PHYSICAL ENVIRONMENT OF FORT WOLTERS MILITARY RESERVATION, PARKER AND PALO PINTO COUNTIES, TEXAS

by

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EXECUTIVE SUMMARY

The purpose of this report is to describe the physical environment of Fort Wolters Military Reservation and to call attention to physical processes occurring on the base, to note availability of data, and to comment on potential limitations to land use. Fort Wolters (3,985 ac) is one of the training areas administered by the Texas Adjutant General for activities of the Texas Army National Guard. The Bureau of Economic Geology reviewed existing publications to identify essential baseline data (climate, geology, soil properties, hydrology, and present land condition) and made additional observations that will assist the Texas Adjutant General in preparing long-term environmental assessments mandated by the National Environmental Policy Act and U.S. Environmental Protection Agency regulations and environmental land-management and land-condition monitoring plans required by the U.S. Army. This report also includes basic digital line graph (DLG) data sets for cultural features, hydrology, topography, and soils.

Fort Wolters is located in North-Central Texas in western Parker County and easternmost Palo Pinto County, about 3 mi northeast of the City of Mineral Wells. The area is within the subtropical subhumid climatic region of Texas, with an average annual precipitation of about 29 inches. Intense thunderstorms result in flashy surface runoff, causing erosion of unprotected soils, and flooding and siltation in area creeks. The principal bedrock geologic unit is the Pennsylvanian Mineral Wells Formation, which consists of shale with interbedded sandstone and limestone. Soils are mostly sandy loam and clayey loam. Because of the shaley nature of the Pennsylvanian strata, there are no major fresh-water aquifers beneath the base. Limited amounts of fresh water are present in fractures in limestone and sandstone interbeds.

The principal environmental impacts at Fort Wolters are the extensive network of roads, trails, and tank tracks, and numerous quarries in clay and limestone. Some of these features have been abandoned and are being overgrown by vegetation. Areas that are still in use or have not grown a protective cover show varying amounts of erosion.

INTRODUCTION

Location

Fort Wolters is located in North-Central Texas in Parker County; a small portion extends into Palo Pinto County, immediately northeast of the City of Mineral Wells (fig. 1). The area straddles the boundary between the Western Cross Timbers and North-Central Prairies vegetation regions of Texas (Kier and others, 1977; U.S. Soil Conservation Service, 1981). The base forms a U-shaped property, open to the south, wrapping around the north half of Lake Mineral Wells State Park (fig. 1). The base commander's office is located in the southwestern part of the base just east of the county line (~4.35 mi northeast of the intersection of U.S. Highways 180 and 281 in downtown Mineral Wells) (pl. 1); storage areas, equipment, and other facilities are located in the southern part of the property, just west of the State Park (~4.75 mi east-northeast of downtown Mineral Wells). Access is by several routes along city and county roads, many of which were constructed as part of the original U.S. Army base (pl. 1).

The training base occupies 3,985 ac in the northeastern part of the Mineral Wells East and southwestern part of the Whitt 7.5-minute topographic quadrangles, and a small portion extends into the northwestern part of the Garner quadrangle (fig. 1) (U.S. Geological Survey, 1979c, 1984e, 1984g). The base lies between latitudes 32°50′ and 32°53.5′ North and longitudes 97°59.7′ and 98°4′ West. All of the surface of Fort Wolters drains directly or through tributaries into Rock Creek, which flows southward across the base and the adjacent State Park (2,843 ac) into Lake Mineral Wells, and then on to the Brazos River about 8 mi farther south.

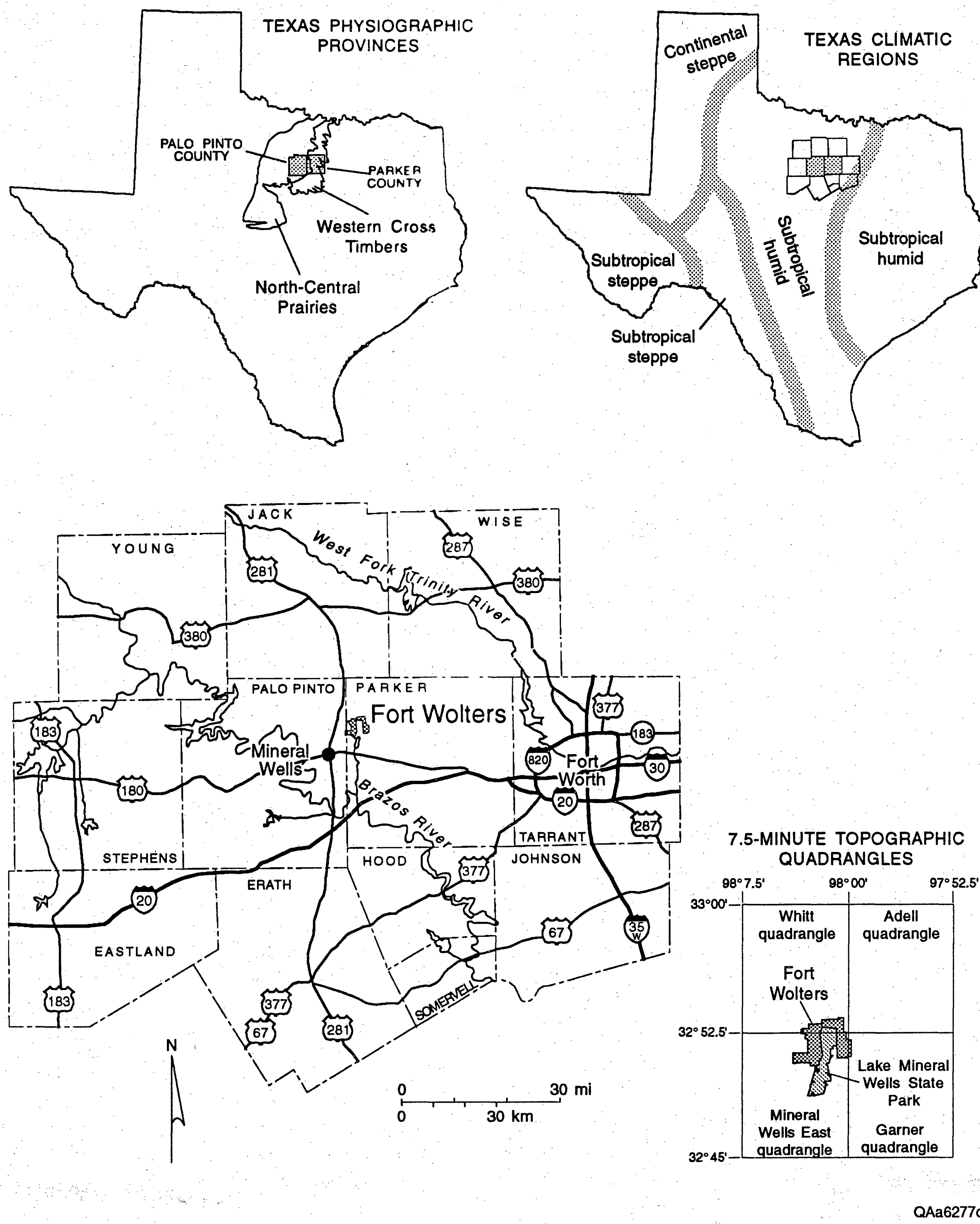

Figure 1. Index map of North-Central Texas region showing immediate vegetation provinces (after Kier and others, 1977), climatic regions (after Larkin and Bomar, 1983), major highways, towns, and rivers, and location of Fort Wolters on 7.5-minute topographic quadrangles.

Brief History of Fort Wolters

Fort Wolters began as Camp Wolters in 1925, when the City of Mineral Wells donated 50 ac and leased 2,300 ac to be used as a field training camp for the 56th Brigade of the National Guard; the commander was Brigadier General Jacob F. Wolters (Texas Parks and Wildlife Department, 1976, p. 128–129). During World War II the camp was enlarged to 7,500 ac and served as an Infantry Replacement Training Center that had a maximum capacity of about 25,000 troops (Texas Parks and Wildlife Department, 1976, p. 128–129). In 1946, plans to abandon the camp were halted upon the outbreak of the Korean War. In 1956, the U.S. Army Primary Helicopter School was established at Camp Wolters and became an important part of the Army training program during the Vietnam conflict (Texas Parks and Wildlife Department, 1976, p. 128–129). The name of the base was apparently changed to Fort Wolters in 1963 (U.S. Federal Insurance Administration, 1977); the 1959 Mineral Wells, Texas, 15-minute topographic map shows the name as "Camp Wolters" (U.S. Geological Survey, 1959a), whereas the 1979 Garner, Texas, 7.5-minute quadrangle (U.S. Geological Survey, 1979c) shows the name as "Fort Wolters."

At its peak size, the base encompassed nearly twice as much area as the present base, including the portion of Lake Mineral Wells State Park north of the lake, and most of the area of barracks, shops, and miscellaneous facilities extending about 2 mi west of the lake (now partly industrial park, city property, and Weatherford College satellite campus). Most of the facilities and roads are visible on 1953 aerial photographs (table 1). Four helicopter stage fields were constructed between the time of 1953 and 1959 aerial photographs (table 1). Two are within the boundaries of the present training site (Helicopter Stage Field No. 1 near the northeast corner, and No. 2 in the northwest corner), and two are outside the boundary (Helicopter Stage Field No. 3 about 1 mi east of Lake Mineral Wells, and No. 4 about 6.5 north, near the community of Whitt [U.S. Geological Survey, 1959a]). In 1958–1959 a Nike anti-ballistic missile site was constructed on the hilltop immediately south of the present Camp

Table 1. Fort Wolters aerial photography examined for this investigation.

Photography Series Code	Frame Numbers	Date of Coverage	Scale	Agency
NAPP	2315-84 to 2315-87 2341-109 to 2341-111 2342-2 2342-67 to 2342-71	12-04-89	1:40,000	U.S. Geological Survey - NAPP (National Aerial Photography Program) series
GS-VEIX	1-10 to 1-17 1-60 to 1-66 1-85 to 1-91	06-04-77	1:20,000	U.S. Geological Survey - VEIX series
BRF & BRG	BRF-3W-179 to BRF-3W-184 BRF-3W-200 to BRF-3W-211 BRG-6W-70 to BRG-6W-80	01-02-59 01-02-59 02-23-59	1:20,000	U.S. Dept. of Agriculture, Soil Conservaton Service - BRF & BRG series
AMS	VV AJ M 1393 & 1394 VV AJ M 1455 & 1456 VV AJ M 2477 & 2478 VV AJ M 2469 & 2470	01-04-53 01-04-53 03-31-53 03-31-53	1:69,000	U.S. Army (Army Map Service)

headquarters. The site was still under construction in the 1959 aerial photographs (table 1). It is now abandoned and is part of the National Guard property.

The active-duty base was deactivated in 1973 (U.S. Federal Insurance Administration, 1977). Most of the developed portion was transferred to the City of Mineral Wells, some became private, and some went to Weatherford College. The undeveloped parts, including firing ranges and other training areas but excluding lands in the center given to the State Park (in 1976?), were transferred to the Texas Army National Guard for the present Fort Wolters. Most of the facilities that may have handled fuels, munitions, and other hazardous materials are now outside the training facility (an important exception is the Nike missile site); most of the original structures that remain are also outside the present training facility.

Fort Wolters Physical Environment

The physical environment of Fort Wolters is controlled by its geology and climate (past and present). Climate influences natural processes, which modify the geological substrate and in turn determine other characteristics such as geomorphology (shape of the land surface), hydrology, soil composition, and type and density of vegetation. Vegetation is an important element in the physical environment as it helps stabilize the landscape by limiting erosion.

Objective and Methods

The main objective of this work was to compile and document sources of available data that describe the physical environment of Fort Wolters and to explain the significance of each element in an overall land-use and management perspective. Most of the data presented here were obtained from published reports, maps, and other literature. Some data were extracted from data bases maintained by Federal or State agencies. Additional information, relating chiefly to geology, was collected by direct observation during 5 days of field work, in July (2 days) and November (3 days) 1993. The description of climate is based mainly on data collected by recording stations at the Mineral Wells municipal airport, about 4.5 mi due south of Camp headquarters; additional data on wind, humidity, and other conditions are from records collected at stations in Dallas-Fort Worth (about 60 mi east) and Abilene (about 100 mi west-southwest). Several vintages of aerial photographs are available and were used to examine historical changes in the land use, vegetative cover, and environmental impact (table 1).

This report contains basic digital line graph (DLG) data sets for Fort Wolters. The data include more than 71,000 digitized points arranged in 74 computer files, and represent cultural features (roads, boundaries, utility lines), hydrology (streams, water bodies, drainage divides, and well and windmill locations), topography (including spot elevations), and soils. The data are in line and point format. Geologic data (formation contacts) are not represented in the digital files but are provided later in this report in figures on an aerial photographic base. Example plates displaying various combinations of the DLG files were prepared by plotting the digital data on a black-and-white electrostatic plotter. The DLG data and example plates are described in greater detail in appendix E.

CLIMATE

Fort Wolters is situated in the eastern part of the subtropical subhumid climatic region of Texas (fig. 1) (Larkin and Bomar, 1983, p. 2). The climate is a modified marine climate dominated by onshore flow of tropical maritime air from the Gulf of Mexico; this onshore flow is modified by westward-decreasing moisture content and intermittent seasonal intrusions of continental air (Larkin and Bomar, 1983, p. 1). Climate influences soil development and, in combination with soil properties, controls the diversity, health, and seasonal changes of vegetation. Awareness of seasonal climatic variations and their effect on vegetation is important for optimizing land use while minimizing erosion.

The information on climate presented here was extracted from Bomar (1983) and Larkin and Bomar (1983); annual precipitation data were obtained from the Texas Water Oriented

Data Bank (Texas Water Development Board, 1993). Data may also be obtained directly from the National Climatic Data Center in Asheville, North Carolina, which receives monthly reports from all stations in the National Weather Service and the Cooperative Weather Observer Network.

Temperature

The climate in this region of Central Texas is characterized by hot summers and dry winters. Temperature variations through the year closely follow the seasonal variations in the amount of sunshine striking the surface (figs. 2a, 2b). The average monthly high temperature for July and August in the nearby City of Mineral Wells has been about 97°F, whereas average monthly low temperatures in December and January have ranged from 32°F to 35°F (table 2) (Bomar, 1983, his tables B-5 and B-7). Freezing conditions in Mineral Wells occur on an average of 50 days per year; the average number of days between the last freeze (March 19) and first freeze (November 13) from 1951 through 1980 was 239 days (Bomar, 1983, his tables B-1 and B-2). Temperature statistics and sources of data are summarized in table 2.

Wind

The prevailing surface winds in this part of North-Central Texas are warm and southerly through most of the year (figs. 3 and 4, table 2, appendices A and B). During the fall and winter, winds of short duration blow from the north as intrusions of continental air (cold fronts) move through the area.

High winds are an important agent of erosion if soils are loose or unprotected by vegetation. Winds of about 13 mph (moderate breeze) are strong enough to raise dust and move small branches (Bomar, 1983, his table F-3); at greater speeds the wind is capable of moving larger silt and sand grains. Winds of this magnitude occur about 20 percent of the time in summer and fall and about 30 to 40 percent of the time in winter and spring (fig. 3,

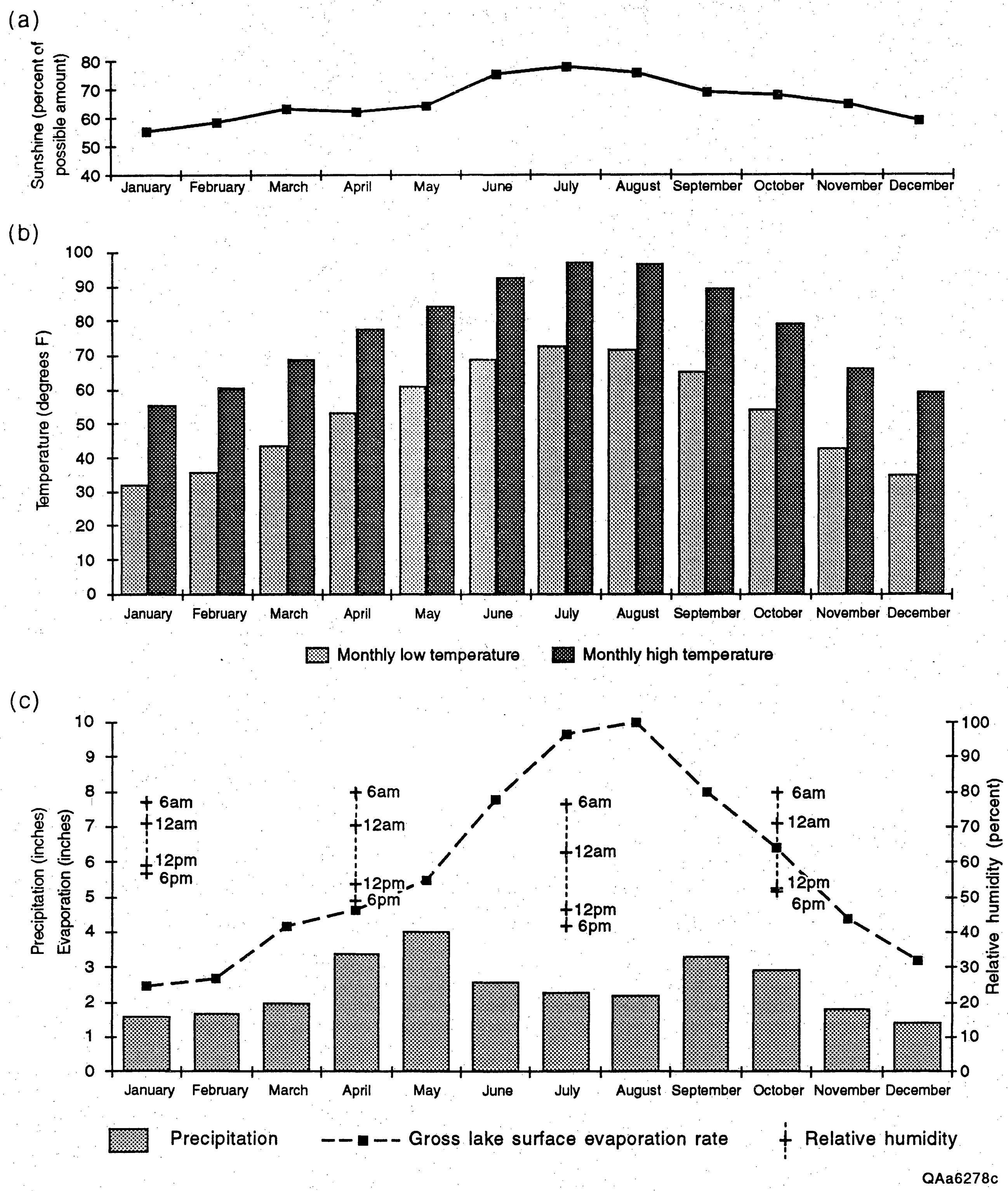

Figure 2. Climatic trends in the Fort Wolters area, Parker and Palo Pinto Counties, Texas: (a) average amount of sunshine (interpolated from data for Abilene and Dallas-Forth Worth areas, 1942–1980); (b) average monthly low and high temperatures (1951–1980); and (c) average monthly precipitation (1951–1980), average gross lake-surface evaporation rate (1950–1979), and average relative humidity (interpolated from data for Abilene and Dallas-Forth Worth areas, at 6 a.m., 12 p.m., 6 p.m., and 12 a.m., 1962–1980); see table 2 for data and sources.

Table 2. Climatic statistics for Fort Wolters area, Parker and Palo Pinto Counties, Texas.

Month	Average Amount of Sunshine (percent of possible amount) [1]	Average Monthly Temperatures (°F) [2]		Average Number of Freezes [3]	Average Number of Days ≥100° F [4]	Average Monthly Precipitation (inches) [5]	Average Monthly Gross Lake Surface Evaporation Rate (inches) [6]	Average Relative Humidity (percent) [7]				Average Wind Direction and Speed (mph) [8]	Average Number of Cold Fronts [9]	Average Number of Days with Various Sky Conditions [10]		
		Low	High					6 a.m.	12 p.m.	6 p.m.	12 a.m.			Clear	Partly Cloudy	Cloudy
January	62 / 51	32.1	55.6	17	0	1.61	2.45	72/80	55/61	51/60	66/74	S12 / S11	6 / 7	11 / 10	6 / 5	14 / 16
February	65 / 54	35.9	60.9	10	0	1.68	2.65									
March	70 / 59	43.5	69.0	4	0	1.99	4.15									
April	70 / 57	53.6	77.9	0	0	3.41	4.65	73/84	47/58	41/54	64/74	SSE14 / S13	8 / 8	11 / 9	8 / 7	11 / 14
May	70 / 61	61.4	84.5	0	0	4.06	5.50									
June	78 / 73	69.2	92.8	0	3	2.59	7.75									
July	79 / 77	72.9	97.3	0	12	2.27	9.65	70/80	44/48	38/44	57/66	SSE11 / S9	4 / 4	14 / 15	10 / 9	7 / 7
August	77 / 75	71.9	96.6	0	11	2.18	10.00									
September	68 / 69	65.5	89.2	0	2	3.30	8.00									
October	72 / 65	54.4	79.3	0	0	2.93	6.40	75/82	51/53	48/54	67/73	SSE11 / S10	6 / 7	15 / 14	7 / 8	9 / 9
November	69 / 62	42.6	66.4	5	0	1.82	4.40									
December	66 / 55	35.1	59.5	13	0	1.43	3.20									

Average annual low temperature [2]	53.2° F
Average annual high temperature [2]	77.4° F
Average annual temperature [2]	65.3° F
Average annual precipitation [5]	29.27 inches
Average annual gross lake surface evaporation rate [6]	69 inches
Coldest observed temperature [11]	3° F (February 2, 1951)
Hottest observed temperature [11]	114° F (June 28, 1980, and earlier dates)

Notes:

(1) Average amount of sunshine at Abilene (left) and Dallas-Fort Worth (right), Texas, 1942-1973, from U.S. Department of Commerce data summarized in Bomar (1983, table F-7).

(2) Average temperatures at Mineral Wells, Texas, 1951-1980, from Bomar (1983, tables B-5 and B-7). Average monthly low temperature is average of daily minimum temperatures for the month; average monthly high temperature is average of daily maximum temperatures for the month. Average annual low temperature is average of monthly lows for the year; average annual high temperature is average of monthly highs for the year; average annual temperature is average of annual low and high temperatures. Original data from National Weather Service and Cooperative Observer Network.

(3) Average number of freezes per month at Mineral Wells, Texas, 1951-1980, from Bomar (1983, table B-2); greatest number in any one year was 67 in 1976-1977.

(4) Average number of days per month with temperature 100° F or greater, at Mineral Wells, Texas, 1951-1980, from Bomar (1983, table B-9); greatest number in any one year was 63 in 1956.

(5) Average precipitation at Mineral Wells, Texas, 1951-1980, from Bomar (1983, table C-2). Data from Cooperative Observer Network of the National Weather Service.

(6) Gross lake surface evaporation rates in Fort Wolters area, 1950-1979, estimated from maps in Larkin and Bomar (1983, p. 51-66); data from Texas Dept. of Water Resources Surface Water Data Unit.

(7) Average relative humidity at Abilene (left) and Dallas-Fort Worth (right), Texas, 1964-1980, from U.S. Department of Commerce data summarized in Bomar (1983, table F-4).

(8) Average wind speed and direction at Abilene (left) and Dallas-Fort Worth (right), Texas, for 20-year period ending 1980, from U.S. Department of Commerce data summarized in Bomar (1983, table F-2).

(9) Average number of cold fronts passing Abilene (left) and Dallas-Fort Worth (right), Texas, 1961-1970, from Illinois State Water Survey data summarized in Bomar (1983, table F-5).

(10) Average number of days with various sky conditions at Abilene (left) and Dallas-Fort Worth (right), Texas, 1954-1980, from U.S. Department of Commerce data summarized in Bomar (1983, table F-6).

(11) Observed temperature extremes at Mineral Wells, Texas, from Bomar (1983, table B-6); highest observed temperature in Texas in 1980 was 119°F in Weatherford, central Parker County, ~15 mi east-southeast of Fort Wolters.

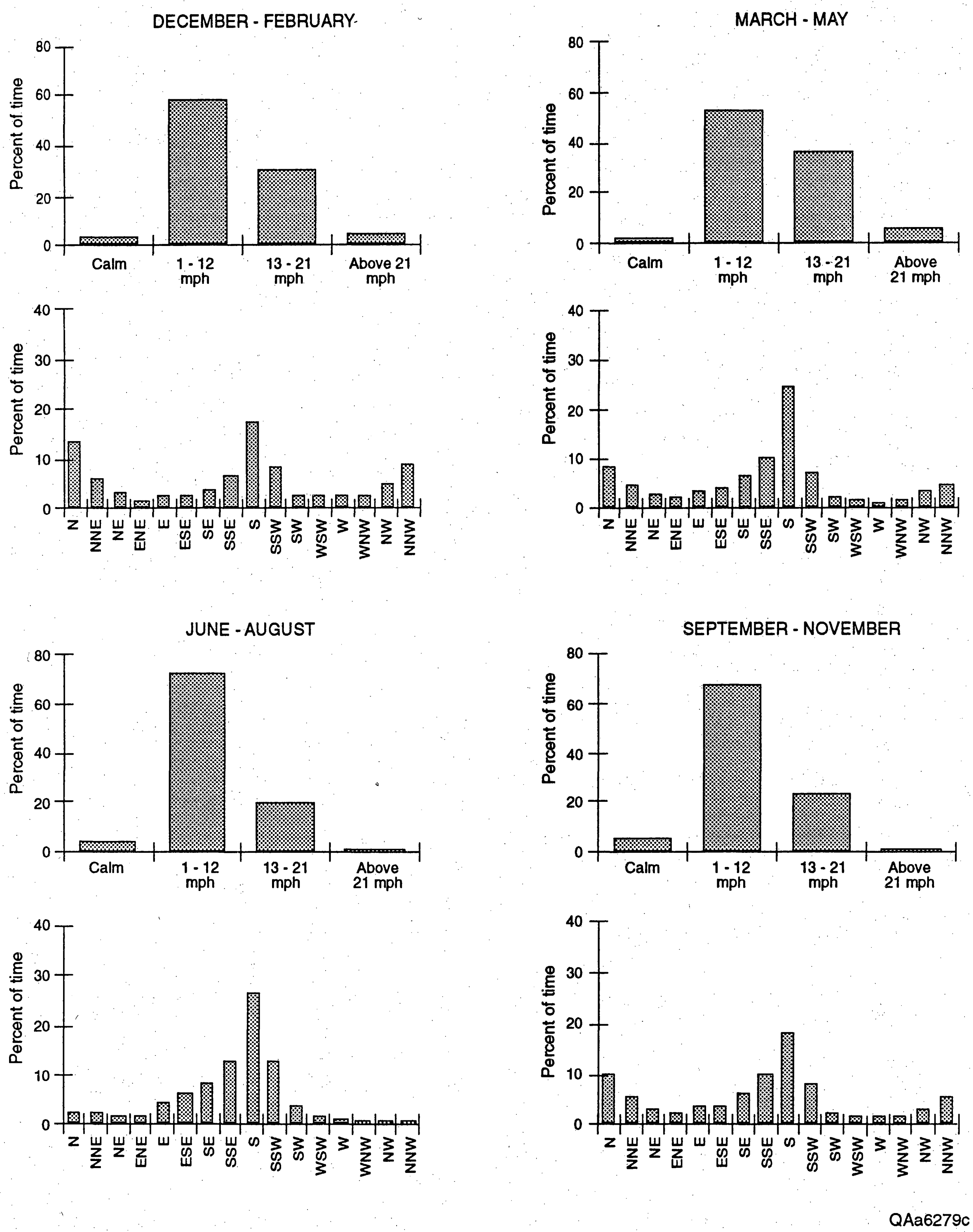

Figure 3. Average wind direction and speed at Dallas-Fort Worth, Texas, 1961–1980. Bar diagrams indicate percent of time of wind conditions by ranges of speed and by direction. Wind speeds of 13 mph and greater are capable of raising dust. See appendix A for data and source.

