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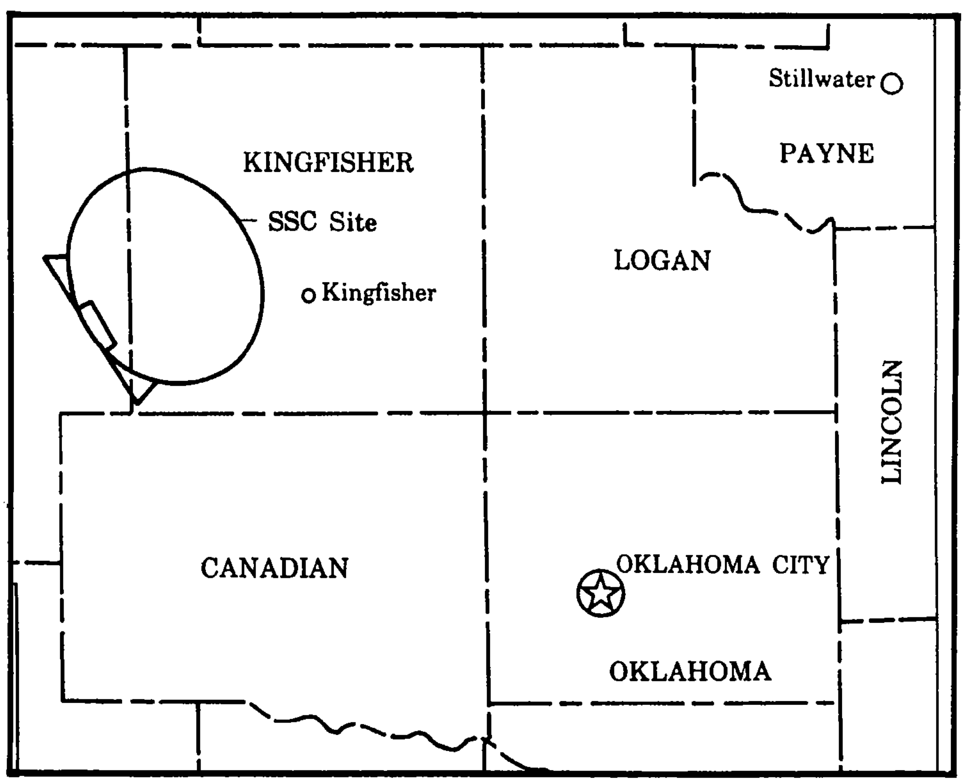
Selection and Geology of Oklahoma's Superconducting Super Collider Site

Kenneth V. Luza and others



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SELECTION AND GEOLOGY OF OKLAHOMA'S SUPERCONDUCTING SUPER COLLIDER SITE

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The chapter on the geology of the Kingfisher site is reproduced, with minor modification, from Oklahoma's Superconducting Super Collider site proposal, submitted by the State of Oklahoma. This information appeared in Appendix A of volume 3, Geology and Tunneling.

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ABSTRACT

The Oklahoma Geological Survey (OGS) developed preliminary exclusionary criteria for a statewide assessment of possible Superconducting Super Collider (SSC) sites in May 1987. Areas excluded from further consideration were those which contained complex geologic terrain, bedrock and alluvial aquifers and their known recharge areas, major alluvial deposits, and those too small to accommodate the SSC oval and associated facilities. This process identified 30 candidate sites located within 13 study zones. These sites were reexamined using three additional geotechnical criteria: potential for rock dissolution, proximity to active faults, and fuel and non-fuel resource development. The statewide study identified 18 possible SSC sites located in eight study zones.

Twelve sites were selected for detailed analysis. These were selected because of their close proximity to major metropolitan centers, airport and transportation facilities, and comprehensive universities. Three site-selection matrices compared topography, lithology, structure, hydrology, resources, seismicity, and site flexibility for each site. The top two sites became the preferred sites, the next two were less preferred, and the other eight were eliminated.

The Benham Group ranked the geotechnically rated top four sites, using natural, environmental, and cultural factors such as regional setting, oil- and gas-well density, urban congestion, regional conditions, utilities, regional and cultural resources and amenities, environmental obstacles, and flood-prone areas. The top geotechnical site, Kingfisher, also ranked highest using these criteria. The Kingfisher site was approved by the Oklahoma SSC Commission as the best qualified site. Oklahoma proposed this site to the U.S. Department of Energy (DOE) for the SSC.

The bedrock geology of the Kingfisher site consists of about 1,900 ft of Permian red beds composed mostly of mudstone, shale, and siltstone. Most of the ring will be excavated in strata of the El Reno Group, which is about 700 ft thick in this area; the remainder will be excavated in the upper part of the Hennessey Group. The structure of the bedrock at the SSC site is a very gently southwest-dipping (less than 1°) homocline. There are no mapped or recognized faults in the area. Most units are typically massive, but locally fractured, jointed, and weathered in outcrop.

The Kingfisher site is located between two major southeast-flowing rivers, the North Canadian River on the southwest, and the Cimarron River on the northeast. The elevation of the Cimarron River is about 1,050 ft above sea level in western Kingfisher County, and the North Canadian River is about 1,500 ft above sea level in eastern Blaine County. A cuesta, commonly known as the Blaine escarpment, parallels the North Canadian River on its northeast side in Blaine and Kingfisher Counties. This escarpment is formed by resistant gypsum and dolomite beds of the Blaine Formation, and supports a line of northwest-trending hills that stand 500-600 ft above the Cimarron River. A high Pleistocene terrace along the southwest side of the Blaine escarpment forms a divide that extends from southeast to northwest. From this drainage divide, streams generally flow northeast across the gently sloping topography of the site. The two major streams at the Oklahoma SSC site are Cooper Creek to the north and Kingfisher Creek to the south.

A sequence of evaporite rocks (the Wellington evaporites), composed of interbedded shale, anhydrite, and salt, occurs deep beneath the proposed SSC site. The shallowest evaporites range in depth from 1,500 to 2,400 ft below land surface in the vicinity of the site. The main evaporite sequence, called the lower salt-anhydrite unit, ranges from 820 ft thick in the northwest to about 620 ft thick in the east. The upper part of the lower salt-anhydrite unit contains layers of rock salt and is referred to as the Hutchinson salt; the lower part of the lower salt-anhydrite unit is devoid of salt in Oklahoma. The Hutchinson salt is as much as 520 ft of interbedded shale, salt, and anhydrite about 10 mi west of the SSC site, but the salt layers grade laterally into shale toward the east and constitute only a small amount of the Hutchinson unit beneath the SSC site. There is no evidence that any of the salt layers in the Hutchinson have been affected by dissolution. The eastward thinning and disappearance of individual salt beds beneath the SSC site are a result of depositional change in the Permian, rather than salt dissolution.

The SSC site lies between major petroleum-producing areas in central Oklahoma, with the Sooner trend to the north and east, the West Edmond field to the southeast, and the Watonga-Chickasha trend to the west. The uppermost of the principal pay zones is within the Marmaton Group, which occurs below 5,800 ft in the site area. The SSC site is located in a mature producing region with limited remaining production. Production rates in the area are generally low. Reservoir pressures are typically low, thus reducing the probability of upward migration of hydrocarbons. The 2,400 ft of overlying Permian shales and evaporites further reduces that probability. No subsidence above oil and gas fields has been identified in Oklahoma, in spite of a 96-yr history of petroleum production.

The historical and instrumental earthquake records indicate that the Kingfisher site is one of low seismic activity. Maximum-magnitude events within the Oklahoma Geological Survey seismic source zones for various time periods were estimated from the spatial and temporal pattern of historical seismicity. The site-specific maximum horizontal ground acceleration for the Oklahoma SSC is about 0.04 g for a 50-yr period, and 0.08 g for a 250-yr period. From a USGS study, the 90-yr site horizontal acceleration is <0.04 g, and the 475-yr site horizontal acceleration is about 0.05 g. The OGS and USGS studies show the site to be one of low expected ground shaking, over the Oklahoma SSC facility lifetime.

The closest known active fault, Meers fault, is 75 mi southwest of the SSC site. Quaternary stratigraphic relationships and ^{14}C age dates constrain the age of the last movement between 1,600 and 800 yr B.P. Although the last movement on this fault is recent, the recurrence interval may exceed several thousands of years.

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SITE SELECTION

INTRODUCTION

In April 1987, the U.S. Department of Energy (DOE) invited States and others to submit a proposal for the land necessary for the U.S. Government to build and operate the world's largest and most advanced particle accelerator. In addition to the land, other contributions were sought to defray the construction and operational costs.

The particle accelerator, Superconducting Super Collider (SSC), will enable physicists to conduct more advanced high energy particle physics research. Similar research has proven beneficial to society in the areas of science, technology, and education. The SSC facility consists of a 53-mi-long racetrack-shaped tunnel with a 10-ft inside diameter (Fig. 1). Other structures on a campus-like setting include four large interaction halls for the conduction of experiments, a series of injector accelerators, and several support buildings. Approximately 10,000 superconducting magnets focus and guide two beams of protons in opposite directions around the tunnel. The beams are accelerated to nearly the speed of light and made to collide head-on with an energy of 40 trillion electron volts. The detection and analyses of the collisions are expected to lead to the discovery of new subatomic particles, thus adding to our understanding of the fundamental nature of matter and energy.

To evaluate the proposals of land received in response to the DOE invitation, support information related to a number of factors was required. Some of these factors included topography and geology of the proposed site, the type of estates and land offered to the Government, utility availability, and the physical and socioeconomic environment of the site and its vicinity. Resources such as schools, housing, and transportation fall under the latter category.

The Oklahoma proposal was submitted to DOE on September 2, 1987. The DOE initially reviewed 43 proposals from the various states to determine whether they were qualified for further consideration. Thirty-six proposals met DOE's qualification criteria. The National Academy of Sciences (NAS) and National Academy of Engineering (NAE) appointed a committee to carry out more detailed analyses of the remaining 36 proposals, using the technical evaluation criteria and cost considerations established by DOE. NAS/NAE then recommended the following eight site proposals that they believed to be the best qualified: Arizona/Maricopa, Colorado, Illinois, Michigan/Stockbridge, New York/Rochester, North Carolina, Tennessee, and Texas/Dallas-Fort Worth. The State of New York withdrew their site from further consideration. The NAS/NAE report was

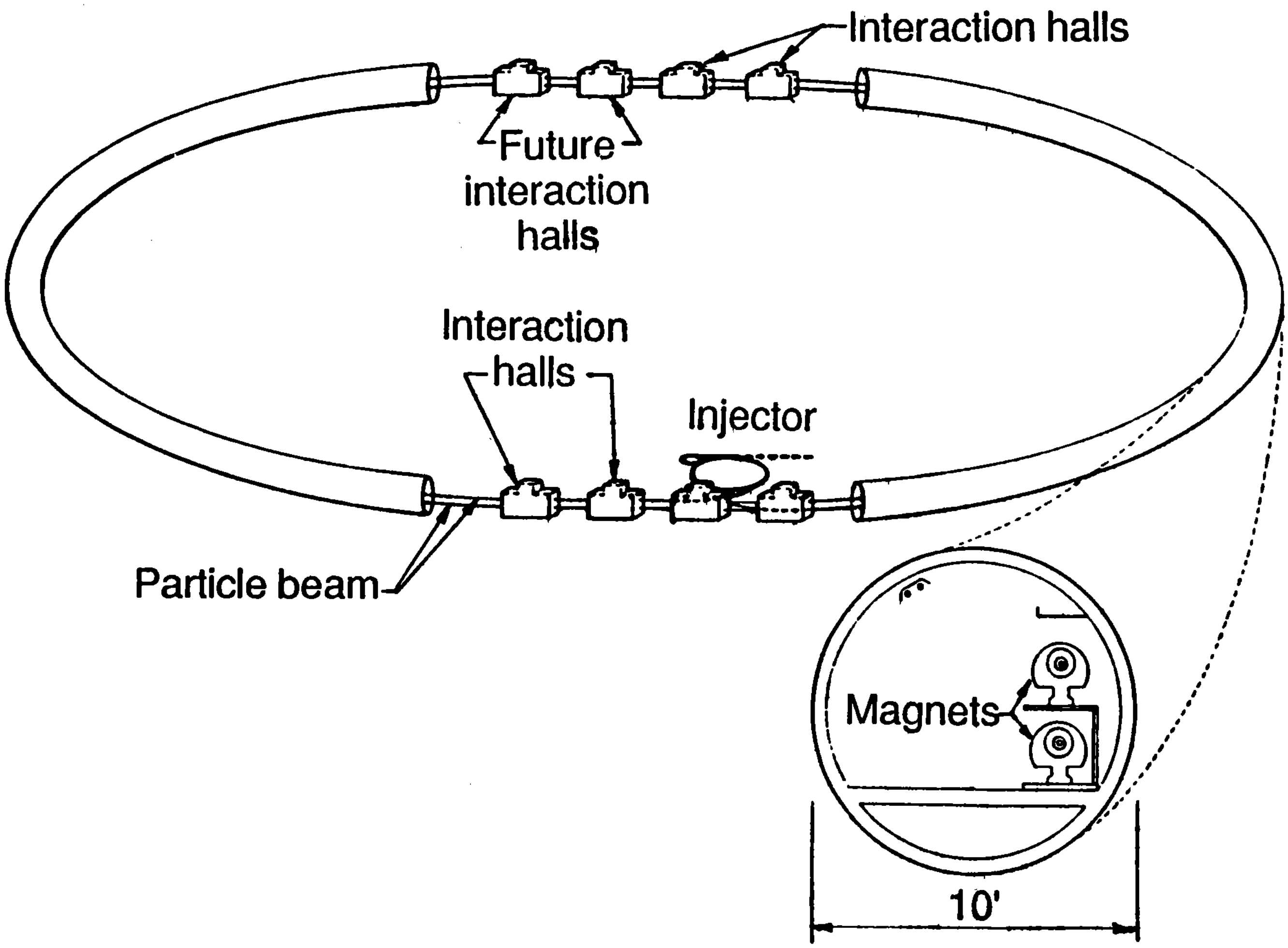


Figure 1. Schematic diagram of the SSC facility.

reviewed and accepted by DOE. After further analyses by DOE, the Texas/Dallas-Fort Worth site was selected as the preferred site in November 1988.

STATEWIDE EXAMINATION

In late April 1987, the Governor of the State of Oklahoma issued a request to the Oklahoma Geological Survey (OGS) to select a site suitable for the SSC by late May or early June. The SSC siting parameters presented by the SSC Central Design Group (1986) and DOE's Invitation for Site Proposals (1987) were used as a basis for developing preliminary exclusionary criteria.

General rock characteristics, ground water conditions, and geologic structure were the principal factors used to initially screen potential sites. The SSC probably could not be constructed without unusual problems and costs in areas meeting any of the following five primary exclusionary criteria:

1) Within or above bedrock aquifers or their known recharge areas.

2) Within or below alluvial or terrace deposits that are major or principal aquifers, or are potentially favorable or moderately favorable for development of ground-water supplies.

3) Within or below alluvial deposits or water courses on the main stem of the 11 major rivers of Oklahoma: Red River, Salt Fork Red River, North Fork Red River, Washita River, Canadian River, North Canadian River, Cimarron River, Arkansas River, Salt Fork Arkansas River, Verdigris River, and Neosho River.

4) Beneath any portion of lakes and reservoirs located on the 11 major rivers of Oklahoma, including those portions of the same lakes and reservoirs that extend up rivers and streams that are tributary to the 11 major rivers.

5) Within the three major mountain systems of Oklahoma (Ouachita, Arbuckle, and Wichita Mountains) because of the presence of complex structures (faults, folds, and/or fracture systems) and the sharp contrast in rock types that would be encountered in tunnelling/excavation. These three areas generally lack the relatively uniform and stable geological properties that are desirable to permit large contiguous segments of a tunnel to be built using a common construction.

Oklahoma Geological Survey's Hydrologic Atlases 1 through 9, Sheet 2 (Marcher, 1969; Marcher and Bingham, 1971; Hart, Jr., 1974; Bingham and Moore, 1975; Carr and Bergman, 1976; Havens, 1977; Bingham and Bergman, 1980; Morton, 1981; Marcher and Bergman, 1983), USGS Hydrologic Investigations Atlases 250, 373, and 450 (Wood and Hart, Jr., 1973; Sapik and Goemaat, 1973; Morton, and Goemaat, 1973), and maps showing the principal ground-water resources and recharge areas in Oklahoma (Johnson, 1983) were used in the preliminary exclusion of areas in Oklahoma. The alluvial deposits and water courses of the 11 major rivers of Oklahoma and major mountain systems of Oklahoma were identified from information found on Sheet 1, OGS Hydrologic Atlases 1 through 9.

Complex geologic terrain, bedrock aquifers or their known recharge areas, and the alluvial deposits associated with the 11 major rivers in Oklahoma were posted on 1:250,000-scale AMS topographic base maps. These areas were excluded from further consideration. Furthermore, any area that could not accommodate an oval that has the shape and dimensions of the proposed SSC was also eliminated.

Thirteen preliminary study zones remained after the initial statewide examination (Fig. 2). These zones were identified and named for either their geographic location or their relationship to a geologic province. Within the 13 study zones, approximately 30 sites could accommodate a SSC facility.

Three additional geotechnical criteria were then applied to the 13 study zones to assess their suitability for a SSC site. These three criteria were as follows:

1) Any area prone to settlement due to rock dissolution and collapse and characterized as being karstic. This included those areas where soluble rock (such as limestone, dolomite, gypsum, and rock salt) crop out or are located within 50 ft of the present land surface (300 ft in the case of rock salt) and are known to contain karstic features such as caves, caverns, and sinkholes.

2) Any area that is near faults that are known to be, or suspected to have been, active in the past 10,000 years.

3) Any area known to have very large hydrocarbon production (past and/or present) and non-fuel resources.

The preliminary study zones were reexamined using the above criteria. Five study zones contained one or more elements of the additional criteria and, therefore, were excluded from further consideration. These areas include the Anadarko basin, Hollis basin, Arkoma basin, Wichita A, and Wichita B. The Anadarko basin, Hollis basin, Arkoma basin, and Wichita B study zones are areas of intense oil and gas drilling and production activity. The Hollis basin and Anadarko basin zones are prone to settlement due to rock dissolution and collapse. The Wichita A and B zones are in close proximity to the Meers fault, a known active fault.

The statewide study, which used all geotechnical criteria, identified eight study zones suitable for further examination. These study zones were Central A, Central B, East Central, Ozark, Arbuckle, Northeastern Shelf A, Northeastern Shelf B, and North Central (Fig. 3). These eight study zones contained 18 possible sites for a SSC facility.

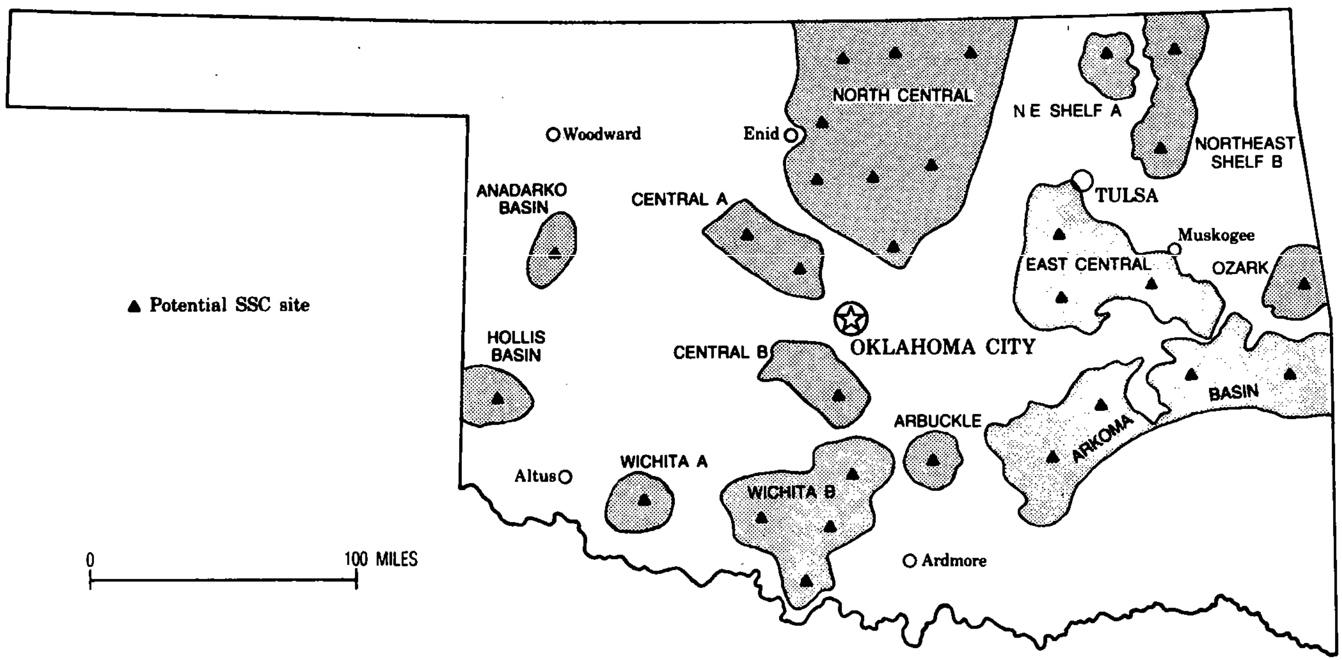


Figure 2. Preliminary study zones that remained after the initial state-wide examination.

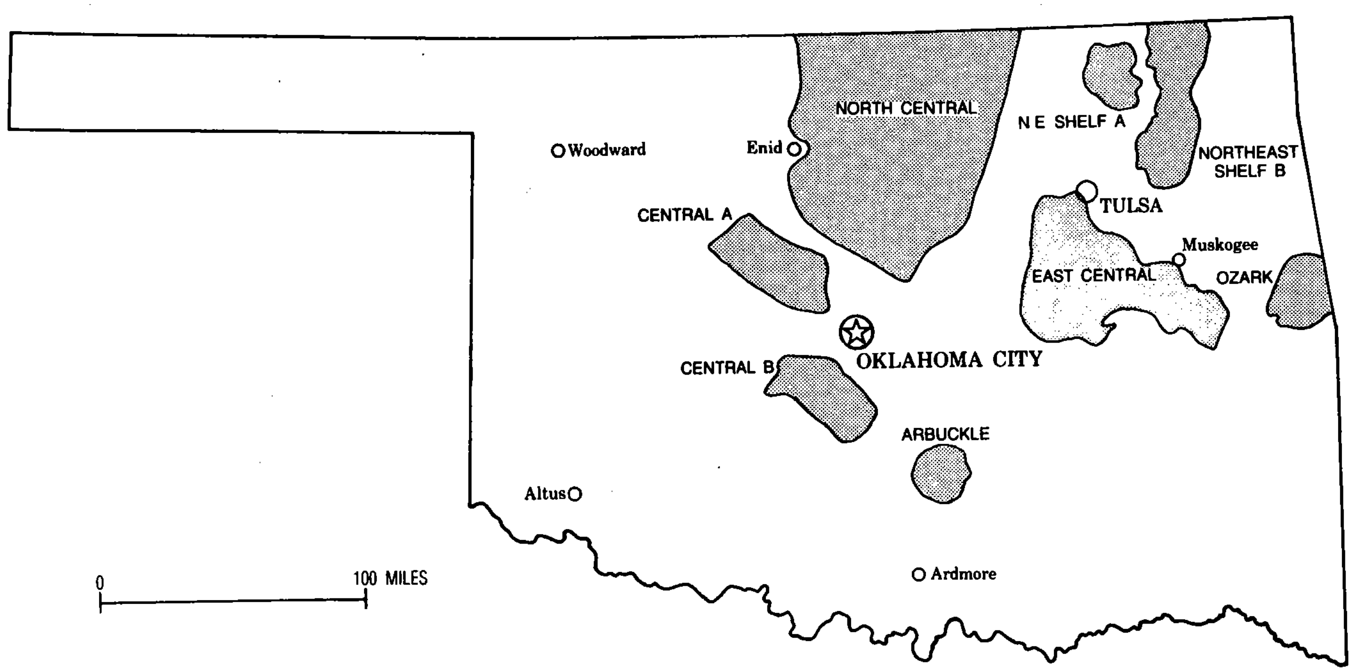


Figure 3. Final study zones suitable for further examination.

SITE EVALUATION

Twelve sites located in six study zones (Fig. 4) were targeted for detailed analysis. These sites were selected because of their close proximity to major metropolitan centers, airport and transportation facilities, and comprehensive universities. If a suitable site could not be found in one of the six study zones, the remaining sites in the North Central, Ozark, and Arbuckle study zones would be evaluated for a candidate SSC site.

The Oklahoma Geological Survey was responsible for the evaluation of the geotechnical conditions for each site. The Benham Group examined the regional resources, environment, regional setting, regional conditions, and utilities for each site. Engineering Enterprises, Inc., assisted the OGS with the evaluation of the geohydrologic conditions for each site. A series of matrices, which contained geotechnical criteria, were used to rank candidate sites. The Benham Group used a similar process to evaluate the non-geotechnical criteria for each site. A composite matrix, which included geotechnical and non-geotechnical factors, was constructed for the top four sites. The site that received the highest total became the best qualified site among the sites evaluated.

Six geotechnical criteria were used to evaluate each site. These criteria included topography, lithology, structure, ground water, fuel resources, and non-fuel resources. Generally sites that were nearly flat or gently sloping were rated higher than sites with irregular surfaces and moderate to high relief. Sites with low relief would allow much of the ring construction to be done by cut and cover techniques which may be a cost advantage over sites that use only tunneling-machine methods.

Lithology, which is the general bedrock characteristics, includes rock types, rock distribution, and rock thicknesses. Sites that contained uniform rock types with similar rock properties were rated higher than sites that contained multiple rock types with variable rock properties. For construction purposes, relatively uniform and stable geological properties are desirable to permit large contiguous segments of the tunnel to be built using a common construction methodology.

Structure included features such as faults, folds, shear zones, and joints. These features could present difficult tunneling, excavation, and foundation conditions and should be avoided. Therefore, sites that contained any of these known structural elements were given a less favorable rating.

Ground water may pose significant underground construction problems if the tunnel traverses water-bearing zones. Excavation through great lengths of water-bearing zones could be time-consuming and costly. Sites that contained rock units that have water-bearing units within the vicinity of the collider ring were considered less desirable. John

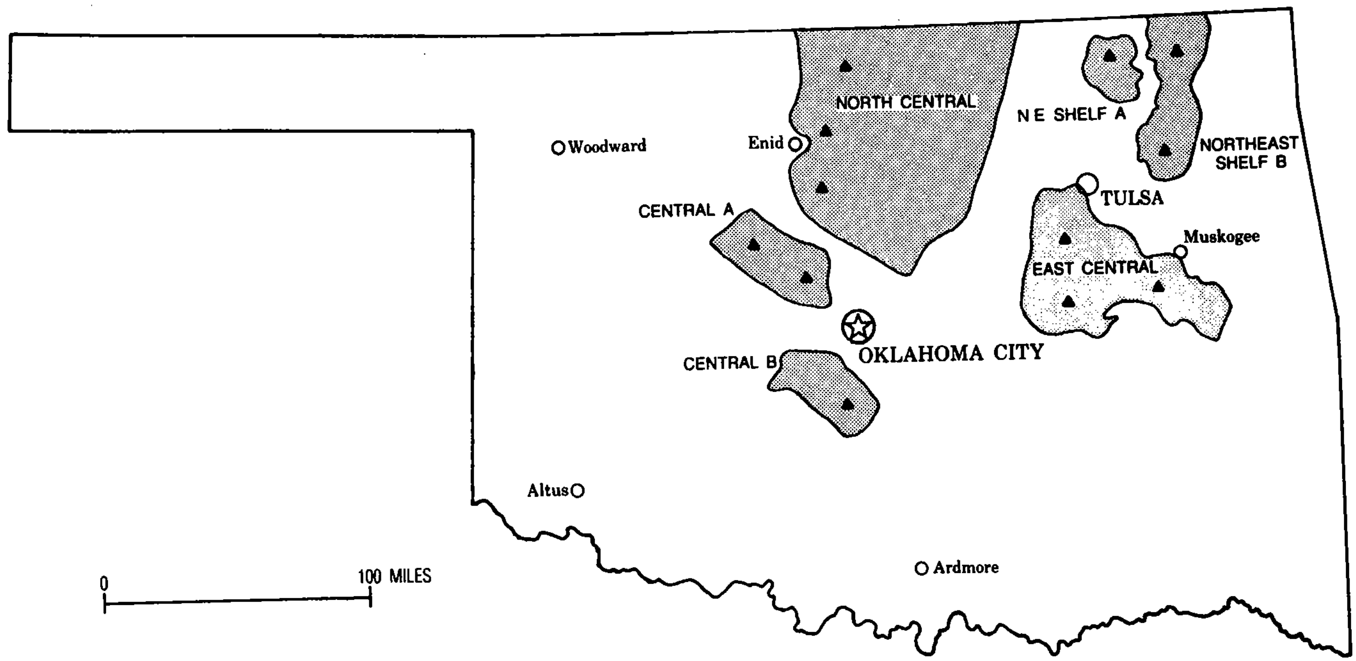


Figure 4. The location of 12 sites in six study zones selected for detailed analysis.

Fryberger, Engineering Enterprises, assisted in the appraisal of the ground water conditions at selected sites.

Fuel and other mineral resources were considered in the site evaluation process. The fuel resources are petroleum and coal. The evaluation of candidate sites included the history of hydrocarbon production, well spacing and depth, drill-hole density, and potential for future development for oil and gas. For known coal resources, their extent, method of extraction (underground versus surface), and potential for future development were evaluated. Non-fuel resources included commodities such as limestone, clay, and shale, which may have unique properties that make them valuable for the manufacturing of speciality items, that are being mined or have the potential for future mining.

Three site selection matrices were used to determine a final site. Each site was given a name which generally coincided with the largest nearby town. In the first matrix, 12 sites were compared against each other and evaluated in six geotechnical categories (Table 1). A three-fold classification, (1) excellent, (2) good, and (3) fair, was used to compare and contrast the geotechnical criteria for each site. The numbers for each site were totaled, and the site with the lowest total received a number 1 ranking. Five sites, Bartlesville, Centralia, Pryor, South Sapulpa, and Henryetta received a rank of 4 or greater and were eliminated from further consideration (Table 1).

The same geotechnical criteria and rating system used in the first matrix were used to evaluate the remaining sites, Muskogee, northeast Enid, southeast Enid, south Perry, Kingfisher, Oklahoma City, and Norman. In the second matrix, the two Enid sites tied for second and the Muskogee site was dropped from further consideration (Table 2). Because the two Enid sites had identical ratings for each geotechnical category, they were combined to form one site.

