, 40, and 41), (d) thicknesses and extents of certain confining beds (Figures 42, 43, and 44), and (e) number of formations above the Cottage Grove (Figure 45) believed to be porous and permeable enough to transmit fluids in large quantities.

Lotus 1-2-3 spread-sheet program was combined with mapping by the Jupiter Mapping Program and printing by multiple-pen line plotter.

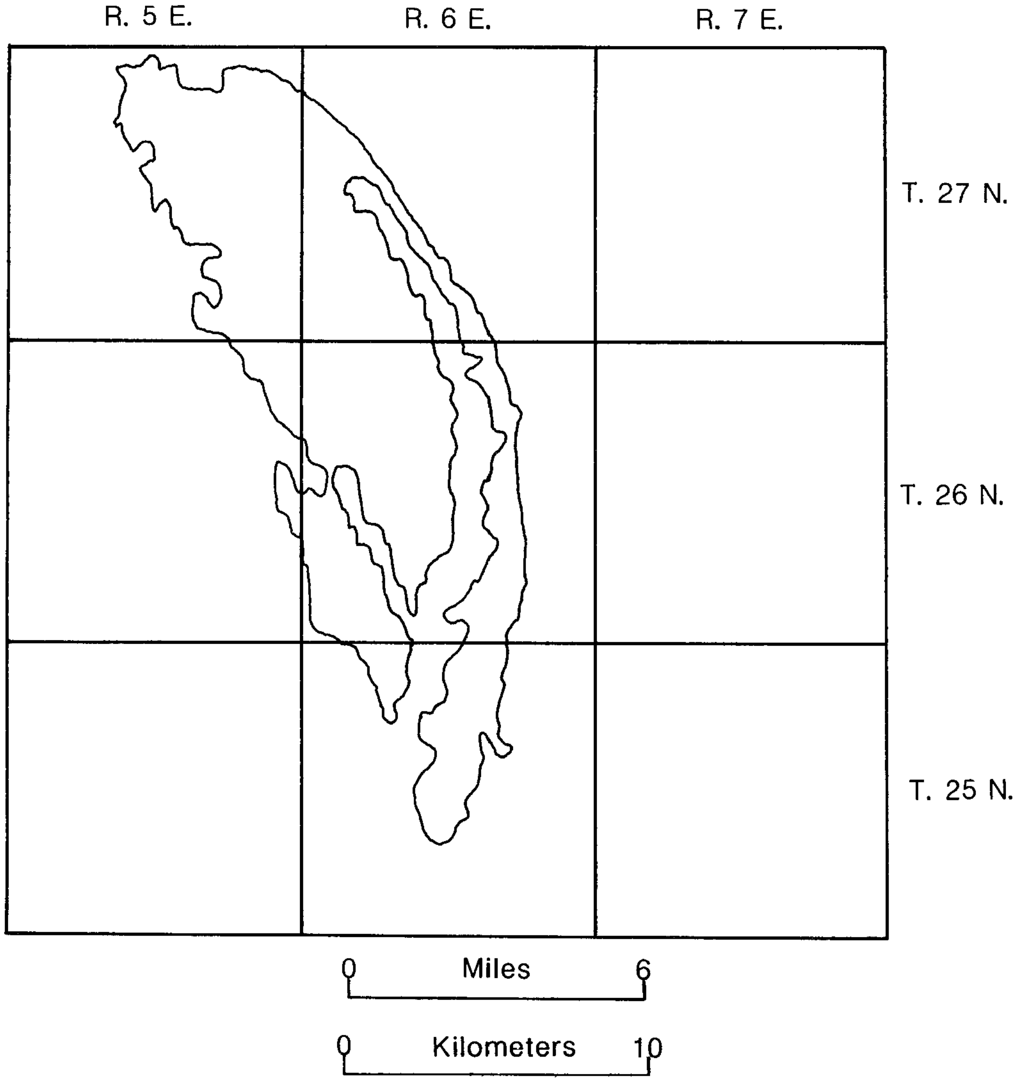

Figure 33. General configuration of Burbank Field. All but the northwesternmost part of the oil field is in Osage County, Oklahoma. The Burbank Sandstone dips southwestward; the arcuate eastern boundary of the field is the up-dip limit of permeable sandstone. The reservoir is a multistoried, multilateral, alluvial-deltaic channel-fill reservoir. In general, trends of the more permeable sandstone "stringers" follow the configuration of the eastern border of the field.

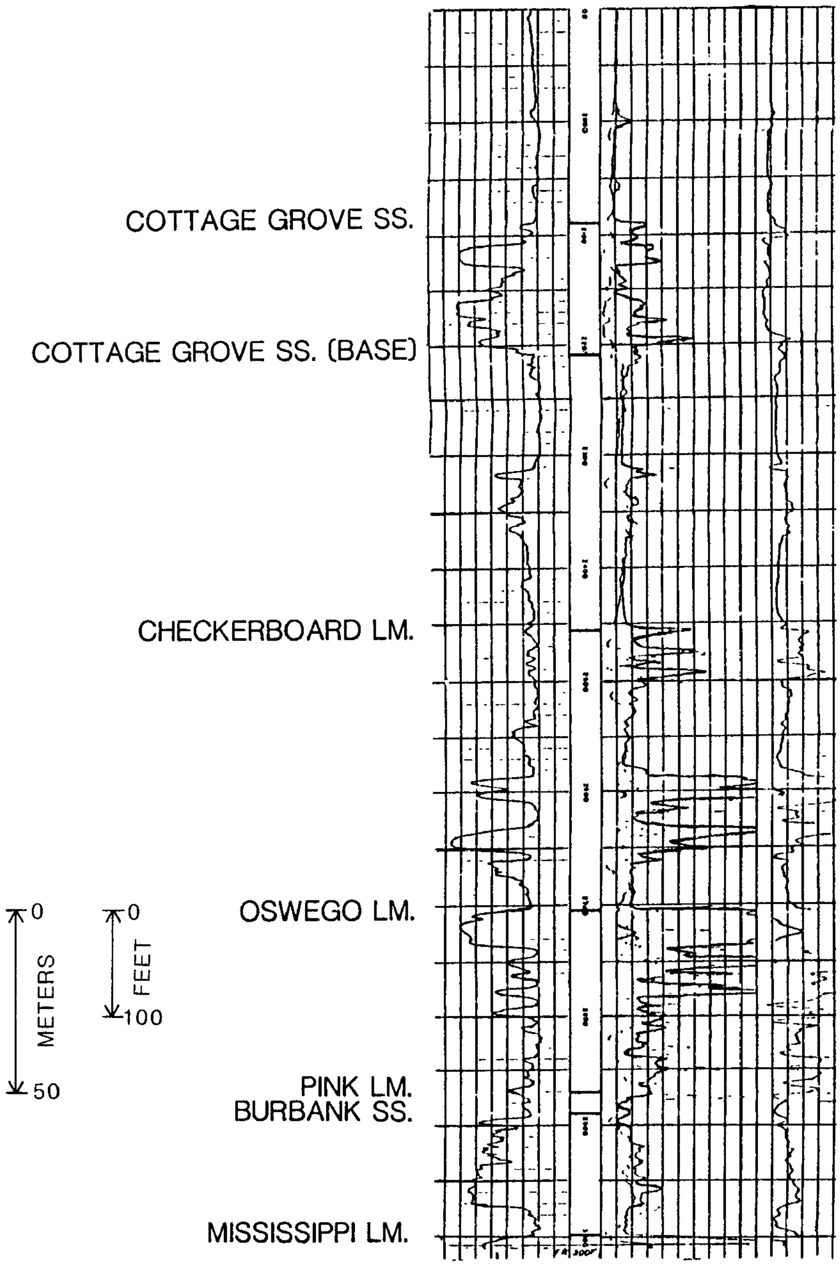

Figure 34. Type electric log, Burbank Field. Important marker-beds are shown. All strata shown above "Mississippi Lime" are Pennsylvanian.

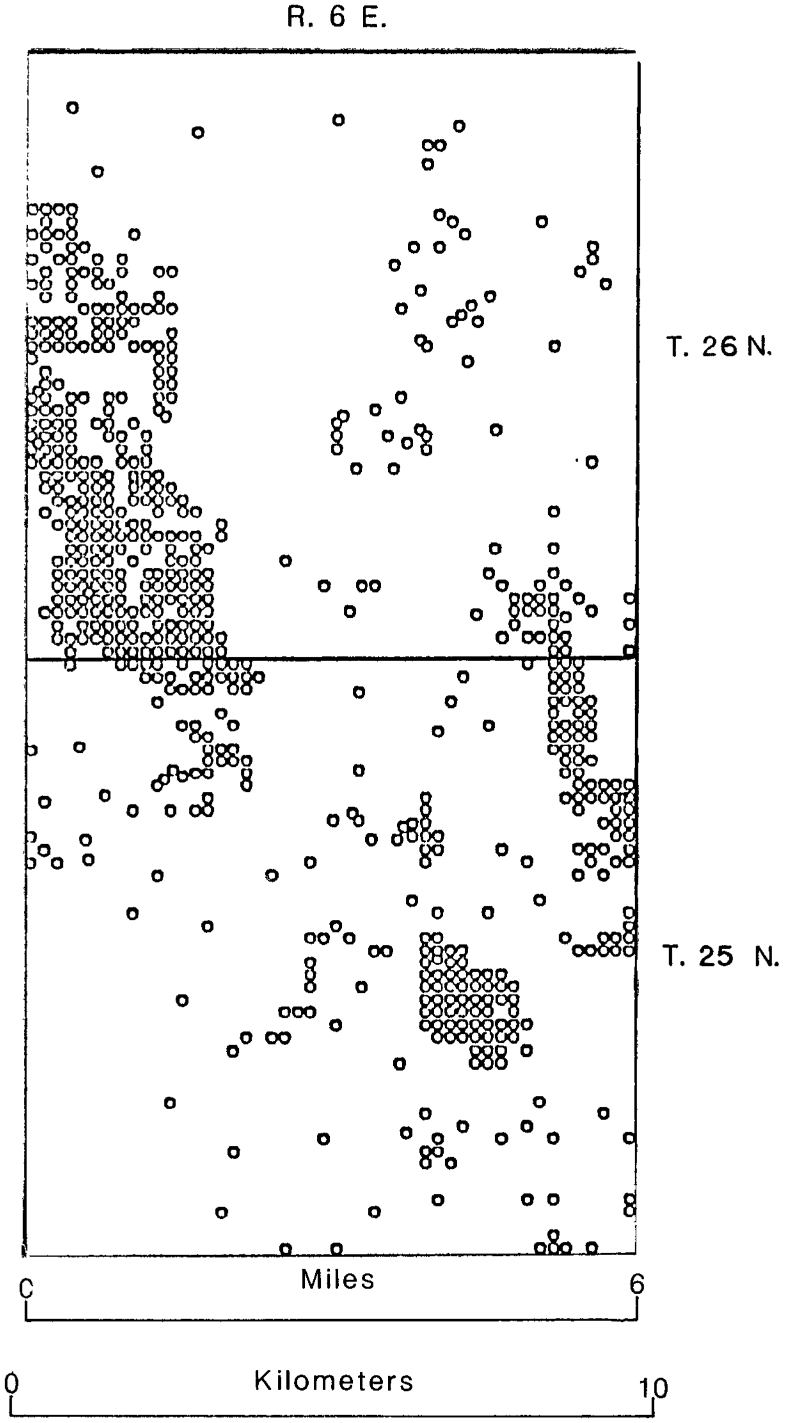

Figure 35. Locations of wells in Burbank Field from logs of which data base was compiled. Lack of control in some areas of the field is due to the fact that much of the drilling predated the application of wireline logs.

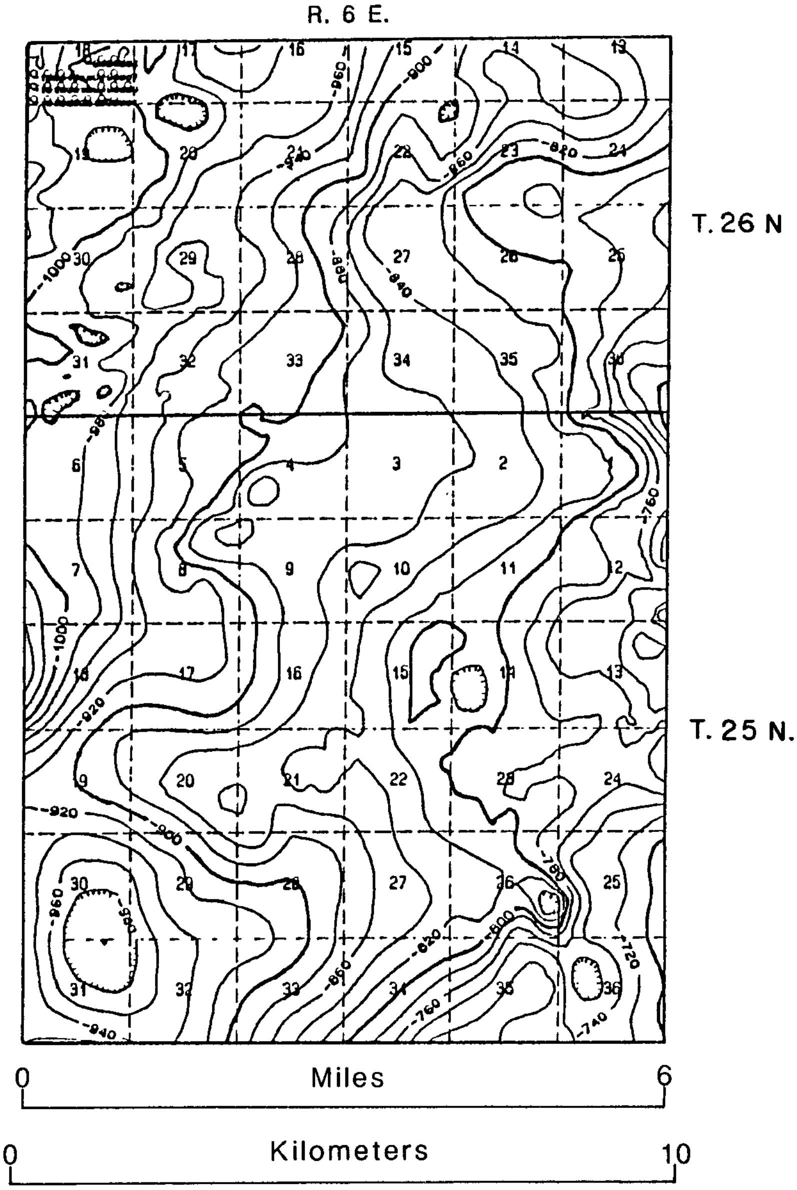

Figure 36. Structural geology, Cottage Grove Sandstone (Figure 34), Burbank Field. Contour interval 20 ft (6.1 m). In Sections 30 and 31, T. 25 N., R. 6 E., a large syncline is shown. Figure 35 shows absence of data in this area. The syncline is an artifact of software; mapping algorithm must consider absence of data in Sections 30 and 31, and from beyond boundaries of map. In northernmost corner of map locations of wells and elevations of the datum are plotted. At this scale, to include data and contour lines is not practical. But scale can be changed, if appropriate for solution of problem.

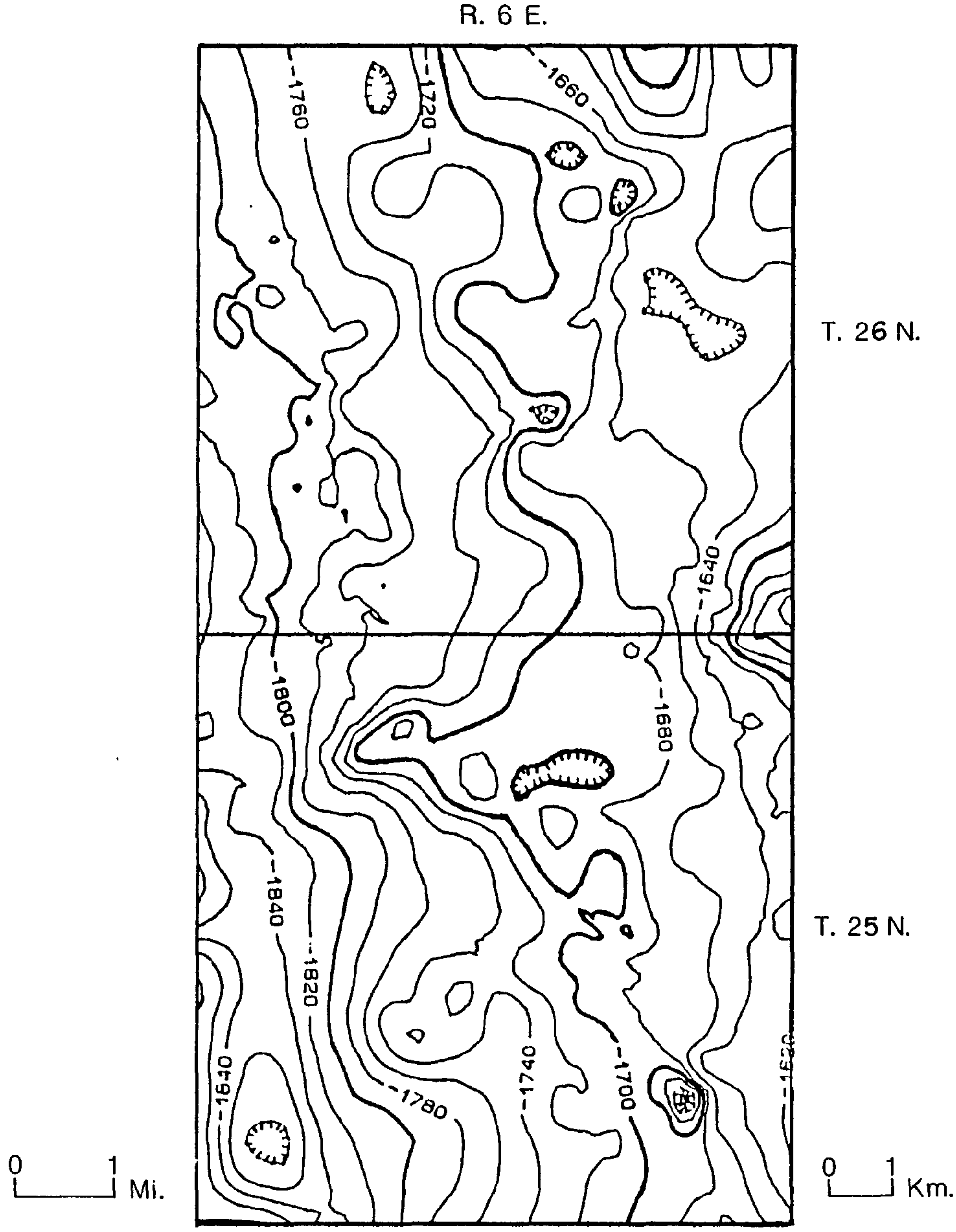

Figure 37. Structural geology, Pink Limestone, Burbank Field (Figure 34), an extensive tabular formation that is excellent for use as a mapping datum. Contour interval 20 ft (6.1 m). At Burbank Field and nearby anticlinal and synclinal noses, and anticlines and synclines are superimposed on a regional, westward-dipping homocline. Mapping from data base, at scale shown, is not sufficient to detect faulting, if indeed detectable faulting is present.

