Geologic and Hydrogeologic Framework of Regional Aquifers in the Twin Mountains, Paluxy, and Woodbine Formations near the SSC Site, North-Central Texas

Draft Topical Report

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Prepared for

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under Contracts No. IAC(92-93)-0301 and No. IAC 94-0108

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ABSTRACT

Water-utility districts and municipalities in North-Central Texas recently obtained as much as 100 percent of their water supply from deep regional aquifers in Cretaceous formations. Use of ground water from the aquifers during the past century has resulted in water-level declines of as much as 800 ft (243.8 m) in Dallas and Tarrant Counties. Future continued water-level decline throughout North-Central Texas will depend on amount of ground-water produced to help meet increased water-supply needs for municipal, industrial, and agricultural growth. It is probable that a significant part of the increased water demand will be met by ground water.

The objectives of this study were to develop a hydrologic model of the complex interrelations among aquifer stratigraphy, hydrologic properties, and ground-water availability and, given expected patterns of future ground-water demand, to predict water-level changes in the regional aquifers that underlie North-Central Texas. A cross-sectional model of both aquifers and confining layers was used to evaluate model boundary conditions and the vertical hydrologic properties of the confining layers. Results and insights from the cross-sectional model were used in a three-dimensional simulation of ground-water flow in the deep aquifers. The layers of a regional confining system were not explicitly included in the three-dimensional model. Hydrogeologic properties were assigned on the basis of aquifer test results and stratigraphic mapping of sandstone distribution in the aquifer units.

INTRODUCTION

Interest in developing ground-water resources in North-Central Texas (fig. 1) mainly has focused on the Lower Cretaceous Twin Mountains and Paluxy Formations and the Upper Cretaceous Woodbine Formation (fig. 2). After the discovery in 1882 of flowing wells with artesian pressure in the Twin Mountains Formation in the Fort Worth area, by 1897 about 150 to 160 wells had been drilled (Hill, 1901). Farther south, Waco was known as the "City of Geysers." By 1914, many wells had stopped flowing as hydraulic head decreased to beneath ground surface (Leggat, 1957). With growth in population and in agricultural and industrial output, ground-water use gradually increased during the twentieth century and accelerated during the past 40 yr. In Ellis County, for example, ground-water use more than doubled from 1974 to 1988, reaching almost 9,000 acre-ft/yr (11.1×10^6 m^3/yr). Cities of Italy, Glenn Heights, and Midlothian in Ellis County recently used ground water for as much as 60 percent of their water. The increased use of ground water resulted in marked declines of water levels in the aquifers. Since the turn of the century, water levels in the Fort Worth area have declined nearly 850 ft (259 m) in the Twin Mountains Formation and 450 ft (137 m) in the Paluxy Formation, and water levels in the Dallas area have declined approximately 400 ft (123 m) in the Woodbine Formation. During the next 40 yr, rural and industrial ground-water use is projected to remain fairly constant while some municipalities will increase their use of ground water. Other municipalities in North-Central Texas are projected to decrease their ground-water use by as much as 60 percent by the year 2030, compared to 1980 usage (Texas Water Development Board, unpublished information, 1987), partly as a response to the historic decline in water levels. Fort Worth earlier abandoned many of its wells and started using surface impoundments for water supply. Waxahachie and Ennis in Ellis County also have turned almost completely to surface-water sources. Even if the regional pumpage rate decreases during the next 40 yr, however, it is probable that water levels will continue to decline because ground-water withdrawals still will exceed inflow from recharge areas.

The purpose of this study was to interpret and better understand the influence of future ground-water pumpage on water levels in the aquifers and to define ground-water flow paths and travel times. Because of the complex interrelation of aquifer stratigraphy, hydrologic properties, ground-water availability, and water level, accurate predictions of future water-level decline in regional aquifers in North-Central Texas need to be based on a numerical model of ground-water flow. The cross-sectional and quasi-three-dimensional numerical models developed in this study were used as tools to estimate amounts of recharge and cross-formational flow, evaluate uncertain hydrologic characteristics of confining layers and aquifer boundaries, and quantitatively estimate as accurately as possible how water level will respond to future pumping rates. Hydrogeologic and stratigraphic data, including transmissivity, storativity, formation thickness, and sandstone thickness, were used for model calibration.

Deterministic models of ground-water flow require information on hydrological properties. Assigning a uniform distribution of properties, for example, on the basis of mean value, to all block or nodes of a computer model is generally unacceptable because heterogeneity affects aquifer performance. Subdividing the model area around aquifer test locations results in unnatural, discontinuous distribution of hydrologic properties. The discontinuities can lead to spurious results, for example, in particle tracking. Assigning hydraulic properties on the basis of both aquifer tests and spatial stratigraphic variables such as sandstone thickness, however, provides a basis for realistic, continuous distributions of hydrologic properties.

The areal distribution of hydrologic properties was estimated from aquifer test results and geologic maps describing the stratigraphy and depositional facies distributions of the aquifers. The models were calibrated by adjusting estimated or assumed hydrologic properties to obtain a best match between recorded and simulated hydraulic heads. First the models were calibrated for assumed steady-state conditions using turn-of-the-century hydrologic observations of Hill (1901). Transient models were then calibrated using historic hydrograph data from the aquifers. Future growth in demand for ground water is based on TWDB projections.

This draft topical report comprises part I of a study of ground-water resources in North-Central Texas. This report documents the stratigraphic and hydrologic framework of the regional aquifers, building on many previous studies. This framework was used to define and calibrate interpretive and predictive models of ground-water flow. Results of a two-dimensional cross-sectional model are discussed in this report. Results of a three-dimensional model will be discussed in part II.

REGIONAL HYDROGEOLOGIC SETTING

Hydrologic Units

The main hydrostratigraphic units in North-Central Texas are (fig. 2):

- a regionally confined aquifer system with principal units the Lower Cretaceous Twin Mountains and Paluxy Formations and Upper Cretaceous Woodbine Formation, which is unconfined where each formation crops out at ground surface;
- a regional confining system in Upper Cretaceous bedrock of the Eagle Ford Formation, Austin Chalk, and Taylor Group, which is weathered near ground surface; and
- local surficial aquifers in Quaternary alluvium.

Regionally Confined Aquifers

The regional aquifers occur in Lower and Upper Cretaceous sandstones of the (stratigraphically, from bottom to top) Twin Mountains, Paluxy, and Woodbine Formations (figs. 2 and 3). The regional aquifer system is underlain by Pennsylvanian age (Strawn Series) shales and limestones and by Jurassic-age (?) Cotton Valley Group sandstones and shales. These formations are assumed to have very low permeability and to not exchange appreciable amounts of ground water with the regional aquifers in Cretaceous formations. At its top the regional aquifer system is overlain and confined by Eagle Ford Formation, Austin Chalk, and Taylor Group (fig. 2). The Washita and Fredericksburg Groups and the Glen Rose, Pearsall, and Sligo Formations make up confining layers within the regional aquifer system.

The Twin Mountains Formation is as much as 550 to 850 ft (167.6 to 259.1 m) thick in North-Central Texas and is composed principally of sandstone with a basal gravel and conglomerate section where most wells are completed. The thickness of the Paluxy Formation decreases toward the southeast from a maximum of approximately 400 ft (121.9 m) in the northern part of North-Central Texas (Nordstrom, 1982). The 250- to 375-ft-thick (76.2- to 114.3-m) Woodbine Formation is a medium- to coarse-grained iron-rich sandstone, with some clay and lignite seams. The Woodbine lies 1,200 to 1,500 ft (365.8 to 457.2 m) above the top of the Twin Mountains. Most wells are completed in the lower part of the formation, which yields better quality ground water. In Ellis County, for example, the top of the Woodbine ranges from 600 to 1,000 ft (182.9 to 304.8 m) beneath ground surface and the top of the Twin Mountains is at depths from 2,000 to 3,000 ft (609.6 to 914.4 m) beneath ground surface.

Regional Confining System

The Upper Cretaceous Eagle Ford Formation, Austin Chalk, and Taylor Group compose a regional confining system (fig. 2), which means that the low permeability of the rock retards the vertical and lateral flow of ground water and separates underlying aquifers from surficial aquifers. The Eagle Ford is composed of a dark shale with very thin limestone beds. The Austin Chalk is made up of fine-grained chalk and marl deposited in a deep-water marine-shelf environment. The Ozan and Wolfe City Formations consist of fine-grained marl, calcareous mudstone, shale, and calcareous sandstone. Weathering and unloading have significantly increased porosity and permeability of the near-surface chalk and marl bedrock, allowing enhanced recharge, storage, and shallow circulation of ground water in otherwise low-permeability, fractured rock strata. Average hydraulic conductivity is almost 1,000 times higher in weathered chalk, marl, and shale than in unweathered bedrock (Dutton and others, 1994). Thickness of the weathered zone is generally less than 12 to 35 ft (3.66 to 10.67 m).

Surficial Aquifers

Unconfined and semi-unconfined aquifers of limited extent occur in surficial Pleistocene and Holocene alluvium in parts of North-Central Texas (Taggart, 1953; Reaser, 1957; Wickham and Dutton, 1991). Only small amounts of ground water from the surficial alluvium historically have been used. The Pleistocene deposits are unconsolidated and typically consist of a thin, basal-pebble conglomerate, and stratified clay, sand, granules, and pebbles capped by calcareous clay and clayey soil. Holocene floodplain deposits of clay and silty clay form an alluvial veneer along rivers and streams in the region and range in thickness from a few feet to more than 30 ft (9.14 m). The alluvial material is normally small in areal extent and typically less than 50 ft (15.2 m) thick. Erosion during the Holocene stripped most of the Pleistocene alluvium from the surface, and Modern streams locally have cut through to underlying Cretaceous bedrock, leaving isolated deposits (terraces) of Pleistocene alluvium at elevations higher than those of the surrounding strata (Hall, 1990).

Regional Structure

The study area is located on the western margin of the East Texas Basin (fig. 4) at the northern limits of the Balcones fault zone, a zone of normal faulting that extends south toward Austin and San Antonio (Murray, 1961; Grimshaw and Woodruff, 1986; Collins and Laubach, 1990). The Mexia-Talco fault zone at the eastern side of the study area is parallel to the Balcones fault zone. Its origin has been interpreted as resulting from sliding of Cretaceous sediments into the East Texas Basin upon Jurassic salt deposits (Jackson, 1982). The general structure of the study area includes an eastward descending ramp from formation outcrop areas in the west and a southward descending ramp from outcrop areas in the north. The hinge between the eastward and southward dipping ramps is the Sherman syncline northeast of Dallas in central Grayson and southwestern Hunt Counties (fig. 4). The stratigraphic horizons dip toward the East Texas Basin and increase in dip across the Balcones and Mexia-Talco fault zones (figs. 5 to 7). For example, dip of the top of the Paluxy Formation increases from about 0.33° in the western part of the study area to 0.81° in the Balcones fault zone in the western part of Ellis County, and again abruptly increases to 1.95° along the Mexia-Talco fault zone farther east (fig. 6).

Structural elevations on the bases of some Cretaceous stratigraphic horizons are rugged. Several dip-oriented troughs record an erosional unconformity at the base of the Hosston Formation. Hill (1901) called this unconformity the Wichita Paleoplain (fig. 3). Similar regional unconformities occur beneath other Cretaceous sandstone-dominated formations in the area. An incised valley system, for example, occurs beneath basal Woodbine sandstones.

Physiography, Climate, and Land Use

Physiographic provinces in North-Central Texas include, from east to west, the Blackland Prairie, Eastern Cross Timbers, Grand Prairie, and Western Cross Timbers. Regional dip of the topographic slope is toward the southeast. Surface water in the study area drains in the Red River, Trinity River, and Brazos River watersheds. Drainage is largely dendritic, but stream positions might be locally controlled by joints or faults, for example, as in the Austin Chalk outcrop. Topography regionally consists of low floodplains, broad, flat upland terraces, and rolling hills. The low-relief hills of the Eastern and Western Cross Timbers provinces coincide with outcrops of the Lower and Upper Cretaceous sandstone-dominated formations, whereas the rolling Blackland and Grand Prairie provinces coincide with outcrops of the Upper Cretaceous carbonate-dominated formations, such as the Austin Chalk, that in the subsurface compose the regional confining system. The White Rock Escarpment marks the western limit of the Austin Chalk. The Eagle Ford Formation underlies the broad valley west of the White Rock Escarpment.

North-Central Texas lies in the subtropical humid and subtropical subhumid climatic zones (Larkin and Bomar, 1983). Major climatological factors are the onshore flow of tropical maritime air from the Gulf of Mexico and the southeastward movement of weather fronts across the continental interior. Average annual precipitation decreases from 38 inches (97 cm) in the eastern part of Ellis County to less than 32 inches (81.3 cm) in Bosque County to the west (Larkin and Bomar, 1983). Winter and spring are the wettest months, whereas summer rainfall is low. Average annual temperature increases from north to south from approximately 63°F (17.2°C) along the Red River to approximately 66°F (18.8°C) between Limestone and Bosque Counties (Larkin and Bomar, 1983). Temperature is coldest during January and hottest during August. Average annual gross lake-surface evaporation rate increases from approximately 63 inches (160 cm) in the eastern part of Ellis County to more than 67 inches (170 cm) in Bosque County (Larkin and Bomar, 1983).

PREVIOUS GEOLOGIC STUDIES

The Cretaceous section in the north Texas study area ranges in thickness from a minimum at its eroded outcrop limit to over 7,000 ft (2,134 m) at the Mexia-Talco fault zone in Kaufman and Hunt Counties. The section comprises limestone, shale, sandstone, and siliciclastic mudstone strata of Lower to Upper Cretaceous age. Sandstone-dominated formations compose approximately 25 percent of the Cretaceous section in Kaufman County but compose approximately 100 percent of the section in western extremes of the outcrop belt in Texas where only the basal Cretaceous sandstones are preserved.

This section outlines the stratigraphic relation between the aquifer units and associated confining beds. Formation nomenclature differs between subsurface and equivalent outcropping stratigraphic units and between areas where distinct mappable units merge and where formation boundaries are no longer mappable. Different formation names were often used in the literature for widely separated locations before rock equivalency was recognized. In addition, some intervals are considered formations in areas where lithology is uniform but are raised to group status where they can be subdivided into mappable units.

Cretaceous strata have been divided into the Coahuilan, Comanchean, and Gulfian Series (Galloway and others, 1983; fig. 8). The Coahuilan Series comprises sandstone and mudstone of the Hosston Formation and limestone of the Sligo Formation. The outcrop of the Hosston (lower Twin Mountains Formation) defines the western boundary of the study area and is the westward limit of eastward-dipping Cretaceous deposits in North-Central Texas. The Hosston overlies Paleozoic strata that dip westward toward the Permian Basin area of West Texas. The Sligo limestone is mostly limited to the East Texas basin and pinches out in the subsurface (fig. 3) along the Mexia-Talco fault zone.

The Comanchean Series includes strata of the upper Trinity, Fredericksburg, and Washita Groups. The upper Trinity Group includes limestone and shale of the Pearsall Formation, sandstone and mudstone of the Hensel Formation, limestone and shale of the Glen Rose Formation, and sandstone of the lower Bluff Dale Formation. The Fredericksburg Group includes sandstone of the upper Bluff Dale and Paluxy Formations as well as limestone and shale of the Walnut and Goodland Formations. The Washita Group includes limestone and shale of the Kiamichi, Georgetown, and Del Rio-Grayson Formations and limestone of the Buda Formation. The Georgetown Formation in Central Texas comprises evenly interbedded limestone and marl or shale. However, in the study area in North-Central Texas, the Georgetown equivalent comprises six distinct "members" or formations. Five are up to > 40-ft

(12.2-m) thick shale beds capped by one or more > 20-ft (6.1-m) thick limestone beds. The sixth member, the Paw Paw Formation, contains > 40 ft (12.2 m) of sandstone in the northern part of the study area. The Del Rio Formation in South Texas is equivalent to the Grayson Formation in North Texas. The unit, therefore, is commonly called the Del Rio-Grayson Formation. The Pearsall and Buda Formations pinch out in the subsurface and do not crop out within the study area.

The Gulfian Series includes sandstone and mudstone of the Woodbine Formation; shale of the Eagle Ford Formation; chalk, marl, and sandstone of the Austin Group (including the Austin Chalk); marl, limestone, shale, and sandstone of the Taylor Group; and marl and shale of the Navarro Group.

Trinity Group

(Sycamore, Hosston, Travis Peak, Hensel, Bluff Dale, Twin Mountains, and Antlers Formations)

The Trinity Division was named by Hill (1889) for the Glen Rose Formation and all underlying Cretaceous sandstones (Trinity Sandstone). Although Hill (1894) later included the Paluxy Formation in the Trinity Division, eventually Hill (1937) moved the upper boundary back to the top of the Glen Rose. Hill (1901) used the name Travis Peak for Trinity units underlying the Glen Rose (fig. 3). He further subdivided the Travis Peak and named the two major sandstone units the Sycamore and the Hensel Sandstones. The Hosston Formation has been interpreted to be the subsurface equivalent of the outcropping Sycamore Formation (Stricklin and others, 1971). Hosston and Hensel sandstones merge in the subsurface due to pinchout of intervening limestone and shale of the Sligo and Pearsall Formations. The Hosston and Hensel Formations are indistinguishable in outcrop and are collectively called the Twin Mountains Formation (Fisher and Rhodda, 1966, 1967). Additional descriptions and depositional analyses of Trinity sandstones, as well as for their laterally equivalent carbonate and shale intervals, were given by Stricklin and others (1971).

Boone's (1968) comprehensive study of Trinity sandstones in the southwestern part of the study area included petrologic analyses and interpretation of depositional histories of the component units. More recently, Hall (1976) mapped Hosston, Hensel, and Twin Mountains sandstone in Central Texas and related sandstone distribution patterns to hydrologic and hydrochemical characteristics. Hall (1976) cited fluvial depositional models of Brown and others (1973), and deltaic depositional models of Fisher (1969) to explain facies occurrences and sandstone geometries.

Hill (1891) defined the "Bluff Dale Member of the "Trinity Division" for fine-grained sandstone strata that lay stratigraphically between coarse-grained "Basement Sands" in Somerville and Hood counties, Texas, and overlying limestone of the Glen Rose Formation. Rodgers (1967) interpreted the lower part of the Bluff Dale to be equivalent to the Hensel sandstone and the upper part to be up-dip clastic facies of the lowermost Glen Rose Formation. In Rodgers' (1967, p. 123) cross section, the updip Glen Rose is capped by a thin sandstone interval that is unconformably overlain by Paluxy sandstone. For the present report this thin, unconformity-bounded sandstone is considered to be the upper Bluff Dale.

Paluxy Formation

Hill (1887) named the Paluxy Sand for outcrops along the Paluxy River in Hood and Somerville Counties, Texas. Hill (1937) reinterpreted the stratigraphic position of the Paluxy, removing it from the top of the Trinity Group and assigned it to the base of the Fredericksburg Group. Lozo (1949) concurred with Hill's reinterpretation. Atlee (1962), cited in Owen (1979), and Moore and Martin (1966) interpreted the Paluxy Formation as comprising marine-continental transitional deposits. The Paluxy and Twin Mountains Formations merge in central

Wise County due to the pinchout of the intervening Glen Rose Formation (Fisher and Rhodda, 1966, 1967). The Paluxy and Twin Mountains are indistinguishable in northern outcrops in the study area and are collectively called the Antlers Formation (originally called Antlers Sand by Hill [1893]).

Owen (1979) identified three members of the Paluxy Formation in its outcrop between Burnet and Wise Counties, Texas, on the basis of interpreted depositional environments, petrology, and stratigraphic relations. The three members are the intertidal, regressive, Lake Merritt Member, the braided fluvial-to-subtidal Georges Creek Member, and the meandering-fluvial, intertidal, and subtidal Eagle Mountain Member. Owen (1979) used the name Lake Merritt Member of the Paluxy Formation for a sandstone unit that interfingers with the lower Glen Rose Formation over much of the study area. Owen's (1979) unit probably correlates with the Bluff Dale Formation of Hill (1887), Rodgers (1967), and this report.

Caughey (1977) interpreted sandstone-thickness maps and suggested sands were transported by rivers from source areas north and northeast of Texas and deposited mainly in moderately destructive deltaic barriers and strand plains. Thin sandstones and mudstones west of the fluvial-deltaic deposits were interpreted as strand-plain deposits. Caughey (1977) cited the destructive-deltaic depositional model of Fisher (1969) to explain Paluxy sandstone distribution.

Hendricks (1957) interpreted the Glen Rose-Paluxy contact as being conformable in Erath, Hood, Somerville, and Parker Counties. Owen (1979) concurred that the contact was conformable over most of his study area. Atlee (1962) interpreted the contact in central Texas as being unconformable.

Atlee (1962), Moore and Martin (1966), and Owen (1979) interpreted the contact between the Paluxy and Walnut Formations as unconformable. Interfingering of Walnut and

Paluxy strata in the subsurface, however, indicates that a transitional relationship also exists and suggests that the unconformity between the formations is restricted to updip areas.

Woodbine Formation

Hill (1901) subdivided the Woodbine Formation into Lewisville and Dexter members. Adkins and Lozo (1951) raised the Woodbine interval to group status, subdivided into the Lewisville and Dexter Formations. Dodge (1969) interpreted paralic environments of deposition for the Woodbine Formation on the basis of outcrop studies. Nichols (1964) more generally interpreted continental, neritic, and transitional environments of deposition on the basis of subsurface studies. Cotera (1956) and Lee (1958 [cited in Oliver, 1971]), concluded from petrographic analyses that Woodbine source areas were in the southern Appalachians, the Ouachitas, and the Centerpoint volcanic area in Arkansas.

Oliver (1971) named the Dexter fluvial, Lewisville strand plain, and Freestone delta depositional systems on the basis of a study of well logs. The Dexter fluvial system consisted of dip-aligned tributaries laterally separated by floodplains. Tributaries from the northeast fed a 50- to 75-mi (80- to 121-km) wide meanderbelt that, in turn, fed channel-mouth bars, coastal barriers, and prodelta-shelf areas of a destructive delta system. The Fisher (1969) depositional model for destructive deltaic deposition was used to explain Woodbine sandstone distribution.

