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GEOTHERMAL RESOURCE ASSESSMENT FOR THE STATE OF TEXAS

Status of Progress, November 1980

Final Report

by

C. M. Woodruff, Jr.
Principal Investigator

and

S. Christopher Caran, Christine Gever, Christopher D. Henry,
G. L. Macpherson, and Mary W. McBride

Prepared for
U.S. Department of Energy, Division of Geothermal Energy
Under Contract No. DE-AS07-79ID12057

March 1982

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin

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letter to Prestwich in Woodruff's file dated 5/20/82.

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EXECUTIVE SUMMARY

This report consists of a two-part text and eight appendices that present the status of research on hydrothermal/geothermal resources in Texas as of November 1980. The first part of the report presents data pertaining to wells and thermal aquifers; the second part discusses our research on lineaments as perceived on Landsat imagery. The appendices include: (A) a folio of county maps showing locations of well data across the state; (B) a computerized tabulation of the wells depicted; (C) an explanation of our computer coding procedures; (D) a selected bibliography on heat flow and geothermics; (E) a folio of maps showing lineaments perceived across the state; (F) an index and critique of the Landsat images used in perceiving the lineaments; (G) a selected bibliography on lineaments; and (H) a discussion of area-specific assessments of geothermal resources near military bases in Bexar, Travis, and Val Verde Counties.

The section on wells (in Part I of the report) is mainly a discussion of method. We learned that our findings on water temperature, on geothermal gradient, and on hydrologic properties--in fact, <u>any</u> interpretation of well data--are constrained by the kinds and quality of topical and locational data available. Locational constraints are often unimportant if one is conducting an overview at a regional scale. However, the constraints become much more important as one refines the data to focus on a particular water-bearing horizon at a specific site. Obviously, uncertainty about well locations influences all subsequent interpretations and all attempts to re-examine the data point in the field. Hence, we gave first attention to problems of locating wells on maps. We found the problems to vary according to the original source of data, but common discrepancies include inconsistent base maps at various scales and projections and a lack of consistency among different sources. Typical of the locational problems is the fact that water wells and oil wells in Texas are located (and data are archived) according to two radically different conventions. Yet, it was incumbent on us to unify these divergent data populations.

Topical data--information derived from any well--is the grist for our interpretations, yet there are inherent problems with these data, too. Examples include interpretations of the specific geologic horizons monitored and recorded at a given well, yet our use of this information is often impaired by nomenclatural complexity or laxity. Also many well-completion procedures and various logging practices may create artifacts in the data. Because of these artifacts, anomalies must be assayed guardedly, knowing that they may represent actual deviations of certain values or that they may result from specious data.

With these caveats in mind, we present findings from a program of field measurements of water temperatures (mainly in South-Central Texas) and an assessment of hydrologic properties of three Cretaceous aquifers (in North-Central Texas).

In Part II of this report we focus on Landsat lineaments and their pertinence to the localization of low-temperature geothermal resources. We found much confusion surrounding the term "lineaments" and, in addition, no standard procedure for viewing or analyzing any of the lineaments perceived. Lineaments may occur in almost every geologic setting, and they may be a product of various processes. Furthermore, there may be "false lineaments" owing to earth surface processes or to the works of man. Our task has been to separate signal from noise by asking, "are the features (lineaments) real?" and "are they geologically meaningful?"

With these problems in mind we have tried to codify (1) a definition of lineaments; (2) a method for perceiving them; and (3) a means of evaluating the lineament data. We define a lineament (in brief) as a straight figure with a high length-to-width ratio perceived on any representation of a solid planetary body and judged to reflect planetary structure. Using this definition, each of 51 images was viewed by three workers in two sessions of 30 minutes each. In this way we perceived more than 31,000 features in Texas and surrounding areas.

Lineament data were compared to structural and stratigraphic features along the Balcones/Ouachita trend in Central Texas in order to test for correlations between loci of geothermal resources and lineaments. Correlations exist in certain areas, suggesting that pervasive faulting provides conduits for circulating ground waters. A depressed geothermal gradient occurs in areas of recharge, whereas anomalously high gradients occur where ground water is upwelling from adjacent basinal areas.

INTRODUCTION

Statewide assessment of geothermal resources in Texas is a geographical and conceptual expansion of an initial survey of hydrothermal resources in Central Texas (Woodruff and McBride, 1979). That initial study demonstrated the extent and quality of geothermal waters in the deep reaches of Cretaceous aquifers along the Balcones and Luling-Mexia-Talco Fault Zones. Although the heat content of these waters is modest (maximum recorded temperatures of 152°F or 66.7°C from a depth of approximately 3,900 ft or 1,189 m), the fact that the resource lies beneath a major population trend comprising the cities of Austin, Dallas, Fort Worth, San Antonio, Temple, Waco, and Sherman means that there are numerous potential users of this kind of resource for space heating and hot water purposes. Moreover, in many places, the warm waters are presently used as domestic or municipal water supplies without regard to their thermal value. In these instances, the major capital expenditure of drilling a well has already been borne; the resource is essentially "in place" and ready to use. Demonstration projects designed to use geothermal waters are presently underway at the Torbett-Hutchings-Smith Memorial Hospital in Marlin, at Navarro Junior College in Corsicana, and at the City of Wilmer in Dallas County. Also, feasibility studies are underway that explore the potential for using the resource at military bases in Bexar, Travis, and Val Verde Counties (fig. 1).

During the initial survey in Central Texas, several problems arose that demonstrated the need for further studies. We found that, although the thermal values and chemical qualities of the warm ground waters were easily obtained, the hydrologic attributes of the various aquifers were almost undocumented in the literature. Assessment of hydrologic properties of the thermal aquifers