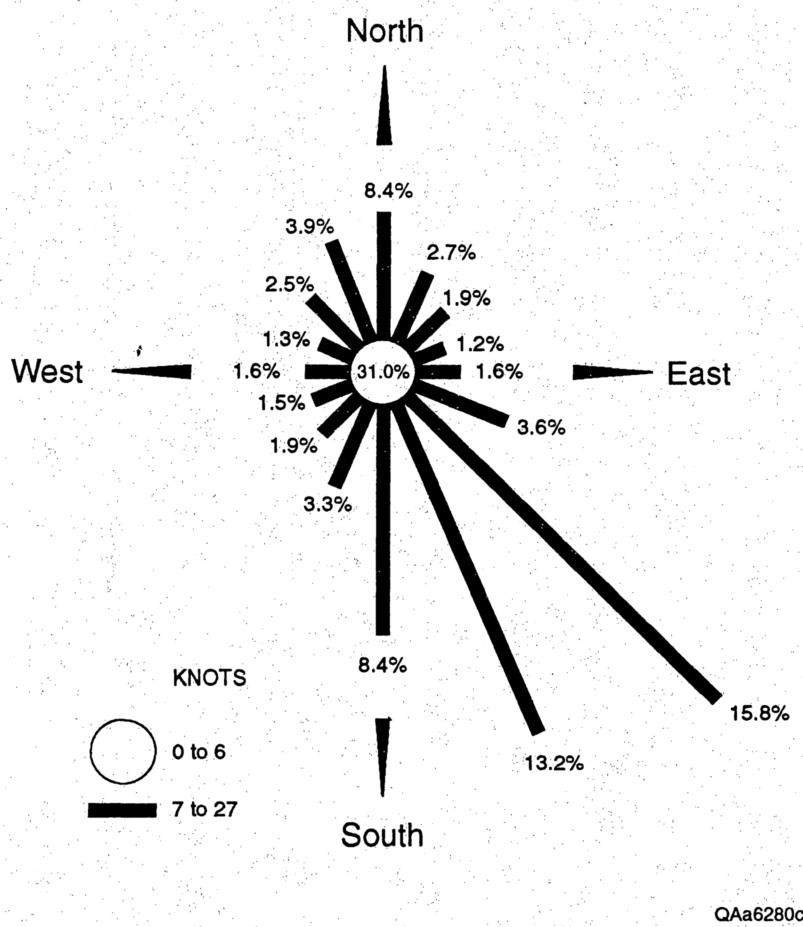

Figure 4. Wind rose for Parker County, Texas, representing a compilation of data for all months and all hours, for years 1948 through 1967; see appendix B for data (from Flemming & Associates, 1971, p. II-6). Central circle represents cumulative percentage of calm conditions and winds of 6 knots and less (1 knot = 1.15 mph); arms of the rose indicate cumulative percentage of winds of 7 knots and greater and direction *from which* those winds blew.

appendix A). The greatest potential for wind erosion would seem to be during the winter, when protective vegetation is likely to be minimal. However, this may be offset by potentially high soil-moisture content, which would tend to increase cohesion and resistance to erosion. High wind-erosion potential may exist during late summer, when rainfall and soil moisture are at a minimum and evaporation is at a maximum.

Precipitation, Evaporation, and Humidity

Precipitation is probably the greatest climatic factor controlling the types and density of vegetation in Texas. Most of the precipitation in North-Central Texas comes in the form of rain, but snowfall averaged 3 to 4 inches per year between 1951 and 1980 (Bomar, 1983, his table F-1). Precipitation in this region is great enough to support a moderately dense vegetative cover comprising a wide variety of plants.

Rainfall distribution through time greatly influences potential for surface runoff and soil erosion. Intense rainfalls, typically brief and associated with thunderstorms, generally exceed the infiltration capacity of the soil and lead to runoff and flooding. Lighter rainfalls are less likely to produce runoff, unless the soils are already saturated or if the rainfall events are of extended duration. Evaporation is another important factor to consider in land management because it is the principal process by which soils are able to dry out and achieve their greatest strengths. Evaporation depends on temperature, precipitation, and moisture content (relative humidity) of the air. Evaporation rates are maximized under conditions of dry air and warm temperatures.

The average annual precipitation at Mineral Wells is about 30 inches (fig. 5, table 2, appendix C). The four greatest rainfall months are April (3.4 inches), May (4.1 inches), September (3.3 inches), and October (2.9 inches) (fig. 2c, table 2). The 11th greatest 1-month precipitation total for Texas was 27.94 inches at Weatherford, Texas, central Parker County (about 15 mi southeast of Fort Wolters), in May 1884 (Bomar, 1983, his table C-5). Peak gross-

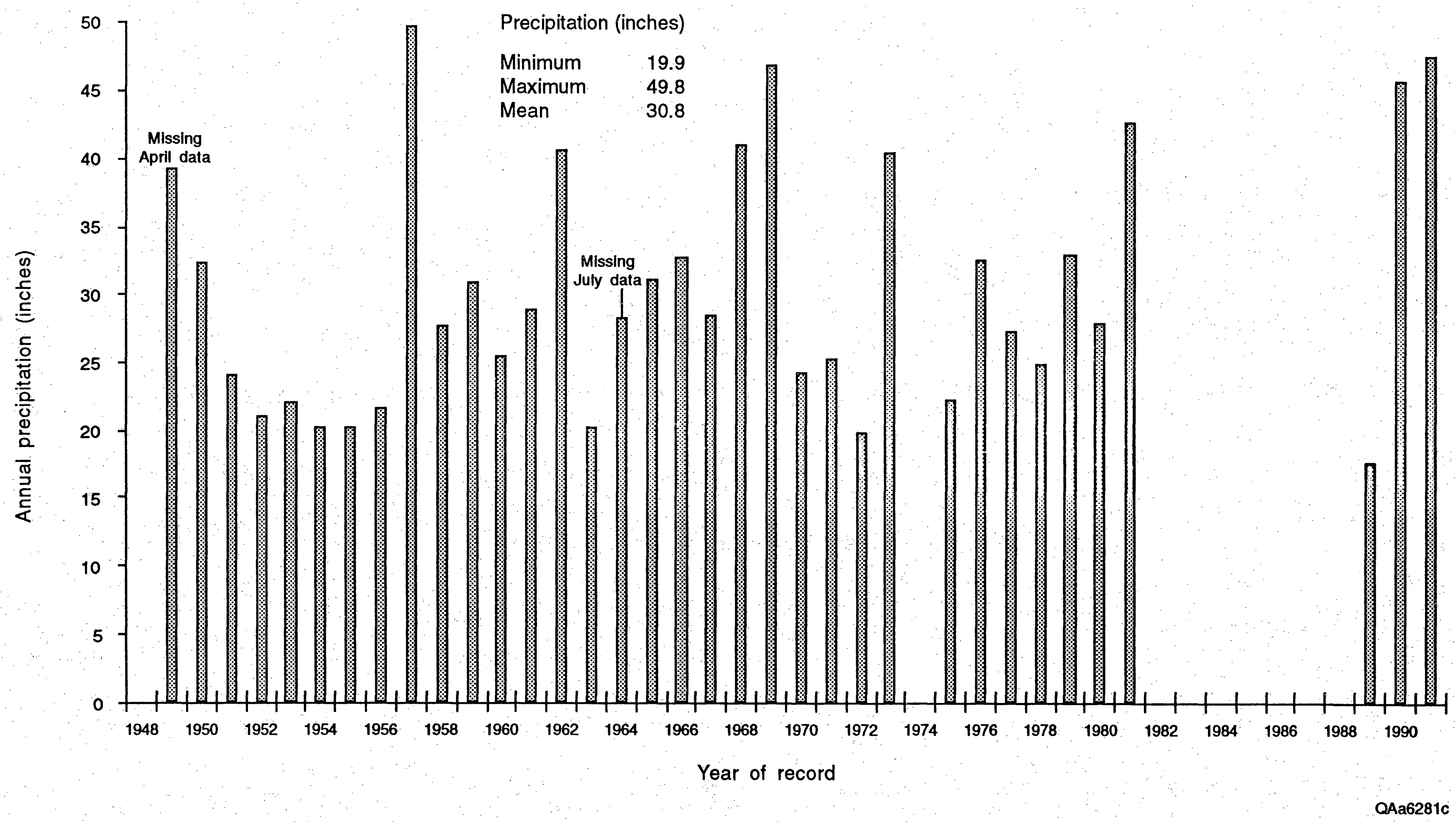

Figure 5. Annual precipitation recorded at Mineral Wells airport, 1948–1991, with summary statistics; see appendix C for data and source. Records are incomplete for 1948, 1949, 1964, 1974, 1982, 1983, and 1989; no data are available for 1984–1988; note that values are plotted for 1949 and 1964, which each lack one month of data. Average annual precipitation at Mineral Wells for 32 years from 1950–1991 (excluding years missing data) was 30.8 inches (compare with average of 29.27 inches for 1951–1980, listed in table 2).

lake-surface evaporation rates in the Fort Wolters area are obtained in July and August (about 10 inches each month) (fig. 2c, table 2); at these times soils are likely to be driest. The lowest relative humidities of the year generally occur in late afternoon in midsummer (fig. 2c). The highest humidities of the year are during the early morning hours in the spring and fall. The greatest daily range of relative humidity is during the summer, when high temperatures and evaporation rates in the daytime allow the air to hold large amounts of water, which causes the relative humidity to rise substantially as the air cools during nighttime.

Previous Major Storms

Heavy rainfalls cause flooding on Rock Creek and its tributaries due to moderate to low permeability of soils and moderately well developed drainage. One storm in the spring of 1970 produced an estimated 12,000 ft^3/s flood on Rock Creek (Forrest and Cotton, 1970), undermining the spillway of Lake Mineral Wells dam and severely eroding around the abutments. This damage required the lake to be drained until extensive repairs and modifications could be completed.

GEOLOGY

Structure and Stratigraphy

The Fort Wolters area is underlain by Pennsylvanian-age strata of the Strawn Group (fig. 6). These strata were deposited in the Fort Worth Basin and across the Bend Arch (or Bend Axis), which bounds the basin on the west. The Fort Worth Basin is an elongate north–south-oriented trough that was the site of significant subsidence and deposition during mid-Pennsylvanian time (~305 to 290 million years ago). Fort Wolters is situated over the western edge of the basin (Ewing, 1990). Strawn strata thicken toward the east and southeast. The sediments were derived mostly from the Ouachita Geosyncline to the east, which was uplifted and eroded in early and

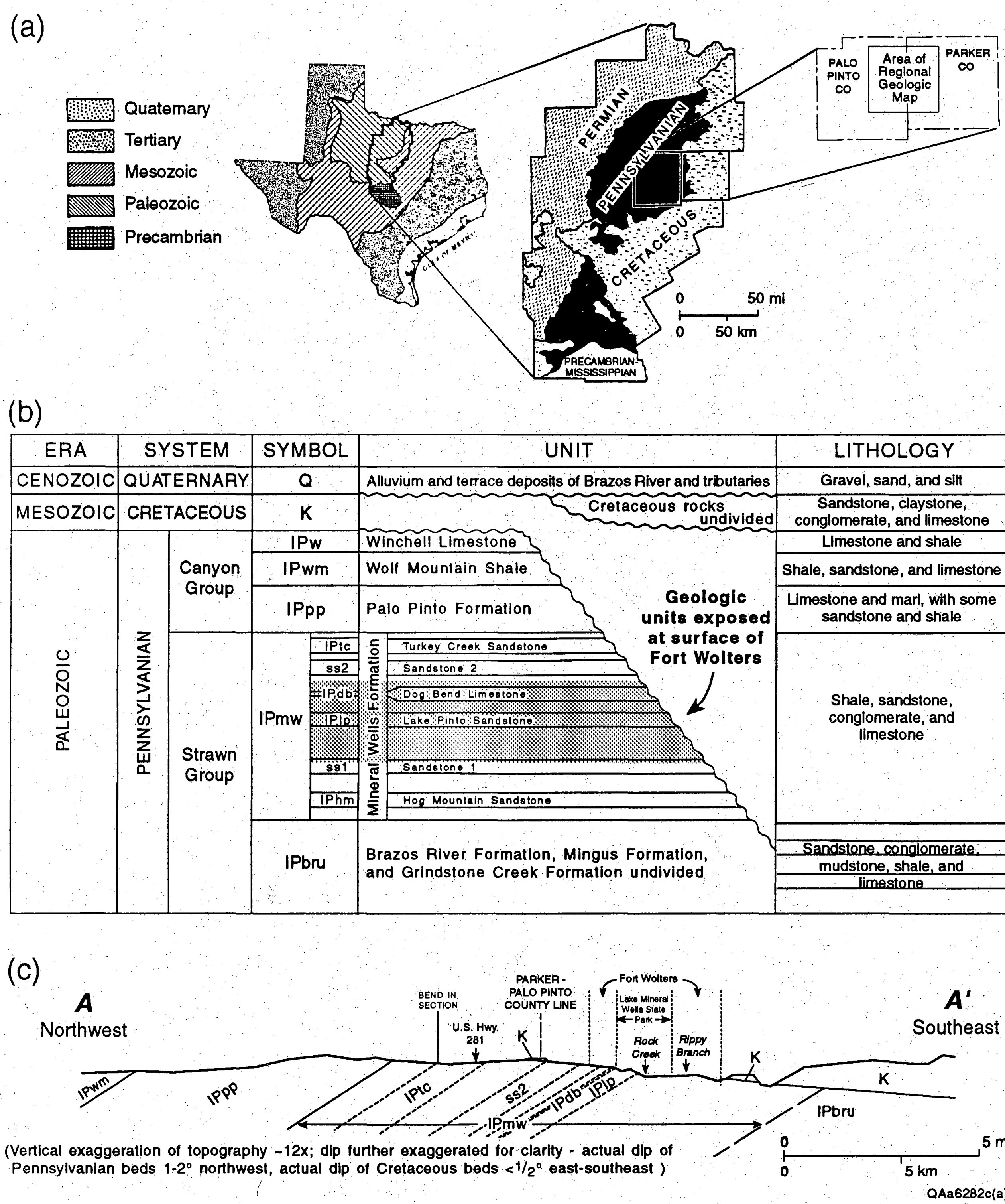

Figure 6. Geologic features in Fort Wolters region: (a) simplified Texas geologic map (from Bureau of Economic Geology black and white post card; enlargement from Laury, 1982, fig. 1), (b) stratigraphy (modified from Brown and others, 1972, and McGowen and others, 1987) - patterned interval indicates section exposed at surface on Fort Wolters, (c) schematic cross section (line shown in [d]), and (d) regional geologic map (modified from Brown and others, 1972, and McGowen and others, 1987) - note that many of the units within the Mineral Wells Formation continue as thin beds beyond the areas indicated.

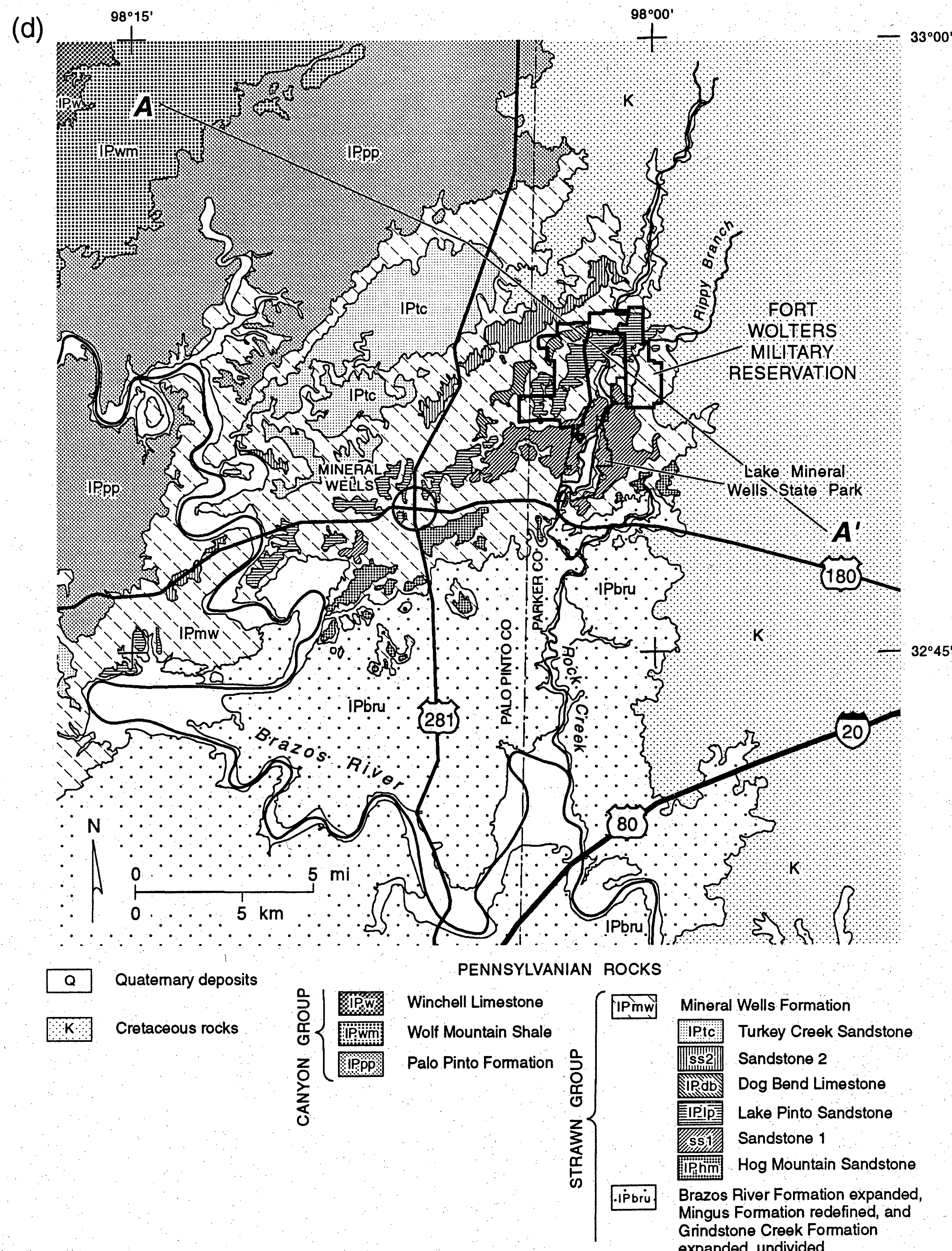

Figure 6 (continued).

middle Pennsylvanian time (Weaver, 1956, p. 11); at times, the Wichita Uplift, Arbuckle-Criner Hills Uplift, and perhaps Muenster Arch supplied arkosic material to delta systems in the northern part of the basin (Cleaves and Erxleben, 1982, p. 52). The Strawn Group consists predominantly of shales, with some sandstones and a few lenticular limestones, and has a composite thickness of about 3,800 ft (Plummer and Moore, 1921, p. 63). Strawn Group strata are overlain northwest of Fort Wolters by Canyon Group strata (fig. 6d), which were deposited in late middle to late Pennsylvanian time. Canyon strata do not thicken appreciably, indicating that the Fort Worth Basin was mostly filled by this time. The Canyon Group consists mainly of limestones and shales, with some sandstones, and has a composite thickness of about 1,000 ft.

The North-Central Texas region continued to be uplifted through late Pennsylvanian and at least Permian time, leading to erosion and eventual truncation of the Pennsylvanian section; by Jurassic time the regional slope had become reversed, and drainage was toward the east, instead of the west (Weaver, 1956, p. 11). Regional downwarping permitted Cretaceous seas to blanket the exposed Pennsylvanian beds over most of the present Fort Worth Basin area, resulting in onlap by Cretaceous strata from the southeast (fig. 6) (Weaver, 1956, p. 13). The Pennsylvanian strata dip gently (about 1 to 2°) toward the northwest (Wermund and Jenkins, 1965), whereas Cretaceous strata dip gently (less than 1/2°) toward the east-southeast (fig. 6a) (Hendricks, 1957, p. 11 and 30). The erosional surface between the Cretaceous and Pennsylvanian, termed the Wichita Paleoplain, has a southeast regional dip and shows very little large-scale irregularity (maximum relief about 50 ft—much less than the present erosional surface of the Pennsylvanian) (Hendricks, 1957, p. 30).

The Strawn Group is a thick sequence of terrigenous clastic and carbonate strata that are interpreted as marine and deltaic deposits (Cleaves and Erxleben, 1982; Trice, 1984). The depositional systems were strongly influenced in space and time by the development of the Fort Worth Basin and associated tectonic elements. The upper part of the Strawn, the portion exposed at the surface in northeastern Palo Pinto and westernmost Parker Counties, is characterized by repeated cycles of fluvial/deltaic sediments (sandstones, conglomerates, mudstones) that prograded (built outward) into marine areas and were in turn overlain by transgressive marine sediments (shales) (Cleaves and Erxleben, 1982; Trice and Grayson, 1988). Upper Strawn rocks contain ripple marks, raindrop imprints, mud cracks, crossbedding, conglomerates, and fossils characteristic of shallow-water sediments (less than 100-ft depth?); many of the shales contain macroscopic plant fossil fragments (Echols, 1959, p. 13). Outcrop studies of the Strawn suggest that there are numerous disconformities within section, indicated by widespread paleosoil zones (evidence of exposure above water level), incised valley-fill sandstone bodies, and meteoric diagenetic exposure zones in carbonate banks (Cleaves, 1991). The upper Strawn thins and becomes more marine influenced toward the southwest.

Many systems of classification have been applied to the Pennsylvanian strata in the Fort Worth Basin and adjacent areas (some of the schemes are shown in fig. 7). The discussion of stratigraphy in this report follows the recent practices of the Bureau of Economic Geology and principal workers in the region (Brown and others, 1972; Cleaves and Erxleben, 1982; McGowen and others, 1987; Trice and Grayson, 1988). As summarized in Trice (1984, p. 7–10), the primary interest of initial stratigraphic studies (1890–1935) was to define and describe rock stratigraphic units; later research (1935–1959) addressed biostratigraphic and time stratigraphic units. In the 1950's, primary interest shifted back to physical stratigraphy and mapping of rock stratigraphic units as research focused on describing sedimentary facies and depositional environments. Most recent work focuses on facies analysis and comparison to modern depositional environments. Uncertainties have revolved around two basic stratigraphic problems: (1) rapid facies changes and lenticular nature of some of the units, and (2) pinching out of marker beds as units thin over positive areas. Cleaves (1991) states that all of the major marine transgressions and many of the deltaic regressive sequences reflect glacially forced coastline changes, not simple delta progradational facies changes controlled by regional tectonism, and advises that "core" shales should be used to correlate major depositional cycles.

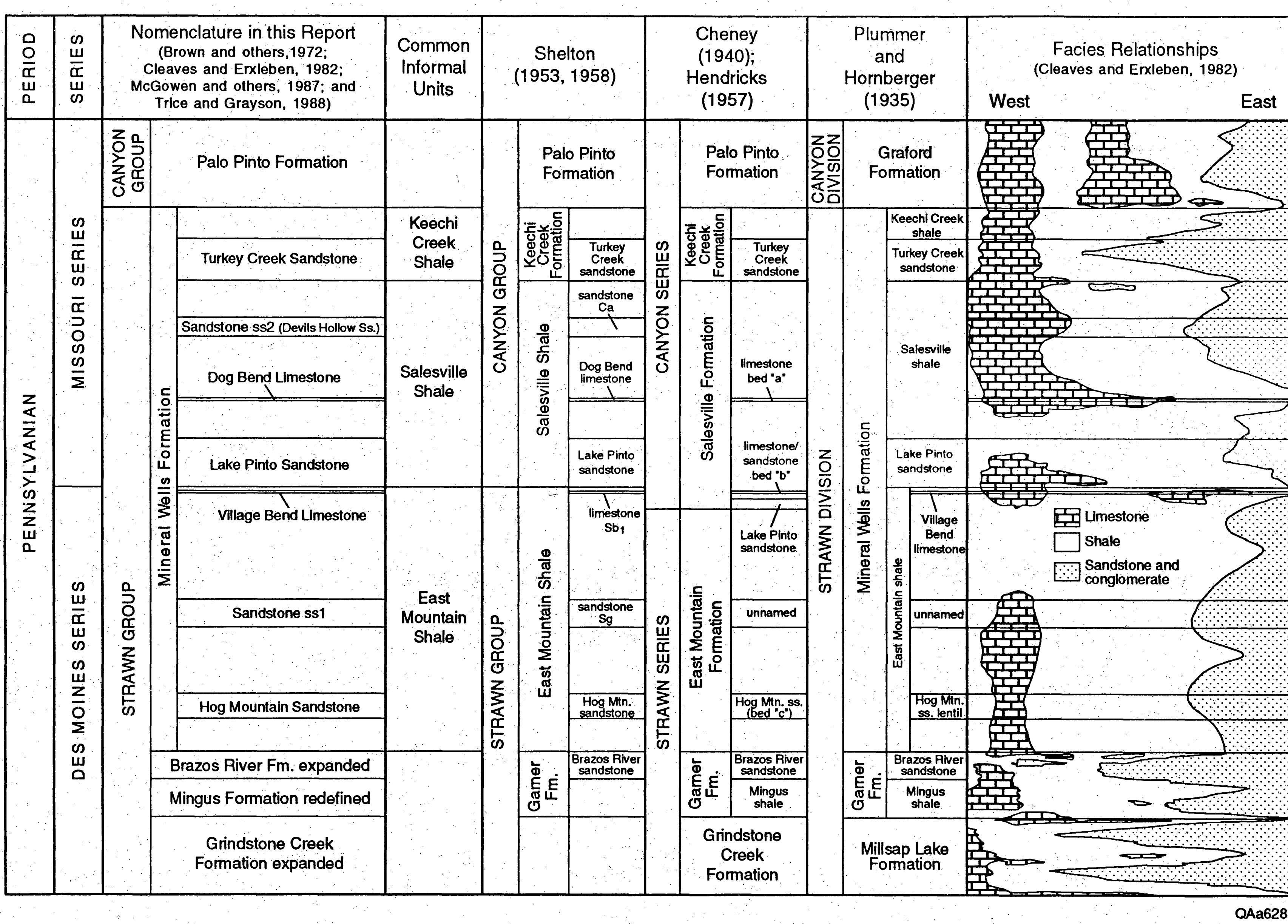

Figure 7. Summary of stratigraphic nomenclature of Pennsylvanian rocks in Fort Wolters area (thicknesses not to scale).