PREVIOUS HYDROGEOLOGIC STUDIES

Hill (1901) inventoried wells in the Twin Mountains, Paluxy, and Woodbine aquifers and provided early geologic and hydrologic data, including qualitative data on aquifer performance. George and Barnes (1945) reported results from hydrologic tests on three flowing wells in Waco in McLennan County. Sundstrom (1948) conducted hydrologic tests on water-supply wells in Waxahachie in Ellis County. Leggat (1957) studied the geology and ground-water resources of Tarrant County and reported on declining water levels. Rayner (1959) documented water-level fluctuations from 1930 through 1957 in Bell, McLennan, and Somervell counties. Osburne and Shamburger (1960) discussed brine production from the Woodbine in Navarro County. Baker (1960) studied the geology and ground-water resources of Grayson County. Henningsen (1962) looked at ground-water chemistry in the Hosston and Hensel sands of central Texas, particularly in relation to the Balcones fault zone. Henningsen (1962) interpreted change in water chemistry across the fault zone as perhaps indicating vertical mixing of waters. He also suggested that meteoric water was slowly displacing connate water in the formations to the east, but that pumping of the aquifers might reverse that trend. Bayha (1967) investigated the occurrence and quality of ground water in the Trinity Group and deeper Pennsylvanian formations of Montague County. Thompson (1967) conducted several aquifer tests in Ellis County. Myers (1969) included data from North-Central Texas in his compilation of aquifer tests. Thompson (1972) summarized the hydrogeology of Navarro County.

Klemt and others (1975) constructed a numerical model of ground-water flow to predict future water-level declines in the Hensel and Hosston Formations in Coryell and McClennan Counties. Klemt and others (1975) provided a record of wells, drillers' logs, water levels, and ground-water chemical analyses for the same area upon which the model was based.

Taylor (1976) compiled water-level and water-quality data for most of North-Central Texas. Nordstrom (1982) assessed the occurrence, availability, and chemical quality of ground water in the regional aquifers of North-Central Texas. Macpherson (1983) mapped regional trends in transmissivity and hydraulic conductivity of the Woodbine, Paluxy, and the Hosston/Twin Mountains aquifers. Nordstrom (1987) investigated ground-water resources of the Antlers and Travis Peak Formations of North Central Texas. Rapp (1988) studied recharge in the Trinity aquifer in Central Texas. Baker and others (1990a, 1990b) evaluated water resources in North-Central and Central Texas.

METHODS AND DATA

Stratigraphic Data

To construct the various stratigraphic and structural maps needed to build the numerical model of ground-water flow, data from approximately 1,200 geophysical well logs was compiled from files at the Surface Casing Unit of the Texas Water Commission (TWC) (now the Texas Natural Resources Conservation Commission [TNRCC]). Locations of wells were taken from maps maintained by the TWC. Spontaneous potential (SP) and resistivity logs were used to delineate sandstone intervals and qualitatively indicate water salinity. Fresh-water zones in sandstones were inferred where resistivities >10 ohm corresponded to subdued or inverted SP responses (fig. 8). Salt-water bearing zones in sandstones were interpreted where resistivities of <5 ohm corresponded to well-developed SP responses. Shales or mudstones were interpreted where low resistivities (<5 ohm) corresponded to subdued or flat SP responses. Limestones were interpreted where exceptionally high resistivities (generally >20 ohm) corresponded to subdued but not inverted SP responses (fig. 8).

Cross sections for specific stratigraphic intervals were made to correlate formation boundaries and sandstone intervals between well logs. Formation boundaries then were extended to correlate sandstone intervals in wells near the cross sections. Maps of the structural elevation of formation boundaries and formation and sandstone thicknesses were made once formation boundaries were determined from the well logs.

Hydrologic Data

Data on water levels and hydrologic properties were compiled from Hill (1901), Baker (1960), Thompson (1967), Myers (1969), Thompson (1969), Thompson (1972), Klemt and others (1975), Nordstrom (1982), Nordstrom (1987), and from open and digitized data files of the Texas Water Development Board (TWDB) and TWC/TNRCC.

A total of 22,241 measurements of water levels in North-Central Texas dating from 1899 to 1993 are included in the computerized water-level data base provided by the TWDB. However, the majority of the data was collected since 1960; few water levels were measured from 1901 to 1936 (fig. 9). Hill (1901) provided numerous measurements and qualitative estimates of water levels in the Twin Mountains, Paluxy, and Woodbine aquifers in North-Central Texas. He also reports information about wells and water-levels provided by cities and town officials. Much of this data is anecdotal and qualitative, often only reporting the formation, approximate location, and whether the well flowed or not at land surface. Water-level maps for the Twin Mountains, Paluxy, and Woodbine aquifers were made for the turn of the century using the quantitative and qualitative water-level data from Hill (1901).

In addition to a "pre-development" potentiometric surface drawn on the basis of on Hill's (1901) data, water-level maps were made for 1935, 1955, 1970, and 1990 on the basis of digitized TWDB data. The 1935 water-level map was made by combining water levels collected from 1930 to 1939 because data from any given year in this decade were sparse. The 1955 maps of the potentiometric surfaces are modified from Nordstrom (1982), in which measurements from 1950 to 1959 were combined. Potentiometric surfaces for 1970 and 1990 were derived from the more extensive TWDB data. Seventy-seven wells had 30 or more water-level measurements. Hydrographs for these wells were used for calibrating the transient numerical model.

Hydrologic properties were inferred from records of aquifer (pumping) tests and from specific capacity tests. Hydrologic properties then were mapped for each hydrostratigraphic unit, following Macpherson (1983), using the distribution of sandstone thickness as a contouring guide. Transmissivity of the Twin Mountains, Paluxy, and Woodbine was determined from water-level and pumping-rate data from aquifer tests at 291 wells, for which specific capacity (drawdown at a given pumping rate at a specified time) was also reported. Specific-capacity data alone were recorded at another 1,973 wells. Hydrologic properties for the confining layers were estimated from generally accepted values (table 1).

Specific capacity is related to transmissivity (Thomasson and others, 1960; Theis, 1963; Brown, 1963). Razack and Huntley (1991) showed that the analytical equations usually do not agree with measured transmissivities, however, and that empirical relationships should be used. For this reason, transmissivity was related to specific capacity on the basis of the abundant aquifer-test data for North-Central Texas (table 1), as follows. Specific capacity first was graphed against transmissivity both measured in 291 wells. One end of the regression line was fixed at the origin because where transmissivity is zero, specific capacity is also zero. The slope, m, was determined from the data by minimizing squared residuals. Transmissivity, T, is related to specific capacity, SC, by

$$T = m\,SC \tag{1}$$

The relation between specific capacity and transmissivity for the Twin Mountains, Paluxy, and Woodbine aquifers is shown in figure 10, respectively. The slopes in equation (1) are 0.63 for the Twin Mountains, 0.59 for the Paluxy, and 0.75 for the Woodbine.

A total of 85 storativity measurements were compiled—64 from the Twin Mountains aquifer, 9 from the Paluxy aquifer, and 7 from the Woodbine aquifer.

No measurements of the porosity for the Twin Mountains, Paluxy, and Woodbine aquifers were found. Porosity in the Woodbine and Paluxy Formations has been measured in oil and gas fields east of the Mexia-Talco fault zone (Galloway and others, 1983). These data have a mean porosity of 24.3 percent for the Woodbine and 22.4 percent for the Paluxy (table 2). Bell (1980) reports that the Woodbine Formation in the Kurten field of Brazos County had a porosity of about 25 percent. Porosity for sandstone typically ranges between 5 and 15 percent (Domenico and Schwartz, 1990). Effective porosity of sandstone, however, ranges between 0.5 and 10 percent (Croff and others, 1985). The average effective porosity for the sandstone was set at 5 percent, about in the middle of these values. Porosity for the Glen Rose Formation and Washita and Fredericksburg Groups was set at 16 percent, reflecting the arithmetic mean of limestone and shale porosities. Dutton and others (1994) determined porosity for the Austin Chalk and Ozan Formation using core plugs. Porosity for the Wolfe City and Navarro Formations was set to the value for the Ozan Formation. Porosity for the Eagle Ford Formation was assigned a value common for a shale (Freeze and Cherry, 1978).

Numerical Modeling of Ground-Water Flow

MODFLOW, a block-centered finite-difference computer program (McDonald and Harbaugh, 1988), was used to simulate ground-water flow. The program's governing equation is the three-dimensional, partial differential equation describing transient ground-water flow:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}+W \qquad (2)$$

where x, y, and z are Cartesian coordinates of the system, K_{xx}, K_{yy}, and K_{zz} are hydraulic conductivities in the z, y, and z directions, h is the hydraulic head, S_s is the specific storage, t is time, and W represents sources and sinks as a volumetric flux per unit volume. Convergence criterion for hydraulic head change was set to 0.001 ft (0.0003 m).

MODPATH (Pollock, 1989) was used to find ground-water pathlines and residence times. MODPATH uses two output files from MODFLOW—hydraulic head and cell-by-cell flow—along with porosity data. Ground-water velocity, v, is found by dividing the darcy flux, q, by the effective porosity, n_e

$$v = \frac{q}{n_e} \qquad (3)$$

Cross-Sectional Model

A two-dimensional, steady state, cross-sectional model was used to evaluate boundary conditions, vertical hydraulic conductivities of confining layers, and hydraulic-conductivity distributions in the aquifers. A cross-sectional model has several layers but only one horizontal dimension. For example, the model has numerous horizontal columns one row wide in each layer. A cross-sectional model assumes that all flow is within the plane of the profile (Anderson and Woessner, 1992). Aquifers in the Twin Mountains, Paluxy, and Woodbine Formations were included in the cross-sectional model. The Glen Rose, Fredericksburg, Washita, Eagle Ford, Austin, Taylor, and Navarro stratigraphic units were explicitly included in the cross-sectional model as confining layers with low hydraulic conductivity.

Nordstrom's (1982) cross section C-C′ was used to build the cross-sectional model (fig. 11). This profile generally is oriented along the "pre-development" ground-water flow paths in the Twin Mountains, Paluxy, and Woodbine aquifers. The model extends 111 miles (178 km) from the Trinity Formation outcrop in Parker County, through Tarrant and Dallas Counties, and ends at the Mexia-Talco fault zone in Kaufman County (fig. 11). The model grid consisted of 54 columns, 1 row, and 10 layers (fig. 12). A total of 340 active blocks was used. Columns were all a uniform length of 10,828 ft (3,300 m). The row was 100 ft (30.5 m) in width. The layers were assigned variable thicknesses on the basis of top and bottom elevations shown in figure 11. The vertical height of the section is 8,000 feet (2,438 m). Hydrologic properties were adjusted by trial-and-error comparison of simulated hydraulic heads and water-level measurements reported by Hill (1901). Initial hydrologic parameters are summarized in table 1.

Because the cross-sectional model is shaped like a wedge, three boundaries are assigned: top, bottom, and down-dip boundaries. The general head boundary (GHB) package of MODFLOW (McDonald and Harbaugh, 1988) was used to prescribe the top boundary at a constant hydraulic head. The hydraulic-head value was placed at the mean annual water level of surficial aquifers, which is about 8 ft (2.4 m) below ground surface in the Ellis County area (Dutton and others, 1994). The presence of shallow, hand-dug wells throughout the study area, including the outcrops of aquifers in the Twin Mountains, Paluxy, and Woodbine Formations, indicate that the use of an average water table in surficial unconfined aquifers is reasonable. The GHB boundary simulates recharge and discharge as head-dependent inflow and outflow at the upper boundary. The bottom boundary of the model, which represents the upper surface of Pennsylvanian and Jurassic formations beneath the Cretaceous section, was considered to be impermeable. Various down-dip boundaries at the Mexia-Talco fault zone were tested for the model—no-flow, hydrostatic, and a highly permeable fault zone—to determine which best reproduced hydraulic head.

Three-Dimensional Model

Results and insights from the cross-sectional model were used in a three-dimensional simulation of ground-water flow in the the Twin Mountains, Paluxy, and Woodbine Formations. The layers of a regional confining system were not explicitly included in the three-dimensional model. The model grid represents a 30,600-mi^2 (78,336-km^2) region in North-Central Texas with 95 rows and 89 columns. Uniform row and column widths of 10,560 ft (3217 m) were assigned to all model blocks. This block size allows allocation of pumping within individual counties and allows accurate simulation of drawdown in the vicinity of Dallas and Tarrant

Counties and other parts of the model area. The three principal aquifer units are represented in 3 model layers. Active finite-difference blocks within each layer are circumscribed by outcrop locations and lateral flow boundaries. The Twin Mountains had 5,465 active cells (fig. 13), the Paluxy had 3,969 active cells (fig. 14), and the Woodbine had 2,081 active cells (fig. 15), for a total of 11,515 active cells in the model.

The base of the three-dimensional model overlying Pennsylvanian and Jurassic formations is assumed to be impermeable. Outcrops of the Twin Mountains, Paluxy, and Woodbine aquifers define one set of boundaries for each layer of the model (figs. 13 to 15). No-flow boundaries were used for the northern boundary of the Twin Mountains at the Red River and for the southern boundary, which is aligned along an inferred ground-water flow path in the Twin Mountains. No-flow boundaries also were used for the northern boundary for the Paluxy at the Red River and for the southern boundary where the Paluxy pinches out in Navarro and southern Hill Counties. The northern boundaries of the Paluxy and Twin Mountains at the Red River were treated as no-flow boundaries because ground-water flow paths are assumed to converge or diverge but not pass beneath major river valleys. The GHB package was used to define the boundary at the north side of the Woodbine Formation. The southern boundaries were set well beyond the historic area of influence of the major area of ground-water production in Dallas and Tarrant Counties, so that inaccurate locations of the no-flow boundaries should have only insignificant consequences on model results. A no-flow boundary was used for the southern limit of the Woodbine where it becomes thin near northern McClennan County. The east side was treated as a hydrostatic boundary based on results from the cross-sectional model, as discussed later. The GHB-package was again used to simulate recharge and discharge on the top of the model and to simulate the overlying confining layers.

The confining layers are implicitly simulated by assigning appropriate vertical conductance values to the aquifer layers on the basis of results of the cross-sectional model.

Flow through the confining layers is assumed to be vertical, which is generally true of most aquifer systems and consistent with results of the cross-sectional model. Vertical conductances were assigned based on the hydraulic conductivity and the thickness of the confining layers and aquifers at each block location. The conductance of a layer, C_i, can be described as the hydraulic conductivity in direction i, K_i, divided by the length in direction i, d_i:

$$C_i = \frac{K_i}{d_i} \tag{4}$$

For the conductance term for a confining layer between two aquifers, a harmonic mean must be used to define the conductance term

$$C_z = \frac{1}{\frac{d_k/2}{K_k} + \frac{d_c}{K_c} + \frac{d_{k+1}/2}{K_{k+1}}} \tag{5}$$

where C_z is the conductance in the z direction, d_k is the thickness of the overlying aquifer, d_c is the thickness of the confining layer, d_{k+1} is the thickness of the underlying aquifer, K_k is the hydraulic conductivity of the overlying aquifer, K_c is the hydraulic conductivity of the confining layer, and K_{k+1} is the hydraulic conductivity of the underlying aquifer. The GHB conductance for blocks at the outcrop of aquifers was assigned the vertical hydraulic conductivity of the aquifer units. The conductance term for the GHB needed to be calculated for the overlying confining layers and the underlying aquifer using

$$C_{ghb} = \frac{1}{\frac{d_c}{K_c} + \frac{d_{k+1}/2}{K_{k+1}}} \tag{6}$$

where C_{ghb} is the conductance term for the GHB in the z direction, d_c is the thickness of the overlying confining layers, d_{k+1} is the thickness of the underlying aquifer, K_c is the harmonic mean of the hydraulic conductivities for the overlying confining layers, and K_{k+1} is the hydraulic conductivity of the underlying aquifer.

STRATIGRAPHY

Stratigraphic Occurrences of Sandstone

Cretaceous strata record variations in carbonate and siliciclastic deposition on local and regional scales during an overall rise in relative sea level. This interpretation is based on three observations. First, the vertical sequence of depositional facies within an individual formation suggests deepening of depositional environments on a local scale. For example, basal Trinity and Woodbine sandstone beds are fluvial whereas uppermost beds are more marine. Second, carbonate formations interfinger with and eventually overlap sandstone formations on a regional scale (fig. 3). For example, marine limestones and claystones of the Walnut Formation interfinger with and overlap deltaic sandstones and mudstones of the Paluxy Formation. Third, also on a regional scale, younger Cretaceous carbonate formations generally pinch out farther updip than do older ones, suggesting marine environments progressively reached farther landward (fig. 3). The oldest (Sligo Formation) carbonates pinch out along the eastern margin of the Mexia-Talco fault zone, the stratigraphically higher Glen Rose Formation pinches out in the central part of the study area, and the overlying Georgetown Group is present in positions that would have been landward of the Glen Rose pinchout in Cretaceous paleogeography. The Eagle Ford Formation and Austin Chalk, judging from the thickness of remaining deposits and facies compositions, probably pinched out even farther landward than the Georgetown Group.

The regional landward progression of marine carbonate formations probably was caused by relative sea-level rise during the Cretaceous. The local differences in siliciclastic depositional environments probably reflect short term sea-level change. For example, once all the sediment accommodation space (water depth) in an area was filled, sea-level fall created a sediment bypass surface upon which local disconformities or unconformities formed.

Embayments between the topographically higher bypass surfaces would then become centers of deposition. Similarly, constructive building of deltas during sea-level lowstand would give way to destructive marine processes when sea level rose.

Depositional environments of the Trinity, Paluxy and Woodbine were probably similar in paleogeography. The fluvial-deltaic depositional systems extended along a coastline from Texas to Florida subparallel to the present Gulf Coast (Saucier, 1985; Bebout and others, 1992). North-Central Texas contains the western flank of these depositional systems. The formations are composed of depositional elements typical of fluvial and destructive-deltaic systems (Fisher, 1969). Preceding deposition of the Trinity and Woodbine sands, and probably preceding deposition of Paluxy sands, erosional unconformities were developed during relative sea-level lowstands. Fluvial-dominated constructive components include dip-aligned, stacked sandbodies deposited in distributaries and channel-mouth bars. Destructive marine-dominated facies include aprons of sand deposited on coastal barriers and strandplains oriented perpendicular to dip, giving a generally arcuate to multi-lobate form to the gross deposit (fig. 16). Sand source areas during the early Cretaceous were probably toward the north and northwest, including Paleozoic rocks in the Red River and Arbuckle Mountains and Ouachita Fold Belt (fig. 17).

Description of Aquifer Units and Depositional Systems

The aquifer units in Cretaceous formations may be generalized as being in basal sandstone members of unconformity-bounded sandstone-carbonate couplets (Lozo and Stricklin, 1956). The Hosston-Sligo-Pearsall makes up one couplet and the Hensel/Bluff Dale-Glen Rose, Paluxy-Georgetown, and Woodbine-Eagle Ford make up three others. The limestone and shale couplet top is a local confining bed that restricts vertical movement of groundwater between the sandstones.

The concept of aquifer and confining-bed couplets does not apply where the carbonate and sandstone deposits are laterally instead of vertically adjacent. For example, the Glen Rose Formation limestone pinches out toward the northern and western parts of the study area. The laterally equivalent Bluff Dale Formation sandstone interfingers with the Glen Rose and thickens as the Glen Rose thins. The Antlers Formation, named where Cretaceous sandstone formations crop out, is equivalent to four subsurface sandstone formations (Hosston, Hensel, Bluff Dale, and Paluxy Formations), each of which have laterally equivalent limestone formations. Lack of the low-permeability limestone and shale beds means that resistance to vertical flow between sandstone beds is less within the Antlers Formation than within its equivalent subsurface section.

Trinity Group

Across North-Central and East Texas, the Trinity Group includes two couplets of aquifers and confining beds: (a) Hosston-Sligo-Pearsall and (b) Hensel/Bluff Dale-Glen Rose. Only a thin interval of the Pearsall Formation, however, extends into North-Central Texas so that the Hosston and Hensel Formations are undivided in the most of the study area. Thicknesses of Hosston, Hensel, and lower Bluff Dale sandstones, therefore, are mapped together as Twin Mountains sandstone (fig. 18).

The top of the Twin Mountains Formation dips eastward and dip increases across the Balcones and Mexia-Talco fault zones (fig. 5). Thickness of Trinity sandstone increases from its outcrop to more than 2,000 ft (609.6 m) at the Mexia-Talco fault zone in Kaufman County. In outcrop the Hosston interval is composed of fine- to medium-grained quartz sandstone interbedded with sandy mud and muddy pebbly sandstone. Beds are thin to massive, with cross bedding common in the conglomeratic intervals (Boone, 1968). Composition and grain-size similarities suggest that the probable source for basal Trinity conglomerates in outcrop is the

Triassic-age Dockum Group to the northwest (Boone, 1968). Hensel sandstone is fine to medium-grained and moderately to well sorted. Lenses of muddy conglomerate occur throughout. Beds are commonly cross-bedded to massive, with some laminated sandstone and mudstone (Boone, 1968). Updip equivalents of the Hosston and Hensel sandstones (Twin Mountains Formation) include pebble conglomerates, sandstone, and sandy mudstone (Boone, 1968). Lower Bluff Dale sandstone includes interbedded muddy sandstone and sandy mudstone with thin interbeds of mudstone and limestone (Boone, 1968). Lower Antlers sandstone was a local source for sand in the Hensel and Bluff Dale. This is inferred because the Hensel and Bluff Dale thin and appear to pinch out onto stratigraphically underlying Cretaceous sandstone.

The distribution of sandstone in the Hosston suggests deposition by fluvial-deltaic systems (Hall, 1976). Three areas have more than 400 ft (121.9 m) of sandstone in the Hosston Formation (fig. 18). One center of deposition is in Grayson, Collin, Dallas, and Ellis Counties. There is also more than 250 ft (76.2 m) of Bluff Dale sandstone in this area. Thickness of sandstone abruptly increases within a mile of the Mexia-Talco fault zone and probably indicates that these growth faults were active during Hosston deposition. The second area is in southern Denton and northern Tarrant Counties. The third center of deposition with more than 400 ft (121.9 m) of sandstone is in southern Cooke County.

Paluxy Formation

The Paluxy depositional system was much smaller in extent than the earlier Trinity or later Woodbine depositional systems. Trinity sandstones extend farther south of the study area (Stricklin and others, 1971) and Trinity and Woodbine sandstones are twice as thick as those in the Paluxy. Thickness of the Paluxy Formation along the outcrop ranges from approximately 50 ft (15.2 m) in Coryell County to more than 320 ft (97.5 m) in Hunt County. The Paluxy merges with the underlying Twin Mountains Formation to form the Antlers Formation in Wise County where the Glen Rose pinches out. In the subsurface the Paluxy Formation thins to the south and is replaced by claystone and limestone of the overlying Walnut Formation (fig. 6).