The third matrix, which used a weighted rating system, was devised to rank the five remaining sites (Table 3). Since all the remaining sites did not have any known unique non-fuel resources, this category was not used in the final evaluation process. In addition to the remaining five geotechnical categories, seismicity and site flexibility were added. The flexibility category rates a site's capability to adjust the collider-ring orientation to avoid and/or minimize the impact on natural and/or cultural features. Topography and lithology were rated on a scale ranging from 1 to 10, with 1 representing the lowest rating and 10 the highest. Structure, hydrology, fuel resources, and flexibility were rated on a scale ranging from 1 to 5, with 1 representing the lowest rating and 5 the highest. Topography and lithology were assigned a much higher rating scale because these categories have the greatest impact on construction methodology and cost. Seismicity was rated on a scale ranging from 1 to 3, with 1 representing the lowest rating and 3 the highest. The

TABLE 1.—THE FIRST GEOTECHNICAL SITE-SELECTION MATRIX USED IN THE EVALUATION OF 12 CANDIDATE SITES

Study Zones	Sites	Geotechnical Criteria (1-3)*						Total	Rank
		Topography	Lithology	Structure	Hydrology	Fuel Resources	Non-Fuel Resources		
Northeast A & B	Bartlesville	2	3	1	3	3	2	14	6
	Centralia	3	3	1	3	3	1	14	6
	Pryor	3	3	2	3	2	1	14	6
East-Central	S. Sapulpa	3	1	1	3	3	1	12	5
	Henryetta	2	1	1	2	3	1	10	4
	Muskogee	1	1	2	2	1	1	8	3
North-Central	NE Enid	1	1	1	1	2	1	7	2
	SE Enid	1	1	1	1	1	1	6	1
	Perry	2	1	1	1	1	1	7	2
Central A & B	Kingfisher	1	1	1	1	1	1	6	1
	Oklahoma City	2	1	1	1	1	1	7	2
	Norman	2	1	1	1	1	1	7	2

*Rating: 1 = Excellent, 2 = Good, 3 = Fair

TABLE 2.—THE SECOND GEOTECHNICAL SITE-SELECTION MATRIX USED IN THE EVALUATION OF THE REMAINING 7 CANDIDATE SITES

Sites	Geotechnical Criteria (1-3)*						Total	Rank
	Topography	Lithology	Structure	Hydrology	Fuel Resources	Non-Fuel Resources		
Muskogee	2	2	3	3	2	1	13	6
NE Enid	2	1	1	1.5	2	1	8.5	2
SE Enid	2	1	1	1.5	2	1	8.5	
S. Perry	3	1	1	2	2	1	10	4
Kingfisher	1	1	1	2	1	1	7	1
Oklahoma City	3	1	1	1.5	2	1	9.5	3
Norman	3	1	1	3	2	1	11	5

*Rating: 1 = Excellent, 2 = Good, 3 = Fair

TABLE 3.—THE THIRD GEOTECHNICAL SITE-SELECTION MATRIX USED IN THE EVALUATION OF THE REMAINING 5 CANDIDATE SITES

Sites	Geotechnical Criteria							Total	Rank
	Topography (1-10)*	Lithology (1-10)	Structure (1-5)	Hydrology (1-5)	Fuel Resources (1-5)	Seismicity (1-3)	Flexibility (1-5)		
Enid	8	9	5	5	4	1	5	37	2
S. Perry	4	10	5	3	3	1	2	28	5
Kingfisher	10	9	5	4	5	2	5	40	1
Oklahoma City	6	9	5	3	3	1	4	31	3
Norman	6	9	5	3	3	2	2	29	4

*Note: Weighted rating, higher numbers are more favorable ratings.

seismic risk zone map of the United States was used to rate the sites (ESSA/Coast and Geodetic Survey, 1969). The sites were compared against each other using each of the seven categories. The highest rating value was then given to the site that had the most favorable conditions that satisfied the geotechnical conditions for each category. The other sites were compared to the best as well as to each other and rated accordingly. Sites that possessed the same attributes for a category, such as structure, were given the same rating.

The total score for each site was calculated by adding the scores for each site. The Kingfisher site with a score of 40 points and the Enid site with 37 points became the preferred or selected sites based on geotechnical criteria. The remaining three sites, Oklahoma City, Norman, and south Perry, with scores that ranged from 31 to 28, ranked third, fourth, and fifth respectively.

The Benham Group evaluated the natural, environmental, and cultural factors that affect the top four rated geotechnical sites. Criteria categories included regional setting, oil and gas well density, urban congestion, regional conditions, utilities, regional and cultural resources and amenities, environmental obstacles, and flood-prone areas. Each site was rated on a scale ranging from 0 to 5, with 0 representing the lowest rating and 5 the highest. The score for each criterion was determined by multiplying the rating by an assigned weight. The total score was calculated by adding the criteria scores for each site (Table 4). The Kingfisher site received the highest total of points, 270. The Enid site was second with 260 points. The Oklahoma City and Norman sites were third and fourth, respectively.

Two independent site selection evaluation methods of the candidate sites resulted in the same order of rank. The Kingfisher site received the highest total of points in both the geotechnical and non-geotechnical analysis (Fig. 5). Therefore, the Oklahoma Geological Survey proposed the Kingfisher site as the best qualified site. On June 3, 1987, the site was presented to the Oklahoma SSC Commission for their approval. The site was accepted and approved by the Commission and became Oklahoma's proposed site to DOE for the SSC.

TABLE 4.—NATURAL, ENVIRONMENTAL, AND CULTURAL CRITERIA USED TO EVALUATE THE TOP 4 CANDIDATE SITES

Criteria	Assigned Weight	Sites							
		Enid		Kingfisher		Oklahoma City		Norman	
		Rating[1]	Score	Rating[1]	Score	Rating[1]	Score	Rating[1]	Score
Regional setting (land ownership)	12	5	60	4	48	4	48	4	48
Oil & gas wells (density/ problems)	10	2	20	4	40	4	40	3	30
Urban congestion	12	5	60	5	60	2	24	1	12
Regional conditions (vibra- (tions, climate, noise)	5	5	25	5	25	5	25	4	20
Utilities (availability)									
water	3	5	15	4	12	4	12	4	12
power	3	5	15	5	15	5	15	5	15
Regional and cultural resources and amenities	10	3	30	4	40	5	50	5	50
Environmental obstacles	5	4	20	4	20	4	20	4	20
Flood-prone areas	5	3	15	2	10	4	20	3	15
Total Score			260		270		254		222

[1]Each site was rated on a scale ranging from 0 to 5. Zero represents the lowest rating and 5 the highest. The score for each criterion is determined by multiplying the rating by the assigned weight. The total score is calculated by adding the scores for each site.

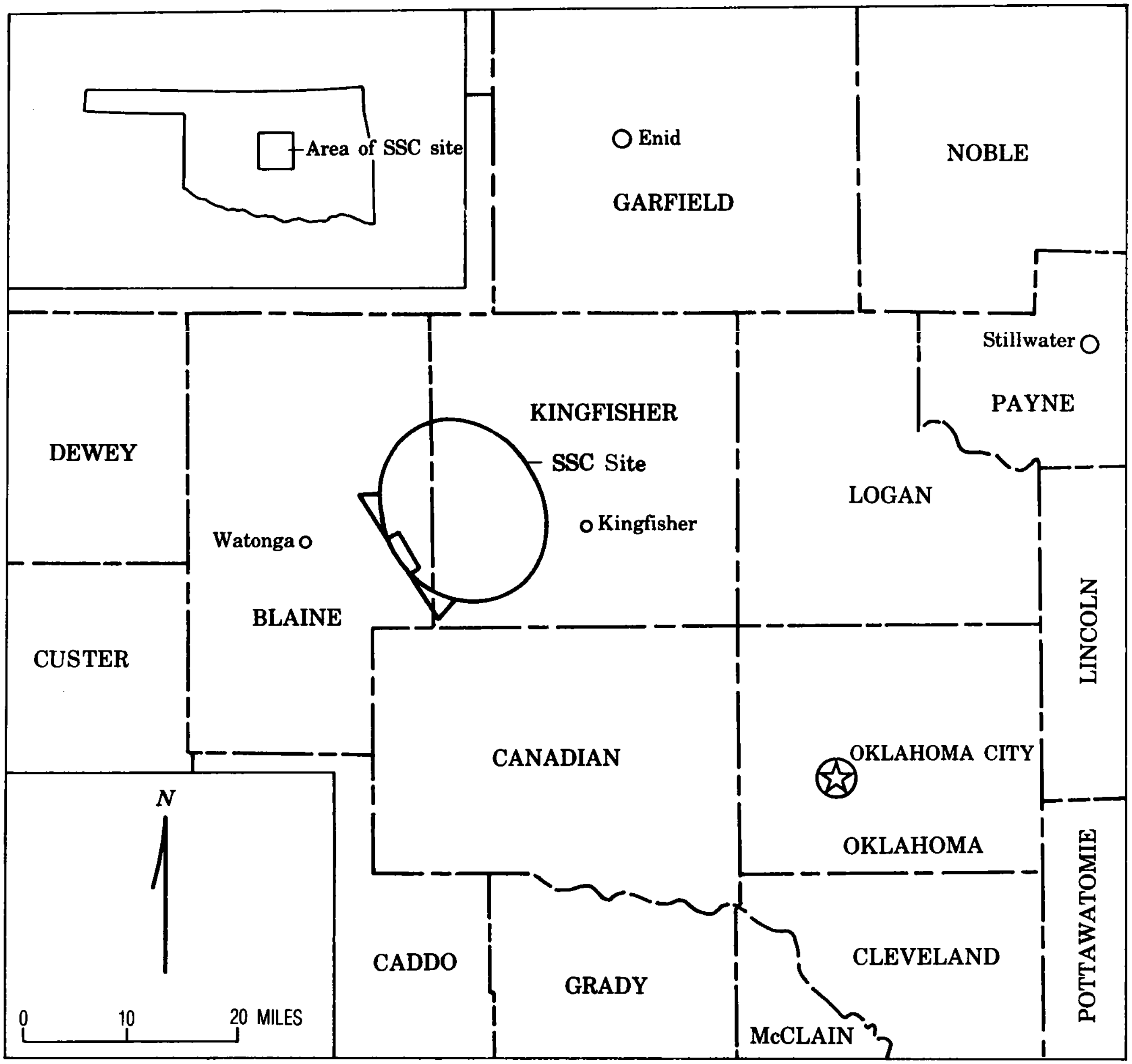


Figure 5. Location of the proposed Kingfisher SSC site.

GEOLOGY OF THE KINGFISHER SITE

INTRODUCTION

The geologic materials at the site are a series of mudstones with engineering properties which are sufficiently uniform to allow for efficient excavation as the first step in the construction of the collider ring. The sites low relief would allow much of the ring construction to be done by cut and cover techniques, with the balance to be done using tunneling-machine methods.

The physical setting is described, first through an examination and summary of the characteristics of regional geology, followed by a discussion of the exposed strata at the site. Following in sequence are descriptions of the regional and local geomorphology and topography, distribution of evaporites under the site, and a discussion of the relation of petroleum production to construction and operation of the super collider. Finally, the seismological character of the site is discussed, including a summary of several of the potentially active geological features in Oklahoma that might contribute to ground shaking at the site.

GEOLOGIC FRAMEWORK

The surficial formations of central and western Oklahoma are primarily Permian red beds. They are mainly mudstones and other fine-grained clastic strata that extend from southern Nebraska through central Kansas into north-central Texas. These beds are part of several thousand feet of sediments that were deposited in a broad, shallow inland sea and along its fluctuating shoreline during the Permian Period. The sediments were eroded from the flanks of the bordering Ozark uplift, the Ouachita and Arbuckle Mountains, and the Bend arch (Fay, 1964), and carried by rivers to the shallow sea (Fig. 6). The typical red color of the Permian rocks (giving rise to the term red beds) is due to the presence of ferric iron that was deposited with the sand, silt, and clay. The red beds that occur on the northeast flank of the Anadarko basin in the vicinity of the proposed SSC site belong to the Leonardian and Guadalupian Series and are composed mostly of reddish-brown mudstones, shales, and siltstones. Gypsum and dolomite beds occur stratigraphically above the formations into which the facility would be constructed, and in the deep subsurface there are other units consisting of shale, anhydrite, and salt. Except for scattered small inclusions of satin spar gypsum, the foundation rock is free of evaporites. Units at the site grade laterally into mudstone conglomerates, sandstones, and siltstones to the southeast of

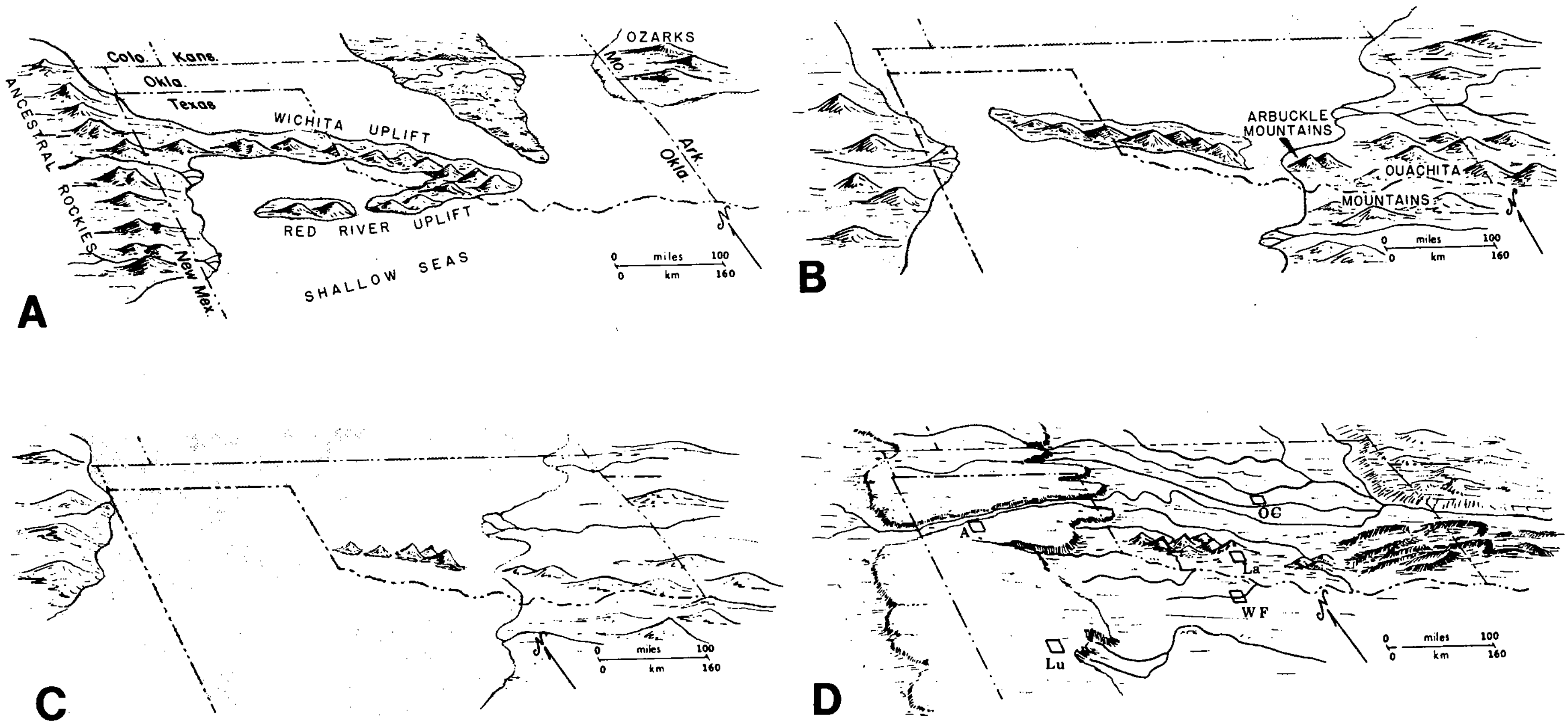


Figure 6. Oblique diagrams of Oklahoma and surrounding areas principal stages of uplift, erosion, burial, and exhumation. A--Early Pennsylvanian time (300-320 m.y. ago) development of the Anadarko basin just north of the Wichita uplift. B--Late Pennsylvanian time (280 m.y. ago) was accompanied by continued subsidence of the Anadarko basin and partial burial of Wichita uplift. C--Early Permian time (250-270 m.y. ago) was the time for deposition of red beds that now crop out at and near the proposed Oklahoma SSC site. D--Today's landscape showing major cities (A, Amarillo; La, Lawton; Lu, Lubbock; OC, Oklahoma City; WF, Wichita Falls). Modified from Johnson (1974).

the site. The generalized geologic map of western Oklahoma shows the distribution of the various sedimentary and igneous rock units that occur in the region (Fig. 7). Time of deposition, environment of deposition, and thickness of the units are also given. The regional structure of the strata in west-central Oklahoma is shown diagrammatically in a south-north cross section (Fig. 8).

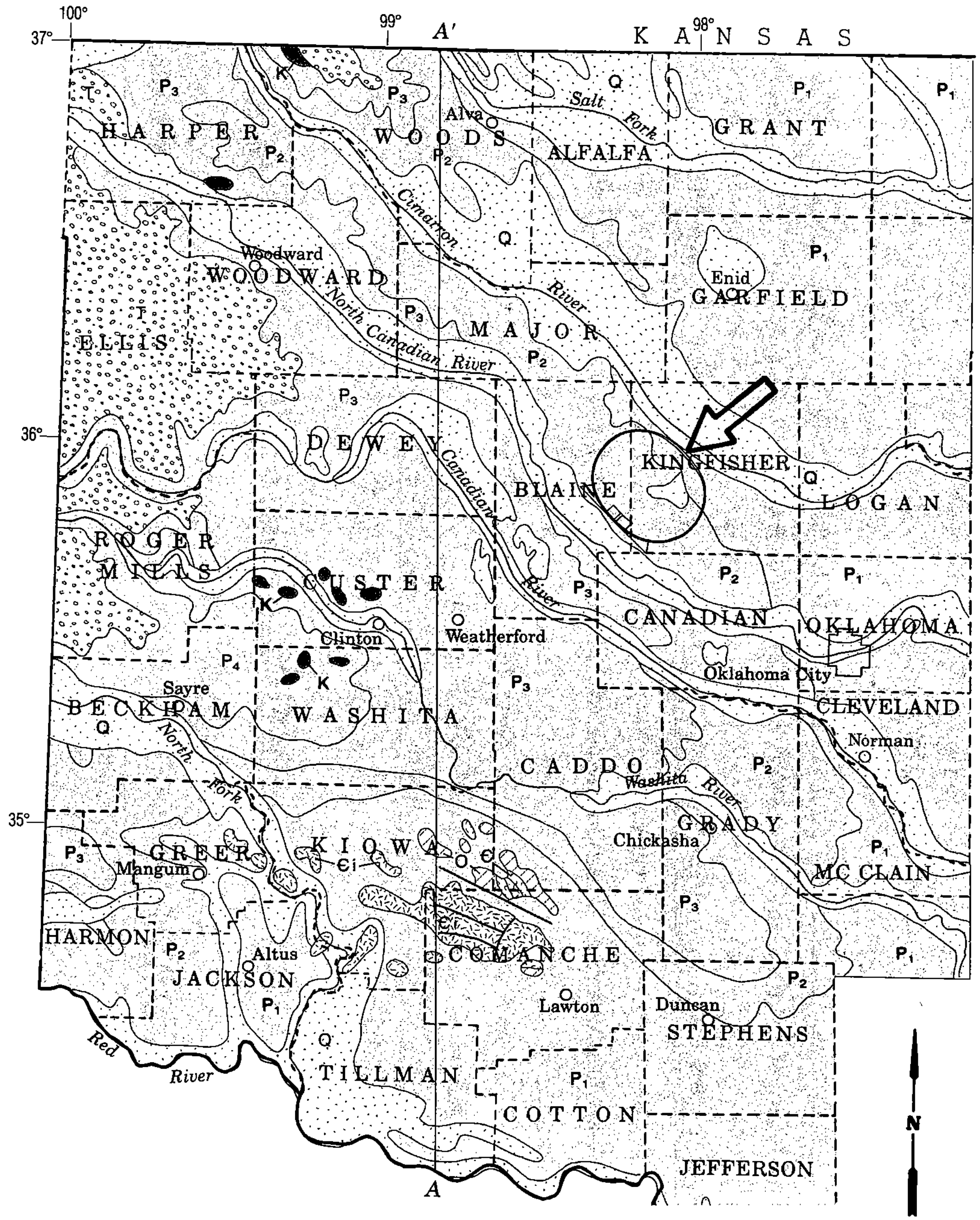
The site is located on the northeastern flank of the Anadarko basin between the northern shelf areas and the deep basin (Fig. 9). This area is characterized by relatively undeformed rock between major tectonic features, the Nemaha uplift and the Wichita frontal fault zone. These features were active predominantly during the Pennsylvanian and Early Permian. The southern part of the Nemaha uplift delimits the northeastern extent of the Anadarko basin. The frontal faults associated with the Wichita uplift delimit the southern extent of the Anadarko basin. The basin is asymmetric. Its axis is adjacent to the Wichita uplift where the structure is complex because of successive crustal movements during the Pennsylvanian and Early Permian (Adler, 1971). The asymmetry of the Anadarko basin is illustrated in Figures 8 and 10, which also show the stratigraphic units between the outcropping Permian rocks and Precambrian basement rocks.

No wells have been drilled to basement rock at the proposed SSC site. However, projections downward from the top of the Arbuckle Group indicate that the Precambrian basement is about 12,000-14,000 ft below the surface. Adkison (1960) and Adkison and Sheldon (1963) examined cuttings from 19 deep oil and gas wells in western Oklahoma and southern Kansas. They described the samples in detail and constructed a cross section showing the lithologic units and their stratigraphic interpretations. Figure 11 is adapted from their report, and summarizes the names and gives the range in thicknesses of the geologic units present in the subsurface. Figure 12 shows the locations of the wells they described. Wells 9 to 12 were drilled near the Oklahoma SSC site: Well 9 was drilled to a depth of 9,639 ft and reached the Simpson Group of Ordovician age; Well 10--7,920 ft deep--reached Chesterian rocks of Mississippian age; Well 11--10,135 ft deep--reached the Bromide Formation of Ordovician age; and Well 12--9,521 ft deep--reached Chesterian rocks of Mississippian age.

STRATIGRAPHY AND STRUCTURE OF EXPOSED STRATA

Site Stratigraphy

The bedrock geology of the Oklahoma SSC site consists of about 1,900 ft of Permian red beds, most of which are mudstone, including shale and siltstone (Bingham and Moore, 1975; Carr and Bergman, 1976; Bingham and Bergman, 1980; Morton, 1981; Fig. 13).



EXPLANATION

Sedimentary Rocks

Q — QUATERNARY — Sand, silt, clay, and gravel in flood plains and terrace deposits of major rivers. Generally 25 to 100 feet thick.

T — TERTIARY — Sand, clay, gravel, and caliche deposited from ancient rivers draining Rocky Mountains. Generally 50 to 500 feet thick.

K — CRETACEOUS — Nonmarine sand and clay and marine limestone and clay up to 100 feet thick.

P_4, P_3, P_2, P_1 — PERMIAN — Dominantly shallow-marine, deltaic, and alluvial deposits of red sandstone and shale. Generally 1,000 to 4,500 feet thick. Gypsum outcrops are conspicuous, and salt units are widespread in subsurface in the far west.

O — ORDOVICIAN — Marine limestone and dolomite, with some sandstone and shale. Thickness is 9,000 feet in south.

Є — CAMBRIAN — Marine limestone and dolomite, with a basal sandstone. Generally 500 to 2,000 feet thick.

Igneous Rocks

Єi — CAMBRIAN — Granite, rhyolite, and gabbro in Wichita Mountains. Formed about 525 million years ago; nearly 20,000 feet thick. In subsurface (cross section), includes metamorphic rocks that may be partly Precambrian.

Geologic contact

Fault

0 10 20 30 40 50 MILES

Figure 7. Generalized geologic map of western Oklahoma showing location of proposed Oklahoma SSC site (from Johnson and others, 1979).

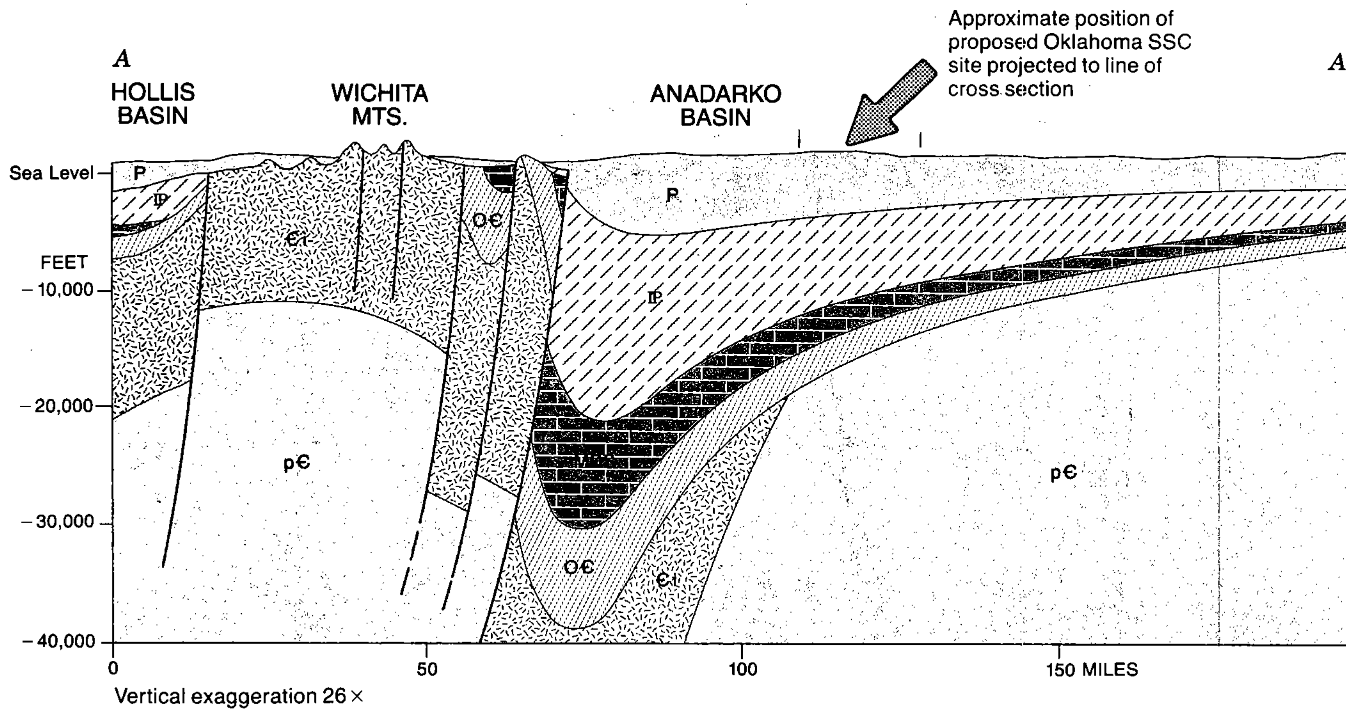


Figure 8. Generalized geologic cross section showing gentle dip of strata on north flank of Anadarko basin in west-central Oklahoma. See Figure 7 for location and explanation (from Johnson and others, 1979).

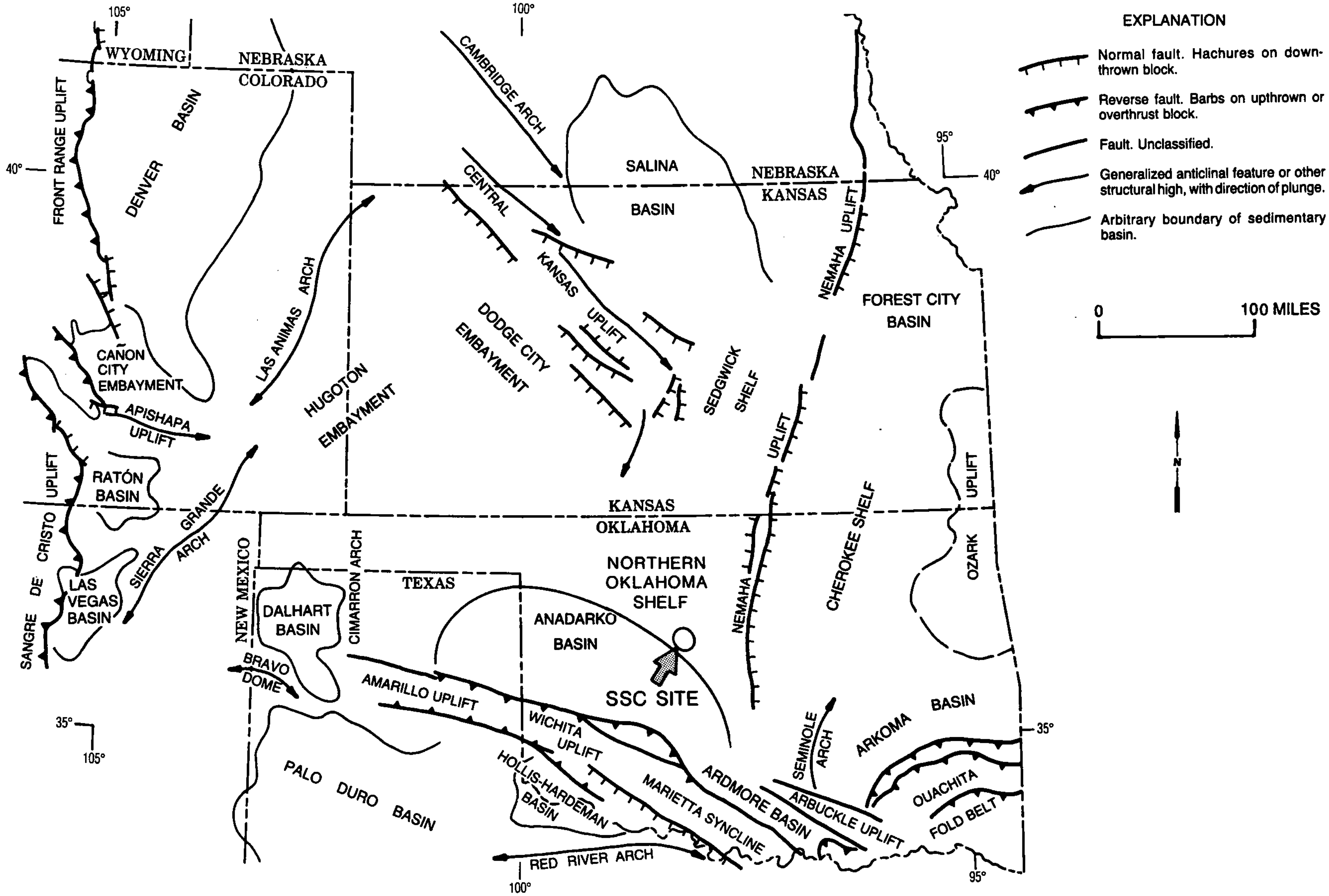


Figure 9. Tectonics Mid-Continent region, with proposed Oklahoma SSC site. Modified from Bayley and Muehlberger (1968).