Brazos River, Mingus, and Grindstone Creek Formations (Pennsylvanian)

The Grindstone Creek Formation (fig. 7) is exposed near the Brazos River, about 10 mi south of Fort Wolters (Brown and others, 1972). The Grindstone Creek Formation (expanded) consists of gray, locally sandy shale, with sandstone and limestone interbeds, and thin lignite beds locally (Brown and others, 1972). Members include the Buck Creek Sandstone and Brannon Bridge Limestone (three beds). The total thickness of the Grindstone Creek Formation (expanded) is about 250 ft.

The Mingus Formation (fig. 7) overlies the Grindstone Creek Formation about 9 mi south of Fort Wolters. The Mingus Formation (redefined) consists of poorly bedded, dark gray to buff sandy shale with sandstone and thin limestone interbeds (Brown and others, 1972). Members include the Goen Limestone, Dobbs Valley Sandstone, and Santo Limestone, and at least one coal seam (in places referred to as the Thurber Coal). The thickness of the redefined Mingus Formation is about 230 ft.

The Brazos River Formation (fig. 7) overlies the Mingus Formation and is last exposed about 2.5 mi south of Fort Wolters (Brown and others, 1972). The unit underlies Fort Wolters at shallow depth, generally less than 100 ft. The Brazos River Formation (expanded) consists of coarse-grained, ferruginous, cross-bedded, thick bedded to massive, reddish-brown sandstone with conglomerate lentils, and gray, silty mudstone lenses (Brown and others, 1972). The formation is about 100 ft thick in this area, thickening toward the southwest. The upper part of the formation contains thick-bedded sandstone and conglomerate up to 25 ft thick, which caps a prominent escarpment with as much as 200 ft of relief. The Brazos River Formation is overlain by the Mineral Wells Formation. The Brazos River Formation and Mingus Formation were members of the Garner Formation in previous stratigraphic classifications (fig. 7) and were later raised to formation status.

Mineral Wells Formation (Pennsylvanian)

All of the geologic units exposed at the surface of Fort Wolters are part of the Mineral Wells Formation (fig. 6). The lower part of the Mineral Wells Formation has commonly been referred to as the East Mountain Shale and the upper part the Salesville Formation (fig. 7). This report follows the recent practice of the Bureau of Economic Geology (Brown and others, 1972; McGowen and others, 1987), Cleaves and Erxleben (1982), and Trice and Grayson (1988), which is to use the name Mineral Wells Formation for the entire section. The Mineral Wells Formation is overlain by the Palo Pinto Formation northwest of Fort Wolters (fig. 6d).

The Mineral Wells Formation consists of shale with interbedded sandstone and limestone. Sandstone and limestone members, in ascending order, include the Hog Mountain Sandstone, informal sandstone unit 1, the Village Bend Limestone, Lake Pinto Sandstone, Dog Bend Limestone, informal sandstone unit 2 (referred to by some as the Devils Hollow Sandstone), and the Turkey Creek Sandstone (fig. 7). The approximate distribution of these units is shown on aerial photographs in figures 8a through 8d. The width of individual units in map view varies greatly with the slope of the surface—outcrop belts are narrowest where the slopes are steepest; outcrop width is controlled secondarily by variations in thickness of the unit. In most cases the individual members contain a mix of rock types, so that typically there is not a clearly defined boundary. The contacts shown on the maps (fig. 8) mark the intervals dominated by a particular rock type. Portions labeled generically as Mineral Wells Formation (IPmw in fig. 8) are dominantly shale, whereas the subdivided members (IPhm, IPss1, IPvb, IPlp, IPdb, IPss2, and IPtc in fig. 8) are dominantly sandstone or limestone. The total thickness of the Mineral Wells Formation (including all members) varies from 275 to 700 ft, with its maximum thickness in the vicinity of Mineral Wells (Brown and others, 1972).

Shaly portions of the Mineral Wells Formation are typically poorly exposed. The shales vary from thin-bedded and fissile to blocky and show a range of greenish, bluish, reddish, and yellowish gray colors (commonly variegated in one outcrop). Some portions are sandy and/or

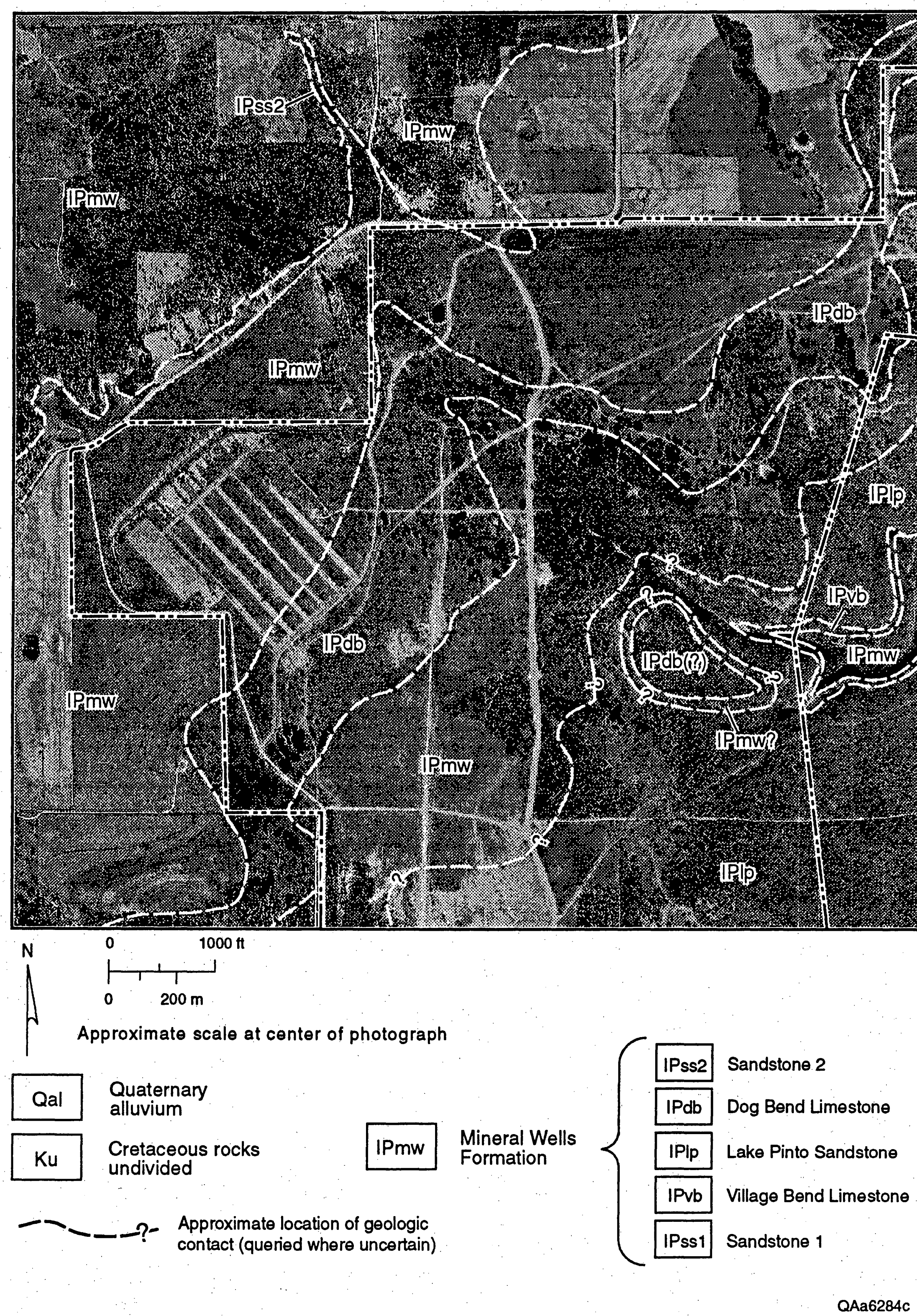

Figure 8a. Geologic map of northwest portion of Fort Wolters on unrectified aerial photograph base (from NAPP 2342-68; see table 1).

Figure 8b. Geologic map of northeast portion of Fort Wolters on unrectified aerial photograph base (NAPP 2342-68; see table 1); see figure 8a for explanation of map symbols.

Figure 8c. Geologic map of southwest portion of Fort Wolters, on unrectified aerial photograph base (NAPP 2342-68; see table 1); see figure 8a for explanation of map symbols.

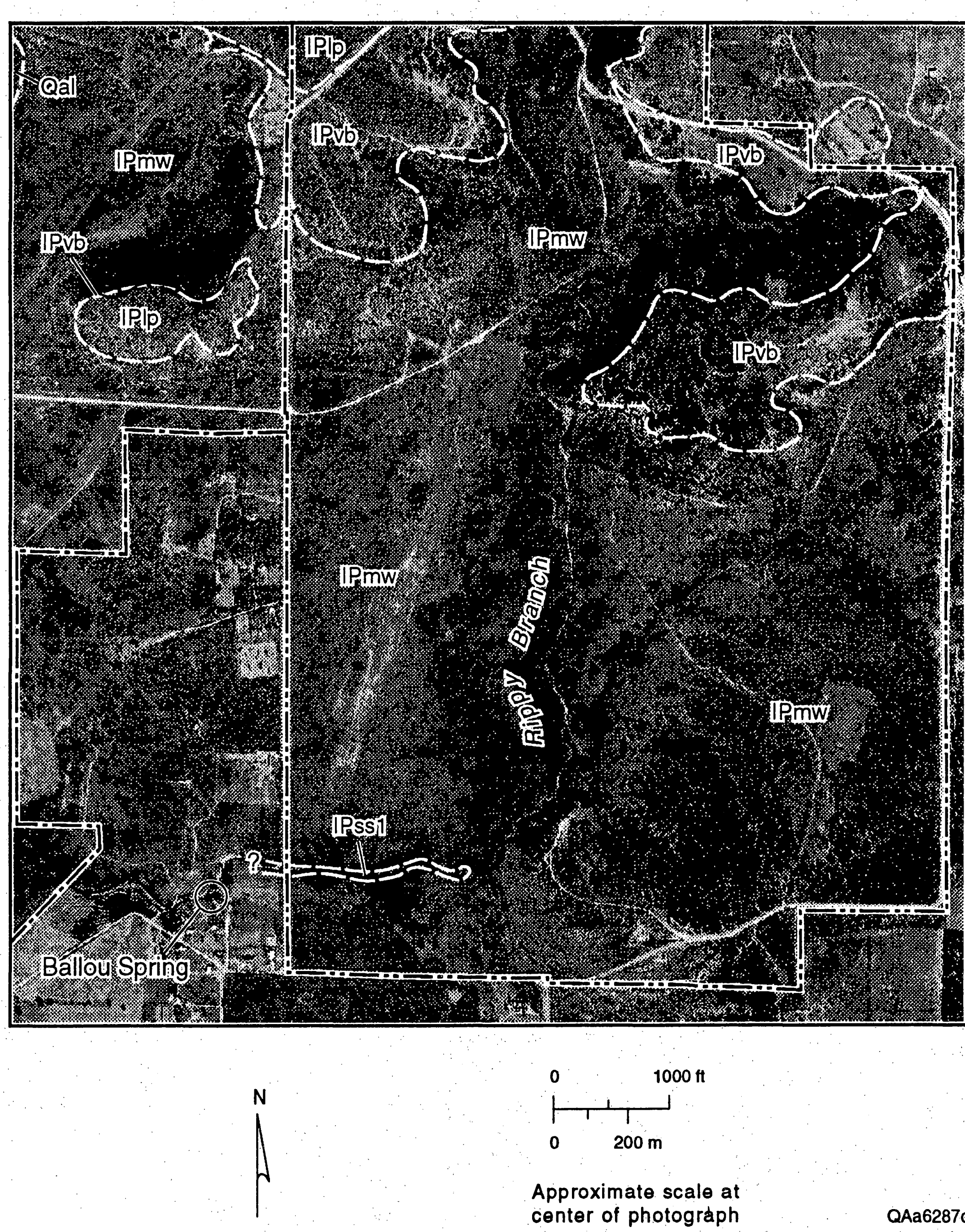

Figure 8d. Geologic map of southeast portion of Fort Wolters on unrectified aerial photograph base (NAPP 2342-68; see table 1); see figure 8a for explanation of map symbols.

calcareous and contain thin sandstone or limestone interbeds, whereas others portions are very clayey. Brown (1959, p. 5) reported the following mineralogy for Mineral Wells Formation shale beds (East Mountain shale) in the Mineral Wells Clay Products Corporation pit, in decreasing order of abundance: muscovite, illite, kaolinite, trace of montmorillonite, iron hydroxide, and quartz. In places the shale is limonitic (bearing one or more iron oxides or hydroxides) and may form a ledge. Reported megafossils include crinoid fragments (most notably column segments), brachiopod, bryozoans, gastropods, pelecypods, cephalopods, and locally plant fossils. Echols (1959) described microfossils in the middle part of the formation (below the Lake Pinto Sandstone), including foraminifers (including fusulinids), ostracodes, conodonts, porifera (sponges), and holothurians (sea cucumbers). In addition, loose pieces of petrified wood were found on the slopes of sandy shale below the Lake Pinto Sandstone and Village Bend Limestone east of Rock Creek, and probably can be found in other areas as well.

Several theses and dissertations provide measured stratigraphic sections or describe outcrops and subsurface features of the Mineral Wells Formation and other Pennsylvanian rocks. These include Shelton (1953), Hodgson (1957), Glass (1958), Kelley (1958), Echols (1959), Trice (1984), and Hitchcock (1985).

Hog Mountain Sandstone

The Hog Mountain Sandstone (IPhm in fig. 8) is the basal member of the Mineral Wells Formation (fig. 7). It is exposed in the canyon of Rock Creek below Lake Mineral Wells and in other areas (fig. 6d). Thickness of the Hog Mountain Sandstone is about 25 ft.

Informal Sandstone Unit 1

Informal sandstone 1 (IPss1 in fig. 8) occurs about 25 ft above the Hog Mountain Sandstone. The two sandstone units are stratigraphically very close and have been mapped together as a single unit in the past. Sandstone 1 is typically conglomeratic. It caps several hills in the southernmost part of Fort Wolters and in the area to the south. The unit is also exposed in the bed of Rippy Branch (fig. 8d) near the State Park, and in a quarry pit (mostly full of water) about 0.1 mi southwest of Helicopter Stage Field No. 3. Sandstone 1 forms the scenic bluff along the east and west sides of Lake Mineral Wells.

Village Bend Limestone

The Village Bend Limestone (IPvb in fig. 8) is exposed in the eastern part of Fort Wolters, where it reaches a total thickness of about 10 ft. The unit is exposed in Lake Mineral Wells State Park and thins toward the western part of the base where it is no longer traceable. In places it occurs as two discrete beds. The Village Bend Limestone on Fort Wolters is probably not the same limestone as the type locality southwest of Mineral Wells but rather a similar limestone in approximately the same stratigraphic position (Shelton, 1958, p. 36–46).

The Village Bend Limestone on Fort Wolters is finely crystalline (grains mostly less than 0.1 mm, but up to 3 mm), thin (2–8 cm) to thick (15–30 cm), irregularly bedded phylloid algal packstone, with colors ranging from light olive gray to pale yellowish brown, and weathering medium light gray to yellowish gray (Echols, 1959, charts 5 and 6; Trice, 1984, p. 85–86). Fossils include crinoid fragments, gastropods, brachiopods, corals, and bryozoans (Trice, 1984, p. 85–86).

Lake Pinto Sandstone

The Lake Pinto Sandstone (IPlp in fig. 8) is a medium to fine grained, locally conglomeratic, thin to thick bedded to massive, resistant ledge-forming sandstone and sandy shale up to 50 ft thick. Colors vary from pale grayish brown to reddish brown to dark brown. The unit is commonly limonitic (iron-oxide/hydroxide-cemented), and unfossiliferous, except for some brachiopods and large plant fragments in the upper part (Echols, 1959). It forms a high scarp near Mineral Wells that becomes less prominent to the southwest (Trice, 1984, p. 19). The Lake

Pinto Sandstone represents a deltaic distributary complex incised into and built across deltaic muds represented by the shales.

Dog Bend Limestone

The Dog Bend Limestone (IPdb in fig. 8) occurs in the northwest part of Fort Wolters and in the small triangular area in the northeast, outside of the main part of the base. The Dog Bend Limestone is an algal wackestone to mudstone that varies from massive to thin bedded, commonly with wavy bedding planes, and is up to 5 ft thick (Trice, 1984, p. 88). The unit is finely crystalline (grains vary from <0.2 mm to 2.0 mm) and locally sandy, having colors that range from light olive gray to yellowish brown to brownish gray (Echols, 1959). The rock is locally fossiliferous, containing brachiopods, crinoids, bryozoans, and corals(?).

Informal Sandstone Unit 2

Informal sandstone 2 (IPss2 in fig. 8) is exposed in the area immediately northwest of Fort Wolters. Sandstone 2 is fine grained, thin bedded to massive, locally crossbedded, and in part calcareous, with colors ranging from yellowish gray light olive, weathering grayish orange to dark gray (Echols, 1959). Maximum thickness is about 12 ft (Brown and others, 1972). Sandstone 2 in several stratigraphic schemes is referred to as the Devils Hollow Sandstone (see fig. 7).

Turkey Creek Sandstone

The Turkey Creek Sandstone (IPtc in fig. 6d) is exposed about 2 mi northwest of Fort Wolters, mostly on the west side of U.S. Highway 281. The rock is a coarse, locally conglomeratic, thick bedded, hard, calcareous sandstone, with colors ranging from light gray to reddish brown (Echols, 1959, chart 6; Trice, 1984, p. 19). The unit varies from 10 to 50 ft thick and forms a prominent escarpment northwest of Mineral Wells. The Turkey Creek Sandstone is unfossiliferous.

Palo Pinto Formation (Pennsylvanian)

The Palo Pinto Formation overlies the Mineral Wells Formation about 5 mi west of Fort Wolters (fig. 6d). The Palo Pinto Formation is dominantly limestone and marl, with some sandstone and shale (Brown and others, 1972).

Paluxy, Glen Rose, and Twin Mountains Formations (Cretaceous)

Cretaceous rocks lap onto the Pennsylvanian section in western Parker County, just east of Fort Wolters (fig. 6d). The lowermost portion of the Cretaceous section is the Twin Mountains Formation, which consists dominantly of sandstone, with some claystone and conglomerate in the lower part, sandstone and claystone in the middle part, and claystone in the upper part (Brown and others, 1972). The formation is as much as 170 ft thick in Parker County, and thins westward to a feather edge where it has been completely eroded from above the Pennsylvanian. The Twin Mountains Formation is overlain by the Glen Rose Formation, which consists of alternating limestone and claystone with a distinctive stair-step topography. The Glen Rose is overlain by the Paluxy Formation, which consists of sandstone with interbedded claystone. The Paluxy, Glen Rose, and Twin Mountains Formations are commonly referred to collectively as the Antlers Sand (or basal Cretaceous, or "Trinity Sand"), particularly where the carbonate (limestone) facies are thin or lacking; the Twin Mountains Formation is sometimes referred to as the Travis Peak Formation, which is the name for equivalent strata to the southwest and south in Brown, Mills, and Lampasas Counties.

Alluvium and Colluvium (Quaternary)

Relatively young, unconsolidated alluvium is present along Rock Creek, particularly where the stream valley widens southward into Lake Mineral Wells State Park. The distribution of alluvium marks the floodplain of Rock Creek. The alluvium is general dark and silty to sandy (Flemming & Associates, 1971, p. VI-4).

Colluvium is a general term applied to any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rainwash, sheetwash, or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides (Bates and Jackson, 1987, p. 132). Small colluvial deposits are common at the base of shale slopes underlying resistant sandstone.

Economic Geology

Industrial Minerals

Industrial minerals (limestone, clay, gravel) have been extracted from a number of places on the Fort Wolters property for use in construction of roads and facilities. Most of the quarries and pits were begun after the time of the 1953 aerial photographs and had nearly reached their present sizes by the time of the 1959 photographs. Pits and quarries are identified in figures 9a through 9d.

Several limestone quarries are present in the Village Bend Limestone. The largest, located near the eastern edge of the base just south of Helicopter Stage Field No. 1, consists of a quarry pit that has been dammed to form a pond, with surrounding areas stripped to bedrock and quarried to various depths (fig. 9b). Stripped areas of Village Bend Limestone indicating past quarrying (or preparation for quarrying) are present about 2,000 ft southwest, 2,000 ft southeast, and 5,000 ft southeast of Helicopter Stage Field No. 1 (fig. 9d). Another quarry from

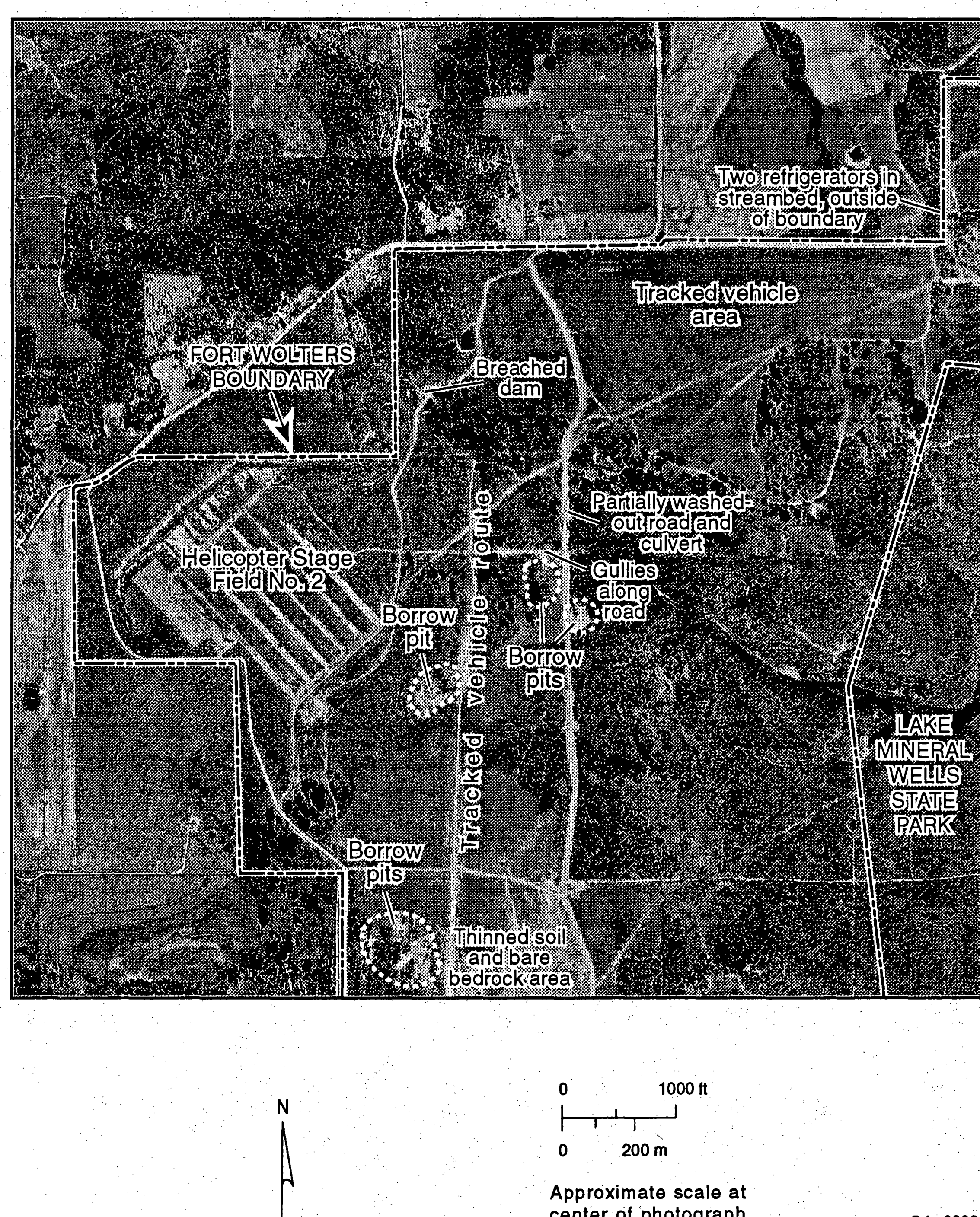

Figure 9a. Pits, quarries, gullies, and other surface disturbance features in northwest portion of Fort Wolters, on unrectified aerial photograph base (from NAPP 2342-68; see table 1).

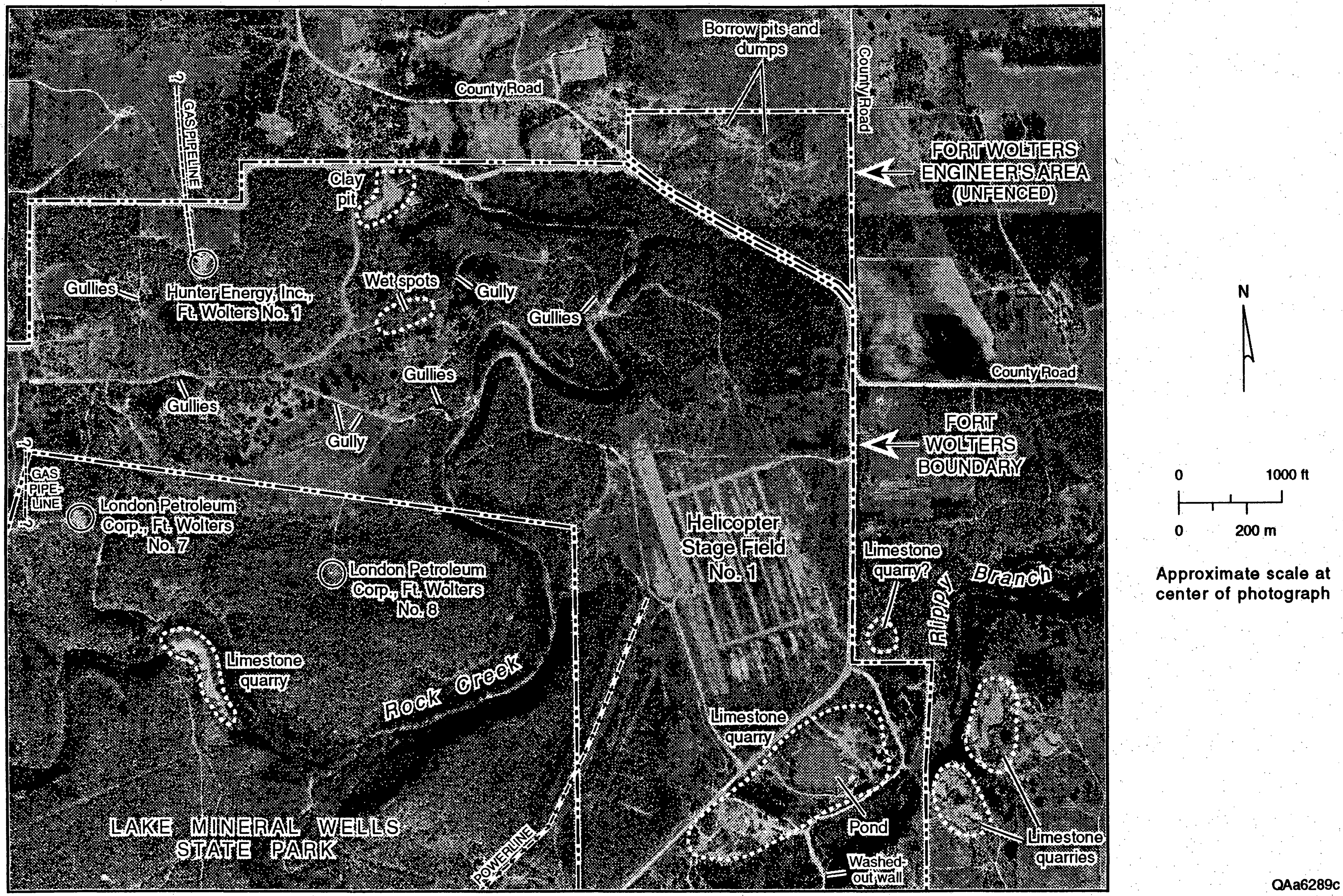

Figure 9b. Pits, quarries, gullies, and other surface disturbance features in northeast portion of Fort Wolters, on unrectified aerial photograph base (from NAPP 2342-68; see table 1).