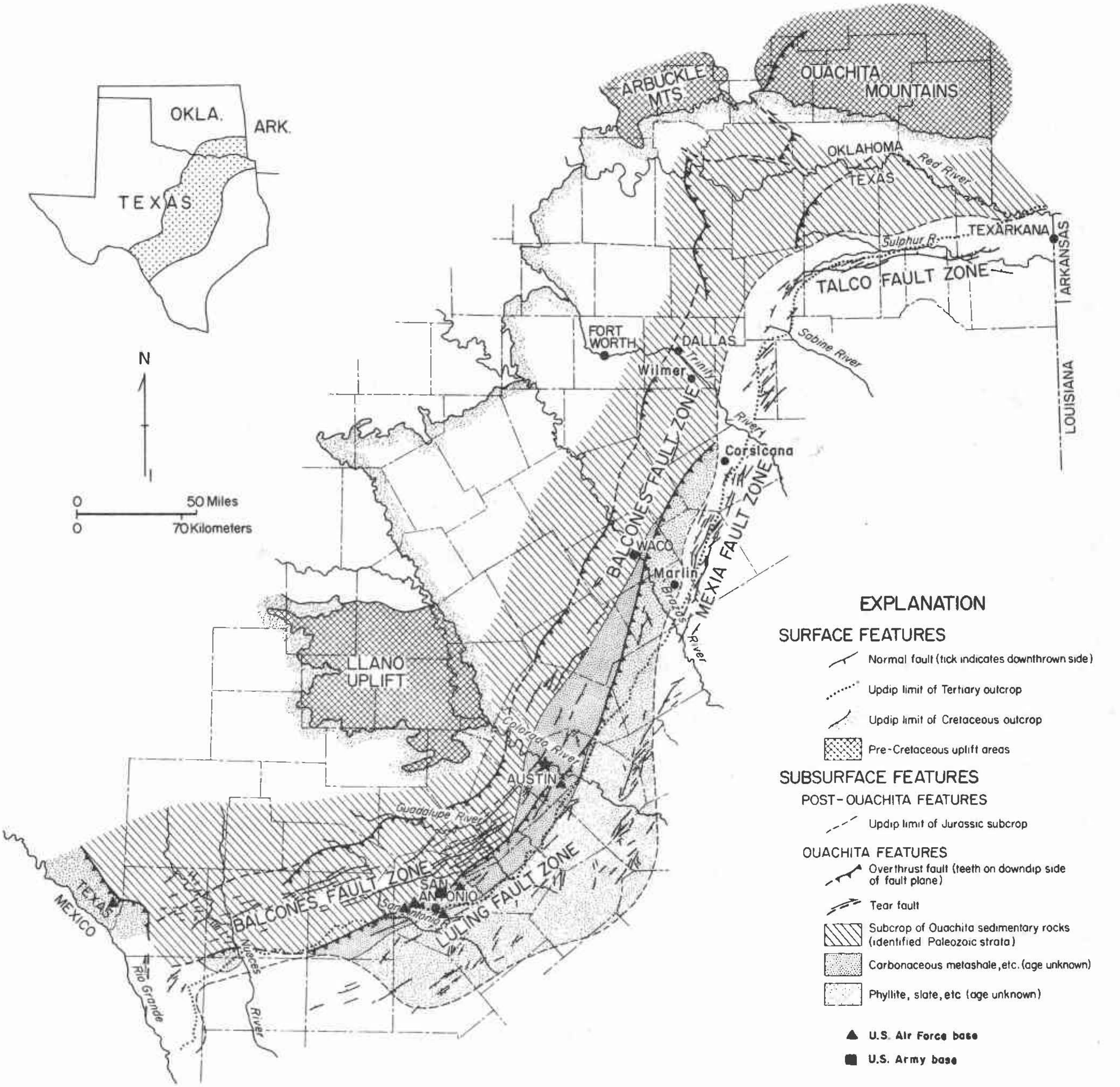


Figure 1. Regional tectonic features along the Balcones/Ouachita trend and locations of current projects aimed at using geothermal waters.

is clearly warranted. We also noted an intriguing coincidence of thermal and tectonic features, which led us to suspect that major structural dislocations provide access for deeply circulating waters. This coincidence might in turn help explain why there is, in certain areas, the unexpected condition of relatively low dissolved solids concentration with increasing depth and increasing water temperatures. At other localities, such as Hot Springs, Arkansas, the area of thermal springs in western Virginia, and parts of the Piedmont and Appalachian provinces of Alabama, similar convergences have been noted (Bedinger and others, 1979; Powell and others, 1970; Geiser, 1979) along with the occurrence of unusual lineament patterns perceived by use of remotely sensed imagery. Might lineaments provide an exploration tool for locating similar convergences of thermal and tectonic features? This question provoked another of our major ongoing efforts--a statewide Landsat lineament assessment. We also discovered other low-temperature geothermal ground water adjacent to our initial study area but in aquifers of ages other than Cretaceous. Hence, a broader geographical inventory was warranted to delineate these resources and to make initial pronouncements as to their thermal quality.

Statewide assessment of geothermal resources in Texas entailed eight tasks:

(1) conduct a quantitative hydrologic assessment of the three major Cretaceous geothermal aquifers denoted during our previous investigation;

(2) conduct a statewide lineament survey;

(3) compare lineaments to faults affecting the three major Cretaceous aquifers;

(4) begin a statewide survey of temperatures of thermal ground waters;

(5) begin data reduction for a map depicting statewide geothermal gradients;

(6) provide data to the U.S. Geological Survey (USGS) GEOTHERM File;

(7) construct a nontechnical ("public") geothermal map of Texas; and

(8) conduct an assessment of geothermal potential for military installations in Bexar, Travis, and Val Verde Counties, Texas.

These tasks were designed to be accomplished over a 2-year period. Hence, at present, we are midway through this research. Data collection is largely complete, but interpretation and refinement of predictive models (for exploration or for determining genesis, for example) must await further analyses.

The purpose of this report is to present findings to date, and since our main efforts have concentrated on collecting data, this report will largely consist of a critical analysis of these data. In order to address the eight tasks called for in our contract with the U.S. Department of Energy (DOE), two fundamentally different kinds of data were collected--well data and data pertaining to remotely sensed lineaments. Hence, the report is organized into two major sections according to these two main types of data. A series of appendices follows, and these present the data in detail.

Well data, addressed in Part I, were obtained from two different sources: (a) geophysical logs that are related mainly (but not exclusively) to oil and gas exploration; and (b) measurements of quality and quantity of ground water as related to water well development. Geophysical logs were employed to make lithic interpretations (tasks 1 and 8), and to ascertain geothermal gradients on the basis of bottom-hole temperature values (task 5). Water well information was used to make judgments of sustained aquifer capabilities (task 1), and to evaluate thermal value of ground water (tasks 4, 6, 7, and 8).

We obtained lineament data by viewing Landsat images, and these data are discussed in Part II. The perceived linear features constitute the "raw data" for a statewide inventory (task 2) and for subsequent analyses of their pertinence to structural and geothermal attributes (task 3).

PART I--DATA FROM WELLS

General

A well is a point source of information. This information has spatial, topical, and (commonly) historical attributes by virtue of any well's occupation of a precise location, its penetration of the earth's third dimension, and its sampling (either directly or indirectly) of rocks and fluids from underground. Depending on the data available for a given well, interpretations may be made regarding lithic properties at depth, various geophysical attributes (for example, temperature), and quantity and composition of fluids at various levels. In our ongoing statewide geothermal survey, we make all three kinds of interpretations, but the quality and quantity of our well data are not uniform.

Our overall data base comprises both water wells and petroleum exploration tests. In both instances, we are dependent on existing data. That is, no new wells were drilled for this study; we compiled our data base from extant sources, in which areal distribution and informational quality are markedly inconsistent. Except in areas of intensive resource development (such as an oil field), wells are seldom evenly spaced, nor do they necessarily penetrate all horizons of potential interest. Depth and spacing of wells are generally dictated by economic realities. Wells are where there is a resource, whether it be water, petroleum, or minerals. The water wells that compose a major part of our data base are distributed according to the areal extent and depth of known aquifers; and, because of drilling and pumping costs, the shallowest dependable water source will be tapped in a given area. These economic imperatives mean that a thermal water data base will consist of a few wells that are generally erratically distributed; thermal water is usually the water resource of last resort. Petroleum exploration wells are distributed according to analogous constraints.

Oil is where you find it, and "where you find it" is where you subsequently have the best subsurface well distribution. In other areas there may be occasional "wildcat" wells, but again distribution of data is likely to be very erratic. An example of a region of heretofore minimal petroleum exploration is along the Balcones/Ouachita structural trend--the very area of much of our current geothermal research interest. Conventional wisdom has maintained that since a crystalline basement complex (the buried Ouachita Mountains) lies at a relatively shallow depth along this trend, there is no reason to drill deep exploration wells. Now, however, given the success of petroleum exploration in other overthrust belts, deep drilling activity may increase in Central Texas.