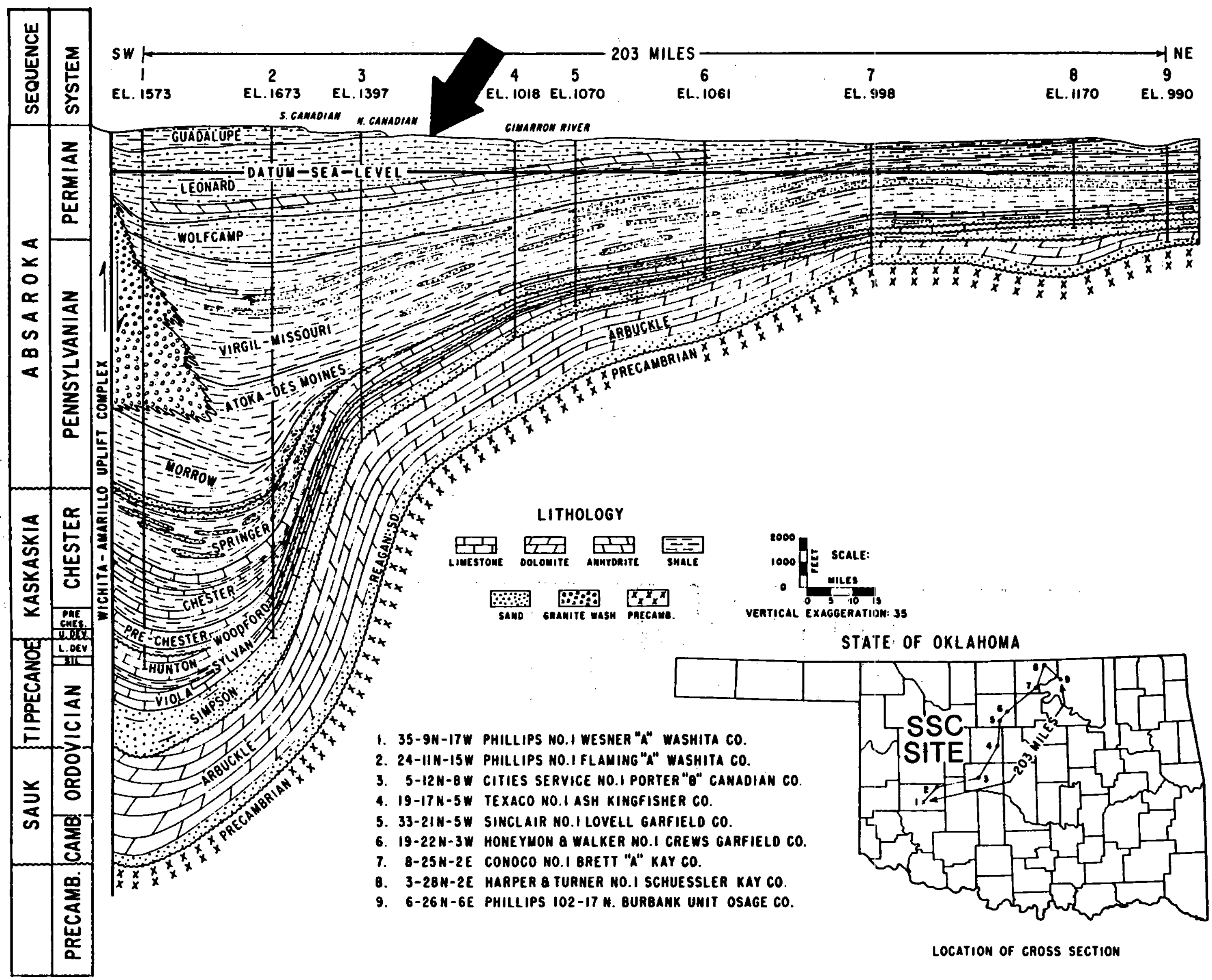


Figure 10. SW-NE geologic section in the Anadarko basin and adjacent shelf; approximate location of the proposed SSC site indicated by arrow. Modified from Alder (1971).

System	Series	Group or groups and thickness (feet)	Formation or member and thickness (feet)
PERMIAN		Whitehorse 390	Rush Springs Sandstone 250 Marlow Formation 140
PERMIAN		El Reno 685	Dog Creek Shale Blaine Gypsum Flowerpot Shale Duncan Sandstone
PERMIAN			Hennessey Shale 845-1240 Garber Sandstone 627-827 Wellington Formation 786-1210
PERMIAN		Chase 375-514	Nolans Limestone Winfield Limestone Barneston Limestone Wreford Limestone
PERMIAN		Council Grove 413-620	Funston Limestone Crouse Limestone Bader Limestone, Stearns Shale and Beattie Limestone Grenola Limestone Red Eagle Limestone, Johnson Shale, and Foraker Limestone
PERMIAN		Admire 303-1111	Houchen Creek? Limestone Bed of Janesville Shale
PENNSYLVANIAN	Virgil	Wabaunsee Equivalent 476-1290	
PENNSYLVANIAN	Virgil	Shawnee Equivalent 470-1726	Topeka Limestone Oread Limestone Member of Vamoosa Formation
PENNSYLVANIAN	Virgil	Douglas Equivalent 133-427	
PENNSYLVANIAN	Missouri	Ochelata 327-837	
PENNSYLVANIAN	Missouri	Skiatook 325-1405	Hogshooter Limestone

System	Series	Group or groups and thickness (feet)	Formation or member and thickness (feet)
PENNSYLVANIAN	Des Moines*	Marmaton 181-704	
PENNSYLVANIAN	Des Moines*	Krebs and Cabaniss 126-486	
PENNSYLVANIAN	Atoka		Upper part of Dornick Hills Formation 0-2424
PENNSYLVANIAN	Morrow		Lower part of Dornick Hills Formation 0-747 Springer Formation 0-1566+
MISSISSIPPIAN	Upper		Rocks of Chesterian age 0-622 Rocks of Meramecian age 135 (well 3)
MISSISSIPPIAN	Lower		Rocks of Osagean age 256 (well 3) Rocks of Kinderhookian? age
DEVONIAN and MISSISSIPPIAN			Woodford Shale 30-1044 Misener Sand
SILURIAN and DEVONIAN		Hunton 0-880	
ORDOVICIAN			Sylvan Shale 0-222 Viola Limestone 22-760
ORDOVICIAN		Simpson 298-1907	Bromide Formation 179-440
CAMBRIAN and ORDOVICIAN		Arbuckle 1287+	

* Lower Des Moines is the Cherokee Group in the subject area

Figure 11. Names and thicknesses of geologic units penetrated in hydrocarbon exploration wells in western Oklahoma near proposed Oklahoma SSC site (from Adkison and Sheldon, 1963).

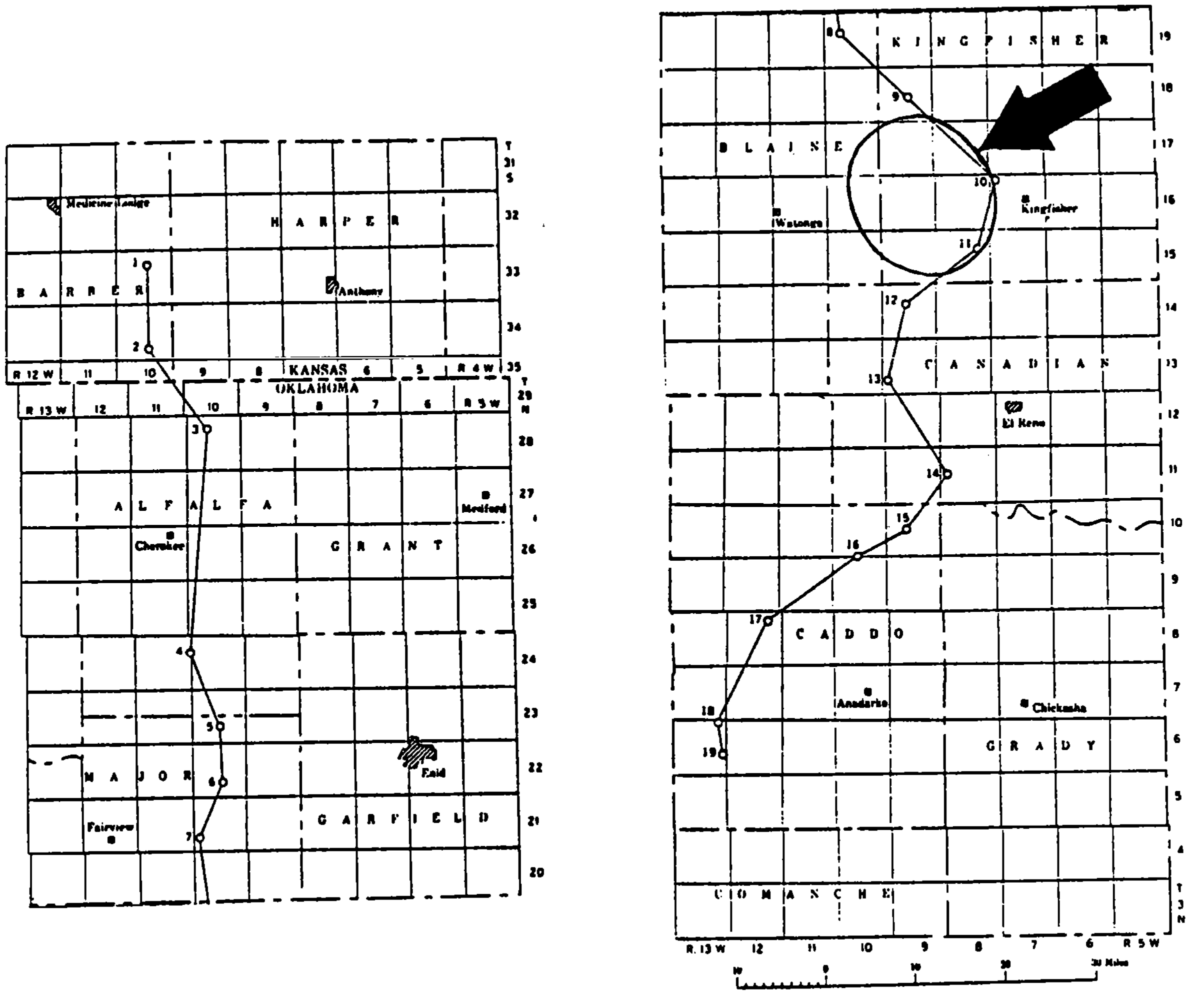


Figure 12. Index map showing location of cross section prepared by Adkison and Sheldon (1963) in the vicinity of the proposed Oklahoma SSC site.

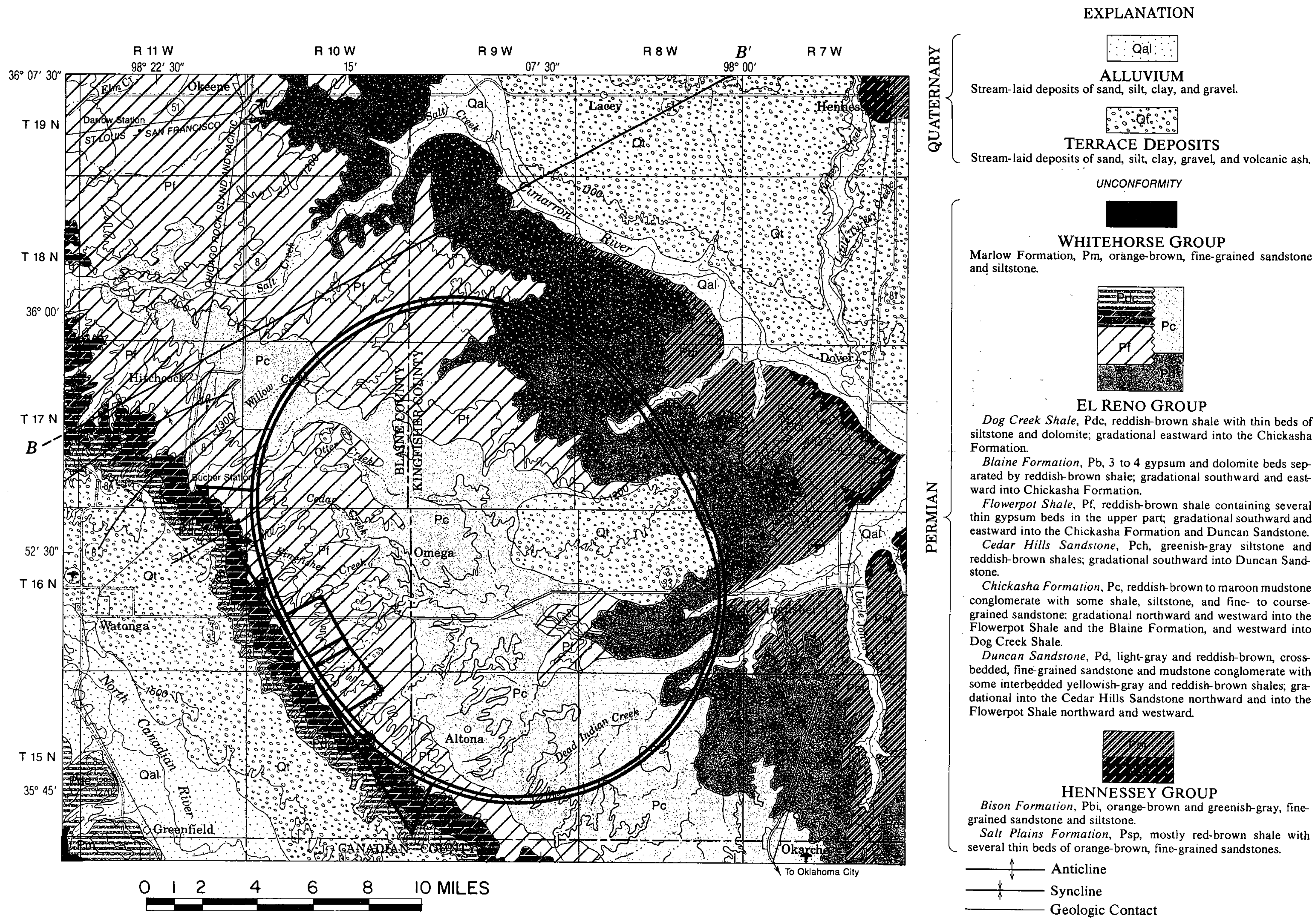


Figure 13. Geologic map of proposed Oklahoma SSC site (B-B' is the approximate location of middle and right part of the geologic section shown on Fig. 14).

(Mudstone is a general term that includes clay, silt, claystone, siltstone, shale, and argillite, and should be used when the amounts of clay and silt are not known or specified or cannot be precisely identified or " . . . when a deposit consists of an indefinite mixture of clay, silt, and sand particles, the proportions varying from place to place, so that a more precise term is not possible . . . " [Twenhofel, 1937].) Most of the ring will be excavated in strata of the El Reno Group, which is about 700 ft thick in this area; the remainder will be excavated in the upper part of the Hennessey Group. The El Reno Group includes, in ascending order, the Cedar Hills Sandstone, Flowerpot Shale, Chickasha Formation (a northwest-thinning wedge within the Flowerpot Shale), Blaine Formation, and Dog Creek Shale (Figs. 14 and 15). The El Reno Group overlies the Bison Formation of the Hennessey Group and underlies the Marlow Formation of the Whitehorse Group. The name El Reno Formation was first applied to these strata by Becker (1930) and subsequently raised to the El Reno Group by Schweer (1937).

Quaternary high terrace sand and gravel lie unconformably on bedrock strata. These deposits form a local veneer on the red beds. Quaternary alluvium occupies the major river and stream valleys. Very fine-grained material derived from the mudstones of the limited drainage area partially fills some tributaries. Formations that will be encountered during excavation for the ring (Table 5) and support facilities are described in greater detail below. These descriptions are based upon measured sections described by Fay and others (1962) (Fig. 16).

TABLE 5.—EXPECTED LINEAR FOOTAGE OF FORMATIONS TO BE ENCOUNTERED IN THE RING ALIGNMENT

Unit	Footage	Percentage
Flowerpot	92,210	32.2
Chickasha	76,210	26.9
Cedar Hills	85,530	30.3
Bison	28,840	10.2

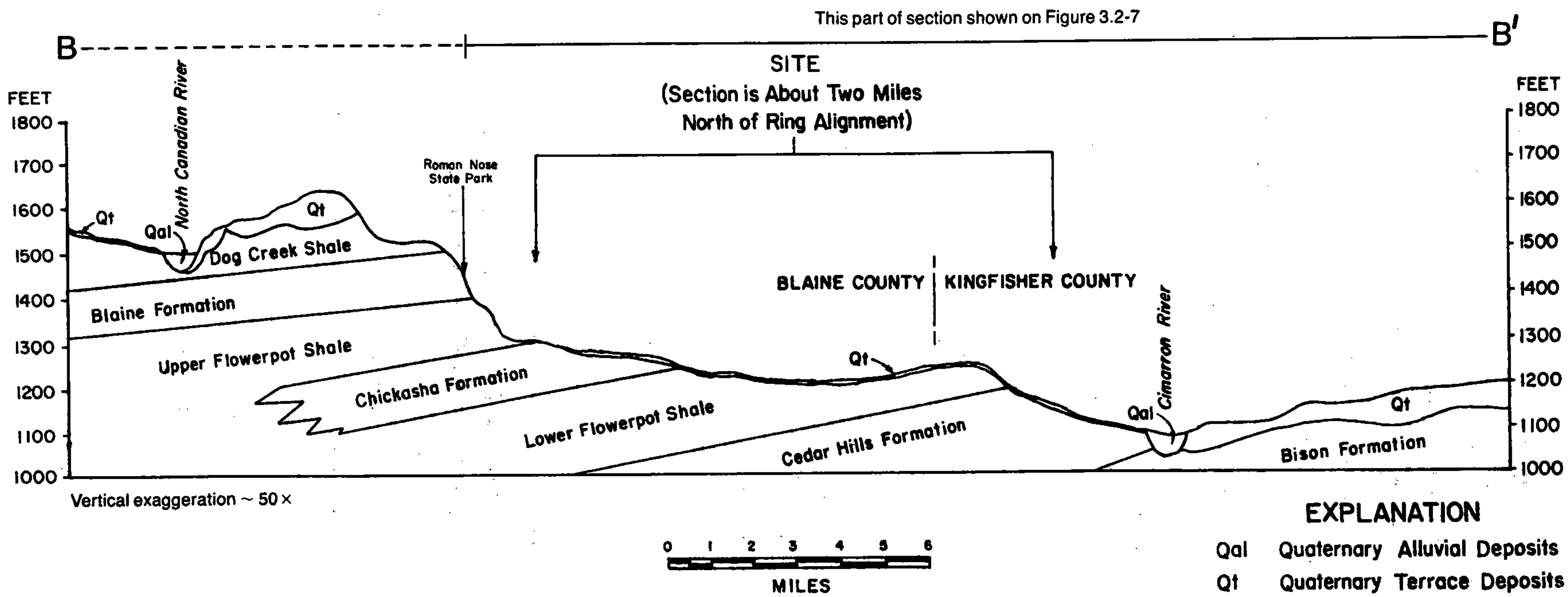


Figure 14. Diagrammatic geologic section of Blaine and Kingfisher Counties, Oklahoma, showing Permian and Quaternary units (see Fig. 13 for location of middle and right part of section. Modified from Fay and others (1962).

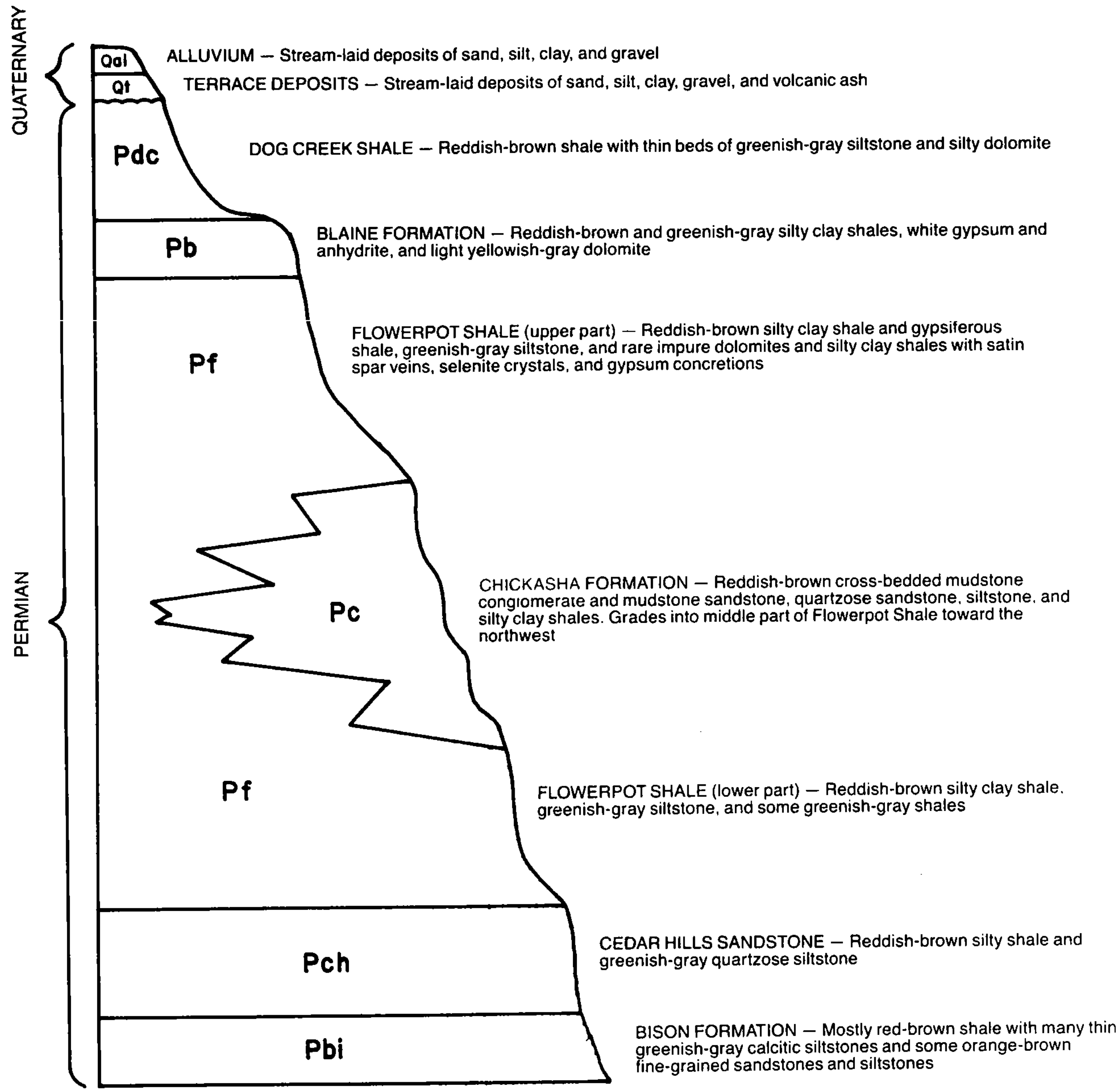


Figure 15. Composite columnar section of strata exposed at the Oklahoma SSC site; all formations are conformable; thicknesses vary and facies change laterally and perpendicular to strike.

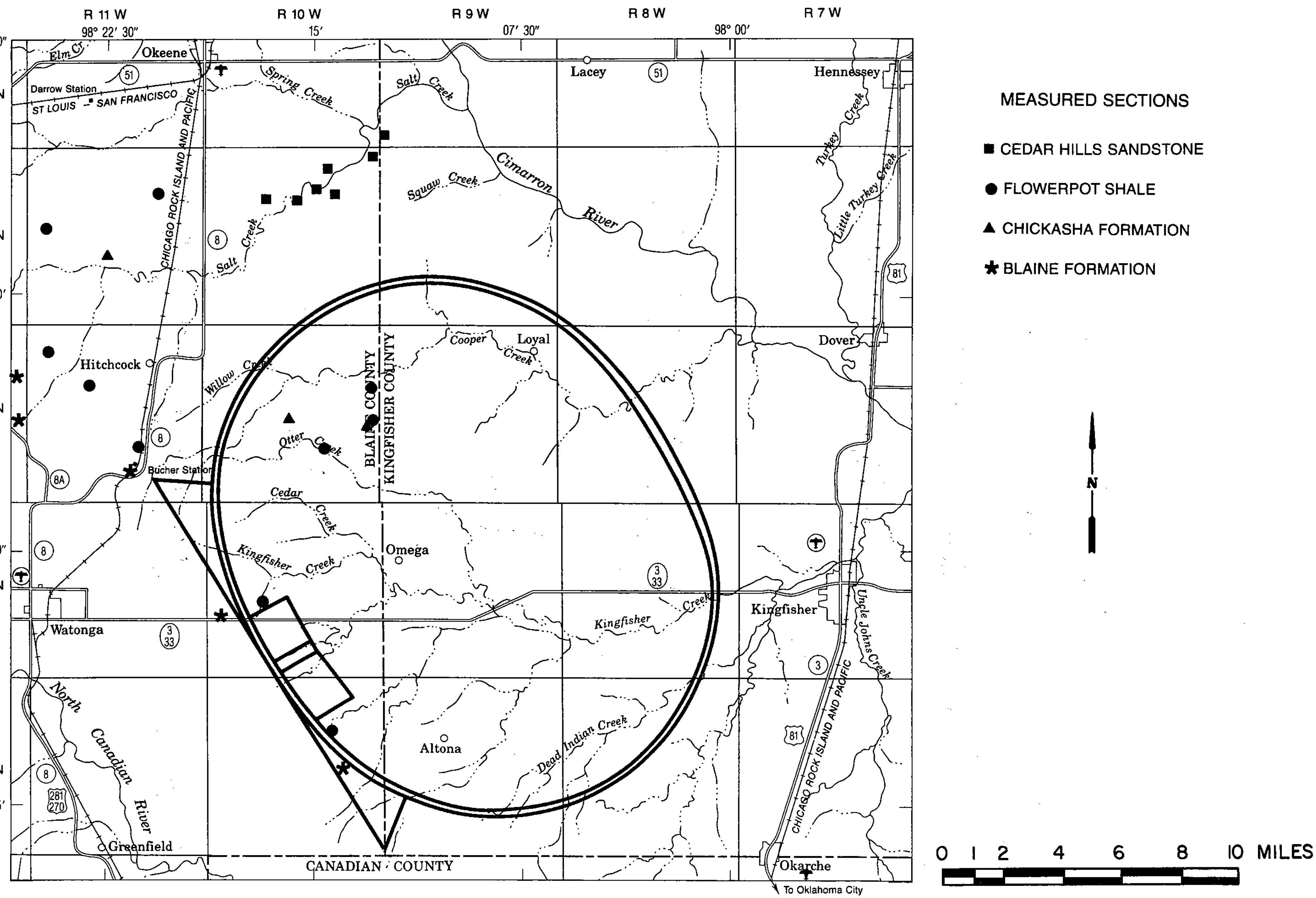


Figure 16. Locations of measured sections in the vicinity of the proposed Oklahoma SSC site (from Fay and others, 1962).

Bison Formation

The Bison Formation, at the top of the Hennessey Group, is the oldest unit to be excavated for the SSC ring alignment. Gillum (1958) describes the uppermost 70-80 ft of Hennessey shale (now considered Bison Formation) southeast of the ring area as an even-bedded, blocky, jointed, brick-red shale. Spherical greenish-gray spots 0.25 to 4 in. in diameter and similar-colored silty zones are scattered throughout the formation. The unit is characterized by relatively abundant calcareous siltstones and small calcite geodes. Locally, joints are also filled with calcite.

Cedar Hills Sandstone

Cedar Hills strata are sandstone in the type section in Barber County, south-central Kansas, but in the SSC area they are interbedded reddish-brown silty shale and greenish-gray quartzose siltstone (Fay and others, 1962). Near the proposed site the Cedar Hills Sandstone is about 180 ft thick. Fay and others (1962) measured sections that included Cedar Hills strata in and immediately outside the site area (Fig. 17).

Of the 216 ft they measured, 120.7 ft (56%) was shale, 77.6 ft (36%) siltstone, 17.0 ft (8%) covered, and 0.7 ft (0.3%) sandstone. Individual siltstone beds are up to 5 ft thick, but average considerably less. Intervening shales are up to 15 ft thick, but are also typically thinner. Fay and others (1962) were able to correlate light-colored siltstone beds a few inches to a foot or more thick into adjacent counties, suggesting that clastic deposition during Cedar Hills time was remarkably uniform over a very large area. The Cedar Hills grades laterally into the Duncan Sandstone just southeast of the site. The Duncan typically consists of shales and sandstones derived from the southeast.

Flowerpot Shale

The most extensive formations in the site area are the Flowerpot Shale and Chickasha Formation. The Flowerpot and Chickasha are lateral time equivalents that undergo transition at and near the SSC site. Within the site area, the Flowerpot is divided into lower and upper parts by a wedge of the Chickasha (Fig. 18).

In Blaine County, just northwest of the site, the Flowerpot is 437-465 ft thick. Fay and others (1962) divided it into four lithologic subunits. The lower 180 ft consists of relatively pure reddish-brown silty clay shale with rare, thin, light greenish-gray siltstone beds and selenite veins. The next overlying 160 ft consists of alternating reddish-brown gypsiferous shales and light greenish-gray siltstones; to the southeast, the lower part of this unit grades into the Chickasha Formation, described below. The remaining two subunits

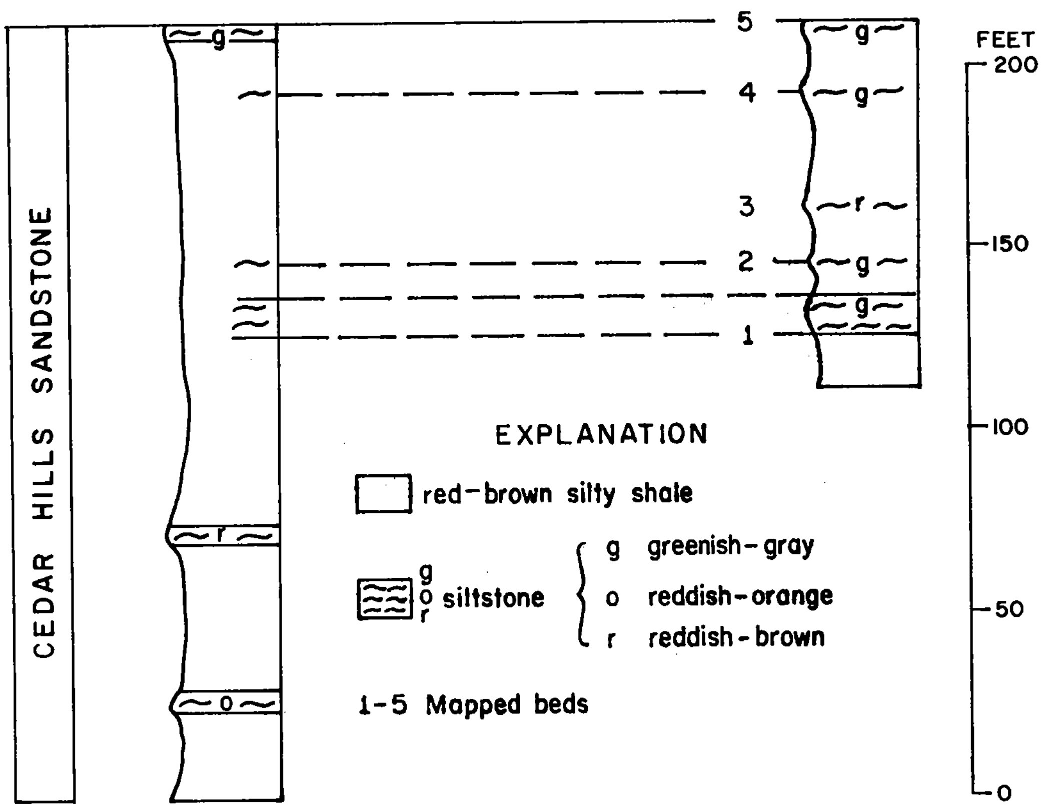


Figure 17. Stratigraphic diagram showing the Cedar Hills Sandstone in Blaine and Canadian Counties, Oklahoma. Modified from Fay and others (1962).