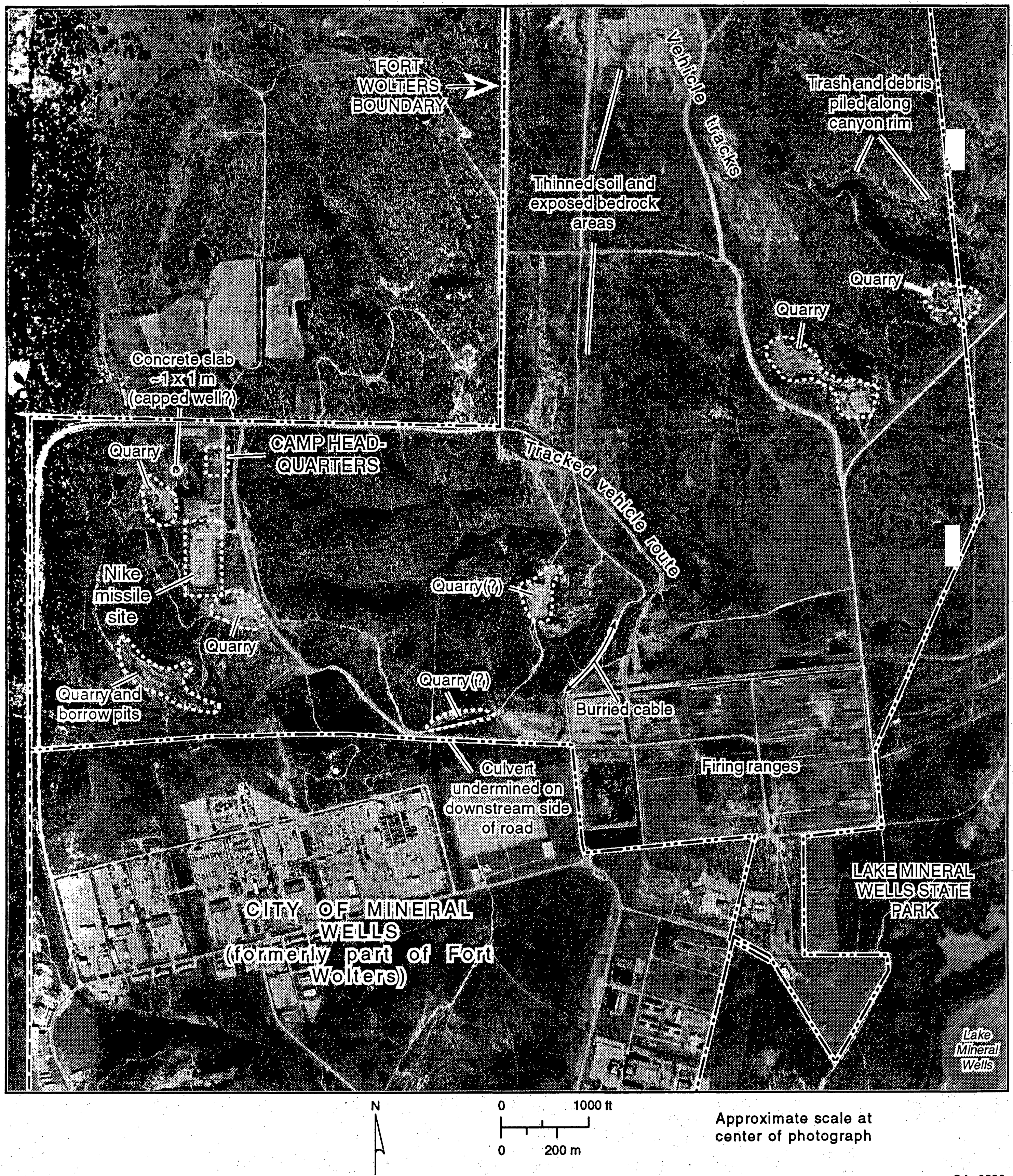

Figure 9c. Pits, quarries, gullies, and other surface disturbance features in southwest portion of Fort Wolters, on unrectified aerial photograph base (from NAPP 2342-68; see table 1).

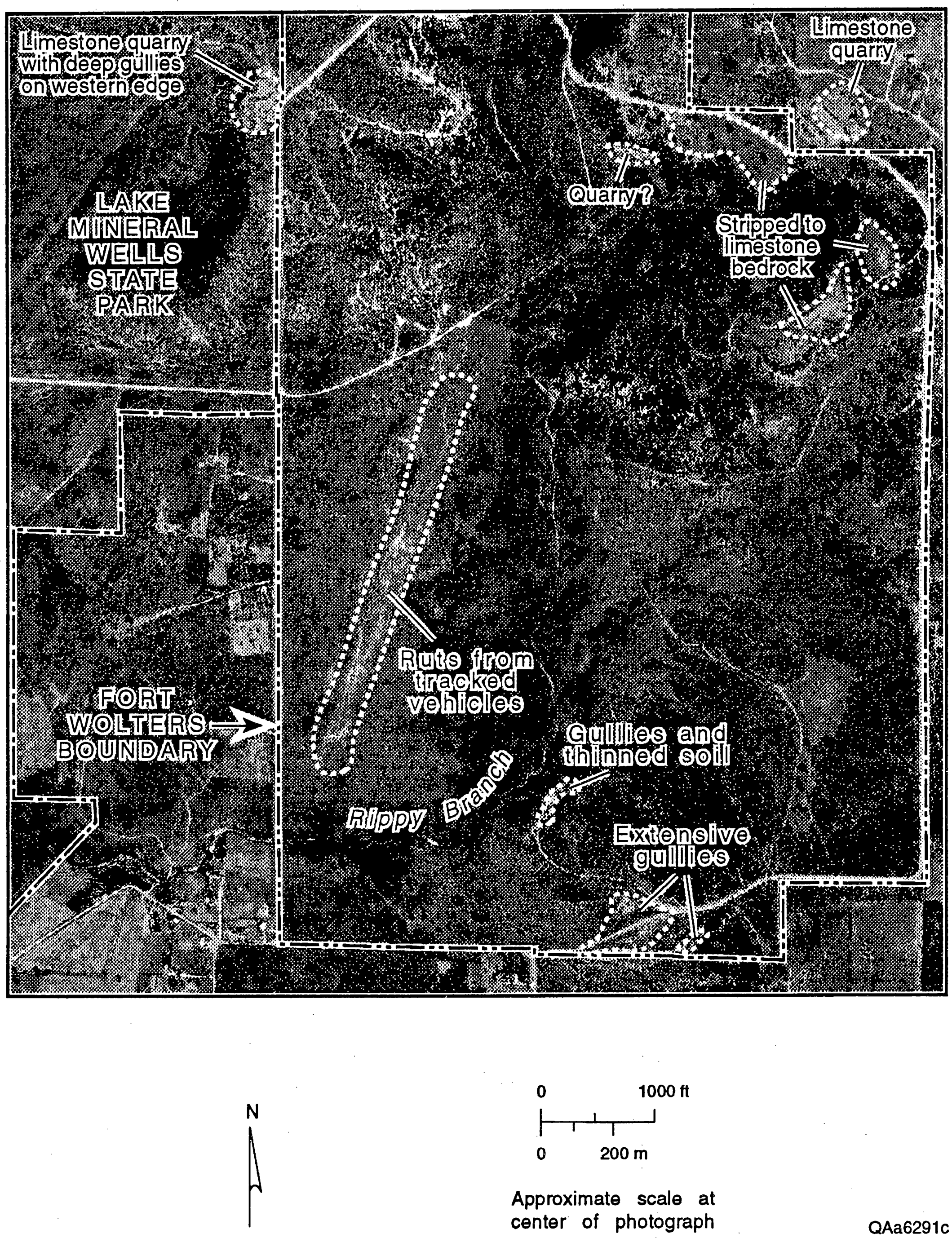

Figure 9d. Pits, quarries, gullies, and other surface disturbance features in southeast portion of Fort Wolters, on unrectified aerial photograph base (from NAPP 2342-68; see table 1).

this period is present in the western half of the base, about 600 ft west of the State Park and 5,000 ft north of Lake Mineral Wells (fig. 9c). Yet another abandoned quarry in the Village Bend Limestone is on an old part of the base that is now in Lake Mineral Wells State Park (fig. 9b). This quarry postdates the 1959 aerial photographs and predates the 1976 acquisition of the land by the State Park. Limestone quarries, perhaps better described as "borrow" pits, are also present in the Dog Bend Limestone in the northern and western parts of the base (figs. 9a and 9c).

Clay pits are present in a number of places on Fort Wolters (figs. 9a–d). One of special interest is located along the northern edge, near Rock Creek (fig. 9b). The pit is not present on 1953 aerial photographs but is present on the 1956 aerial photographs. Most of the clay was extracted in the mid-1950's and used in roadbuilding on the base. The pit is especially interesting because it exposes fossil trees, present as fallen, detached, flattened trunks as much as 20 ft long, and as in-place stumps, some with radiating roots. The material is heavily carbonized (coalified) and fractured, black, and commonly contains gypsum and iron oxides that add yellow, red, and brown highlights. The trees are probably conifers (of the type *Cordaites*), or possibly a lepidodendron (club moss), although their poor preservation precludes positive identification (Theodore Delevoryas, The University of Texas at Austin, Botany Department, personal communication, March 1994). Crystalline masses of gypsum (variety selenite) of ≥5 cm in long dimension are scattered throughout this pit; some show well-developed crystal forms. A number of other clay and/or crushed stone pits are present on the western half of the base, particularly in the escarpment below the Lake Pinto Sandstone (fig. 9c).

Oil and Gas

At least three oil and gas wells are present in the immediate Fort Wolters area—one (Hunter Energy Inc., Fort Wolters No. 1) is within the boundaries of the base, the other two

(London Petroleum Corp., Fort Wolters No. 7 and No. 8) are in the northern part of Lake Mineral Wells State Park (fig. 9b). New ownership signs had been placed on the wells sometime between visits to the field in July and November 1993. Fort Wolters No. 1 (Railroad Commission of Texas No. 101685) was operating on November 24, 1993 (producing both oil and gas). Fort Wolters No. 7 (Railroad Commission No. 100671) was not operating on November 24, although a faint "hissing" sound could be heard in the pipes. Fort Wolters No. 8 (Railroad Commission No. 110804) has apparently been temporarily abandoned since September 28, 1988, according to a note in the meter box. These wells apparently produce(d) from the "Conglomerate," an informal term for an Atokan (or Morrowan?) age (early Pennsylvanian) conglomeratic sand at the base of the Big Saline Formation, part of the Bend Group that underlies the lower Strawn (Herkommer and Denke, 1982, p. 101, 103, 108). Herkommer and Denke (1982, their table 2) list only one well in the Fort Wolters field, with a cumulative production through (January 1, 1980) of ~564 million ft^3 of gas and ~7,000 bbl of condensate. Herkommer and Denke (1980, their table 2 and fig. 12) list several other fields in the vicinity of Fort Wolters, including the Lake Mineral Wells, Coyle, Sandra K., HPM, Bethesda and Bethesda SW, Church, and LBC fields.

Coal

Coal was mined underground from several seams near the middle of the Mingus Formation (fig. 7) in the area where Dry Creek enters Rock Creek, about 2.5 mi south of Fort Wolters (Herkommer and Denke, 1980, p. 114; Cummins, 1891, p. 519–521, 526–534). Most of the mining occurred between 1890 and 1907 (Parker County Historical Commission, 1980, p. 56). This area was referred to as the town of Rock Creek and once had a population of about 1,000, though the physical features of the town were limited to a few company buildings, shacks, and the mines (Texas Parks and Wildlife Department, 1976, p. 128).

GEOMORPHOLOGY

Fort Wolters is in the transition zone between the Cross Timbers and Prairies vegetation regions. The area is characterized by rolling to undulating sandstone hills with nearly level uplands underlain by sandstone and shale, deeply dissected by streams and canyons with local terraces. Overall slope of the region is to the southeast; local drainage is toward the south and southwest.

Elevation

The elevation of Fort Wolters Ranges from a maximum of about 1,030 ft in the northwestern part of the base near Helicopter Stage Field No. 2 to a minimum of about 870 ft in the southeast, where Rippy Branch of Rock Creek flows westward off the base onto private property. The relief across the entire property is 160 ft. Most of the elevation change occurs across shale escarpments capped by resistant sandstones and limestones.

Cuestas, Escarpments, and Canyons

The landscape of Fort Wolters consists of cuesta, escarpment, and canyon morphology. Cuestas are sloping plains that are terminated on one side by a steep slope. Cuestas form in areas of gently dipping strata with alternating soft and resistant layers—the softer layers erode back, leaving a thin mantle or completely exposing a dip slope of the underlying resistant unit. In the Fort Wolters area, the relatively soft shales erode easily to produce broad undulating surfaces on the more resistant sandstone (or limestone) layers, which are exposed as the capping units on the steep slopes and escarpments that separate the cuestas. Two major cuestas and one minor cuesta are present on Fort Wolters (fig. 10). The lower cuesta is underlain by informal sandstone unit 1 and by the Lake Pinto Sandstone. Separating these two cuestas is an escarpment that exposes varying thicknesses of Lake Pinto Sandstone and underlying shales.

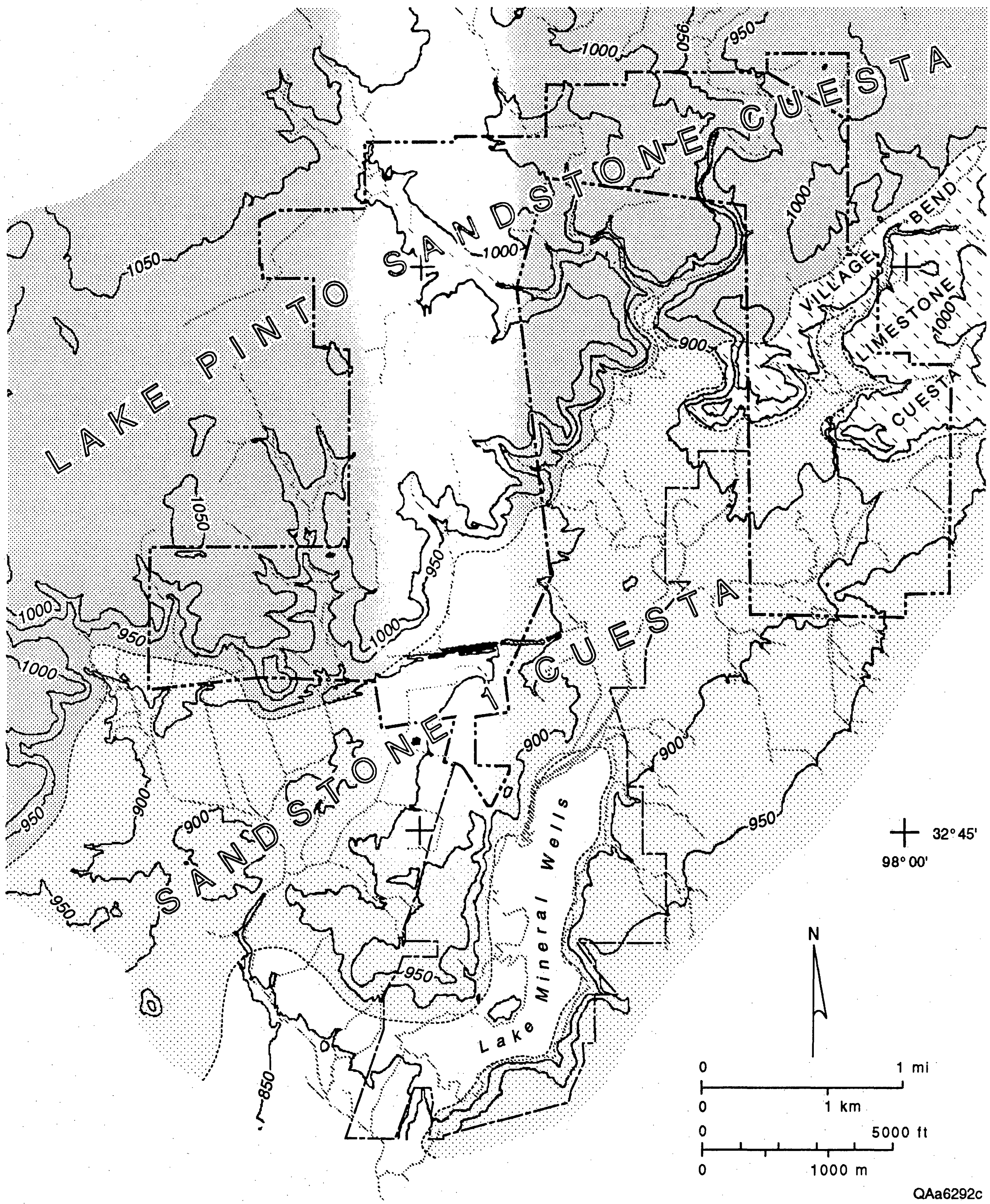

Figure 10. Topographic map of Fort Wolters area showing cuesta, escarpment, and canyon geomorphology. Topographic contours (dark lines, at 50-ft intervals) and streams (light stippled lines) digitized from U.S. Geological Survey 7.5-minute topographic quadrangle maps.

The escarpment is notched by several short canyons and by the canyon of Rock Creek. In the eastern part of Fort Wolters a minor cuesta has developed on the Village Bend Limestone where it is thickest and where the overlying Lake Pinto Sandstone either thins, becomes shaly, or has been eroded back (fig. 10).

A common feature of the cuestas is that the upper surfaces have few rock outcrops—most of the outcrops are on or near the cuesta faces and slopes. Also, there are commonly seasonal or perennial wet spots on the upper parts of the cuestas as drainage tends to be poorer because of lower gradients.

Trice (1984, p. 16–19) identified eight discontinuous, approximately northeast–southwest-striking, southeast-facing cuestas in the Fort Wolters region, each capped by a resistant sandstone, conglomeratic sandstone, or limestone, with escarpment faces of friable sandstone, shale, and thin limestone. In ascending stratigraphic order they are: Meek Bend Limestone cuesta (Lazy Bend Formation, beneath Grindstone Creek Formation), Brannon Ridge Limestone cuesta (Grindstone Creek Formation), Buck Creek Sandstone cuesta (Grindstone Creek Formation), Dobbs Valley Sandstone cuesta (Mingus Formation), Brazos River Formation cuesta, Hog Mountain Sandstone cuesta (Mineral Wells Formation), Lake Pinto Sandstone cuesta (Mineral Wells Formation), and Turkey Creek Sandstone cuesta (Mineral Wells Formation). The escarpments separating these become more subdued toward the southwest as the resistive units thin. The Brazos River Formation forms the most continuous cuesta in the Strawn Group. The cuesta of sandstone 1 described in this report is probably the same as that identified as the Hog Mountain Sandstone cuesta by Trice (1984), as the two surfaces are difficult to recognize separately.

Stream Morphology

The Fort Wolters region has a well-developed dendritic drainage network. Major streams and tributaries have well-defined channels and have carved canyons where they cross resistant units. Channels of smaller tributaries widen and become less obvious on the upper cuesta (Lake Pinto Sandstone cuesta, fig. 10), whereas channels on the lower cuesta (sandstone 1 cuesta, fig. 10) have been modified (deepened and rerouted) to improve drainage. Streams that run perpendicular to the strike of the cuestas are typically short and have high gradients where they cross escarpments, whereas streams that run parallel to the strike of the cuestas have gentler gradients, larger watersheds, more tributaries, and more sustained flow (fig. 10). Stream terraces are present in the State Park along Rock Creek where it crosses the lower cuesta, between the Lake Pinto Sandstone escarpment and Lake Mineral Wells.

SURFACE HYDROLOGY

Principal Streams and Drainage Basins

The Fort Wolters region is drained by the southeasterly flowing Brazos River (fig. 1). Tributary drainage basins in this region are elongate and oriented northeast-southwest, approximately parallel to the strike of the underlying geologic units that control their development (fig. 11). Basins on the north side of the Brazos River drain toward the south and southwest. Fort Wolters is entirely within the Rock Creek drainage basin, about halfway between its headwaters and where it empties into the Brazos River (fig. 11). The surface of Fort Wolters is divided over six subbasins (fig. 12). Five drain into Rock Creek upstream from Lake Mineral Wells, and one (subbasin G) downstream from the lake (fig. 12). The subbasins have well-developed drainage networks on all but the gentlest slopes of the cuestas. Subbasin F incorporates the canyon reach of Rock Creek, short tributaries and rills that drain off of the floodplain and surrounding escarpment, and Lake Mineral Wells.

Rock Creek is an intermittent stream, though some reaches may have puddles and trickles even during the dry parts of the year. The stream heads in northwestern Parker County in Cretaceous sandstones and claystones that overlap the Pennsylvanian rocks. In the past, flow on Rock Creek may have been sustained by springs and seeps from the Cretaceous sands; most

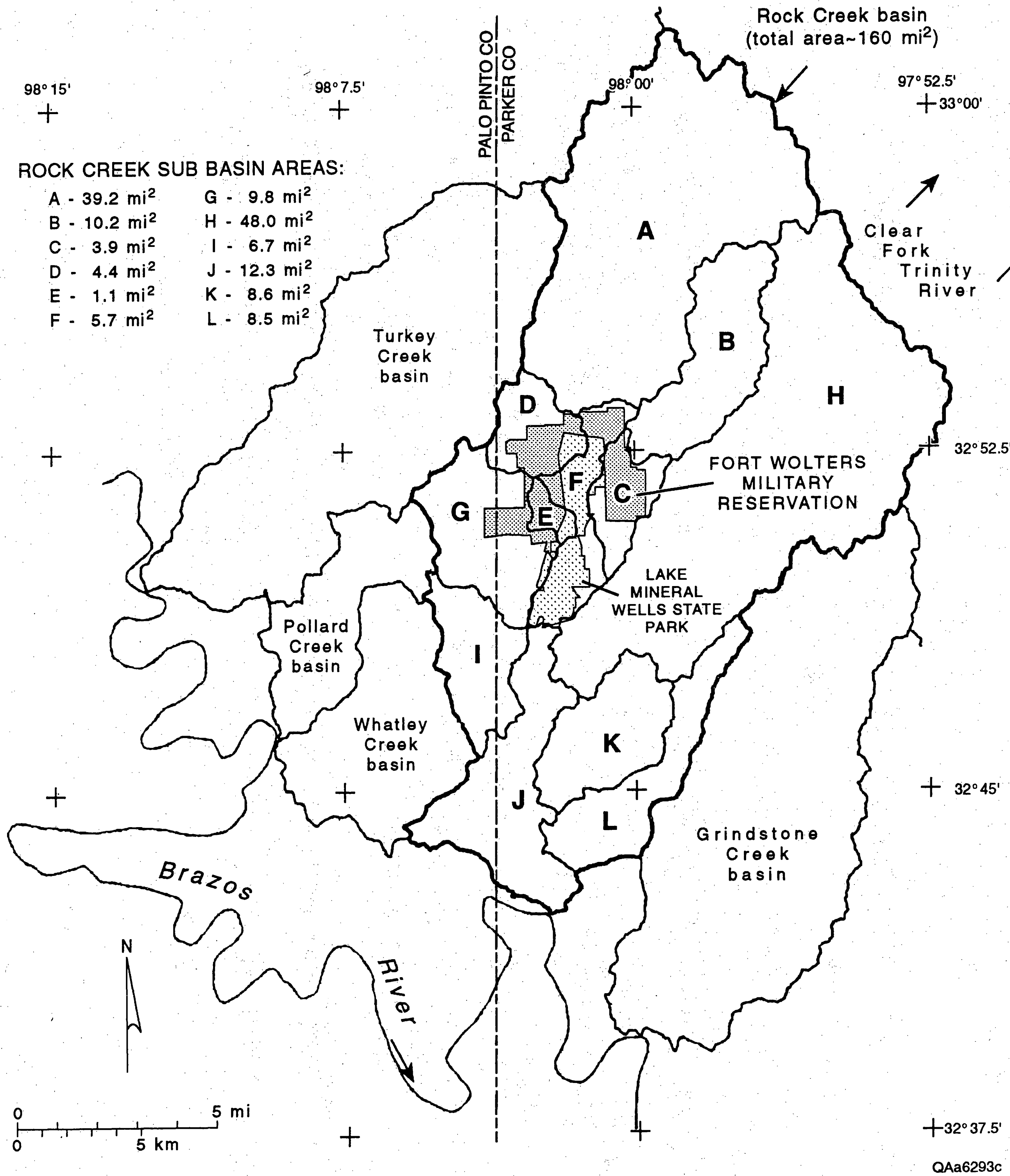

Figure 11. Surface drainage in the Fort Wolters region. Brazos River and drainage basin outlines digitized from U.S. Geological Survey 7.5-minute topographic quadrangle maps. Heaviest line marks outline (drainage divide) of Rock Creek basin; finer lines mark sub-basin drainage divides within Rock Creek basin, and drainage divides of adjacent creek basins. Total area of Rock Creek basin is ~160 mi^2; areas of sub-basins are listed at upper right of figure.