There are two areas where net thickness of Paluxy sandstones is more than 200 ft (60.96 m) (fig. 19). The largest center of deposition is in Hunt and Kaufman Counties; a smaller center of deposition is in Wise and Denton Counties. Lying between the two depositional centers is a belt with as much as 150 to 200 ft (45.7 to 60.96 m) of sandstone. Caughey (1977) interpreted the regional patterns of sandstone thickness as suggesting destructive deltaic processes whereby onshore wind and wave action reworked dip-aligned, fluvially transported sand into strike-aligned coastal barriers.

Woodbine Formation

The top of the Woodbine Formation dips eastward and dip increases across the Balcones and Mexia-Talco fault zones (fig. 7). Thickness of the Woodbine Formation increases from its outcrop to more 800 ft (243.8 m) in Hunt and Kaufman Counties (fig. 20). The Woodbine Formation has been divided into four members in its northern outcrop in Cooke and Grayson Counties: (from oldest to youngest) Dexter, Red Branch, Lewisville, and Templeton Members (McGowen and others, 1972; McGowen and others, 1991). The Woodbine Formation is undivided in its western outcrop south of Denton County (McGowen and others, 1972; McGowen and others, 1991). Oliver (1971) divided the Woodbine Formation into the lower Dexter and the upper Lewisville members. The lower Woodbine comprises mainly fluvial-deltaic sandstone while the upper Woodbine is dominated by strandplain and distal-deltaic sandstones and shelf mudstone. Oliver (1971) used the name "Freestone delta" for deltaic deposits of the Dexter member and "Harris delta" for the deltaic deposits of the Lewisville member.

The Woodbine Formation was deposited upon a regional unconformity that developed during a relative sea-level lowstand, recorded by truncated Buda and Del Rio-Grayson strata (fig. 3). The erosional surface forms a series of west-east-oriented, incised valleys in southwestern Grayson County. There is one major and one minor center of deposition in the Woodbine Formation (fig. 20). More than 400 ft (121.9 m) of Woodbine sandstone lies along the Mexia-Talco fault zone. Rapid lateral changes in net sandstone values along the Mexia-Talco fault zone probably indicates that these growth faults continued active through Woodbine deposition (Barrow, 1953; Oliver 1971). More than 200 ft (60.96 m) of Woodbine sandstone lies in the Sherman syncline in the northwestern corner of the study area (fig. 20), just down dip of the outcrop belt in Cooke, Grayson, Denton, and Collins Counties. Sandstone thickness, however, is much greater than the 70-ft (21.3-m) relief of the incised valleys. Sediment deposition, therefore, continued in this area after the valleys were filled by the basal Woodbine sand.

Lewisville strandplain-mudstone facies in the eastern part of the study area are stratigraphically equivalent to Eagle Ford shelf-mudstone and shale facies. Eagle Ford Formation shale interfingers with and overlies the Woodbine Formation and records progressive deepening of the marine environment, as previously described.

Summary of Aquifer Stratigraphic Framework

- Aquifer units are made up of Cretaceous-age sandstone units that are evenly bedded to cross bedded, moderate to well sorted, very fine- to medium-grained quartzose sandstone.
- Each of the three main aquifers in the Twin Mountains, Paluxy, and Woodbine Formations have dominant centers of deltaic deposition in the eastern and northeastern parts of the study area and subordinate centers of fluvial deposition on the west side.
- The Hosston and Woodbine Formations are underlain by regional unconformities formed by valley incision during emergent periods prior to deposition. These valleys were

filled with sands during initial Hosston and Woodbine deposition. There also are local unconformities at the base of the Hensel and Paluxy Formations.

- The Hosston and the Hensel sandstones extend into southern Texas, whereas the Paluxy and Woodbine sandstones are essentially limited at their southern margins to the study area.
- The dominant structure of the area is that of an eastward descending ramp with two north-trending strike-aligned hinges. The westernmost hinge coincides with the Balcones fault zone; the easternmost hinge coincides with the Mexia-Talco fault zone.
- The sandstone aquifers are locally bounded by mudstone, shale, and limestone and regionally confined by the overlying carbonate-dominated (Comanchean Series) Fredericksburg and Washita Groups and (Gulfian Series) Eagle Ford through Navarro Groups and the underlying Pennsylvanian section.

HYDROGEOLOGY

Hydraulic Head

Predevelopment water levels in the confined aquifers were reportedly near or above land surface and many water wells flowed at land surface at the beginning of the twentieth century (Hill, 1901; Thompson, 1967). A well drilled into the Twin Mountains aquifer in Fort Worth in 1890 had pressure equal to a water level 90 to 100 ft above ground surface. By 1914, many wells had stopped flowing as hydraulic head decreased to beneath ground surface (Leggat, 1957). Rate of decline in ground-water pressure was rapid in the early part of the twentieth century but slowed for a time after WW I as development slowed (Leggat, 1957). For example, the Tucker Hill Experimental Well was drilled into the Paluxy in 1890 in Fort Worth. The water level fell from 90 ft below ground surface in 1890, to 277 ft (84 m) in 1942, and

285 ft (87 m) below ground surface in 1954. Water levels in the Fort Worth area have declined nearly 850 ft (259 m) in the Twin Mountains since the turn of the century (fig. 21a). Water levels have declined approximately 450 ft (137 m) in the Paluxy aquifer near Fort Worth (fig. 21b) and approximately 400 ft (123 m) in the Woodbine aquifer near Dallas (fig. 21c). Water levels in the Paluxy suggest either short-term recovery or a decrease in rate of decline since 1976 (fig. 21b), perhaps because municipalities have turned to surface-water sources. Figure 22 illustrates ranges of pumping rates by county in 1990.

Direction of ground-water flow before ground-water development is inferred to have been to the southeast (Nordstrom, 1982). Figures 23a, 24a, and 25a show estimated potentiometric surfaces for 1900, based on both quantitative and qualitative water-level data of Hill (1901). Because early-1900 data are sparse and because the regional aquifers already were heavily pumped, synoptic water-level measurements are inadequate for mapping a predevelopment potentiometric surface of the aquifers.

Figures 23b, 24b, and 25b show 1990 water-level elevations for the Twin Mountains, Paluxy, and Woodbine aquifers. Hydraulic-head decline has resulted in a regional depression of the potentiometric surface centered in the Twin Mountains and Paluxy aquifers (fig. 23b and 24b) in the Dallas–Fort Worth metropolitan area (Nordstrom, 1982). The regional depression affects direction of ground-water flow throughout North-Central Texas. Under present conditions the direction of ground-water flow in the Twin Mountains aquifer inferred from the potentiometric surface, for example, in Ellis County (fig. 23b), actually is northwestward toward the Dallas–Fort Worth area.

Hydrologic Properties

Transmissivity has a log-normal distribution for the Twin Mountains, Paluxy, and Woodbine aquifers (fig. 26). Geometric means of transmissivity were 437 ft^2/d (40 m^2/d) for the

Twin Mountains, 251 ft^2/d (23 m^2/d) for the Paluxy, and 316 ft^2/d (29 m^2/d) for the Woodbine. Table 3 compares geometric means of transmissivities calculated from aquifer tests and from specific capacity. Transmissivities determined from aquifer tests generally had a higher geometric mean but a much smaller sample size than transmissivities determined from specific-capacity tests. Vertical hydraulic conductivities of aquifer units in the cross sectional model were set at ten times less than the horizontal hydraulic conductivity values (table 1).

Direct measurement of hydrogeologic properties for confining layers is uncommon. Horizontal hydraulic conductivity of the Austin Chalk was determined from packer tests in Ellis County (Dutton and others, 1994). Horizontal hydraulic conductivity of the Taylor Marl was determined from packer tests and model calibration of a cross-sectional model in Ellis County (Mace, 1993, Dutton and others, 1994). Porosities of the Austin Chalk and Taylor Marl were determined from core plugs (Dutton and others, 1994). Vertical hydraulic conductivities of the Austin and Taylor were assumed to be 100 times less than the horizontal hydraulic conductivity. Vertical and horizontal hydraulic conductivities and porosity of the Navarro Group were assumed to be the same as those of the Taylor Group, which is similar in composition. Hydraulic conductivity and porosity of Eagle Ford Shale was assumed to be typical of shales (Freeze and Cherry, 1979). Vertical hydraulic conductivity was assumed to be 100 times less than horizontal hydraulic conductivity.

Hydrologic parameters for the Washita and Fredericksburg Groups and Glen Rose Formation were not found. Properties of these hydrologic units were estimated on the basis of rock type. These units are composed of approximately 40 percent shale and 60 percent limestone, as indicated by resistivity well logs located along the cross section. The geometric means of the shale and limestone permeabilities were used. A typical value of hydraulic conductivity for shale is 10^{-6} ft/d ($10^{-6.5}$ m/d) and a typical value of hydraulic conductivity for limestone is 10^{-2} ft/d ($10^{-2.5}$ m/d) (Freeze and Cherry, 1979). The arithmetic mean of horizontal hydraulic conductivity, K_a, between two formations is given by

$$K_g = \frac{K_l L_l + K_s L_s}{L} \tag{7}$$

where L is total thickness of the formations (1.0), L_l is the thickness of the limestone (0.6), L_s is the length of the shale (0.4), K_l is the hydraulic conductivity of limestone, and K_s is the hydraulic conductivity of shale. The arithmetic mean used for horizontal hydraulic conductivity of the Washita, Fredericksburg, and Glen Rose confining layer was $10^{-2.22}$ ft/d ($10^{-2.74}$ m/d).

The geometric mean (calculated as average of logarithm of data) of vertical hydraulic conductivities of shale and limestone, 10^{-8} and 10^{-4} ft/d ($10^{-8.5}$ and $10^{-4.5}$ m/d), respectively, was determined from

$$K_h = \frac{L}{\frac{L_l}{K_l} + \frac{L_s}{K_s}} \tag{8}$$

where K_h is the geometric mean of hydraulic conductivity. The geometric mean used for vertical hydraulic conductivity of the Washita, Fredericksburg, and Glen Rose confining layer was $10^{-7.60}$ ft/d ($10^{-8.1}$ m/d). A geometric mean for porosity was used on the assumption that only cross-formational flow would occur through the Washita, Fredericksburg, and Glen Rose confining layer.

Storativity is the volume of water released per unit volume aquifer per unit drop in hydraulic head, and is a function of porosity, aquifer elasticity, and water compressibility. These parameters were assumed to be constant in time. Mean storativities were $10^{-3.88}$ for the Woodbine, $10^{-3.73}$ for the Paluxy, and $10^{-3.49}$ for the Twin Mountains (table 4). The distribution of storativity in the Twin Mountains aquifer is possibly bimodal (fig. 27). Most data come from the confined part of the regional aquifer where storativity is small ($<10^{-3}$). Higher values reflect semi-unconfined to unconfined conditions (Kruseman and de Ridder, 1976) nearer to the aquifer outcrop. Storativity values for unconfined aquifers are much larger and close to the porosity values because water is added to or removed from storage by change in the water content of pores. In confined conditions, pores remain fully wet and water moves into or out of storage by change of water pressure, compression of water, and expansion of the aquifer. Storativity values for semi-confined and semi-unconfined aquifers can represent a combination of compression and drainage and thus lie between storativity values for confined and unconfined aquifers.

DISCUSSION

Recharge

The Twin Mountains, Paluxy, and Woodbine aquifers are recharged by precipitation over their outcrops. Thompson (1967) estimated recharge on the sandy parts of the Trinity Group outcrop to be 0.5 in/yr (1.3 cm/yr). Klemt and others (1975) assumed recharge for the Twin Mountains aquifer to be 1.2 in/yr (3 cm/yr), which is about three percent of mean annual rainfall. Nordstrom (1982) suggested that recharge on the northern Twin Mountains and Paluxy outcrops (Antlers Formation [fig. 3]) amounted to less than 1 in/yr (2.5 cm/yr). Klemt and others (1975) estimated recharge on the Paluxy outcrop to be 0.13 in/yr (0.33 cm/yr) and recharge on the Woodbine outcrop to be 0.3 in/yr (0.76 cm/yr), less than 1 percent of mean annual rainfall. Water moves into the subsurface beneath overlying confining beds. The aquifers are defined as confined when hydraulic head exceeds the elevation of the top of the aquifers.

Discharge

Discharge occurs by pumping at water-supply wells, cross-formational flow in the subsurface, and possibly by spring discharge in the vicinity of faults. County-wide ground-water pumping ranged from a low of 101 acre-ft to a high of 3,328 acre-ft (124,582 to 4,105,047 m^3) in 1990 (fig. 22). Ground-water pumping for 1990 in Ellis County alone was 2,609 acre-ft (3,218,169 m^3). Cross-formational flow is limited by hydraulic-head gradients between aquifers and by vertical hydraulic conductivity of confining layers. Comparison of water levels measured in 1976 (Nordstrom, 1982) suggests that the cross-formational flow component is directed downward between aquifers in the Woodbine and Twin Mountains Formations in the Ellis County area.

The ultimate fate of recharged waters in the Twin Mountains, Paluxy, and Woodbine is poorly known. Baker and others (1990) stated that discharge in the aquifer outcrops occurs naturally by springs and evapotranspiration and artificially by pumping. Klemt and others (1975) stated that discharge from the Twin Mountains was through cross-formational flow and along faults that connect the confined aquifer to ground surface, such as in the Mexia-Talco fault zone. In addition, deep flow in the aquifers might pass down dip beyond the Mexia-Talco fault zone into the East Texas Basin. The avenue of discharge is important because it determines the boundary for the numerical model. Unfortunately, there are few water wells near the Mexia-Talco fault zone on which to base hydrologic assumptions, due to increased salinities in the eastern portions of the aquifers.

Flow Velocity

Ground-water flow rates in the Twin Mountains aquifer have been estimated to be 1 to 2 ft/yr (0.3 to 0.6 m/yr) in the northern part of the study area (Antlers Formation) but 10 to 40 ft/yr (3 to 12 m/yr) regionally (Baker, 1960; Thompson, 1967). No estimated flow rate was found for the Paluxy Formation. Estimates of ground-water flow rates in the Woodbine have ranged from 6 to 40 ft/yr (1.8 to 12 m/yr) (Thompson, 1972) to 15 ft/yr (4.6 m/yr) (Baker, 1960).

These velocity estimates suggest that the age of ground water in the regional aquifer system is between approximately 8,000 and 40,000 yr, from west to east across Ellis County.

Simulation of Ground-Water Flow

Cross-Sectional Model

The goal of applying a cross-sectional model of regional ground-water flow with was to

- determine the nature of the down-dip boundary at the Mexia-Talco fault zone,
- estimate vertical conductances of the confining layers,
- evaluate hydraulic conductivity distributions, and
- estimate ground-water velocity and travel time between points of interest.

The cross-sectional model explicitly included the Twin Mountains, Paluxy, and Woodbine aquifers as well as the confining layers in the Glen Rose, Fredericksburg, Washita, Eagle Ford, Austin, Taylor, and Navarro Groups. The model was run as a steady-state simulation.

Calibration

Data available for calibration were hydraulic heads from maps of the 1900 potentiometric surface (figs. 23a, 24a, and 25a). Hydraulic heads calculated by the model were compared to hydraulic heads along the cross section. A FORTRAN program extracted hydraulic heads from specific model blocks, compared their values to measured values, and calculated mean absolute errors for the Twin Mountains, Paluxy, and Woodbine aquifers and for the combined system.

First, the affect of the down-dip boundary on the model was assessed. Three types of boundary scenarios were attempted for the down-dip side of the model: (1) no-flow boundary,

(2) specified head boundary assuming hydrostatic conditions, and (3) a no-flow boundary with a column of high vertical hydraulic conductivity.

The no-flow boundary at the down-dip side of the model with the initial parameters listed in table 1 was found to be unrealistic. This boundary caused ground water to flow up-dip in the aquifer formations. The potentiometric surface maps clearly show that ground water flows down-dip in all the aquifer units. The direction of ground-water flow was corrected by increasing the vertical hydraulic conductivity of the confining layers in the model. To match the inferred direction of flow, however, values of vertical hydraulic conductivity of the confining layers had to be nearly the same as those of the aquifers.

A specified head boundary assuming hydrostatic pressure allowed simulated flow in the down-dip direction with the initial hydrogeologic properties shown in table 1. Predicted hydraulic heads were also on the order of the earliest recorded values early in the century, but the agreement was not close enough to be an acceptable match.

As a third boundary condition, a vertical zone of enhanced permeability, representing a fault zone, was placed in the model. Hydraulic conductivities were slightly adjusted to obtain the best fit. The conductance term in the GHB-boundary blocks was increased and decreased to effect recharge rate into the aquifers.

Distributed hydraulic conductivities were also used in the model to attain a better fit to the measured data. Hydraulic conductivity was distributed in the aquifer units on the basis of maps from Macpherson (1983). Net sand maps for the aquifers were used to extend Macpherson's (1983) hydraulic conductivity maps through the domain of the model.

Results

Results of the cross sectional model with distributed permeability in the aquifer units offered the best fit to the pre-development potentiometric surface. The specified head boundary and fault zone models both provided reasonable head matches. Both of these boundaries remove water from the system. The no-flow boundary did not result in a good match with hydraulic head if reasonable values were used for vertical hydraulic conductivity. These results suggest that water might be moving through the formations and discharging at or near the down-dip boundary of the aquifers in the vicinity of the Mexia-Talco fault zone. The exact mechanism is not known and needs to be investigated, perhaps by analyzing oil well data from the area or using hydrogeochemical methods.

The cross sectional model with distributed permeability and a specified head boundary at the down-dip end of the model gave a good fit with the pre-development potentiometric surface. Predicted heads in the Twin Mountains (fig. 28a) had a mean absolute error of 25.1 ft (7.7 m). Predicted heads in the Paluxy (fig. 28b) had a mean absolute error of 17.5 ft (5.3 m) and predicted heads in the Woodbine (fig. 28c) had a mean absolute error of 11.9 ft (3.6 m). Mean absolute error for all aquifers was 18.7 ft (5.7 m). Some hydraulic conductivities needed to be adjusted in order to reproduce hydraulic head in the formations. Figure 29 shows initial and the calibrated hydraulic conductivity distributions for the Woodbine, Paluxy and Twin Mountains Formations. Hydraulic-conductivity distribution in the Twin Mountains was modified from the hydraulic conductivity distribution determined by Macpherson (1983) in order to match observed hydraulic heads. The calibrated trend in hydraulic conductivity, lower to higher values, was reversed from the initial trend. Average hydraulic conductivity for the calibrated model was 30 percent higher than the initial values. A minor change in the hydraulic conductivity near the outcrop of the Paluxy was needed for the best match. The hydraulic conductivity in the Woodbine was not adjusted. These differences may indicate that ground-water flow may not be moving entirely within the plane of the model. Also, the cross section of the model passes through small areas of low hydraulic conductivity in the Twin

Mountains Formation. Hydraulic head in these areas may be different than the values used for calibration.

Ground-water flow velocities in the aquifers were determined by taking output from MODPATH and dividing travel time by travel distance for each cell of the model. Velocities change through the aquifer due to changes in the hydraulic gradient and hydraulic conductivities. Ground-water velocity in the Twin Mountains increases from 20 to about 90 ft/yr (6.1 to about 27.4 m/yr) and then decreases again to 20 ft/yr (6.1 m/yr) with a mean velocity of 52.5 ft/yr (16 m/yr) (fig. 30a). Ground-water velocity in the Paluxy decreases along the flow path from 100 to 30 ft/yr (30 to 9 m/yr) with a mean velocity of 55.6 ft/yr (17.0 m/yr) (fig. 30b). Ground-water velocity in the Woodbine is relatively constant with a mean velocity of 11.4 ft/yr (3.5 m/yr) (fig. 30c). Ground-water flow rates in the Paluxy and Twin Mountains are nearly the same, increasing near the down-dip boundary of the model. Travel times show that ground-water flow in the Paluxy and Twin Mountains is much faster than that in the Woodbine (fig. 31).

Recharge rates predicted by the numerical model are 0.11 in/yr (0.28 cm/yr) for the Twin Mountains, 0.25 in/yr (0.64 cm/yr) for the Paluxy, and 0.017 in/yr (0.04 cm/yr) for the Woodbine.

The potential for cross-formational flow can be investigated by comparing hydraulic head between the formations. A plot of pre-development hydraulic head along the cross section shows potential for cross-formational flow from the Paluxy down-dip to the Twin Mountains and suggests that no flow occurs between the Paluxy and Woodbine (fig. 32). The numerical model shows similar conclusions except that farther down dip in the aquifer, the potential for cross-formational flow may reverse—from Twin Mountains to Paluxy (fig. 32). It again appears there is no cross-formational flow between the Woodbine and Paluxy.

Summary of Aquifer Hydrologic Framework

- Water levels in regional aquifers in North-Central Texas have declined during the twentieth century because rate of pumping of ground water exceeded recharge rates. Total decline in the Dallas and Tarrant Counties area has been as much as 850 ft (259 m) in the Twin Mountains Formation, 450 ft (137 m) in the Paluxy, and approximately 400 ft (123 m) in the Woodbine Formation.
- The drawdown of the potentiometric surfaces has been regionally extensive, affecting the aquifers throughout most of North-Central Texas. Comparison of 1976 (Nordstrom, 1982) and 1990 potentiometric surfaces shows that hydraulic-head drawdown in each aquifer unit has continued to increase.
- Transmissivity estimates added to results of previous studies with additional data from specific capacity and aquifer-test results. Geometric means of transmissivity were estimated as 437 ft^2/d (40 m^2/d) for the Twin Mountains, 251 ft^2/d (23 m^2/d) for the Paluxy, and 316 ft^2/d (29 m^2/d) for the Woodbine. Mean storativities were $10^{-3.88}$ for the Woodbine, $10^{-3.73}$ for the Paluxy, and $10^{-3.49}$ for the Twin Mountains.
- A cross-sectional model of ground-water flow was used to evaluate boundary conditions and the hydrologic properties of confining layers. The cross-sectional model suggests that ground water exits the aquifers through the Mexia-Talco fault zone. Once in the fault zone, the water probably discharges from springs in river valleys at land surface. The model shows that cross-formational flow between the aquifers is not an important control on ground-water movement compared to the discharge through the fault zone.
- Confining layers consist of the Washita and Fredericksburg Groups and Glen Rose, Pearsall, and Sligo Formations, which lie within the regional aquifer system, and the Eagle Ford Formation, Austin Chalk, and Taylor Group, which overlie the regional

aquifer system. The geometric mean of vertical hydraulic conductivity in the Washita, Fredericksburg, and Glen Rose confining layer was estimated to be $10^{-7.60}$ ft/d ($10^{-8.1}$ m/d) on the basis of thicknesses of shale and limestone.