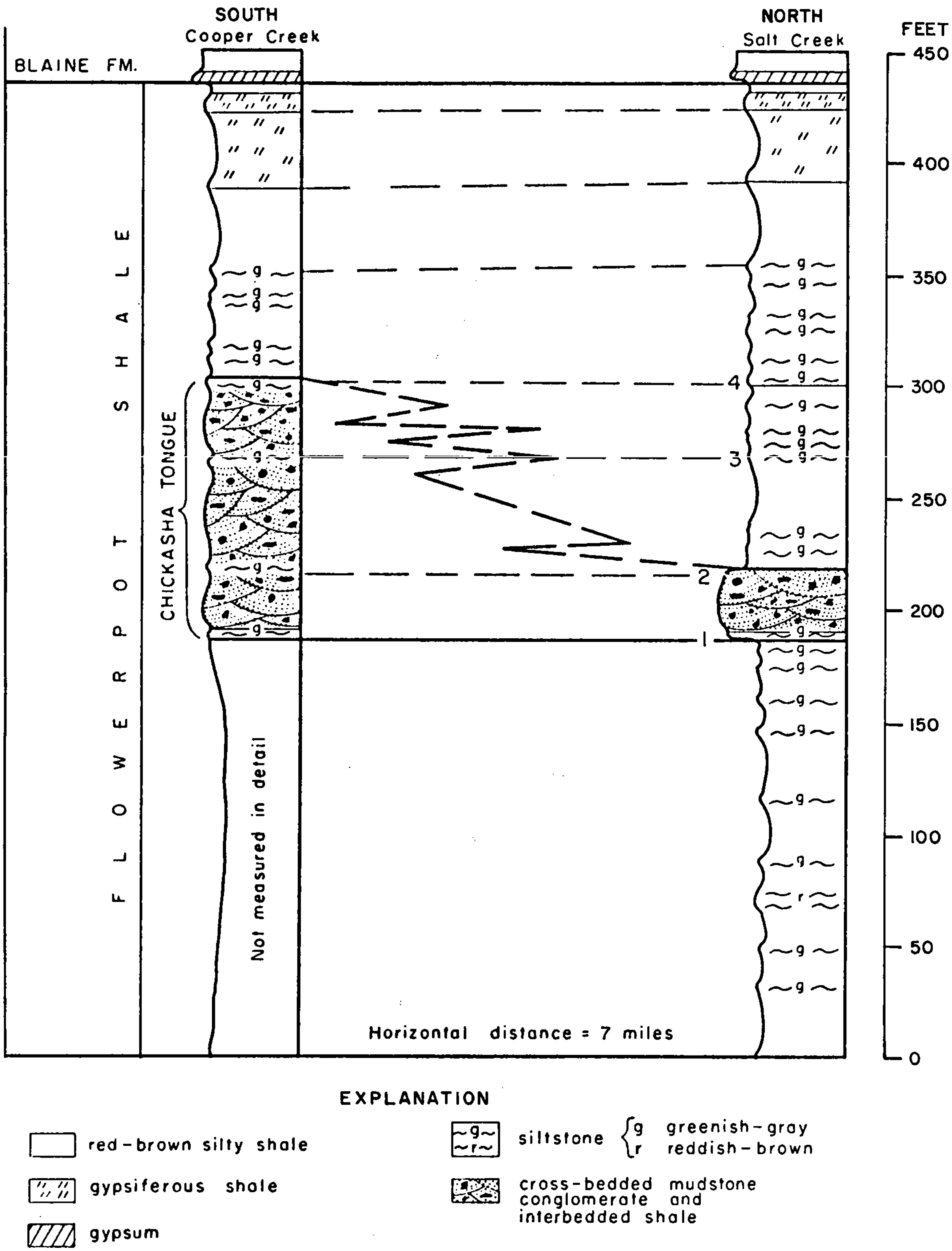


Figure 18. Stratigraphic diagram showing relationships of the Flowerpot Shale to the Chickasha Tongue in Blaine County, Oklahoma. The mapped units, numbered 1, 2, 3, and 4, are light-colored siltstones or indurated mudstone-conglomerates that can be traced locally for a few miles. These units grade into shale northward and grade into thick siltstones and mudstone conglomerates southward, forming a thick wedge in the middle of the Flowerpot Shale. Modified from Fay and others (1962).

are 90 ft thick and are above the ring and experimental halls excavations. The lower of these is 40 ft thick and consists of reddish-brown shale. The upper subunit is 50 ft thick and consists of: 6 ft of reddish-brown silty clay shale; 7-8 ft of silty clay shale with thin, wavy layers of satin spar and a local impure dolomite 2-3 in. thick; and 30-40 ft of reddish-brown, blocky, silty clay shale with satin spar, selenite, and a layer of white gypsum concretions. Fay and others (1962) described measured sections, many of them composite, that included the Flowerpot Shale (Fig. 16). Of the 1,155 ft he measured, 1,075.44 ft (93%) was shale (mudstone), 59.25 ft (5%) siltstone, 18.30 ft (2%) gypsum, 2.15 ft (0.1%) dolomite, 0.20 ft (0.01%) sandstone, and 0.06 ft (0.005%) hematite. Pure gypsum beds are rarely greater than 0.25 to 0.5 ft thick; gypsum beds up to 1 ft thick are always described as silty. Individual shale beds range from <1 ft thick to >15 ft thick, and siltstone beds are as much as 4 ft thick but generally <1 ft thick. Certain siltstone beds can be traced into Kansas, again illustrating that clastic deposition was uniform over a large region around and to the north of the site area during the Permian.

Chickasha Formation

The Chickasha Formation occurs as a wedge or tongue in the lower to middle part of the Flowerpot Shale. It thickens to the southeast within the site area from about 30 ft near Salt Creek to about 300 ft near Kingfisher Creek. The top of the formation becomes younger to the south and the amount of shale decreases to the south. Southeast of Kingfisher Creek, the lower Flowerpot pinches out and the Chickasha conformably overlies the Cedar Hills.

The Chickasha Formation consists of reddish-brown, cross-bedded, lenticular mudstone conglomerates (mudstone clasts in a mudstone matrix) and mudstone sandstones, interbedded with quartzose sandstones, siltstones, and silty clay shales. The mudstone conglomerate consists of soft pebbles, granules, and grains of reddish-brown mudstone and siltstone in a matrix of reddish-brown to greenish-gray siltstone and silty clay shale. The quartzose sandstone is fine grained, micaceous, cross bedded, and moderately to well-indurated. The siltstones are light greenish gray to reddish brown, quartzose, and micaceous. Fay and others (1962) described 153.30 ft of Chickasha Formation in several measured sections. Of that total, 76.25 ft (50%) was siltstone, 42.25 ft (27%) shale, and 34.80 ft (23%) conglomerate. A typical description of one of the mudstone conglomerate beds is (Fay and others, 1962):

> "Siltstone-mudstone conglomerate, moderate reddish-brown, mottled greenish-gray, well-indurated; grading into sand-sized particles or smaller, in a siltstone matrix; cross-bedded, lenticular-bedded; with interbedded cross-bedded siltstone and fine-grained quartzose sandstone that is argillaceous and micaceous and weakly indurated . . . 10.0 [ft]."

The thickest mudstone conglomerate bed described by Fay is 15 ft thick.

Blaine Formation

The Blaine Formation overlies the uppermost unit to be excavated at the site. In the site area, the Blaine is about 70-100 ft thick and consists of interbedded evaporites (gypsum and dolomite) and reddish-brown silty clay shales (Fig. 19). The gypsum and dolomite beds have local names, and several can be traced northward into Kansas where they are significantly thicker and the intervening shales thinner. The sequence of beds within the Blaine is, from oldest to youngest, Cedar Springs Dolomite, Medicine Lodge Gypsum, shale, Kingfisher Creek Gypsum, shale, Magpie Dolomite, Nescatunga Gypsum, shale, Altona Dolomite, and Shimer Gypsum. All these individual beds are conformable and the entire Blaine Formation is conformable with the underlying Flowerpot Shale and overlying Dog Creek Shale.

Gypsum beds within the Blaine Formation are all white, compact, finely to coarsely crystalline, and form ledges. The thickest gypsum beds in Blaine County are in the upper part of the formation: the Nescatunga ranges from about 7 to 14 ft thick and the Shimer from about 7 to 15 ft. The lower gypsum beds, the Medicine Lodge and Kingfisher Creek gypsum beds, are about 1-6 ft thick. Locally, the Nescatunga contains 2-6 ft of anhydrite that is light gray, compact, fibrous, weathers white, and forms a bright, white ledge.

Dolomite within the Blaine is mostly light gray to yellow-gray, finely crystalline, oolitic, and has a dense, non-oolitic base. The Cedar Springs is locally malachite stained, and the Magpie and Altona are locally fossiliferous. Each of the dolomites grades upward into the overlying gypsum.

The Blaine shale layers are moderate to dark reddish brown to greenish gray. Many layers contain small selenite and satin spar particles. Most beds are silty and have a distinctly mottled appearance.

Fay and others (1962) described measured sections in the SSC site area that contained the Blaine Formation. Of the total 543.65 ft of Blaine Formation measured, 348.85 ft (64%) was shale, 162.15 ft (30%) gypsum, 15.4 ft (3%) dolomite, 15.0 ft (3%) anhydrite, and 2.25 ft (0.4%) siltstone. The gypsum is concentrated in the upper part of the Blaine and two beds (Medicine Lodge and Nescatunga) thin to the south near the site.

Quaternary

The Quaternary units in the site area consist of terrace deposits and alluvium. These Pleistocene deposits, which are composed of lenticular beds of sandy silt, clay, and gravel,

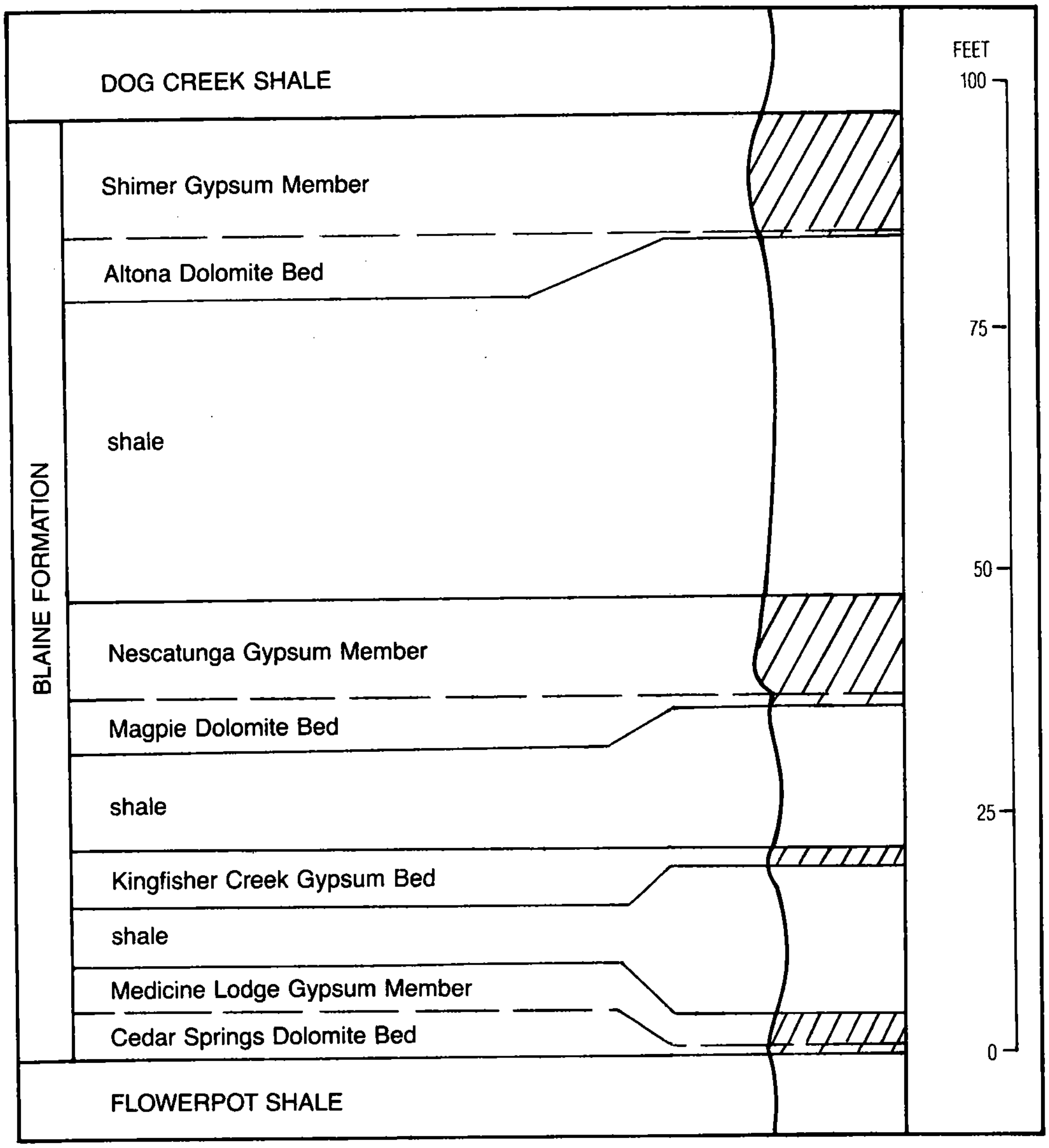


Figure 19. Stratigraphic diagram showing relationships of the members of the Blaine Formation at the type section on State Highway 33, Blaine County, Oklahoma. Modified from Fay and others (1962).

mostly occur at the southeast corner of the site (Fig. 13). Thicknesses range from a few feet to about 50 ft. Holocene alluvium partially fills some of the minor and major tributary streams. The alluvium is mostly fine-grained material because the source for this alluvium is predominantly fine-grained rock. Nonsystematic observations of the alluvium in several streams seems to confirm this.

Site Structure

The structure of the bedrock at the SSC site area is a very gently southwest-dipping homocline. Fay and others (1962) noted that the Cedar Hills through Blaine Formations dip 14 ft/mi to the southwest throughout the area; this represents a regional dip of 0.15°. Two very broad synclines with an intervening anticline are present along the west side of the site area (Fig. 13).

There are no mapped or recognized faults in the site area. Surface mapping has shown there are no faults cutting any of the outcropping rocks to be excavated for the SSC ring (Fig. 13). Furthermore, structure mapping on deep Pennsylvanian strata also shows that the rocks in the subsurface are not faulted (Fig. 20). These deep Pennsylvanian strata dip to the southwest about 80 ft/mi, or about 1°.

Bison, Cedar Hills, Chickasha, and Flowerpot mudstones and siltstones are typically massive but are locally fractured, jointed, and weathered in outcrop. These same rocks are relatively massive in cores. Nonsystematic fractures occur locally within the mudstone beds. The fractures are closely spaced (about 1 in.) and curviplanar with random orientations. Steeply dipping joints typically flatten within several feet and pass into bedding planes. The rock is deeply weathered along fractures and horizontal bedding planes and gives outcrops a *spheroidal* appearance. Siltstone beds are less fractured (6-in. to 5-ft spacing). These fractures do not vary significantly in attitude over distances of tens of feet, either horizontally or vertically. None of the fractures shows evidence of offset.

GEOMORPHOLOGY AND TOPOGRAPHY

Regional Geomorphology

Land areas of the United States have been categorized into major geomorphic divisions, provinces and sections, based primarily on physical features. Fenneman's (1931) publication on the physiography of the western United States has long served as a standard reference on regional geomorphology.

Fenneman (1931) showed most of central and west-central Oklahoma to be in the Interior Plains Physiographic Division of the United States. This division includes the vast

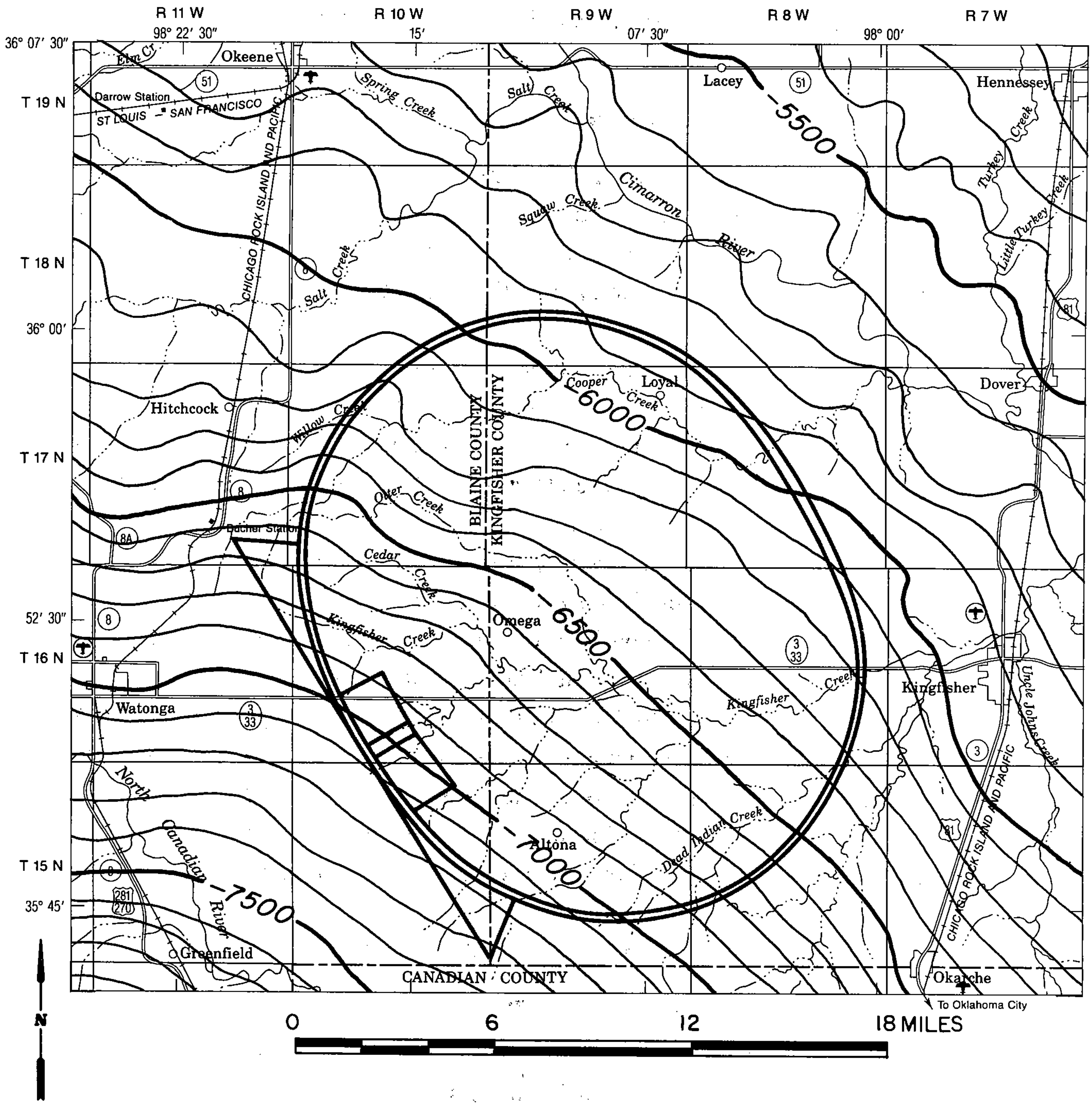


Figure 20. Structure contour map on top of the Oswego Limestone (Middle Pennsylvanian) beneath the proposed Oklahoma SSC site (from Fritz, 1978). Contour interval is 100 ft; datum is sea level.

plains that lie between the Rocky Mountains on the west and the Appalachian Plateaus on the east. The proposed SSC site is located in the Central Lowland Province, which is the largest and lowest part of the Interior Plains Division (Fig. 21). He further subdivided the Central Lowland Province into several sections. The SSC site is in the Osage Plains Section, which is characterized by an old erosion surface on gently inclined strata.

Johnson and others (1979) provided a more detailed classification of Oklahoma's geomorphic features by dividing the state into 26 different subprovinces. Figure 22 shows that the Oklahoma site is in the Central Redbed Plains, one of 10 of these subprovinces in western Oklahoma.

Site Geomorphology

The Oklahoma SSC site is located between two major southeast-flowing rivers, the North Canadian River on the southwest, and the Cimarron River on the northeast (Fig. 22). The elevation of the Cimarron River is about 1,050 ft above sea level in western Kingfisher County, and the North Canadian River is about 1,500 ft above sea level in eastern Blaine County. The difference in elevation is partly explained by the fact that the Cimarron River has been eroding through weakly resistant rocks, whereas the North Canadian has been eroding through more resistant rocks (Fay and others, 1962). A cuesta, commonly known as the Blaine escarpment, parallels the North Canadian River on its northeast side in Blaine and Kingfisher Counties. This escarpment is about 1,480 ft above sea level. It is held up by resistant gypsum and dolomite beds of the Blaine Formation, and supports a line of northwest-trending hills that stand 500-600 ft above the Cimarron River. The escarpment, which is part of the Cimarron Gypsum Hills, bounds the proposed campus facilities on the southwest.

The geomorphic development can be traced as far back as the close of the Permian Period (220 m.y. ago), when the region was uplifted above sea level (Fay and others, 1962). Weathering and erosion progressed slowly during the Mesozoic Era (70-220 m.y. ago). The Permian deposits were eroded along their eastern edge by streams flowing westward from the Ozarks, creating small escarpments.

Fay and others (1962) believed that the North Canadian and Cimarron Rivers were initiated during the early Tertiary Period when the Rocky Mountains were uplifted. Valleys were carved parallel to the strike of the bedrock, and produced the Blaine escarpment. The Cimarron River eroded its way westward, accentuating the relief of the Blaine escarpment. By the late Tertiary (7-13 m.y. ago) the Rocky Mountains provided a source for the sand and gravel of the Ogallala Formation, an extensive, coarse-grained, fluvial deposit in western Oklahoma. The Ogallala sands and gravels were reworked in the Pleistocene to form the Quaternary terrace deposits near the site area.

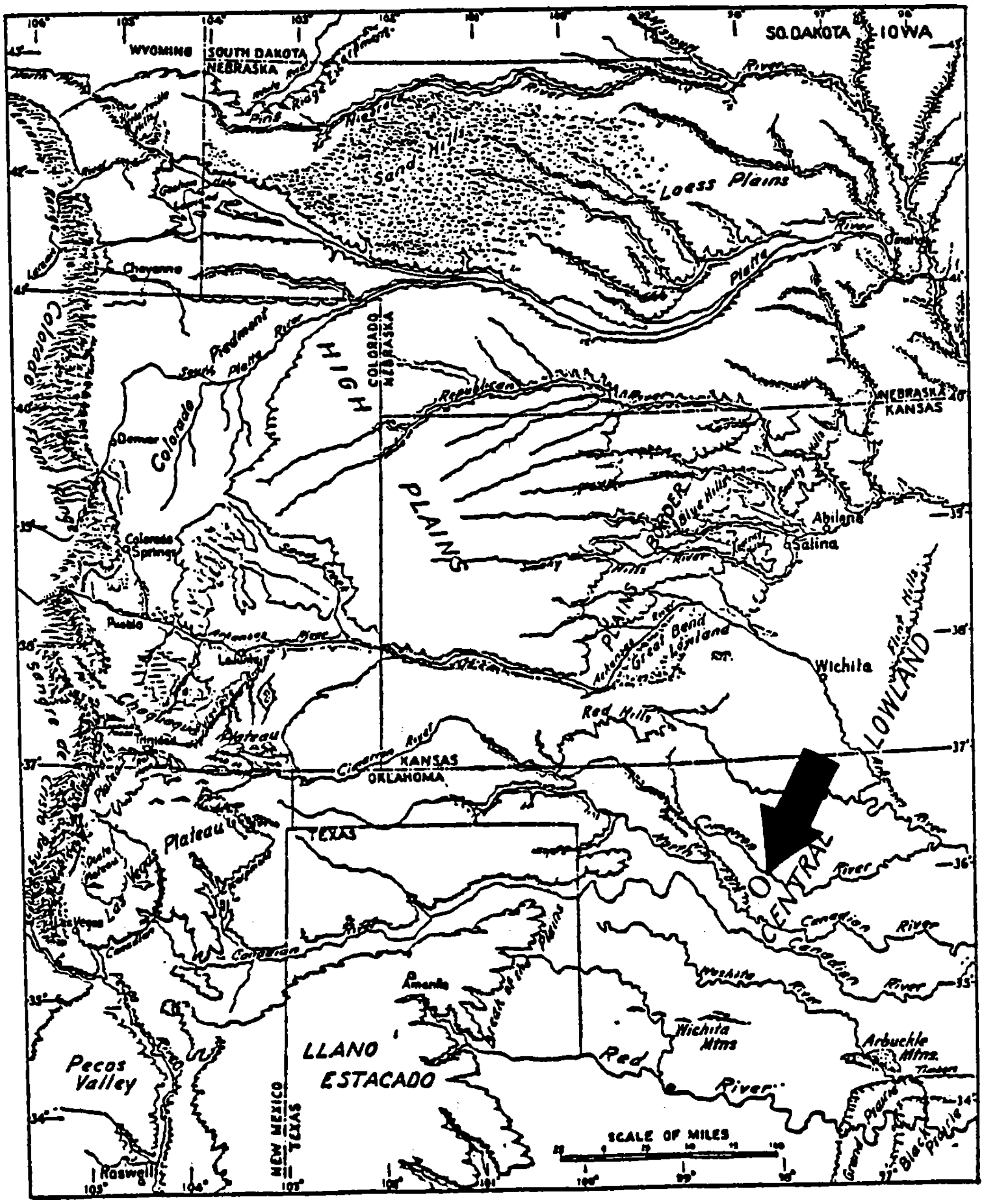


Figure 21. Southwestern portion of the Interior Plains Physiographic Division of the United States, showing location of proposed Oklahoma SSC site. Modified from Fenneman (1931).

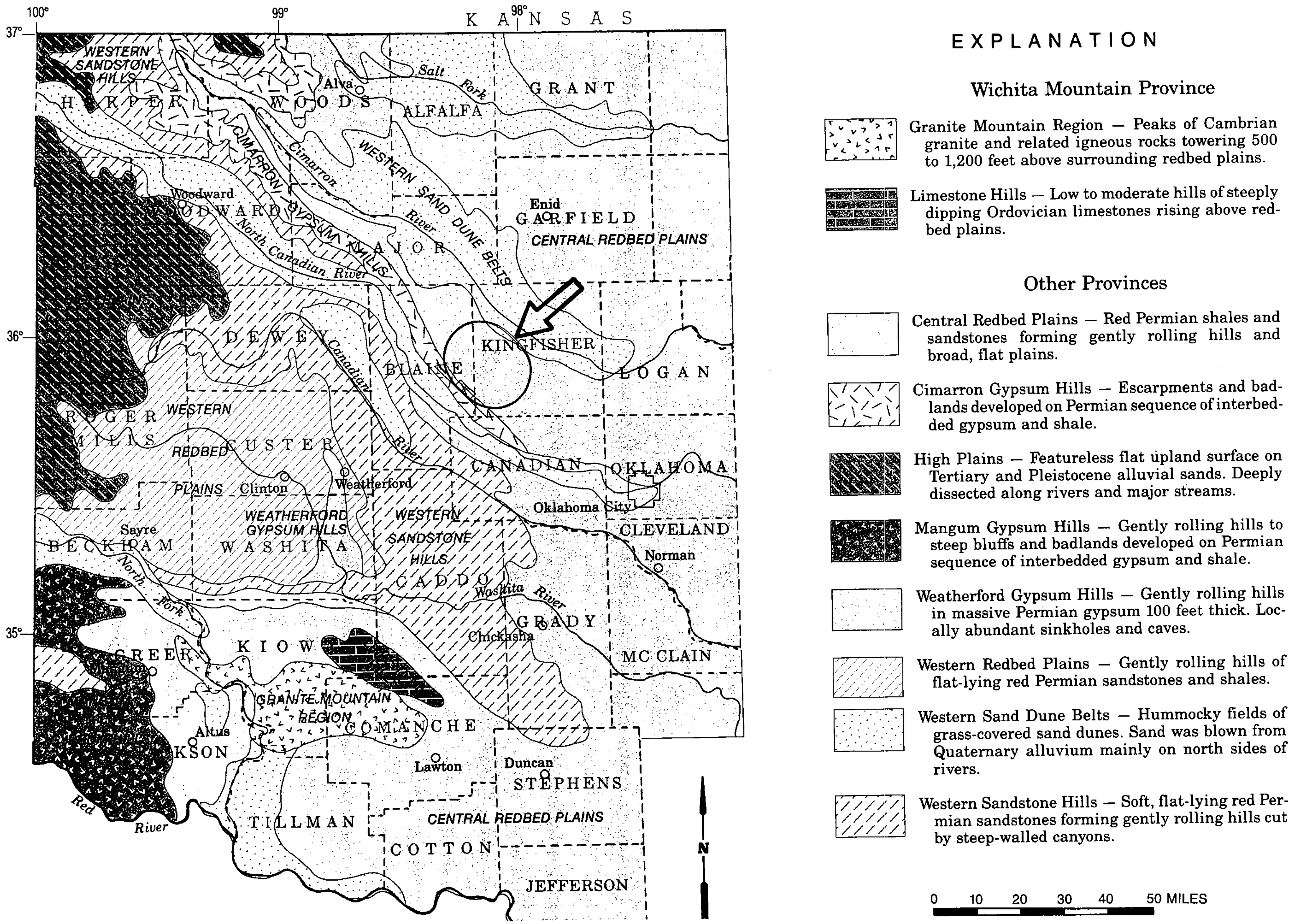


Figure 22. Major geomorphic provinces of western Oklahoma showing location of the proposed Oklahoma SSC site (from Johnson and others, 1979).

Pleistocene rivers (10,000 yr to 2.5 [?] m.y. ago) formed valleys during periods of maximum melting of ice from glaciated regions to the northwest. (Oklahoma was not located in the glaciated area during the ice age.) The valleys were partially filled with alluvium during a time of minimum melting, forming terrace levels. Fay and others (1962) identified at least three terrace levels associated with the Cimarron and North Canadian Rivers. The high terrace level (140-190 ft above the flood plain of the Cimarron) was dated as Late Kansan or older because it contained Pearlette-type volcanic ash. The intermediate terraces (50- to 90-ft levels) and low terrace (20-ft level) of the Cimarron are probably Illinoian and Wisconsinan, and formed at the same time as the intermediate and low terraces of the North Canadian River. Much of the Oklahoma SSC site area appears to be a high-level strath terrace associated with the Cimarron River.