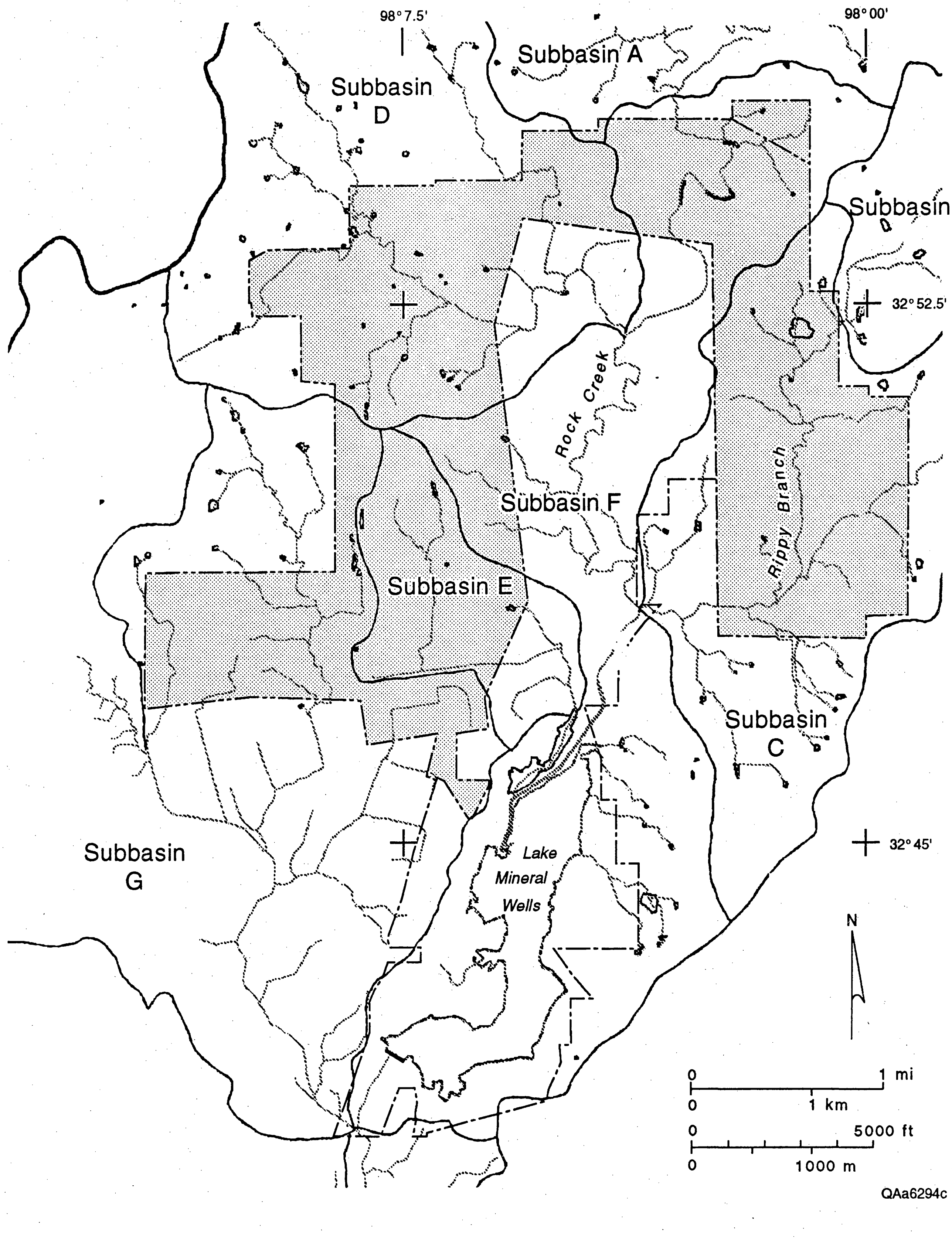

Figure 12. Streams (light stipple pattern), waterbodies (small dark outlines), and drainage sub-basins (heavy dartk lines) in the immediate Fort Wolters area (sub-basin areas shown in figure 11).

of the historic springs have stopped flowing because water tables have been lowered by pumping and stream channels have become clogged with silt from surrounding farmlands (Brune, 1981, p. 352–354). Most of the flow is now from runoff and seepage through the soil. Some flow is probably contributed by small amounts of ground water seeping from sandstones and fractured limestones.

Lake Mineral Wells

Lake Mineral Wells (surface area 646 ac) is located in southern half of Lake Mineral Wells State Park (fig. 12) on land that was once part of Fort Wolters. An examination of the literature leaves some uncertainty about the early history of the lake. A water-supply report by Henningson, Durham and Richardson, Inc. (1979) states that the original dam was constructed in 1920 by the City of Mineral Wells for municipal use, and the spillway height increased by 2 ft in 1943. The development plan document for the State Park indicates that the lake was originally constructed in 1929 as a water supply for Camp Wolters, then later obtained by the City of Mineral Wells and used as the primary water supply until the development of Lake Palo Pinto southwest of the City on the south side of the Brazos River (Texas Parks and Wildlife, 1976, p. 129, and Biological Survey section). The document also states that the height of the dam was increased in the 1930's. The State Park brochure notes that the lake was constructed in the 1930's by the City and the Civilian Conservation Corps (CCC) and that many of the facilities were constructed by the CCC. A summary of the history of the lake and its engineering and safety characteristics is provided in a safety inspection report by the Texas Department of Water Resources (1980). The lake and an additional 1,095 ac of land were donated to the State by the City of Mineral Wells in 1976 and combined with property transferred from Fort Wolters by the U.S. Army to form Lake Mineral Wells State Park.

Streamflow and Flooding

Fort Wolters has rapid surface drainage because it is underlain mainly by slowly permeable soils and has a well-developed drainage network. Heavy rainfalls cause flooding on Rock Creek and its tributaries. One storm in the spring of 1970 produced an estimated 12,000 ft^3/s flood on Rock Creek (Forrest and Cotton, 1970), which undermined the spillway of Lake Mineral Wells dam and severely eroded around the abutments. This damage required the lake to be drained until extensive repairs and modifications could be completed.

Flooding is probably not a great problem on Fort Wolters except at stream crossings. Most of the floodplain of this segment of Rock Creek is in the State Park, whereas the portion of Rock Creek that crosses the base is entrenched in a canyon that restricts flow to a narrow channel. Rock Creek is not gauged, and therefore there are no records to describe its long-term discharge history. However, a technique is presented by Schroeder and Massey (1977) to estimate flood magnitudes with recurrence intervals of 2, 5, 10, 25, 50, and 100 years for unregulated rural streams with drainage basins ranging in area from 0.3 mi^2 to about 5,000 mi^2, based on data from existing gauges (through September 1974). This technique was applied to estimate floodflows for several locations on Rock Creek (table 3). Rock Creek is in flood-frequency Region 2, in which drainage area and slope are the variables significant to flood-frequency analysis (Schroeder and Massey, 1977). The results suggest that the estimated 12,000 ft^3/s flood that damaged Lake Mineral Wells dam in 1970 has a recurrence interval of between 10 and 25 years, which seems too frequent based on historical information about flood experience at Lake Mineral Wells. This can be reconciled by realizing that the flood estimate technique of Schroeder and Massey (1977) is based on least-squares regression analyses of data from entire regions, so that there is an inherent error to the estimate, which in Region 2 ranges from about 40 to 55 percent. It is also possible that the flood that damaged the dam had a discharge greater than the 12,000 ft^3/s estimated (by an unreported method) by Forrest and Cotton (1970). It should be further realized that a recurrence interval is the statistical average

Table 3. Estimated discharge for 2, 5, 10, 25, 50, and 100-year floods at selected locations on Rock Creek (by method of Schroeder and Massey, 1977).

Location	Contributing Drainage Area (sq mi) [1]	Streambed Distance from Site to Basin Drainage Divide (mi) [2]	Elevation of Streambed Above Site [2]		Estimated Flood Discharge (cu ft/s)					
			10 percent of Distance Upstream from Site (ft)	85 percent of Distance Upstream from Site (ft)	2-yr flood	5-yr flood	10-yr flood	25-yr flood	50-yr flood	100-yr flood
Point where Rock Creek flows across northern boundary of Fort Wolters	39.2	12.9	945	1135	2,500	5,300	8,000	11,000	14,000	17,000
Point where Rock Creek flows out of Lake Mineral Wells State Park	64.5	21.3	865	1080	3,200	7,000	10,000	15,000	17,000	21,000

[1] Contributing drainage area from figure 11.

[2] Streambed distances and elevations measured and estimated from topographic maps (U.S. Geological Survey, 1979c, 1984e, 1984g).

interval of time within which a flood of a given magnitude will be equaled or exceeded once. It does not imply that a flood of a specific recurrence interval will occur on schedule at regular intervals. It is possible that several large floods may occur within a period of a few years, or, that many years may pass without a major flood. Also, flood height at a particular location will depend not only on flood discharge but also on the channel characteristics (width, depth, roughness) and their variations upstream and downstream from the site of interest.

Surface Water Quality and Stream Sediment

There is little published information on surface water quality in the Fort Wolters area. Several data from the early to mid-1970's were found for Lake Mineral Wells (table 4). The data indicate that the water is slightly alkaline and hard (150 mg/L and greater) and has moderate to low total dissolved solids (TDS). Surface water in this part of Texas generally improves in an easterly direction, reflecting the increasing distance from Permian evaporite deposits (which commonly discharge saline ground water), and increasing precipitation and associated dilution by fresher surface water and ground water. For example, Brazos River water quality improves as it progresses downstream from headwaters—at the Palo Pinto-Parker County line, TDS drops below 500 mg/L and sulfate below 250 mg/L; chloride remains in the 251–500 mg/L range (Rawson, 1974, fig. 1).

Most of the water-quality problems in the Rock Creek drainage are caused by materials eroded from surrounding disturbed lands, particularly farmlands on Cretaceous sands upstream from Fort Wolters. The Texas Parks and Wildlife Department (1976, Biological Survey section) found that much of Lake Mineral Wells exhibits heavy siltation, although some areas have a firm gravel bottom. The maximum depth is about 35 ft, although most of the lake is 8 to 16 ft deep, or less. Flemming & Associates (1971, p. VII-7) reported that Lake Mineral Wells has a 5,005 ac-ft conservation capacity, a 3,415 ac-ft sediment capacity, and in 1971 had a yield of 2,525 ac-ft, which was projected to be down to 200 ac-ft by the year 2020. Henningson,

Table 4. Water quality data for Lake Mineral Wells.

Depth	Temperature (°F)	Dissolved oxygen (ppm)	pH	Total alkalinity (ppm)	Total hardness (ppm)	Specific conductance (at 25° C)	Total dissolved solids (ppm)
Northern part of lake (station A) [1]							
Surface	79	7.6	7.9	125	150	355	231
Bottom (6.9 ft)	78	7.6	7.3	130	160	375	325
(secchi disc visible to 8 inches depth)							
Southern part of lake (station B) [1]							
Surface	77	7.3	7.8	130	150	360	250
Middle	76	6.3	7.8	130	150	362	212
Bottom (26 ft)	70	1.2	7.8	135	160	376	250
(secchi disc visible to 17 inches depth)							
Unspecified location(s) [2]							196 - 262

[1] Data from Biological Survey section in Texas Parks and Wildlife Department (1976); sampling conducted on May 23, 1975, at 2:25 p.m. (Station A) and 3:00 p.m. (Station B); weather conditions - sky 90% overcast, air temperature 85°F, wind 15-20 mph from south.

[2] Data from Flemming & Associates (1971, p. VII-6 - VII-7).

Durham and Richardson, Inc. (1979) estimated that 73.7 ac-ft of sediment is added to the lake each year, and that water capacity would be reduced to 4,550 ac-ft by the year 2000 (see also Texas Department of Water Resources, 1980). Water turbidity reportedly remains fairly high much of time because of shallow average depth, abundance of silt, and prevailing southerly wind that impinges on the surface of the lake. Water quality is apparently adequate for fish production, although the turbidity probably reduces the primary productivity of the lake (limiting penetration of sunlight and opportunities for photosynthetic plants) and thus lowers the standing crop of desirable species.

SOILS

The soils of Fort Wolters are mainly grouped in the Truce-Bonti association, except for soils of the easternmost part, which are grouped in the Chaney-Truce-Bonti association (Greenwade and others, 1977). A soil association is defined as a landscape that has a distinctive proportional pattern of soils. It normally consists of one or more major soils and at least one minor soil, and it is named for the major soils. The soils in one association may occur in another, but in a different pattern. Both the Truce-Bonti and Chaney-Truce-Bonti associations are classed as neutral to slightly acid loamy and sandy soils on uplands. The Truce-Bonti association is characterized by gently sloping to steep, deep and moderately deep loamy soils over sandstone or shaly clay; the Chaney-Truce-Bonti association is characterized by gently sloping to moderately steep, deep and moderately deep sandy or loamy soils over sandstone, shaly clay, or sandy clay (Greenwade and others, 1977).

The distribution of soil types is controlled by the underlying geologic units from which they are derived and the landscape in which they accumulate. The soils on Fort Wolters (fig. 13, table 5) can be assigned to five informal groups on the basis of parent materials: (1) Bonti soils, which have formed on moderately to strongly cemented sandstone, (2) Truce-Chaney-Duffau soils, which formed on shale and interbedded sandstone, and locally

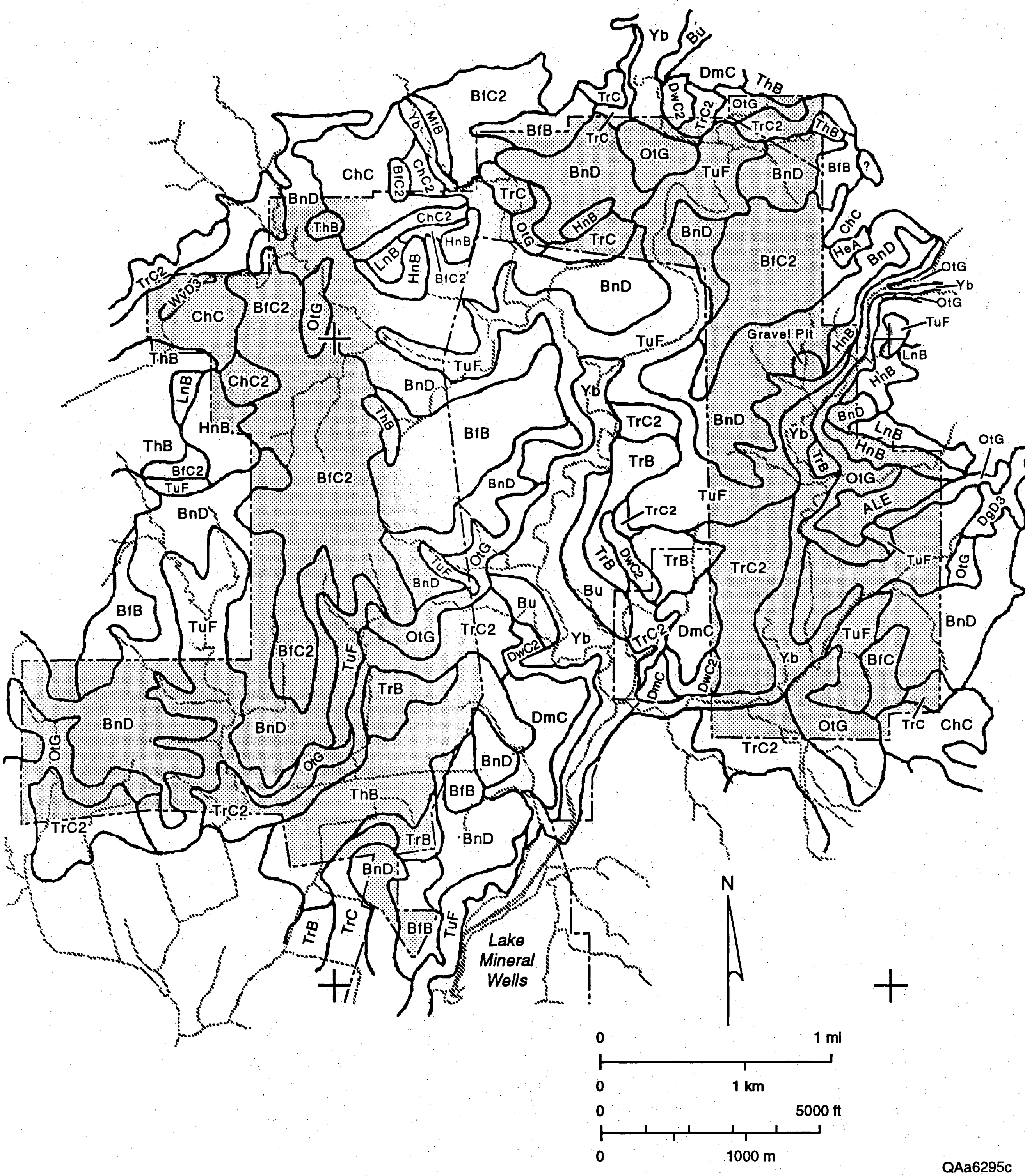

Figure 13. Soil map of Fort Wolters and north half of Lake Mineral Wells State Park (boundaries approximated from Greenwade and others, 1977 and Moore, 1981; see table 5 for soil unit symbols and soil properties).

Table 5. Properties of soils on Fort Wolters (from Greenwade and others, 1977).

Soil series	Depth	Soil unit	Surface texture	Slope (percent)	Permeability	Runoff	Drainage	Erosion hazard	Shrink-swell potential	Corrosivity to uncoated steel	Corrosivity to concrete	Comments
Aledo	shallow	ALE	clay loam	1 to 8, undulating	moderate	rapid	well drained	moderate (water)	moderate	moderate	low	
Bonti	moderate to deep	BfB	fine sandy loam	1 to 3	moderately slow	rapid	well drained	moderate (water)	low	low	moderate	
		BfC	fine sandy loam	3 to 5	moderately slow	rapid	well drained	severe (water)	low	low	moderate	
		BfC2	fine sandy loam	1 to 5	moderately slow	rapid	well drained	severe (water)	low	low	moderate	eroded
		BnD	stony fine sandy loam	1 to 8	moderately slow	rapid	well drained	moderate (water)	low	low	moderate	
Bunyan	deep	Bu	fine sandy loam	nearly level	moderate	slow	well drained	slight (water)	low	low	low	occasionally flooded
Chaney	deep	ChC	loamy fine sand	1 to 5	slow	slow	well drained	slight (water); severe (wind)	very low	low	low	
		ChC2	loamy fine sand	3 to 5	slow	slow	well drained	moderate (water); severe (wind)	very low	low	low	eroded
Duffau	deep	DmC	loamy fine sand	1 to 5	moderate	slow	well drained	slight (water); severe (wind)	very low	moderate	low	
		DgD3	fine sandy loam	3 to 8	moderate	medium	well drained	severe (water)	low	moderate	low	severely eroded, critical silt sources
		DwC2	fine sandy loam	2 to 5	moderate	medium	well drained	moderate (water)	low	moderate	low	eroded
Hassee	deep	HeA	fine sandy loam, loam	0 to 1	very slow	very slow	poorly drained	slight (water)	low	high	low	water is ponded in many areas
Hensley	shallow	HnB	clay loam	0 to 3	slow	slow	well drained	moderate (water)	low	high	low	
Lindy	moderate to deep	LnB	loam	1 to 3	slow	moderate	well drained	moderate (water)	low	high	low	
May	deep	MfB	fine sandy loam	1 to 3	moderate	slow	well drained	slight (water)	low	low	low	
Owens	shallow	OtG	clay	5 to 30	very slow	rapid	well drained	severe (water)	high	high	low	
Thurber	deep	ThB	clay loam	1 to 3	very slow	slow	moderately well drained	moderate (water)	moderate	high	low	
Truce	deep	TrB	fine sandy loam	1 to 3	slow	rapid	well drained	moderate (water)	low	low	low	
		TrC	fine sandy loam	3 to 5	slow	rapid	well drained	severe (water)	low	low	low	
		TrC2	fine sandy loam	2 to 5	slow	rapid	well drained	severe (water)	low	low	low	eroded
		TuF	stony fine sandy loam	5 to 20	slow	rapid	well drained	severe (water)	low	low	low	
Windthorst	deep	WvD3	fine sandy loam	1 to 8	moderately slow	rapid	moderately well drained	severe (water)	low	high	low	severely eroded
Yahola	deep	Yb	fine sandy loam, loamy fine sand, sandy clay loam	nearly level	moderately rapid	slow	well drained	not mentioned	low	low	low	frequently flooded

interbedded limestone, (3) Owens soils, which formed in material weathered from shale, (4) Aledo-Hensley-Lindy soils, which have formed on limestone, and (5) Yahola-Bunyan-Thurber soils, which formed on alluvium and colluvium. The information on soils provided here was taken from Greenwade and others (1977) (Parker County) and Moore (1981) (Palo Pinto County). Specific engineering properties (including some soil test data) are listed in tables 5 and 7 in that report.

Bonti Soils

Bonti soils are moderately deep, gently sloping to sloping, noncalcareous soils on uplands. Parent material is strongly cemented sandstone. The soils are characterized by a slightly stony surface layer of light brown to reddish fine sandy loam underlain by clay. Bonti soils are typical of the Lake Pinto sandstone.

Truce-Chaney-Duffau Soils

Truce, Chaney, and Duffau soils are deep, gently sloping to steep, noncalcareous sandy and loamy soils on uplands. Included in this group is a single mapped occurrence of Windthorst soil (fig. 13, table 5) on the northwest side of Helicopter Stage Field No. 2. Soils in this group formed in material weathered from shales and weakly cemented sandstones. These soils are characterized by surface layers of grayish to yellowish-brown to dark brown fine sandy loam to loamy fine sand, underlain by red to yellowish-brown to light-gray sandy to silty clay. These soils typically are found on sandstone with interbedded shale and locally interbedded limestone.

The soils in the area of Lake Mineral Wells dam are mapped as Truce soils by Greenwade and others (1977). Some tests were performed on soils around the dam by McClelland Engineers (1971, p. 5). In their report they described residual soils as being mainly very stiff to hard, jointed shaly clays, with natural moisture content 5 to 10 percent less than the plastic limit. They also described "residual clays" [bedrock?] of low to medium plasticity and low compressibility, with shear strength (of cores) in the range 0.8 to 3.2 tons/ft^2. They also referred to East Mountain shale and cited a compressive strength range of 2950 to 5900 psi (low strength) and noted that samples had a low modulus of deformation, typical of sedimentary formations.

Owens Soils

Owens soils are shallow, gently sloping to steep, calcareous clayey stony soils on uplands. Included here is a single mapped occurrence of Hassee soil located just off the base about 0.2 mi east of Helicopter Stage Field No. 1 (fig. 13, table 5). Owens soils are characterized by light olive brown to brownish gray calcareous clay surface layers, underlain by light gray to yellowish gray shaly clay. Hassee soils are characterized by a surface layer of grayish brown fine sandy loam to loam, underlain by brownish gray clay. Owens (and Hassee) soils formed in material weathered from shale and clay.

Aledo-Hensley-Lindy Soils

Aledo soils are shallow to very shallow, undulating, calcareous loamy soils on uplands. The only mapped occurrence of Aledo soil on Fort Wolters is on the stripped limestone bench about 1 mi south-southwest of Helicopter Stage Field No. 1 (fig. 13). Aledo soils have a very thin upper layer of grayish brown calcareous clay loam underlain by gravely clay loam and fractured limestone bedrock.

Hensley soils are also shallow, nearly level to gently sloping loamy soils on upland but are noncalcareous. Two mapped occurrences of Hensley soil are present immediately north, and about 0.5 mi north, of the Aledo location (fig. 13). Hensley soils have a surface layer of reddish brown clay loam, underlain by clay, and then limestone bedrock.

The only mapped occurrence of Lindy soil is about 1000 ft northeast of the Aledo location (fig. 13). Lindy soils are moderately deep, gently sloping, noncalcareous loamy soils on uplands.

The surface layer is typically reddish brown loam, underlain by clay, and then by limestone bedrock. Aledo, Hensley, and Lindy soils formed on material weathered from limestones and marls.

Yahola-Bunyan-Thurber Soils

Yahola soils are deep, nearly level, calcareous loamy soils on bottom lands. The soils formed in calcareous alluvial sediments and are located along Rock Creek in the Fort Wolters area. Yahola soils consists of layers of fine sandy loam to loamy fine sand and clay loam in various shades of brown. Yahola soils are frequently flooded.

Bunyan soils are also deep, nearly level loamy soils of bottom lands but are noncalcareous. Bunyan soils are located on slightly elevated terraces along Rock Creek. The soils consist of a surface layer of brown fine sandy loam underlain by stratified sandy clay loam. Bunyan soils are occasionally flooded.

Thurber soils are deep, gently sloping, noncalcareous loamy soils on uplands. They apparently formed on calcareous colluvium and ancient alluvium. The soils are characterized by a surface layer of clay loam, underlain by several layers of calcareous clay. Colors are typically grayish brown to pale brown.

Also included in this group are May soils. There is only one mapped occurrence of May soil in the immediate Fort Wolters area, about 1 mi northeast of Helicopter Stage Field No. 2 (fig. 13). May soils are deep, gently sloping, noncalcareous loamy soils on uplands. They formed on local patches of loamy alluvium on tributary streams. The soils consist of a surface layer of brown fine sandy loam underlain by sandy clay loam and clay loam.

VEGETATION

The Fort Wolters area straddles the boundary between the Western Cross Timbers and North-Central Prairies physiographic regions of Texas (Kier and others, 1977), or alternately the

Cross Timbers and Prairies ecological area (Frye and others, 1984). Most of Fort Wolters lies within the Oak-Mesquite-Juniper Parks/Woods and small portions within the Silver Bluestem-Texas Wintergrass Grassland and Ashe Juniper Parks/Woods areas as classified by the Texas Parks and Wildlife Department (Frye and others, 1984). Many other schemes have been developed over the years to classify vegetation regions on the basis of various criteria. DeGraaf and others (1988) compared five different schemes and produced a tabulated cross reference of the different terms used to describe the same areas. These other terms include: (a) Oak and Bluestem Parkland, Mesquite-Buffalo Grass, and Juniper-Oak-Mesquite ecoregions of Bailey (1980); (b) Osage Plain-Cross Timbers physiographic region of Bystrak (1981); (c) Oak-Hickory forest and nonforest forest types of Eyre (1980); (d) Mesquite Savanna, Bluestem Prairie, Bluestem Prairie and Oak-Hickory Forest mosaic, Cross Timbers, Mesquite-Buffalo Grass, and Juniper-Oak Savanna potential-natural-vegetation areas of Küchler (1964); and (e) Texas North-Central Prairies and West Cross Timbers land-resource areas of U.S. Soil Conservation Service (1981).

The Texas Parks and Wildlife Department (1990) describes three general habitat types in Lake Mineral Wells State Park: (1) sandstone slopes and nearly level uplands, which currently support deciduous or mixed evergreen deciduous woodlands, (2) nearly level to rolling areas underlain by sandstone or shale, which currently support mid- to tallgrass grasslands (or savannas), and (3) terraces along upper Rock Creek, which support bottomland deciduous forest. Five representative sites that currently support representatives of these habitats and plant communities are described in that report. The Little Bluestem-Indiangrass Series grasslands are reported to be the park's plant communities of highest regional significance.

The Texas Parks and Wildlife Department (1976, p. 4) notes also that despite a wide variation in soils and range sites, climax vegetation in the park is rather uniform (Texas Parks and Wildlife Department, 1976, p. 4). Prairie grasses dominate upland savannas with some brush species. Prairies and savannas give way to deep canyons rimmed with thick brush. As the canyons break away to form the fertile bottomland, scrub brush also gives way to large, beautiful pecan, cottonwood, and ash bottoms.

The Fort Wolters region is in the "Texan" biotic province, very near its arbitrarily drawn gradational boundary with the Kansan province to the west, as defined by Blair (1950, p. 100, 109–111). The Texan region as a whole is characterized by interfingering of forest associations extending from areas of moisture surplus in the east and grassland associations extending from areas of moisture deficiency in the west, and thus represents an "ecotone," or transitional region (Blair, 1950, p. 100). The distribution of vegetation types is controlled principally by soil composition and climate and secondarily by topography. Sandy soils tend to support oak-hickory forest, the dominant species being post oak, blackjack, and hickory, whereas clay soils originally supported tall-grass prairie but are now generally under cultivation.