- Previous studies (Thompson, 1967; Klemt and others, 1975; Nordstrom, 1982) estimated a range of recharge rates for the aquifers: 0.13 to 1.2 in/yr (0.33 to 3 cm/yr). Recharge rates predicted by the cross-sectional numerical model are 0.11 in/yr (0.28 cm/yr) for the Twin Mountains, 0.25 in/yr (0.64 cm/yr) for the Paluxy, and 0.017 in/yr (0.04 cm/yr) for the Woodbine.
- Average ground-water velocities in the Twin Mountains (52.5 ft/yr [16 m/yr]) and Paluxy (55.6 ft/yr [17.0 m/yr]) are much faster than that in the Woodbine (11.4 ft/yr [3.5 m/yr]).

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Table 1. Initial hydrologic parameters used in model.

Formation	Composition	Horizontal hydraulic conductivity (ft/day)	Vertical hydraulic conductivity (ft/day)	Porosity
Navarro	shale	$10^{-5.49}$	$10^{-7.49}$	0.35
Taylor	shale	$10^{-5.49}$	$10^{-7.49}$	0.35
Austin	chalk	$10^{-4.24}$	$10^{-6.24}$	0.27
Eagle Ford	shale	$10^{-6.00}$	$10^{-8.00}$	0.10
Woodbine	sandstone	$10^{+0.63}$	$10^{-0.37}$	0.05
Washita	shale & limestone	$10^{-2.22}$	$10^{-7.60}$	0.16
Fredricksburg	shale & limestone	$10^{-2.22}$	$10^{-7.60}$	0.16
Paluxy	sandstone	$10^{+0.75}$	$10^{-0.25}$	0.05
Glen Rose	shale & limestone	$10^{-2.22}$	$10^{-7.60}$	0.16
Twin Mountains	sandstone	$10^{+0.80}$	$10^{-0.20}$	0.05

Table 2. Porosities in Woodbine and Paluxy Formations in oil and gas fields east of the Mexia-Talco fault zone (data from Galloway and others (1983)

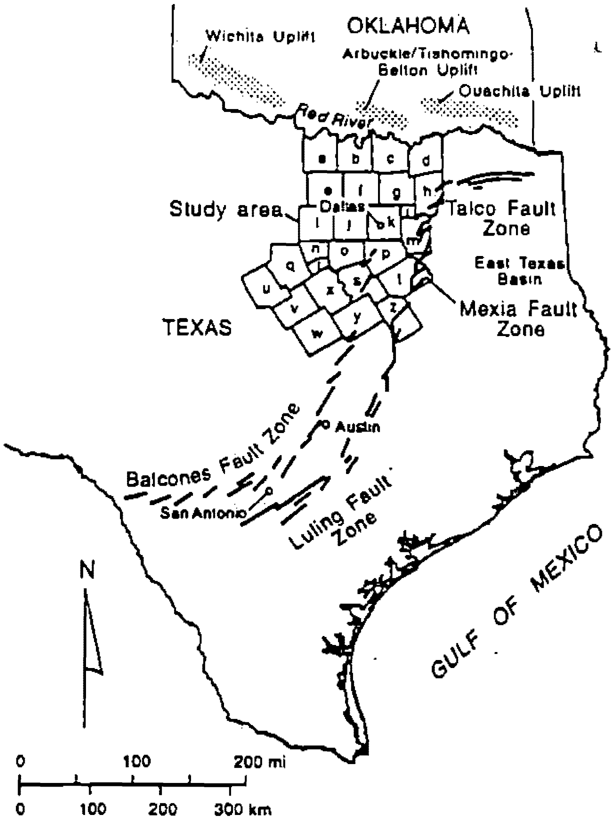
Aquifer	Region of Texas	Field and reservoir	Porosity (%)
Woodbine	East	East Texas	25
	East	Kurten	15
	East	New Diana	26
	North-Central	Cayuga	25
	North-Central	Hawkins	26
	North-Central	Long Lake	25
	North-Central	Neches	25
	North-Central	Van	29
	North-Central	Mexia	25
	North-Central	Wortham	22
Paluxy	North-East	Pewitt Ranch	24
	North-East	Sulphur Bluff	25
	North-East	Talco	26
	East	Coke	22
	East	Hitts Lake	22
	East	Manziel	20
	East	Quitman	22
	East	Sand Flat	18

Table 3. Comparison of transmissivities from aquifer tests and from specific capacity tests. Values are the log of the transmissivity in ft^2/day.

	Woodbine	**Paluxy**	**Trinity**
Aquifer tests			
Mean	2.60	2.79	2.91
St. Dev.	0.45	0.27	0.33
Min	1.65	2.23	1.38
Max	3.55	3.27	3.60
Number of tests	36	35	205
Specific capacities			
Mean	2.49	2.37	2.59
St. Dev.	0.54	0.43	0.53
Min	0.89	0.74	0.48
Max	3.68	3.46	4.11
Number of tests	236	375	1,067
Combined			
Mean	2.50	2.40	2.64
St. Dev.	0.53	0.47	0.51

Table 4. Comparison of storativity (logarithm) from aquifer tests.

	Woodbine	Paluxy	Trinity
Storativity			
Mean	-3.88	-3.73	-3.49
St. Dev.	0.49	0.81	1.07
Min	-4.70	-4.40	-4.70
Max	-3.13	-1.72	-0.89
Number of tests	7	9	63



County names

a	Montague	n	Hood
b	Cooke	o	Johnson
c	Grayson	p	Ellis
d	Fannin	q	Erath
e	Wise	r	Somervell
f	Denton	s	Hill
g	Collin	t	Navarro
h	Hunt	u	Comache
i	Parker	v	Hamilton
j	Tarrant	w	Bosque
k	Dallas	x	Coryell
l	Rockwall	y	Mc Lennan
m	Kaufman	z	Limestone

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Figure 1. Location of study area in North-Central Texas.

Era	System	Series	Group	Stratigraphic Unit	
Cenozoic	Quaternary	Holocene		Alluvium	
		Pleistocene		Fluviatile terrace deposits	
Mesozoic	Cretaceous	Gulf	Taylor	Wolfe City Formation Ozan Formation "lower Taylor Marl"	
			Austin	Austin Chalk	
			Eagle Ford	Eagle Ford Shale Formation	
			Woodbine	undifferentiated	
		Comanche	Washita	undifferentiated	
			Fredericksburg	undifferentiated	
					Paluxy Formation
			Trinity	Antlers Formation	Glen Rose Formation
					Twin Mountains Formation

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Figure 2. Major stratigraphic units in North-Central Texas.

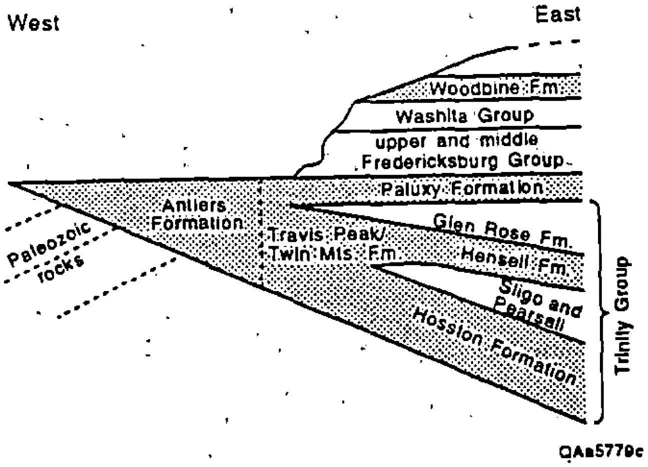

Figure 3. Schematic relationship between stratigraphic units in an east-west cross section. Sandstone-dominated intervals are stippled. Unconformity beneath the Hosston Formation is referred to as the Wichita Paleoplain. No scale.

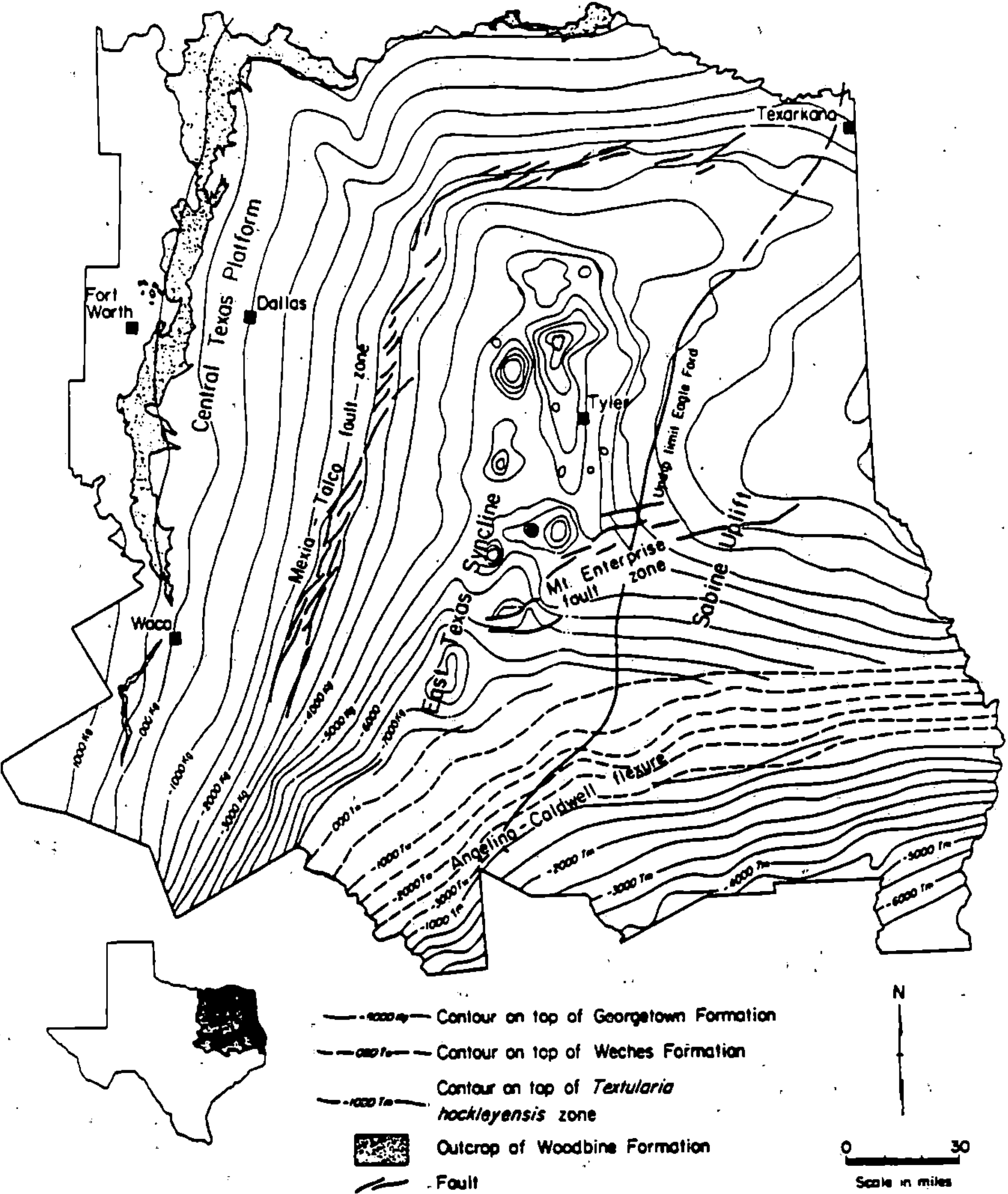

Figure 4. Major structural features and paleogeographic elements of the study area and East Texas basin. Study area is within the Central Texas Platform and extends to the west of the map boundaries. The Sabine Uplift developed during deposition of the upper part of the Woodbine Formation. Also shown is the Woodbine Formation outcrop belt. Modified from Oliver (1971).

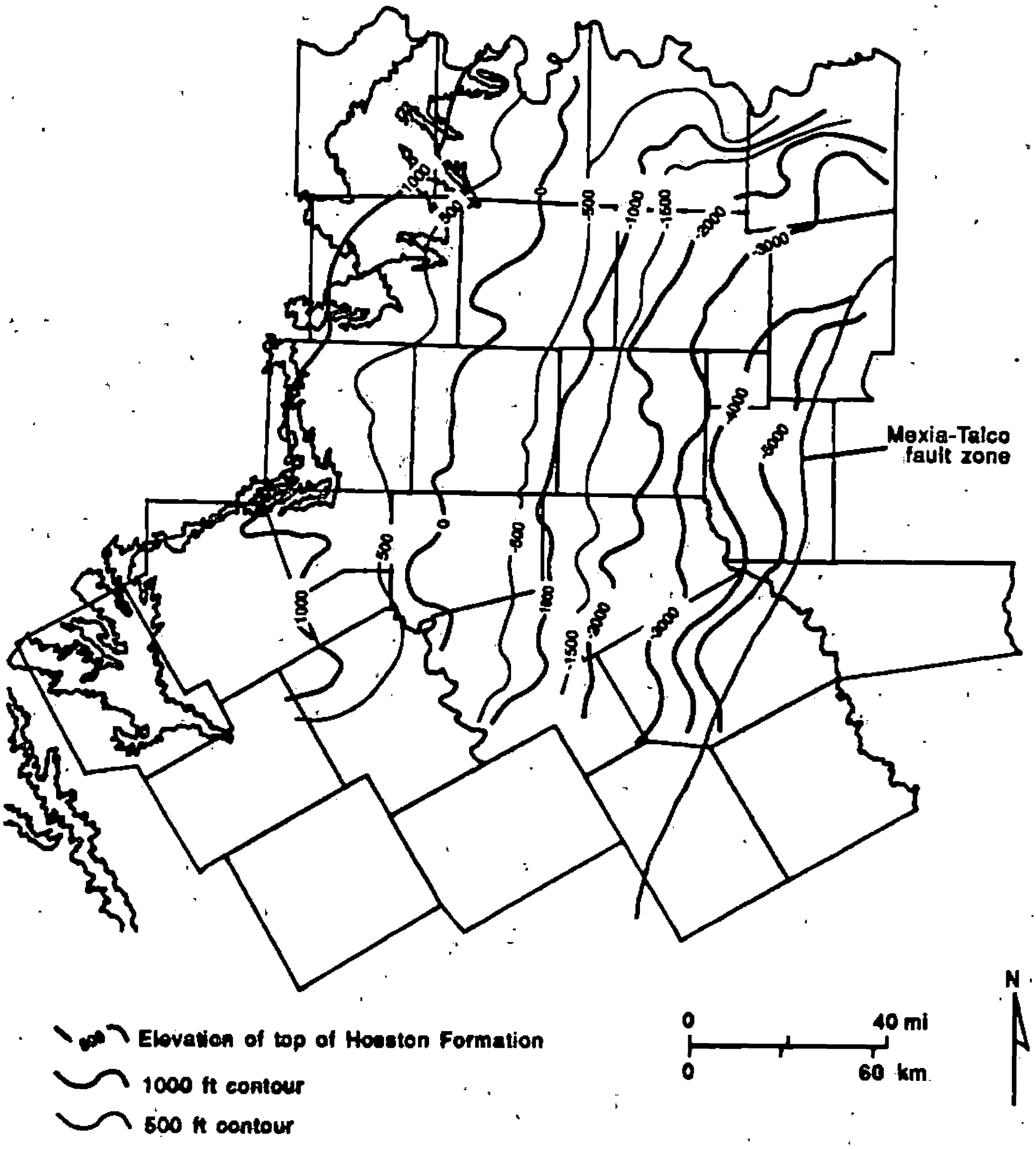

Figure 5. Elevation of the top of the Hosston Formation. Westward excursions of contours from average trends (for example, in Wise and Denton Counties) may result from incised valley at top of the Trinity Group. Contour interval increases from 500 to 1,000 ft along the north-south trending Balcones fault zone (see fig. 4).

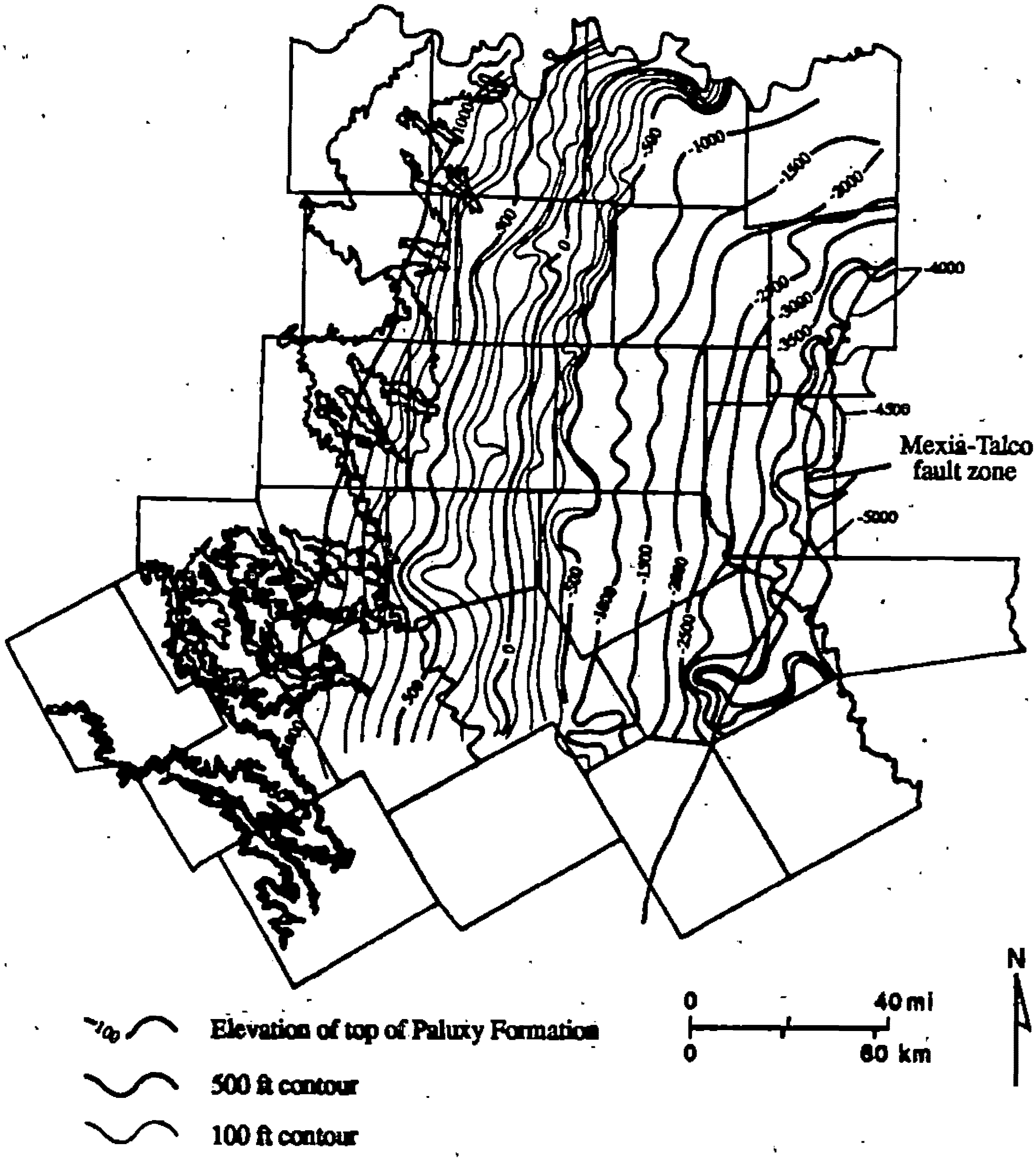

Figure 6. Elevation of the top of the Paluxy Formation. Contour interval increases from 100 to 500 ft along the north-south trending Balcones fault zone (see fig. 4).

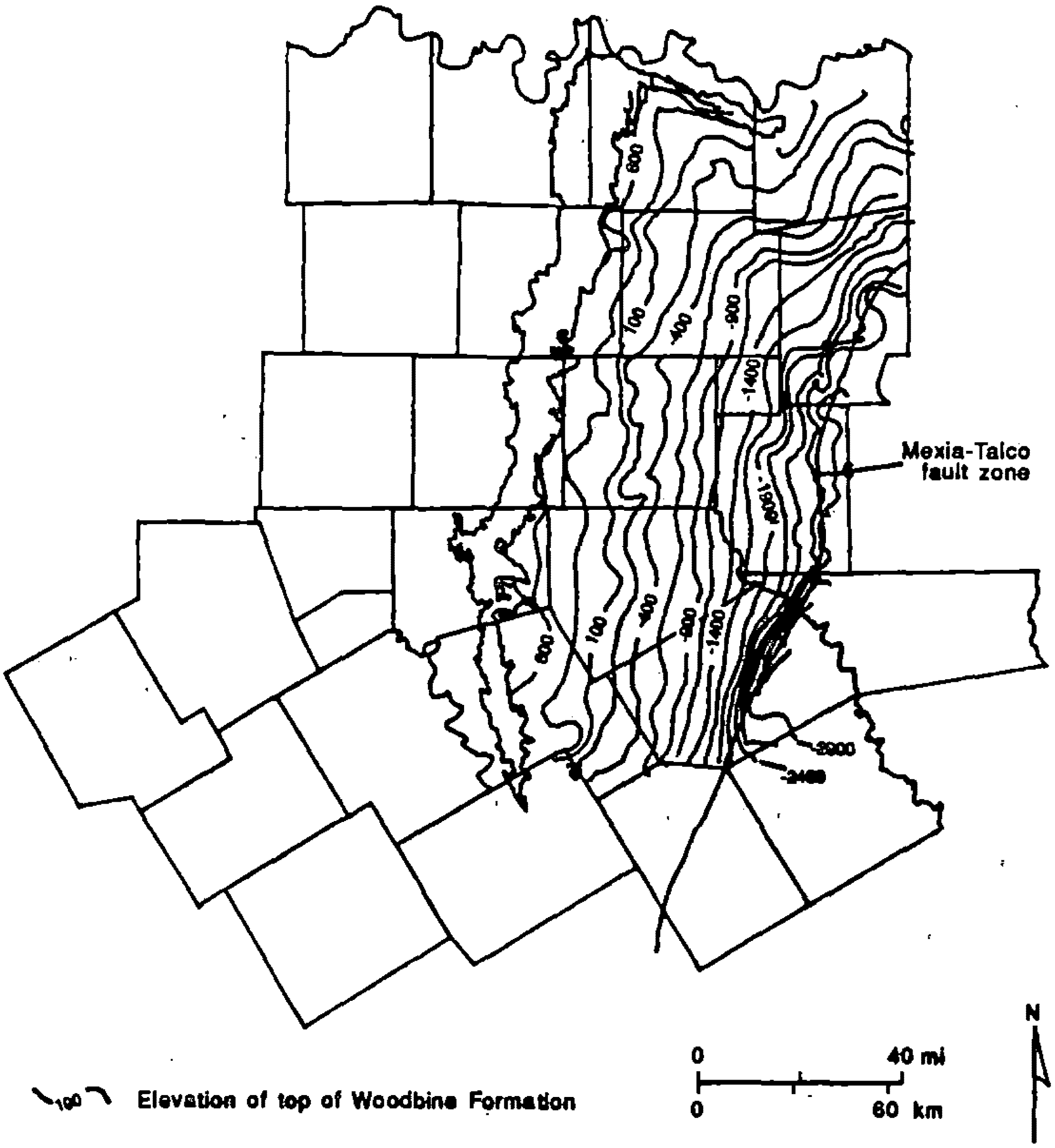

Figure 7. Elevation of the top of the Woodbine Formation. The Sherman and central Fannin County synclines are in the northern and northeast parts of the area.