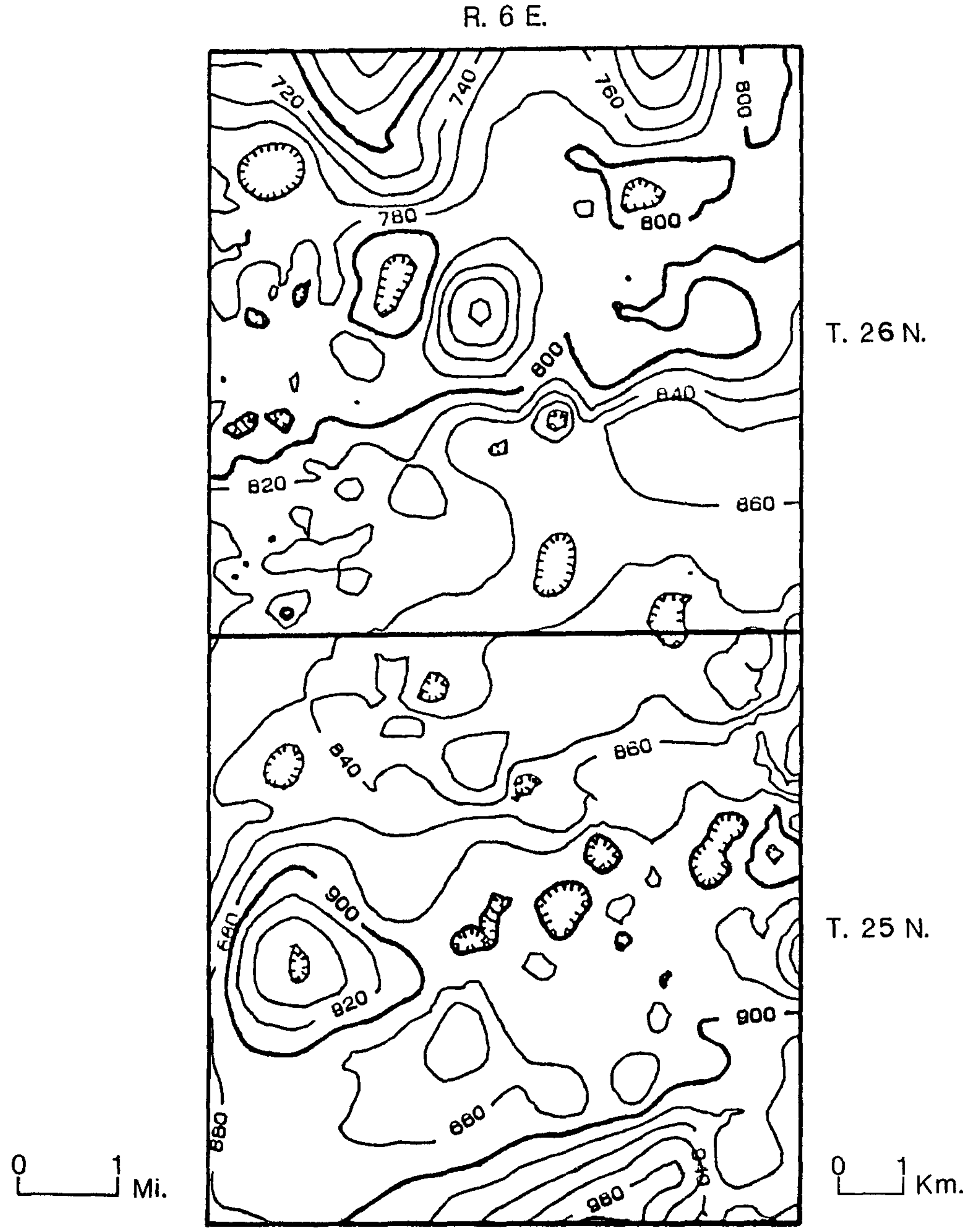

Figure 38. Thickness of stratigraphic interval, Cottage Grove Sandstone to Pink Limestone, Burbank Field. Contour interval 20 ft (6.1 m). The map was designed to test the working hypothesis that anomalous thickening or thinning of the interval would indicate faulting. Thickening of the interval in a linear trend northeastward across south-central part of T. 26 N., R. 6 E. is suggestive of faulting (but not diagnostic of faulting). Hachured, closed contours show areas of thick rock.

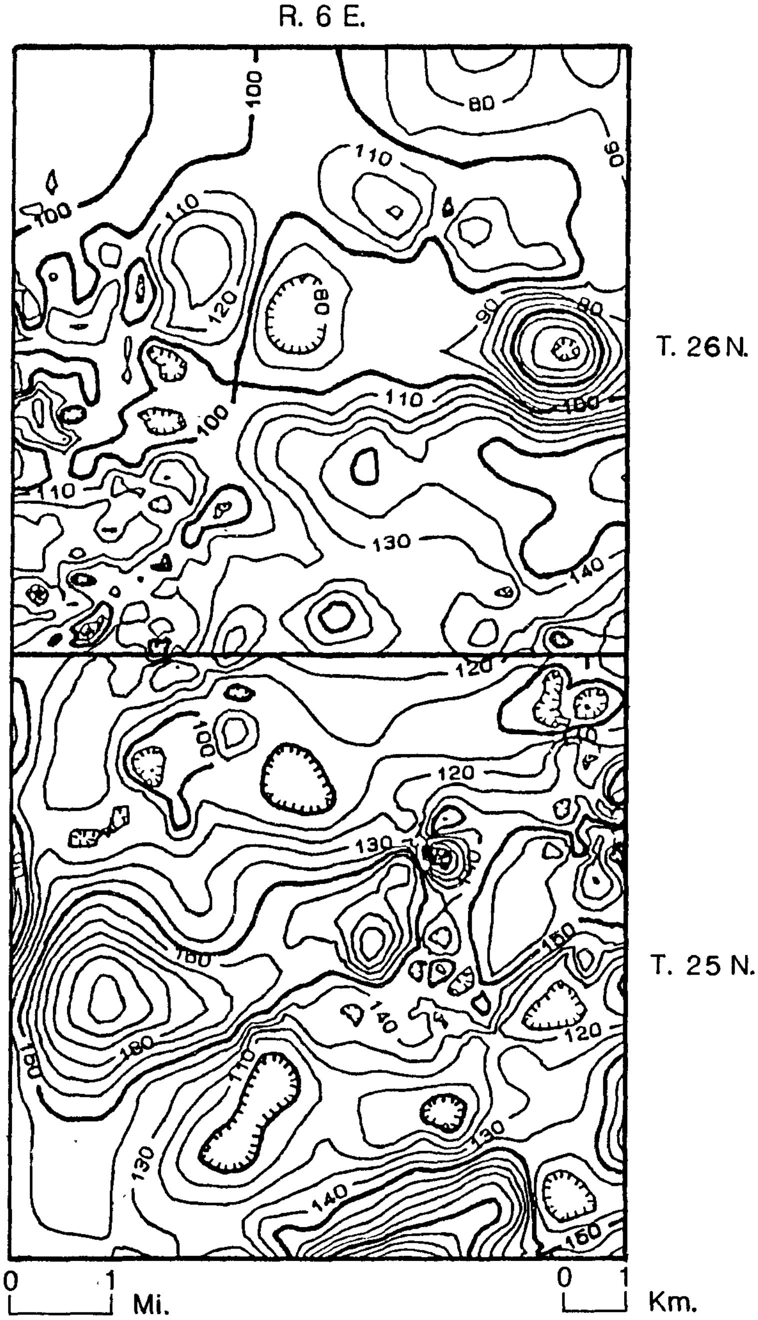

Figure 39. Thickness of Cottage Grove Sandstone, Burbank Field. Contour interval 10 ft (3 m). Compare Figures 35 and 39 for evidence that the map is rather interetive where data are sparse, with tendency to show ovate "thicks" and "thins " at such places. In general the map is quite useful. It would be especially useful for general assessment of the extent and thickness of an injection zone.

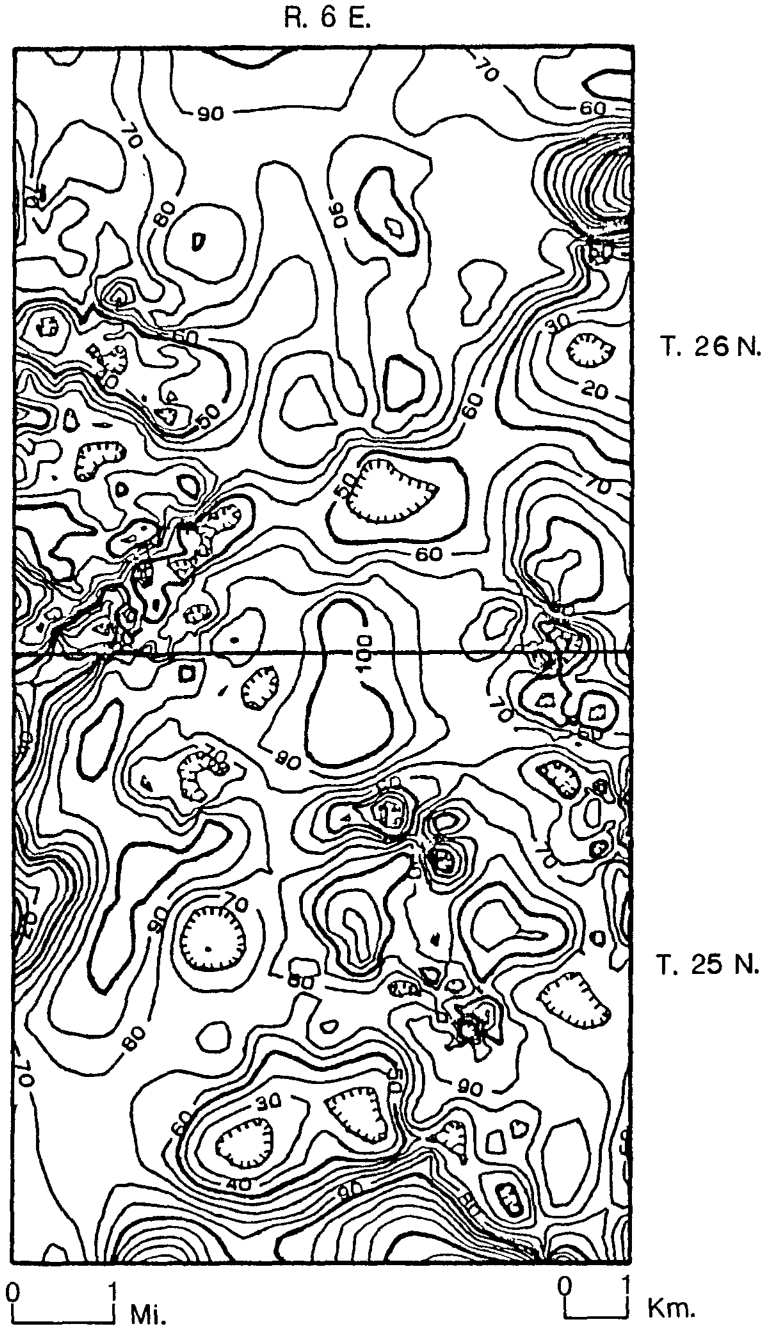

Figure 40. Thickness of net sandstone in Cottage Grove Sandstone, Burbank Field. Contour interval 10 ft (3 m). Map shows thickness of sandstone in Cottage Grove that should be of "reservoir-quality". Interbeds of shale were eliminated in calculation. The map would be useful for general assessment of storage-unit potential. Effects of sparse data and map-boundary effects are apparent by comparison of Figures 35 and 40.

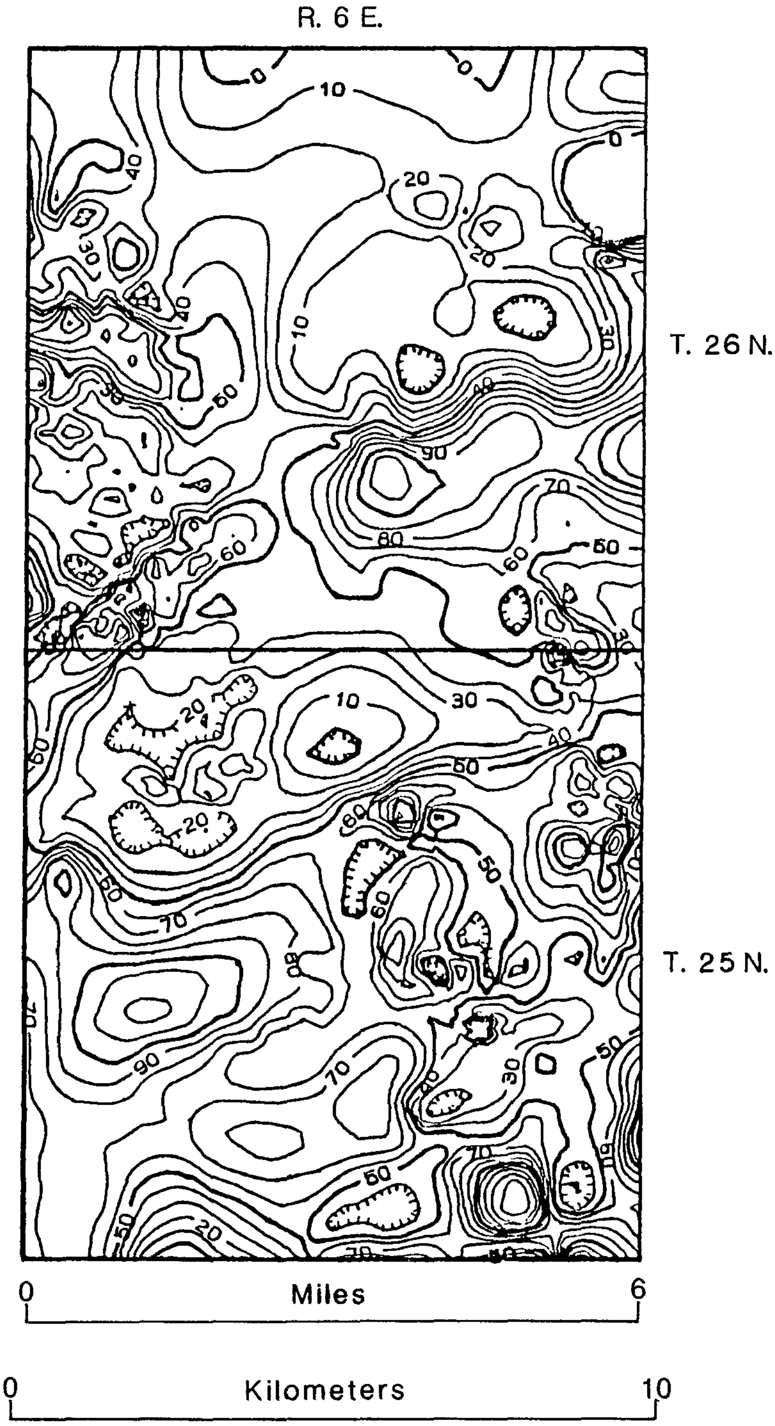

Figure 41. Thickness of net shale in Cottage Grove Sandstone, Burbank Field. Contour interval 10 ft (3 m). This map would be useful for broad assessment of potential confining beds within the Cottage Grove Sandstone.

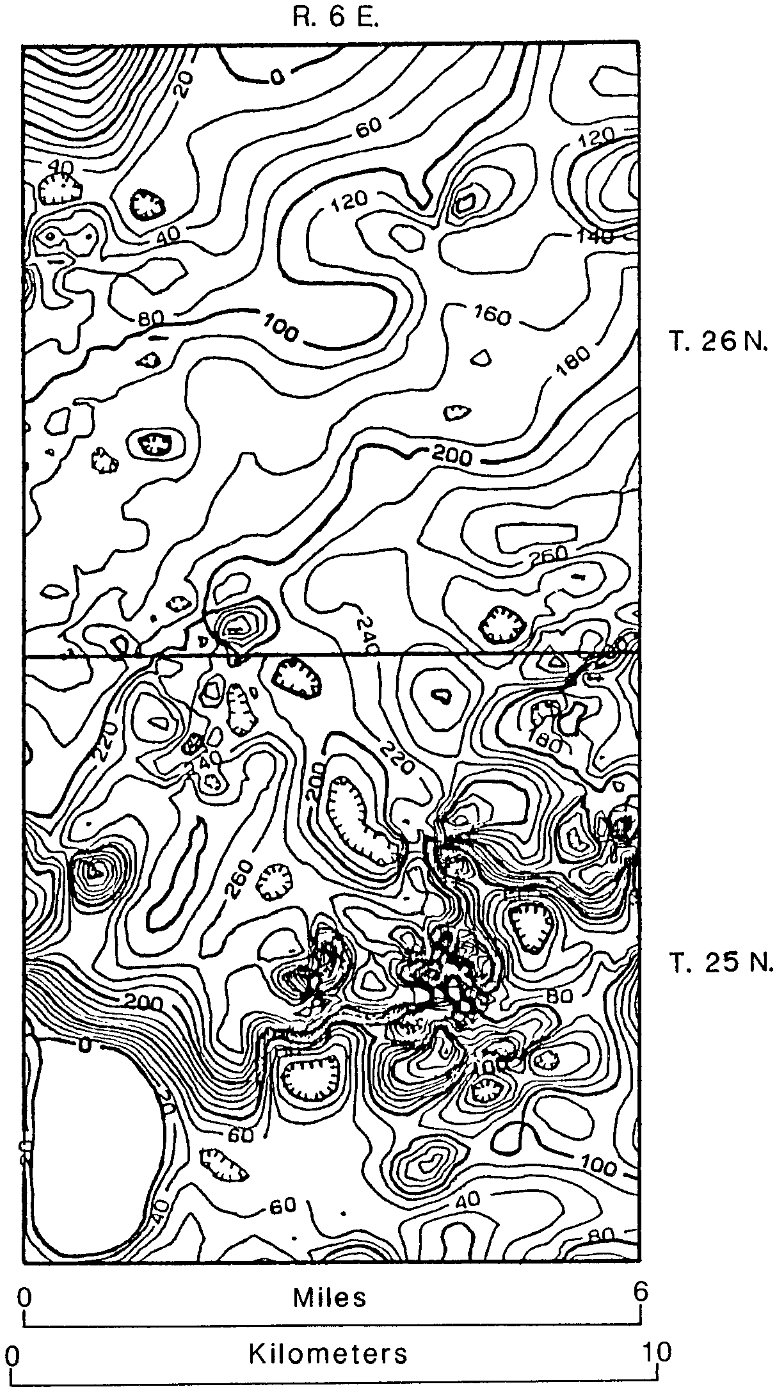

Figure 42. Thickness of confining unit directly above Cottage Grove Sandstone, Burbank Field. Contour interval 20 ft (6.1 m). Maps of this type would be useful in general evaluation of confining-bed potential. Merging of lines is due to small scale and small contour interval, both of which could be modified during use of the software.