In Texas, the universe of wells is large; there are more than 200,000 water wells on record at the Texas Department of Water Resources (TDWR), and this by no means includes all such wells in the state. Oil and gas exploration wells number more than 250,000, but these vast numbers of data points have often imposed a burden on our inventory process and data assessment. The large potential data population commonly constitutes a "poverty of riches" because of difficulties in locating, identifying, and making qualifying judgments on individual data. The specific problems are different for oil wells and water wells because the wells have been located using different conventions, the data have been collected for different ends, and the information has been stored by different agencies. We will address these particular problems for each major type of well in some detail, but suffice it to say that, to date, we have mainly employed compiled data--that is, data that is on record--usually intended for an altogether different goal than that of our project. We have no assurance either that a given well is located correctly or that any specific value cited is correct. We are at the mercy of these compiled data; hence, it is incumbent upon us to address problems that add to our uncertainty.

Procedures

For all types of wells and all sources of information, we compiled or collected two fundamental types of data: well location, which we plotted on maps, and topical (thematic) data, which we tabulated. In addition, we were careful to establish correct identifying linkages between topical data and their respective map locations.

Locational data consist of the precise 3-dimensional position of a well. They consist of areal ("x-y") coordinates, and the vertical ("z") coordinates, the latter of which are commonly overlooked in registering well locations. Vertical coordinates comprise both ground elevation and well depth. Sources of locational data include maps, citations of coordinates such as latitude/longitude, and narrative descriptions of survey records.

Topical data consist of the information that "flows" from the well, beginning with drilling and continuing through any production or monitoring activities. These data consist of direct lithic sampling (such as cuttings or cores), geophysical logs, data incidental to logging (such as bottom-hole temperature, or BHT), data on well completion, yield or production figures, and data on fluid attributes such as type, quality, and amount produced under given conditions.

The identifiers are the essential links between the recorded well location and the topical data. Identifiers, to be usable, must be inseparable from map location; that is, they must be included along with the data point on the map. Numerous conventions exist for identifiers. Examples include name of the well (operator/fee), various numbering systems (commonly an artifact of a regulatory agency, for example), and rarely, locational coordinates such as latitude/longitude, or township/range in states that use that convention. Various other topical or locational facts about the well are commonly used to corroborate a correct identifying link between a location and an accompanying data file; these include date of completion, ground elevation, well depth, and the like. However, the best identifiers are both unique and succinct, and preferably they connote location. Locational coordinates fit the first and last criteria, but they are unwieldy for presentation on maps. Other commonly used identifiers have similar defects.

The Texas state well numbering (TWN) system is a preferred identification convention in that it connotes location. Each well or spring may be identified by a unique nine-digit alpha-numeric code (fig. 2) that is divided into four subsets. In this system, the first two digits (the first subset) compose an "alpha code" denoting county (<u>see</u> Addendum C-2 of Appendix C); the other seven digits are numerical. The first two numerical digits (the second subset) specify the 1-degree quadrant; the next two digits (the third subset) identify the 7.5-minute quadrant; the next digit (the first item in the fourth subset) denotes the 2.5-minute subquadrant within which the data point is located; and the last two digits are assigned sequentially. The major problem with this number is that it is too long to be presented in its entirety on most maps.

The Texas state well numbering system was introduced by TDWR in 1962. Thus, for wells completed since that time, the state well number is designed to identify a well unequivocally, to signify its location, and to provide a unique "address" whereby data and information pertaining to the well may be found in TDWR files. The TWN system, however, is vulnerable to appropriation by non-TDWR workers, who may use the system's form (but not its content) by assigning identifying numbers in the state well number format to their own data points. This process has occurred, and it breeds "apparent" and "duplicate" state well numbers, both of which are incorrect. When such appropriation occurs, it becomes virtually impossible to decide whether data points compiled from different sources represent the same well or not.

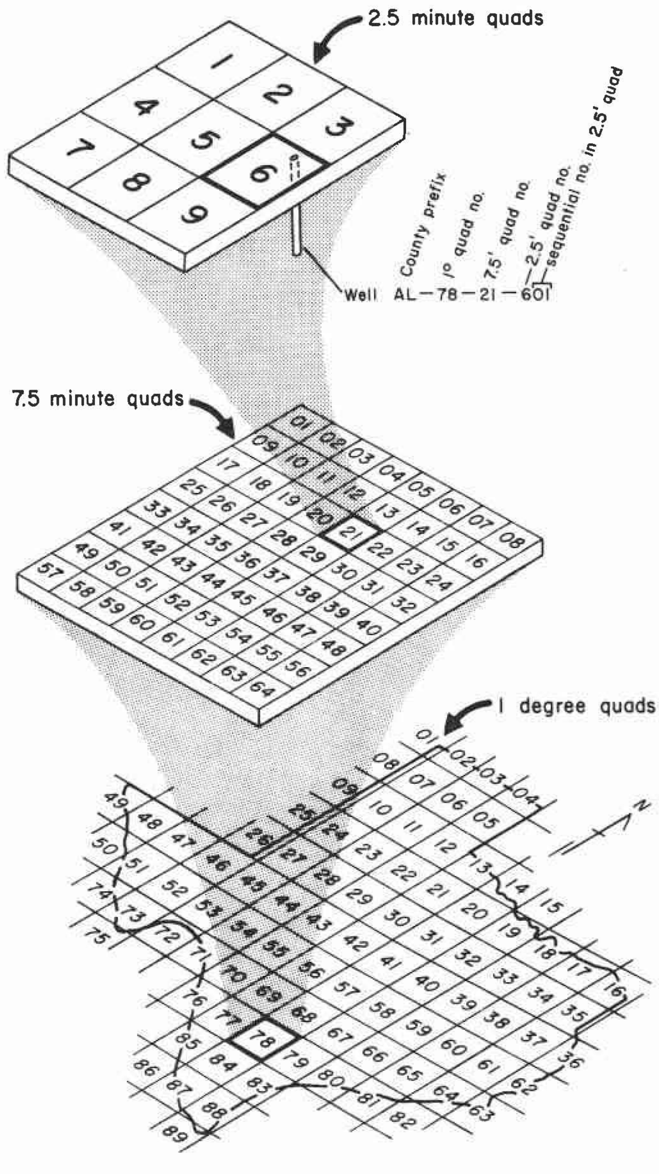
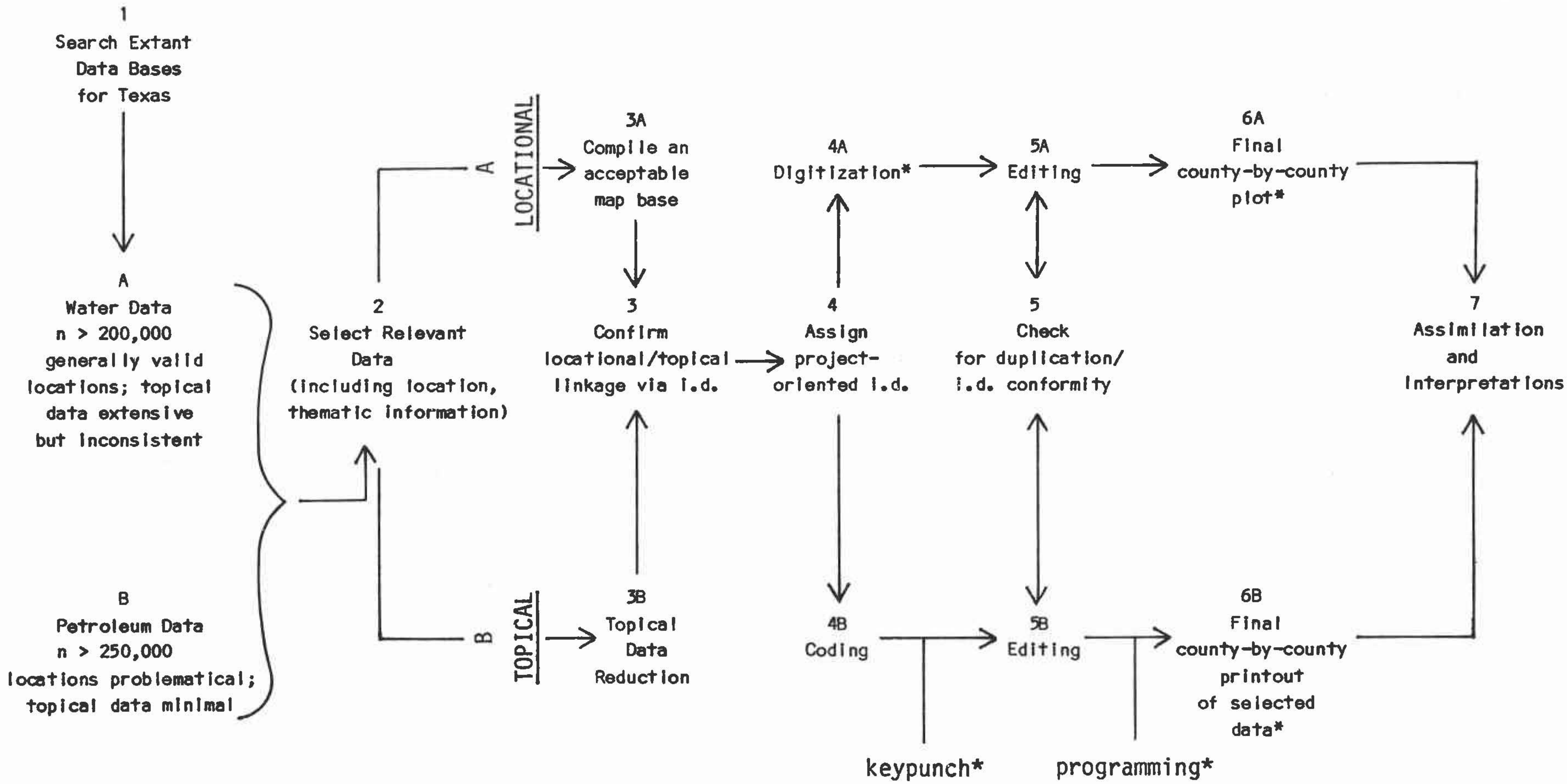