Site Topography

A high Pleistocene terrace along the southwest side of the Blaine escarpment forms a divide that extends from southeast to northwest. From this drainage divide, streams generally flow northeast across the gently sloping topography of the site. The two major streams at the Oklahoma SSC site are Cooper Creek to the north and Kingfisher Creek to the south. Cooper Creek has a drainage basin area of about 160 mi^2 and Kingfisher Creek has a drainage basin area of about 250 mi^2. The flow direction of tributary streams within each of these major drainage basins ranges from almost due north to almost due south; most flow either east or northeast. Stream gradients, calculated by using a straight-line method and ignoring meanders, range from about 75 ft/mi near the heads of most of the streams along the near-side of the ring to about 7 ft/mi on the far-side of the ring (Fig. 23).

Drainage divides within the site area range from about 50 ft to about 4 ft above adjacent streams (Fig. 24). The highest divides are located west of the ring alignment and on the far-side of the ring. The relatively high relief on the far-side of the ring is associated with the drainage divide between Kingfisher and Cooper Creeks and the divide between Cooper and Salt Creeks. Part of this high relief is due to the entrenchment of Kingfisher Creek. The lowest divides are located on the near-side of the ring just east of the Blaine escarpment.

EVAPORITE DEPOSITS BENEATH THE SITE

Deep beneath the proposed SSC site is a sequence of evaporite rocks consisting of interbedded shale, anhydrite, and salt (halite). These strata are the Wellington evaporites. The shallowest evaporites range in depth from 1,500 to 2,400 ft below land surface in the

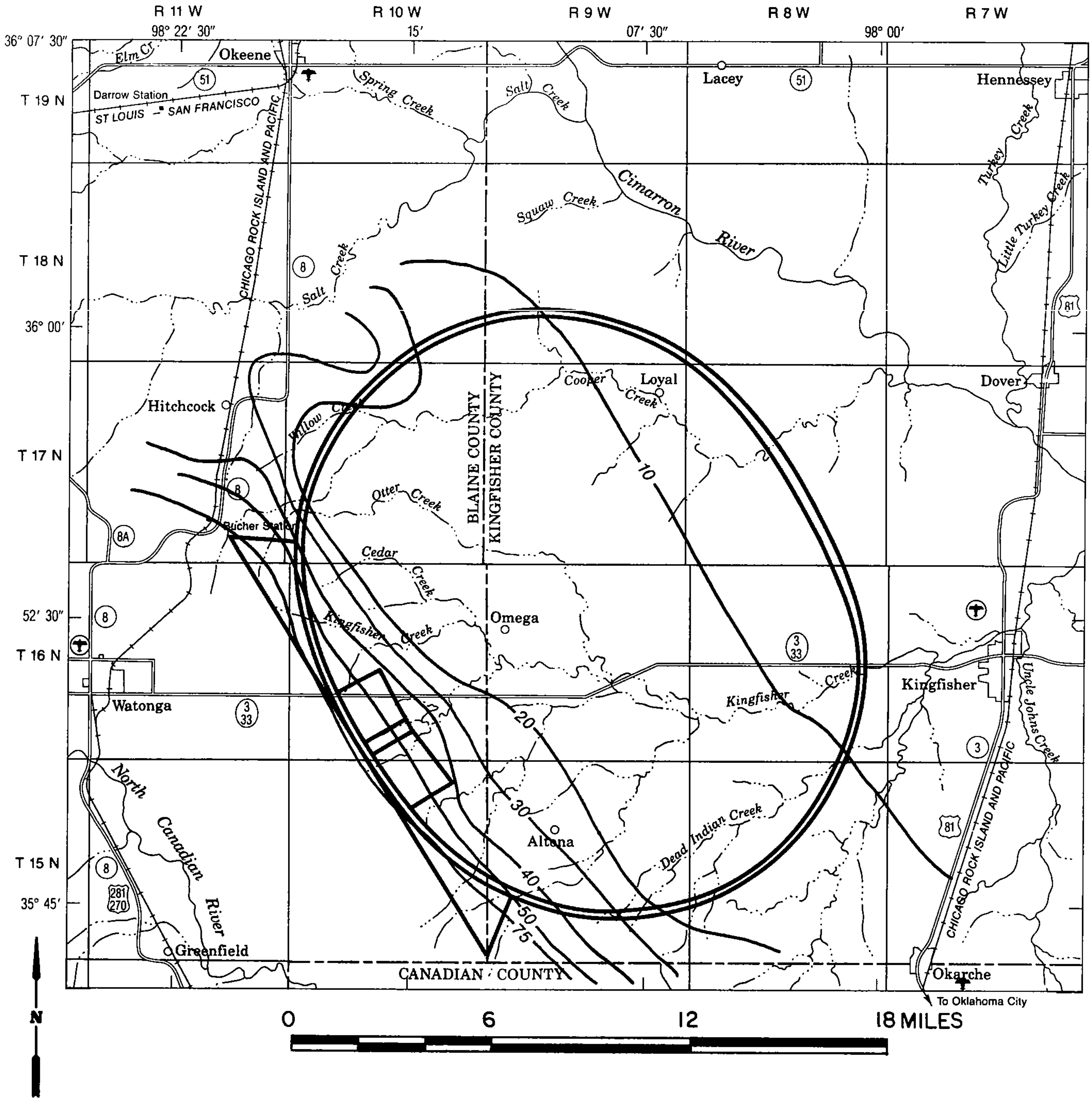


Figure 23. Isogradient map showing average gradient of streams within the proposed Oklahoma SSC site area. Contours are in feet per mile; data calculated from 1:24,000 U.S. Geological Survey 7.5-minute topographic quadrangle maps.

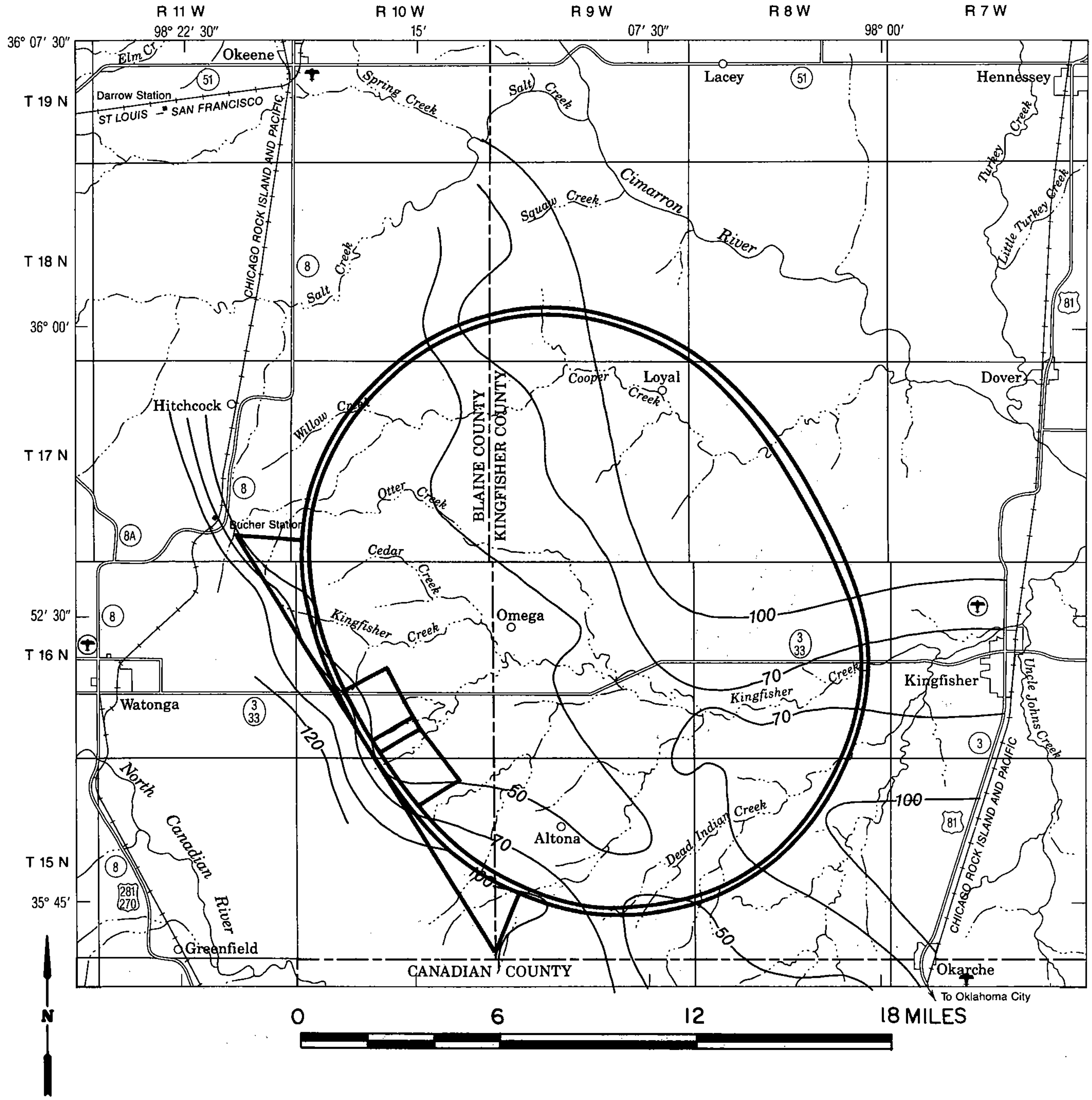


Figure 24. Isorelief map showing average height (in feet) of drainage divides between streams that are spaced about 2-4 mi apart. Data calculated from 1:24,000 U.S. Geological Survey 7.5-minute topographic quadrangle maps.

vicinity of the site (Pl. 1; Figs. 25 and 26). The Wellington evaporites are briefly described for Blaine County by Bado and Jordan (1962), are described from drill cuttings of wells within and near the SSC site by Adkison and Sheldon (1963), and are discussed for the entire Anadarko basin region by Jordan and Vosburg (1963). Individual beds of Wellington anhydrite and salt are persistent in the Anadarko basin, and each of the beds ranges from 2 to 15 ft thick in the vicinity of the SSC site.

The Wellington evaporites in the subsurface are approximately equivalent to the Wellington Formation sandstones and shales that are exposed about 40 mi east of Kingfisher. Major facies changes occur in the Wellington beneath the SSC site. Therefore, both subsurface and outcrop nomenclature are presented on the accompanying cross sections (Pl. 1; Figs. 25 and 26).

The Upper anhydrite unit, at the top of the Wellington evaporites (Jordan and Vosburg, 1963), is 5 ft thick on the west and grades laterally into shale just east of the Blaine-Kingfisher County line (Pl. 1; Figs. 25 and 26). This thin, but persistent unit is about 2,070 ft deep under the near-side of the ring.

The main evaporite sequence, called the lower salt-anhydrite unit (Jordan and Vosburg, 1963), ranges from about 820 ft thick in the northwest to about 620 ft thick in the east (Pl. 1; Fig. 25). The top of the unit is about 2,450 ft deep in the southwest and about 1,515 ft deep in the northeast (Pl. 1; Fig. 26). The upper part of the lower salt-anhydrite unit contains layers of rock salt and is referred to as the Hutchinson salt in Kansas; the lower part of the lower salt-anhydrite unit is devoid of salt in Oklahoma.

The Hutchinson salt is as much as 520 ft of interbedded shale, salt, and anhydrite about 10 mi west of the SSC site (Well 1, Pl. 1), but the salt layers grade laterally into shale toward the east and constitute only a small amount of the Hutchinson unit beneath the SSC site. Near the northwest end of the site (Well 2, Pl. 1) the Hutchinson is 463 ft thick and consists of about 60% shale, 24% salt, and 16% anhydrite: individual salt beds range from 2 to 15 ft thick and average about 5 ft thick; individual anhydrite beds range from 6 to 11 ft thick and average about 8 ft thick. At the southeast end of the site (Well 5, Pl. 1) the same sequence of strata is 355 ft thick and consists of about 90% shale, 2% salt, and 8% anhydrite: salt beds are only 3 ft thick, whereas anhydrite beds range from 4 to 7 ft thick and average about 5 ft thick.

The lower part of the lower salt-anhydrite unit contains only interbeds of shale and anhydrite. In the northwest (Well 2) these strata are 385 ft thick and consist of about 36% shale and 64% anhydrite; individual anhydrite beds range from 4 to 15 ft thick and average about 9 ft thick. To the southeast (Well 5) the strata are 263 ft thick and consist of about 55% shale and 45% anhydrite: individual anhydrite beds are 4-11 ft thick and average about 7 ft thick.

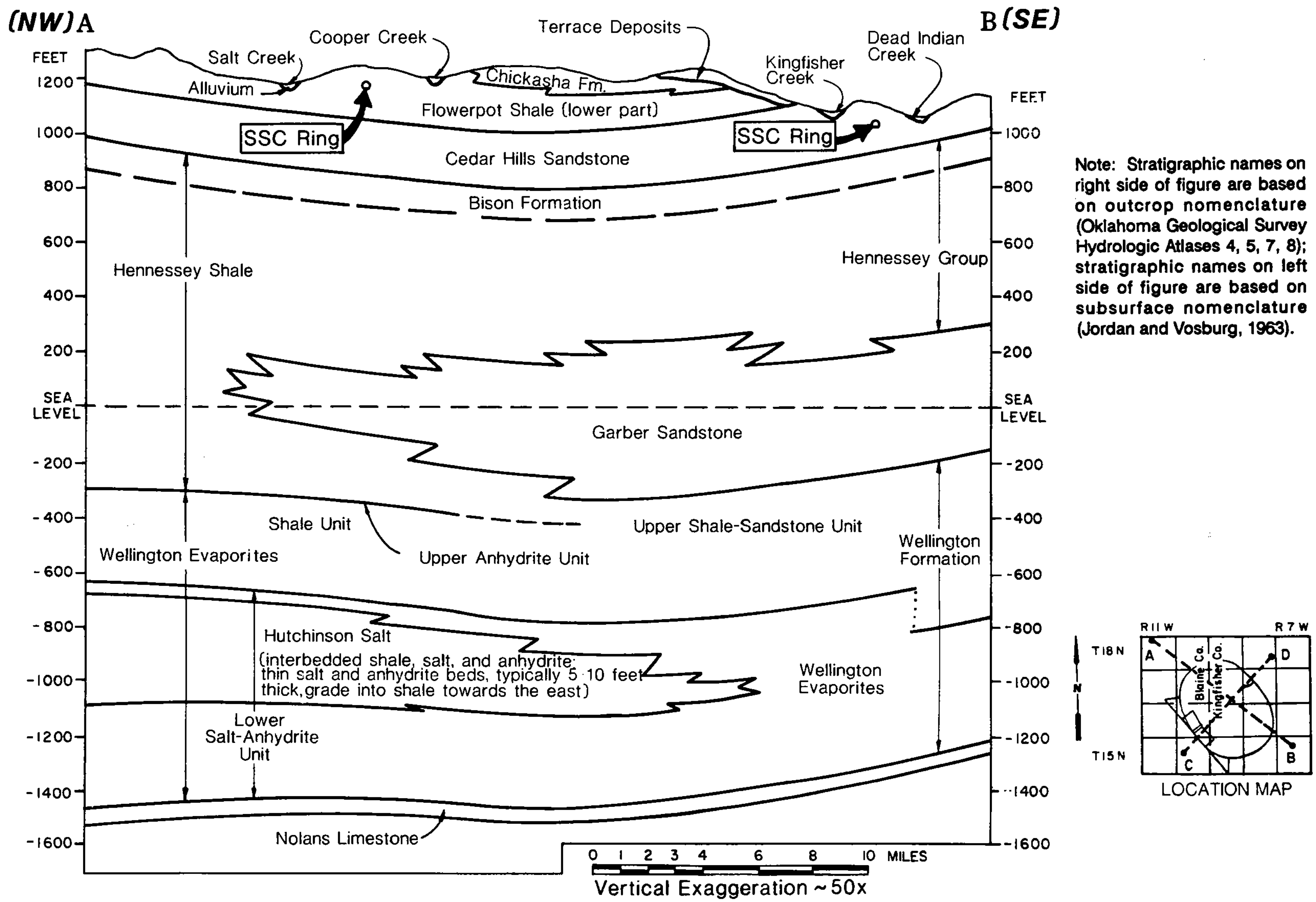
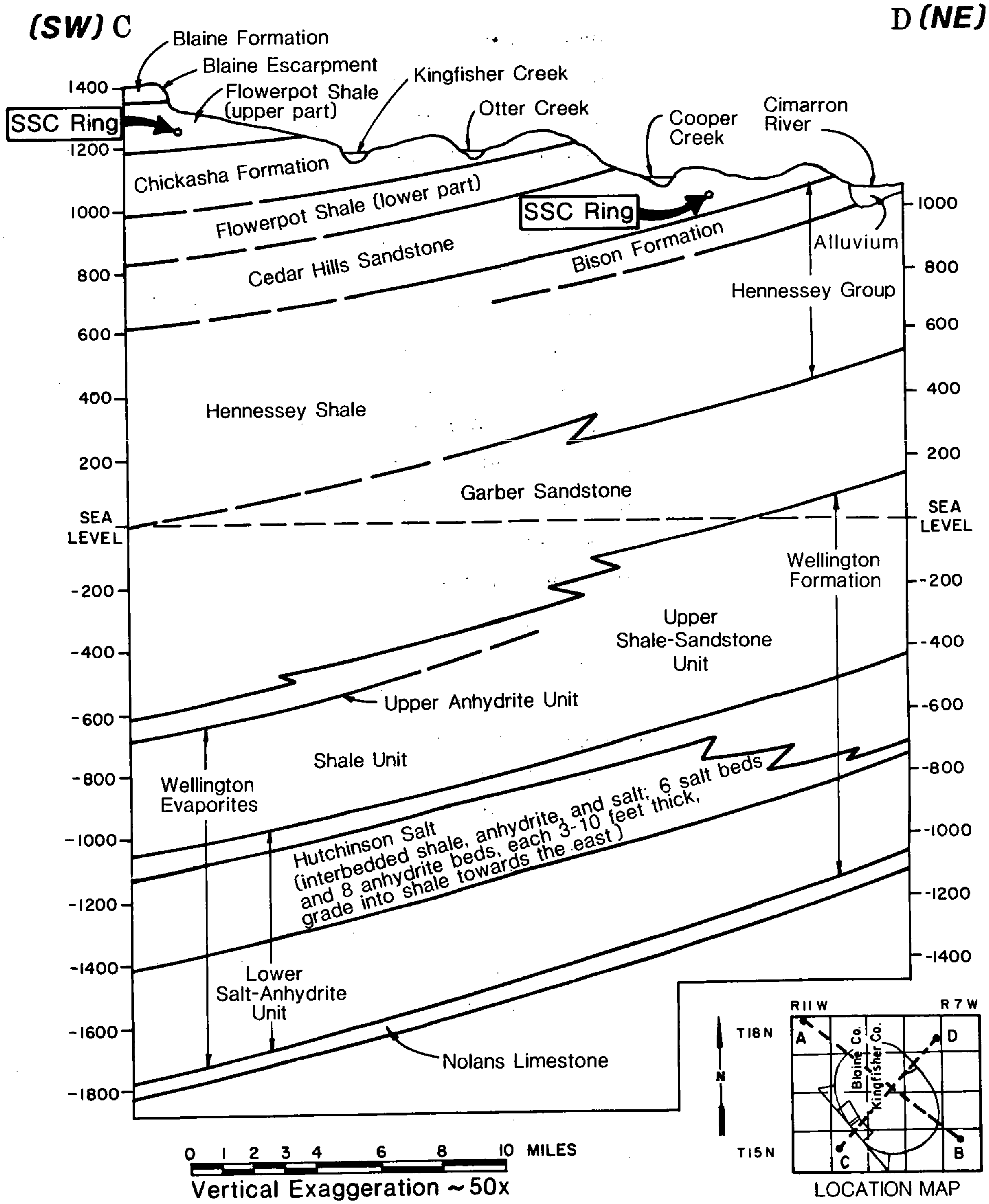


Figure 25. Schematic geologic section A-B showing Permian and Quaternary strata at proposed Oklahoma SSC site (looking northeast).



Note: Stratigraphic names on right side of figure are based on outcrop nomenclature (Oklahoma Geological Survey Hydrologic Atlases 4, 5, 7, 8); stratigraphic names on left side of figure are based on subsurface nomenclature (Jordan and Vosburg, 1963).

Figure 26. Schematic geologic section C-D showing Permian and Quaternary strata at proposed Oklahoma SSC site (looking northwest).

The Hutchinson salt contains the only salt present beneath the SSC site. The top of the salt layers ranges from about 1,800 to 2,500 ft below land surface in the wells drilled in the area (Pl. 1; Figs. 25 and 26), and thus is far below the depth at which salt dissolution has occurred at other areas in the Anadarko basin. Furthermore, individual salt beds are only 2-15 ft thick beneath the SSC site, and thus if one or several of the beds should be dissolved locally, the small cavity would be bridged by overlying competent strata and subsidence would not extend upward more than a few tens of feet.

In some of the western portions of the Anadarko basin, two other Permian salt units (the Flowerpot salt and the Upper Cimarron salt) are being dissolved by shallow ground water. This has caused subsidence and disruption of overlying strata (Jordan and Vosburg, 1963; Johnson, 1972, 1981). The nearest areas of such subsidence are at least 20 mi west of the SSC site, in parts of Custer, Dewey, Woodward, and western Woods Counties. In all those areas, thick salts equivalent to the upper part of the Flowerpot Shale have been dissolved where the salt beds are at shallow depths below the land surface. However, the Flowerpot salt was not deposited in or near the study area. Its easternmost limit of deposition was about 20 mi west of the site, but as a result of dissolution it is now limited to areas at least 30 mi west of the site (Jordan and Vosburg, 1963).

Dissolution of Upper Cimarron salt at its eastern limits has created natural brine springs at the head of Salt Creek Canyon, about 10 mi west of the SSC site, in T. 18 N., R. 12 W. There is no evidence of subsidence associated with the brine springs. The Upper Cimarron salt grades into parts of the Cedar Hills Sandstone and the upper Hennessey Shale about 10 mi west of the SSC site. This salt was not deposited in the vicinity of the site (Jordan and Vosburg, 1963).

In summary, the Hutchinson salt is the only salt-bearing unit that underlies the site. Also, there clearly is no evidence that any of the salt layers in the Hutchinson have been affected by dissolution. Overlying and interbedded strata are predominantly shales, mudstones, and siltstones that have exceedingly low permeabilities. There are no known aquifers or other water-bearing zones within or above the salt strata that could be a water source for dissolution of the salt, and such a source of unsaturated water is a requirement before salt dissolution can occur (Johnson, 1981). Eastward thinning and disappearance of individual salt beds beneath the SSC site are a result of depositional changes in the Permian rather than salt dissolution.

PETROLEUM DEVELOPMENT

The SSC site lies between major petroleum-producing areas in central Oklahoma, with the Sooner Trend to the north and east, the West Edmond field to the southeast, and the Watonga-Chickasha Trend to the west (Northcutt, 1985).

History of Petroleum Development

The first exploratory well in the area was the Plower Drilling Co. No. 1 Chalker, completed in 1918 as a 3,471-ft dry hole in sec. 7, T. 17 N., R. 8 W. However, significant exploration for petroleum in the area did not commence until just after World War II, by which time it was realized that the potential for finding petroleum lay primarily in strata >4,000 ft deep. The uppermost of the principal pay zones is within the Marmaton Group (Upper Desmoinesian), which occurs below 5,800 ft in the site area (Adkison, 1960; Fritz, 1978).

The petroleum-producing district that has become known as the Sooner Trend was discovered in 1945, and the West Edmond field was discovered in 1946. However, by 1955 there were only 88 wells, or about three per township, in Kingfisher County outside of the West Edmond field (Arnold, 1956). In Blaine County, there were only 20 wells prior to 1955, or less than one per township (De Jong, 1959). As the Sooner Trend developed and expanded to the south, its southern boundary was eventually defined on the northern edge of the site. Additional producing formations were established from 1951 through 1973. Other production in and adjacent to the area was established from 1961 through 1975. Although considerable exploration was conducted in the late 1970s and early 1980s only two small discoveries were made, one in 1979 (West Omega) and one in 1980 (South Omega). Figure 27 illustrates the producing fields; Figures 28 through 38 describe the areas of the major producing reservoirs that underlie the site. The most areally extensive production has been from three relatively deep reservoirs, the Chesterian (Fig. 34), the Osagean and Meramecian (Fig. 35), and the Hunton Group (Fig. 36).

Production characteristics for the area show that recovery rates are declining. An examination of leases intersected by the path of the collider ring, laboratories, and campus indicates that wells on 68% of those leases are classified as stripper wells. A stripper well yields <10 bbl of oil per day, or <60 Mcf (thousands of cubic feet) of gas per day. In fact, only four of 231 oil-producing wells in or adjacent to the site facilities yield >15 bbl of oil per day. Only six gas-producing wells yield >500 Mcf per day. All data are as of March 1987 and are based on run-ticket and division-order information of the Oklahoma Tax Commission.

Future Petroleum Development

The area has been explored extensively, and continuing exploration and development are expected to be light. The major petroleum accumulations have been delimited, with economic production having been established locally as deep as the Ordovician (Figs. 37 and 38). The established production in those reservoirs, as well as that from the overlying

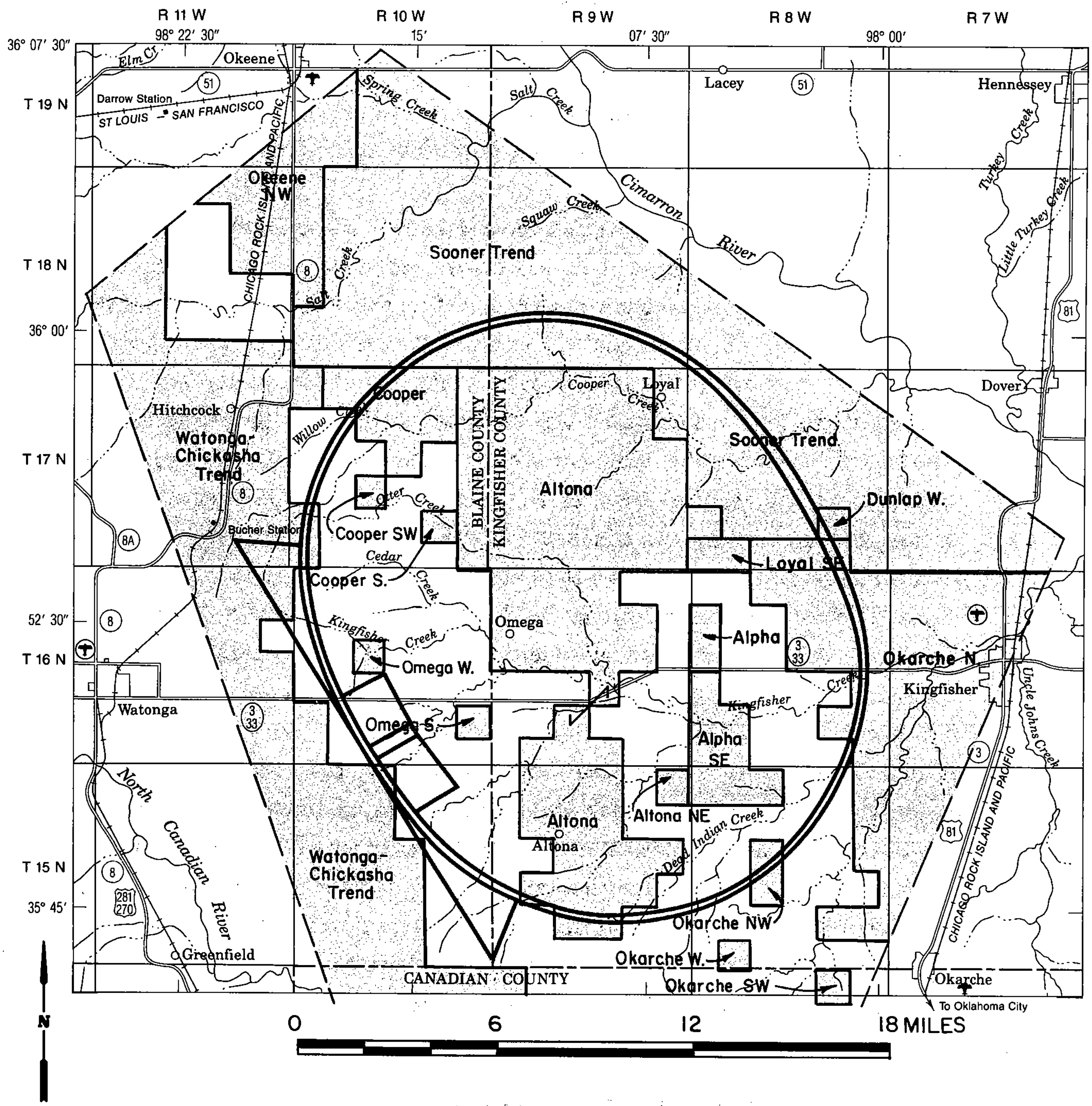


Figure 27. Oil and gas field boundaries in the vicinity of the proposed Oklahoma SSC site as recognized by the Oklahoma Nomenclature Committee of the Midcontinent Oil and Gas Association.

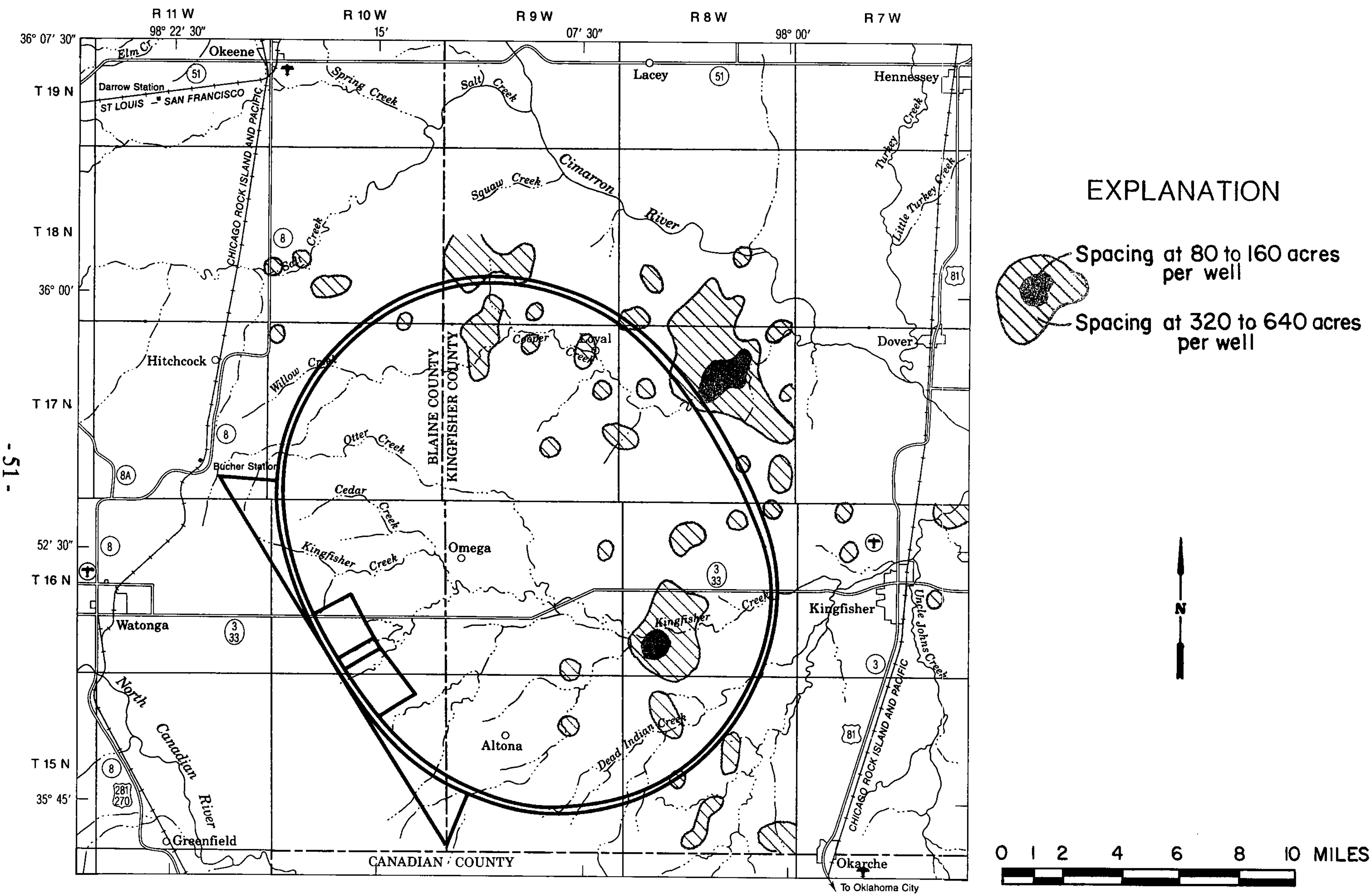


Figure 28. Total producing area of the Oswego and Big Lime Formations (upper Desmoinesian, Marmaton Group) in the immediate vicinity of the proposed Oklahoma SSC site.