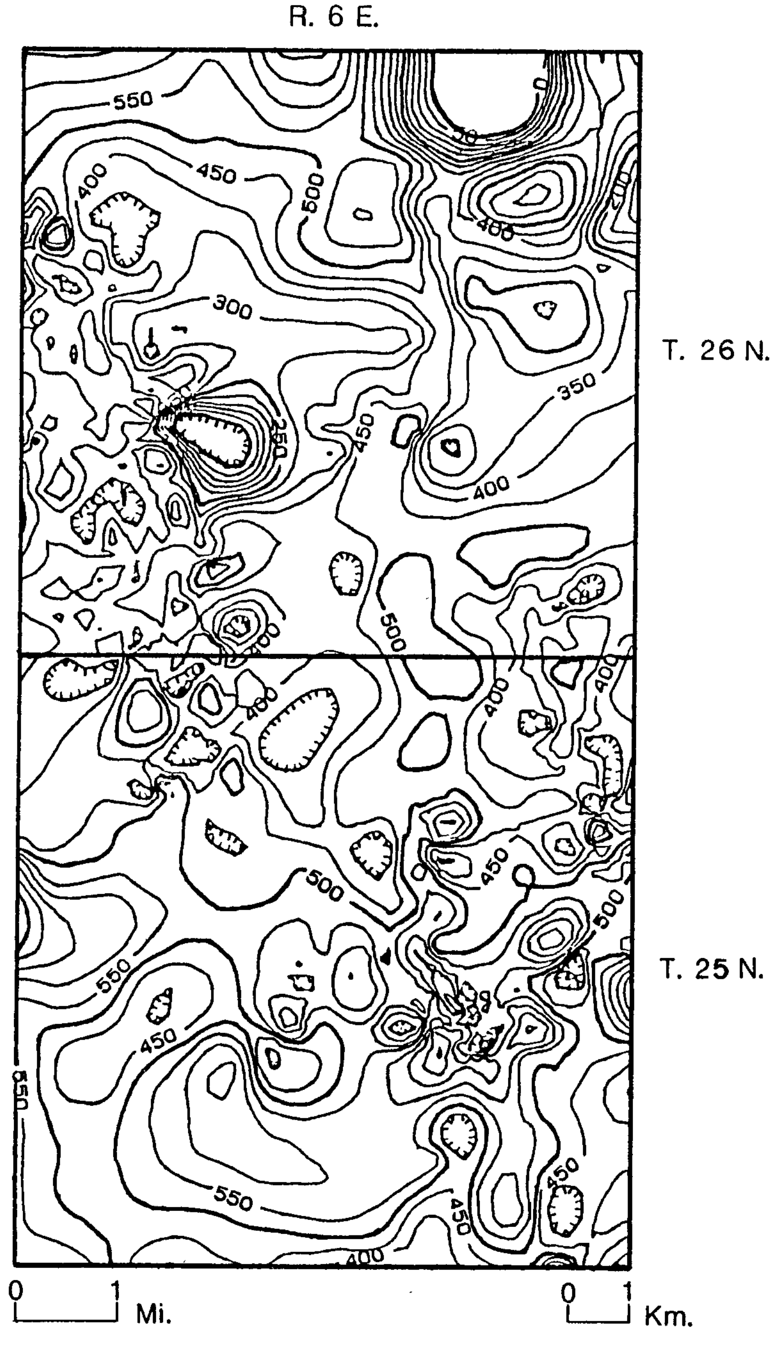

Figure 43. Cumulative thickness of shale above Cottage Grove Sandstone, Burbank Field. Contour interval 50 ft (15.2 m). The map shows general distribution of total shale (and total confining-bed potential) in stratigraphic section overlying Cottage Grove. Boundary-effects and sparse-data effects are apparent (for example, northeastern corner of map and hachued contour in southwest-central part of T. 26 N., R. 6 E.).

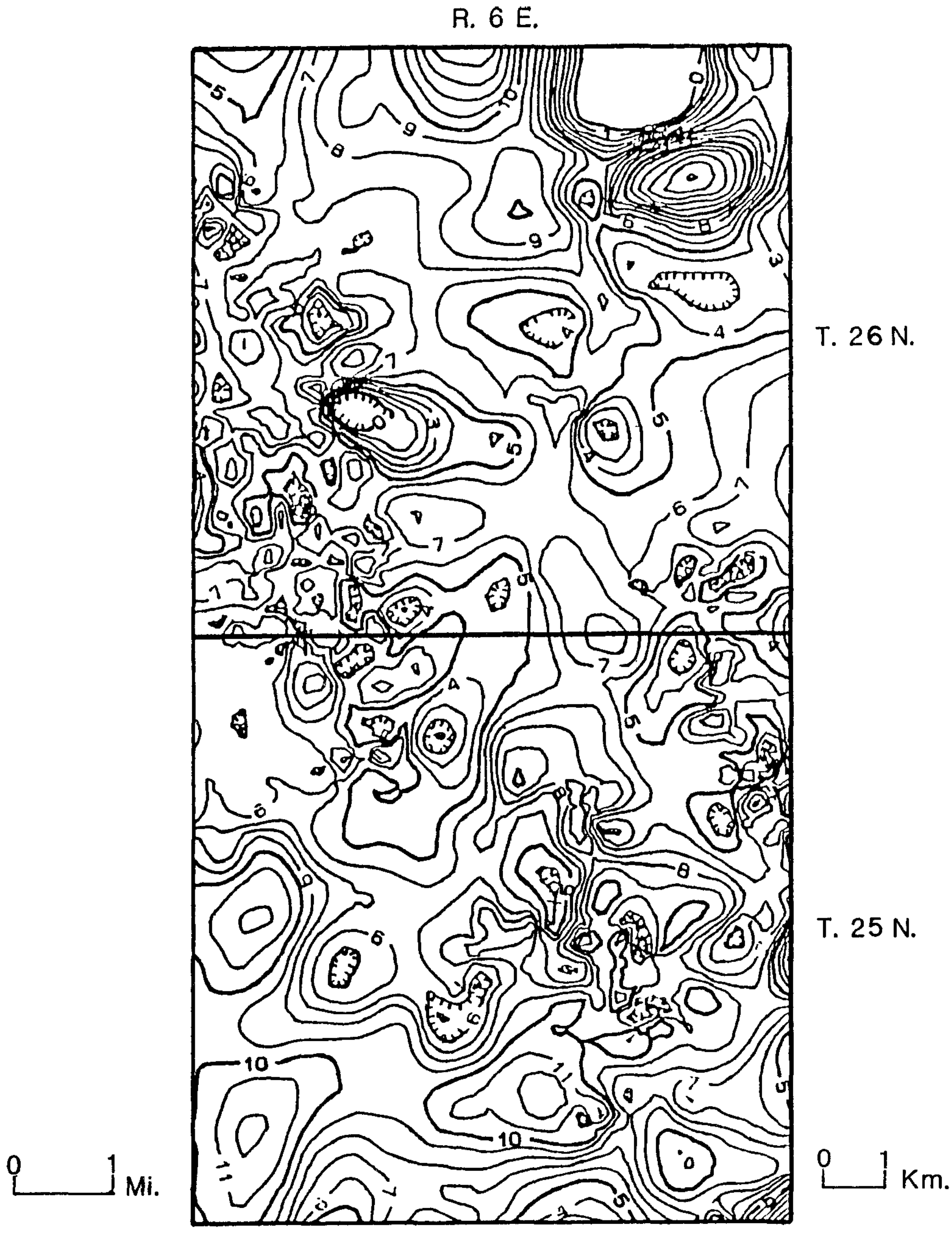

Figure 44. Total number of shale "breaks" in stratigraphic section above Cottage Grove Sandstone, Burbank Field. Each shale break is 20 ft (6.1 m) thick or thicker, by definition. In effect, the map shows the number of confining beds above the Cottage Grove. This map would be useful for general evaluation of the study area. False patterns showing no shale breaks are shown at some places, owing to scarcity of data and to map-edge effects.

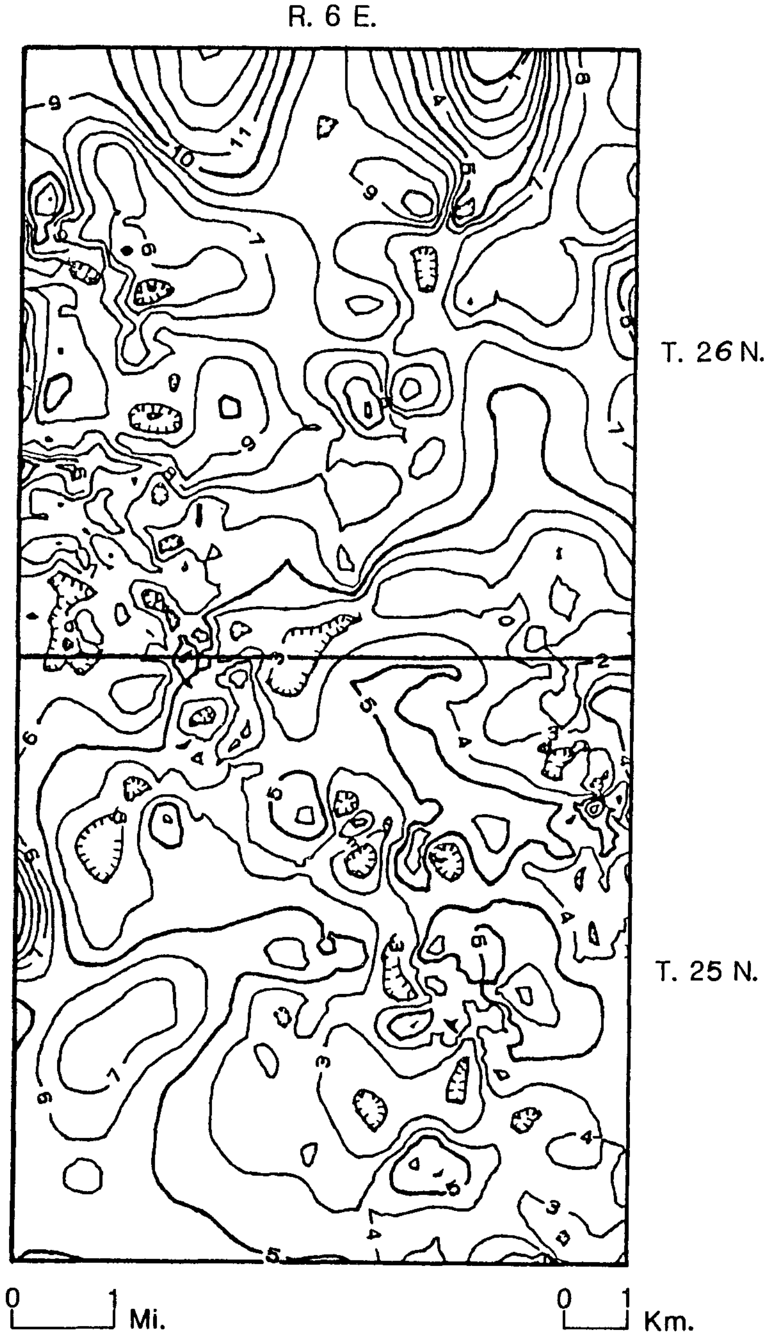

Figure 45. Possible injection zones between top of Cottage Grove Sandstone and depth of about 1000 ft (305 m), Burbank Field. Map shows number of sandstone formations as thick as about 6 ft (2 m) or thicker. These data also would be useful for estimation of the number of reservoirs into which upwardly mobile, overpressured fluids might escape.

STRUCTURAL GEOLOGY

Configuration of the Pink Lime marker bed shows that structural geology fundamentally is homoclinal, with dip westward at about 1/2 deg. The homocline is interrupted by anticlinal and synclinal noses, and by a few anticlines and synclines (Figure 37).

Structural geology of the Cottage Grove Sandstone is similar. Figure 36 shows general westerly dip with few closed folds. However, because no data were available in the southwesternmost part of T. 25 N., R. 6 E. the software interpreted a closed syncline; minimal elevation is shown to be less than -980 ft.

Figure 38 indicates rates of variation in thickness of the stratigraphic section between the Cottage Grove Sandstone and the Pink Limestone marker.

The Cottage Grove Sandstone extends throughout the study area; its thickness and extent (Figure 39) indicate that the formation has good potential as a fluid-injection reservoir. Figure 40, a net-sandstone-thickness map shows the general amount of reservoir-quality sandstones at specific sites, exclusive of shale interbedded with sandstone (Figure 41). Figures 39, 40 and 41 illustrate that the Cottage Grove is a heterogeneous reservoir. Nevertheless, sandstone in the Cottage Grove is thicker than 50 ft (15 m) at most places.

The Cottage Grove is overlain by a thick sequence of clayey shale (Figure 42). At some places this shale is thicker than 200 ft (60 m), but at other localities it is as thin as about 20 ft (6 m). Thicknesses of about 100 ft (30 m) are common; indeed in about 80 percent of the wells in Burbank Field, Cottage Grove Sandstone is overlain directly by 100 ft (30 m) or more of clayey shale. In only about 6 percent of the wells is the shale thinner than 80 ft (24 m). (Thicknesses of zero feet shown in Figure 42 are regarded as being artifacts of the software.)

Figure 43 shows the extent and thickness of cumulative shale above the Cottage Grove interval. Throughout the study area the Cottage Grove is covered directly or indirectly by a substantial thickness of confining shales; altogether, cumulative shale is as thick as about 175 ft (53 m) to 600 ft (180 m).

Figure 44 delineates the areas where multiple layers of confining shale -- 20 ft (6 m) thick or thicker -- overlie the Cottage Grove. Based on the assumption that a stratigraphic unit of shale 20 ft (6 m) thick or thicker would also be extensive laterally, this map should be valuable in estimating the confining-potential of shales.

Figure 45 simply shows areas where possible injection-reservoirs are above the Cottage Grove Sandstone and below the general depth of about 1000 ft (300 m). However, few of these formations are as thick and extensive as the Cottage Grove. The map also could be used for a general assessment of the number of reservoirs into which injected fluids might escape, if fluids were to travel upward through abandoned wells or along unsealed fractures.

RECOGNITION OF FRACTURE TRENDS

SUBSURFACE-MAPPING TECHNIQUES

Initial investigation of geologic data pertaining to Burbank Field and available to the public indicated that three subsurface-mapping techniques could be useful in detecting fracture trends in the reservoir: (1) An initial-potential map of wells drilled early in development of Burbank Field (Figure 46), (2) an effective-reservoir thickness map of the Burbank Sandstone (Figure 47), and (3) a structural contour map of the Pink Limestone marker bed, which is close above the Burbank (Figure 34; general example of map is in Figure 37). Initial-production maps were considered to be unbeneficial, because most leasehold blocks in the Burbank Field are 160 acres (65 hectares) or more. Spacing of wells is 10 acres (4 hectares). Therefore oil produced from more than one well would have been measured at a tank battery. Because most fracture trends are believed to be quite narrow, on a 160-acre (65-hectare) tract, the large production of wells affected by fractures could have been offset by small production from wells not affected by fractures. This production-monitoring problem was aggravated by the historical formation of secondary-recovery units within boundaries of the field, which makes the establishment of cumulative-production values for single wells nearly impossible. Moreover, no satisfactory method was found for discounting the effects of artificial fracturing of the reservoir.

Initial-potential Maps

The initial-potential map of wells producing from the Burbank Sandstone (example, Figure 46) was based on data from wells drilled before 1936. For an initial-potential map to be effective in fracture-trend study of the Burbank reservoir, factors influential on initial potential must be considered,

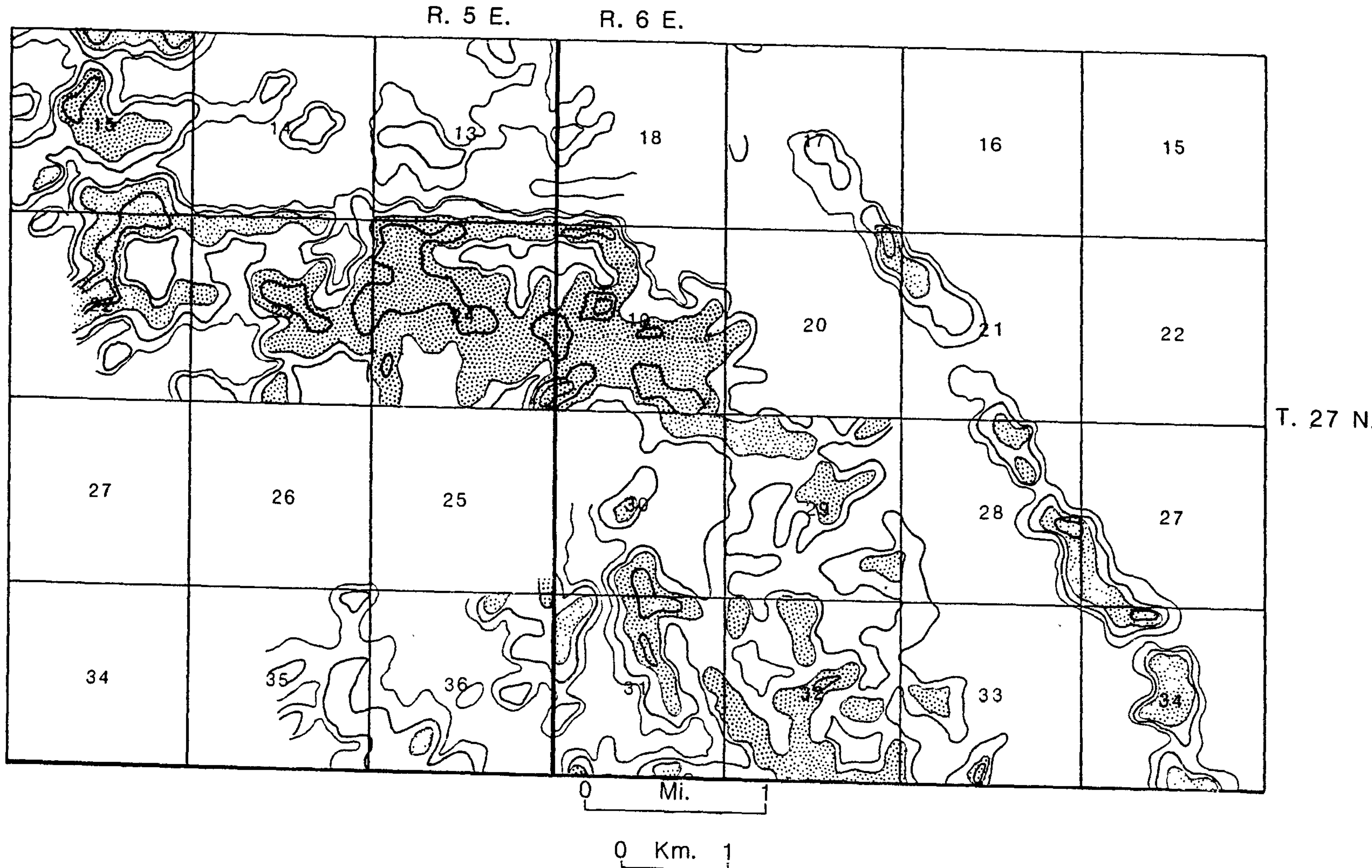

Figure 46. Initial-potential map, Burbank Sandstone, Burbank Field. Stippling shows areas within which initial-potential production of wells was more than 1000 bbl per day. Index to contour lines: 250 to 500 bbl per day; 500 to 1000 bbl per day; 1000 to 2000 bbl per day; 2000 to 4000 bbl per day; more than 4000 bbl per day.