Geologic Controls on Vegetation Types

Several features of the distribution of vegetation types are notable. Oak trees (post oaks) are particularly common on the Lake Pinto Sandstone and on several areas of sandstone lower in the section. Live oaks are common on the Dog Bend Limestone. Junipers are common on the Village Bend Limestone; live oaks are also present, but not in as great abundance as on the Dog Bend Limestone.

GROUND-WATER HYDROLOGY

Literature on ground water in the Strawn Group in Palo Pinto and Parker Counties is sparse. The lack of detailed information on ground water reflects the paucity of local water wells and the fact that most of the porous strata below 700 or 800 ft depth carry brackish, saline, or mineralized water (Plummer and Hornberger, 1935, p. 162). Most of the communities on the Strawn outcrop belt rely on surface water supplies; summaries of surface water are provided in Corlett, Gray & Probst (1967) and Henningson, Durham and Richardson (1979).

Descriptions of ground water in the adjacent and onlapping Cretaceous sands and conglomerates are more complete.

In describing public water supplies of North-Central Texas, Sundstrom and others (1949) subdivide the region into four separate areas having different dependencies on surface and ground water. Fort Wolters lies within the area that they describe as having little or no ground water available for public supply, with few exceptions.

Palo Pinto County has no permanent springs, with the exception of a few seeps at canyon heads along the Brazos River, and seeps at the bases of sandstone units and fractured limestone units during sustained wet-weather cycles. In contrast, Parker County in the past had many springs issuing from sands in the Cretaceous section. The sands originally had a growth of timber, which was cut, and the land put into cultivation, which led to widespread soil erosion (Brune, 1981, p. 352). Many of the springs have ceased flowing as a result of ground-water pumping and because stream channels where the springs issued have filled with sand; some of the springs may continue to flow in the subsurface. Ballou Springs (sometimes spelled Ballew [U.S. Geological Survey, 1959a], or Blue Springs) were at the Ballew Springs Church, next to Rippy Branch about 0.1 mi west of the western boundary of the eastern half of Fort Wolters. This spring, or springs flowed from informal sandstone 1, in a grove of post oaks. They were "mineral springs" valued for their healthful properties. The springs still trickled in 1931 but failed soon after (Brune, 1981, p. 353).

The earliest ground-water production in the area may have been from the Crazy Well in the Mineral Wells, which produced mineral waters that were purportedly endowed with superior curative properties (Texas Parks and Wildlife Department, 1976, p. 128). The mineral waters of this area are described in Turner (1934) and Plummer and Hornberger (1935, p. 168–192).

Hydrogeologic Units

Pennsylvanian Aquifers

According to Hendricks (1957), Fort Wolters nearly overlies the Bend Arch, a structure dividing the Eastern shelf of the Permian Basin from the Fort Worth Basin. At the apex of the Bend Arch the hydrostratigraphic units of the Pennsylvanian age strata are flattened so that topography becomes the principal control for the piezometric surface in the subsurface below Fort Wolters. Kier and others (1977) interpret the Strawn Group to be composed of strata with low to poor infiltration capacity at the surface and having poor to moderate aquifer potential.

The Mineral Wells Formation contains two sandstone units with potential as minor aquifers beneath Fort Wolters; these units are the Hog Mountain Sandstone, and informal sandstone 1, which is about 25 ft higher in the section. The Lake Pinto Sandstone may also serve as a minor aquifer, even though Fort Wolters is situated at its updip limit, because its extensive exposure probably enables rapid recharge during wet periods. The Brazos River Formation, which underlies Fort Wolters at shallow depth (generally less than 100 ft), contains a sandstone that is locally highly permeable and acts as a minor aquifer. The sandstone is about 30 ft thick and provides small amounts of domestic and stock water. The Goen Limestone, at the base of the Mingus Formation (fig. 7), may also yield small amounts of water from fractures. The underlying Grindstone Creek Formation has no aquifer potential. Shale units that compose the greater part of the Pennsylvanian section behave as aquicludes, or leaky aquicludes, preventing significant ground-water flow between formations.

Informal sandstone unit 2 and overlying Turkey Creek Sandstone of the Mineral Wells Formation (fig. 7) also locally form minor aquifers. However, neither is accessible from Fort Wolters as they are situated higher in the section and have already eroded back to points northwest of the training site (fig. 6).

Historical water-level changes in wells producing from Strawn Group strata seem to reflect variations in annual rainfall, although records are incomplete (figs. 14, 15a, 15b, and 15c,

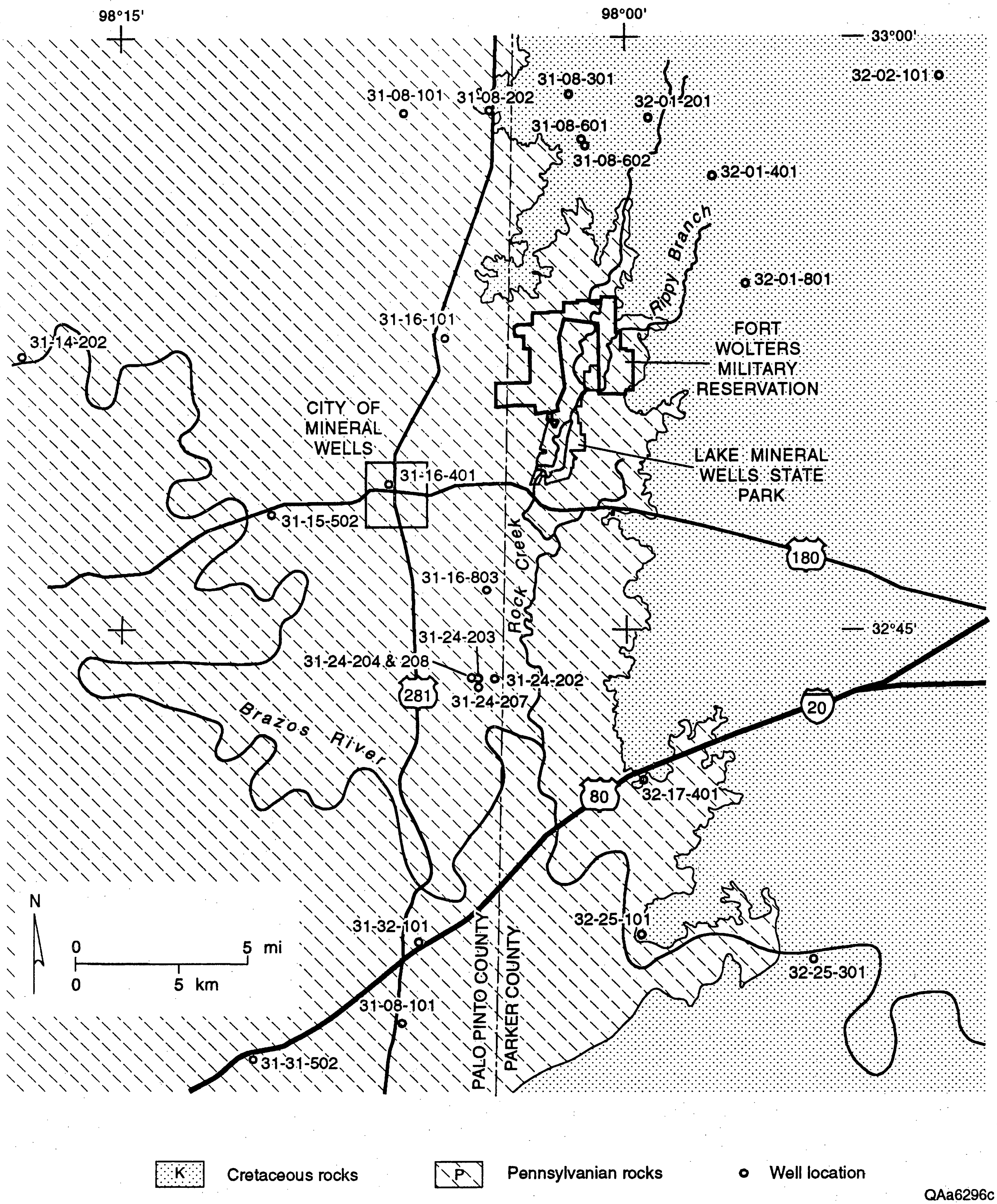

Figure 14. Locations of selected Fort Wolters area water wells for which water level and hydrochemical data are presented (table 6 and appendix D). Distribution of Cretaceous and Pennsylvanian bedrock is also show (from fig. 6).

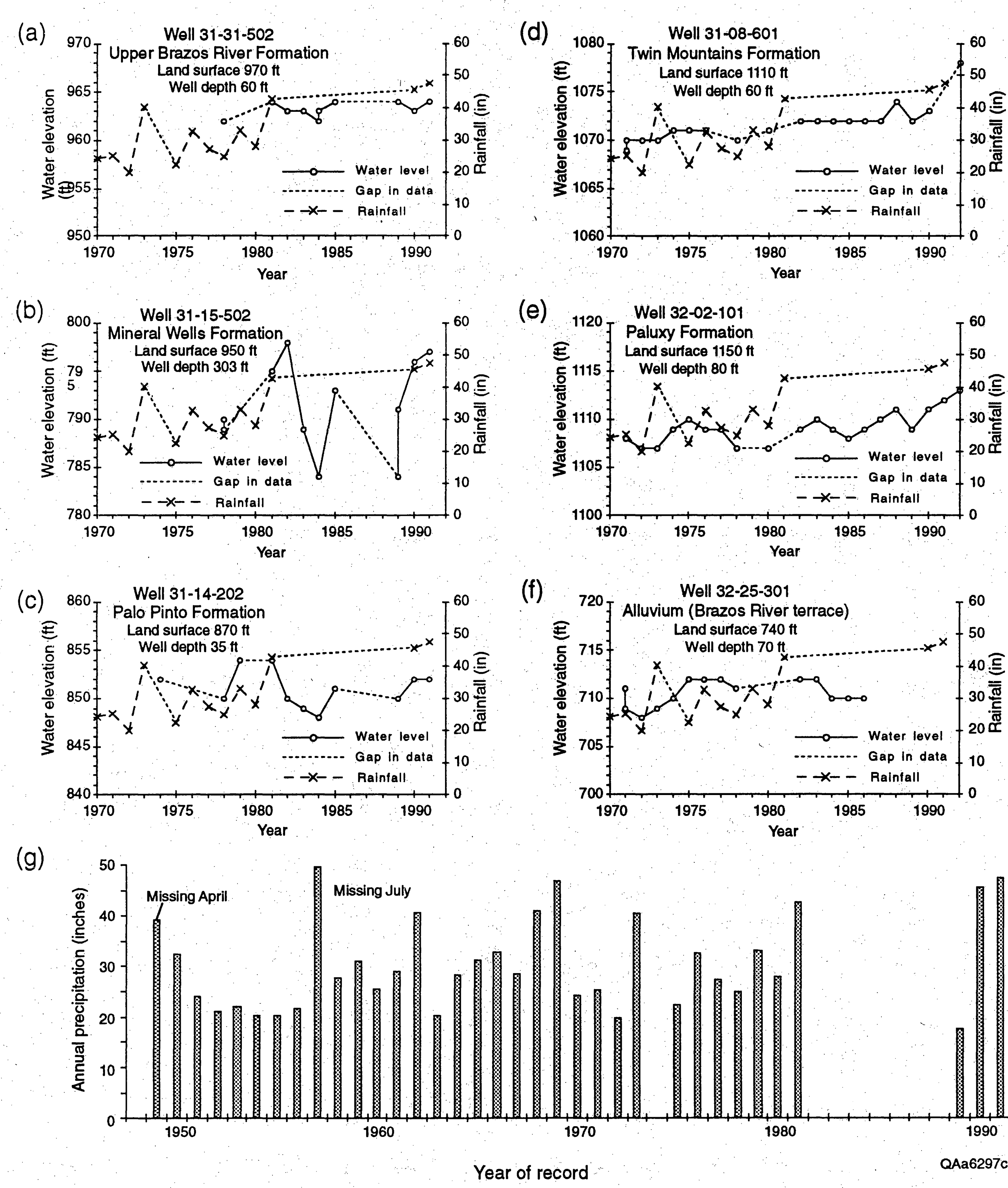

Figure 15. Historical water-level changes in selected wells in the Fort Wolters are (data from Texas Water Development Board,1993b, 1993c; see appendix D). Plot of annual precipitation reproduced from figure 5 in this report (data from Texas Water Development Board, 1993a; see appendix C).

appendix D). The relatively small range of water levels in the well in the upper Brazos River Formation (fig. 15a) suggests that recharge to that aquifer is slow or limited; it may be that matrix pores make up a great part of the aquifer and that recharge is dissipated throughout the volume. The greater range of water levels in wells in the Mineral Wells Formation (fig. 15b) and the Palo Pinto Formation (fig. 15c) suggests that the wells produce from fractures that are at most replenished slowly from the aquifer matrix pores during dry periods but that respond rapidly during wet periods by direct recharge from the surface.

Cretaceous Aquifers

Northeast of the Fort Wolters basal Cretaceous sands of the Twin Mountains Formation lap onto Pennsylvanian strata. These and overlying sands and conglomerates are part of an important outcrop recharge zone for the Cretaceous aquifers. In the outcrop the aquifer is unconfined, but immediately downdip to the southeast it forms a major confined Texas aquifer. The geologic and hydrologic setting of the Cretaceous aquifers is summarized in Stramel (1951) and Baker and others (1990).

The small area used in the past by engineer battalions on the northeast property boundary of Fort Wolters may have a thin cover of Twin Mountains Formation sand in the northeasternmost part. However, the slope and drainage on this parcel, as on most of the eastern half of Fort Wolters, is southwest toward Rock Creek. It is not likely that water draining the eastern half Fort Wolters can enter (and potentially pollute) the Cretaceous aquifers. It is possible that minor aquifers within the Pennsylvanian section could be naturally recharged by waters percolating downward through the Cretaceous strata.

Water levels in local wells in the Cretaceous correlate weakly with annual rainfall (figs. 14, 15d, and 15e, appendix D). In outcrop the Cretaceous sands and conglomerates are relatively uncemented and open. The relatively small range of water levels in wells producing from this aquifer system suggests that transmissivity of the aquifer is high and that the effects of pumpage and recharge are dissipated through a large enough volume that fluctuations at single points remain small. It may require weekly or monthly water-level measurements to demonstrate the relationship between rainfall and water levels in these wells.

Quaternary Aquifers

Minor aquifers are present in Quaternary alluvial terrace deposits along the Brazos River. The limited alluvial deposits along tributaries, including Rock Creek, may also yield small amounts of potable ground water. There are no wells known to be currently producing from alluvial materials in the Fort Wolters area. Water levels in one selected alluvium well along the Brazos River show a weak correlation with annual rainfall (figs. 14, 15f, appendix D).

Ground-Water Quality

Ground-water quality in the Fort Wolters area is generally poor to moderate in the Pennsylvanian aquifers and moderate to good in the Cretaceous aquifers. Total dissolved solids (TDS) in 8 of the 14 selected wells producing from Pennsylvanian aquifers is greater than 1,000 mg/L, whereas TDS in only 1 of the 6 selected wells producing from Cretaceous aquifers is greater than 1,000 mg/L (table 6). Correspondingly, chloride and/or sulfate in six of the Pennsylvanian wells exceed the 300 mg/L standard set by the Texas Natural Resources Conservation Commission, whereas chloride and sulfate exceed the standard in only one of the Cretaceous wells (table 6).

The well-water chemistry data (table 6) suggest that most of the ground water in the Fort Wolters area is very hard (hardness greater than 180 mg/L; see Hem, 1985, p. 159). Water in four of the wells producing from Pennsylvanian aquifers, however, has hardness less than 70 mg/L, which is considered moderately hard (61–120 mg/L) to soft (up to 60 mg/L).

Ground waters in Pennsylvanian aquifers span the range of common chemical types (fig. 16a). Calcium and sodium are the dominant cations, and bicarbonate (HCO_3^-) and chloride

Table 6. Hydrochemistry in selected wells in the Fort Wolters area (data from Texas Water Development Board, 1992a, 1992b; all concentrations in mg/L; well locations shown in fig. 14).

Well No.	Aquifer Code [1]	County	Depth [2]	Collection Date	Temp (°C)	pH	Si	Ca	Mg	Na	K	HCO3	SO4	Cl	F	NO3	TDS	Conductivity (micromhos/ cm @ 25°C)	Hardness as CaCO3
Pennsylvanian Aquifers																			
31 08 101	321PLPN	Palo Pinto	238	12/15/60		6.6	12	115	30	72		388	87	109	0.5	3.8	620	1060	410
31 08 101	321PLPN	Palo Pinto	238	09/21/82	21	8.2	11	103	32	106		410	110	120	0.9	7.0	691	984	390
31 08 202	324MLWL	Palo Pinto	465	07/15/83		8.3	29	4	2	414	1	622	224	125	1.4	3.0	1109	1968	19
31 16 101	324MLWL	Palo Pinto	340	12/16/60		6.6	18	182	72	201		651	353	202	0.4	0.8	1349	2070	750
31 16 401	324MLWL	Palo Pinto	380	12/20/60		7.7	14	14	7	215	2	386	74	95	0.8	2.2	614	1020	69
31 16 803	324BZRVU	Palo Pinto	40	03/09/31				710	167	508		296	507	1180			4216		
31 24 202	324STRN	Palo Pinto	23	04/13/76		7.3	15	55	16	23	10	279	17	14	0.5	0.7	288	525	203
31 24 203	324STRN	Palo Pinto	40	04/13/76		7.2	15	308	95	334	17	630	750	463	0.4	5.1	2297	4370	1160
31 24 204	324STRN	Palo Pinto	65	04/13/76		7.5	19	89	27	456	6	497	398	387	0.4	1.7	1628	3045	334
31 24 207	324STRN	Palo Pinto	17	04/14/76		7.9	15	95	11	56		353	63	40	0.3	2.6	456	828	281
31 24 207	324STRN	Palo Pinto	17	09/21/82	22	8.0	15	115	9	25		409	16	16	0.3	1.1	398	729	323
31 24 208	324STRN	Palo Pinto	44	04/14/76		7.3	22	271	103	291	18	1635	<4	437	0.5	<0.4	1950	4056	1089
31 32 101	324STRN	Palo Pinto	15	12/19/60			17	123	17	29	1	401	55	38	0.2	3.2	480	801	377
31 32 401	324STRN	Palo Pinto	140	12/21/60		7.7	10	14	6	1150		756	80	1300	3.8	2.0	2937	4990	58
31 08 301	321PLPN	Parker	200	08/18/83	26	8.2	13	42	23	168	4	327	68	173	0.2	0.2	652	1254	200
31 08 602	300PLZC	Parker	410	01/29/75	21	8.0	9	14	4	720	3	476	452	530	2.1	5.8	1973	3770	52
31 08 602	300PLZC	Parker	410	05/16/91	24			5	2	673	6	686	472	225	2.6	3.7	1736	2540	23
Cretaceous Aquifers																			
31 08 601	218TVPK	Parker	60	12/20/49		7.2	19	98	56	35		399	83	66		55.0	608		75
31 08 601	218TVPK	Parker	60	02/10/71		7.5	16	137	71	94		418	165	149	0.3	110.0	947	1450	630
31 08 601	218TVPK	Parker	60	11/09/73	20	7.4	15	153	79	95		411	201	170	0.4	170.0	1085	1610	710
31 08 601	218TVPK	Parker	60	07/16/76		8.0	16	152	71	82		421	187	141	0.2	133.0	989	1470	670
31 08 601	218TVPK	Parker	60	03/24/83	19	8.2	19	112	47	29		351	90	106	0.1	32.0	607	953	474
32 01 201	218TWMT	Parker	260	08/18/83		8.2	16	37	22	147	4	471	57	54	0.2	0.1	568	1040	185
32 01 401	218TVPK	Parker	130	12/20/49	21	8.0	14	266	61	170		429	519	275		5.5	1521	2270	914
32 01 801	218TVPK	Parker	65	01/24/50		7.5	48	56	46	93		516	69	21		7.5	594	937	328
32 17 401	218PLXY	Parker	75	11/15/49		7.2	16	90	21	46		376	42	42		0.8	442	754	311
32 25 101	218TVPK	Parker	90	02/12/75		7.2	24	96	14	34	2	210	74	75	0.3	34.0	456	810	299

(1) Explanation of aquifer codes: 324BZRVU - aquifer in upper Brazos River Formation; 324MLWL - aquifer in Mineral Wells Formation; 324STRN - aquifer in unspecified Strawn Group formation; 321PLPN - aquifer in Palo Pinto Formation; 300PLZC - aquifer in unspecified Paleozoic formation; 218TWMT - aquifer in Twin Mountains Formation; 218TVPK - aquifer in Travis Peak Formation (equivalent to Twin Mountains Formation); 218PLXY - aquifer in Paluxy Formation.

(2) Bottom of sampled interval

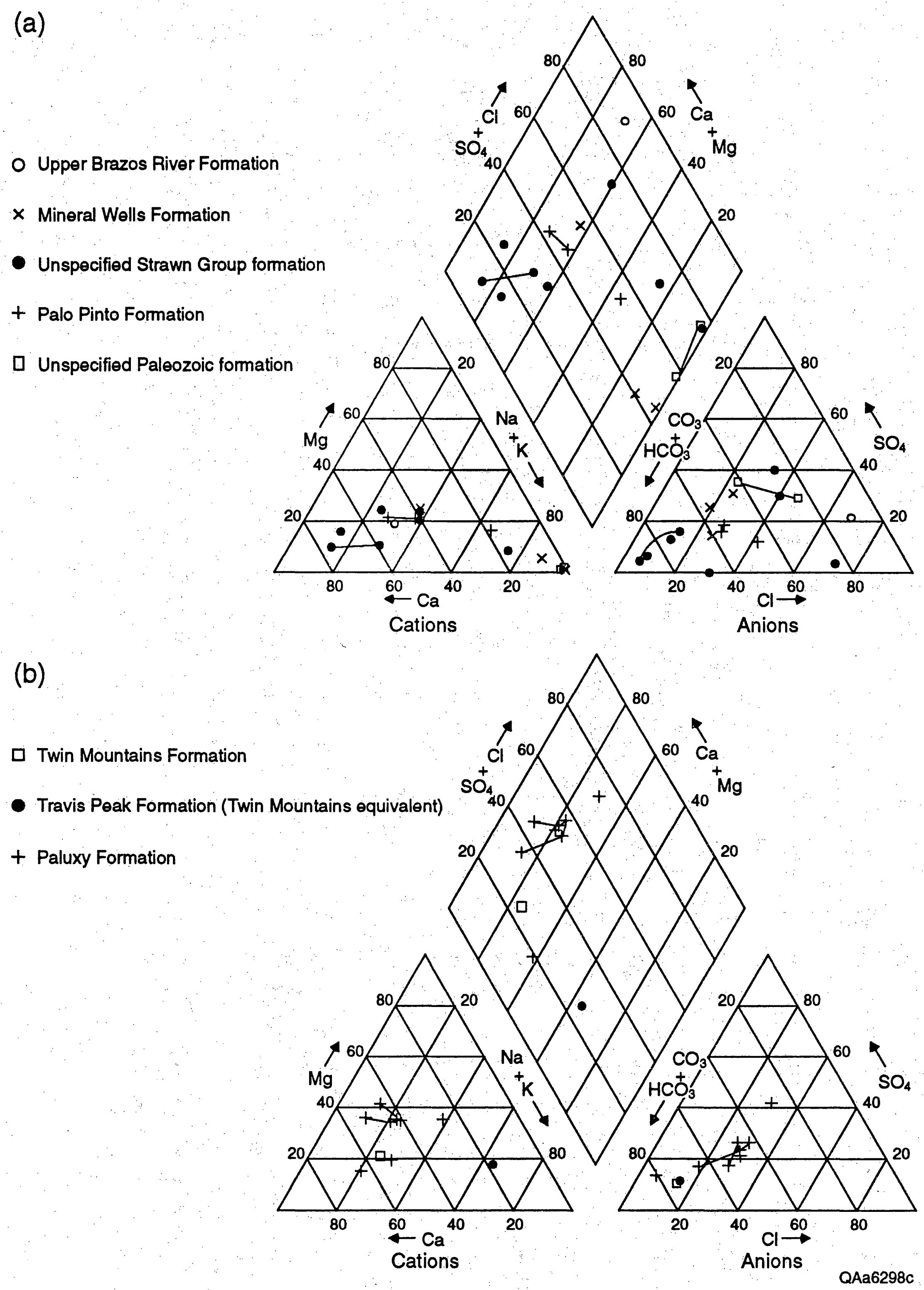

Figure 16. Trilinear Piper diagram of ground-water chemistry in selected wells in the Fort Wolters area (data from Texas Water Development Board, 1992a and 1992b). (a) Wells producing from Pennsylvanian aquifers, (b) wells producing from Cretaceous aquifers (see fig. 14 for well locations, table 6 for chemical data). Solid lines connect multiple analyses for single wells.

are dominant anions. In several wells the percentage (by milli-equivalents) of sulfate nearly equals, or even exceeds, that of bicarbonate or chloride.

Ground waters in Cretaceous aquifers range from sodium bicarbonate type through calcium-magnesium bicarbonate type to calcium-magnesium sulfate-chloride type (fig. 16b). The proportion of cations varies with position of the sample point (well) along the ground-water flow path. Bicarbonate is the dominant anion, though in one well sulfate is the dominant anion, and bicarbonate and chloride are nearly equal.

ENVIRONMENTAL IMPACTS AT FORT WOLTERS

The Texas Parks and Wildlife Department (1976, Biological Survey section of report) commented that much of the land acquired from the U.S. Army for Lake Mineral Wells State Park was in private ownership before World War II and was used for livestock grazing or hay. During that time the land was overgrazed, causing site deterioration. After the Army took control, little grazing occurred, and much of the vegetation was allowed to recover. Because grazing pressure has remained light, much of the vegetation is in climax stage, particularly in the northern part of the State Park.

The principal environmental impacts on Fort Wolters fall into three broad categories: (1) modifications to the landscape, which include clearings, roads, quarries, and associated erosional features, (2) constructed features, which include buildings, lots, disposal sites, and oil and gas wells, and (3) impacts to surface (and ground) water.

Modifications to Landscape

Off-Road Training Areas, Helicopter Stage Fields, and Other Clearings

The largest impacted areas are the clearings for drop zones, helicopter stage fields, firing ranges, and other uses. These areas were observed in the summer and fall of 1993 to have fairly good covers of grasses. Exceptions are the Drop Zone in the west-central part of Fort Wolters (figs. 9a and 9c), which apparently receives regular vehicular traffic and several tank/tracked vehicle routes in the northern (fig. 9a) and southeastern (fig. 9d) parts of the base. In these locations, grasses were sparse, exposing soil and locally rock outcrop. The exposed soils are vulnerable to erosion. In contrast, the helicopter stage fields are nearly unrecognizable at ground level as most of the pavement of the landing strips has been cracked, heaved, and overgrown by vegetation (possibly first torn up by bulldozers). The individual strips are recognized only by the regular pattern of flat berms and intervening swales and landing lights at the ends. The main tarmac areas of the stage fields are still intact, presumably because of heavier duty construction, including concrete.