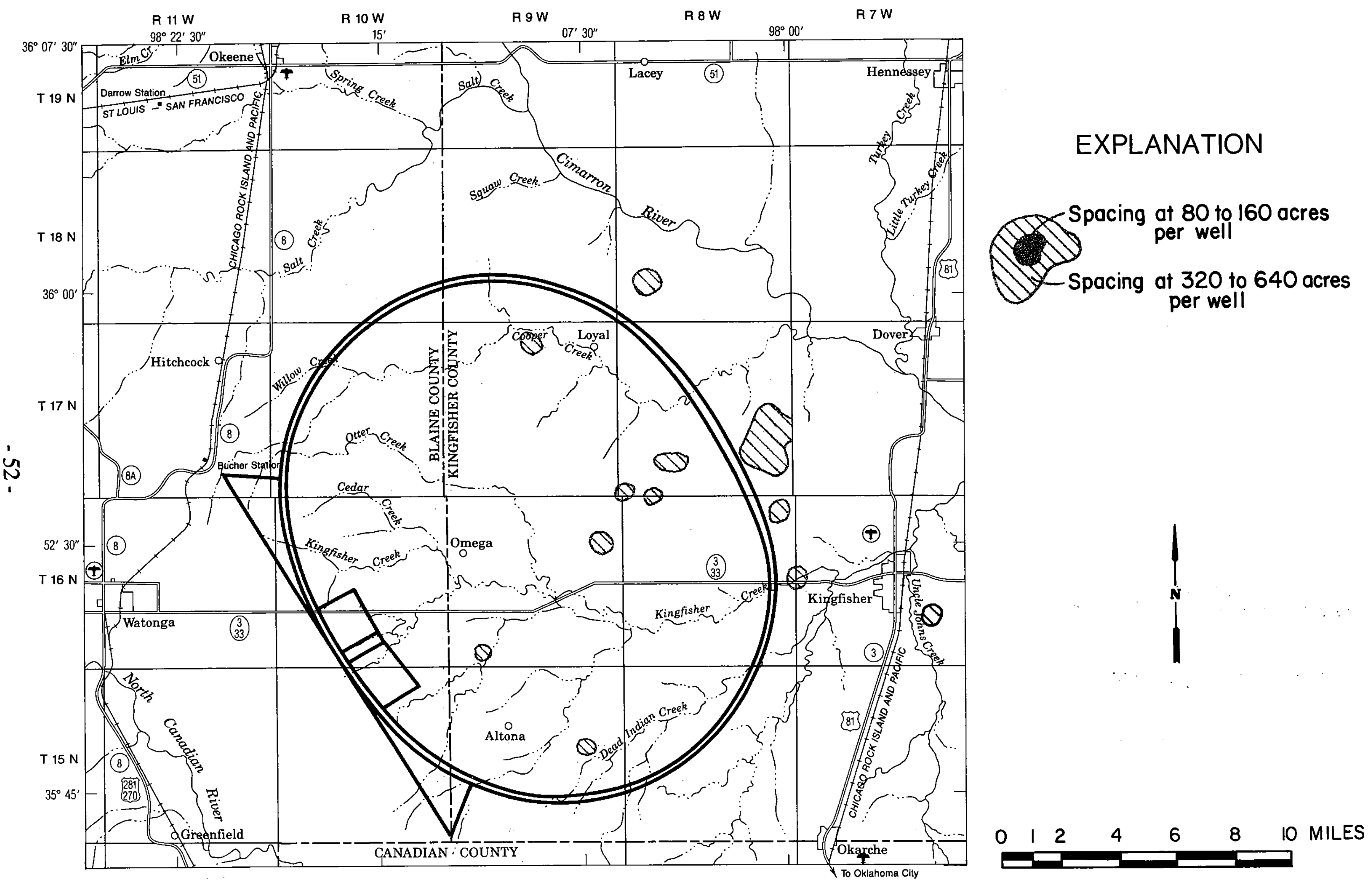


Figure 29. Total producing area of the Prue sand (lower Desmoinesian, Cherokee Group) in the immediate vicinity of the proposed Oklahoma SSC site.

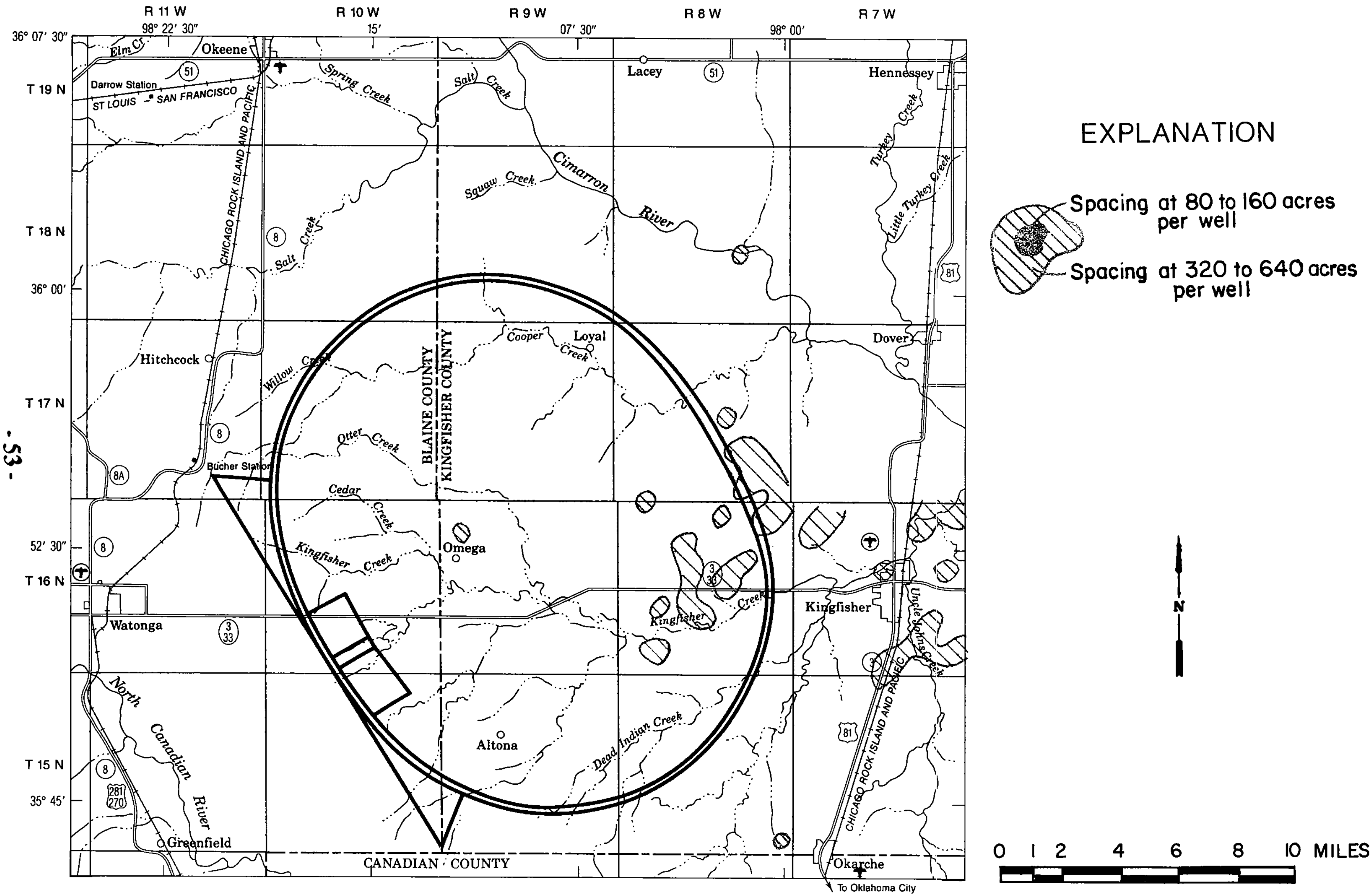


Figure 30. Total producing area of the Skinner sand (lower Desmoinesian, Cherokee Group) in the immediate vicinity of the proposed Oklahoma SSC site.

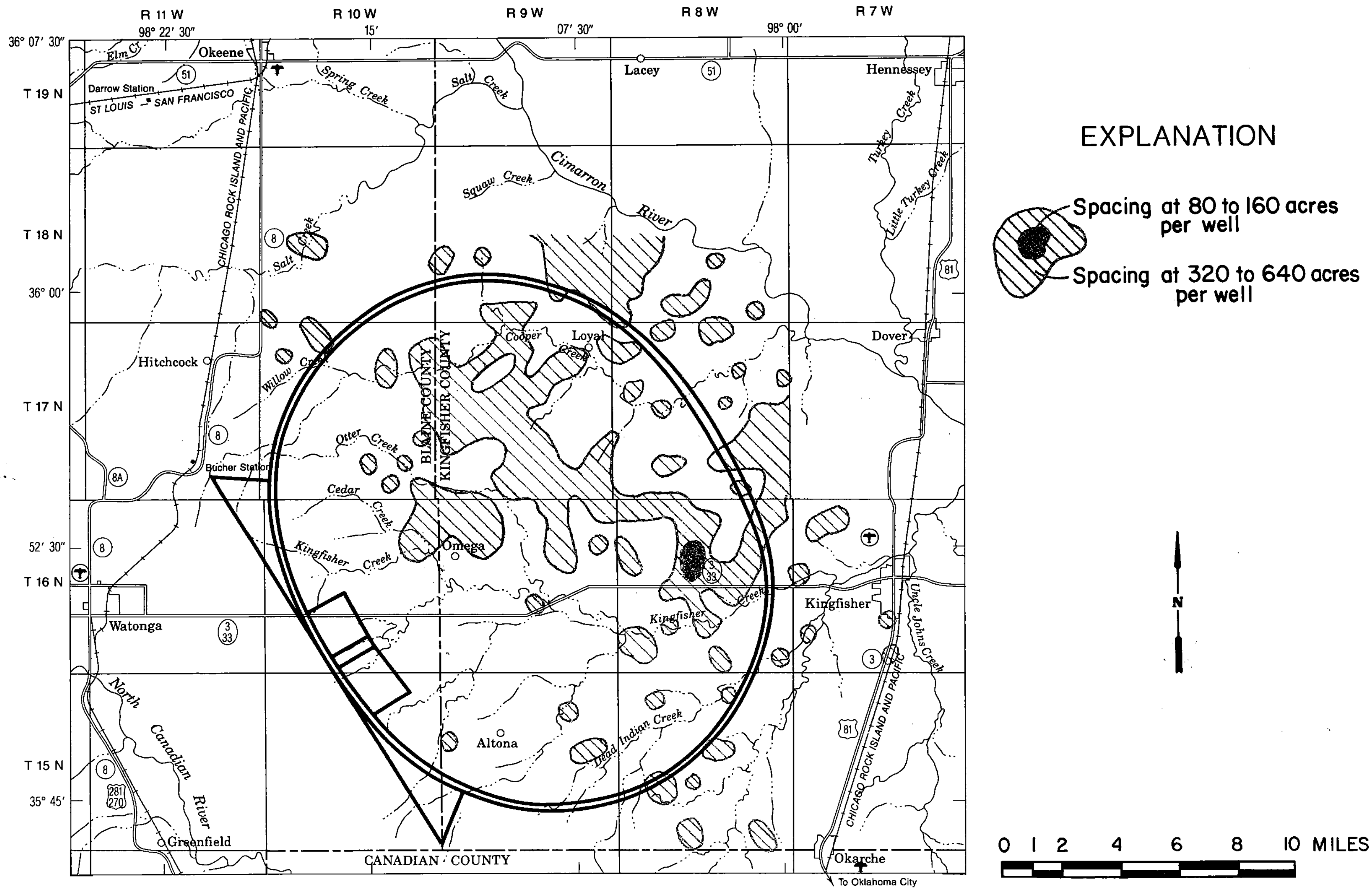


Figure 31. Total producing area of the Red Fork sand (lower Desmoinesian, Cherokee Group) in the immediate vicinity of the proposed Oklahoma SSC site.

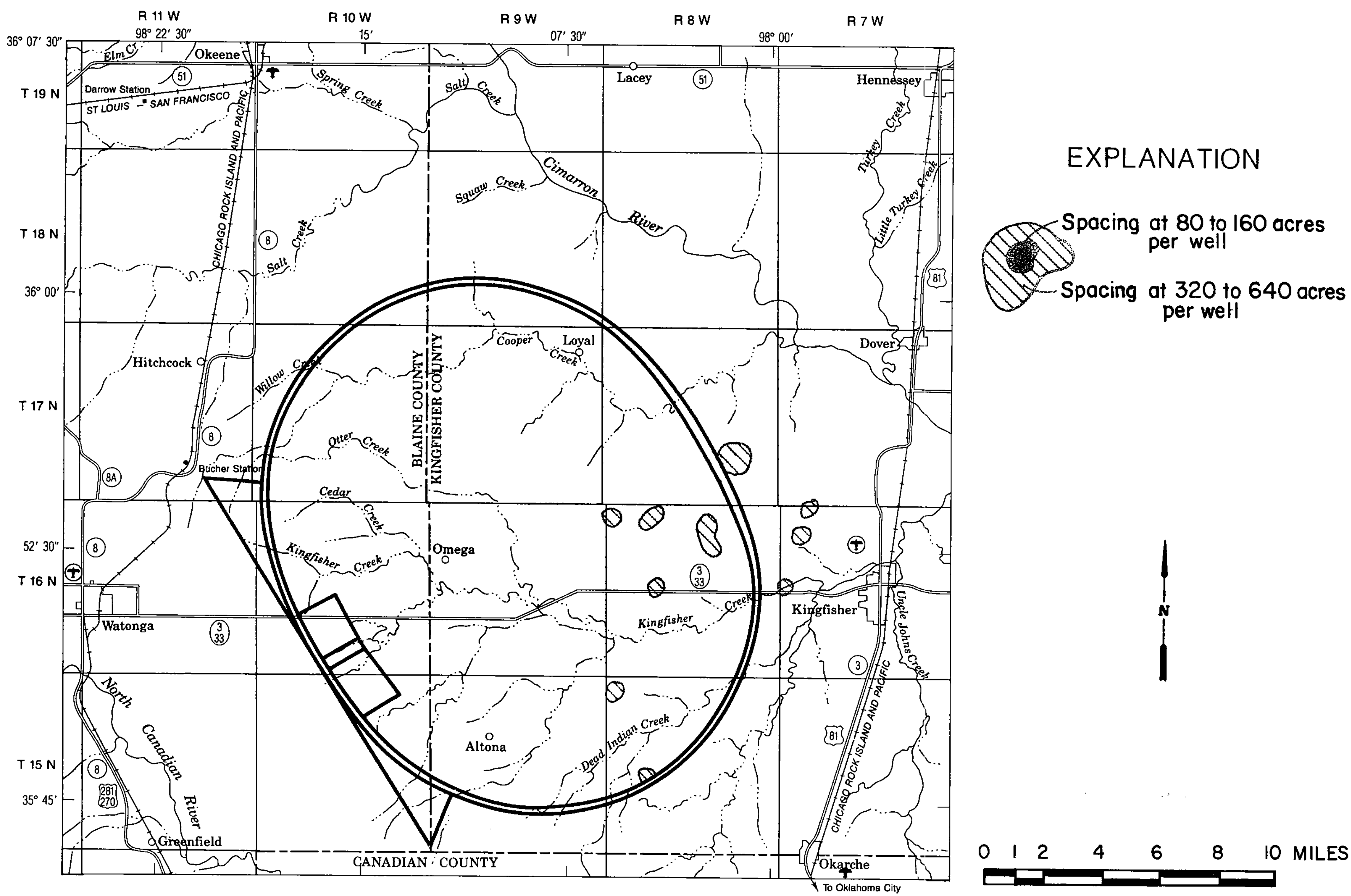


Figure 32. Total producing area of the Inola sand (lower Desmoinesian, Cherokee Group) in the immediate vicinity of the proposed Oklahoma SSC site.

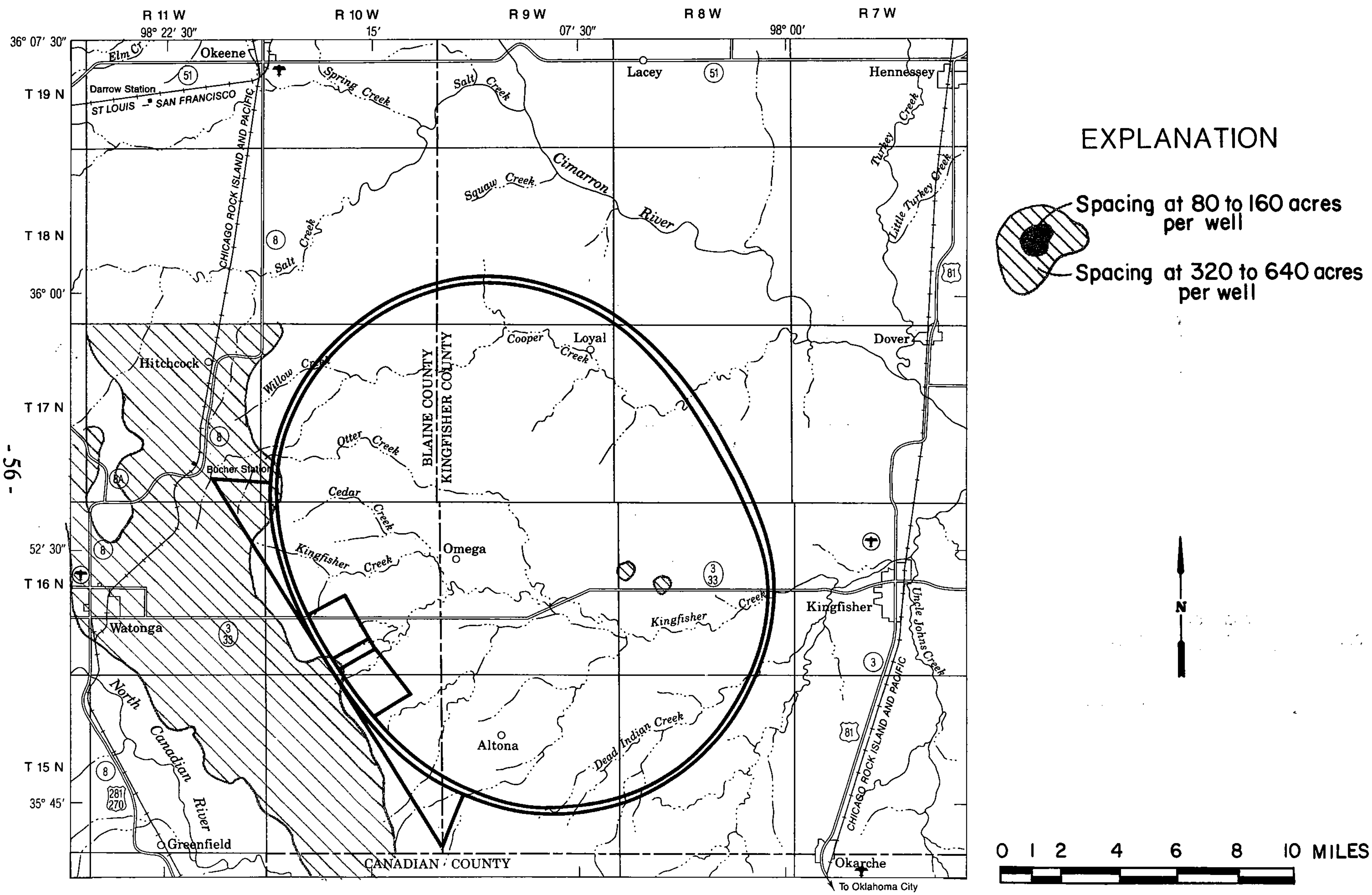


Figure 33. Total producing area of sandstone units within the Morrowan and Atokan Series in the immediate vicinity of the proposed Oklahoma SSC site.

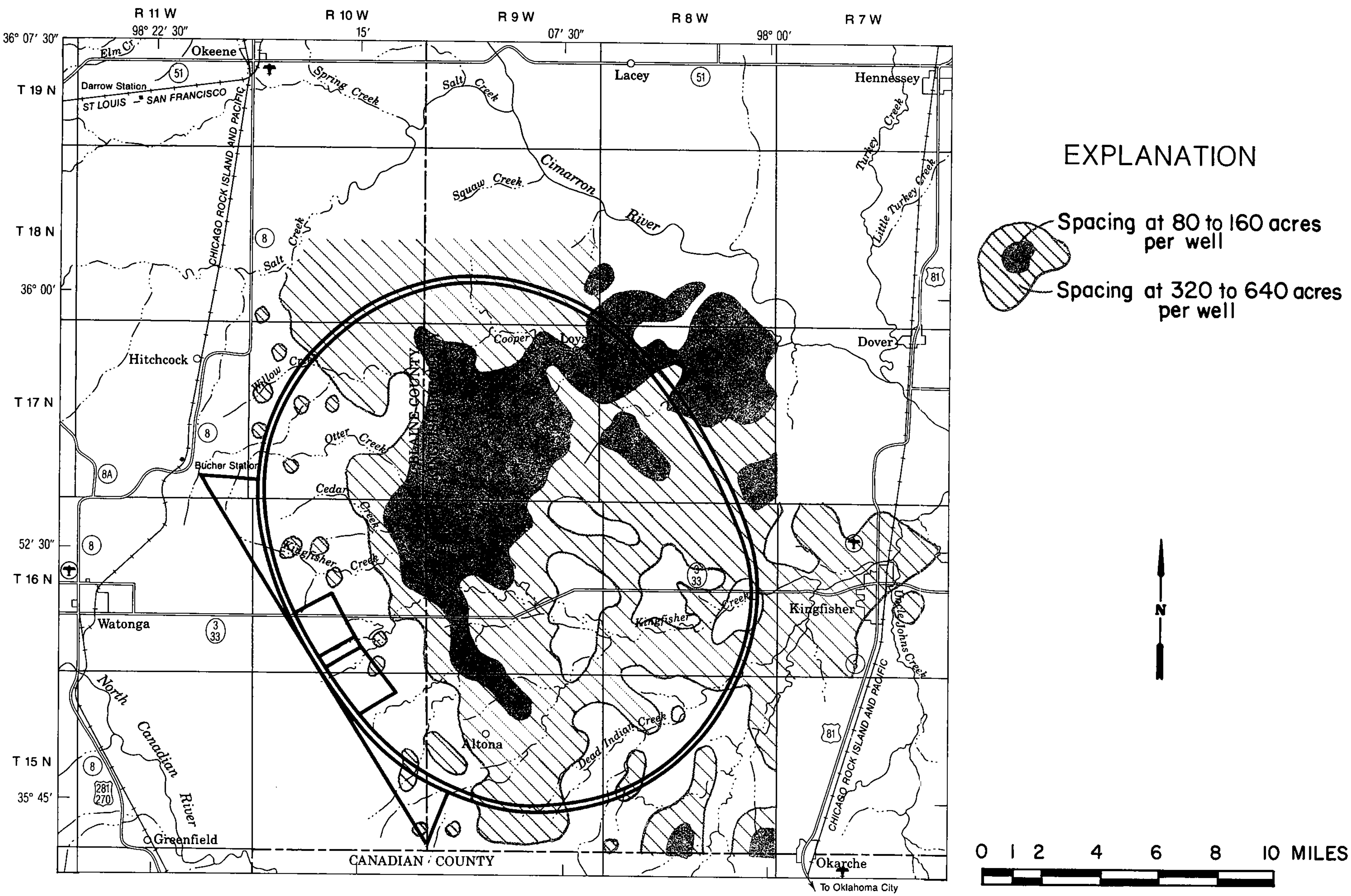


Figure 34. Total producing area of strata of Chesterian Series in the immediate vicinity of the proposed Oklahoma SSC site.

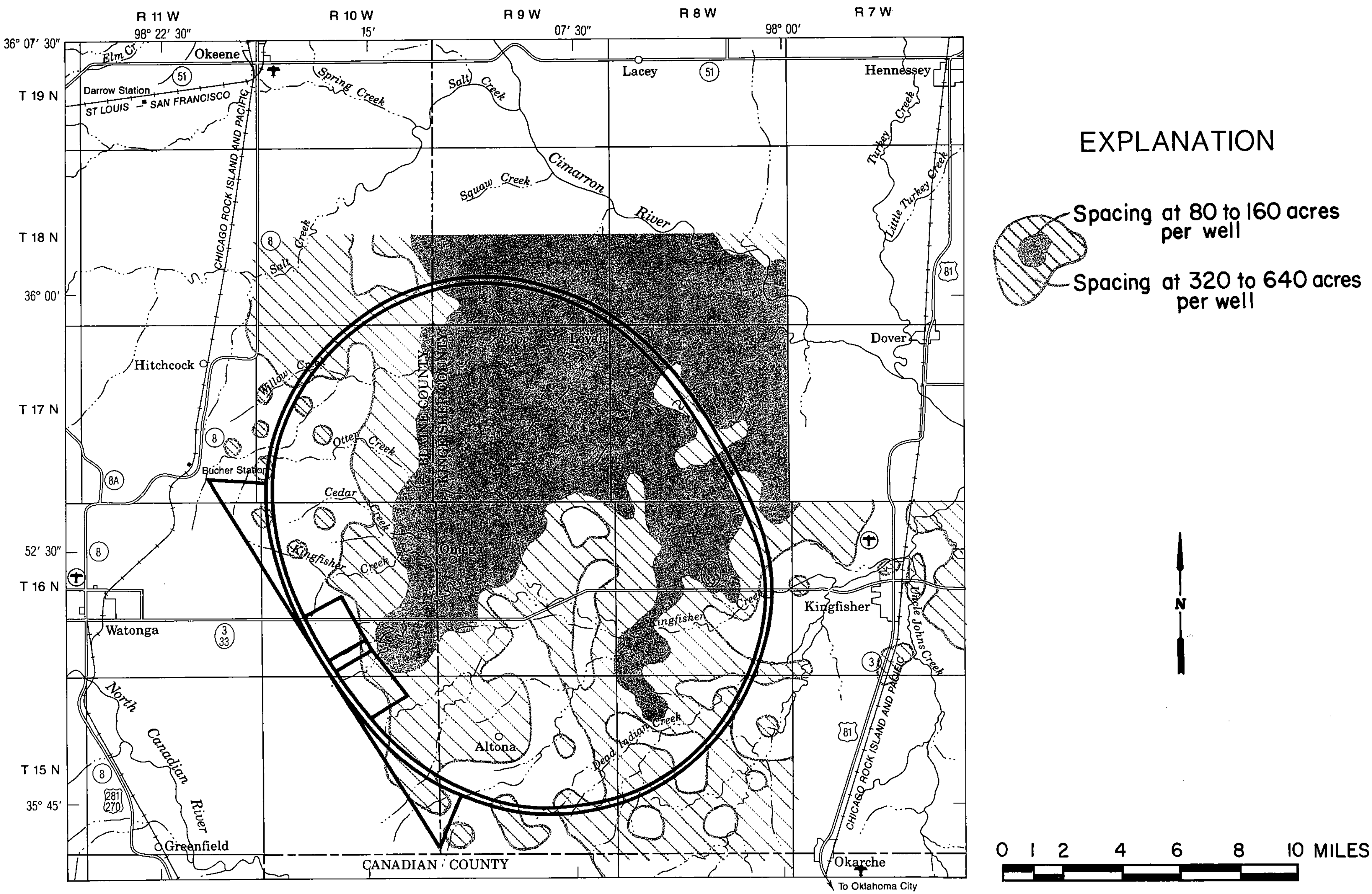


Figure 35. Total producing area of the Mississippi lime (Osagean and Meramecian Series) in the immediate vicinity of the proposed Oklahoma SSC site.