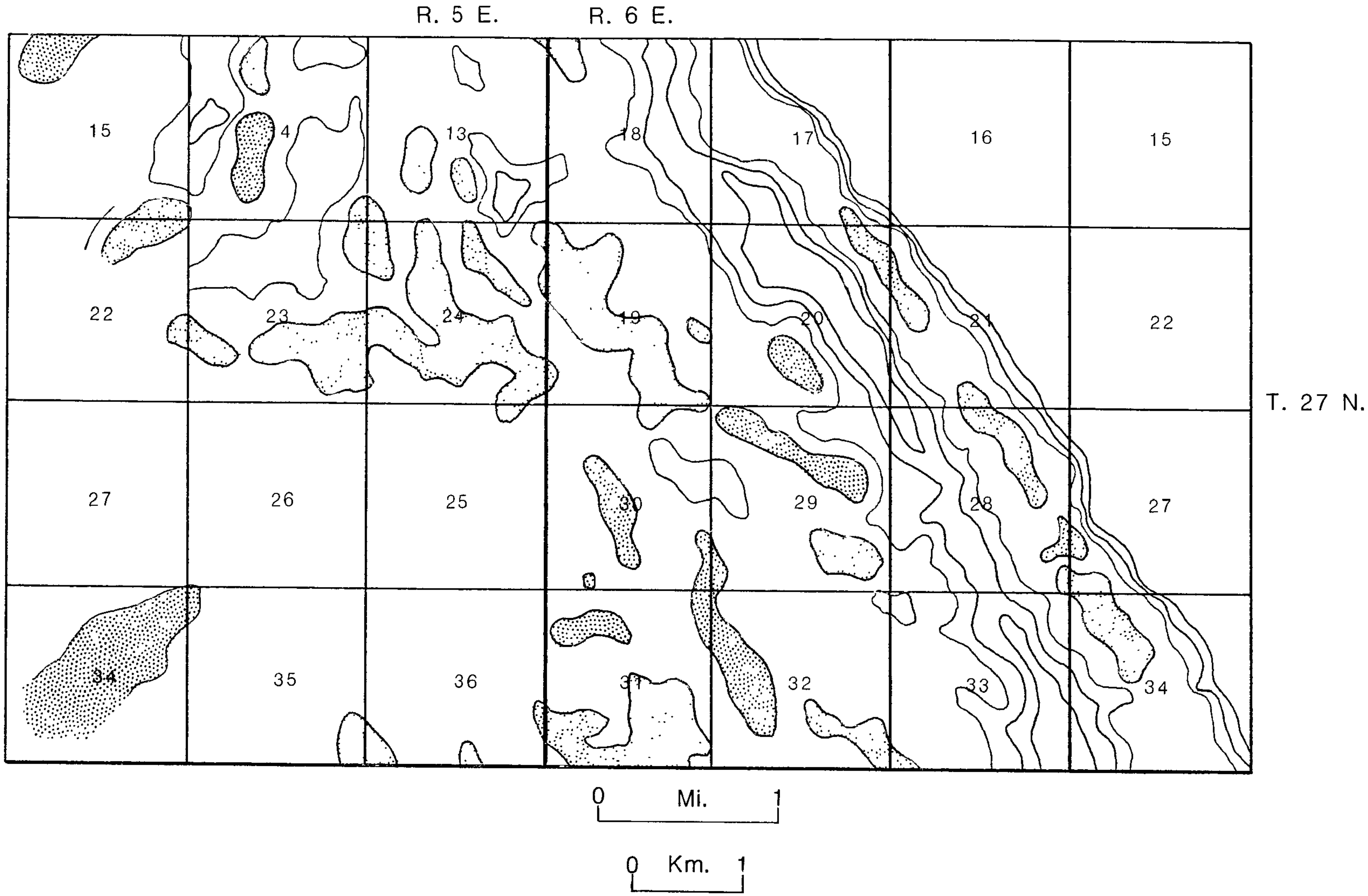

Figure 47. Thickness of effective reservoir rocks, Burbank Sandstone, Burbank Field. Contour interval 25 ft (7.6 m). Stippling shows areas within which Burbank Sandstone is thicker than 75 ft (23 m).

including: (a) Ages of wells and effects of reservoir-pressure depletion on initial production, (b) completion techniques (thickness of reservoir drilled and artificial stimulation), (c) operator-introduced bias in reporting initial-production rates, and (d) changes in reservoir character.

To eliminate the effects of reservoir depletion on initial potential, only data for wells drilled in the early stages of Burbank Field were used.

Completion techniques used were similar for all wells. Most wells were drilled entirely by cable-tool rigs or else the Burbank Sandstone was drilled with cable tools. This basic technique resulted in relatively undamaged reservoir faces in the borehole, and hydrostatically unbalanced conditions that allowed oil and gas to flow freely into the borehole. In most wells the reservoir was fractured by nitroglycerin, to enhance flow. Therefore, "after-shooting" flow rates were used where available. Because of the ages of the wells used in the study, no flow rates after hydraulic fracturing were used to map initial-production rates.

Most wells in the Burbank Field were drilled into the Burbank Sandstone until a satisfactorily large flow of oil and gas was developed or until the entire sandstone section had been exposed. This practice was not followed near the western border of the field because operators recognized an oil-water contact. They drilled into the top part of the reservoir, exposed several feet of rock, and stopped drilling above the oil-water contact. The amount of reservoir exposed by drilling seems not to have had an overriding effect on initial-production rates; very large initial flow-rates were recorded from wells drilled close to the oil-water contact.

Operator-introduced bias due either to inflation or suppression of initial flow rates is believed to have been insignificant in most areas of Burbank Field. As was noted earlier, leases in the field covered at least 160 acres (65 hectares); much variation in initial potential can be recognized within the boundaries of a 160-acre (65-hectare) tract. However, operator-introduced bias cannot be eliminated entirely; this fact creates doubt about the validity of large initial-potential trends situated along boundaries between leases of different operating companies.

The most significant factor in initial potential of wells in the Burbank Sandstone was variation in reservoir quality or thickness. The Burbank Sandstone is composed of channel-fill units, "stacked" by cut-and-fill, and multilateral. Individual channel-fill, "shoestring" sandstone units or combinations of units were porous, permeable, highly productive reservoirs. However, the uppermost and youngest sandstone unit was an exceptionally good reservoir across the entire field. Many wells near the oil-water contact drilled only a few feet of this uppermost unit, but they produced at larger rates than wells where much thicker sections of the Burbank were drilled and the uppermost unit was absent. The highly productive uppermost sandstone has significant impact on reliability of fracture-trend recognition in Burbank Field.

Reservoir-thickness Maps

Owing to the stacking of channel-sandstone units, sandstone thicker than 75 ft (23 m) is common, as is abrupt thinning. The initial-potential map (Figure 46) and reservoir-thickness map (Figure 47) indicate that large initial-potential trends and thick reservoir trends are correlated closely over the entire field, except in part of T. 27 N., R. 5 E. An easterly trend of large initial potential is along the northern boundaries of Sections 22, 23, and 24. This trend appears to be "normal" to the northerly and northwesterly trends of thicker Burbank sandstone reservoir-rock; it may be evidence of fracture-enhanced initial production. However, in form of a counter-argument, different operating companies drilled wells in Sections 13, 14, and 15 and wells in Sections 22, 23, and 24. Operator-introduced bias cannot be eliminated as a possibly significant origin of large differences in initial potential of wells along the boundary between these two areas.

Structural Geologic Maps

In study of West Edmond Field, structural contour maps set out considerable evidence to support the interpretation of faults in the reservoir. Structural geologic maps of parts of Osage County are published and copyrighted by the Osage Tribe of Native Americans. Structural contour maps of Burbank Field were reviewed, but no significant evidence of faulting was recognized. Electric-log surveys are scarce over large areas of the field, which makes the search for missing stratigraphic section on logs quite difficult. Such omissions of strata commonly indicate normal faults of small throw, which would not be manifest in ordinary structural contour mapping. Nevertheless, the hypothesis that structural geologic mapping would indicate faulting in the reservoir was tested by mapping the configuration of the Pink Limestone, which is a short distance above the Burbank Sandstone (Figure 34). At a contour interval of 10 ft (3 m) the map showed considerable evidence of folding by differential compaction of shale between the Pink Limestone and the Burbank "shoestring" sandstones, but little of the evidence would be explained best by faulting. Considering the available published maps, the scarcity of evidence about faulting recoverable from them, and the paucity of electric-logs in some areas of the field, the conclusion was reached that for the purpose of detecting faults of small displacement, structural contour maps yield little useful information.

Conclusions

Study of the Burbank reservoir by ordinary subsurface-mapping methods and testing for recognition and delineation of fracture-trends had these results:

(1) Abrupt changes in thickness, and the general linear geometry of the Burbank channel-fill sandstone reservoir make mapping of fracture-trends by standard subsurface-geologic methods an endeavor of small reward.

(2) Fracture trends may be identifiable in some sandstone reservoirs where initial-potential trends or initial-production trends are "normal" to reservoir-thickness trends, or otherwise are conspicuously detectable.

(3) In the Burbank Field, initial-potential maps are valuable for mapping trends of highly productive rock, but initial-production maps cannot be used effectively for this purpose.

(4) The likelihood of operator-introduced bias in reporting initial-production rates seems to justify reserved judgment about validity of large initial-production trends located along boundaries of leases owned by different operators.

(5) In the Burbank Field, the quality of reservoir exposed for production had more influence on initial production rates than total thickness of reservoir drilled.

(6) Effects on initial-potential production by reservoir pressure depletion and hydraulic-fracturing techniques were eliminated by using wells drilled early in development of the field.

(7) Explosion-fracturing of the Burbank reservoir had greater effect on initial productions of wells with small natural-production rates than on wells with large natural-production rates.

(8) Study of the Burbank reservoir strongly indicates that abrupt changes in thickness and geometry make most channel-fill sandstone reservoirs generally unsuited for use in developing methods to detect fracture trends by standard methods of mapping. Attention should be directed toward sandstone reservoirs of other depositional settings.

SURFACE-MAPPING TECHNIQUES

Satellite imagery of the eastern part of Burbank Field was studied to map lineaments. Imagery consisted of a Band-7, black-and-white image from Landsat 5, at an approximate scale of 1:1,000,000. A zoom-magnifier enlarged the image by a factor of five. Lineaments mapped on the magnified image were grouped with topographic-map lineaments and with joint clusters mapped by Hagen (1972). Satellite-image lineations follow stream-drainage patterns closely and also linear features detectable on topographic maps. From an empirical point of view, a strong relationship seems to exist between orientations of joint patterns mapped by Hagen (1972) and lineations detectable on satellite images and topographic maps.

Figure 48 shows the mapped orientations of joint patterns recognized by Hagen (1972) from surface geologic mapping and photogeologic mapping. These joint patterns are represented by single lines on the map, but they were shown as joint-clusters on Hagen's map. Principal orientations of joint clusters, satellite lineaments, and topographic features correlate rather closely with recognized subsurface fracture trends determined by Hagen (1972) and by Trantham and others (1980).

Satellite lineaments tend to be somewhat longer than joint clusters and to be strongly related to drainage patterns. This suggests that the lineaments could be taken as evidence of fractures that penetrate a thick part of the stratigraphic column.

Conclusions

Satellite imagery provides good evidence of large lineaments that are oriented primarily northeastward and that seem to be related closely to stream-drainage patterns. Topographic maps are useful for delineating drainage-related lineaments. Orientations of some of the major streams may be due to superposition of drainage and adjustment to zones of weakness in bedrock. (For added information see Melton, 1959.)

Figure 38 was constructed to test the working hypothesis that penetrative faults in Burbank Field might be suggested by abrupt, linear changes in thickness of the stratigraphic section between the Cottage Grove Sandstone and Pink Limestone. In the lower middle part of T. 26 N., R. 6 E., trending east-northeast (arrows, Figure 38), crowded contour lines show evidence of uncommon thickening. This zone of transition seems loosely correspondent to a broad aggregation of joint clusters

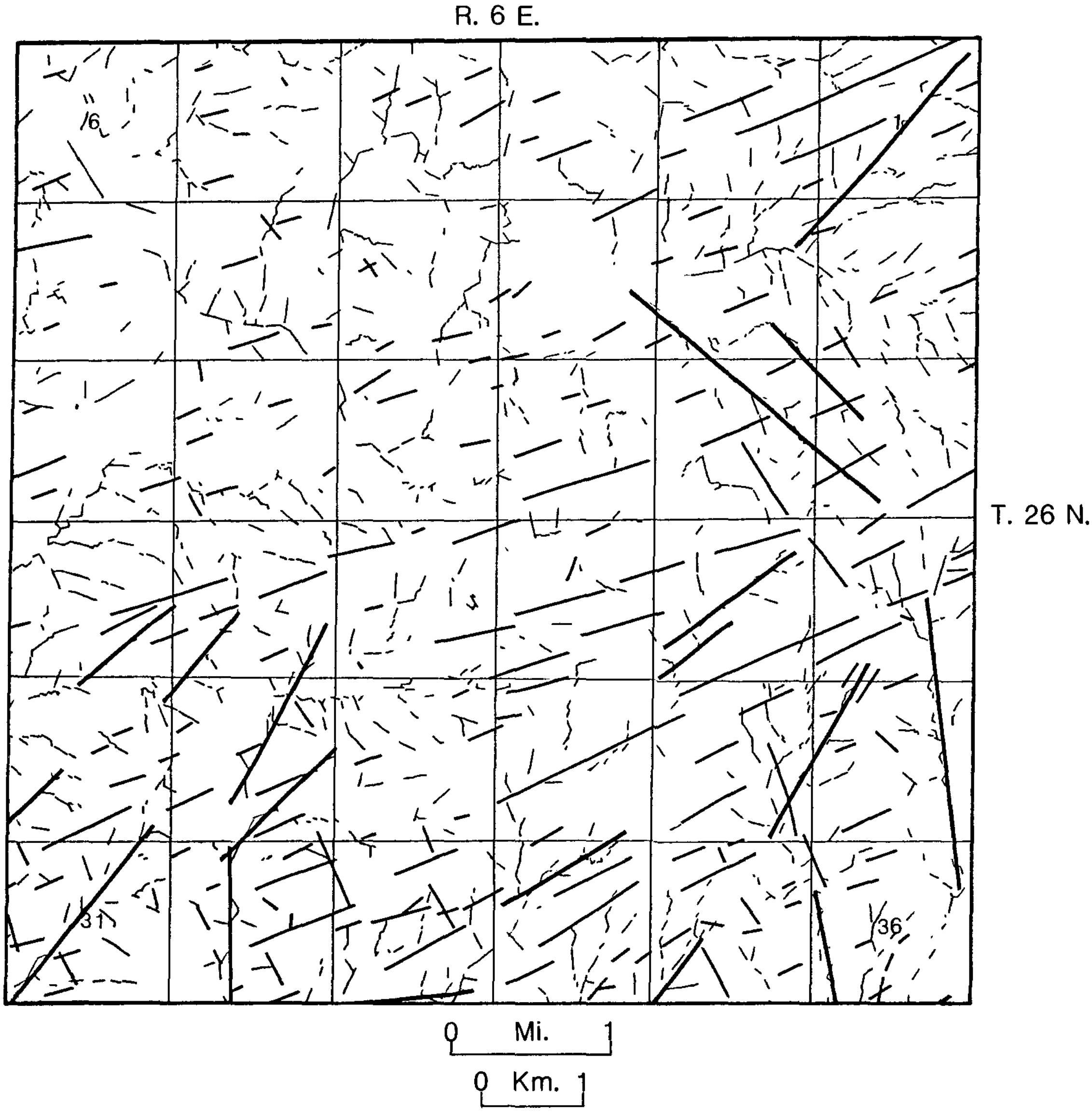

Figure 48. Lineaments and joint clusters, T. 26 N., R. 6 E., Burbank Field. Long, broad, dark lines are lineaments mapped from remote-sensing imagery. Short, straight lines of intermediate width show localities and trends of joint clusters mapped by Hagen (1972). Short, narrow, "broken" lines are topographic-map lineaments, many of which are related to drainage patterns. Observe concentration of northeast-trending joint clusters and lineaments in southern part of township.

and lineaments (Figure 48).

INJECTION-SENSITIVITY MAP

Examination of lineaments evident on satellite imagery led to expression of localities with possible sensitivity to fluid injection. This mapping was based on working assumptions believed to be worthy in conservative judgment of injection-potential:

(1) Systematic joints are in the Burbank Sandstone, and are in the rock unit next above (Hagen, 1972; Dickey, 1979).

(2) Under overpressured injection, this network of fractures is a conduit for fluids (Dickey, 1979).

(3) Communication between wells exceeds 1 mi (1.6 km) at some localities (Dickey, 1979, p. 384).

(4) Anomalously dense and extensive concentrations of lineaments suggest penetrative or incipiently penetrative fractures in the sedimentary-rock column.

Systematic fracturing within the Burbank Sandstone has been documented well. The effect of fracturing seems evident in the record of water-flooding (see summary account by Dickey, 1979, p. 384-387). The concept of abundant joints in an orderly arrangement within the Burbank reservoir seems to be supported formidably by physical evidence. Of course, joints in the reservoir and confining beds would not be detectable by the standard methods of subsurface mapping used here. If faults penetrate reservoir and confining beds and extend to the surface, then they are not made apparent by subsurface-mapping methods and they are not clearly evident in the surface geology. General trends of lineaments are in keeping with trends of joint clusters mapped by Hagen (1972). Hagen and Trantham and others (1980) described evidence to support the assumption that fractures in the Burbank Sandstone and fractures in rocks at the surface are strongly similar. The provisional operating assumption follows that lineaments may be manifestations of deep-seated zones of weakness in bedrock, and that they might reasonably be interpreted as localities within which fluids injected under extraordinary pressure could penetrate confining beds.