Figure 2. Texas state well numbering system. Note if any well in our data file is not documented to have a state well number assigned by TDWR, then we use only the first 7 digits of this numbering convention and leave the last 2 digits blank.

Prior to 1962, wells were identified by numbers arbitrarily assigned by state or federal agencies or other researchers for the purposes of specific publications; hence, the same well often appears in different reports under different numbers, or the same number may identify different wells in different reports. Cross-references may or may not be provided, so that for some counties, data compiled from several reports had to be inspected, well by well, for correlative data.

We employ a mutation of the TDWR state well numbering system, which is described in detail in Appendix C. For ease of cartographic presentation, we also denote a simple unique integer for each well within each county; we use this "county number" to cross-reference the well to the actual TDWR number, if one exists; this same system applies to both water wells and oil and gas tests.

With these data we used a computer for information storage and retrieval. Input into the computer is manipulated differently according to whether the data are locational or topical (fig. 3). Locational data are generally indexed in our data bank by digitization of mapped points. Latitude/longitude values are subsequently computed by machine from these digitized map locations. Conversely, when we have only latitude/longitude values and no mapped location, these "x-y" coordinates are encoded directly and a digitized map location is derived. We present the digitized locations of all our subsurface control in a county-by-county folio of maps (Appendix A). Topical data constituting these files were coded on standard computer forms, keypunched, and ultimately printed as a series of tabulations (Appendix B) for each digitized point. Appendix B, however, does not include all the information encoded for each data point; Appendix C shows the kinds of locational, nominal, and topical data that we stored in the computer.



*Tasks performed by computer services staff

Figure 3. Flow chart of tasks involved in acquiring, storing, and retrieving geothermal data in Texas.

These procedures seem simple, but the schematic tidiness belies great uncertainties with each stage of the process and with each type of information. The uncertainties generally stem from our use of information compiled from a variety of sources. Often we do not know who originally collected the data, and even if we do, we have no systematic basis for evaluating the collector's competence, techniques, or other extenuating circumstances that affect the quality of both locational and topical data. We have found random errors in both types of data, and we have noted inconsistencies with the identifying links. There is also a temporal component, which further adds to our uncertainty regarding well data. Underground fluids constitute dynamic systems, so that pressure (hence amounts and types of fluid yielded), fluid temperature, and fluid chemistry all change with time. These factors also affect the host rock and the well bore, resulting in further changes. There are changes, too, in our perception of physical or chemical characteristics owing to the state-of-knowledge or the state-of-technology regarding a particular component. Other "perceptual changes" in locating a well are due to imprecisions inherent in the use of maps. Topical data, however, can often be rechecked if the well can be located; therefore, we regard factors that affect well location to be most critical. This is because an imprecise location can transmute good topical data into poor information or even misinformation, by attributing it to an ambiguous area or to the wrong place.

Locational Data

Entering locational data into our computerized information system generally entails dealing with maps. Yet, since our data are from a variety of sources, we have been forced to compile locations using a variety of maps having different scales, projections, and hence, different degrees of accuracy. Location precision is also constrained by the choice of survey methods used initially in constructing each map base, by the care taken by the original locator of a well, and by the competence of subsequent cartographers in plotting data. In addition to all these possible sources of error, paper and cloth maps are subject to distortion and eventual deterioration. Distortion problems are apparent whenever maps are copied from one paper base to another; shrinkage is especially common when wet-copy (such as "blueline") methods are employed. These problems are compounded when maps that are copies are, in turn, copied, and this process may continue for an unknown number of generations of copies. Furthermore, at any stage of map use, there may be deletion or modification of the numerical or nominative identifier that links the map data point with its corresponding topical information.

In sum, locational (map base) problems are many. For example, even though the actual location of a well is static and unique, the accuracy and precision with which it may be represented are so variable that different sources of data can ascribe different locations to the same well, or the same location to different wells, thus resulting in specious locational data. Our uncertainty concerning the location of any compiled well data depends on factors attendant to the original collection of these data: the date of collection, purpose of collection and, in particular, limitations imposed by the format of the data (including map scale, projection, and the like).

For wells actually visited in the field, locational problems generally are minimal. Field locations are plotted on 7.5-minute maps and subsequently digitized, thus affording a high level of accuracy and precision.

Our confidence in the accuracy of locations for compiled data depends largely on the source of the information. We derive most of our water data from state water agency files, whereas most oil and gas well locations are obtained from county plat maps that show leases and land-ownership status. In general the locations of water wells constitute the more reliable data base of the two, but there are difficulties inherent with each of the two types of sources.