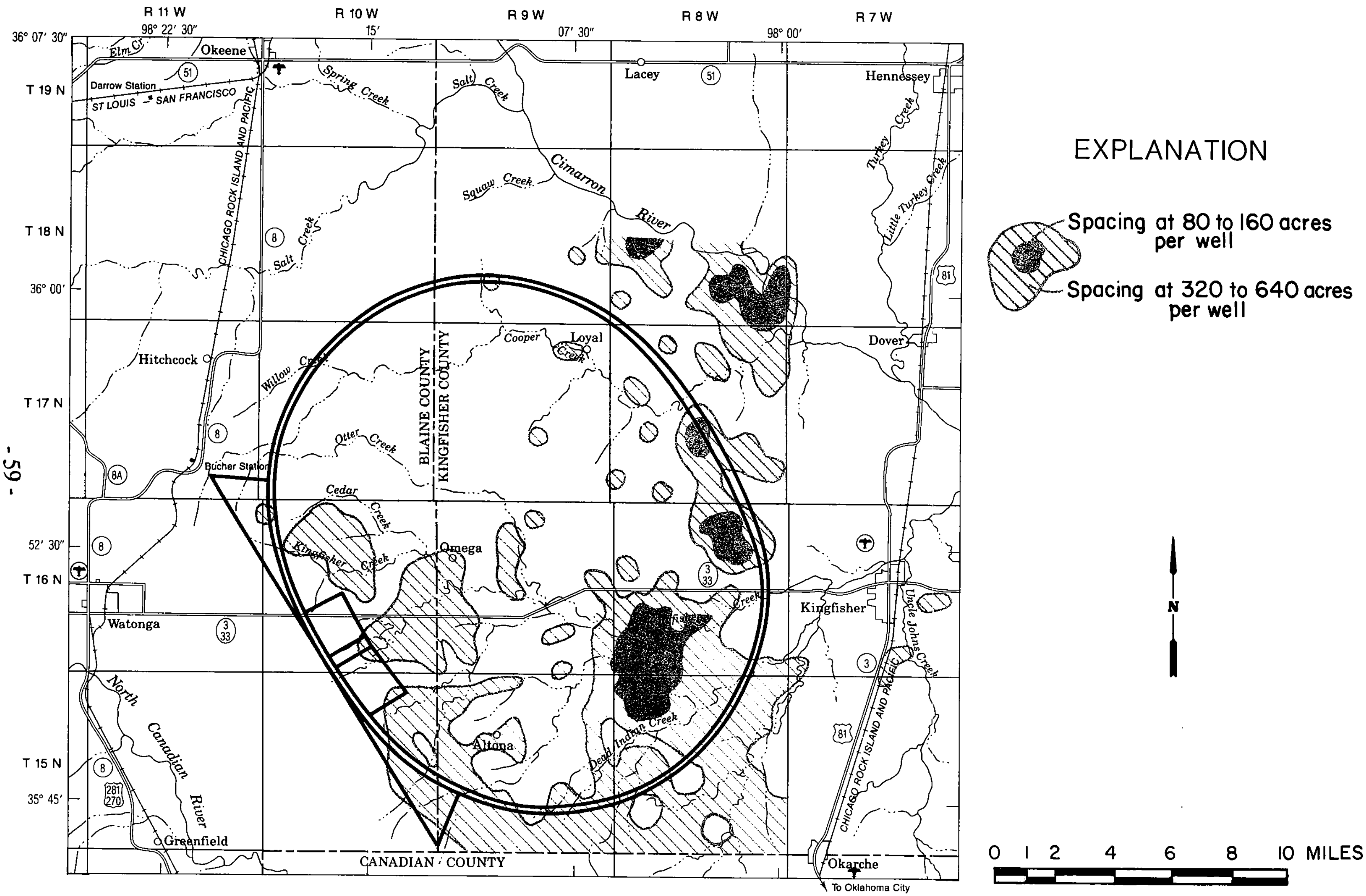


Figure 36. Total producing area of the Hunton Group (Silurian and Devonian) in the immediate vicinity of the proposed Oklahoma SSC site.

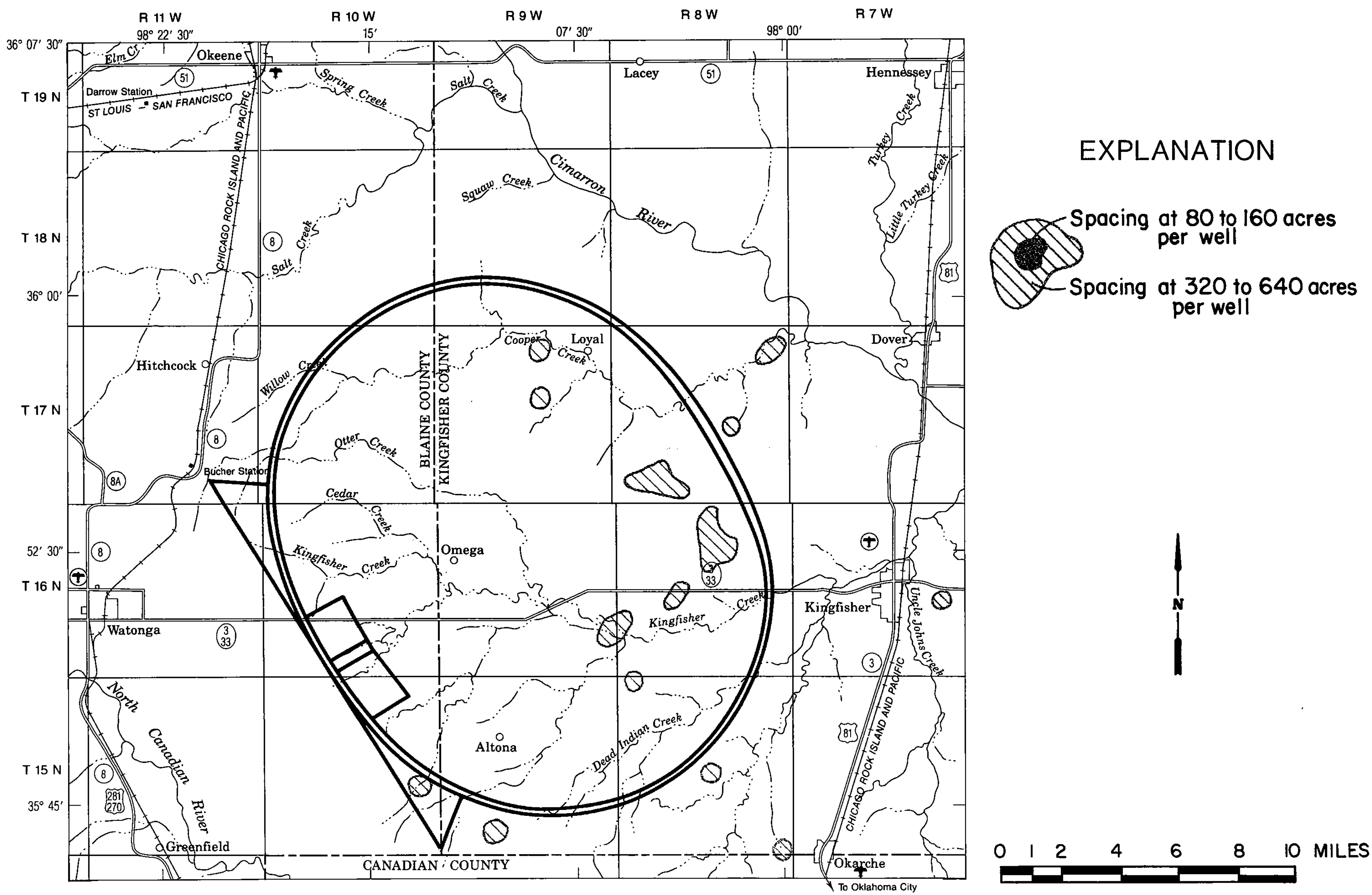


Figure 37. Total producing area of the Viola Group (Ordovician) in the immediate vicinity of the proposed Oklahoma SSC site.

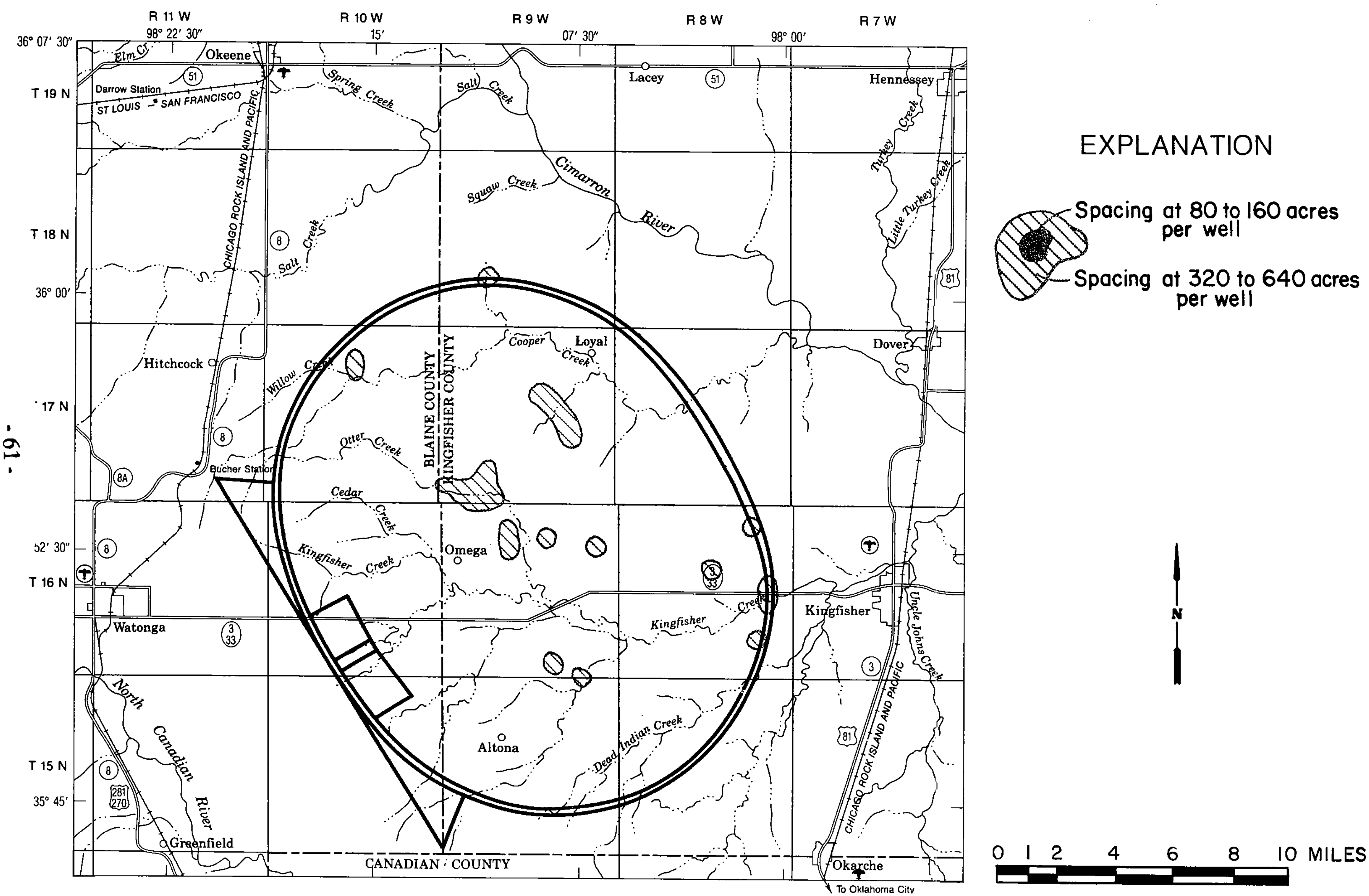


Figure 38. Total producing area of strata within the Simpson Group (Ordovician) in the immediate vicinity of the proposed Oklahoma SSC site.

Siluro-Devonian, Mississippian, and Pennsylvanian reservoirs, indicates that any future discoveries will occur in small, subtle stratigraphic traps. Indeed, the potential for their occurrence may be too small to warrant the risk of drilling. The Arbuckle Group, at 9,500-10,500 ft, remains the only major, lightly explored potential reservoir in the proposed SSC site area. The Arbuckle is understood to offer favorable prospects in the region on structural highs where reservoir conditions also occur in the unit. These strata have been tested on structural highs in the vicinity of the City of Kingfisher, but east of the site, without establishing production. One of these wells penetrates the entire sedimentary section to granite. Although numerous wells have been drilled to the Arbuckle in the region, especially along the Nemaha uplift, the nearest Arbuckle production is 38 mi southeast of the site, at the West Moore field, and about the same distance to the north-northwest at the Northwest Helena field. Therefore, it is apparent that there is little promise for future development of the Arbuckle in this area.

Relation of Petroleum to SSC Construction and Operations

Three aspects of hydrocarbon production (principally natural gas) in the vicinity of the ring alignment are discussed in this report: decommissioning of wells, hydrocarbon seepage, and subsidence.

Decommissioning of Wells

The Oklahoma Department of Transportation has established that 48 producing wells would be impacted by the ring and its associated structures. If 68% of these wells are stripper wells, as previously mentioned, then 33 of the 48 wells probably produce at stripper rates.

Operating wells along the alignment will be decommissioned using at least current Oklahoma standards that stringently require the following:

- That each petroleum-producing zone be plugged with cement, through a distance of 50 ft above and below that zone;
- That casing shall be set to 50 ft below the deepest potable water, with cement completely filling the annular space around the well casing. Upon abandonment, a cement plug must be set in the well, from 50 ft below the deepest potable water to 3 ft below ground surface;
- All intervals between cement plugs are to be filled with *mud*, a dense, oil- or water-based fluid, weighing ≥ 9 lb/gal.

Decommissioning of operating wells will be done prior to excavation or tunneling and will effectively prevent gas leakage into subsurface facilities during operations. Proposed regulations would require plugging from the surface through the producing zone (i.e., >5,000 ft below the surface in this area).

There are also seven dry and abandoned exploratory wells within the area of SSC construction (Table 6). All of these wells penetrated Pennsylvanian strata, and five of them were drilled well into rocks of Mississippian age. None recovered significant quantities of hydrocarbons. The formations tested either contained too little oil or gas to be produced, or the rocks lacked reservoir conditions. All of the wells were plugged and abandoned as dry. These wells will be checked to verify the quality of the seal, and prepared and re-plugged prior to or during excavation, if necessary.

Hydrocarbon Seepage

As the result of plugging procedures applied to operating and abandoned wells, there will be no hyrocarbon leakage into the SSC facilities. This area is not in one of the major petroleum-producing trends, and production is now mainly at a mature or old-age stage; therefore, reservoir pressures have declined, significantly reducing the risk of natural-gas leakage through the bedrock into the facilities. In fact, tests for methane gas in bore holes drilled for this report along the ring alignment were negative.

Oil and natural gas seeps have not occurred in the SSC area. In other areas evidence for natural hydrocarbon seepage through red beds is a color change from red to buff or tan owing to reduction of oxidized iron by hydrocarbons. No such evidence is present in the proposed SSC site area. More than 5,000 ft of strata overlie the shallowest petroleum reservoir below the site. The uppermost 2,400 ft of those strata are predominantly impermeable mudstones, shales, and evaporites, which effectively seal the site from natural hydrocarbon seepage.

Subsidence

Subsidence related to petroleum fluid withdrawal is not a problem at this site. No subsidence above oil and gas fields has been identified in Oklahoma, in spite of its 96-yr history of petroleum production. While subsidence due to fluid withdrawal has been observed in other parts of the country, it typically occurs where the sediments of the fluid reservoirs and the overlying strata are young, unconsolidated sediments. Petroleum production in Oklahoma is from old (Paleozoic), well-lithified rocks of substantial strength, and the oil and gas reservoirs are largely overlain by old rocks of a similar mechanical

TABLE 6.—ABANDONED WELLS ASSOCIATED WITH SSC FACILITIES

Location	Operator and Lease	SSC Location	Total Depth and Rock Unit	Rock Units Tested	Date Plugged
Watonga, SE Quadrangle					
1. NE/SW 3, T. 15 N., R. 10 W.	Pan American Pierce Unit "B"	Area B	9,500 ft Mississippian	Red Fork[a] Morrow[a] Mississippian[b]	8/05/65
2. SW/SW 3, T. 15 N., R. 10 W.	Vanderbilt Resources no. 1 Eddie Bohr	Ring Path	9,390 ft Mississippian	Chester[a]	1/31/80
3. Ctr./NW 10, T. 15 N., R. 10 W.	Marlin Oil Co. no. 1 Loosen	Area I	9,335 ft Morrow	Morrow[b]	6/11/75
Hitchcock Quadrangle					
4. Ctr./NW 6, T. 16 N., R. 10 W.	Continental Oil Co. no. 1 Rice	Ring Path	8,950 ft Mississippian	Mississippian[b]	8/05/75
5. Ctr./NW 7, T. 16 N., R. 10 W.	May Petroleum, Inc. no. 1 Veatch	Ring Path	9,150 ft Mississippian	None	2/11/82
6. SE/NW 12, T. 16 N., R. 11 W.	Texaco, Inc. no. 1 Hazel Dyke	Area I	9,350 ft Mississippian	Oswego[c] Morrow[a] Chester[a]	5/24/62
7. SE/SE 36, T. 17 N., R. 11 W.	Petroleum, Inc. no. 1 Parvin Unit	Area I	8,925 ft Morrow	Inola[a] Morrow[a]	11/27/78

[a]No hydrocarbons recovered.
[b]Recovered minor amounts of gas (too small to measure), and no oil.
[c]Recovered 5 barrels of oil, and no gas.

nature. This rock has sufficient strength to sustain the load of overlying strata without significant deformation that would result in subsidence. Furthermore, much of Oklahoma, including the SSC site area, is in a mature state of petroleum development, in which reservoir pressures have diminished significantly. If subsidence due to petroleum withdrawal were to occur in Oklahoma, it is likely that it would have developed some time ago.

Conclusions

- Major hydrocarbon accumulations have been delimited, and those as yet undiscovered will occur primarily in stratigraphic traps of a very subtle nature and small size.
- The area is best described as a mature producing area, with limited remaining potential. Production rates of wells in the area are generally low.
- Reservoir pressures are typically low, thus significantly reducing the probability of upward migration of hydrocarbons. The presence of 2,400 ft of overlying Permian shales and evaporites further reduces that probability.
- There is no significant risk of subsidence related to petroleum fluid withdrawals in the area.

SEISMICITY AND FAULTING

Seismicity

Introduction

The Oklahoma site has experienced only low horizontal ground acceleration due to historical earthquakes, and it is in seismic hazard Zone 1 of the Uniform Building Code (UBC). Consideration of data available from the statewide network (Fig. 39) of high-gain seismographs run by the Oklahoma Geophysical Observatory since 1977, and related geologic data, support the conclusion that the site is one of low seismic hazard.

Preinstrumental Seismicity

There are only sparse early historical seismicity data in Oklahoma because it is in a region of low seismicity. Before 1900, only two earthquakes are known to have occurred in Oklahoma. During the period 1900-60, 52 earthquakes were located in Oklahoma based on felt, or damage, reports (Fig. 40; Lawson and others, 1979). Seismographs in surrounding states gave some limited magnitude and location information on a few of these felt earthquakes.

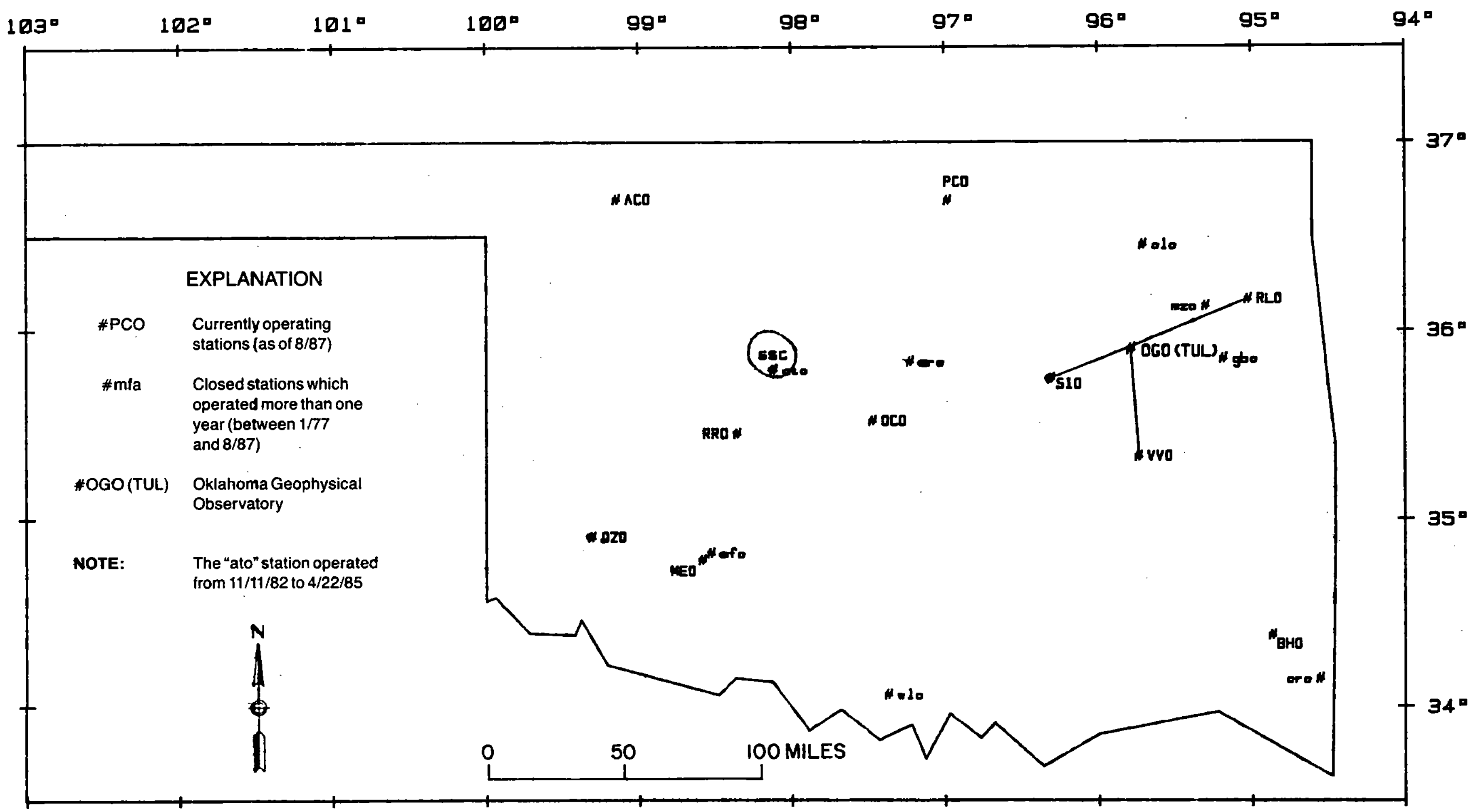


Figure 39. Oklahoma seismographic network of the Oklahoma Geological Survey.

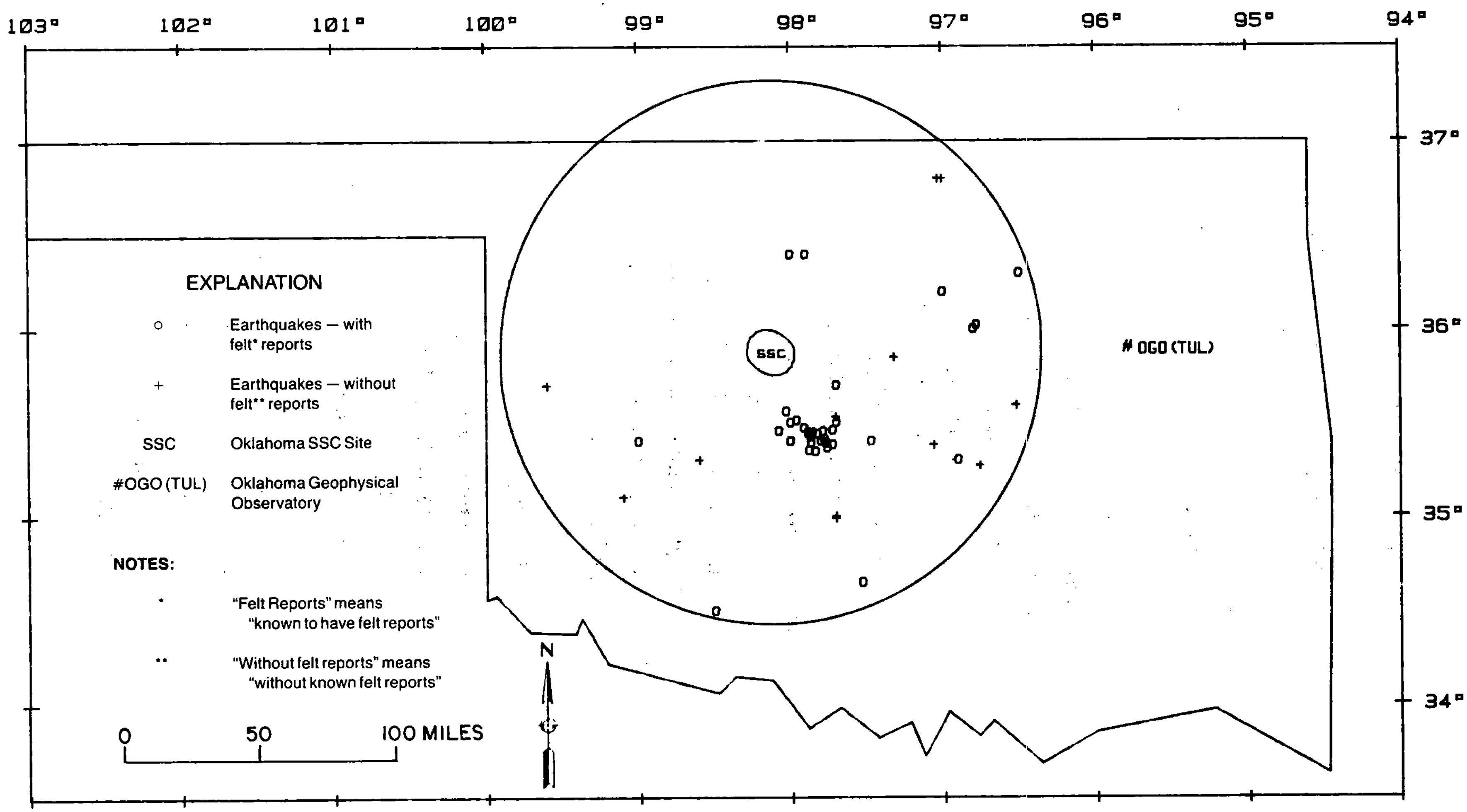


Figure 40. All earthquakes between 1900 and 1976 within 100 mi of the proposed Oklahoma SSC site.

Seismicity Since Instrumentation

Characterization of seismicity in the vicinity of the Oklahoma SSC site has been greatly enhanced since 1960 by the sensitive seismic network operated by the Oklahoma Geophysical Observatory for the Oklahoma Geological Survey (OGO/TUL on Fig. 39).

The Observatory (located near Leonard, in Tulsa County) began continuous seismic recording in December 1961. During the period 1962-76, the seismograms from the Observatory aided in the location of 74 earthquakes in Oklahoma; only 27 of these were felt. In 1977, a statewide network of sensitive seismographs was installed. This network, along with the outline of the proposed collider ring, is shown in Figure 39. At any given time since 1977, from 10 to 13 of the stations have been operative. The network identified 309 earthquakes within 100 mi of the SSC site between January 1, 1977, and March 31, 1987 (Fig. 41). All of these earthquakes were less than magnitude 3.5; only 32 were magnitude 2.5 to 3.5 (Fig. 42) and only six were magnitude 3.0 to 3.5 (Fig. 43).

The Altona seismograph station (*ato* on Fig. 39) provides a particularly useful record for the Oklahoma SSC site. The station is located just inside the proposed collider ring alignment, and thus provides an unusually site specific substantiation of the network data set. The Altona seismograph recorded for 463 days, mostly in 1983 and 1984. Significantly, *ato* recorded no earthquake which was not well recorded at a minimum of three other network stations (typically five to 11 other stations). Monitoring in the immediate vicinity of the collider ring did not detect earthquakes that would have been missed by any configuration of the network since 1977; therefore, it is concluded that the network record is an adequate representation of seismic activity at the site.

Ground Motion due to Historical Earthquakes

The Oklahoma SSC site can be confidently characterized as one that has experienced only low horizontal ground acceleration. Only 10 earthquakes are estimated to have caused horizontal ground acceleration at the collider ring center in excess of 0.01 g (Table 7), using Nuttli's (1973) mbLg magnitudes and Nuttli and Herrmann's (1978) ground motion attenuation formulae.

Three of the four earthquakes causing greatest estimated site accelerations are the 1811-12, New Madrid, Missouri, events. The fourth earthquake was the 1952 El Reno, Oklahoma, event. The felt area for the El Reno earthquake implies a magnitude of 4.9, based on Nuttli and Zollweg (1974). This estimate is very similar to that which was found in a recent study of seismic hazard for the central and eastern United States (McGuire, 1986).

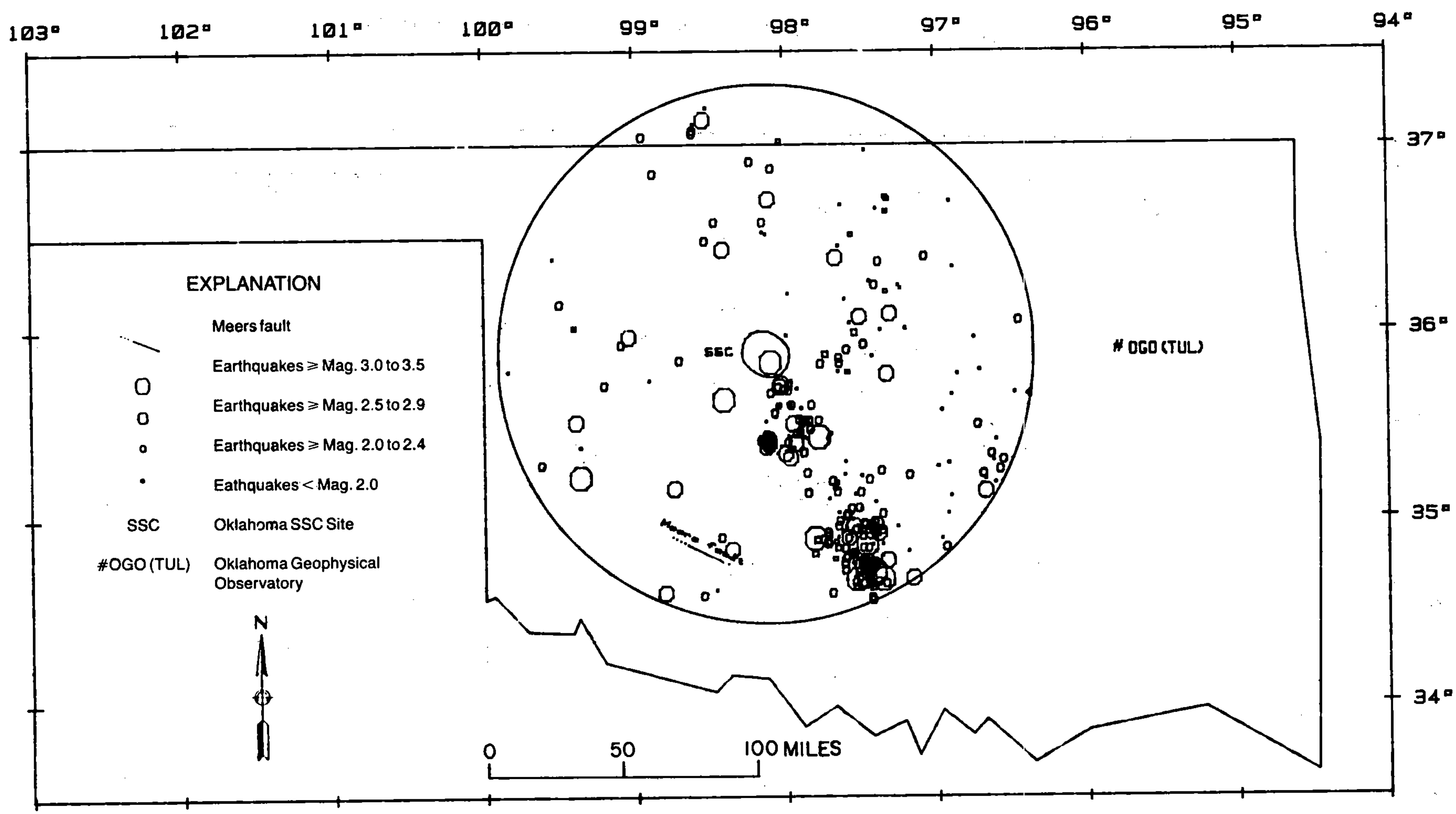


Figure 41. Network-located earthquakes within 100 mi of the proposed Oklahoma SSC site.