Roads and Trails

Roads and trails, including utility service roads, are present in all parts of Fort Wolters. Many of these appear to have been abandoned, as they are heavily overgrown by vegetation. Their extent is best determined with the aid of aerial photographs. A good example is the grid-like system of trails that extends from the western part of the training site into the State Park, in the dense post oak woods just northwest of the main (Lake Pinto Sandstone) escarpment. Examination of aerial photographs reveals that these roads were cut sometime between 1953 and 1959. Most of these trails are now overgrown or impassable to vehicles.

Quarries and Pits

The most long-lasting environmental impact features are the quarries and pits from which materials were extracted during various construction stages of the military base. The floors and walls of the limestone quarries are generally on resistant, stable materials (remaining limestone, interbedded sandstone), and are slowly being reclaimed by vegetation. The natural reclamation is limited by the slow development of soil on the limestone substrates. Quarries and pits in sandstone and shale along the main escarpment are overgrown where the slopes are gentle and soil has been able to accumulate and vegetation take hold. The steeper slopes are unstable and continue to erode, producing deep gullies and releasing ample supplies of sediment that are ultimately washed into Rock Creek and Lake Mineral Wells. Other pits that dot the area are becoming revegetated. A notable exception is the clay pit near the northern boundary of the property (fig. 9b), which remains bare and is deeply gullied. The pit exposes a very clayey shale that softens and is easily eroded when wet. Gypsum ($CaSO_4 \cdot H_2O$) crystals are abundant in the clay and suggest high sulfate content in the rock. The paucity of vegetation in this pit may reflect the high sulfate content as only sulfate-tolerant plants can grow in such areas.

Gullies and Other Erosional Features

Gullying and erosion does not seem to be a big problem on Fort Wolters, except along the escarpment at quarry and pit locations, at the fringes of cleared areas near the escarpment, and along roads. Perhaps this is because the regional northwestward dip of the strata causes the areas of weaker, shaly rocks to be protected or rimmed by the more resistant sandstone and limestone layers, which also retard the headward extension of streams. Another factor may be that land use before acquisition of the land by the U.S. Army was limited by water supply, such that intensive farming and cultivation did not occur, as it had on sandy soils on Cretaceous strata to the east.

Constructed Features

Most of the buildings, paved lots, and equipment storage and maintenance areas that were part of the U.S. Army base are located on land that is now outside the Fort Wolters property. Most of the constructed features that are part of the present National Guard facility, including vehicle maintenance areas, are located along the southern edge of the property. Exceptions are the Headquarters building and nearby shops and abandoned Nike missile site in the western part of the base, and a group of abandoned(?) shops west of the road climbing the escarpment between the main firing ranges and south end of the Drop Zone. A few small buildings remain at the helicopter stage fields. Active or abandoned underground storage tanks may be present at any of these sites.

There are several small trash dumps on the Fort Wolters property. Piles of old roofing materials, bottles, cans, and miscellaneous items are present along the north rim of a reentrant canyon in the escarpment, just west of the State Park (fig. 9c). Several appliances were observed in a streambed immediately outside the northern boundary, just north of the "choke" point between the State Park and neighboring private lands (fig. 9a). Trash, in the form of shell casings, artillery parts, and packing materials, is common on the firing ranges.

At least one oil and/or gas well is located on Fort Wolters, and two others on nearby State Park land. These facilities include pump equipment, above-ground and buried pipelines, and tanks, much of which appeared to be unused at the time of the field visits. There is also evidence of spilled or leaked oil (and possibly also produced brine) at these sites.

Surface and Ground Water

The principal environmental impact on surface water by Fort Wolters has been the siltation of streams and Lake Mineral Wells by eroded soil. Most of this probably occurred during the main phases of construction and training during the 1940's and 1950's. It is likely, however, that the greater proportion of the silt that nearly fills Lake Mineral Wells was eroded from farmlands upstream from Fort Wolters and that the base simply passes, rather than supplies, the sediment.

It is difficult to determine whether there have been any impacts on ground water by activities at Fort Wolters because there are so few wells and even fewer historical data. Water quality in the Pennsylvanian aquifers is generally poor, so changes would be difficult to recognize.

CONSIDERATIONS FOR FORT WOLTERS LAND-MANAGEMENT PLAN

Potential for Future Environmental Impact

Surface Disturbance and Erosion

The ongoing and most likely future environmental impact to Fort Wolters is the surface disturbance that results from the necessary training activities on the base. This will be accompanied by varying amounts of soil erosion, depending on geomorphic setting, soil type, and degree of surface disturbance. Gently sloping areas will naturally be able to tolerate greater disturbance before significant erosion occurs, whereas steep areas characterized by swift rainfall runoff will be more vulnerable. Clayey soils have a greater potential to be soft and easily disturbed when wet whereas sandy soils and rock outcrops are resistant. This may be particularly true on the upper parts of the gentle cuesta slopes, where soils tend to be thicker and drainage less developed. The soil map (fig. 13, table 5), which incorporates slope and material properties of the soils, provides an approximation of erosion hazard.

Surface and Ground Water

The main hazards to surface water are siltation by eroded soil and potential pollution by runoff contaminated by fuels, cleaning solvents, or other materials that may be accidentally spilled or otherwise released during normal activities.

The potential for contamination of ground water is minimal, as much of the area is underlain by poorly permeable soils. Near rock outcrops and over thin soils, however, recharge of the minor aquifers may occur through fractures, pores, and artificial openings (for example, there is an open, drilled hole about 12 inches in diameter and 6 to 9 ft deep, about 3 ft from the Fort Wolters No. 8 oil and gas well).

The main aquifer of the region is the Cretaceous Twin Mountains, Glen Rose, and Paluxy Formations aquifer system, which does not extend onto Fort Wolters. The small area on the northeast property boundary of Fort Wolters may have a thin cover of Twin Mountains Formation sand in the northeasternmost part. However, the slope and drainage on this parcel, as on most of the eastern half of Fort Wolters, is southwest toward Rock Creek. It is not likely that water draining the eastern half Fort Wolters can enter and potentially contaminate the Cretaceous aquifer.

Similarly, the outcrop and recharge of the minor aquifers of informal sandstone unit 2 and the Turkey Creek Sandstone are upslope and outside the boundary of Fort Wolters, eliminating the possibility of contamination by training activities.

Precautions and Possible Limitations to Land Use

The overall environmental quality of Fort Wolters will benefit from precautions aimed at minimizing soil erosion and disturbance of vegetation. Clayey soils should be avoided when wet to minimize rutting and other damage to topsoil and vegetation. This problem may be greatest on the upper parts of the cuestas where clayey soils are common. Steep areas, where runoff may be swift, should be used lightly to prevent loss of stabilizing vegetation. In general, disturbance of vegetation should be coordinated with the growing seasons of the various species present to optimize their recovery.

Handling of hazardous materials should be avoided over potential ground-water recharge areas on or near rock outcrops and sandy soils.

Flooding and flood erosion will occasionally be a problem at crossings of Rock Creek and several of its major tributaries. Sediment deposited by floods may potentially present quicksand hazards, or simple nuisances.

Archeological sites may be present within the boundaries of Fort Wolters (three sites were recognized in the adjacent State Park by Ing [1976]). If a site is found or suspected, it should be protected until a proper assessment of its importance can be performed.

Suggestions for Research, Monitoring, and Remediation

Further literature research and survey of surrounding landowners would be helpful for compiling a complete list of active and abandoned water wells. A complete list of all active and abandoned oil and gas wells in the immediate area would also be useful. This information, including any well logs that may exist, may best be obtained by contacting the lease operators. Periodic monitoring of water quality (including chemistry and suspended sediment) of streams flowing across the base should be considered. Several existing area wells should be selected for periodic sampling and water-quality determinations. These may be wells already monitored by the Texas Water Development Board and should include species that may not ordinarily be analyzed (for example, lead, solvents, oils, and fuels).

At some time, a complete catalog (ideally on aerial photographic base) of all disturbed areas should be compiled, and their distribution and size monitored periodically to identify problem areas. As digital data for the base become refined, it will be possible to produce fairly precise maps describing the variations in land capability across the base. These maps would be based primarily on physical properties of the soil, vegetative cover, and physical factors of slope, climate, and land use, yielding estimates of soil erosion potential (Wischmeier and Smith, 1978; Warren and others, 1989), which can ultimately be used to specify by area the allowable level of use of tracked vehicles (Shaw and Diersing, 1989).

A catalog of all sites (shops, storage tanks, parking areas, dumps, filed sites) where hazardous or unknown materials may have been handled or disposed of should be compiled, and these sites investigated to determined how much, if any, spillage or soil contamination may have occurred. The locations and conditions of all active and abandoned underground storage tanks should be documented, and remedial measures undertaken where leakage has occurred. Trash and debris, such as appliances dumped in streams, should be removed and disposed of properly. Bullets (lead, some with copper jackets) and shell casings (copper and zinc) are common on the property, but they are probably not causing contamination because these metals in their elemental forms are not very soluble in natural waters (Hem, 1985, p. 141–144). The other types of munitions that may be present on Fort Wolters should be examined to determine if there is potential for release of hazardous substances. Unexploded ordnance should be removed.

Active management of vegetation, such as prescribed burning, may be required at various times. Also, habitat protection may be locally necessary—for example, some of the nearly level portions of the base may offer wetland habitat during parts of the year. The Texas Parks and Wildlife Department is the best source of information on ecological management.

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REFERENCES

Bailey, R. G., compiler, 1980, Description of the ecoregions of the United States: U.S. Department of Agriculture Miscellaneous Publication 1391, 77 p.

Baker, B., Duffin, G., Flores, R., and Lynch, T., 1990, Evaluation of water resources in part of North-Central Texas: Texas Water Development Board Report 318, 67 p.

Bates, R. L., and Jackson, J. A., eds., 1987, Glossary of geology (3d ed.): Alexandria, Virginia, American Geological Institute, 788 p.

Blair, W. F., 1950, The biotic provinces of Texas: Texas Journal of Science, v. 2, no. 1, p. 93–117.

Bomar, G. W., 1983, Texas weather: The University of Texas Press, 265 p.

Brown, L. F., Jr., 1959, A review of Pennsylvanian clay mineral industries, North-Central Texas: The University of Texas at Austin, Bureau of Economic Geology Mineral Resource Circular 39, 7 p.

Brown, L. F., Jr., Goodson, J. L., and Harwood, P., 1972, Geologic atlas of Texas, Abilene sheet: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000.

Brune, Gunnar, 1981, Springs of Texas, volume I: Fort Worth, Texas, Branch Smith, Inc., 566 p.

Bystrak, D., 1981, The North American breeding bird survey: Studies in Avian Biology, v. 6, p. 34–41.

Cleaves, A. W., 1991, Sequence stratigraphy and new subsurface mapping strategies in the Middle and Upper Pennsylvanian of the Bend Arch, north-central Texas (abs.): American Association of Petroleum Geologists Bulletin, v. 75, no. 1, p. 198.

Cleaves, A. W., and Erxleben, A. W., 1982, Upper Strawn and Canyon (Pennsylvanian) depositional systems, surface and subsurface, north-central Texas, *in* Cromwell, D. W., ed., Middle and Upper Pennsylvanian System of north-central and west Texas (outcrop to subsurface): Permian Basin Section, Society of Economic Paleontologists and Mineralogists, 1982 Symposium and Field Conference Guidebook, Publication 82-1, p. 49–85.

Corlett, Gray & Probst, Inc., 1967, A comprehensive water & sewer plan for Palo Pinto County: report prepared by Corlett, Gray & Probst, Inc., Engineers, Surveyors, Planners, Wichita Falls, Texas, financed by grant from Farmers Home Administration, variously paginated.

Cummins, W. F., 1891, Report on the geology of northwestern Texas, *in* Dumble, E. T., Second Annual Report of the Geological Survey of Texas, 1890: Department of Agriculture, Insurance, Statistics, and History, p. 359–554.

DeGraaf, R. M., Bailey, R. G., and Brooks, R. T., 1988, A comparison of five national land classification maps: U.S. Department of Agriculture, Forest Service, Agriculture Handbook No. 672, 335 p.

Echols, J., 1959, Microfauna and biostratigraphy of the upper Strawn Group, Eastland and Palo Pinto Counties, Texas: The University of Texas at Austin, Master's thesis, 176 p.

Ewing, T. E., compiler, 1990, Tectonic map of Texas: The University of Texas at Austin, Bureau of Economic Geology, 4 sheets, scale 1:750,000.

Eyre, F. H., ed., 1980, Forest cover types of the United States and Canada: Washington, D.C., Society of American Foresters, 148 p.

Flemming & Associates, 1971, A comprehensive water plan for water and sewer, Parker County: Fort Worth, Texas, D. H. Flemming & Associates, Consulting Engineers, variously paginated.

Forrest and Cotton, Inc., 1970, Preliminary investigation of Lake Mineral Wells spillway repair: Dallas, Texas, report prepared for City of Mineral Wells, Texas, by Forrest and Cotton, Inc., Consulting Engineers, unpaginated.

Frye, R. G., Brown, K. L., McMahan, C. A., compilers, 1984, The vegetation types of Texas: Texas Parks and Wildlife Department, scale 1:1,000,000.

Glass, D. L., 1958, A structural study of some upper Strawn–lower Canyon beds near Mineral Wells, Texas: Texas Christian University, Master's thesis.

Greenwade, J. M., Kelley, J. D., and Hyde, H. W., 1977, Soil survey of Parker County, Texas: U.S. Department of Agriculture, Soil Conservation Service, in cooperation with Texas Agricultural Experiment Station, 90 p.

Hem, J. D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Hendricks, L., 1957, Geology of Parker County, Texas: The University of Texas Publication 5724, 67 p.

Henningson, Durham and Richardson, Inc., 1979, Preliminary study for a long range water supply development: Prepared for the Palo Pinto County Municipal Water District No. 1, 80 p.

Herkommer, M. A., and Denke, G. W., 1982, Stratigraphy and hydrocarbons, Parker County, Texas, *in* Martin, C. A., ed., Petroleum geology, Fort Worth Basin and Bend Arch area: Dallas Geological Society, p. 97–127.

Hitchcock, K. B., 1985, Petrographic analysis of the Pennsylvanian Mineral Wells Formation, Strawn Group, north-central Texas: Stephen F. Austin University, Master's thesis, 175 p.

Hodgson, W. D., 1957, An environmental study of some sands, silts, clays, and nodular limestone beds in Hood, Parker, and Jack Counties, Texas: Texas Christian University, Master's thesis.

Ing, J. D., 1976, Archeological survey of Lake Mineral Wells State Park Site, *in* Texas Parks and Wildlife Department, Development concept plan and program for Lake Mineral Wells State Park, Parker County, Texas: Texas Parks and Wildlife Department, Master Planning Branch.

Kelley, M. L., 1958, Physical stratigraphy of some upper Strawn and lower Canyon beds in Parker and Palo Pinto Counties, Texas: Texas Christian University, Master's thesis.

Kier, R. S., Garner, L. E., and Brown, L. F., Jr., 1977, Land resources of Texas—a map of Texas lands classified according to natural suitability and use considerations: The University of

Texas at Austin, Bureau of Economic Geology Land Resources Laboratory Series, 42 p., 4 map sheets scale 1:500,000.

Küchler, A. W., 1964, Potential natural vegetation of the conterminous United States: American Geographical Society Special Publication 36, 116 p.

Larkin, T. J., and Bomar, G. W., 1983, Climatic atlas of Texas: Texas Department of Water Resources, Limited Printing LP-192, 151 p.

Laury, R. L., 1982, Geology of the type area, Canyon Group, North-Central Texas, *in* Cromwell, D. W., ed., Middle and Upper Pennsylvanian System of North-Central and West Texas (outcrop to subsurface): symposia and field conference guidebook: Permian Basin Section, Society of Economic Paleontologists and Mineralogists, Publication 82-21, p. 87–122.

McClelland Engineers, 1971, Soil and foundation study, free overfall secondary spillway, Lake Mineral Wells, Mineral Wells, Texas: report to City of Mineral Wells, Texas, by McClelland Engineers, Inc., Soil & Foundation Consultants, Houston, Texas, 11 p.

McGowen, J. H., Proctor, C. V., Jr., Haenggi, W. T., Reaser, D. F., and Barnes, V. E., 1987, Geologic atlas of Texas, Dallas sheet [revised]: The University of Texas at Austin, Bureau of Economic Geology, scale 1:250,000.

Moore, J. D., 1981, Soil survey of Palo Pinto County, Texas: U.S. Department of Agriculture, Soil Conservation Service, 150 p.

Parker County Historical Commission, 1980, History of Parker County: Weatherford, Texas, Parker County Historical Commission Book Committee, 703 p.

Plummer, F. B., and Hornberger, J. Jr., 1935, Geology of Palo Pinto County, Texas: University of Texas Bulletin 3534, 240 p.

Plummer, F. B., and Moore, R. C., 1921, Stratigraphy of the Pennsylvanian formations of north-central Texas: University of Texas Bulletin 2132, 237 p.

Rawson, J., 1974, The quality of surface waters in Texas: U.S. Geological Survey Water-Resources Investigations 7-74, 73 p.

Schroeder, E. E., and Massey, B. C., 1977, Technique for estimating the magnitude and frequency of floods in Texas: U.S. Geological Survey, Water Resources Investigation No. 77-110, 22 p.

Shaw, R. B., and Diersing, K. A., 1989, Allowable use estimates for tracked vehicular training on Piñon Canyon Maneuver Site, Colorado, U.S.A.: Environmental Management, v. 13, no. 6, p. 773–782.

Shelton, J. W., 1953, Studies of the Strawn–Canyon boundary, Pennsylvanian, in north-central Texas: University of Illinois, Urbana, Ph.D. dissertation, 126 p.

__________ 1958, Strawn–Canyon (Pennsylvanian) boundary in north-central Texas: Geological Society of America Bulletin, v. 69, p. 1515–1524.

Stramel, G. J., 1951, Ground-water resources of Parker County, Texas: Texas Board of Water Engineers Bulletin 5103, 55 p., 1 pl., scale ~1:125,000.

Sundstrom, R. W., Broadhurst, W. L., and Dwyer, B. C., 1949, Public water supplies in central and north-central Texas: U.S. Geological Survey Water-Supply Paper 1069, 93 p.

Texas Department of Water Resources, 1980, Brazos River basin, Lake Mineral Wells dam, Parker County, Texas, inventory no. TX01225, phase I inspection report, National Dam Safety Program: report prepared for U.S. Army Engineer District, Fort Worth, Corps of Engineers, Fort Worth, Texas, 17 p. + appendices.

Texas Parks and Wildlife Department, 1976, Development concept plan and program for Lake Mineral Wells State Park, Parker County, Texas: Texas Parks and Wildlife Department, Master Planning Branch, 135 p.

_________ 1990, Lake Mineral Wells State Park—summary of representative plant communities: Texas Parks and Wildlife Department, variously paginated.

Texas Water Development Board, 1992a, Ground water quality samples—Palo Pinto County, Texas: computer printout dated October 13, 1992, from Texas Water Development Board, Ground Water Data System, 3 p.

_________ 1992b, Ground water quality samples—Parker County, Texas: computer printout dated October 13, 1992, from Texas Water Development Board, Ground Water Data System, 8 p.

_________ 1993a, National Weather Service monthly precipitation data for Mineral Wells FAA airport, Palo Pinto County, Texas, 1948–1991: computer printout dated September 13, 1993, from Texas Water Development Board, Texas Water Oriented Data Bank, Monthly Data Extraction System, 2 p.

_________ 1993b, Water level publication report–Palo Pinto County, Texas: undated computer printout, from Texas Water Development Board, Ground Water Data System, 5 p.

_________ 1993c, Water level publication report–Parker County, Texas: undated computer printout, from Texas Water Development Board, Ground Water Data System, 20 p.

Trice, E. L., 1984, Conodont biostratigraphy and stratigraphic relationships of the Strawn Group (Pennsylvanian) Colorado and Brazos River Valleys, central Texas: Baylor University, Master's thesis, 140 p.

Trice, E. L., and Grayson, R. C., Jr., 1988, Middle and late Pennsylvaniana rocks, North-Central Texas, *in* Hayward, O. T., ed., Centennial Field Guide, v. 4: Geological Society of America, v. 4, p. 317–322.

Turner, S. F., 1934, Mineral-water supply of the Mineral Wells area: U.S. Geological Survey Circular 6, 9 p.

U.S. Federal Insurance Administration, 1977, Flood insurance study, City of Mineral Wells, Parker and Palo Pinto Counties, Texas: U.S. Department of Housing and Urban Development, Federal Insurance Administration, 22 p., with maps.

U.S. Geological Survey, 1959a, Mineral Wells quadrangle, Texas [Palo Pinto–Parker Cos.], 15-minute series (topographic): U.S. Geological Survey, scale 1:62,500.

_________ 1959b, Poolville quadrangle, Texas—Parker County, 7.5-minute series (topographic): U.S. Geological Survey, scale 1:24,000.

_________ 1960, Gibtown quadrangle, Texas—Jack, Parker, and Wise Counties, 7.5-minute series (topographic): U.S. Geological Survey, scale 1:24,000.

_________ 1961, Perrin quadrangle, Texas—Jack, Palo Pinto, and Parker Counties, 7.5-minute series (topographic): U.S. Geological Survey, scale 1:24,000.

_________ 1979a, Adell quadrangle, Texas—Parker County, 7.5-minute series (topographic) (photorevised 1979 from 1959 edition): U.S. Geological Survey, scale 1:24,000.

_________ 1979b, Brock quadrangle, Texas—Parker County, 7.5-minute series (topographic) (photorevised 1979 from 1959 edition): U.S. Geological Survey, scale 1:24,000.

_________ 1979c, Garner quadrangle, Texas—Parker County, 7.5-minute series (topographic) (photorevised 1979 from 1959 edition): U.S. Geological Survey, scale 1:24,000.

_________ 1984a, Brazos East quadrangle, Texas—Palo Pinto and Parker Counties, 7.5-minute series (topographic) (provisional edition, map number 32098-F1-TF-024): U.S. Geological Survey, scale 1:24,000.

_________ 1984b, Brazos West quadrangle, Texas—Palo Pinto County, 7.5-minute series (topographic) (provisional edition, map number 32098-F2-TF-024): U.S. Geological Survey, scale 1:24,000.

_________ 1984c, Graford East quadrangle, Texas—Palo Pinto County, 7.5-minute series (topographic) (provisional edition, map number 32098-H2-TF-024): U.S. Geological Survey, scale 1:24,000.

_________ 1984d, Lone Camp quadrangle, Texas—Palo Pinto County, 7.5-minute series (topographic) (provisional edition, map number 32098-F3-TF-024): U.S. Geological Survey, scale 1:24,000.

_________ 1984e, Mineral Wells East quadrangle, Texas—Palo Pinto and Parker Counties, 7.5-minute series (topographic) (provisional edition, map number 32098-G1-TF-024): U.S. Geological Survey, scale 1:24,000.

_________ 1984f, Mineral Wells West quadrangle, Texas—Palo Pinto County, 7.5-minute series (topographic) (provisional edition, map number 32098-G2-TF-024): U.S. Geological Survey, scale 1:24,000.

_________ 1984g, Whitt quadrangle, Texas—Palo Pinto and Parker Counties, 7.5-minute series (topographic) (provisional edition, map number 32098-H1-TF-024): U.S. Geological Survey, scale 1:24,000.

U.S. Soil Conservation Service, 1981, Land resource regions and major land resource areas of the United States: U.S. Department of Agriculture, Agriculture Handbook 296, 156 p.

Warren, S. D., Diersing, V. E., Thompson, P. J., and Goran, W. D., 1989, An erosion-based land classification system for military installations: Environmental Management, v. 13, no. 2, p. 251–257.

Weaver, O. D., 1956, An introduction to the Fort Worth Basin, *in* Stewart, W. J., ed., Symposium of the Fort Worth Basin area and field study of the Hill Creek beds of the lower Strawn, southwestern Parker County, Texas: Permian Basin Section, Society of Economic

Paleontologists and Mineralogists, Guidebook for Spring meeting and field symposium, May 11 and 12: Fort Worth, ABC Printing and Letter Co., p. 10–18.

Wermund, E. G., and Jenkins, W. A., Jr., 1965, Late Missourian tilting of the Eastern Shelf of the West Texas basins (abs.): Geological Society of America Special Paper 82, p. 220–221.

Whitaker, D. G., 1956, Stratigraphic study of some upper Strawn beds in Palo Pinto County, Texas, *in* Stewart, W. J., ed., Symposium of the Fort Worth Basin area and field study of the Hill Creek beds of the lower Strawn, southwestern Parker County, Texas: Permian Basin Section, Society of Economic Paleontologists and Mineralogists, Guidebook for Spring meeting and field symposium: Fort Worth, ABC Printing and Letter Co., p. 58–69.

Wischmeier, W. H., and Smith, D. D., 1978, Predicting rainfall-erosion losses; a guide to conservation planning: U.S. Department of Agriculture, Science and Education Administration, prepared in cooperation with Purdue Agricultural Experiment Station, Agriculture Handbook No. 537, 58 p.

Appendix A. Average wind direction and speed at Dallas-Fort Worth, Texas, 1961–1980.

DECEMBER - FEBRUARY

(Calm 4.2 percent of time; average direction and speed in January: S 11 mph [1])

Direction	Estimated percentage [2] 1 - 12 mph	13 - 21 mph	Above 21 mph	Cumulative percentage
N	7.3	5.3	1.2	13.8
NNE	4.3	2.0	0.3	6.6
NE	2.7	0.7	0.0	3.3
ENE	1.8	0.2	0.0	2.0
E	2.5	0.3	0.0	2.9
ESE	2.4	0.5	0.0	2.9
SE	3.7	0.7	0.0	4.3
SSE	5.2	1.9	0.1	7.2
S	9.3	7.3	1.0	17.6
SSW	4.8	3.3	0.5	8.6
SW	2.1	0.9	0.1	3.2
WSW	2.5	0.5	0.0	3.0
W	2.0	0.7	0.2	2.9
WNW	1.7	0.9	0.3	2.9
NW	2.7	2.1	0.6	5.4
NNW	4.1	4.0	1.2	9.3
Totals	59.0	31.3	5.5	95.8

MARCH - MAY

(Calm 3.3 percent of time; average direction and speed in April: S 13 mph [1])

Direction	Estimated percentage [2] 1 - 12 mph	13 - 21 mph	Above 21 mph	Cumulative percentage
N	4.7	3.6	0.5	8.9
NNE	3.4	1.7	0.1	5.2
NE	2.4	0.7	0.0	3.0
ENE	2.0	0.5	0.0	2.5
E	3.5	0.7	0.0	4.2
ESE	3.5	1.0	0.1	4.7
SE	4.7	2.0	0.2	7.0
SSE	5.7	4.6	0.3	10.6
S	9.4	12.8	2.7	25.0
SSW	3.3	3.7	0.7	7.8
SW	1.9	0.8	0.1	2.7
WSW	1.4	0.6	0.1	2.1
W	0.7	0.7	0.2	1.6
WNW	1.3	0.7	0.2	2.2
NW	2.2	1.3	0.5	4.1
NNW	2.7	2.0	0.5	5.3
	53.0	37.4	6.3	96.7

JUNE - AUGUST

(Calm 5.1 percent of time; average direction and speed in July: S 9 mph [1])

Direction	Estimated percentage [2] 1 - 12 mph	13 - 21 mph	Above 21 mph	Cumulative percentage
N	2.5	0.5	0.0	3.0
NNE	2.2	0.5	0.0	2.7
NE	1.7	0.3	0.0	2.0
ENE	1.8	0.3	0.0	2.0
E	4.5	0.4	0.0	4.9
ESE	6.1	0.7	0.0	6.8
SE	8.0	1.1	0.0	9.1
SSE	10.4	2.8	0.0	13.2
S	18.4	8.3	0.6	27.3
SSW	9.3	4.1	0.2	13.5
SW	3.4	0.9	0.0	4.3
WSW	1.8	0.2	0.0	2.0
W	1.2	0.1	0.0	1.4
WNW	0.7	0.1	0.0	0.7
NW	0.6	0.1	0.0	0.7
NNW	1.1	0.1	0.0	1.2
Totals	73.6	20.4	0.8	94.9

SEPTEMBER - NOVEMBER

(Calm 6.2 percent of time; average direction and speed in October: S 10 mph [1])

Direction	Estimated percentage [2] 1 - 12 mph	13 - 21 mph	Above 21 mph	Cumulative percentage
N	7.2	3.3	0.2	10.7
NNE	4.2	1.4	0.1	5.6
NE	3.2	0.5	0.0	3.7
ENE	2.3	0.4	0.0	2.7
E	3.8	0.3	0.0	4.2
ESE	4.0	0.3	0.0	4.3
SE	5.6	0.8	0.0	6.4
SSE	7.6	2.5	0.1	10.2
S	11.3	6.8	0.6	18.7
SSW	5.2	2.8	0.3	8.3
SW	2.5	0.5	0.0	3.0
WSW	1.9	0.2	0.0	2.1
W	1.7	0.3	0.0	2.1
WNW	1.3	0.7	0.1	2.1
NW	2.4	1.0	0.1	3.5
NNW	4.2	1.9	0.2	6.2
	68.3	23.8	1.7	93.8

Notes:

(1) Average wind direction and speed for approximately 20-year period ending in 1980, reported in Bomar (1983, table F-2).