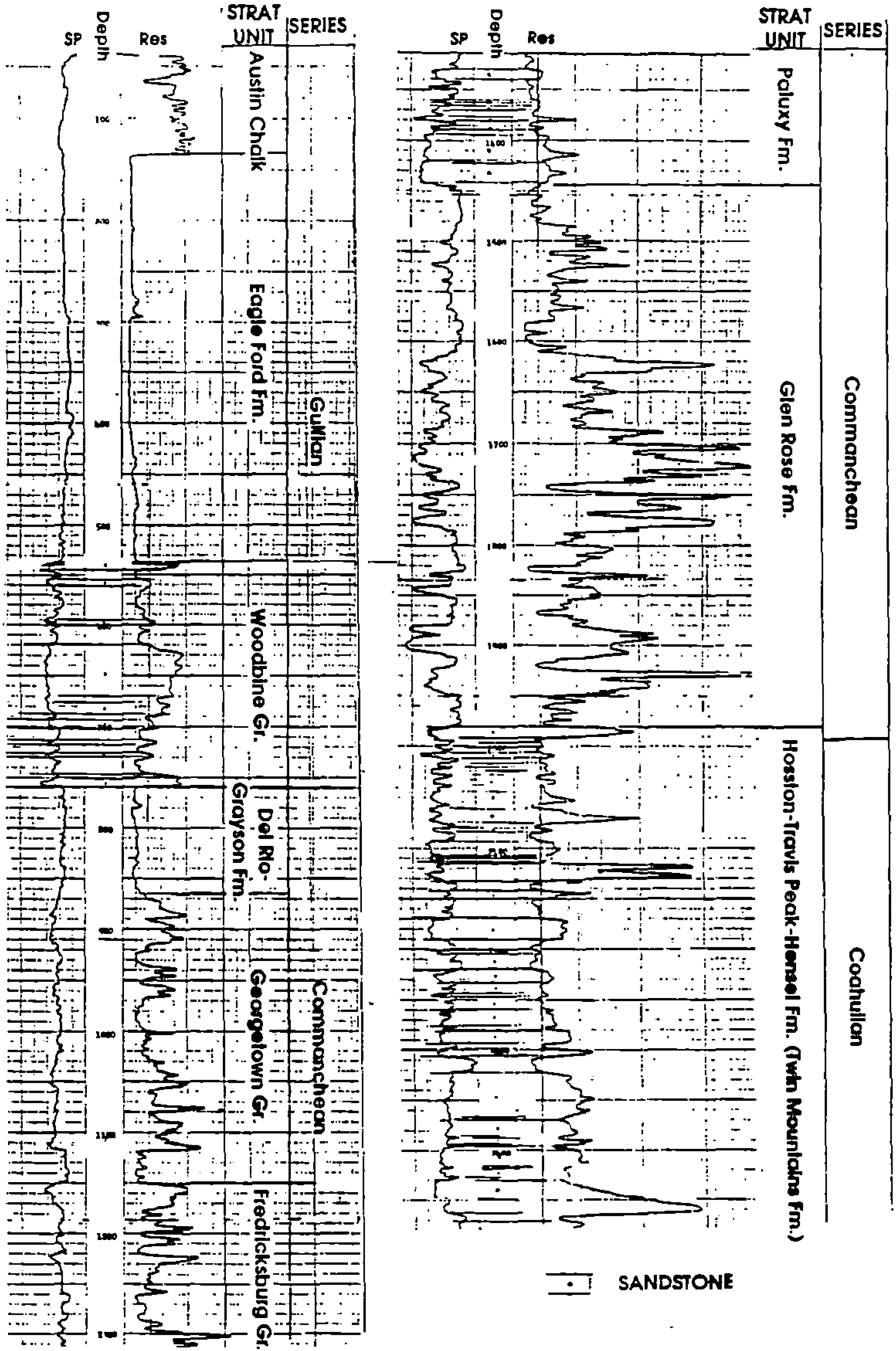

Figure 8. Typical spontaneous potential-resistivity log, showing typical well-log responses for stratigraphic units. Meadows-Hi View Ranch No. 1 well located near Midlothian, Texas.

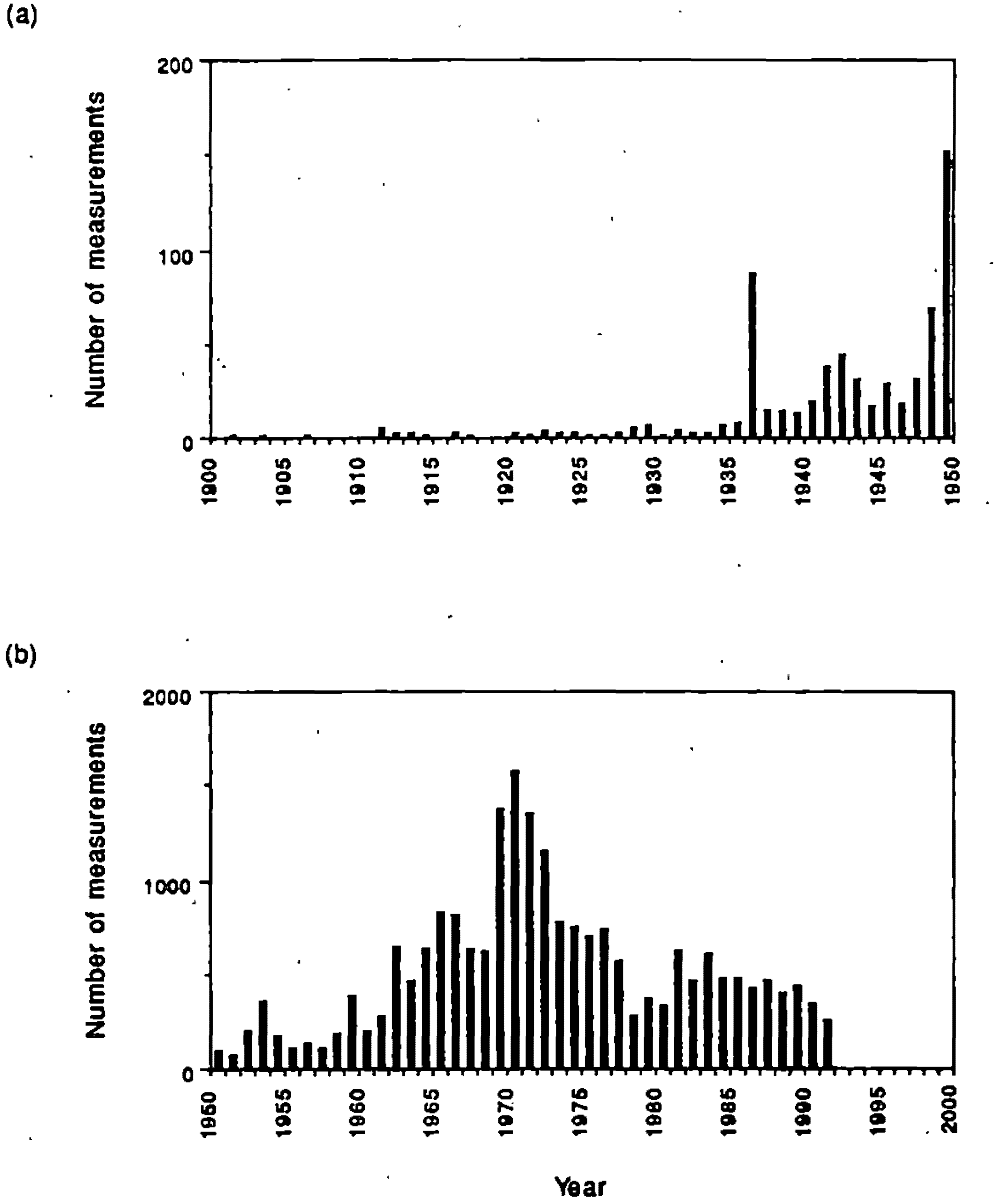

Figure 9. Histogram of water-level measurements made in the study area from (a) 1901 to 1950 and (b) 1951 through 1992. Note different vertical scales in (a) and (b).

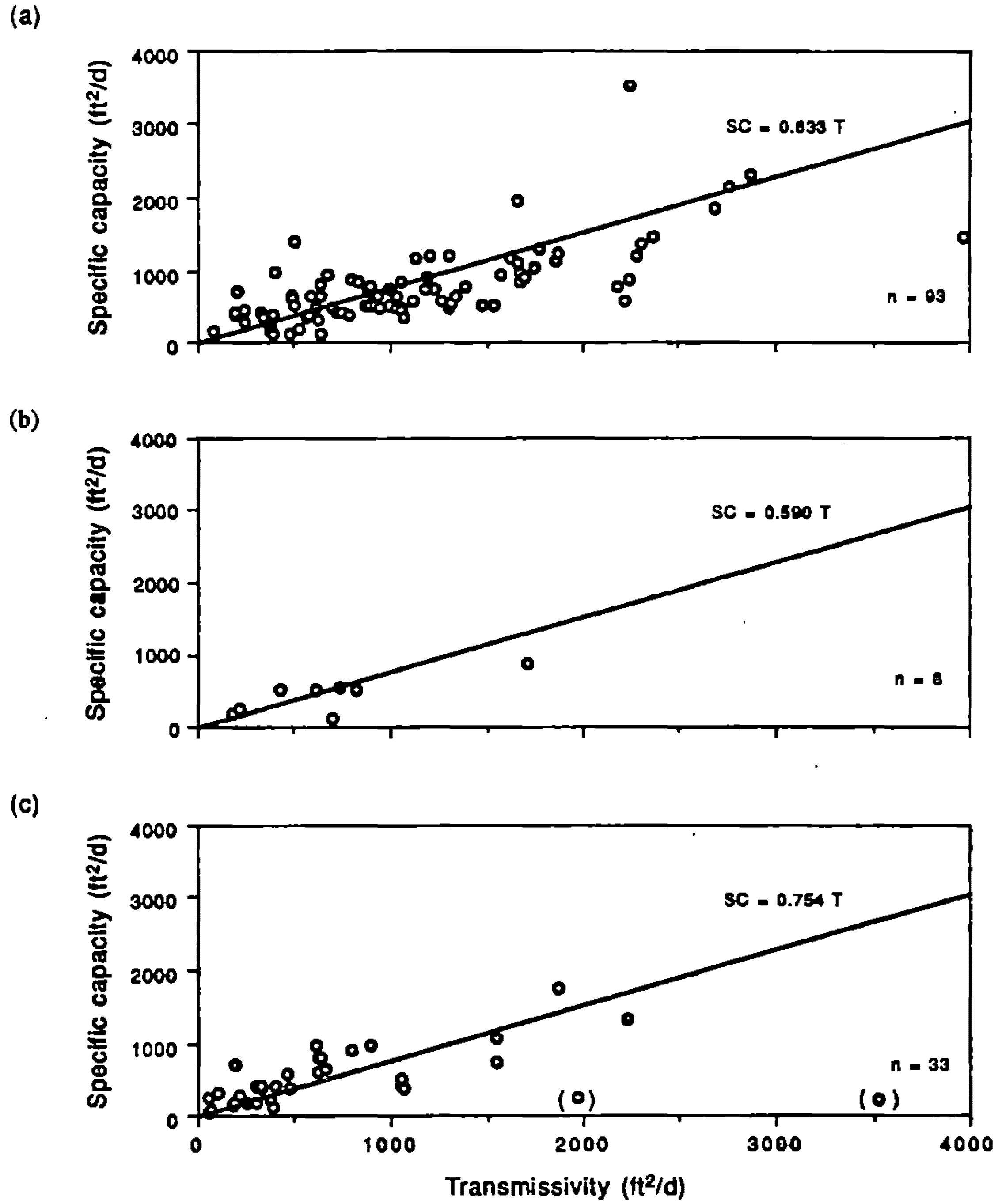

Figure 10. Relation between specific capacity and transmissivity for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formations. SC is specific capacity; T is transmissivity; *n* is sample size. Regression lines fixed at origin and represent the least-squares fit to data. Data marked in brackets were not included in least squares regression.

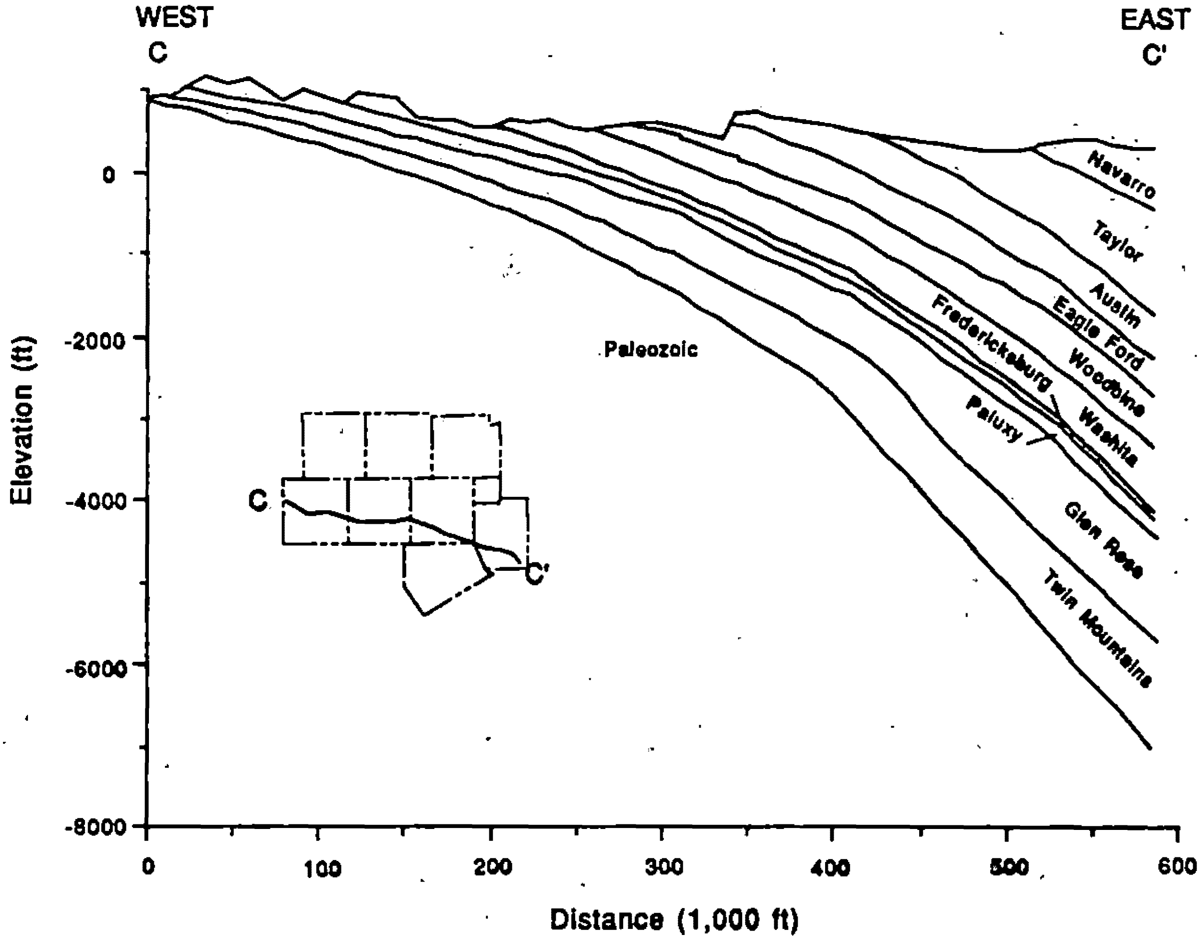

Figure 11. Geologic cross section showing hydrostratigraphic units used for numerical profile model. Modified from Nordstrom (1982).

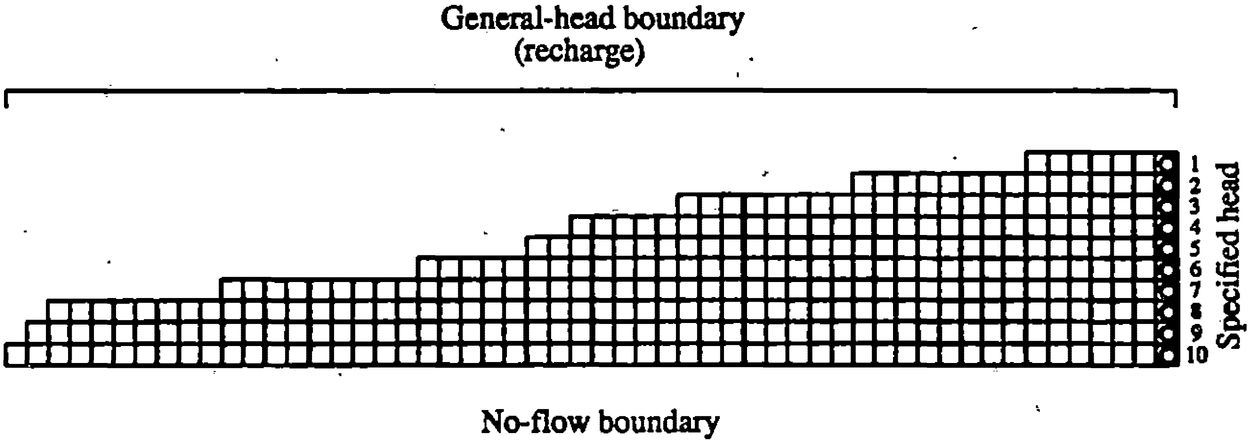

Figure 12. Finite-difference grid used for numerical cross-sectional model. Hydrologic properties were assigned and hydraulic heads calculated for the center of each grid cell. Layers are (1) Twin Mountains, (2) Glen Rose Formation, (3) Paluxy Formation, (4) Fredericksburg Group, (5) Washita Group, (6) Woodbine Formation, (7) Eagle Ford Group, (8) Austin Chalk, (9) Taylor Group, and (10) Navarro Group.

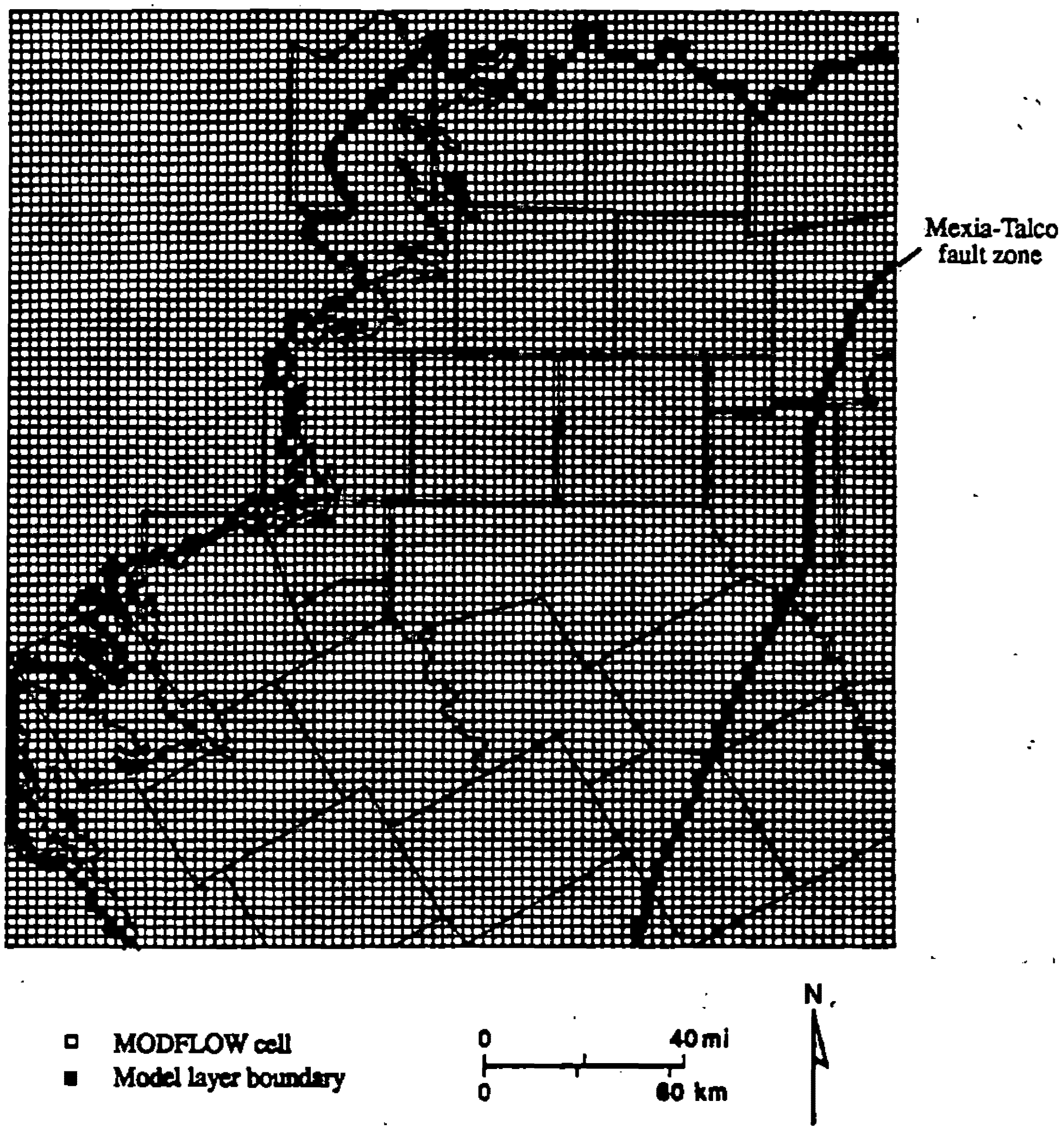

Figure 13. Active cells used in the three-dimensional model to represent the Twin Mountains Formation.