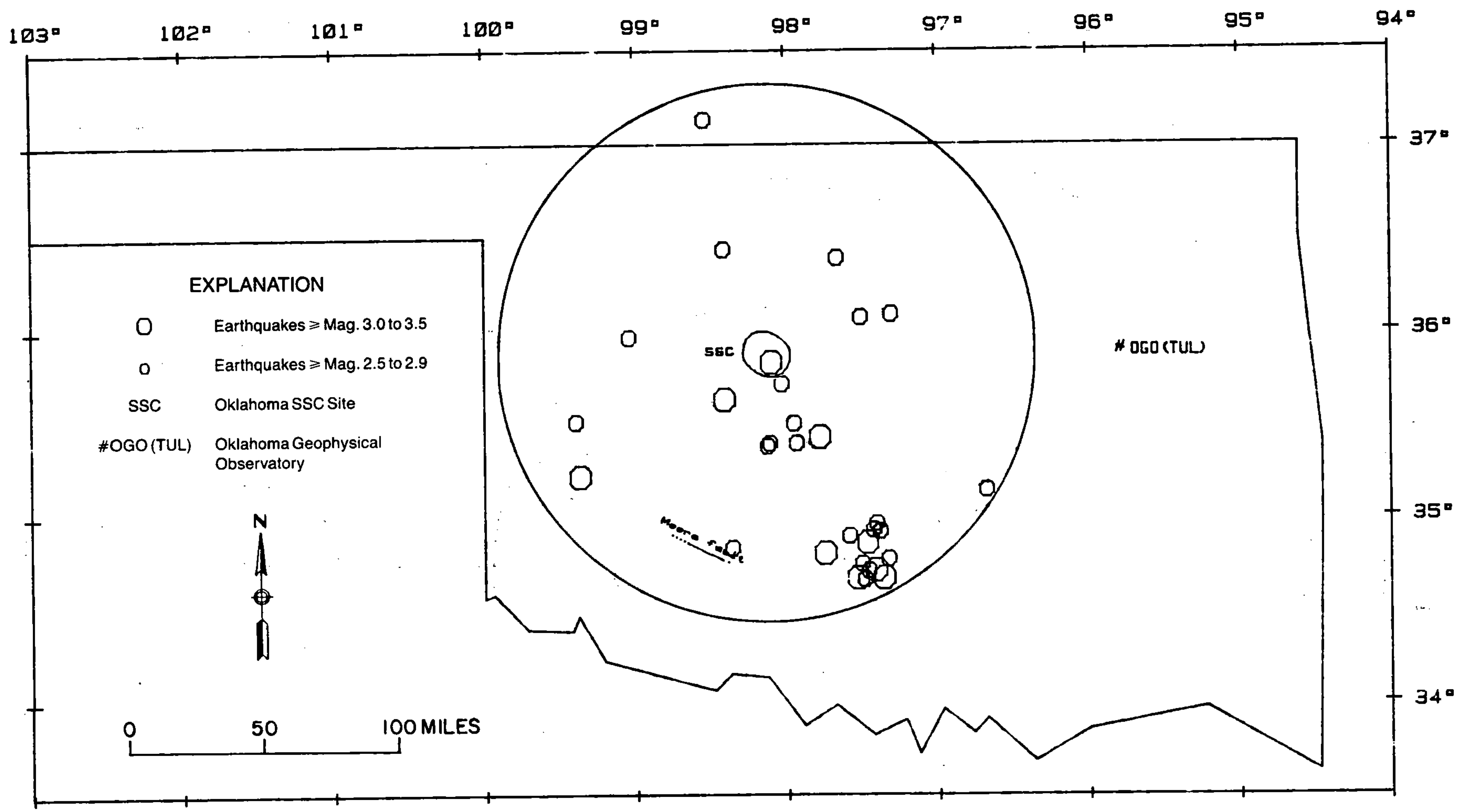


Figure 42. Earthquakes of magnitude 2.5 to 3.5 within 100 mi of the proposed Oklahoma SSC site (1/1/77 to 3/31/87).

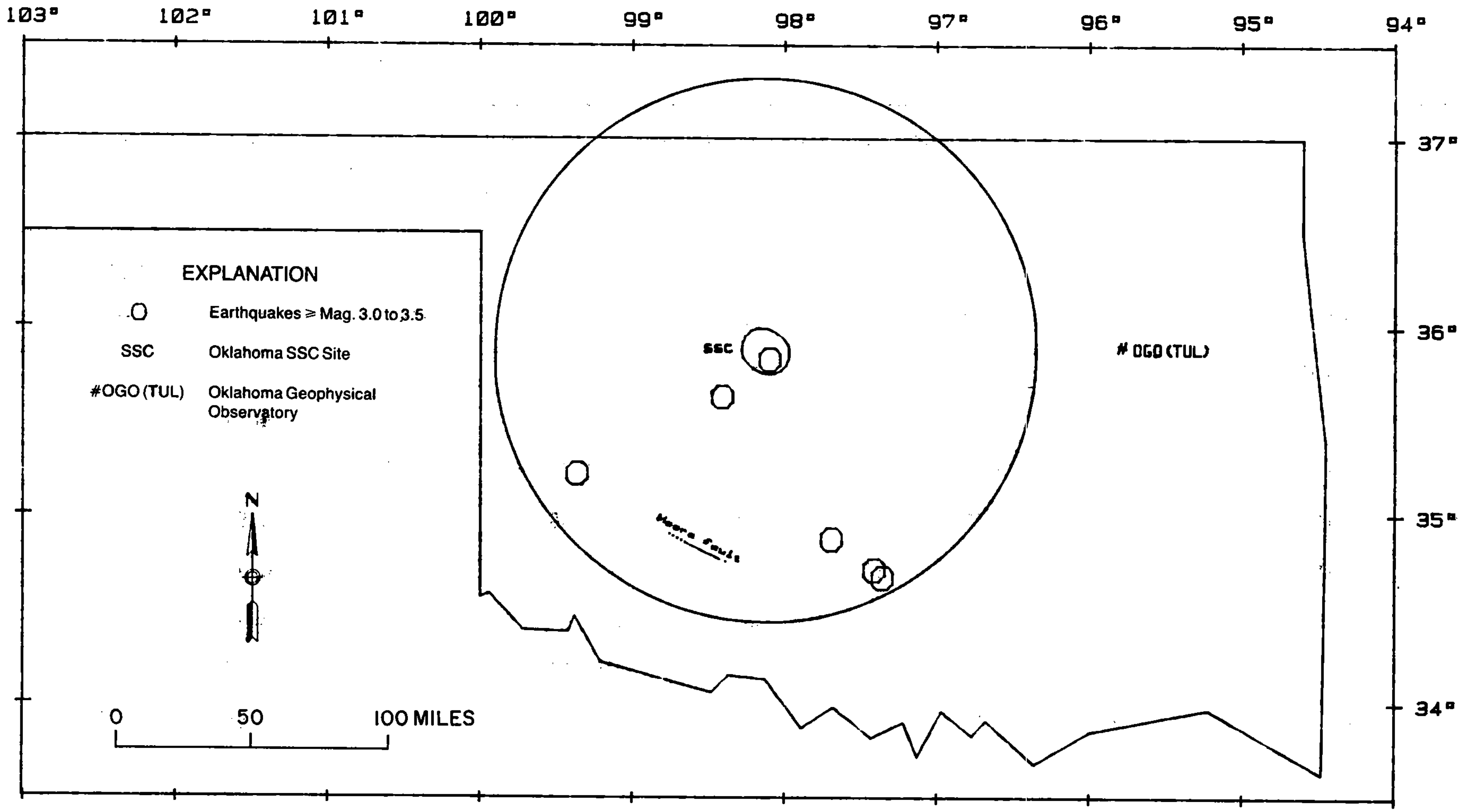


Figure 43. Earthquakes of magnitude 3.0 to 3.5 within 100 mi of the proposed Oklahoma SSC site (1/1/77 to 3/31/87).

TABLE 7.—HISTORICAL EARTHQUAKES EXPERIENCED AT THE OKLAHOMA SITE

Year	Date	Time	Latitude °N	Longitude °W	State	MM	MAG	Delta (mi)	Delta (km)	Ah (g)	Vh (cm/sec)
1812	02-07	0945	36.600	89.600	MO	12	7.4	478.0	769.3	0.057	39.2
1811	12-16	0815	36.600	89.600	MO	12	7.2	478.0	769.3	0.046	24.8
1952	04-09	1629	35.400	97.800	OK	7	5.0	39.5	63.5	0.043	2.1
1812	01-23	1500	36.600	89.600	MO	12	7.1	478.0	769.3	0.039	19.7
1987	01-24	1608	35.828	98.097	OK	5	3.1	5.5	8.9	0.018	0.1
1929	12-28	0030	35.500	98.000	OK	6	4.0	28.7	46.2	0.018	0.3
1953	03-17	1425	35.400	98.000	OK	6	3.8	35.4	57.0	0.011	0.1
1952	04-16	0605	35.400	97.000	OK	5	3.8	39.5	63.5	0.010	0.1
1952	04-11	2030	35.400	97.800	OK	4	3.8	39.5	63.5	0.010	0.1
1952	04-16	0558	35.400	97.800	OK	Felt	3.8	39.9	63.5	0.010	0.1

Notes: Events are listed in order of acceleration experienced at the SSC site.
Edmond event not attributed to a seismic source (see Lawson, 1984).
Modified Mercalli (MM) intensities are at the epicenter for each event.

The earthquake causing the fifth largest acceleration at the site was a January 24, 1987, mbLg 3.1 earthquake just inside the ring. It produced MM V felt effects over an area including part of the ring. This earthquake produced a calculated horizontal ground acceleration of 0.018 g over most of the ring site.

The remaining five earthquakes that caused estimated horizontal ground accelerations at the site $\geq$0.01 g were all aftershocks of the 1952 El Reno earthquake.

Site-Specific Maximum Horizontal Ground Acceleration

Two independent estimates of site maximum horizontal ground acceleration are considered for the Oklahoma SSC site. The first is developed from a conservative extension of an earlier study of the Arcadia, Oklahoma, dam site about 7 mi northeast of Oklahoma City (Lawson, 1985). The second is taken directly from seismic hazard maps published by the USGS (Algermissen and others, 1982).

It is estimated that the maximum horizontal ground acceleration that will be experienced at the Oklahoma site during the 25-yr life of the facility will be $\leq$0.05 g. The estimate is based on the Oklahoma Geological Survey seismic source zones for Oklahoma and surrounding areas (Lawson, 1985; Fig. 44), developed for the Arcadia dam project.

The methodology of this study combined elements of both probabilistic and deterministic ground motion characterization. Seismic sources and maximum magnitude events within these sources for various periods of time were estimated from the spatial and temporal pattern of historical seismicity. Horizontal ground accelerations at the SSC site from the largest earthquake in each source zone (Fig. 44) during several time intervals were next found using the acceleration attenuation relationships of Nuttli and Herrmann (1978).

The site-specific maximum horizontal ground acceleration for the Oklahoma SSC, based on these source zones, is about 0.04 g within a 50-yr period (Table 8). The maximum horizontal acceleration for a 250-yr period is about 0.08 g. In both cases, the time-interval dependent maximum expected earthquake is assumed to occur at the nearest point of the zone to the ring.

The USGS study (Algermissen and others, 1982) presents 90- and 475-yr accelerations at the site based on a broad characterization of seismic source zones and source zone parameters and acceleration attenuation relationships modified for use in the central and eastern United States from Schnabel and Seed (1973). According to the maps in this study, the 90-yr site horizontal acceleration is $<$0.04 g, and the 475-yr site horizontal acceleration is about 0.05 g. Thus, the USGS (Algermissen and others, 1982) methodology leads to roughly comparable, but somewhat lower estimates of site hazard than does the

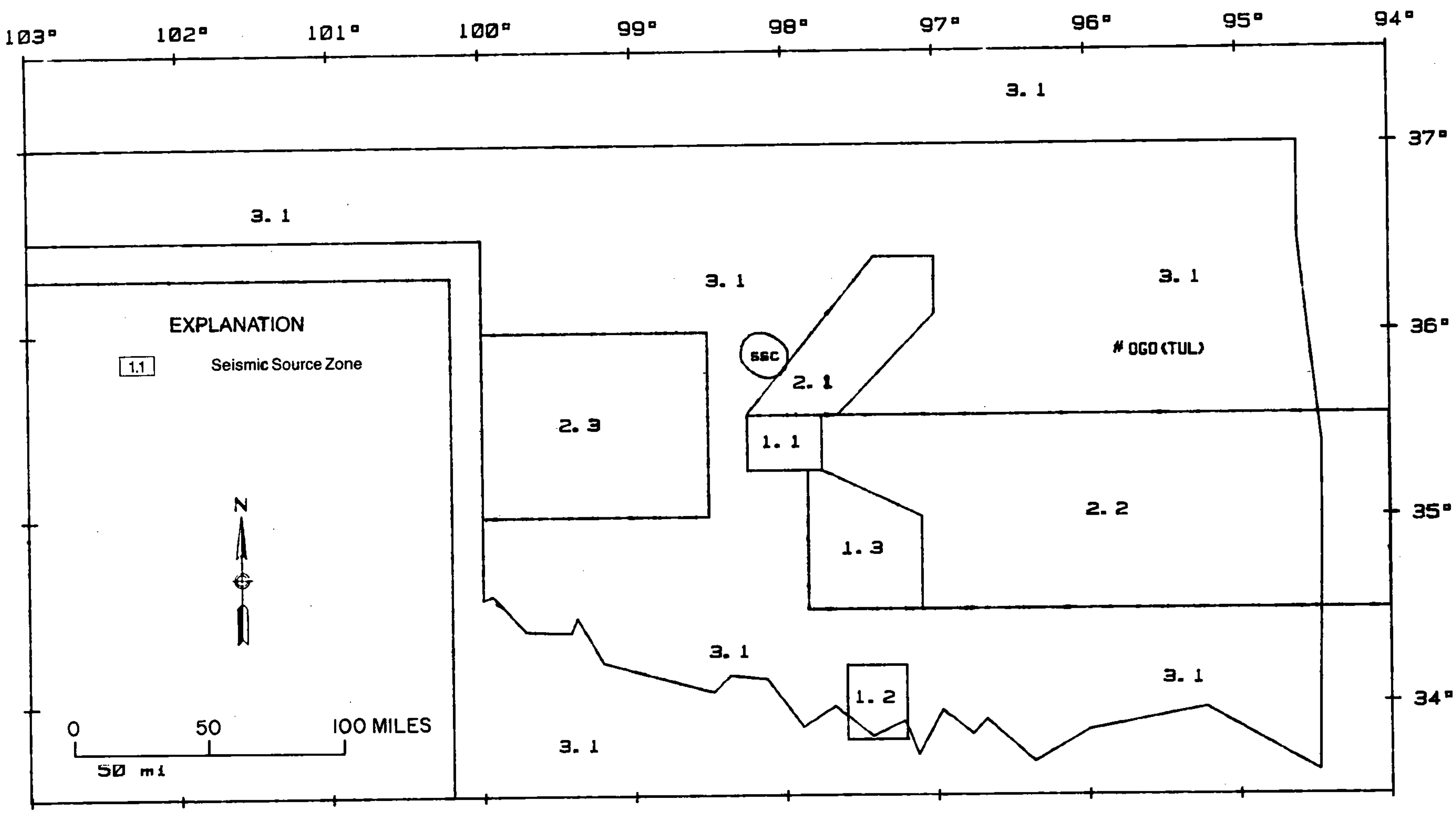


Figure 44. Seismic source zones in Oklahoma and surrounding areas. Modified from Lawson (1985).

TABLE 8.—MAXIMUM HORIZONTAL GROUND ACCELERATION FOR THE OKLAHOMA SSC SITE BASED ON OGS SOURCE ZONES

Zone	Distance of Point of Zone to Ring (mi/km)	Largest Earthquake Expected in 50 Years (mbLg)	50-Year Horizontal Acceleration (g)	Largest Earthquake Expected in 250 Years (mbLg)	250-Year Horizontal Acceleration (g)
1.1	16.7/26.9	4.2	0.039	4.8	0.080
2.1	1.5/2.4	3.3	0.023	3.9	0.047
3.1	0.0/0.0	1.9	0.004	2.8	0.012

Lawson methodology (Lawson, 1985). Both studies show the site to be one of low expected ground shaking, over the Oklahoma SSC facility lifetime.

Faulting and Seismic Trends

Nemaha Uplift

The Nemaha uplift, which occurs about 30 mi east of the site, is the closest major structural feature. The uplift developed mainly during the Pennsylvanian Period as a number of small, well-defined crustal blocks. These blocks typically are 3-5 mi wide and 5-20 mi long, and are bounded by faults on the east and/or west side (Huffman, 1959). Fine- to medium-grained clastic rocks of Permian age, which overlie the Nemaha uplift structures in central Oklahoma, are unfaulted. Only in northern Kansas and southeastern Nebraska are Nemaha faults exposed at the surface.

Structure-contour maps reveal a complex fault pattern associated with the Nemaha uplift (Luza and Lawson, 1983). This fault pattern is dominated by several discontinuous uplifts such as the Oklahoma City, Lovell, Garber, and Crescent uplifts. These features form a fault zone that extends from Oklahoma City to the northwest. Near the Kingfisher-Garfield County line, the orientation of the fault zone becomes north-northeast and extends northward through Kansas and terminates in southeastern Nebraska. The southern end of the Nemaha ridge is believed to be the Oklahoma City uplift and its associated faults.

Another zone, the McClain County fault zone, intersects the Oklahoma City uplift in southern Oklahoma County. This fault zone, which is composed of a number of subparallel faults and is thought to be temporally related to the Nemaha faults, trends south-southwest and terminates against the Pauls Valley uplift in Garvin and southern McClain Counties.

The pre-1977 earthquake data, when combined with the 1977-86 earthquake data, define at least two areas of seismic activity (Fig. 45). A 25-mi-wide and 90-mi-long zone appears to extend northeastward from near El Reno (Canadian County) toward Perry (Noble County). The El Reno-Perry trend appears to cut diagonally across the Nemaha uplift structures at about a 30° angle. The southern end of this trend, the El Reno-Mustang area (Canadian County), appears to be more active than the middle and northern parts. It is not clear what the earthquake activity between El Reno and Perry represents. This zone may either be the result of a coincidental plot of earthquake epicenters or related to some unknown northeast-trending structure(s). There do not appear to be any major Paleozoic structures in the vicinity of the zone. However, aeromagnetic data suggest northeast-southwest-trending Precambrian features in the vicinity of the earthquake zone (Luza and Lawson, 1983).

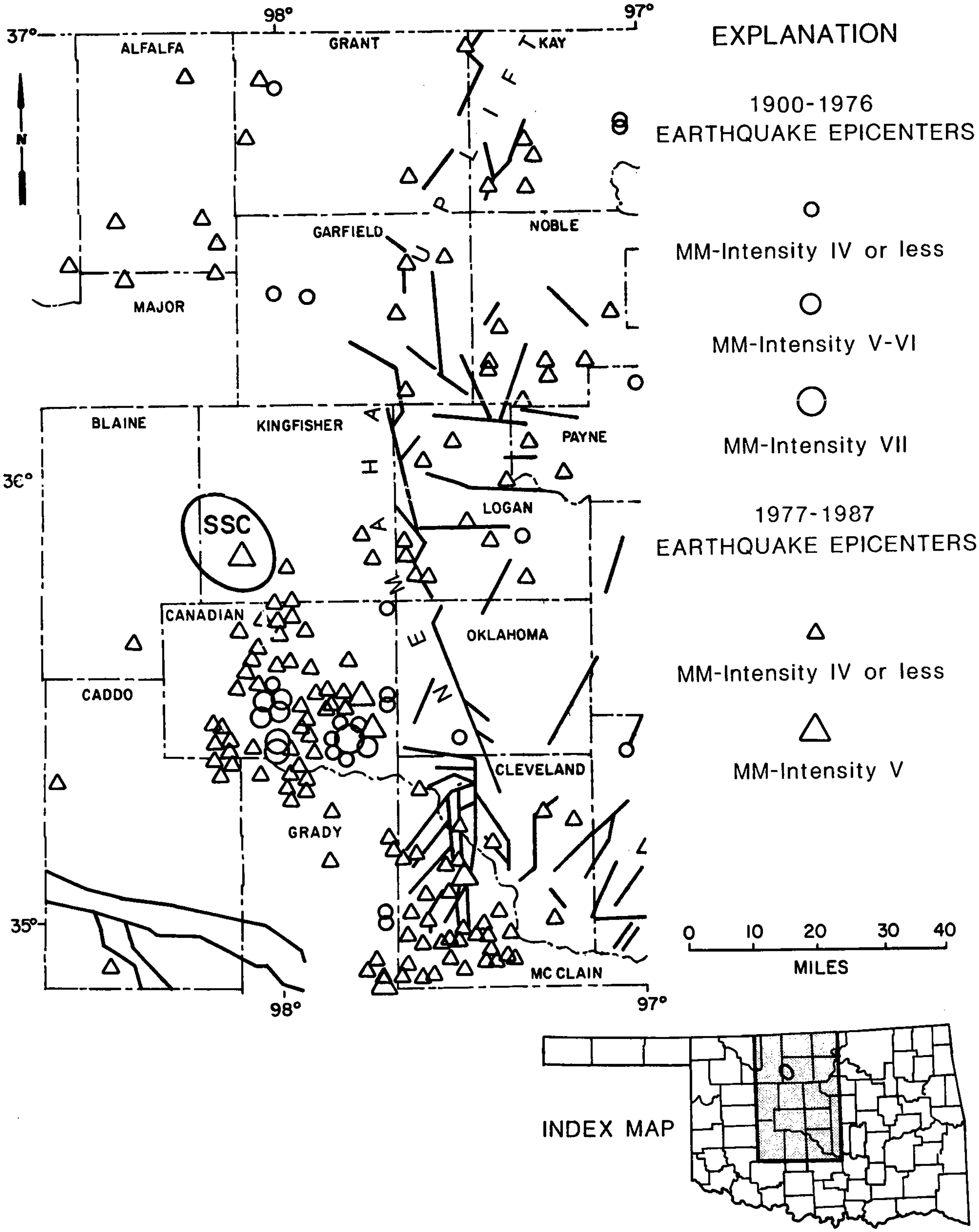


Figure 45. Faults that cut pre-Pennsylvanian strata, and earthquake epicenters for north-central Oklahoma. Modified from Luza and Lawson (1983).

Most of the earthquakes in Canadian County occur 18-24 mi west of the Nemaha structures. The focal depths of most of these earthquakes range between 2.5 and 3.7 mi. In the vicinity of Oklahoma City, the Nemaha faults extend almost vertically for at least 2 mi below the surface. Therefore, it does not seem plausible that the Nemaha structures are directly related to most of the earthquake activity in Canadian County. The Canadian County earthquakes appear to coincide with northern shelf-Anadarko basin interface. The breakover from shelf to basin appears to coincide with lower Paleozoic faults that probably were initiated when the Anadarko basin began to develop in Middle Cambrian time. It should be noted that most of these structures are not manifested in the upper Paleozoic rocks. Hayden (1985) interpreted a northwest-southwest structure in the crystalline basement from gravity and magnetic data in Canadian County. He suggests the Anadarko basin is still undergoing some form of isostatic adjustment, which may be one of the mechanisms responsible for some of the earthquake activity in Canadian County.

A second earthquake trend is situated between Norman and Pauls Valley. This trend closely parallels the McClain County fault zone, which is about 25 mi wide and 37 mi long. This fault zone consists of a number of subparallel faults. The faulting has created a number of fault blocks within the zone. Perhaps small adjustments between fault blocks may be producing some of the earthquakes in this region. Furthermore, this area is the site of recent oil and gas activity. Some of the earthquakes may be related to reservoir-stimulation techniques utilized by the petroleum industry.

Meers Fault

About 60-70 mi south and southwest of the SSC site, a series of uplifts (Amarillo, Wichita, and Arbuckle) trend N.60° to 70°W. across the southern Midcontinent (Fig. 46). The central part of the uplift trend, near Lawton, Oklahoma, contains the Wichita Mountains uplift. The Wichita uplift is bounded on the north and south by major fault zones. On the north, the Wichita frontal fault system separates the uplift from the Anadarko-Ardmore basins (Harlton, 1963). Most of the movement of this fault system was during the Pennsylvanian. The Mountain View fault, Duncan-Criner fault, Cordell fault, and the Meers fault are the major faults of the Wichita frontal fault system (Fig. 46). The frontal fault system is dominated by moderately dipping to steeply dipping reverse faults which have a combined net vertical displacement of >5 mi (Ham and others, 1964). Of these faults, the Meers fault has the greatest net separation, about 4 mi.

A portion of the Meers fault is exposed at the surface in northern Comanche County and strikes approximately N.60°W. where it offsets Permian conglomerate and shale for at least 15 mi. The movement on the fault is consistently down to the south, with a maximum

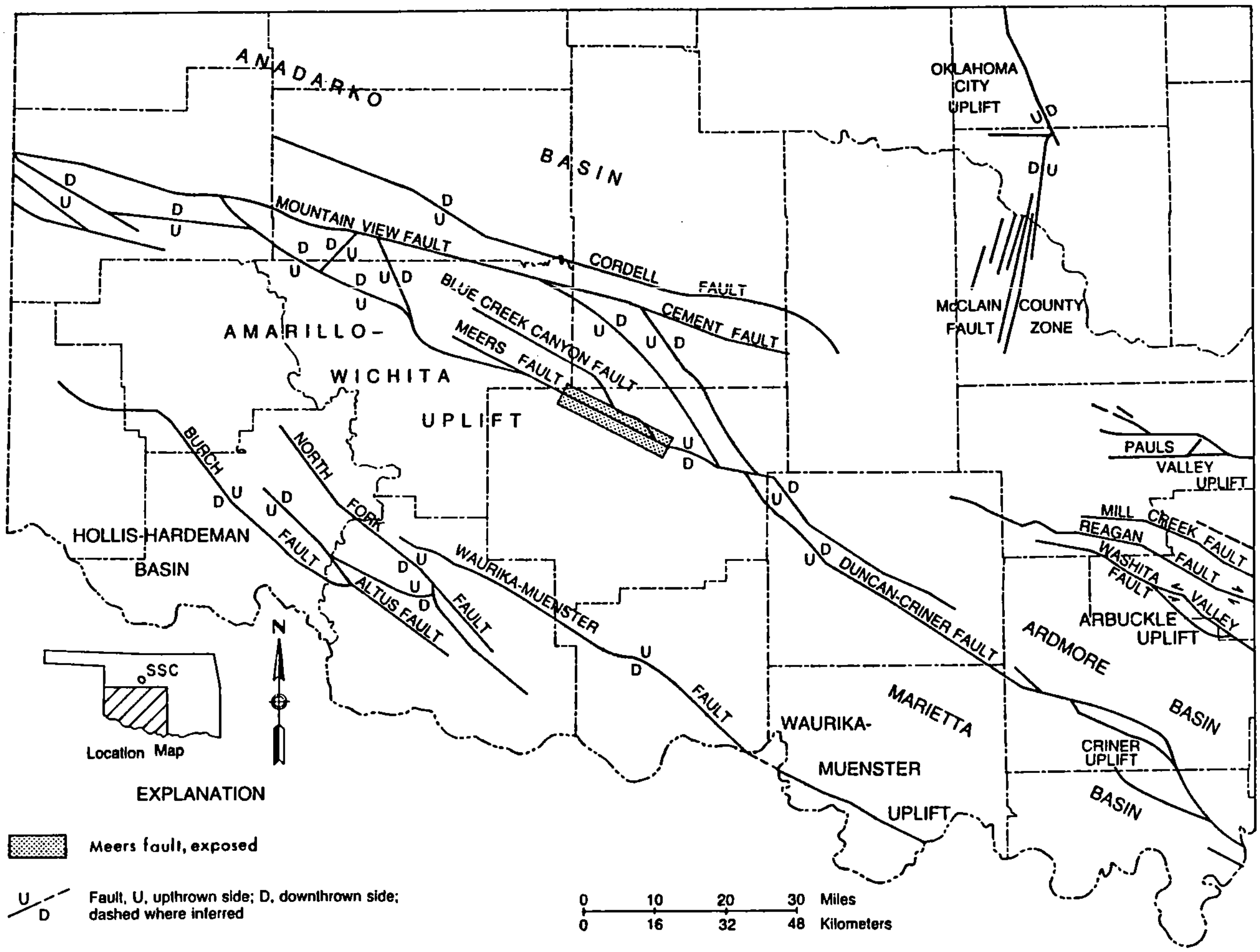


Figure 46. Major structural features in southwestern Oklahoma (from Luza and others, 1987).

relief of 15 ft on the scarp near the center of the fault trace. Recent studies by Madole (1986), Ramelli and Slemmons (1986), Crone and Luza (1986), Ramelli and others (1987), and Luza and others (1987) indicated that at least a portion of the Meers fault ruptured in Holocene time. Quaternary stratigraphic relationships and ^{14}C age dates constrain the age of the last movement between 1,600 and 800 yr B.P. Although the last movement on this fault is recent, the recurrence interval may exceed several thousands of years (Ramelli and Slemmons, 1986; Luza and others, 1987).

A microearthquake study was initiated in April 1984. A volunteer-operated seismograph station, equipped with a Geotech S-13 short-period vertical seismometer and a Sprengnether MEQ 800-B recording unit, was installed about 1 mi north of the fault trace. In May 1985, Meers fault station MFO was closed, and a new station, MEO, was opened on June 11, 1985. This station is located at the store in Meers, 2.5 mi southwest of the Meers fault. A 36-month period of monitoring has revealed only two possible earthquakes; however, these two events may only be quarry blasts.

There is a high likelihood that no earthquakes exceeding magnitude 4 have occurred along the Meers fault since Fort Sill was established 116 years ago. No earthquake exceeding magnitude 3 has occurred in this area since station OGO/TUL (near Tulsa, Oklahoma) was established in December 1961 (station WMO, west of Meers, Oklahoma, was in operation from December 1961 to June 1971). Only one earthquake exceeding magnitude 1.6 has occurred in the vicinity of the Meers fault since the Oklahoma seismic network was established in 1977. Therefore, the Meers fault has been essentially aseismic for the last 25 yr or longer (Lawson, 1985).

According to Nuttli (1983) an intraplate magnitude 6.5 earthquake would produce a 3.6-ft offset along a fault length of 15 mi. If such movements were occurring at an interval of less than the 10,000 yr estimated by Ramelli and Slemmons (1986), the cumulative effect should be obvious. The absence of obvious cumulative effects suggests that the Meers fault is not a seismic hazard to the site relative to other potential seismic source zones (Table 7; Fig. 44).

Conclusion

The historical and instrumental earthquake records indicate that the site is one of low seismic activity. This is also reflected in the UBC seismic hazard zone 1 characterization of the site, and in the low expected acceleration at the site over the life of the SSC project as indicated in two independent studies (Lawson, 1985; Schnabel and Seed, 1973). This conclusion is not altered by a recent investigation of the Meers fault (that is about 75 mi south-southwest of the site) because of the very long recurrence intervals between significant earthquakes on this fault.

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