Sources of Locational Data

The TDWR maintains a vast archive of ground-water data along with information on selected oil and gas wells. For some of these wells, TDWR has established an elaborate data storage and retrieval system that encompasses topical information, well location, and identification. Whenever possible, we use this system directly. Commonly, however, it is necessary for us to modify the form of the TDWR topical, locational, and identifying data to meet our needs. These modifications are necessary because the TDWR data exist not in a single integrated system but in a series of unrelated files. Moreover, there are other ground-water data that do not exist in TDWR archives, and for many of these, locational problems are more confounding yet. Thus the problem with our using TDWR locational data is that the locations do not occur on a single type of base map (fig. 4).

Wells indexed by TDWR are plotted on one or more base maps provided by the Texas Department of Highways and Public Transportation (TDH&PT). These TDH&PT maps are in two formats: (1) "full-scale" (approximately 1:62,500) maps that display all wells having state well numbers, and (2) "half-scale" maps (1:125,000 for most counties; 1:250,000 for exceptionally large counties) that display wells composing selected data files. Both formats display a 7.5-minute grid appropriately labeled according to the Texas state well numbering convention (see fig. 2).

The TDH&PT maps are planimetric, employ a Lambert projection, and are conspicuously more accurate in rendering roads than natural features such as streams. These maps are also somewhat constrained by scale in that closely

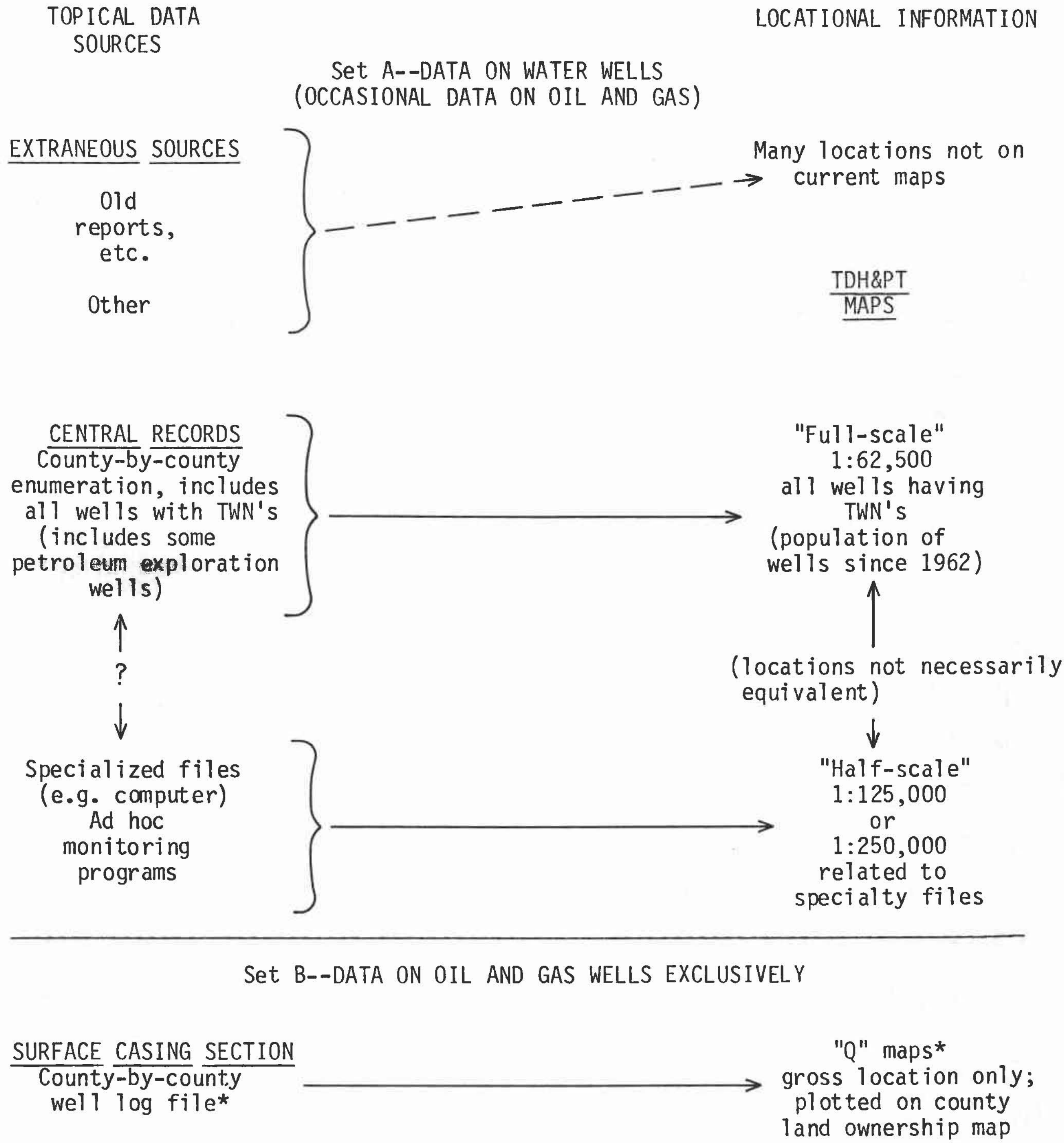


Figure 4. Schematic depiction of relations among topical and locational data in TDWR files. Note that many wells in "Set B" are also part of "Set A," but there is no existing convention for cross-reference between the two sets.

spaced wells are commonly shown as a single data point. The distinction of the two localities would be possible if a 7.5-minute map (from the U.S. Geological Survey topographic map series) were used, and in some cases, well locations are plotted at this scale.

Of the two TDH&PT formats used by TDWR, the smaller scale maps are consistently more accurate than the full-scale depictions. In other words, the smaller scale maps are not simple derivates of the larger scale version. Moreover, according to conventional agency procedure, the location of a well on the large-scale (full-scale) base maps is not ordinarily changed unless a change in state well number is called for. Thus, the radius of uncertainty ascribable to well locations not plotted from recent field data may cover at least a 2.5-minute subquadrant. Finally, locations obtained from TDWR half-scale and full-scale maps alike are subject to the distortion endemic to blueline reproductions. The eventual deterioration of blueline maps is a further problem; the paper becomes brittle and discolored, and the printed lines fade with time.

In some instances, the poor quality or absence of locational data from other sources requires a search of the TDWR Central Records Division. There, files of well schedules contain records for more than 200,000 wells and springs indexed by state well number within each of Texas's 254 counties. These files of well schedules may provide locational data of three forms: a gross schematic map, a plot on a 7.5-minute map segment, or a field sketch map of the well location. The gross schematic is not generally useful for our purposes, but the 7.5-minute plot and the detailed field sketch both provide valuable information. The field sketch is commonly detailed and accurate, as it is prepared by TDWR personnel when the well site is located in the field. It shows large-scale features such as fences, driveways, houses, and distances in terms of feet or tenths of a mile. For data points that are so closely spaced as to appear on the TDWR blueline maps as coincident, these sketches enabled us to distinguish each well and to plot the wells on USGS 7.5-minute topographic maps, if no such depiction already exists. Since this process is time- and labor-intensive, however, it has been employed only for coincident data points or for wells that we wish to visit in the field and not for all wells having such sketches.