Figure 49 shows areas of suspected injection sensitivity. Because of the lack of clear-cut evidence to favor correspondence of lineaments and penetrative fractures, the areas are described as Zones of Caution. For injection wells planned within the Zone of Caution, the proposition of nearby faults that penetrate storage zone and confining beds should be rejected by consideration of documented evidence, or an acceptable level of risk should be demonstrated. Injection should be into partly depleted reservoirs or reservoirs that

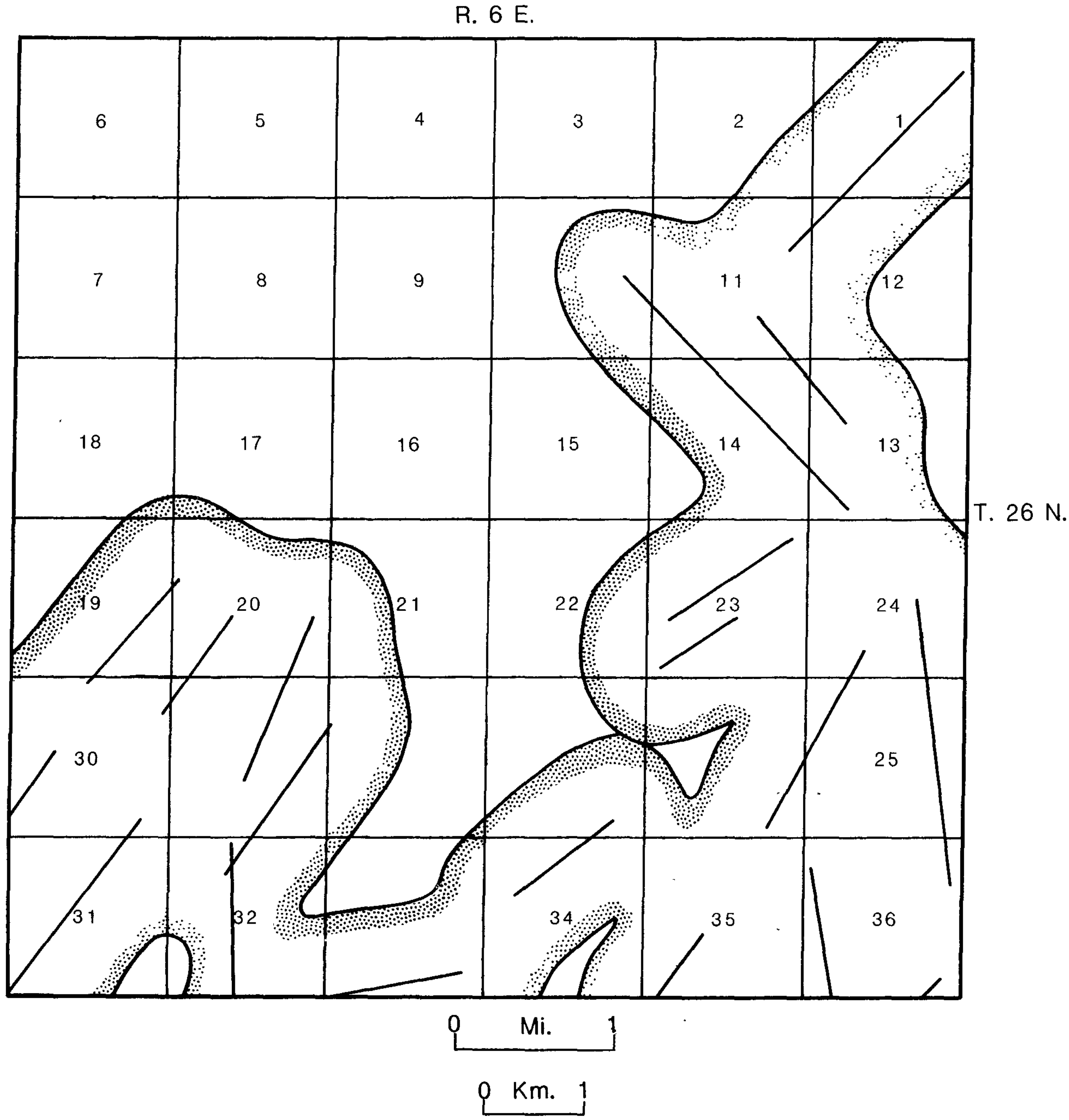

Figure 49. Injection-sensitivity map, T. 26 N., R. 6 E., Burbank Field. Stippling outlines Zones of Caution, areas within which lineaments and joint clusters are suggestive of faulted rocks in the subsurface. In Zones of Caution geologic evidence should accumulate to show that risks associated with injection of fluid are acceptable.

GENERAL CONCLUSIONS

A data base and mapping by computer allow quick generation of various maps, including structural contour maps, interval-thickness maps, and cumulative-thickness maps of confining beds and potential storage units. Routine use of data bases and mapping software would allow geologists with limited experience in subsurface geology to collect, enter and manipulate data to develop a large variety of maps. This method would free experienced geologists for generation of maps that would be more definitive for judgment about injection-sensitivity of specific areas.

Initial-potential and initial-production maps are of seriously limited usefulness in delineation of suspected trends of fractures in the Burbank reservoir. Large leases made initial-production maps effectively useless, whereas methods of reporting initial flow rates and operator-introduced bias reduced confidence in mapping from initial-flow potentials.

The most significant variable in initial-potential mapping of the Burbank Sandstone was the overall character of the reservoir rock and abrupt changes in reservoir quality associated with narrow, channel-fill sandstones. Although study of initial-potential maps led to identification of several localities where fractures were suspected to have influenced production, this explanation was rejected on the grounds that the production could show strong effects of the operators' management of leases.

Structural contour maps are not informative for the purpose of detecting fractures in the Burbank reservoir, even at the contour interval of 10 ft (3 m).

Remote-sensing imagery, including satellite imagery and topographic maps, provides information useful for conjectural mapping of fracture trends and for construction of injection-sensitivity maps.

SECTION 7

FITTS POOL, PONTOTOC COUNTY

INTRODUCTION

Pontotoc County is divisible into five geologic provinces (Figure 50): (1) the Hunton Arch, (2) the "Northeast Province", (3) the Lawrence Uplift, (4) Franks Graben, and (5) the Arbuckle Uplift. The Arbuckle Uplift, Franks Graben, and Lawrence Uplift are bounded by extensive faults (Figure 50). In the course of this research, general attention was given to the geology of Pontotoc County, but of particular concern was the Fitts Pool, in Franks Graben (Figure 50).

SUBSURFACE GEOLOGY

Cropping out on the deeply eroded Arbuckle Uplift are chiefly carbonate rocks of the Arbuckle and Simpson Groups (Table 2). Strata that crop out in Franks Graben mostly are Pennsylvanian shales and sandstones. Thick shales, primarily of the Boggy Formation (Table 2), are the seal above the Fitts Pool (location, Figure 50).

The Fitts Pool has produced oil and gas from the Ordovician Simpson Group and Viola Group, the Silurian-Devonian Hunton Group, and strata of the Pennsylvanian System. The trap is a large faulted anticline (Figure 51); most production from rocks older than Pennsylvanian is related to folding of strata, but some entrapment in Pennsylvanian rocks is stratigraphic. The Pennsylvanian confining beds are in the range of 2000 to 3000 ft (600 to 900 m) thick, but locally within the Franks Graben some of the faults shown in Figure 51 penetrate Springeran and Morrowan strata. The Franks Fault Zone, the Stonewall Fault, and the Ahloso Fault to the north are traceable at the surface, although the Stonewall Fault is obscure locally, and the Ahloso Fault is not evident throughout the length shown in Figure 50.

In study of West Edmond Field, initial-potential production maps were used to advantage, because on the whole, reservoir rocks are limestones of the Hunton Group. At Fitts Pool, of the several reservoirs, only the Hunton Group has generally similar lithic properties; the Hunton is suited for use of initial-potential production as a means to estimate the effects of fracturing in the reservoir. At Fitts Pool the more porous and permeable formations in the Hunton Group are the

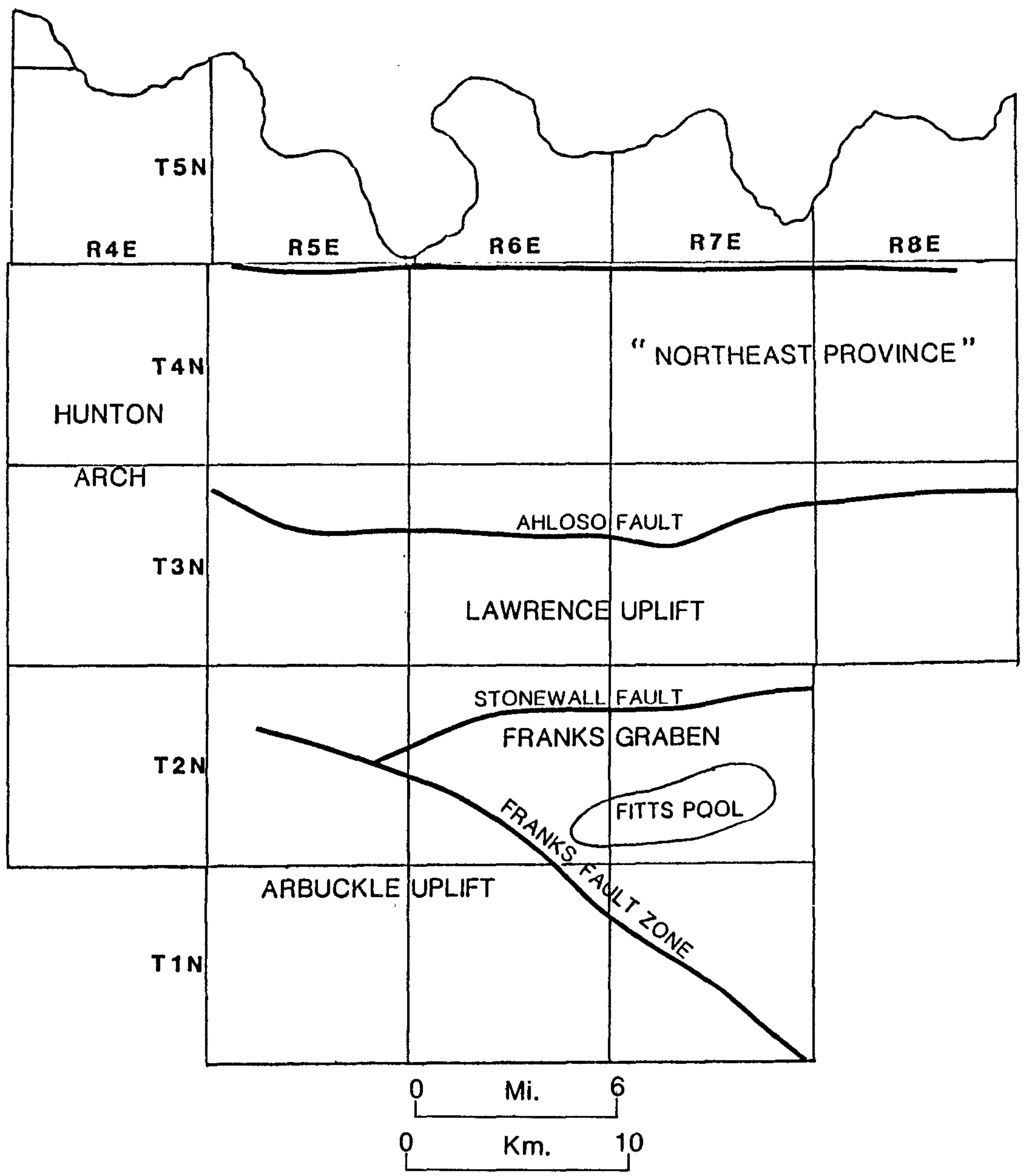

Figure 50. Generalized map of geologic provinces, Pontotoc County. Major faults include large, unnamed fault in the subsurface that extends through northern part of Township 4 North.

Table 2. ROCK-STRATIGRAPHIC UNITS, EASTERN PONTOTOC COUNTY (AFTER MORGAN (1924), BARKER (1951), MISER (1954), GILLERT (1952))

SYSTEM	STAGE	ROCK-STRATIGRAPHIC UNITS
Pennsylvanian	Virgilian	Vanoss Formation Ada Formation Vamoosa Formation
	Missourian	Belle City Limestone Francis Formation Seminole Formation
	Desmoinesian	Holdenville Formation Wewoka Formation Wetumka Shale Calvin Sandstone Senora Formation Stuart Shale Thurman Sandstone Boggy Formation Savanna Formation McAlester Formation
	Atokan	Atoka Fromation
	Morrowan	Wapanucka Limestone Wapanucka Shale Union Valley Limestone Union Valley shale
	Springeran	Springer Formation
Mississippian		Caney Shale Welden Limestone
		Woodford Shale
Devonian		
		Hunton Group
Silurian		
Ordovician		Sylvan Shale Viola Group Simpson Group Arbuckle Group (upper part)

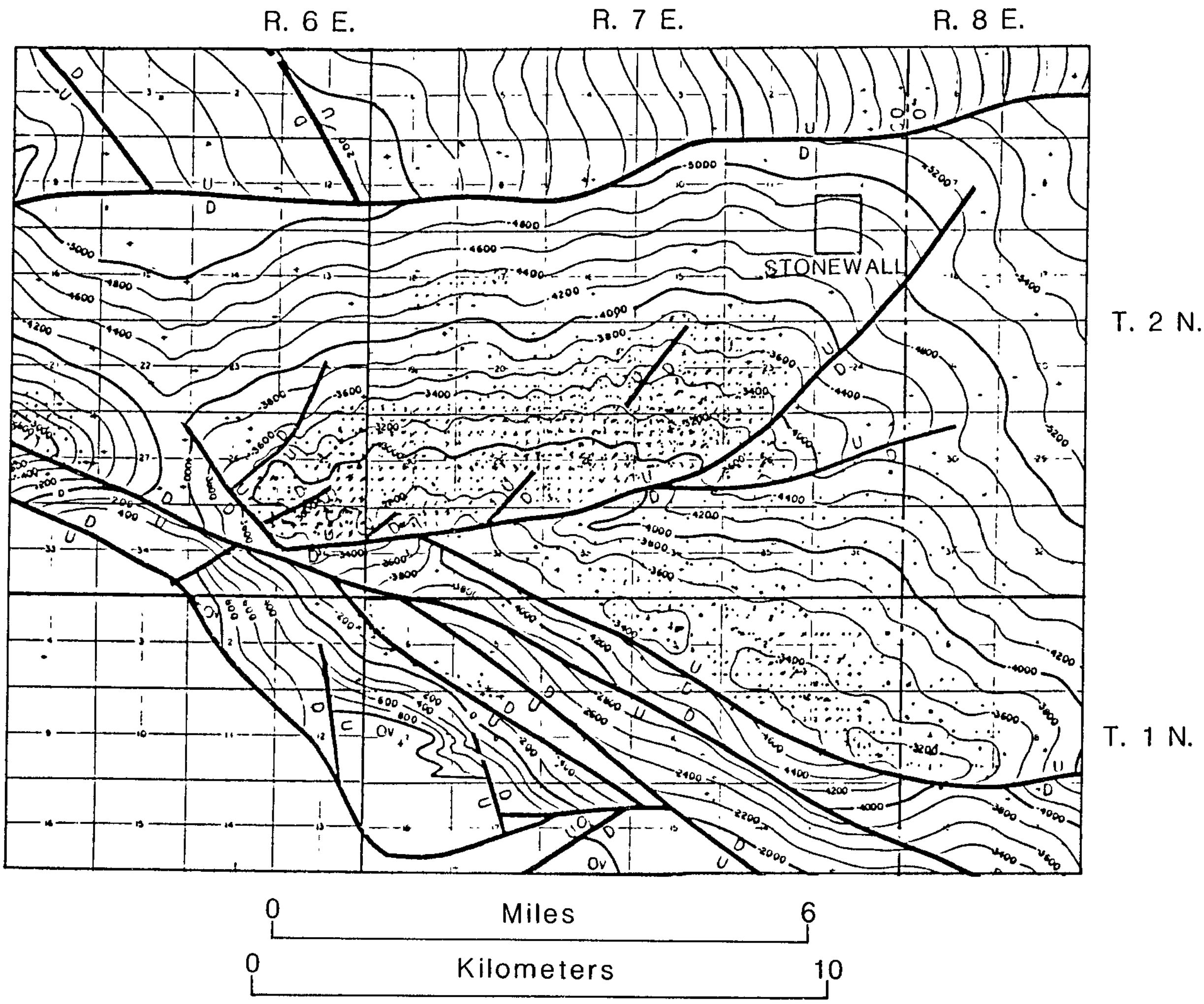

Figure 51. Structural contour map, Fitts Pool and nearby areas. Datum: Top of Viola Group. Broad, curved black lines are traces of faults that cut Viola Group. Contour interval 100 ft (30 m) north of Stonewall Fault and 200 ft (60 m) south of Stonewall Fault. Fitts Pool is large oil field in T. 2 N., R. 7 E., on north side of large convex-southward fault. Oil and gas are trapped in anticline, with closure against fault that extends from Stonewall southwestward to southeastern corner of T. 2 N., R. 6 E.

Frisco and Bois d'Arc (see Figure 16, p. 37, for stratigraphic position). The upper part of the Hunton Group is eroded, and thickness of the Frisco-Bois d'Arc section varies accordingly. Therefore study of initial production centered on localities where high-production trends are inconsistent with thickening of the Frisco-Bois d'Arc sequence. (Compare Figures 52 and 53, with special notice given to broad dashed lines.) Insofar as was practical, calculation of initial-potential production eliminated variation due to (a) methods of reporting production, (b) completion techniques, (c) ages of wells relative to decline of reservoir pressure, and (d) lease-line protection (Puckette, 1989). The amount of error that remains is believed to not affect placement of the 1000 bbl-per-day contour intervals. Because the Fitts Pool is located where rocks generally are strongly folded and faulted, definite and positive effect of faulting and fracturing on production is a reasonable expectation. The evidence available for this research did not yield such information, for the trends of large initial production shown in Figure 53 are few. Altogether they suggest an eastward- to northeastward-striking mosaic of fractures.

MAPPING OF FRACTURE TRACES AND LINEAMENTS

Aerial photographs, topographic maps and satellite imagery were used to map lineaments and fracture traces. Aerial photographs were "standard black-and-white," at the scale of 3.2 in. per mi (5.1 cm per km). Fracture traces and lineaments were mapped on clear overlays, reduced in scale and posted to 7.5-minute topographic maps by careful registration (Figure 54). Black-and-white thematic-mapper satellite imagery covering 115 mi square (71.5 x 71.5 km) was chosen because the Band-7 data increase resolution of linear features. Images were winter scenes with no cloud cover, at the scale of 1:125,000.