(2) Percentage of winds blowing from each of 16 principal directions within ranges of speed indicated, estimated from graphic plots in Larkin and Bomar (1983, p. 67-68, and 90-93), based on original U.S. Department of Commerce dataset of measurements made at 3-hr intervals at 12 a.m. (midnight), 3 a.m., 6 a.m., 9 a.m., 12 p.m. (noon), 3 p.m., 6 p.m., and 9 p.m.

Appendix B. Wind speed and direction data for Parker County, Texas, 1948–1965 (from Flemming & Associates, 1971).

	Percentage of Time, by Speed (knots)						Cumulative	Mean Speed
Direction	1-3	4-6	7-10	11-16	17-21	22-27	Percent	(knots)
N	0.4	1.6	2.3	1.8	0.4	0.1	6.6	9.5
NNE	0.4	1.3	1.7	0.9	0.1	0.0	4.4	8.2
NE	0.5	1.4	1.3	0.5	0.1	0.0	3.8	7.2
ENE	0.2	0.8	0.9	0.3	0.0	0.0	2.2	7.5
E	0.3	1.0	1.2	0.4	0.0	0.0	2.9	7.5
ESE	0.3	1.7	2.6	0.9	0.1	0.0	5.6	8.1
SE	0.5	4.5	10.8	4.4	0.6	0.0	20.8	8.9
SSE	0.3	1.7	5.6	5.7	1.7	0.2	15.2	11.3
S	0.2	1.1	2.7	3.7	1.7	0.3	9.7	12.3
SSW	0.1	0.5	1.0	1.5	0.7	0.1	3.9	12.2
SW	0.3	0.7	1.0	0.7	0.2	0.0	2.9	9.4
WSW	0.2	0.7	0.7	0.5	0.2	0.1	2.4	9.3
W	0.4	0.9	0.8	0.5	0.2	0.1	2.9	8.5
WNW	0.1	0.5	0.6	0.5	0.2	0.0	1.9	10.0
NW	0.3	0.8	1.2	1.0	0.3	0.0	3.6	9.6
NNW	0.2	0.8	1.5	1.7	0.6	0.1	4.9	11.2
Variable							0.2	
Calm							6.1	
Totals	4.7	20.0	35.9	25.0	7.1	1.0	100.0	9.2

Table reproduced from Flemming & Associates (1971, table 2). Numbers represent cumulative percentages by speed and direction for all hours and all months, years 1948–1965 (total number of observations = 154,507).

Appendix C. Annual precipitation recorded at Mineral Wells airport, 1948–1991.

Year	Mineral Wells	Year	Mineral Wells
1948	9.0 (a)	1970	24.4
1949	39.3 (b)	1971	25.4
1950	32.4	1972	19.9
1951	24.1	1973	40.5
1952	21.1	1974	1.9 (d)
1953	22.2	1975	22.4
1954	20.3	1976	32.8
1955	20.4	1977	27.5
1956	21.7	1978	25.0
1957	49.8	1979	33.1
1958	27.9	1980	28.0
1959	31.1	1981	42.9
1960	25.7	1982	6.7 (e)
1961	29.1	1983	1.3 (f)
1962	40.7	1984	no data
1963	20.4	1985	no data
1964	28.5 (c)	1986	no data
1965	31.3	1987	no data
1966	33.0	1988	no data
1967	28.6	1989	17.7 (g)
1968	41.1	1990	45.8
1969	47.1	1991	47.6
Minimum	19.9	Mean	30.8
Maximum	49.8		

Data from National Weather Service, via Texas Water Oriented Data Bank (Texas Water Development Board, 1993a). No data are available for 1984 through 1988, and incomplete for the following years: (a) missing Jan, Feb, Mar, Apr, and May, (b) missing Apr, (c) missing Jul, (d) Jan and Feb data only, (e) Jan, Feb, and Nov data only, (f) Aug data only, (g) missing Jan, Feb, Mar, Apr, and May. Values for minimum, maximum, and mean do not include years with missing data.

Appendix D. Historical water-level data for selected wells in the Fort Wolters area, Palo Pinto and Parker Counties (data from Texas Water Development Board, 1993b, 1993c; well locations shown in fig. 14).

Palo Pinto County						Parker County					
Well 31-31-502 (aquifer 324STRN) [1]		Well 31-15-502 (aquifer 324MLWL) [2]		Well 31-14-202 (aquifer 321PLPN) [3]		Well 31-08-601 (aquifer 218TVPK) [4]		Well 32-02-101 (aquifer 218PLXY) [5]		Well 32-25-301 (aquifer 100ALVM) [6]	
Date	Water Level	Date	Water Level	Date	Water Level	Date	Water Level	Date	Water Level	Date	Water Level
07/13/78	962	07/12/78	790	02/01/74	852	12/20/49	1071	11/25/49	1098	02/23/50	712
10/07/78	962	10/07/78	789	07/12/78	850	02/20/71	1069	02/09/71	1108	02/09/71	711
11/19/81	964	11/20/81	795	10/07/79	854	10/31/71	1070	11/16/72	1107	10/31/71	709
09/21/82	963	09/22/82	798	11/19/81	854	11/16/72	1070	11/09/73	1107	11/15/72	708
10/21/83	963	10/21/83	789	09/21/82	850	11/09/73	1070	11/13/74	1109	11/12/73	709
10/13/84	962	10/16/84	784	10/20/83	849	11/13/74	1071	11/14/75	1110	11/13/74	710
10/16/84	963	09/24/85	793	10/16/84	848	11/14/75	1071	11/08/76	1109	11/14/75	712
09/24/85	964	01/10/89	784	09/24/85	851	11/08/76	1071	11/07/77	1109	11/08/76	712
01/10/89	964	10/13/89	791	01/10/89	850	10/05/78	1070	10/05/78	1107	11/17/77	712
11/01/90	963	11/01/90	796	11/01/90	852	10/15/80	1071	10/15/80	1107	10/06/78	711
11/15/91	964	11/15/91	797	11/15/91	852	03/17/82	1072	03/17/82	1109	03/17/82	712
						03/24/83	1072	03/24/83	1110	03/24/83	712
						03/20/84	1072	03/20/84	1109	03/20/84	710
						03/19/85	1072	03/19/85	1108	03/19/85	710
						03/14/86	1072	03/14/86	1109	03/14/86	710
						03/11/87	1072	03/11/87	1110		
						01/14/88	1074	01/14/88	1111		
						02/02/89	1072	02/02/89	1109		
						01/25/90	1073	01/25/90	1111		
						01/22/92	1078	01/17/91	1112		
								01/22/92	1113		

Explanation of aquifer codes:
(1) 324STRN - aquifer in unspecified Strawn Group strata (Brazos River Formation?)
(2) 324MLWL - aquifer in Mineral Wells Formation
(3) 321PLPN - aquifer in Palo Pinto Formation
(4) 218TVPK - aquifer in Travis Peak Formation (equivalent to Twin Mountains Formation)
(5) 218PLXY - aquifer in Paluxy Formation
(6) 100ALVM - aquifer in Quaternary alluvium

Appendix E. Explanation of Digital Line Graph Data.

Data and Sources

Most of the data presented here were digitized from printed paper originals of the U.S. Geological Survey 1:24,000-scale, 7.5-minute topographic maps of the Adell, Garner, Mineral Wells East, and Whitt quadrangles (U.S. Geological Survey, 1979a, 1979c, 1984e, 1984f) (fig. E1). Additional data representing drainage divides, the main stream of Rock Creek, and the Brazos River were digitized from surrounding quadrangles (U.S. Geological Survey, 1959b, 1960, 1961, 1979b, 1984a, 1984b, 1984c, 1984d, 1984g) (fig. E1). Drainage divides were determined by examination of topographic contours. Soil unit boundaries were transferred to topographic maps from soil maps in Greenwade and others (1977) and Moore (1981) and then digitized.

Digitizing Equipment, Quality Control, and Editing

Maps were digitized using a Summagraphics ID-2 digitizer table and electronics, under the control of the program DIGIT, version 3.10, modified by the Bureau of Economic Geology from an earlier (1986–87) version originally supplied by Radian Corporation. Each map was digitized during several separate sessions, and in some cases the map was removed from the table between sessions. Reference points (usually the map corners) were selected on each map and used to align data sets from different sessions and to join data sets at the edges of adjacent maps.

The 7.5-minute topographic maps in this area are in a Lambert conformal conic projection, in the central zone of the Texas coordinate system. The data are supplied in relative cartesian coordinates, in units of 1,000 per map inch, with a resolution of 5 units or 0.005 inch (0.005 inch equals approximately 10 ft at the nominal map scale of 1:24,000). The (x,y) coordinates

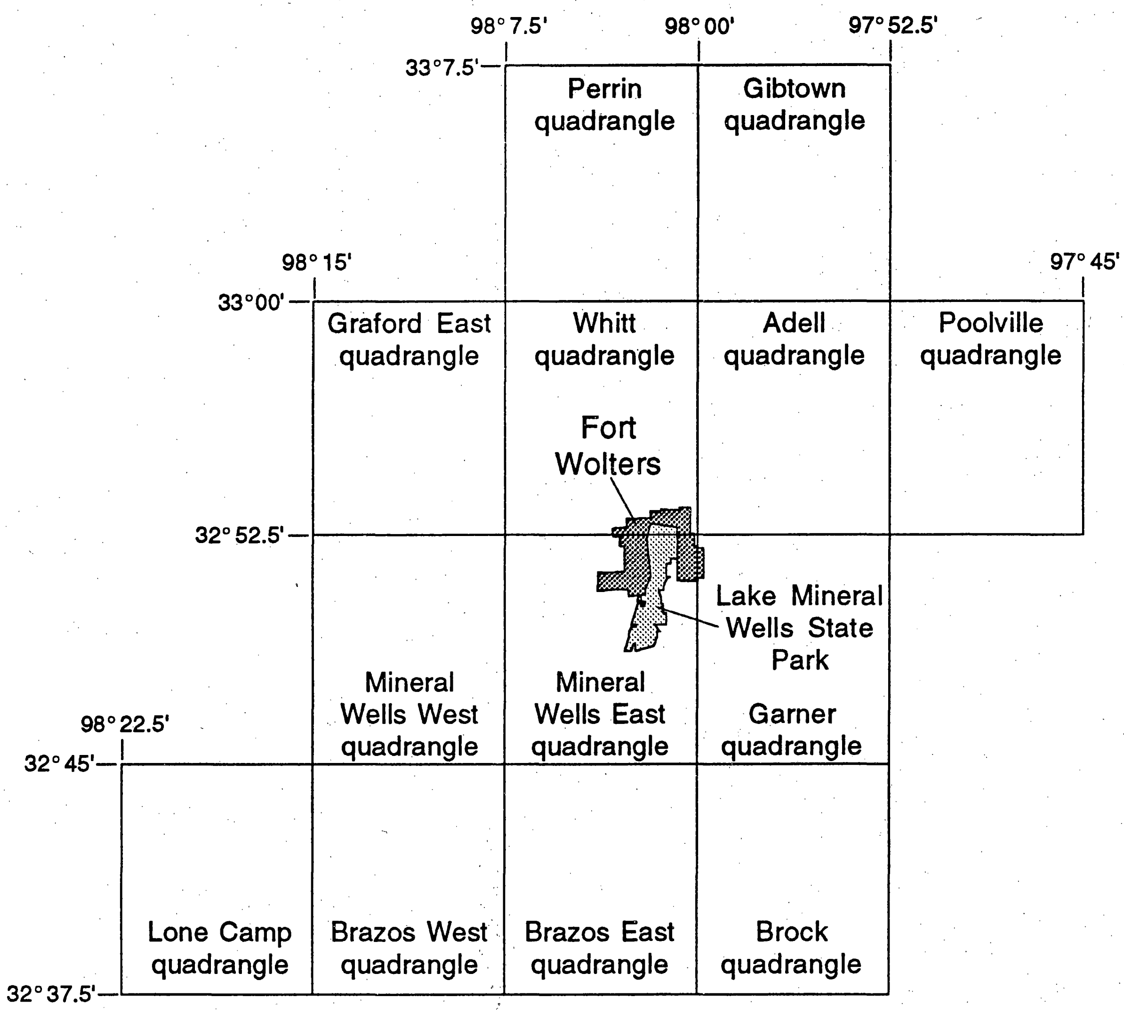

Figure E1. Index to 7.5-minute topographic map quadrangles from which data were digitized. The (x,y) coordinates in the data files are relative to an origin placed at longitude 98°00'W (x=0) and latitude 32°52.5'N (y=0).

for each data set were translated so that the point representing longitude 98°00.0′W, 32°52.5′N would have the value (0,0) (see fig. E1). To compensate for slight scale differences between adjacent map sheets, the data sets were also rotated and rescaled about the origin by very small amounts to bring into coincidence the selected reference points that were duplicated at the edges of adjacent maps. The relative positions of the data points have not been changed—they retain the original distribution of the Lambert conformal conic projection. It should be possible to exactly reproduce the original map upon replotting the data, but typically there is some mismatch owing to several types of error: (1) distortion of the paper map originals caused by changes in environment (the scale of one map may be slightly different from the scale of an adjacent map), (2) slight imperfections in the digitizing and plotting equipment, (3) slight shifting of the map original on the table during digitizing, and (4) incorrect placement of digitizer crosshair. These factors combine to produce a small but noticeable mismatch between the replotted map and the original. The data are provided in separate data files for each digitizing session to allow each data set to be corrected (georeferenced) separately.

DATA FILES AND DATA TRANSFER

The data are supplied in compressed form in the self-extracting archive named "WLTRSDXF.EXE" on a DOS-formatted, 3.5-inch diskette titled "Ft. Wolters DLG data (DXF)" (see table E1), available separately upon request from the Bureau's Open-File Library. This file should be copied to a hard drive on an IBM-compatible computer. The individual files are extracted by entering the command "WLTRSDXF"; the uncompressed files will have the extension ".DXF" and will require 5.65 megabytes of disk space. The data files are ASCII text files in DXF format. The free software program LHARC, used to compress the files, is also included on the diskette.

The digital data represent (1) line segments, and (2) solitary points grouped in 74 separate files (table E2). Descriptive labels, keyed to the corresponding coordinate data file by point or

Table E1. Diskettes containing digital data, available from open file.

Diskette	Files
Ft. Wolters DLG data (DXF)	WLTRSDXF.EXE
	WLTRSLIS.COM
	LHARC.EXE
	LHARC.MAN
Ft. Wolters DLG data (ARC)	WLTRSARC.EXE
	WLTRSLIS.COM
	LHARC.EXE
	LHARC.MAN
Ft. Wolters DLG data (DAT)	WLTRSDAT.EXE
	WLTRSLIS.COM
	LHARC.EXE
	LHARC.MAN

Table E2. List of data file names and brief descriptions of contents.

Data File Name [*]	Data Type	Quadrangle [*]				Brief Description
		Adell (AQ)	Garner (GQ)	Mineral Wells East (MQ)	Whitt (WQ)	
aaBASIN2	Line			X		Drainage basin divide
aaBASINR	Line	X	X	X	X	Drainage basin divides, includes surrounding quadrangles
aaBASINS	Line	X	X	X	X	Drainage basin divides, includes surrounding quadrangles
aaBDRYBS	Line		X	X	X	Fort Wolters base boundary
aaBDRYOT	Line			X		Mineral Wells city limits that are not also base or park boundary
aaBDRYPK	Line			X		Lake Mineral Wells State Park boundary that is not also base boundary
aaBRAZSR	Line			X		Brazos River on quadrangles south and west of Mineral Wells West quadrangle
aaCITY	Point		X	X		Approximate centers of area communities
aaCNTYLN	Line			X	X	Palo Pinto - Parker County line
aaCONT01	Line	X	X	X	X	Topographic contours, interval 50 ft
aaCONT02	Line				X	Topographic contours, interval 50 ft
aaELEV	Point	X	X	X	X	Spot elevations (.LIS label file includes character codes from maps)
aaPHOTEL	Point				X	Spot elevations near aerial photograph centers
aaPHOTO	Point			X	X	Aerial photograph centers
aaPIPELN	Line			X		Pipeline
aaPITS	Point		X	X		Sand, gravel, or clay pits
aaPOWRLN	Line	X		X	X	Powerlines
aaRAIL	Line		X	X		Railroads
aaRDSIB1	Line		X	X	X	Roads inside base boundaries
aaRDSOB1	Line	X	X	X	X	Roads outside base boundaries
aaRDSOB2	Line			X		Roads outside base boundaries
aaRDSOB3	Line			X		Roads outside base boundaries
aaRDSOB4	Line			X		Roads outside base boundaries
aaROCKCK	Line			X		Main branch of Rock Creek, includes quadrangles south and west of Mineral Wells East
aaSTREA1	Line	X	X	X	X	Area streams
aaSTREA2	Line			X		Area streams
aaSTREA3	Line			X		Area streams
aaSTREA4	Line			X		Area streams
aaSTREA5	Line			X		Area streams
aaTICS	Point	X	X	X	X	2.5-minute latitude/longitude tic marks
aaWATBOD	Line	X	X		X	Water bodies
aaWATER2	Line			X		Water body
aaWATERB	Line			X		Water bodies
aaWELLS	Point		X	X	X	Wells (water, oil, gas)
aaWTANK	Point			X		Water tanks
FWSOIL1	Line	not separated by quadrangle				Soil unit boundaries
FWSOIL2	Line	not separated by quadrangle				Soil unit boundaries
FWSOIL3	Line	not separated by quadrangle				Soil unit boundaries

* Note: The first two characters in each file name (shown in this list as "aa") are "AQ", "GQ", "MQ", or "WQ". Files exist for each combination indicated by an "X" in the quadrangle columns. For example, aaBASINR data files include AQBASINR, GQBASINR, MQBASINR, and WQBASINR, whereas the only aaBASIN2 data file is MQBASIN2.

line-segment identification number, are provided in compressed form in the self-extracting archive named "WLTRSLIS.COM", also on the diskette "Ft. Wolters DLG data (DXF)". The individual files are extracted by entering the command "WLTRSLIS"; the uncompressed files will have the extension ".LIS" and will require 79.2 kilobytes of disk space.

The data are also available in Arc-Info format on a diskette titled "Ft. Wolters DLG (ARC)" (see table E1). The files are in a self-extracting archive named "WLTRSARC.EXE" and are extracted by entering the command "WLTRSARC"; the uncompressed files will have the extension ".ARC" and will require 1.51 megabytes of disk space. The descriptive labels for the Arc-Info files are provided separately on that same disk in the "WLTRSLIS.COM" archive.

The data are available in yet another, more fundamental format that includes the labels within the data file. These files are on the diskette title "Ft. Wolters DLG data (DAT)" (see table E1) in the self-extracting archive "WLTRSDAT.EXE". The files are extracted by entering the command "WLTRSDAT"; the uncompressed files will have the extension ".DAT" and will require 2.95 megabytes of disk space.

Sample plots of the DLG data in various combinations are included with this document (plates 1–5). For clarity, some of the data files and most of the descriptive labels have been omitted from the sample plots. Also, the data have been cropped to a plotting window that has a smaller extent than the actual data coverage. A list of data files in each plate is given in table E3.

FINAL PREPARATION OF DATA FOR GIS USE

As noted above, the data as supplied are in the Lambert conformal conic projection of the digitized maps. The (x,y) coordinate values are relative to an origin (x = 0, y = 0) at longitude 98°00.0′W, latitude 32°52.5′N (fig. E1). Each individual data file contains as the first four data records the four reference points representing the map corners. The latitude/longitude values that correspond to the cartesian coordinates for these map corners are provided the .LIS files.

Table E3. List of illustrations that contain digital data.

Illustration	Data Files Represented
Plates in Appendix E	
Plate E1 - Fort Wolters base map	GQBDRYBS, MQBDRYBS, WQBDRYBS, MQBDRYOT, MQBDRYPK, MQCNTYLN, WQCNTYLN, MQPHOTO, WQPHOTO, MQPIPELN,GQPITS, MQPITS, AQPOWRLN, MQPOWRLN, WQPOWRLN, GQRAIL, MQRAIL, GQRDSIB1, MQRDSIB1, WQRDSIB1, AQRDSOB1, GQRDSOB1, MQRDSOB1, WQRDSOB1, MQRDSOB2, MQRDSOB3, MQRDSOB4, AQTICS, GQTICS, MQTICS, WQTICS, GQWELLS, MQWELLS, WQWELLS, MQWTANK
Plate E2 - Fort Wolters regional surface drainage	MQBASIN2, AQBASINR, GQBASINR, MQBASINR, WQBASINR, AQBASINS, GQBASIN MQBASINS, WQBASINS, GQBDRYBS, MQBDRYBS, WQBDRYBS, MQBRAZSR, MQROCKCK, AQSTREA1, GQSTREA1, MQSTREA1, WQSTREA1, MQSTREA2, MQSTREA3, MQSTREA4, MQSTREA5, AQTICS, GQTICS, MQTICS, WQTICS
Plate E3 - Fort Wolters local surface hydrology	MQBASIN2, AQBASINR, GQBASINR, MQBASINR, WQBASINR, AQBASINS, GQBASIN MQBASINS, WQBASINS, GQBDRYBS, MQBDRYBS, WQBDRYBS, MQBDRYPK, MQROCKCK, AQSTREA1, GQSTREA1, MQSTREA1, WQSTREA1, MQSTREA2, MQSTREA3, MQSTREA4, MQSTREA5, AQTICS, GQTICS, MQTICS, WQTICS, AQWATBOD, GQWATBOD, WQWATBOD, MQWATER2, MQWATERB
Plate E4 - Fort Wolters topography	GQBDRYBS, MQBDRYBS, WQBDRYBS, MQBDRYPK, AQCONT01, GQCONT01, MQCONT02, WQCONT01, WQCONT02, AQELEV, GQELEV, MQELEV, WQELEV, WQPHOTEL, MQROCKCK, AQSTREA1, GQSTREA1, MQSTREA1, WQSTREA1, MQSTREA2, MQSTREA3, MQSTREA4, MQSTREA5, AQTICS, GQTICS, MQTICS, WQTICS
Plate E5 - Fort Wolters soils	GQBDRYBS, MQBDRYBS, WQBDRYBS, MQBDRYPK, FWSOIL1, FWSOIL2, FWSOIL3 MQROCKCK, AQSTREA1, GQSTREA1, MQSTREA1, WQSTREA1, MQSTREA2, MQSTREA3, MQSTREA4, MQSTREA5, AQTICS, GQTICS, MQTICS, WQTICS
Figures in Main Body of Report	
Figure 10 - Topographic map	MQROCKCK, AQSTREA1, GQSTREA1, MQSTREA1, WQSTREA1, MQSTREA2, MQSTREA3, MQSTREA4, MQSTREA5, AQCONT01, GQCONT01, MQCONT02, WQCONT01, WQCONT02
Figure 11 - Regional surface drainage	MQBASIN2, AQBASINR, GQBASINR, MQBASINR, WQBASINR, AQBASINS, GQBASIN MQBASINS, WQBASINS, MQBRAZSR, MQROCKCK, AQSTREA1, GQSTREA1, MQSTREA1, WQSTREA1, MQSTREA2, MQSTREA3, MQSTREA4, MQSTREA5
Figure 12 - Local surface hydrology	MQBASIN2, AQBASINR, GQBASINR, MQBASINR, WQBASINR, AQBASINS, GQBASIN MQBASINS, WQBASINS, MQROCKCK, AQSTREA1, GQSTREA1, MQSTREA1, WQSTREA1, MQSTREA2, MQSTREA3, MQSTREA4, MQSTREA5, AQWATBOD, GQWATBOD, WQWATBOD, MQWATER2, MQWATERB
Figure 13 - Soil map	FWSOIL1, FWSOIL2, FWSOIL3, MQROCKCK, AQSTREA1, GQSTREA1, MQSTREA1, WQSTREA1, MQSTREA2, MQSTREA3, MQSTREA4, MQSTREA5

These reference points should be used to properly georeference and correct each data file so that the various data coverages can be merged into fewer files on the destination GIS computer. One special note: there are nine files (AQBASINR, AQBASINS, GQBASINR, GQBASINS, MQBASINR, MQBASINS, MQBRAZSR, WQBASINR, WQBASINS) containing data for drainage basin divides and the Brazos River that actually include data from quadrangles that surround the four central quadrangles (see fig. E1 and table E2); these files, and the corresponding .LIS files, contain four additional records for each added quadrangle, embedded at the location in the file where data from the added quadrangle(s) begin.

Final data preparation for GIS use should include additional editing to correct imperfections such as localized misalignments between streams and contours and drainage basin boundaries, random gaps, and irregularities that do not match lines on the original map. Also, junction points, or nodes where line segments are intended to meet, should be defined; at present, many of the lines that should meet do not share a common point. Similarly, polygons must be constructed from the line segments to enable area calculations and other operations.

Most applications of digital geographic data require the ability to manipulate the data in various groups defined on the basis of one or more attributes. Simple attribute information in the form of descriptive labels is provided in the appendix. More detailed attributes may be assigned that will enable more precise retrieval than the existing record labels. Data that are not included here but might be considered for future digitizing include (1) outlines of individual soil mapping units, (2) outlines of vegetated areas, (3) historical sites, and (4) sites of special ecological importance.