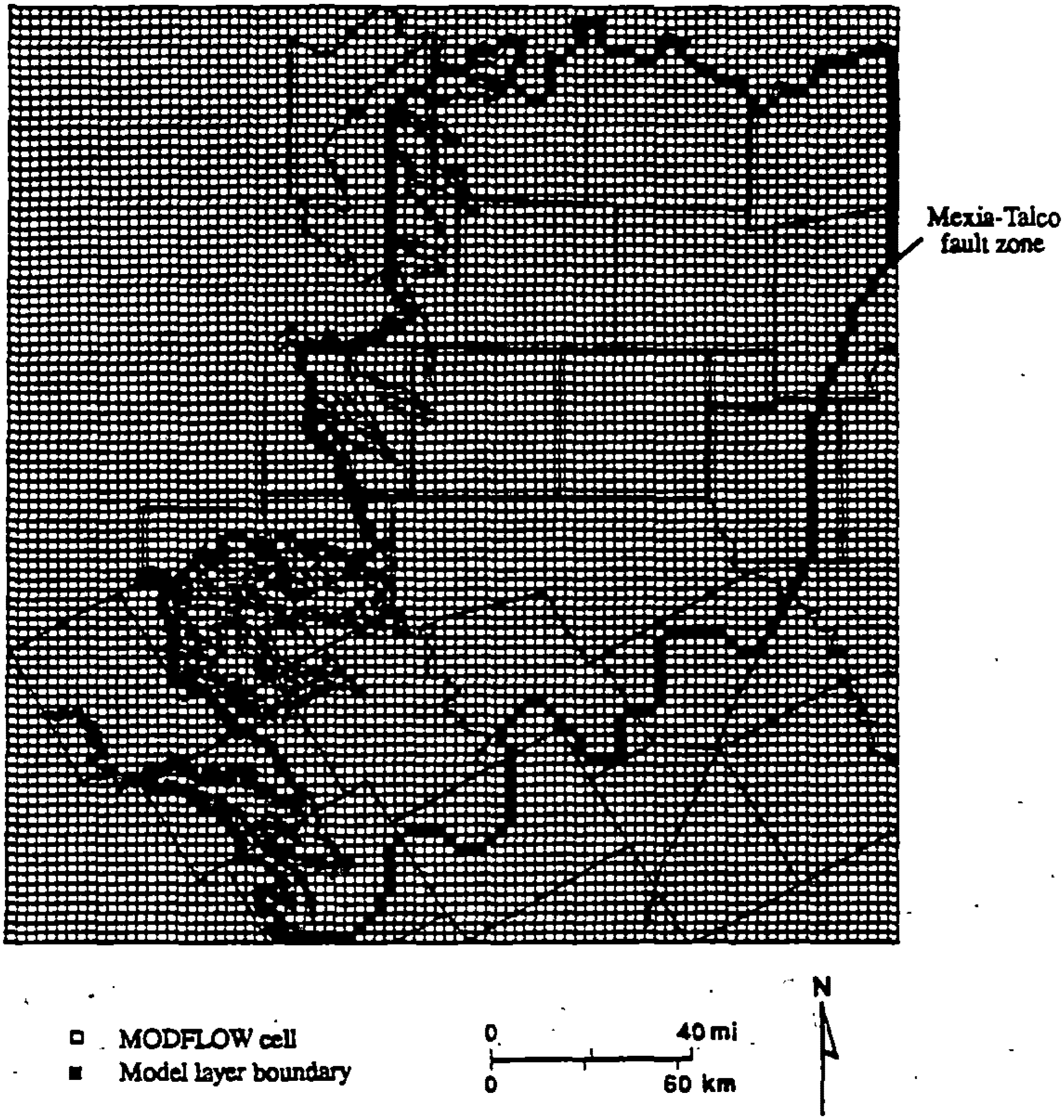

Figure 14. Active cells used in the three-dimensional model to represent the Paluxy Formation.

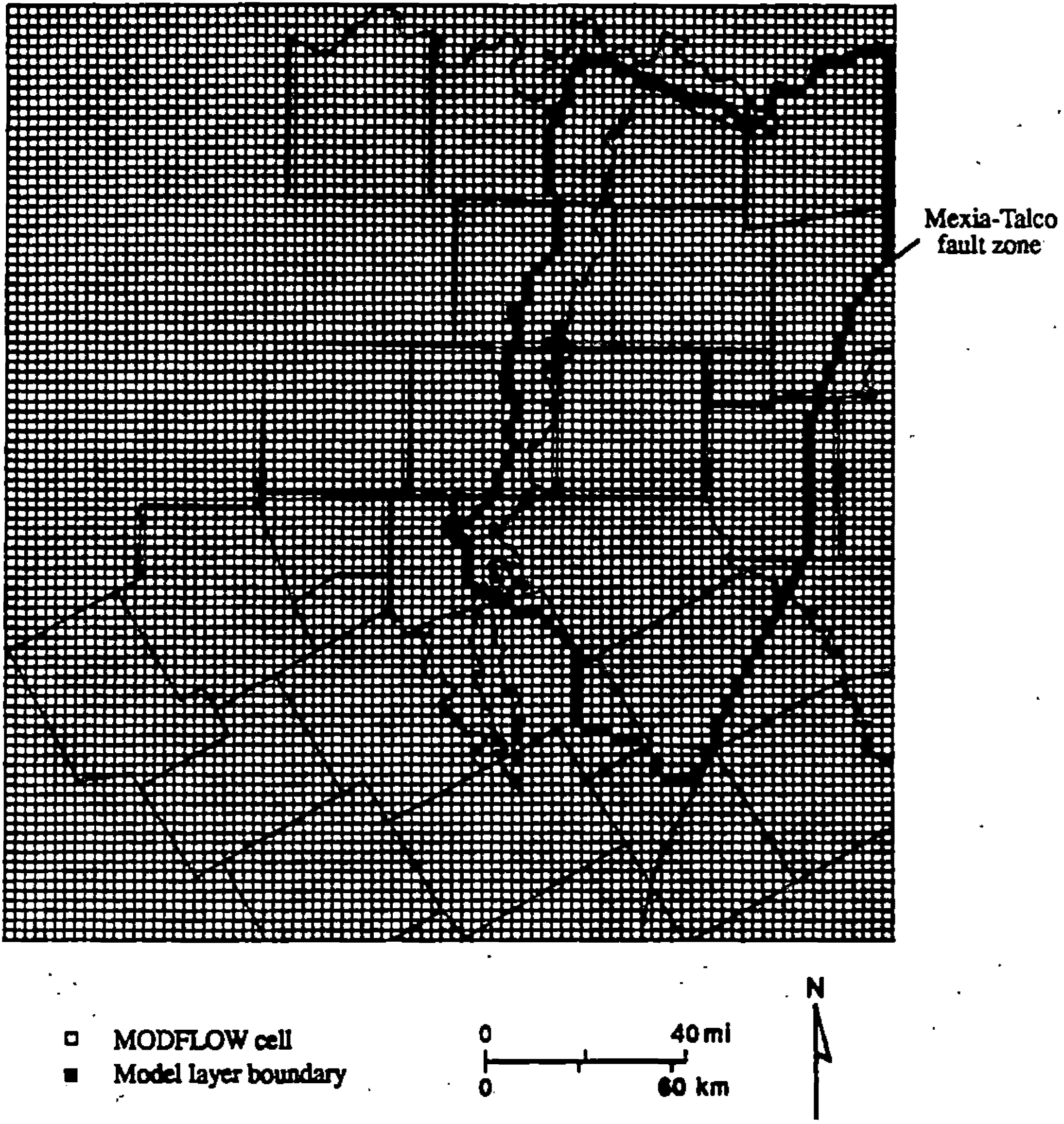

Figure 15. Active cells used in the three-dimensional model to represent the Woodbine Formation.

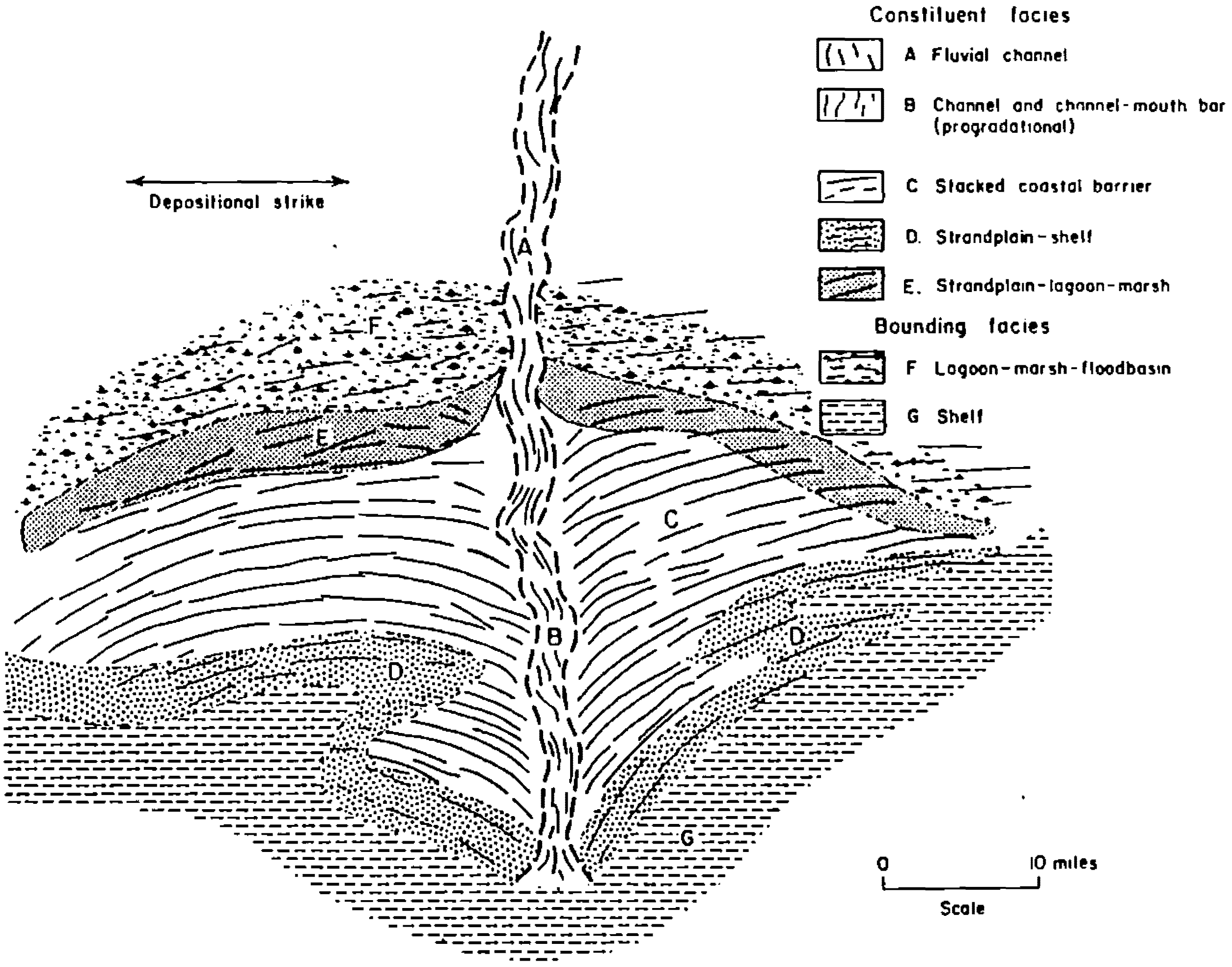

Figure 16. Model of high-destructive delta system. From Fisher (1969).

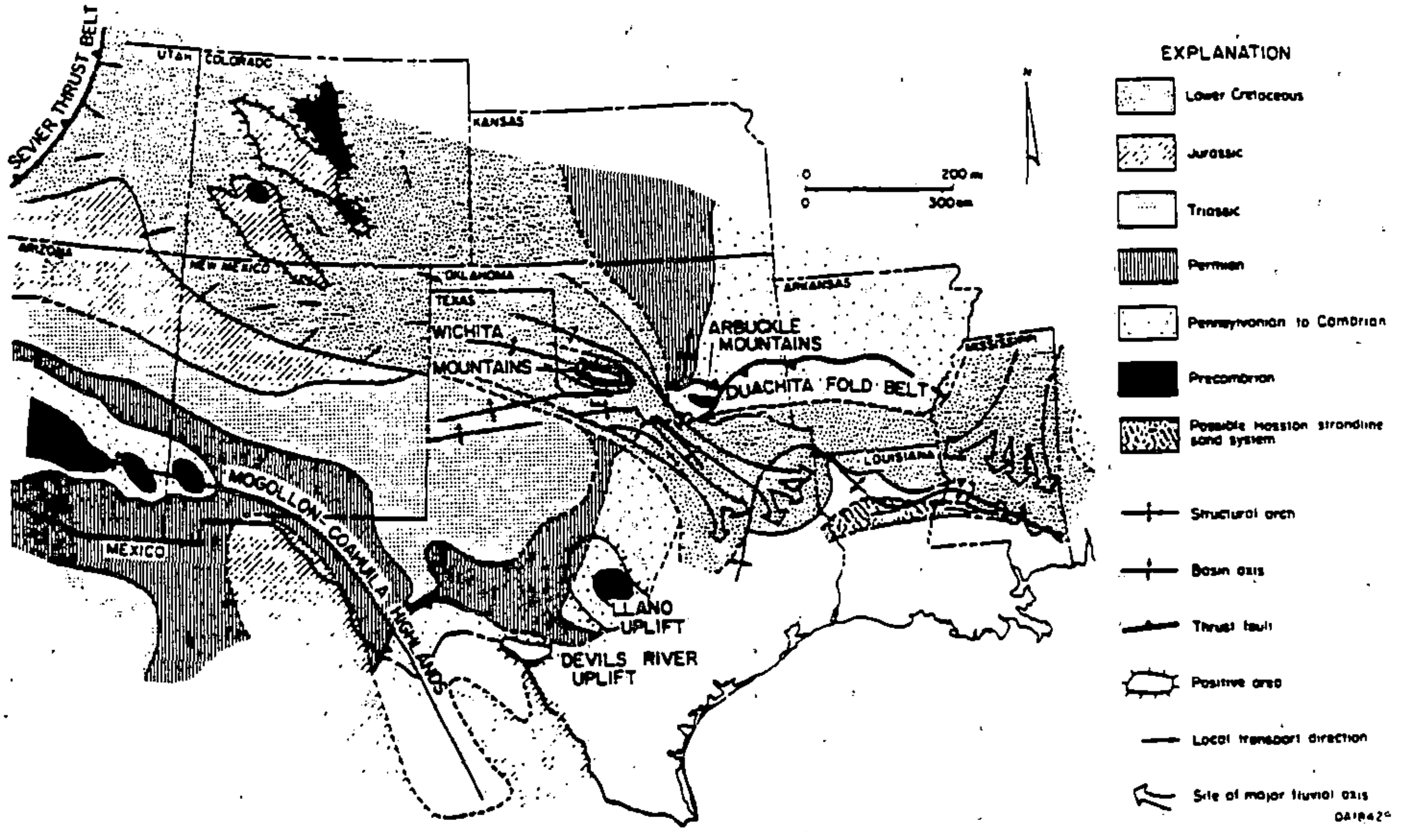

Figure 17. Early Cretaceous (Coahuilan) paleogeology and paleogeography of south-central and southwestern United States showing general sediment-source areas and gross directions of transport. Similar paleogeography characterized the other siliciclastic depositional periods of the Cretaceous. From Saucier (1985).

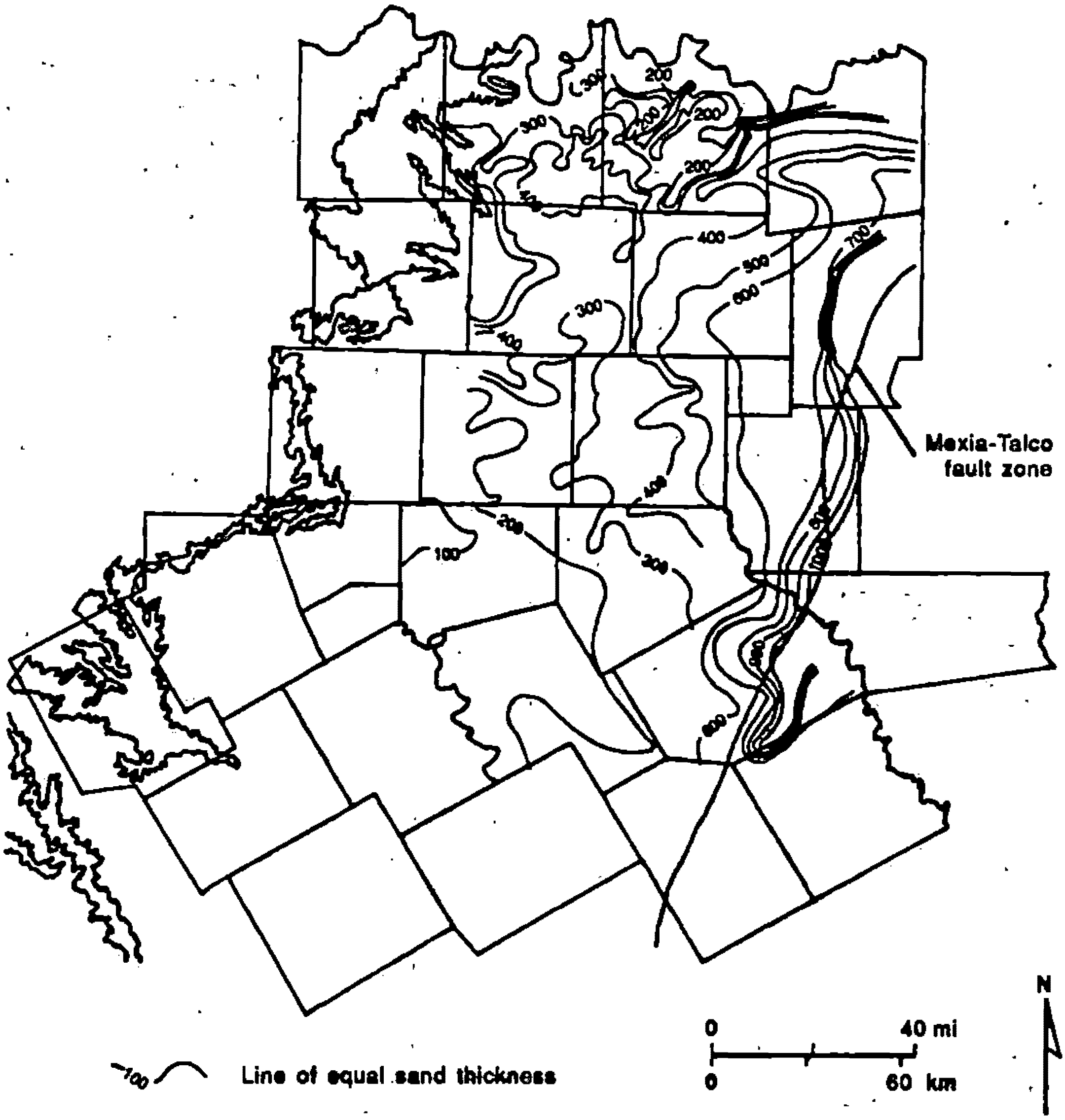

Figure 18. Net sandstone map of the Trinity Group sandstones (Hosston and Hensel Formations and equivalents).

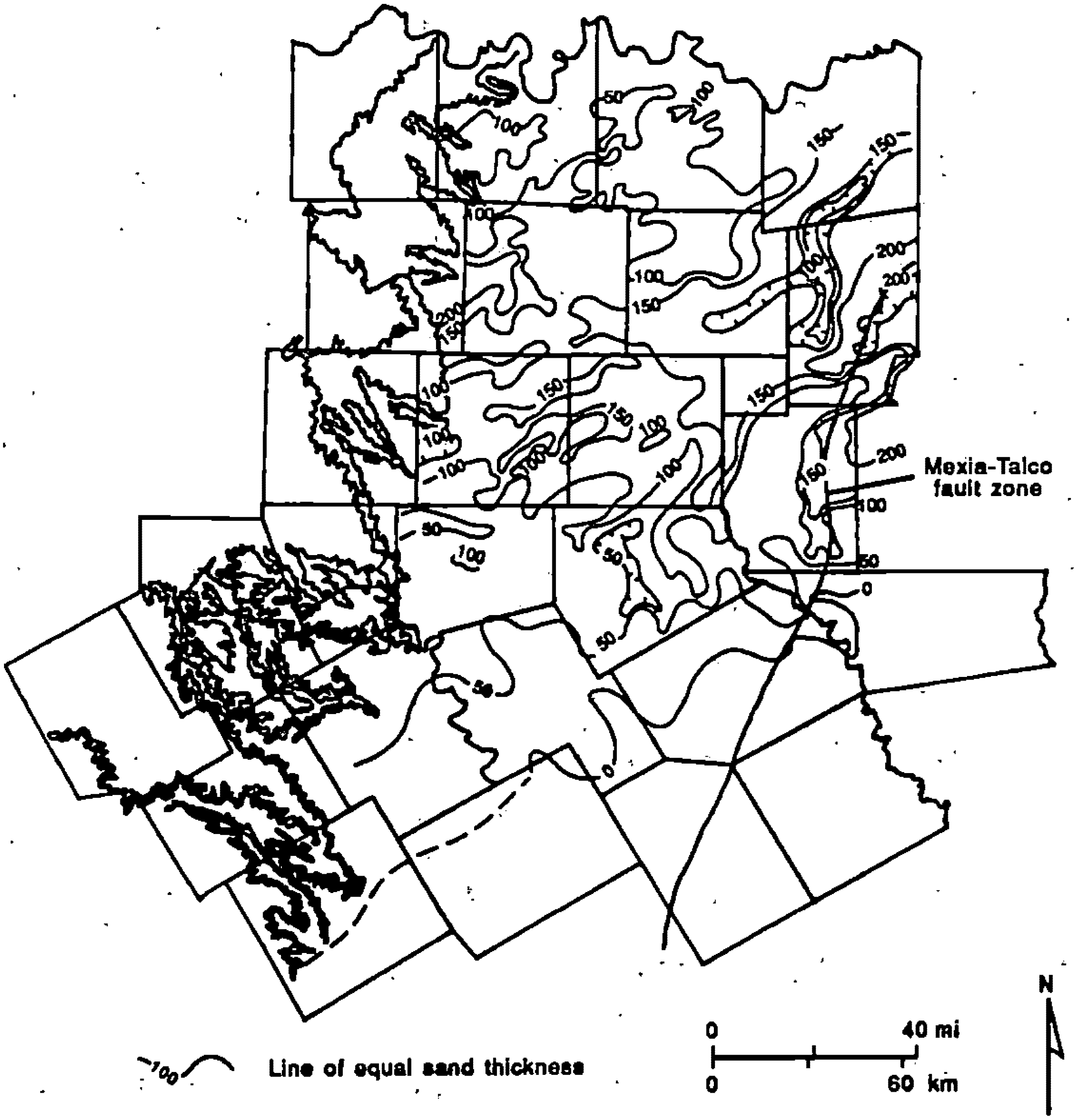

Figure 19. Net sandstone map of the Paluxy Formation.