Fracture traces and some lineaments (Figures 55, 56, 57, and 58) were mapped on aerial photographs, mostly under stereoscopic inspection with magnification. Lineaments were mapped also on satellite imagery (Figure 59). Geomorphic features interpreted as fracture traces and lineaments included uncommonly straight segments of streams, straight-line topographic features (many of them escarpments, some of them swales), and alignments of vegetation (Figure 54, 55, 56, 57, 59). Fracture traces and lineaments are abundant where bedrock is composed of the hard, brittle strata of the Arbuckle, Simpson, Viola and Hunton Groups; they are fewer where the thick Pennsylvanian shales are bedrock. As shown by Figure 54, mapping from aerial photographs under stereoscopic viewing with

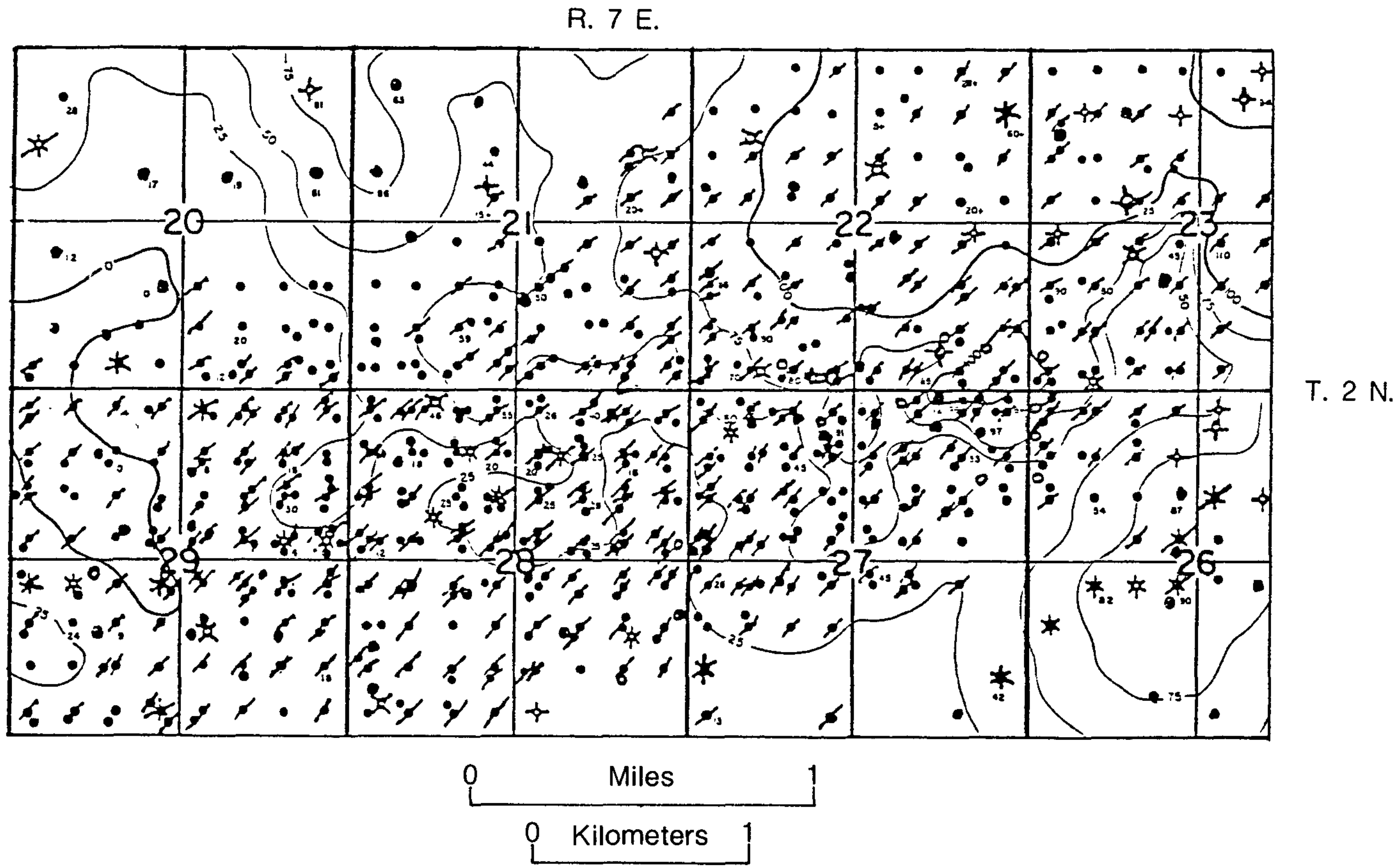

Figure 52. Thickness of Frisco-Bois d'Arc Formations, eastern part of Fitts Pool. Contour interval 25 ft (6.1 m). Upper part of Hunton Group was eroded before deposition of Woodford Shale.

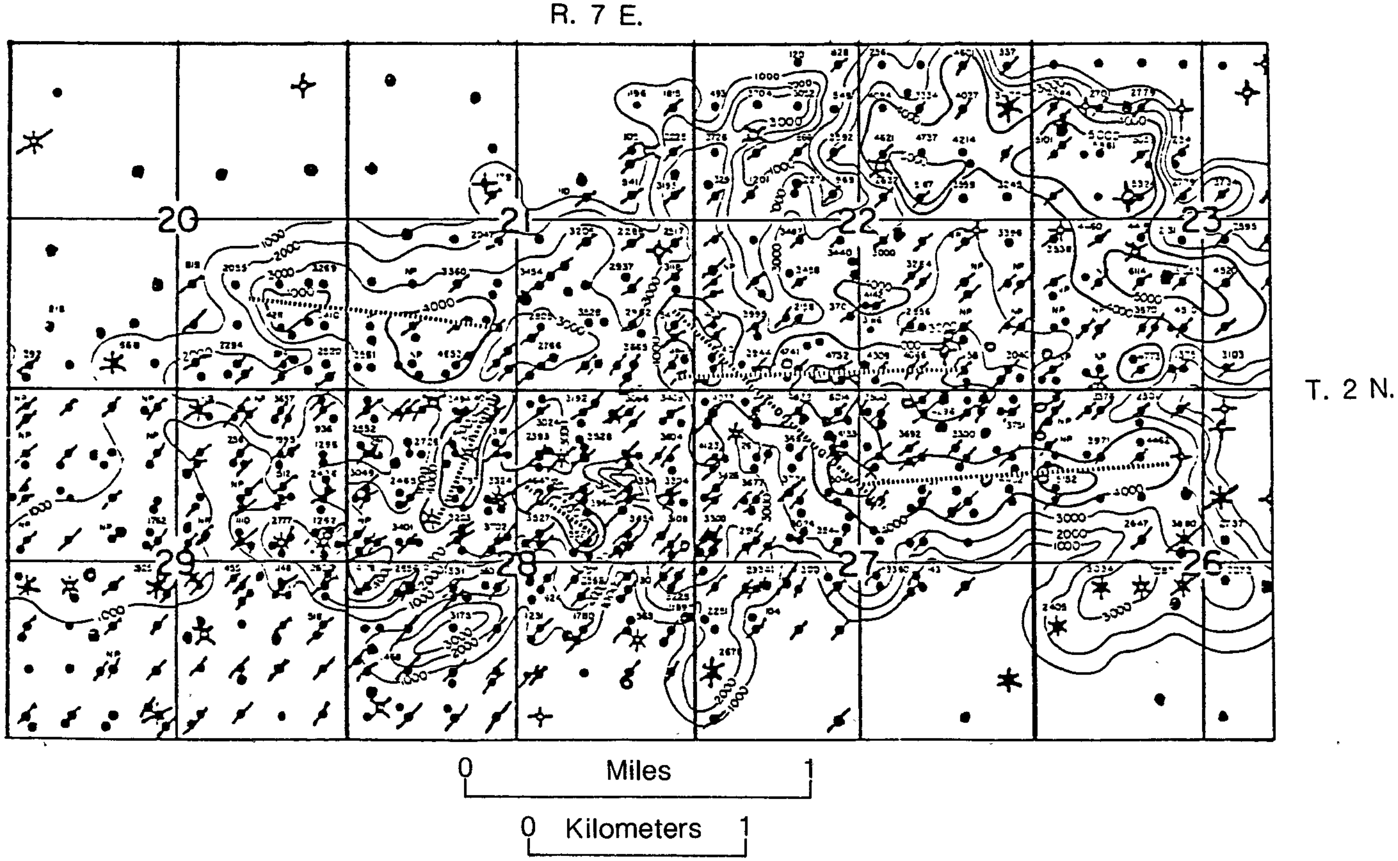

Figure 53. Initial-potential production of wells completed in Hunton Group before 1938, eastern part of Fitts Pool. Contour interval 1000 bbl per day. Broad black line is 4000 bbl-per-day contour. "NP" signifies that no potential was reported. Broad dashed lines show trends of large production that do not vary with thickening of Frisco-Bois d'Arc Formations. Because Frisco-Bois d'Arc is the most productive part of Hunton Group, divergence between thickness and production suggests the contribution of fracturing to production.

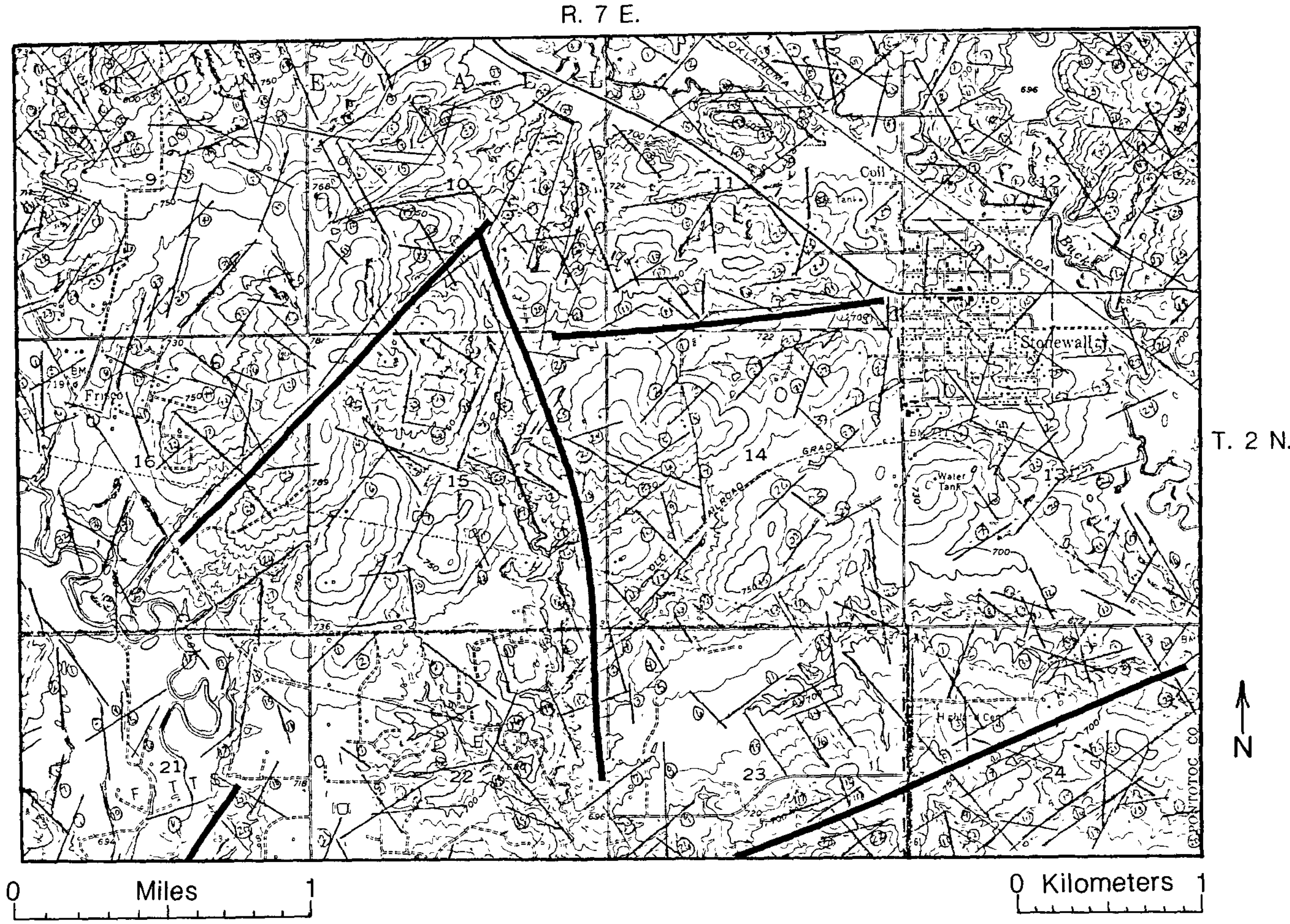

Figure 54. Topographic map, east-central part of T. 2 N., R. 7 E., showing fracture traces mapped from aerial photographs (short, straight, narrow lines with index numbers) and lineaments mapped from satellite imagery (broad black lines). At the surface, the extensive Stonewall Fault (Figure 51) strikes eastward through the central part of Section 9, into northern part of Section 11, but is not shown directly by fracture traces.

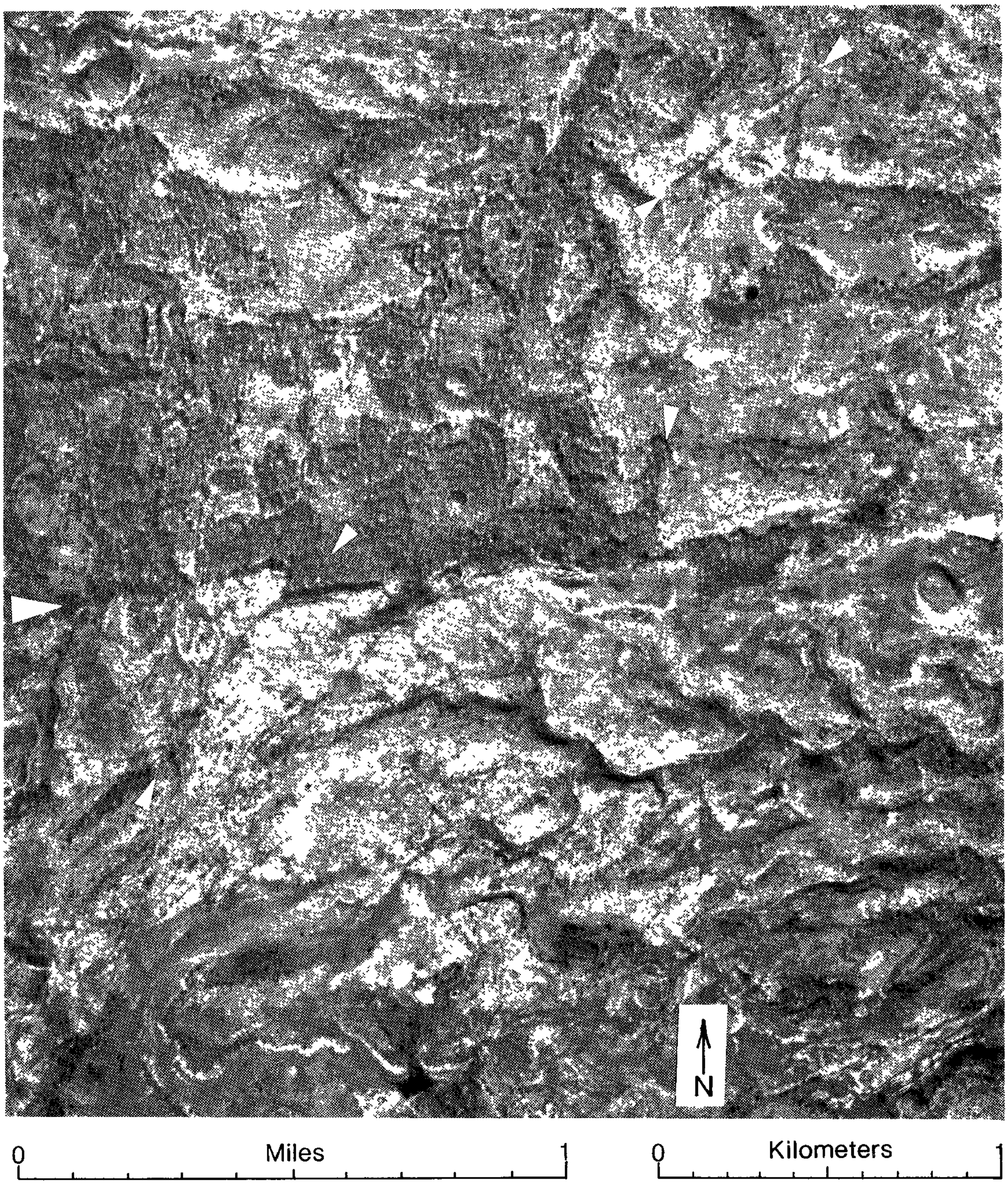

Figure 55. Lineament (large opposed arrows) and numerous fracture traces (some shown by small opposed arrows). Bedrock chiefly is sandstone of the Simpson Group. Lineament is mapped as a fault (Gillert, 1952); north side is downthrown. Fracture traces and lineament shown mainly as alignments of vegetation. Lineament extends through northern parts of Sections 33 and 34, T. 1 N., R. 7 E.

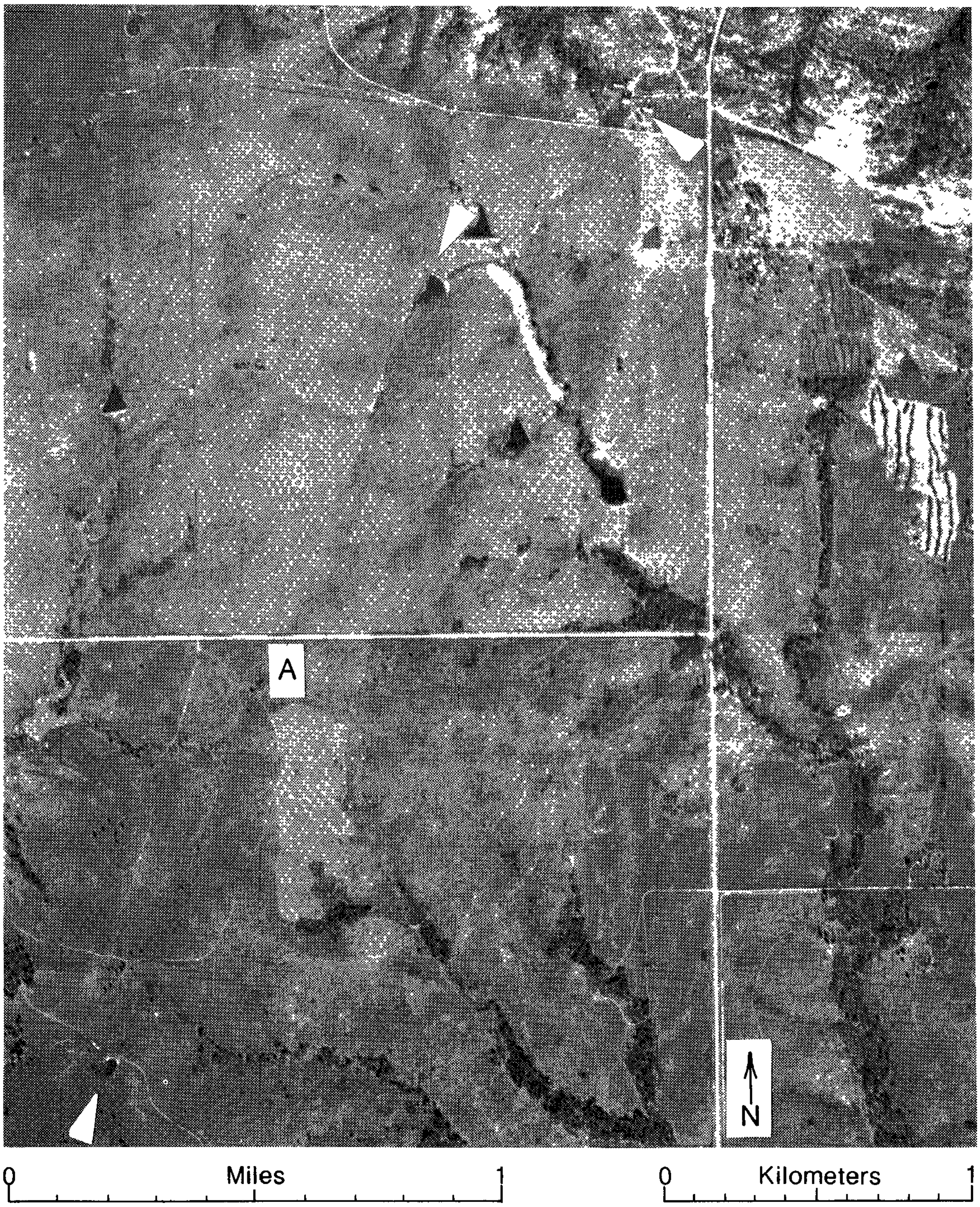

Figure 56. Lineament (opposed arrows) in upland terrain of carbonate rocks, Arbuckle Group. Lineament is swale in grassland (Figures 57 and 58). Southern boundary, Franks Fault Zone, is on trend with single arrow. Dark pattern, northeastern corner, shows truncated, folded strata north of fault. Lineament is in Sections 14 and 23, T. 1 N., R. 6 E.