Certain problems also occur with our use of TDWR data owing to the presence in their files of locations provided by other agencies responsible for monitoring the wells, such as the USGS and the International Boundary and Water Commission (IB&WC). Such locations include the uncertainties inherent in secondhand data compilation, as well as another possible loss of precision if, for example, the original source locations were plotted at a scale smaller than 1:62,500. We have also encountered wells that have been assigned state well numbers but not an official location; these are mainly oil tests used as data points in published reports.

Finally, many well data from reports published before 1962 may not occur on any of the easily retrievable TDWR base maps, because 1962 is the year in which the Texas state well numbering system was initiated, along with the corresponding master files using TDH&PT maps. Well locations shown on maps accompanying these older reports resist compilation: map scale is typically smaller than even the "one-half scale" TDH&PT blueline maps; the few features displayed on maps in old reports bear little or no resemblance to current roads and drainage patterns; and latitude/longitude lines (if given) do not register precisely with respect to county boundaries as shown on detailed modern maps. The best locations that we were able to compile from these maps were determined approximately by measuring from latitude/longitude lines with proportional dividers, with some corroboration furnished by mapped cultural or physical features. More imprecise locations were obtained using an optical transfer scope; the amount of uncertainty accompanying transfer of locations, perceived visually as blurred lines and swollen points, is a function of the amount of magnification, the lack of registry of the two maps, and distortion resulting from other technical limitations. Locations compiled from these maps are almost always inferior to those obtained from any of the TDWR blueline maps, yet such data constitute the only locational information available for certain wells.

Data points compiled from the earliest water-agency publications lack any map location, however poor; instead well locations are described verbally, in terms of city blocks, geographical directions, and reference points such as "The County Courthouse." While such locations can often be established in the field, they presuppose a familiarity with the physical environment from which a map is abstracted. These data points could sometimes be located on a map by identifying them with a data point in a later source, that is, by scanning the well data for similar or identical names or identifying values.

A fairly extensive file of electric logs of oil and gas wells is housed at TDWR, along with maps showing the approximate locations of the wells. These data are filed at the agency's Surface Casing Section (fig. 4), where data are maintained for many of the oil and gas exploration wells that have been drilled in Texas since approximately 1950. The wells are identified by the registration of a "Q" followed by a number that is sequential in time of posting and corresponds to a file containing the respective geophysical log or logs. However, more than one log may be stored in a single "Q" file; hence the "Q" numbers are not unique. Nor do these maps provide a precise location. The number and maps are maintained for intra-agency use only, and are not systematically cross-referenced to any other well identification system. For their "Q" maps, the Surface Casing Section uses blueline copies of county property survey maps that have no latitude/longitude tics, no topographic contour lines, and only crude renderings of drainage and cultural features.

Central to our location problems with oil and gas wells is the fact that Texas does not use the Township-Range system. Instead, Texas uses a cumbersome title/abstract land survey and record system, based largely on original land grants. Counties are subdivided into surveys, which are nonsystematic, are not related to latitude/longitude, and are irregular in size and shape. Surveys may further be subdivided into blocks and abstracts. None of these survey divisions or subdivisions appear on Army Mapping Service (AMS) maps, 7.5-minute USGS quadrangle maps, or county maps such as those provided by TDH&PT for the location of TDWR water well data. This means that locating oil and gas wells depends on survey maps prepared by the Texas General Land Office or by commercial land and title companies, or on derivatives of these maps prepared by petroleum-information firms. Such maps generally do not even show latitude/longitude coordinates, and have only an incidental, minimal, and often incorrect or outdated display of cultural and natural features. Furthermore, Texas county surveys are usually registered in varas, an archaic Spanish unit of measure that equals 33.33 inches; county survey maps commonly employ a scale of 2,000 (or 3,000) varas to an inch. If the Township-Range system were used, then points could be located quickly on any standard map with latitude/longitude coordinates; precision of location would depend only on the accuracy of the initially recorded locational information and on map scale.

We derived all locations of wells that constitute our stratigraphic control points from preexisting sources, none of which was ideally suited to our needs. Sources for our locations included: Geomap, a commercially prepared map series showing locations of oil and gas wells; open-file maps (the "Q maps") from the Surface Casing Section and other branches of TDWR; Texas Railroad Commission (TRC) maps; published geologic reports; Petroleum Information (PI) computer-generated maps; and various county cadastral maps on which wells have been located by commercial firms.

In no instance do these maps show topography, yet the "z coordinate" is clearly important for any correlation among adjacent well locations. A well site is always carefully surveyed, but this survey focuses entirely on the areal position of the well with respect to the leased acreage. The entire purpose of this surveying process is not to establish correct "x-y" coordinates but to establish that the well is on the correct leased property. The vertical component is often ignored entirely. Even if elevation is cited on the log it is often an ambiguous value, because it may refer to the elevation of the ground, or to some part of the drilling rig such as the derrick floor or the kelly bushing. Omission of a precise elevation occurs because the petroleum engineer, who logs the well, is concerned mainly with depth, regardless of datum. Only later, when a geologist tries to correlate the well stratigraphically, does the omission of elevation on the log become problematic.

Unified Base Map for Project

We digitized the locations of wells from the various source maps on several types of base maps. For most compiled water data, we digitized from the "one-half scale" TDH&PT base maps, although in some instances we used the corresponding "full-scale" maps. For wells located in the field and other data where we had exceptional assurance of precise location, we used 7.5-minute quadrangles (or 15-minute quadrangles where the larger scale format is not available). For all other data, including most oil and gas wells and certain poorly located water wells, we used the AMS, 1:250,000-scale, one-degree by two-degree quadrangles.

Computer output may be designed to print at any desired scale. However, we chose a scale of 1:250,000 as the preferred format to display all data from all diverse sources. This was done so that our data could be readily transferred to work maps on an AMS base, which has: (1) Transverse Mercator Projection;

(2) topographic contours (generally with 50 or 100 ft intervals); (3) latitude/longitude coordinates; and (4) reasonably detailed depictions of natural, political, and cultural features.

We chose this base because: (1) it is readily available and is of regional scale for compiling data across much of Texas (allowing comparison all along the Balcones/Ouachita structural trend, for example), yet it is also reasonably accurate for depiction of cultural or natural features in individual counties; (2) it shows topography and thus allows us to check approximate ground elevation (the important "z" coordinate); and (3) it allows construction of various locational grids (latitude/longitude or Universal Transverse Mercator, or UTM). In sum, these attributes qualify this map series as a unified base for display of data from disparate sources, and especially for the merging of the petroleum exploration data and geohydrologic data on the same map.

The convergence of two distinct data populations on a single map base has resulted in occasional duplications of the same well. We have detected some of these duplications, but because of the common inconsistencies or omissions of corroborating topical data or identifiers, some duplications may still occur.

We use the computerized presentations of map data at 1:250,000 scale to construct various thematic maps. These we interpret and contour for various stratigraphic, hydrologic, or thermal attributes which are in turn submitted for drafting and reproduction. Most of our contouring is done at 1:500,000 scale, although in certain areas having a large population of data, we contour at a scale of 1:250,000. These work maps are generally drafted at a scale of 1:1,000,000, and are reduced to a page-sized format.