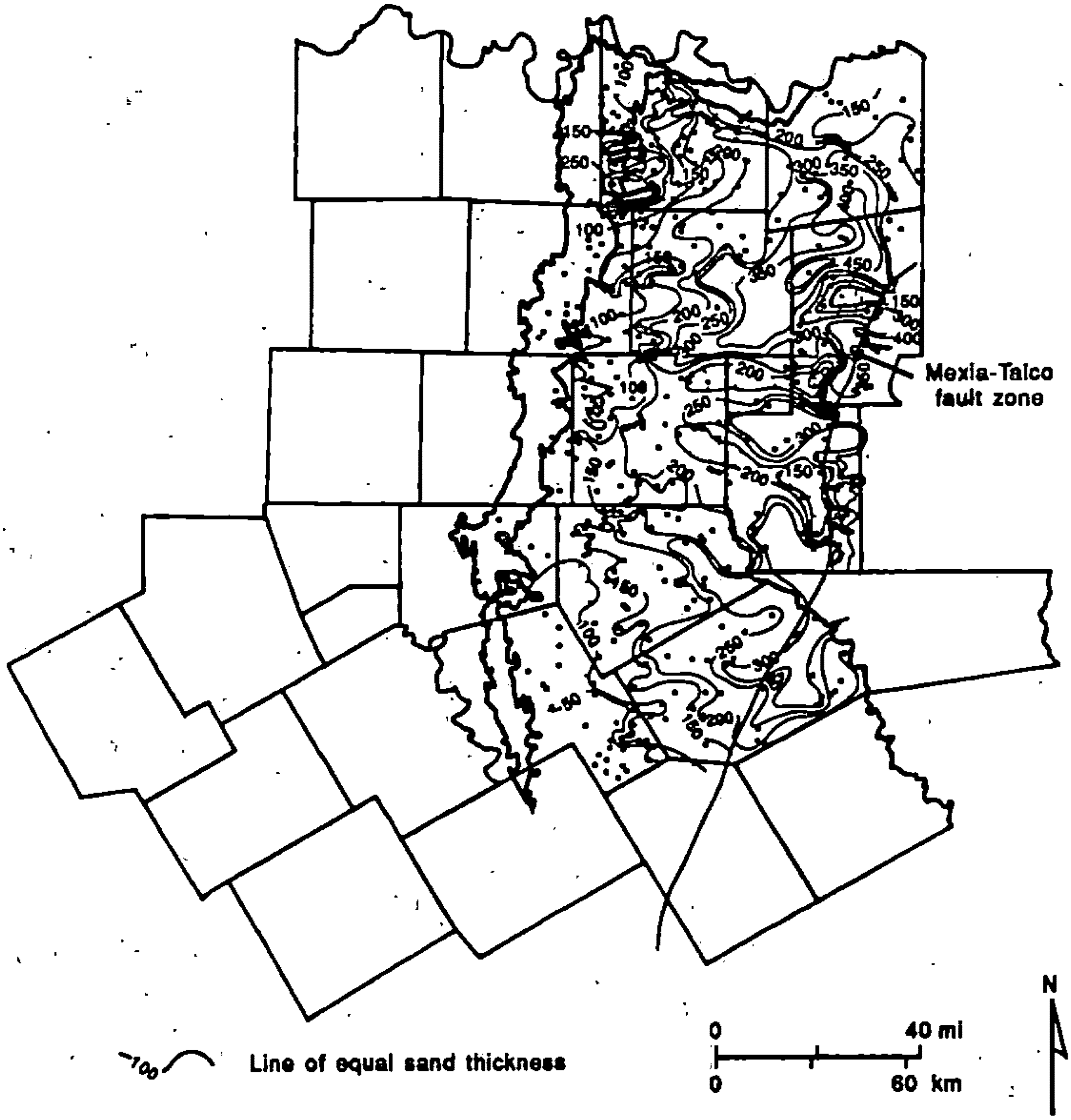

Figure 20. Net sandstone map of the Woodbine Formation.

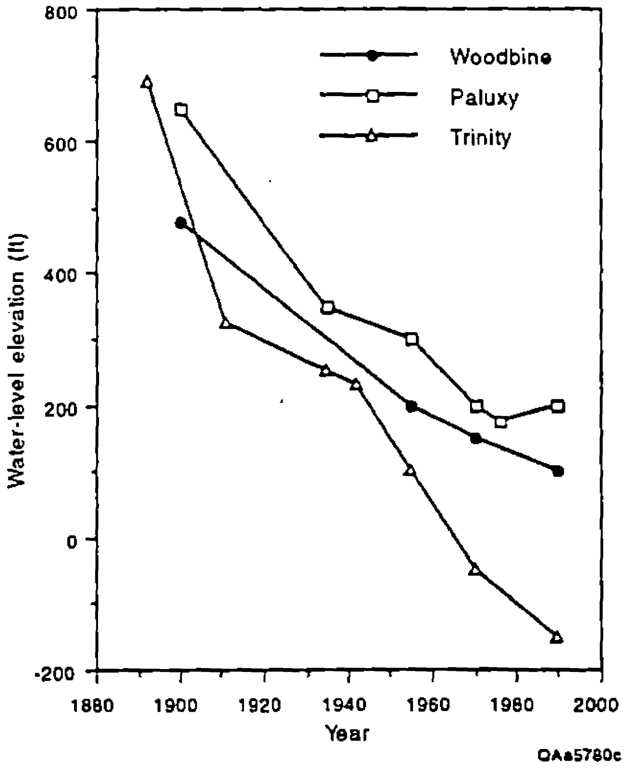

Figure 21. Water-level declines in (a) Twin Mountains Formation in the Fort Worth area, (b) Paluxy Formation near Fort Worth, and (c) Woodbine Formation near Dallas.

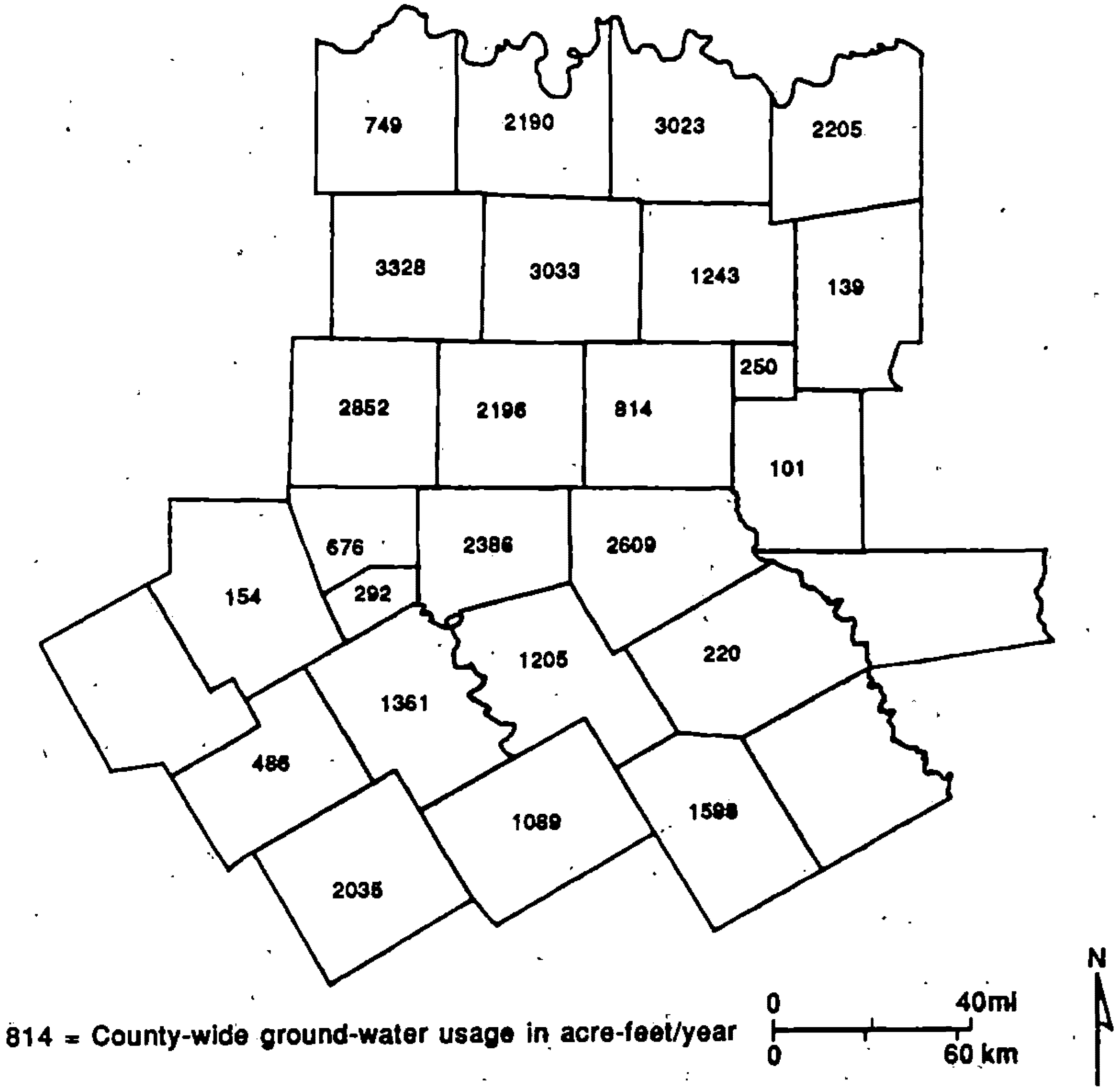

Figure 22. Pumpage rates during 1990 for counties in the study area.

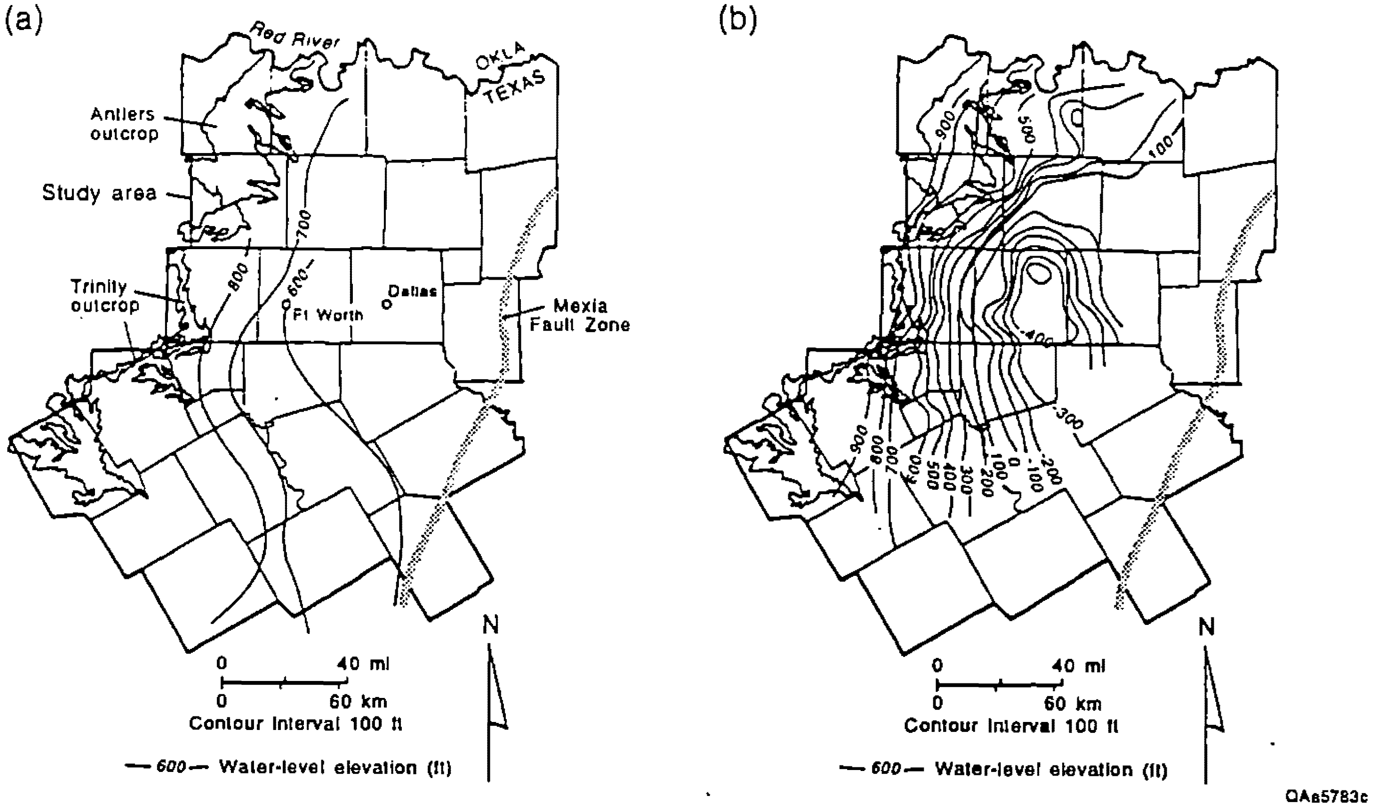

Figure 23. Estimated potentiometric surfaces for the Twin Mountains Formation in (a) 1900 and (b) 1990.

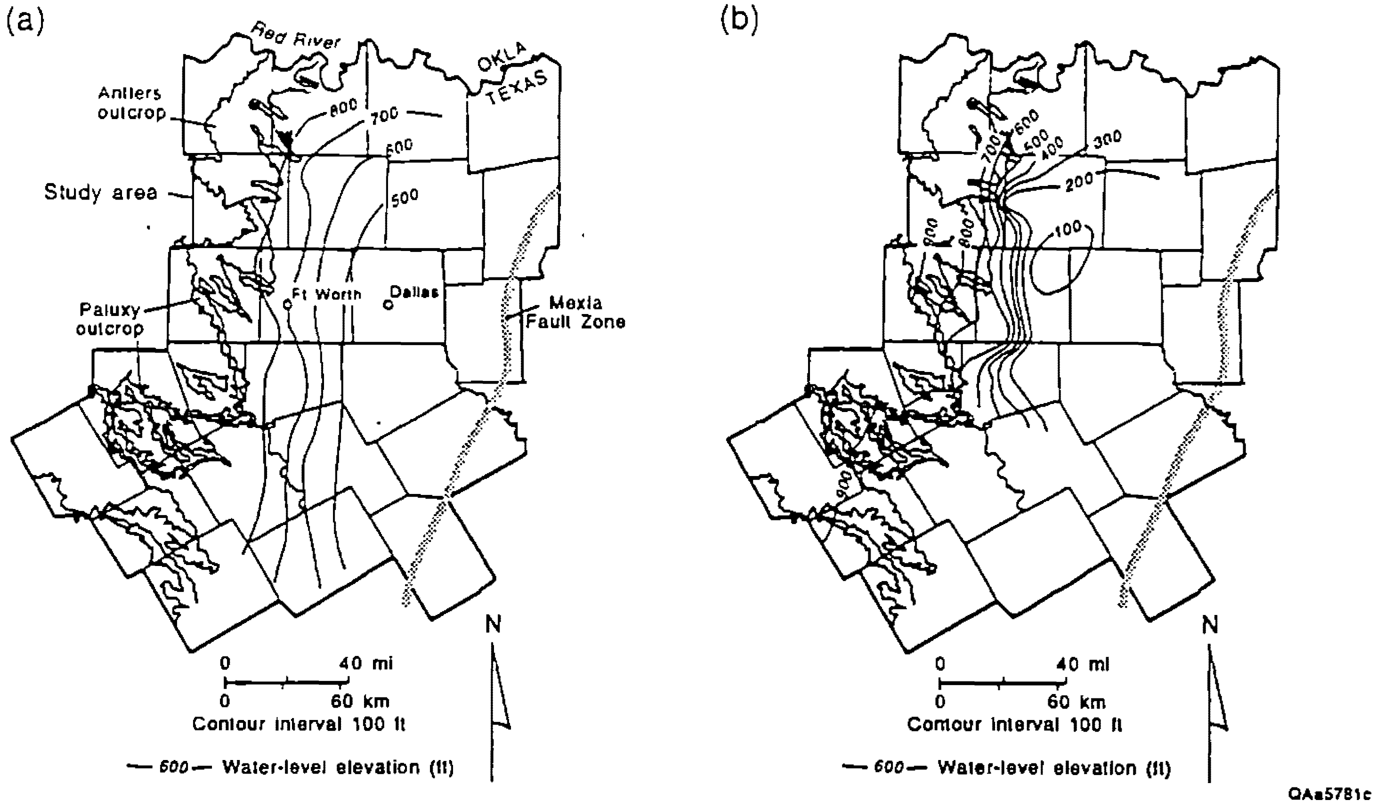

Figure 24. Estimated potentiometric surfaces for the Paluxy Formation in (a) 1900 and (b) 1990.

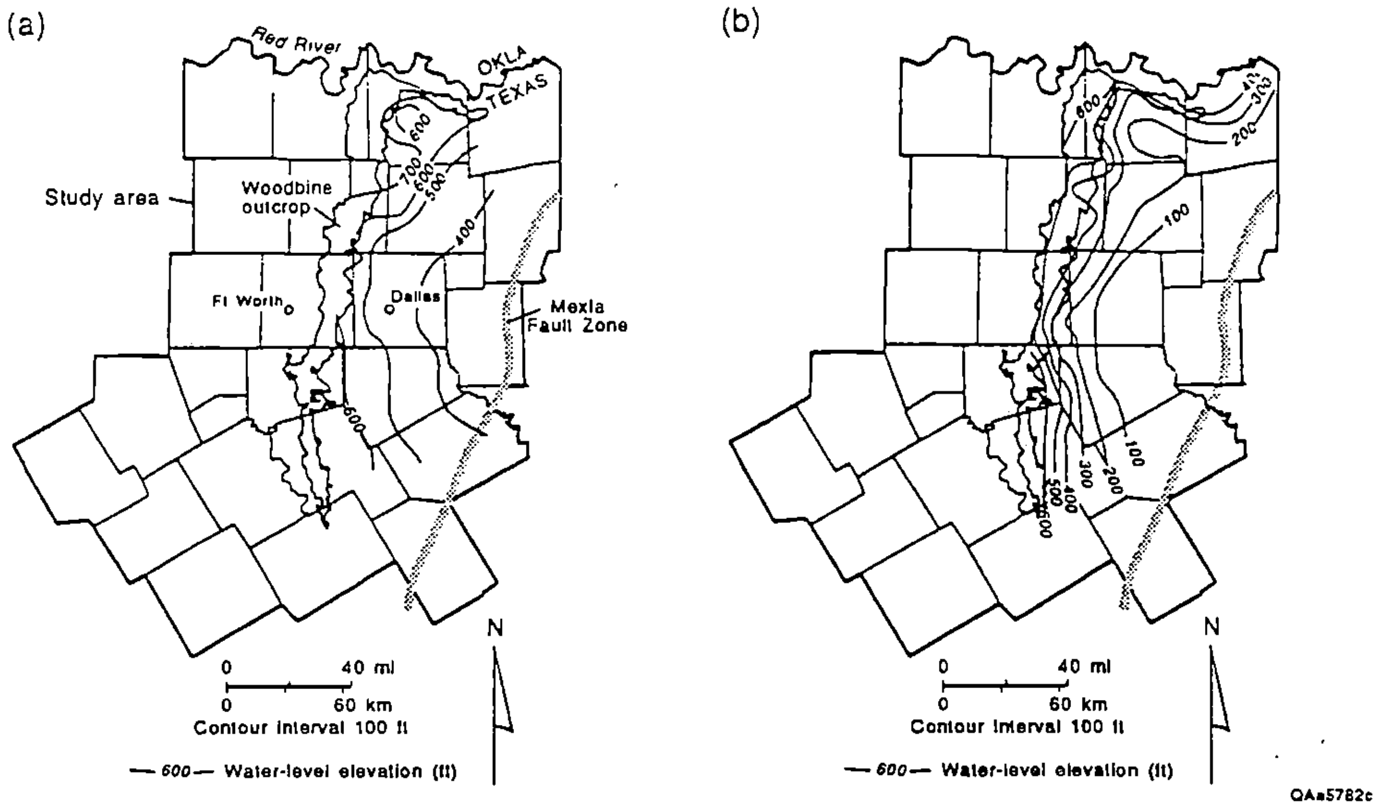

Figure 25. Estimated potentiometric surfaces for the Woodbine Formation in (a) 1900 and (b) 1990.