Figure 57. View northeastward along lineament shown in Figure 56. Lineament expressed physiographically as swale in grassy uplands. Viewer's position was in county road, near the place marked "A". Small tree in central part of horizon is in the lineament.

Figure 58. View southwestward along lineament shown in Figure 56. Lineament expressed physiographically as poorly defined, broad swale. Viewer's position was in county road, near the place marked "A". Lineament extends through cluster of trees located behind and to the left of crooked, middle fence post.

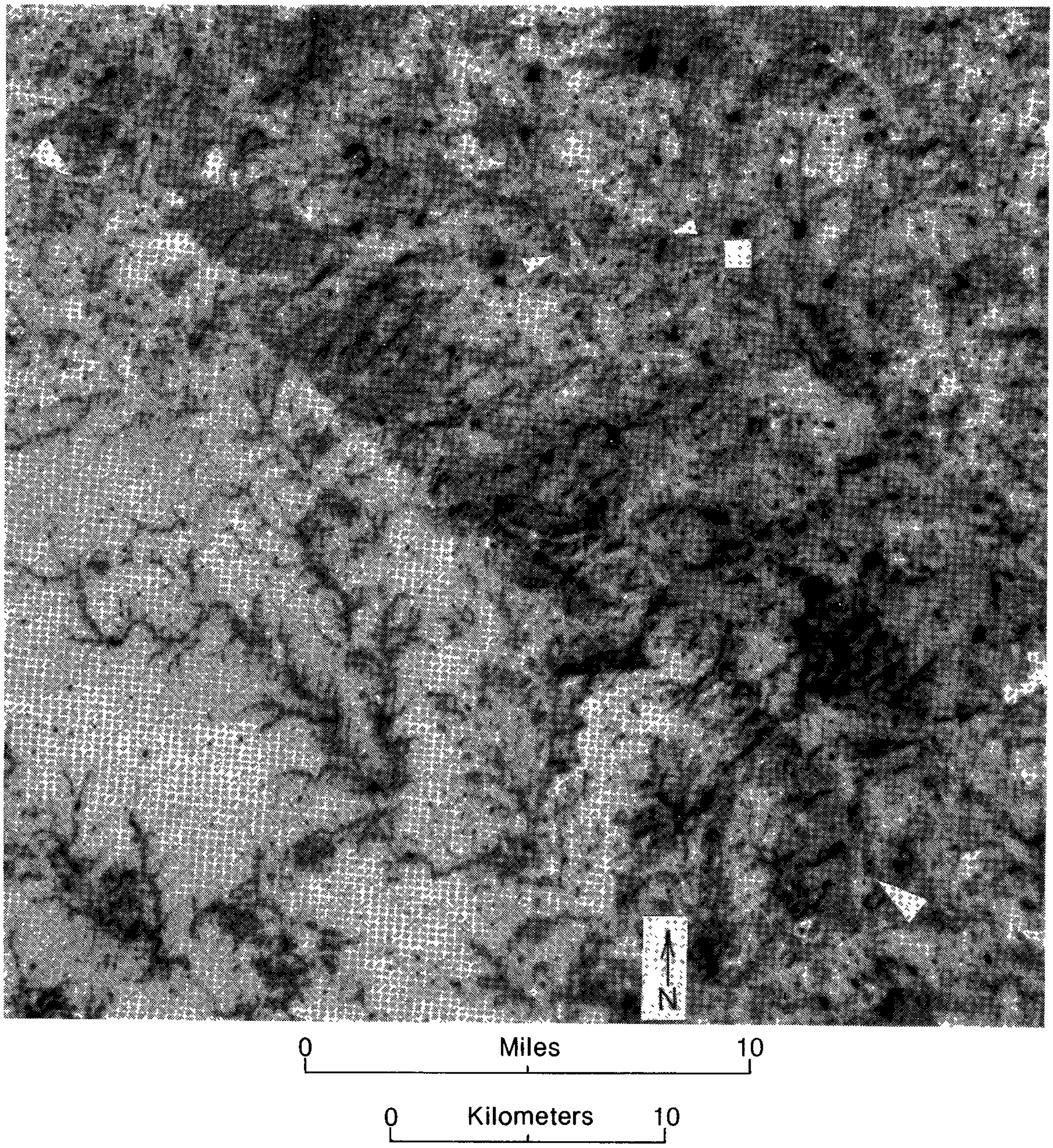

Figure 59. Satellite imagery, western part, Franks Graben. Scale, 1:250,000. Large opposed arrows mark general extent of Franks Fault Zone, a prominent lineament. Southwestern part of image is Arbuckle Uplift. Square shows location of Stonewall. Small opposed arrows are at ends of small lineament that probably is part of Stonewall Fault.

magnification produces much data -- an advantage for the study of a few square miles, but perhaps too much detailed information when the objective is to evaluate a region.

INJECTION-SENSITIVITY MAP

Figure 60 is an injection-sensitivity map of Franks Graben, constructed on the assumption that fluids would be emplaced in pre-Pennsylvanian strata. The entirety of the Franks Fault Zone is regarded as being injection-sensitive, because of the brittleness of lower Paleozoic rocks within the zone, the many large faults and more small ones, and the associated general fracturing of rock. Altogether these circumstances lead to the inference that within the fault zone, many faults are likely to be unsealed.

A questionable Zone of Sensitivity is mapped south of the Stonewall Fault (Figure 60). This fault penetrates from the deep subsurface to the surface, but because it bounds the more downthrown side of the graben, subsurface geologic evidence close by is scarce. Plans for disposal wells in proximity to the fault should take geologic evidence into careful account, especially if fluid is to be injected under extraordinary pressure.

Because of the abundance of lineaments mapped in the interior of the graben (Figure 61), all but small parts of the province are classified as being in a Zone of Caution. Clearly, the thick sequence of shaly Pennsylvanian confining beds sealed Fitts Pool, but the many lineaments suggest that a system of fractures involves the confining beds. The proposition of injection into pre-Pennsylvanian rocks should take into account the nearby geologic circumstances, particularly if plans include the emplacement of more fluids than have been withdrawn from the reservoir, or injection at pressures larger than the original formation pressure.

CONCLUSIONS

(1) Mapping of lineaments from satellite imagery is effective and quicker than mapping from aerial photographs. Different observers can produce interpretations that are strongly similar (Figure 61).

(2) Thematic-mapper data have good resolution. Band-7, black-and-white imagery tends to emphasize linear features moreso than does false-color imagery. Winter scenes were the more useful. Purchase of film-negative imagery offers the

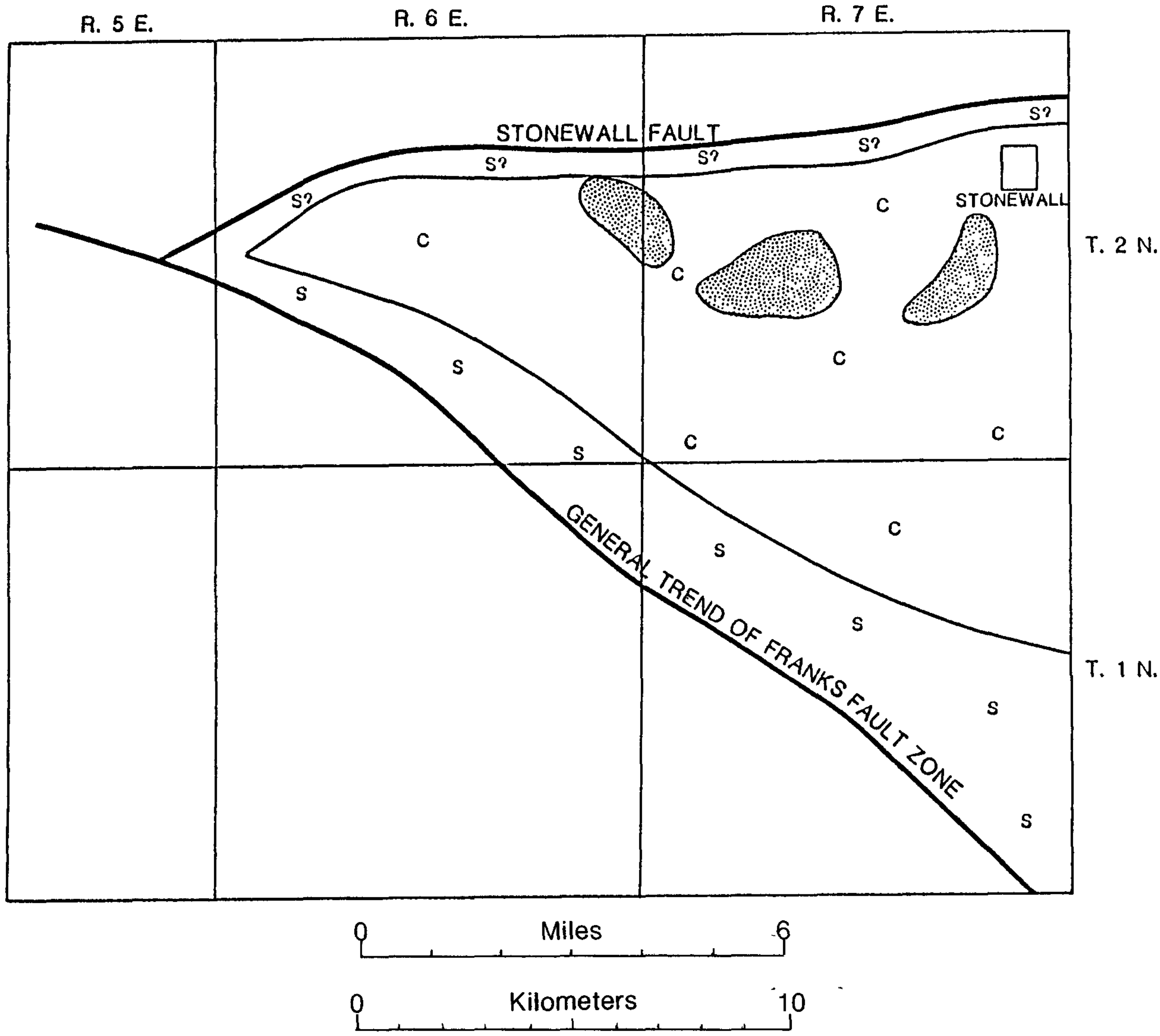

Figure 60. Injection-sensitivity map, Franks Graben, based on the assumption that injection zones would be in pre-Pennsylvanian rocks. Extensively faulted rocks in Franks Fault Zone are in Zone of Sensitivity (S). The area near the Stonewall Fault is suspected to be injection-sensitive, in the general absence of subsurface geologic data. Most of the interior of the graben is in Zone of Caution (C).

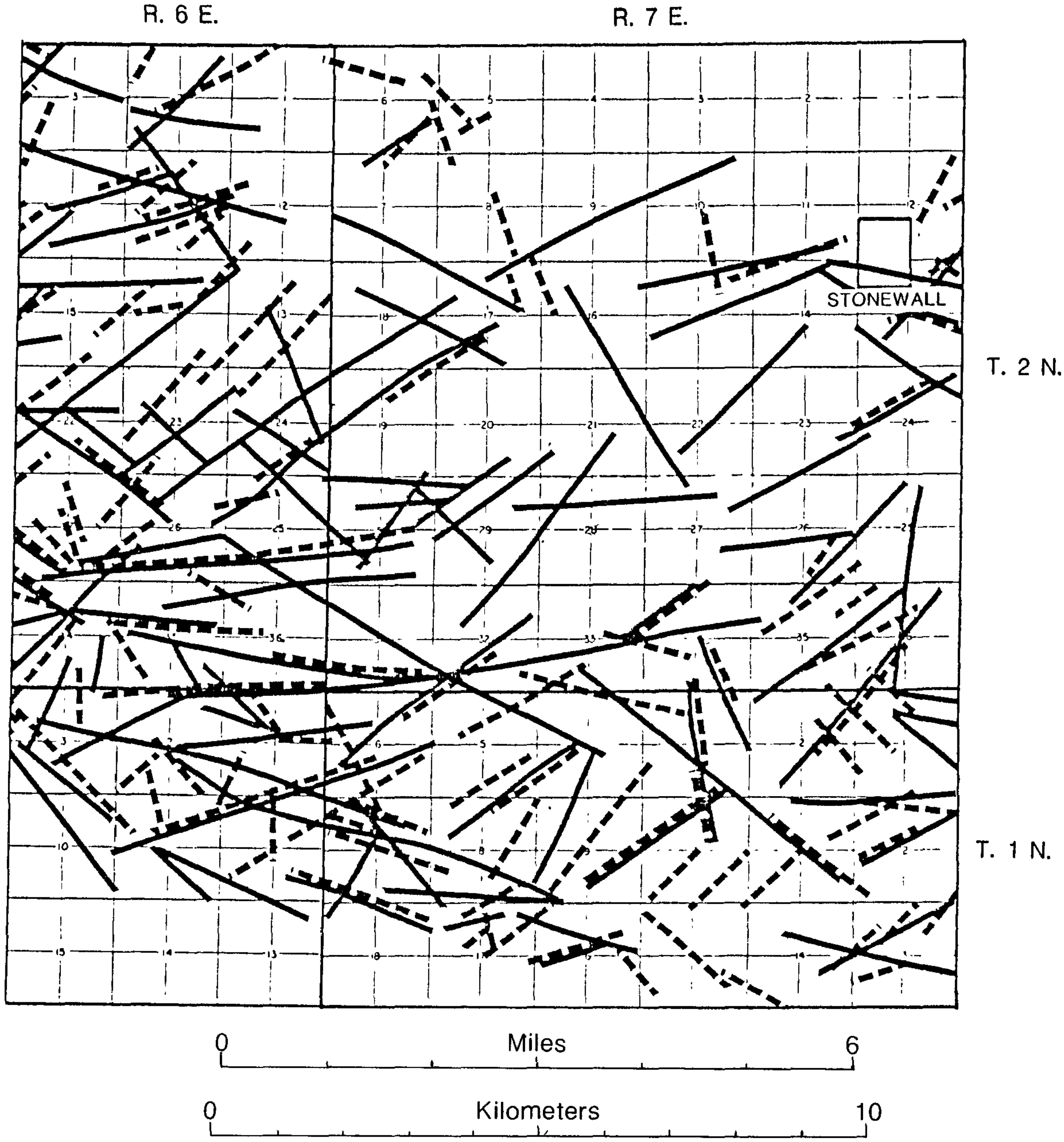

Figure 61. Map of lineaments in Franks Graben. Dashed and solid lines are interpretations of two observers. Interpretations are in general agreement.

option of working with images at several scales.

(3) Band-7 data reduce the likelihood of misinterpreting cultural features as lineaments. Posting of lineaments to topographic maps further reduces the probability of such error.

(4) Lineaments are significantly more numerous in terrain underlain by limestone, dolomite and sandstone than in terrain underlain by shale.

(5) Mapping of fracture traces and lineaments from aerial photographs is affected rather strongly by differences in cover of vegetation. The number of detectable fracture traces is markedly less in grassland than in forested land.

(6) In the complexly deformed Franks Graben, mapping of lineaments is valuable for construction of injection-sensitivity maps. In the interior of the graben a system of fractures in Pennsylvanian confining beds is suggested by the fabric of lineaments.

SELECTED REFERENCES

Alpay, O. A., 1973, Application of aerial photographic interpretation to the study of reservoir natural fracture systems: Jour. Petroleum Tech., v. 25, p. 37-45.

Amsden, T. W., and Rowland, T. L., 1967, Geologic maps and stratigraphic cross-sections of Silurian strata and Lower Devonian formations in Oklahoma: Okla. Geol. Survey Map GM-14.

Andresen, M. J., 1962, Paleodrainage patterns: Their mapping from subsurface data, and their paleogeographic value: Amer. Assoc. Petroleum Geologists Bull., v. 46, no. 3, p. 398-405.

Arbenz, J. K., 1956, Tectonic map of Oklahoma: Okla. Geol. Survey Map GM-3.

Azimi, Esmaeil, 1978, Use of remote sensing for fracture discrimination and assessment of pollution susceptibility of a limestone-chert aquifer in northeastern Oklahoma: Unpub. Master of Science thesis, Okla. State Univ., 98 p.

Barker, J. C., 1951, The geology of a portion of the Lawrence Uplift, Pontotoc County, Oklahoma: Tulsa Geol. Soc. Digest, v. 19, p. 169-191.

Bates, R. L., and Jackson, J. A., (ed.), 1984, Dictionary of geological terms: Anchor Press/Doubleday, 3rd ed., 571 p.

Beardall, G. B., Jr., 1983, Depositional environment, diagenesis and dolomitization of the Henryhouse Formation, in the western Anadarko Basin and Northern Shelf, Oklahoma: Unpub. Master of Science thesis, Okla. State Univ., 127 p.

Benoit, E. L., 1957, The Desmoinesian Series, Edmond area, central Oklahoma: Shale Shaker Digest, v. 16, p. 338-350.

Berger, Zeev, 1986, New technique for structural analysis of low-relief basins: Amer. Assoc. Petroleum Geologists Bull., v. 70, no. 5, p. 564.

Berger, Zeev, 1988, Detection and analysis of basement structures in low-relief basins using integrated analysis of Landsat data: Proceedings, Sixth Thematic Conference on Remote Sensing for Exploration Geology, Environmental Research Inst. of Michigan, v. 1, p. 111.

Bingham, R. H., and Bergman, D. L., 1980, Reconnaissance of the water resources of the Enid quadrangle, north-central Oklahoma: Okla. Geol. Survey Map HA-7.

Bingham, R. H., and Moore, R. L., 1975, Reconnaissance of the water resources of the Oklahoma City quadrangle, central Oklahoma: Okla. Geol. Survey Map HA-4.

Blanchet, P. H., 1957, Development of fracture analysis as an exploration method: Amer. Assoc. Petroleum Geologists Bull., v. 41, no. 8, p. 1748-1759.

Bogli, Alfred, 1980, Karst hydrology and physical speleology: Springer-Verlag, 284 p.

Brasier, Francoise, 1987, Injection of hazardous wastes: EPA overview, in Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes, New Orleans, La., U. S. Nat. Water Well Assoc., p. 1-2.

Brown, H. A., 1967, Structural control of Canadian River in western Oklahoma: Okla. Geol. Survey, Okla. Geology Notes, v. 27, p. 135-149.