Topical Data

Topical data include all information derived from a well. Topical water data include water temperature, total dissolved solids (TDS), rate of flow, and date of collection. Many wells for which a geophysical log is obtained (that is, most recent petroleum exploration wells) provide data on bottom-hole temperatures. This information, in conjunction with depth, allows a rough estimation of geothermal gradient. In certain instances, well completion data are valuable for interpretations of both water wells (for assessing aquifer properties) and oil and gas tests (for computing equilibrated down-hole temperatures). Also, in many instances, data that we obtain are actually either interpretations or the raw material for subsequent interpretations. Examples include the "aquifer designations" (for water wells) as an interpretation already made, and the geophysical logs as grist for the interpretative mill. Finally, for both water wells and petroleum exploration tests, we collect a variety of data that serve to verify either location or identifiers. Examples include well depth, ground elevation, date of drilling, names of owners and operators, and established well number(s).

We employ topical data to answer several fundamental questions. How hot is the water from a given aquifer? How saline is that water? What is a safe, sustainable well yield? Answers to the queries about the water are founded in part on lithic interpretations, that is, judgments on which aquifer is producing water at a locality, and on the local stratigraphic or structural discontinuities that might, of themselves, account for thermal anomalies. Our lithic interpretations depend on whatever stratigraphic information is at hand, be it drillers' logs, electric logs, or second-hand citations from existing files. Finally, as already stated, stratigraphic data points based on geophysical logs commonly provide a second approach to the assessment of geothermal resources in an area; these data (in their simplest form) include BHT and depth, which allow the computation of approximate values for geothermal gradients. For each type of topical data, however, there are sources of error, the major ones of which warrant explication.

For topical data, in general, newly collected information is generally more valid than old data. This is largely because of the increasing sophistication of instruments and techniques. That recent data are more accurate is true especially of water quality data and geophysical logs, and to some extent of water temperatures and hydrologic data.

The quality of older data is necessarily limited by the state-of-the-art during the time when it was collected, as well as the prevailing state-of-knowledge concerning the particular type of data in question. The quality of older data is limited in another way: the physical characteristics of thermal water actually change with time. All things being equal, we consider the most recent measurements of temperature, flow, and TDS to represent most correctly the current state of the aquifer in question. But changes in the recently collected data may result from changes in the well itself. Decay of the casing and clogging of the screens or perforations cause water from other aquifers to contaminate the well. Likewise, such changes in the well may actually prevent water from the original aquifer from entering the well. These factors result in apparent changes in the measured characteristics of the water--either temperature, salinity, or flow--yet the actual characteristics of the water from the aquifer of interest to us may not have changed. Thus, recent data may actually be providing information on the physical state of (altered) environment of a particular well, rather than on the physical attributes of its (presumed) aquifer. For this reason, the interpreter of water data, especially when using compiled data, must continually exercise critical judgment as to whether the data reflect actual changes in the aquifer over time or only local well conditions at a single, particular "moment" of measurement.

Another important constraint on topical data quality is the data source, irrespective of temporal considerations. Water quality data, unlike locational data, are susceptible to the "mission effect," that is, the quality of certain data depends upon the purpose for which the data were originally collected. For example, TDWR measures water-temperature and water-chemistry constituents as part of statewide monitoring of water quality. In view of this mission, the focus is on water quality and not on temperature. Similarly, data collectors for DOE's National Uranium Resource Evaluation (NURE) program were primarily interested in the uranium-bearing possibilities of the water they sampled, as well as in collecting a large number of samples in a brief period of time (a few months for a 1-degree-latitude by 2-degree-longitude sheet); hence, water temperature was measured almost casually at times, as a parameter associated with, but subordinate to, water chemistry (in some instances, water temperature is recorded only to calibrate a pH meter). The number of anomalously high NURE water temperatures in otherwise nonthermal areas testifies to the inaccuracy of these data as representing formation temperature. In our study, water temperature is a more important datum than it has been for any previous collectors of water data; therefore, even though the USGS and TDWR observe high standards of collection, our temperature measurements have the highest relative validity because of our mission.

An example of the "mission effect" affecting thermal information from the stratigraphic data base is seen with bottom-hole temperature. BHT is obtained primarily to calibrate mud resistivity, and not to obtain a true equilibrated downhole temperature. In fact, almost no BHT of a recently completed well would provide an equilibrium temperature, because a considerable amount of time must elapse after mud circulation has stopped for dissipation of the thermal disturbance near the well bore. Moreover, the restricted purpose of technicians conducting logging operations has resulted in a cavalier attitude with respect to temperature measurements. The narrow scope of their mission has resulted in a high frequency of lost data or invalid measurements for this important geophysical parameter.

In addition to these general constraints, common to water data and oil and gas data alike, there are also specific problems that cast uncertainty on the main topics (water temperature, salinity, and the like) compiled in our data base. It is important to maintain a critical awareness of the various sources of uncertainty.

Water Temperature

Erroneously high temperatures may be encountered in shallow wells during hot-weather months, owing to an influx of unduly warm recharge waters. Likewise, a measurement made from water obtained directly from a holding or pressure tanks during warm weather will represent the addition of solar heat to a possibly nonthermal resource; in cold weather, such a measurement may be deceptively low. For thermal waters under artesian pressure, on the other hand, an erroneously low temperature value may be obtained if the well bore has not been evacuated prior to measurement. None of our sources of compilation indicates measuring point, air temperature, or other conditions of measurement, but these seasonal influences on perceived ground-water temperature indicate that date of collection is a relevant factor for the evaluation of temperature data. Conflicting data from different sources, as well as field observation of selected compiled data points, indicate that these "random" errors are widespread. In some instances, there is so much supporting evidence for or against a particular datum that we made decisions to include or delete a given point without field verification. In short, date of collection and well depth provide presumptive evidence that may corroborate or refute a thermal temperature value. Anomalies, however, are not eliminated indiscriminately. We exclude some temperature values on the grounds of both date of collection (summer) and well depth (less than 50 to 100 feet) if there is contradictory evidence (such as other measured values from nearby wells) suggesting the absence of a thermal resource. We do, on the other hand, include some questionable anomalies located in "geothermal frontier" areas as targets for field verification.

The water-temperature data introduce another, unique variety of uncertainty into the compiled data base: the use of qualitative temperature data, such as the notation "hot." These data are reported and are not collected. Their sources are typically old reports that also have relatively poor identifying and locational information. Field investigation of such data points suggests that the datum "hot" was taken from drillers' reports, and was usually associated with oil tests long since plugged and abandoned. Generally, there is no possibility of reoccupying these sites and collecting precise, quantitative data. These data in fact exhibit a minimum of precision and a maximum of vagueness; they cannot be combined with other, quantitative data either in calculations or as points for contouring thermal values within the aquifer. They provide presumed temperature data with virtually no "hard" informational content; they are "thermal" data points in only the most tenuous sense. Yet, these data points perform a useful function within the compiled water data base when they provide information concerning the geographic extent of otherwise untested thermal aquifers. In the case of the only Hosston well in Uvalde County, for example, the datum "hot" implies the presence of thermal water from this aquifer far beyond its thermal reach as defined by quantitative data alone.

Total Dissolved Solids

Commonly, no two determinations of total dissolved solids (TDS) are absolutely identical, even for two samples collected simultaneously from the same well but analyzed by different laboratories. Collection techniques and field conditions, as well as those of the laboratory, affect the minute concentrations of constituents measured by analysis. Furthermore, experts themselves differ as to the best methods for conducting such analyses, adding to the limitations of precision (reproducibility) of such determinations. The actual constituents of the water, meanwhile, continually vary with time in response to myriads of variables that compose the dynamic system within an aquifer. For these reasons, the most recent value for TDS is in every case selected for compilation unless it is significantly inconsistent with previously substantiated values for the same data point. In no case is an anomalous value disregarded, but we have noted apparent discrepancies in the compiled data base. We also compile the dates of water-sample collection to aid in our qualifying interpretations.