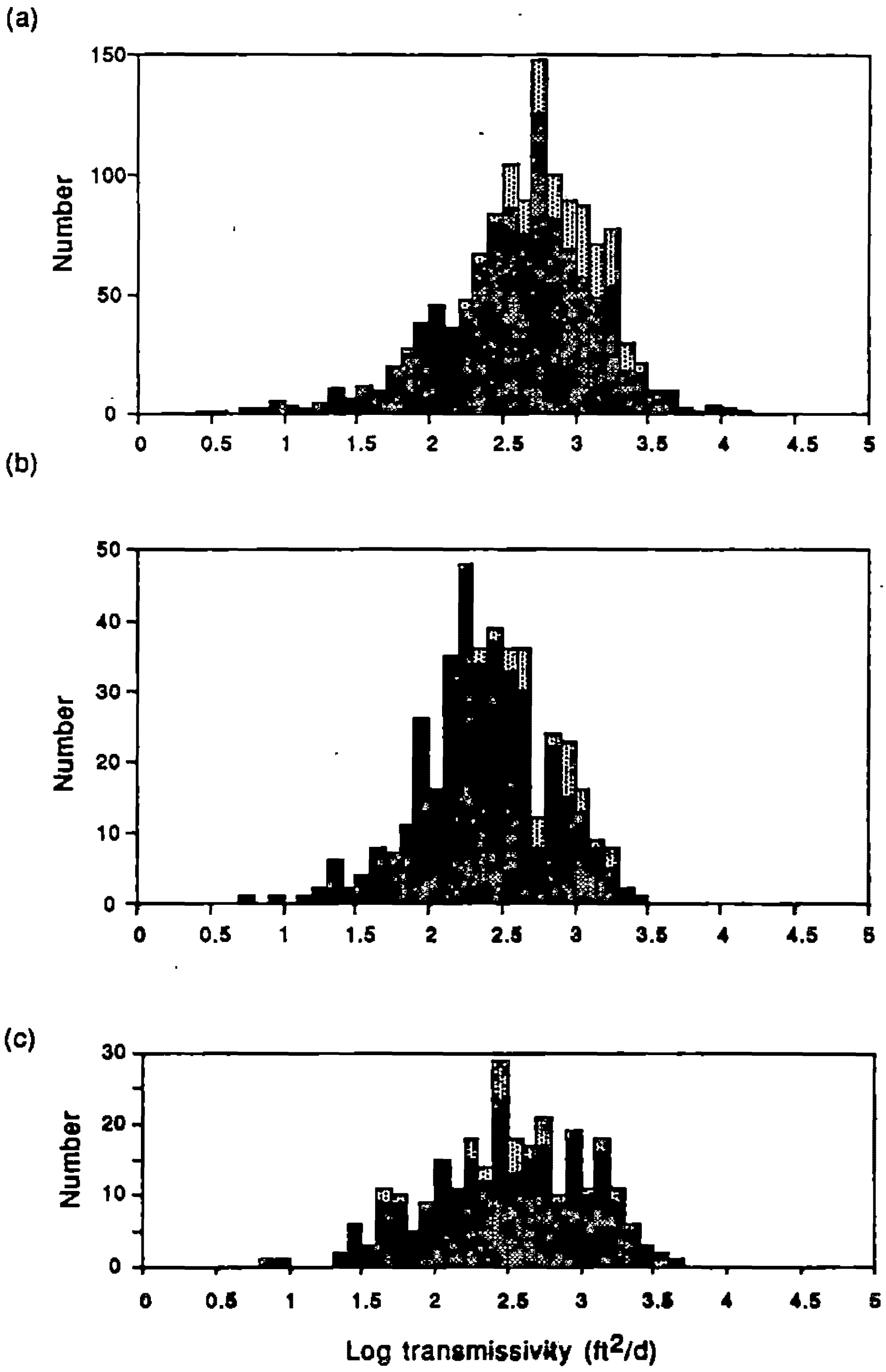

Figure 26. Histogram of transmissivity for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formations. Solid bar represents transmissivities determined from aquifer tests and shaded bar represent transmissivities determined from empirical relationships between specific capacity and transmissivity.

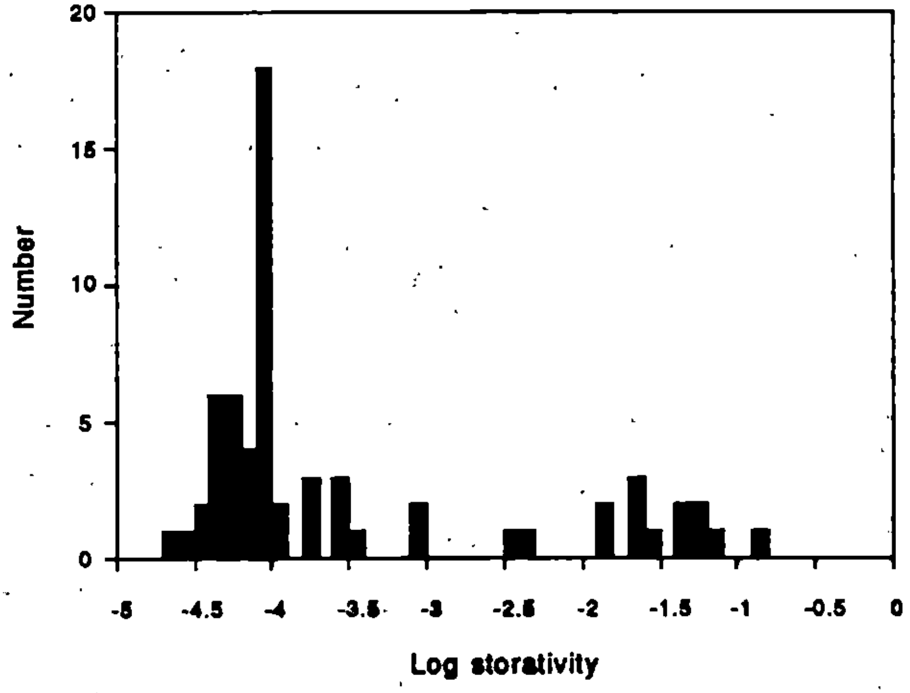

Figure 27. Histogram of storativity for the Twin Mountains Formation. Data are not sufficient for histograms of storativity for the Paluxy and Woodbine Formations.

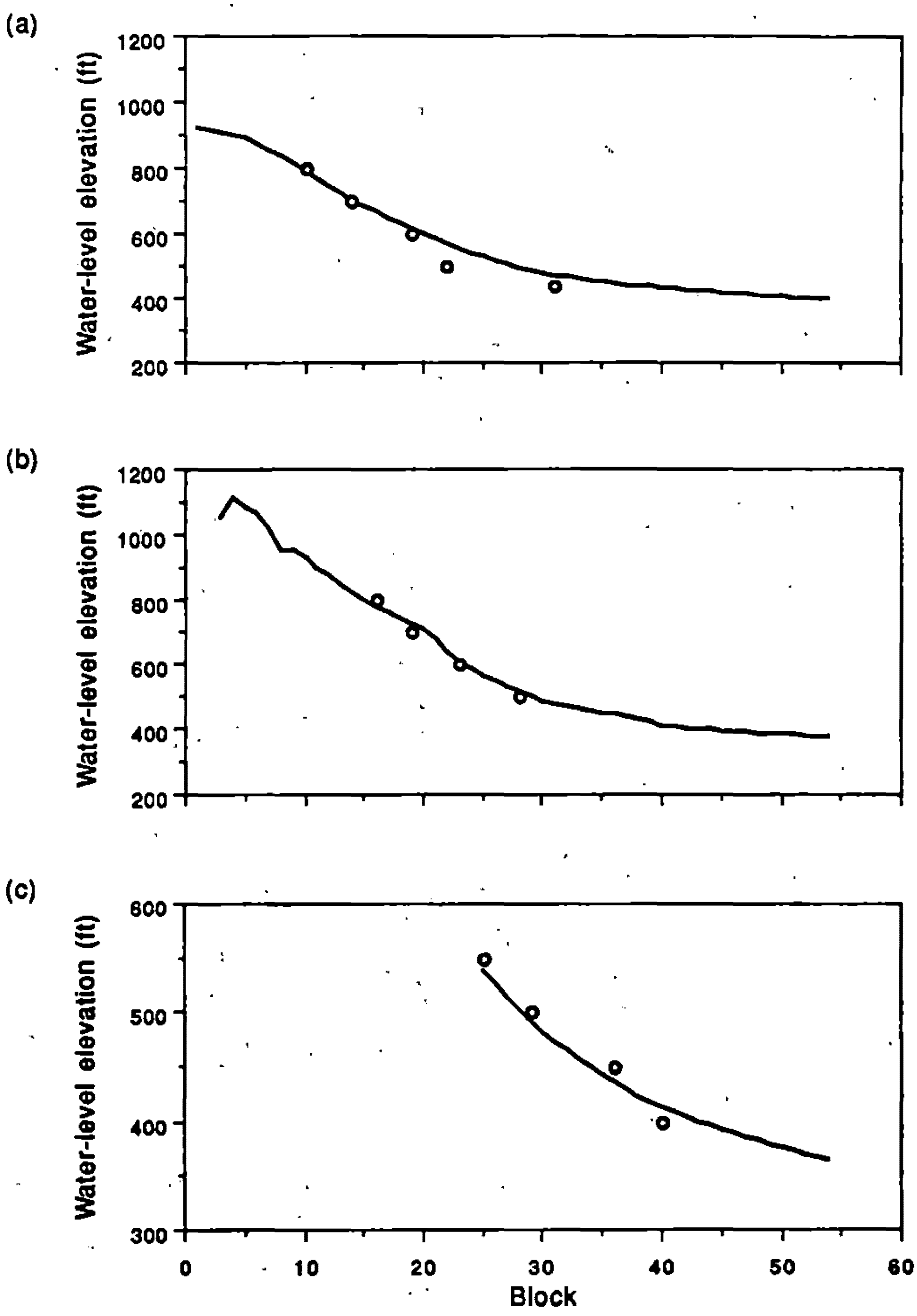

Figure 28. Comparison between measured and simulated hydraulic head from the cross-sectional model for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formations. Open circles represent measured pre-development water levels. Lines are numerically calculated water levels.

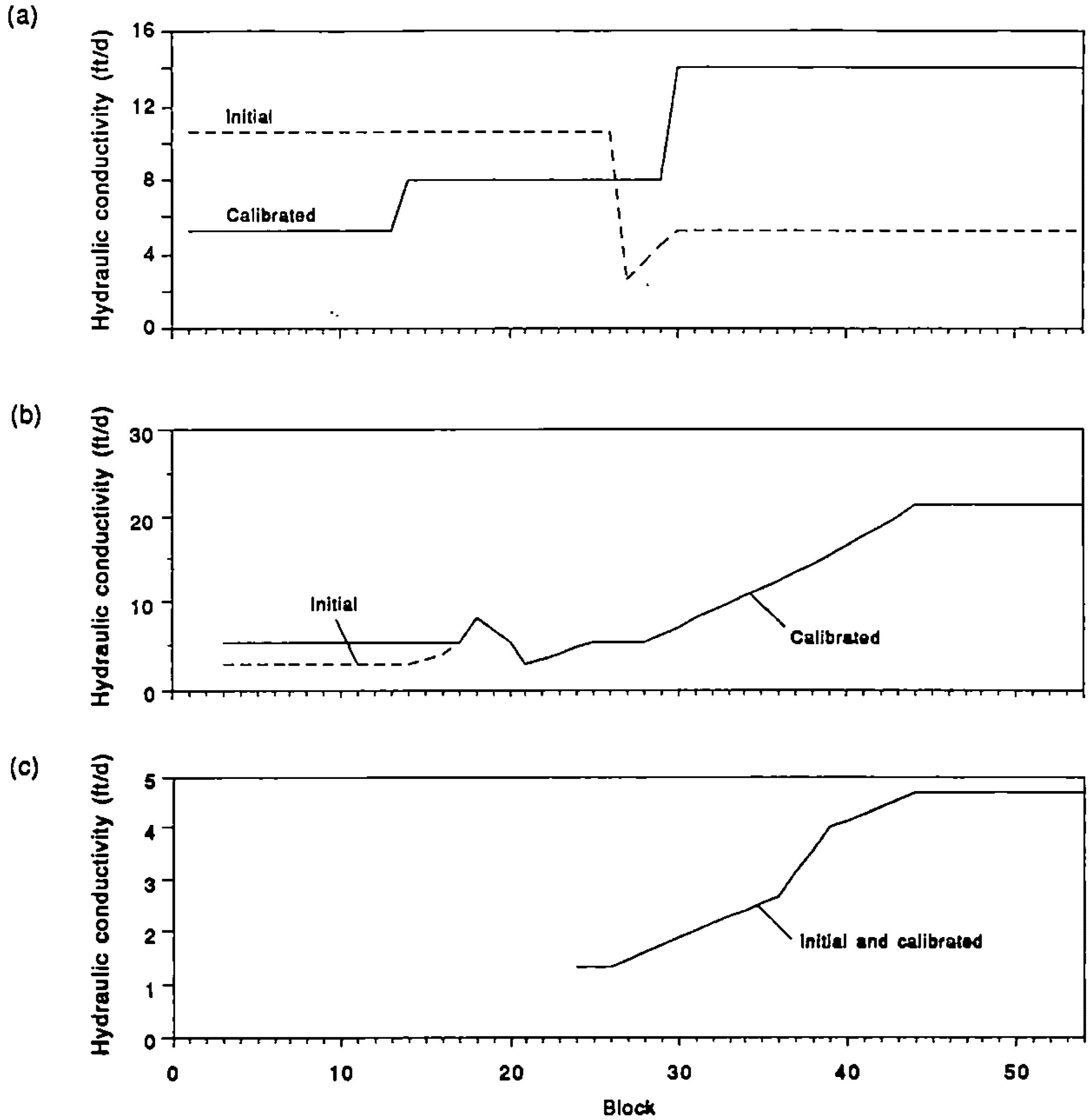

Figure 29. Initial and calibrated hydraulic conductivity distributions used for numerical modeling for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formation.

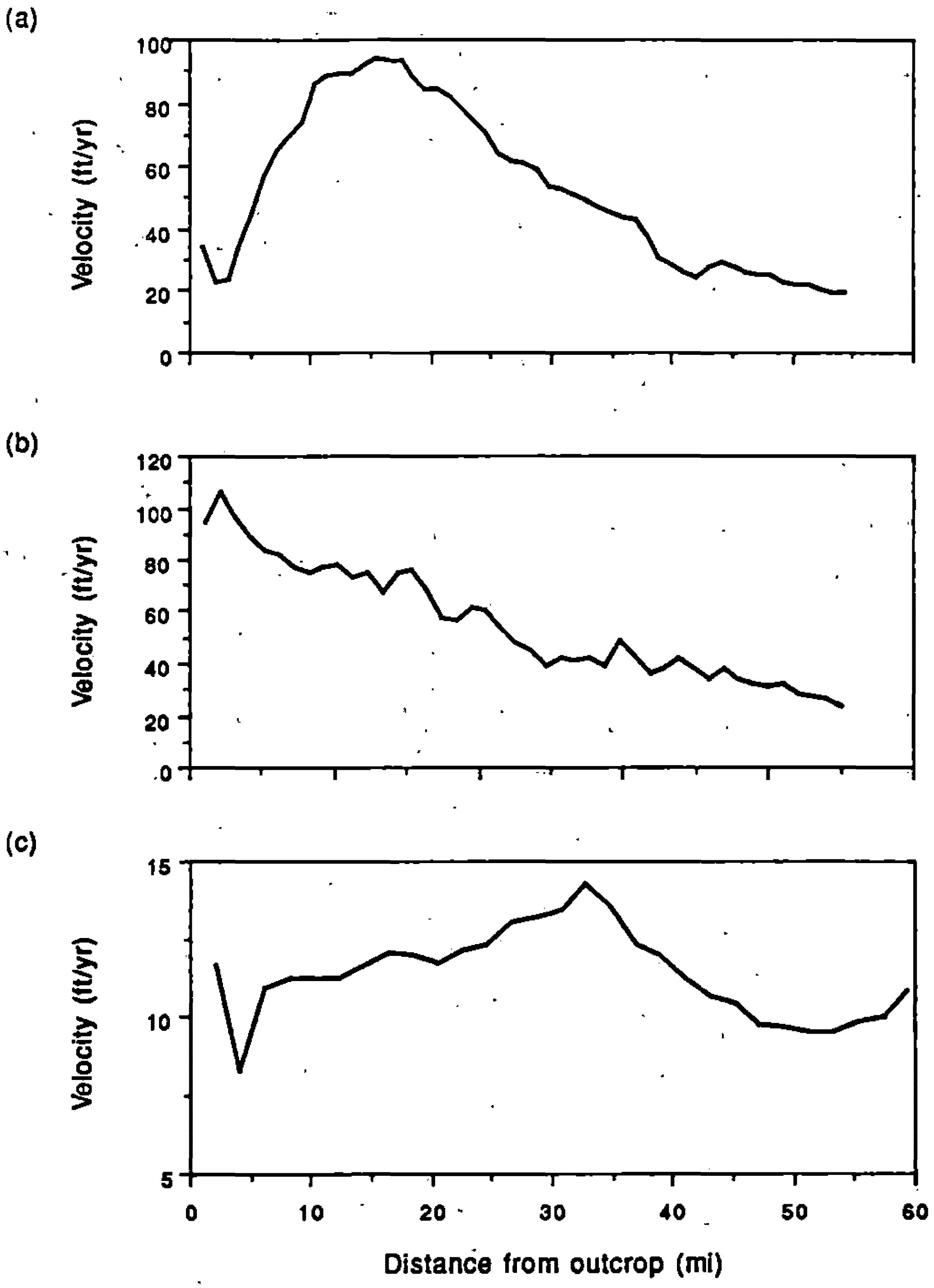

Figure 30. Numerically calculated ground-water velocities for the (a) Twin Mountains, (b) Paluxy, and (c) Woodbine Formations. Effective porosity is assumed to be 5 percent.

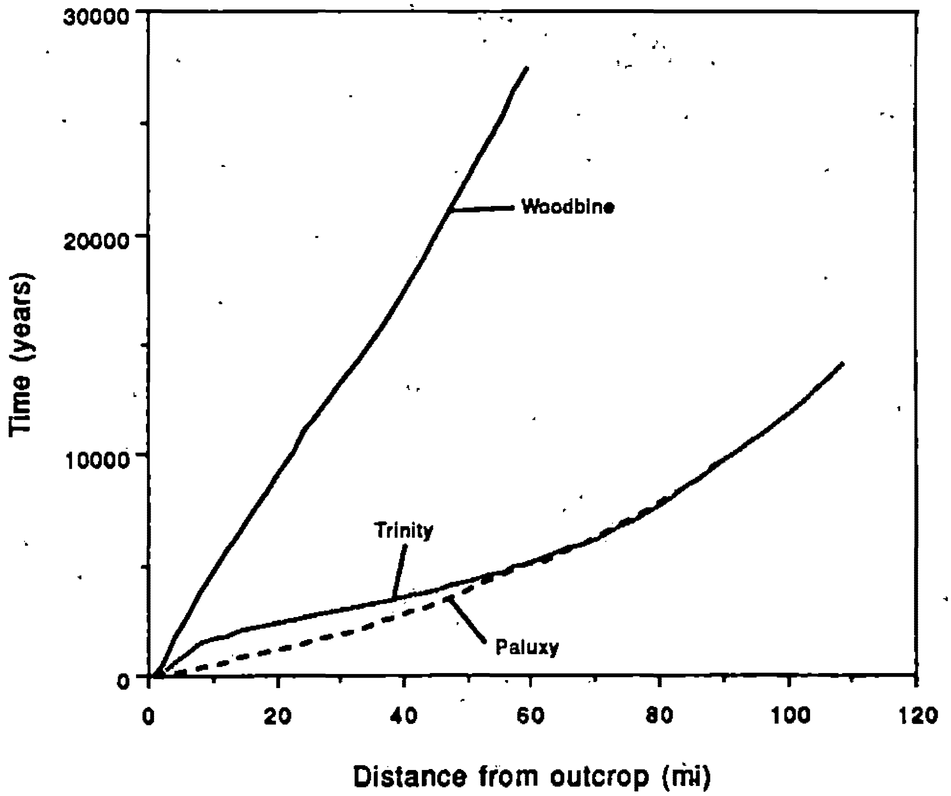

Figure 31. Numerically calculated cumulative travel times, assuming effective porosity of 5 percent for the Twin Mountains, Paluxy, and Woodbine Formations.

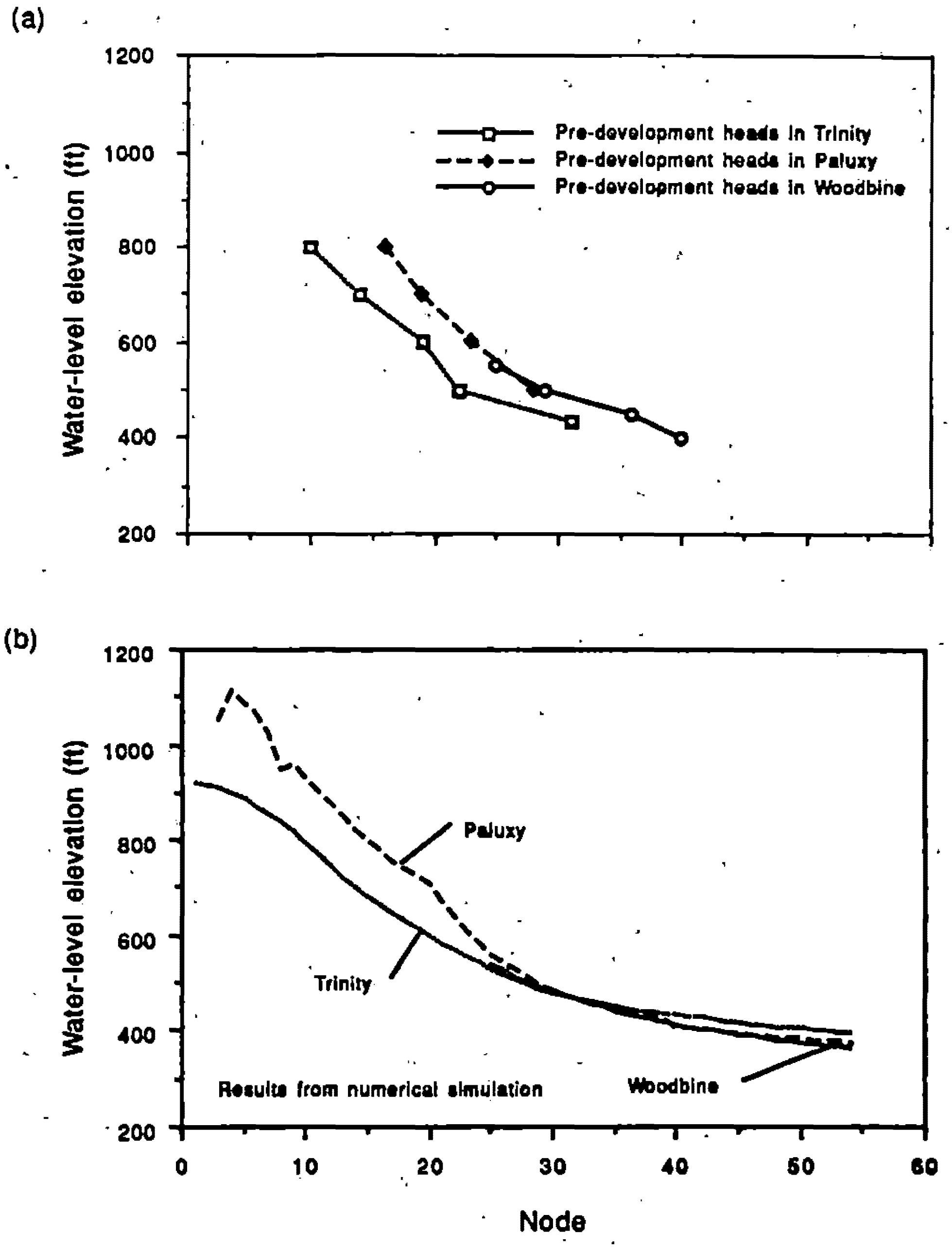

Figure 32. (a) Predevelopment (observed) hydraulic-head profile for the Twin Mountains, Paluxy, and Woodbine Formations, showing potential cross-formational flow between the Paluxy and the Twin Mountains Formations, and (b) numerically calculated predevelopment head profile for the Twin Mountains, Paluxy and Woodbine Formations.