Brown, R. O., and Forgotson, J. M., Jr., 1980, Predicting the orientation of hydraulically created fractures in the Cotton Valley Formation of East Texas: Soc. Petroleum Engineers, AIME, SPE 9269, 12 p.

Bruce, L. G., 1989, A method for predicting fracture-enhanced permeability in regions of "flat-lying" strata (draft): Unpub. Doctor of Philosophy dissertation, Okla. State Univ.

Burchfield, M. R., 1985, Map of Oklahoma oil and gas fields: Okla. Geol. Survey Map GM-28

Cardott, B. J., and Lambert, M. W., 1987, Thermal maturation by vitrinite reflectance of Woodford Shale, Anadarko Basin, Oklahoma: Amer. Assoc. Petroleum Geologists Bull., v. 71, no. 7, p. 898-899.

Carr, J. E., and Havens, J. S., 1976, Records of wells and water quality for the Garber-Wellington aquifer, northern Oklahoma and southern Logan Counties, Oklahoma: U. S. Geol. Survey open-file report 76-619, 32 p.

Carr, J. E., and Marcher, M. V., 1977, A preliminary appraisal of the Garber-Wellington aquifer, southern Logan and northern Oklahoma Counties, Oklahoma: U. S. Geol. Survey open-file report 77-278, 23 p.

Caylor, J. W., 1957, Surface geology of western Garfield County, Oklahoma: Unpub. Master of Science thesis, Univ. of Okla., 78 p.

Christenson, S. C., and Parkhurst, D. L., 1987, Ground-water quality-assessment of the central Oklahoma aquifer, Oklahoma: project description: U. S. Geological Survey open-file report 87-235, 30 p.

Clark, L. H., 1983, Briefing and policy review: Underground injection of hazardous waste (draft): U. S. Environ. Protect. Agency.

Clemons, R. R., 1984, The remote sensor exploration of the Ardmore and Marietta basins of Oklahoma: Unpub. Doctor of Philosophy dissertation, Texas Tech Univ., 452 p.

Cooley, M. E., 1986, Divisions of potential fracture permeability, based on distribution of structures and lineaments in sedimentary rocks of the Rocky Mountains-High Plains region, western United States: U. S. Geol. Survey Water-resources Investigation Rept. No. WRI 85-4091.

Cox, J. C., and Harrison, S. S., 1979, Fracture-trace influenced stream orientation in glacial drift -- northwestern Pennsylvania: Can. Jour. Earth Sci., v. 16, no. 7, p. 1511-1514.

Dennis, P. E., 1954, Water-loss investigations: Lake Hefner studies, technical report: U. S. Geol. Survey Prof. Paper 269, p. 10-16.

Dickey, P. A., 1979, Petroleum development geology: Petroleum Publishing Co., 398 p.

Dix, O. R., and Jackson, M. P. A., 1981, Statistical analysis of lineaments and their relation to fracturing, faulting, and halokinesis in the East Texas Basin: Bureau Econ. Geol., Univ. Texas at Austin, Rept. Investigations No. 110, 30 p.

Dolan, R., and Howard, A., 1978, Structural control of the rapids and pools of the Colorado River in the Grand Canyon: Science, v. 202, p. 629-631.

Elkins, L. F., 1969, Internal anatomy of a tight, fractured Hunton Lime reservoir revealed by performance -- West Edmond Field: Jour. Petroleum Tech., Feb., p. 221-232.

Eliason, J. R., 1984, A technique for structural geologic analysis of topography (digital, Idaho, Oregon, Washington):

Unpub. Doctor of Philosophy dissertation, Washington State University, 196 p.

Evans, D. M., 1966, Man-made earthquakes in Denver: Geotimes, v. 10, no. 9, p. 11-18.

Feder, A. M., 1984, Contemporary remote sensing for hydrocarbon exploration and development: Oil and Gas Jour., v. 82, pt. 9, p. 150-151.

Flanagan, K. D., 1989, Selected attributes of confining beds, Burbank oil field and nearby areas, north-central Oklahoma: Unpub. Master of Science thesis (draft), Okla. State Univ., 114 p.

Gillert, M. P., 1952, The geology of the Simpson Group on the northeast flank of the Arbuckle Mountains, Oklahoma: Unpub. Master of Science thesis, Univ. of Okla., 76 p.

Gordon, Wendy, and Bloom, Jane, 1987, Deeper problems: Limits to underground injection as a hazardous waste disposal method: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes, New Orleans, La., U. S. Nat. Water Well Assoc., p. 3-50.

Graham, L. L., and others, 1985, Protection of public water supplies from ground-water contamination: U. S. Envir. Prot. Agency Seminar Pub., EPA/625/4-85/016, 182 p.

Hagen, K. B., 1972, Mapping of surface joints on air photos can help understand waterflood performance problems at North Burbank Unit: Unpub. Master of Science thesis, Univ. of Tulsa, 77 p.

Ham, W. E., 1969, Regional geology of the Arbuckle Mountains, Oklahoma: Okla. Geol. Survey, Guidebook 17, 52 p.

Harris, S. A., 1970, Bends of the South Canadian River of Oklahoma as related to regional geomorphology: Shale Shaker Digest, v. 6, p. 160-175.

Harris, S. A., 1975, Hydrocarbon accumulation in the "Meramec-Osage" (Mississippian) rocks, Sooner Trend, northwest-central Oklahoma: Amer. Assoc. Petroleum Geologists Bull., v. 59, no. 4, p. 633-664.

Harvey, R. L., 1972, West Campbell (Northeast Cedardale) gas field, Major County, Oklahoma: Amer. Assoc. Petroleum Geologists Mem. 16, p. 568-578.

Hendricks, T. A., 1937, Geology and fuel resources of the southern part of the Oklahoma Coal Field; Part 1, the McAlester District: U. S. Geol. Survey Bull. 874-A, 90 p.

Hyatt, D. L., 1936, Preliminary report on the Fitts Pool, Pontotoc County, Oklahoma: Amer. Assoc. Petroleum Geologists Bull., v. 20, p. 951-974.

Jennings, J. N., 1985, Karst geomorphology: Basil Blackwell, Inc., New York, 293 p.

Johnson, K. S., 1969, Mineral map of Oklahoma, exclusive of oil and gas fields: Okla. Geol. Survey, Map GM-15.

Johnson, K. S., Burchfield, M. R., and Harrison, W. E., 1984, Guidebook for Arbuckle Mountain field trip, southern Oklahoma: Okla. Geol. Survey Special Publ. 84-1, 21 p.

Jordan, Louise, 1962, Geologic map and section of pre-Pennsylvanian rocks in Oklahoma, showing surface and subsurface distribution; Okla. Geol. Survey, Map GM-5.

Judson, S. and Andrews, G., 1955, Pattern and form of some valleys in the Driftless Area, Wisconsin: Jour. Geol., v. 63, p. 328-336.

Kennedy, L. G., 1989, Confining layer study in the West Edmond oil field area, using subsurface, remote sensing and geochemical methods: Unpub. Master of Science thesis (draft), Okla. State Univ., 173 p.

Knepper, D. H., 1987, Remote-sensing studies of the Anadarko Basin: Okla. Geol. Survey, Okla. Geology Notes, v. 47, no. 3, p. 117.

Komar, C. A., Such, L. Z., Overbey, W. K., Jr., and Anderson, T. O., 1973, Delineating a subsurface fracture system in a petroleum reservoir -- an experiment: Jour. Petroleum Tech., v. 25, p. 531-537.

Kreitler, C. W., 1985, Hydrogeology of sedimentary basins as it relates to deep-well injection of chemical wastes: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes, New Orleans, La., U. S. National Water Well Association, p. 398-416.

Kuhleman, J. H., 1951, Mississippian and Lower Pennsylvanian stratigraphy of portions of Stonewall and Atoka quadrangles, Oklahoma: Tulsa Geol. Soc. Digest, v. 19, p. 192-213.

Lattman, L. H., 1958, Technique of mapping geologic fracture traces and lineaments on aerial photographs: Photogrammetric Engineering, v. 24, no. 4, p. 568-576.

Lattman, L. H., and Parizek, R. R., 1964, Relationship between fracture traces and the occurrence of groundwater in carbonate rocks: Jour. Hydrology, v. 2, no. 2, p. 73-91.

Lawson, J. E., and Luza, K. V., 1988, Oklahoma earthquakes, 1987: Okla. Geol. Survey, Okla. Geol. Notes, v. 48, no. 1, p. 54-63.

Lillesand, T. M., and Kiefer, R. W., 1987, Remote sensing and image interpretation: John Wiley and Sons, 612 p.

Low, J. W., 1957, Geologic field methods: Harper and Brothers, 489 p.

Luza, K. V., and Lawson, J. E., Jr., 1979, Seismicity and tectonic relationships of the Nemaha Uplift in Oklahoma: U.S. Nuclear Regulatory Commission, NUREG/CR-0500, 66 p.

Luza, K. V., 1981, Seismicity and tectonic relationships of the Nemaha Uplift in Oklahoma; Part III: U.S. Nuclear Regulatory Commission, NUREG/CR-1500, 70 p.

McGee, D. A., and Jenkins, H. D., 1946, West Edmond oil field, central Oklahoma: Amer. Assoc. Petroleum Geologists Bull., v. 30, no. 11, p. 1797-1829.

Maarouf, A. M. S., 1981, Morphostructural analyses of space imagery in the central Colorado Plateau: Unpub. Doctor of Philosophy dissertation, University of Utah, 130 p.

Mann, Wallace, 1957, Subsurface geology of the Franks graben, Pontotoc and Coal Counties, Oklahoma: Unpub. Master of Science thesis, Univ. of Okla., 62 p.

Manni, F. M., 1985, Depositional environment, diagenesis, and unconformity identification of the Chimneyhill Subgroup in the western Anadarko Basin and Northern Shelf of Oklahoma: Unpub. Master of Science thesis, Okla. State Univ., 133 p.

Melton, F. A., 1929, A reconnaissance of the joint-systems in the Ouachita Mountains and central plains of Oklahoma: Jour. Geology, v. 37, p. 729-746.

Melton, F. A., 1955, Photo-geology in flatland regions of low dip: Shale Shaker, v. 6, no. 3, p. 5-8, 11-12, 15-20, 39.

Melton, F. A., 1959, Aerial photographs and structural geomorphology: Jour. Geology, v. 67, no. 4, p. 351-370.

Miser, H. D., 1954, Geologic map of Oklahoma: Okla. Geol. Survey.

Morgan, G. D., 1924, Geology of the Stonewall quadrangle: Okla. Bureau of Geology Bull. 2, 248 p.

Morgan, G. D., 1924, Boggy unconformity and overlap in southern Oklahoma: Okla. Bureau of Geology Circ. 2, 8 p.

Morton, R. B., 1981, Reconnaissance of the water resources of the Woodward quadrangle, northwestern Oklahoma: Oklahoma Geol. Survey Map HA-8.

Naff, J. D., 1962, Geology and paleontology of the upper Boggy drainage area, Coal and Pontotoc Counties, Oklahoma: Unpub. Doctor of Philosophy dissertation, Univ. of Kansas, 470 p.

Nelson, R. A., 1975, Fracture permeability in porous reservoirs: An experimental and field approach: Unpub. Doctor of Philosophy dissertation, Texas A & M Univ., 171 p.

Nelson, R. A., 1985, Geologic analysis of naturally fractured reservoirs: Gulf Publishing Co., 320 p.

Okonny, I. P., 1981, Geologic analysis of remote sensing imagery of the eastern Niger delta, Nigeria: Unpub. Doctor of Philosophy dissertation, Purdue Univ., 294 p.

O'Leary, D. W., Friedman, J. D., and Pohn, H. A., 1976, Lineament, linear, lineation: Some proposed new standards for old terms: Geol. Soc. America Bull., v. 87, no. 10, p. 1463-1469.

Paine, J. W., 1958, Subsurface geology of T. 4 N., R. 4 and 5 E., Pontotoc County, Oklahoma: Unpub. Master of Science thesis, Univ. of Okla., 46 p.

Parizek, R. R., 1975, On the nature and significance of fracture traces and lineaments in carbonate and other terranes, in Karst hydrology and water resources, v. 1: Proceedings of the U. S.-Yugoslavian Symposium, Dubrovnik, p. 3-1 - 3-62.

Peters, D. C., Speirer, R. A., and Shea, V. R., 1988, Lineament analysis for hazard assessment in advance of coal mining: Proceedings, Sixth Thematic Conference on Remote

Sensing for Exploration Geology, Environmental Research Inst. Of Michigan, v. 1, p. 253-260.

Pittman, E. D., 1981, Effect of fault-related granulation on porosity and permeability of quartz sandstones, Simpson Group (Ordovician), Oklahoma: Amer. Assoc. Petroleum Geologists Bull., v. 65, no. 11, p. 2381-2387.

Podwysocki, M. H., Moik, J. G., and Shoup, W. C., 1975, Quantification of geologic lineaments by manual and machine processing techniques, in NASA Earth Resources Survey Symposium: Volume 1-B, Geology, information systems and services: Nat. Aeronautics and Space Admin., NASA-TM-X-58168, v. 1-B, p. 885-903.

Probst, G. L., 1988, Predicting subsurface joint trends in undeformed strata: Proceedings, Sixth Thematic conference on Remote Sensing for Exploration Geology, Environmental Research Inst. of Michigan, v. 2, p. 423-436.

Puckette, J. O., 1989, Evaluation of confining-bed integrity, Pontotoc County, Oklahoma: Unpub. report, School of geology, Okla. State Univ., 33 p.

Rausch, R. W., and Beaver, K. W., 1964, Case history of successfully water flooding a fractured sandstone reservoir: Jour. Petroleum Tech., v. 16, p. 1233-1237.

Ray, R. G., 1960, Aerial photographs in geologic interpretation and mapping: U. S. Geol. Survey Prof. Paper 373, 230 p.

Richason, B. F., Jr., ed., 1978, Introduction to remote sensing of the environment: Second edition, Kendall-Hunt Pub. Co., Dubuque, Iowa, 582 p.

Sabins, F. F., Jr., 1978, Remote sensing, principles and interpretation: : W.H. Freeman and Co., 426 p.

Schridder, L. A., Watts, R. J., and Wasson, J. A., 1970, An evaluation of the East Canton oil field waterflood: Jour. Petroleum Tech., v. 22, p. 1371-1378.

Shelton, J. W., Ross, J. S., Garden, A. J., and Franks, J. L., 1985, Geology and mineral resources of Payne County, Oklahoma: Okla. Geol. Survey bull. 137, 85 p.

Shoup, R. C., 1980, Correlation of Landsat lineaments with geologic structures, north-central Oklahoma: Unpub. Master of Science thesis, Univ. of Okla., 106 p.

Stearns, D. W., Berger, Zeev, Hopkins, H. R., and Nelson, R. A., 1988, The contribution of remote sensing data to exploration of fractured reservoirs: Proceedings, Sixth Thematic Conference on Remote Sensing for Exploration Geology: Environmental Research Inst. of Michigan, v. 1, p. 113-122.

Stohl, L. P., 1988, Photogeologic-geomorphic mapping provides clues to structural features beneath glacial terrain: Proceedings, Sixth Thematic Conference on Remote Sensing for Exploration Geology, Environmental Research Inst. of Michigan, v. 1, p. 373-382.

Swesnik, R. M., 1948, Geology of West Edmond oil field, Oklahoma, Logan, Canadian, and Kingfisher Counties, Oklahoma: Amer. Assoc. Petroleum Geologists, Structure of Typical American Oil Fields, A Symposium, v. 3, p. 359-398.

Sullivan, K. L., 1985, Organic facies variation of the Woodford Shale in western Oklahoma: Shale Shaker, v. 35, no.4, p. 76-89.

Thomas, E. P., 1986, Understanding fractured oil reservoirs: Oil and Gas Jour., v. 84, pt. 7, p. 75-79.

Thornbury, W. D., 1956, Principles of geomorphology: John Wiley & Sons, Inc., 618 p.

Thornhill, M. R., 1989, Lineaments and fracture traces, eastern Pontotoc County, Oklahoma (draft): Unpub. Master of Science thesis, Okla. State Univ., 126 p.

Tillman, J. E., 1983, Exploration for reservoirs with fracture-enhanced permeability: Oil and Gas Jour., v. 81, pt. 2, p. 165-179.

Trantham, J. C., Threlkeld, C. B., and Patterson, H. L., Jr., 1980, Reservoir description for a surfactant/polymer pilot in a fractured, oil-wet reservoir - North burbank Unit Tract 97: Jour. Petroleum Tech., v. 32, p. 1647-1656.

Walsh, S. J., and Mynar, F., II, 1985, Comparison of Landsat digital enhancement techniques for lineament detection: Geol. Soc. America, 98th Ann. Mtng., Abstracts with Programs, p. 743.

Warner, D. L., Davis, S. N., and Syed, Talib, 1986, Evaluation of confining layers for containment of injected wastewater: Proceedings of International Symposium on Subsurface Injection of Liquid Wastes, New Orleans, La., U. S. Nat. Water Well Assoc., p. 417-446.

Watson, D. F., and Philip, G. M., 1987, Neighborhood-based interpolation: Amer. Assoc. Petroleum Geologists, Geobyte, v. 2, no. 2, p. 12-16.

Watts, K. R., 1977, Assessment of Landsat imagery for the investigation of fracturing in an unconfined chert and carbonate aquifer: Unpub. Master of Science thesis, Okla. State Univ., 85 p.

Weber, N. V., 1974, A quantitative analysis of the relationship between geologic structure and drainage line orientation in a neotectonic region: Dept. of Geology and Geography, Indiana State Univ., Prof. Paper No. 6, p. 41-55.

Whiteside, R. F., and Raef, S. F., 1986, Mechanical integrity of Class 1 injection wells: Proceedings of International Symposium on Subsurface Injection of Liquid Wastes, New Orleans, La., U. S. Nat. Water Well Assoc., p. 57-76.

Wilkinson, W. M., 1977, Fracturing in Spraberry reservoir, West Texas, in Kostura, J. and Ravenscroft, J., ed., Fracture-controlled production: Amer. Assoc. Petroleum Geologists Reprint No. 21, p. 40-55.

Withrow, P. C., 1972, Star-Lacey Field, Blaine and Kingfisher Counties, Oklahoma: Amer. Assoc. Petroleum Geologists Mem. 16, p. 520-531.

Wood, P. R., and Burton, L. C., 1968, Ground-water resources in Cleveland and Oklahoma Counties: Okla. Geol. Survey Circular 71, 75 p.

Woodruff, J. and Parizek, E. J., 1956, Influence of underlying rock structures on stream courses and valley profiles in the Georgia Piedmont: Assoc. Amer. Geogr. Annals, v. 46, p. 129-139.

Woodruff, J. D., Talley, J. H., and Miller, J. C., 1974, Selection sites for high yielding wells in the Delaware Piedment: Geol. Soc. America, Northeastern Section, Abstracts with Programs, p. 87.

Zall, L. and Russell, O., 1979, Ground water exploration programs in Africa: Proceedings, 5th Ann. William T. Pecora Memorial Symposium on Remote Sensing, p. 416-425.

☆ U S GOVERNMENT PRINTING OFFICE 1989 - 648-163/00330