Rate of Flow

Flow measurements or estimates refer only to wells (or springs) that are under sufficient hydrologic head to flow at the ground surface. These data appear somewhat haphazardly in our sources, and their values are commonly qualitative. As with TDS, we try to compile the most recent data, along with their date of collection. Most flowing thermal wells exhibit a steady decrease in rate of flow over time, and our data record many such wells that no longer flow at all. Springs are less predictable from measurement to measurement, but seem to change less over the long term. The compiled water-data base includes a relatively small number of thermal springs, plus several "sub-thermal" springs along the Rio Grande in Val Verde County. Flow data provide a crude representation of certain aquifer properties, while documenting the histories of particular data points; such data, however, are generally inadequate to determine in any detail the relevant attributes of specific aquifers as sustainable sources of geothermal energy.

Other parameters are more important for judging an aquifer's sustainable well yield: transmissivity, hydraulic conductivity, and storage coefficient. But determination of values for these properties entails numerous assumptions about the aquifer, the well bore, and the fluid. These assumptions, in turn, demand a compilation of an entirely new set of data, which are treated in detail in this report under the section on "quantitative hydrologic data."

Bottom-Hole Temperature

We obtain BHT values directly from the headings of electric logs; the data are obtained originally to calibrate log response to mud resistivity. As mentioned, however, the reported bottom-hole temperatures may not accurately reflect the nature of the thermal environment in which the temperature was taken because of two reasons. (1) The temperature or the corresponding depth at which the measurement is made may be read or recorded inaccurately. (2) The temperature may not be the equilibrium temperature; that is, the temperature in the well bore may not represent that of the formation at the measured depth.

The first of these problems is the result of simple human or instrument error and is largely unavoidable. Such errors can often be recognized from careful inspection of the well log and other records, and from comparison of data from several nearby wells. A related source of error is the former practice by logging technicians of reporting a calculated rather than an observed BHT derived from an assumed prevailing geothermal gradient that is extrapolated to the reported well depth. In any event, single-point gradient anomalies should be viewed with suspicion; one or more corroborative points should be obtained whenever possible before an apparent anomaly is seriously evaluated.

The occurrence of nonequilibrated temperatures reported as BHT mainly results from the mediating effects of mud circulation on formation temperatures. There is, of course, a cessation of circulation while the drill pipe is out of the hole for logging, and the longer the period during which mud is not circulated, the less will be the expected deviation between BHT and actual formation temperature. However, the downhole temperature perturbations may also be caused by downward migration of fluids from a shallow horizon, thus perpetuating a means for subsequent BHT measurements that are anomalously low.

There are empirical formulae for converting "raw" BHT values to equilibrated earth temperatures (see Kehle and others, 1970, and Oxburgh and Andrews-Speed, 1981). However, these empirical adjustments may not be valid for all geologic settings. Suffice it to say, estimations of deep-seated thermal regimes based on BHT must be conducted with awareness of the kinds of uncertainties that may arise.

A final problem with our computing BHT values is inaccurate depth recordings. In very deep wells the drill may deviate substantially off the vertical, and this may measurably increase the footage drilled to an actual (straight-line) depth. Such an error may account for anomalously low geothermal gradients in some wells.

Topical Identifiers

Compiled water data points include such information as driller, owner, and date of well completion, which, along with well depth and aquifer designation, may also function as identifiers. In other words, this topical information may be used to correlate a map location with its appropriate tabular data. These identifiers are especially useful for delineating or distinguishing data points from different sources when, for example, different well numbers are used, or a water data point seems to be the same as a stratigraphic data point. However, if a reasonable doubt as to the factual identity of two data points could not be allayed, then we compiled the two data points separately. In this way, some spurious data points are likely to remain in the compiled data base, despite our efforts to identify and remove as many as possible.

TDWR well schedules often provide historical information, documenting changes in the status of water wells; hence, well schedules are important sources for identifying wells. Using information from these files, we have been able to delete many spurious data points (different mapped points that in fact represent the same well), even though many of the topical identifiers such as ownership, well depth (if the well is deepened or plugged back), and well number itself (according to our source), are subject to change. The identities of two data points can usually be verified, as long as one data point can be associated with a state well number for which a well schedule exists.

Operator/Fee; Driller/Owner

Establishing the coincidence or noncoincidence of a stratigraphic data point with a water data point poses difficulties because of the range of variability for the nominative identifiers; that is, even the name of the well may be reported in various ways. The operator of an oil test may not be the same as the driller of the water well completed in the same hole; the fee designation may not be the same as the owner of the well.

The driller generally is the individual who actually operates the drilling rig. A driller may work for a company (the "operator"), but a common practice in water-well records is to list the individual's name, so that "driller" and "operator" are one and the same. This practice probably reflects the fact that, historically, water-well drilling concerns have often consisted of simply an individual and his own drilling rig. The overlap in function and identity reflected in water-well records has resulted in ambiguity. In some instances, the same water well may be identified by different drillers/operators, if, in fact, the driller and operator are not the same person. For oil-well records, such duplications seldom occur. The operator is the company or individual responsible for drilling the well, whereas the driller is one of the workers on the rig, and generally he remains anonymous on drilling records.

The owner cited by most TDWR ground-water reports and well schedules is the owner of the property on which the well occurs when the data are compiled. Consequently, this datum may not agree with the fee (lessor of the mineral estate) designation for oil wells or, in fact, with the owner cited on any previous or subsequent source of water data, depending on the ownership status of the property. TDWR well schedules sometimes record changes in ownership. Ground-water reports, on the other hand, make no mention of past ownership, and for compiled data points with no state well number, this information is difficult or impossible to retrieve. The usefulness of this identifier (operator or driller/fee or owner) is also limited by its frequent absence from older sources of data.

Date of Completion

Date of completion as presented on a well schedule is unequivocal, unless the well has been recompleted, a situation that is rare for water wells. However, for oil and gas wells (and some water wells) this date is often confused with the date of logging. The distinction is an important one. A well may be reoccupied and relogged long after completion. Even when the logging is conducted during the same general time as the drilling activity, several days may elapse between well completion and logging. Any elapsed time--whether long or short--is important to the estimations of possible equilibration of downhole temperatures. Date of completion is also a sort of identifier; this date alone may be the grounds for deciding that two data points are disparate if their dates of completion differ and no record of recompletion is found. Completion date, however, cannot establish the identity of two data points without corroboration from other identifiers.

Well Depth

Although strictly a component of the "z-coordinate" of location, well depth may also be used with caution as a topical identifier. When specified precisely (to the nearest foot), depth has often provided conclusive evidence for identifying two water data points.

Well depth, however, may vary considerably, depending on the source of the data (depth logged, depth drilled, depth of producing horizon, and so forth). Two data points, in all other respects identical, have been known to exhibit a recorded discrepancy of several hundred feet in well depth; they seem, nonetheless, to be the same well. On the other hand, several wells within a small area may have been drilled to almost identical depths during a single year.

Well depth is also useful at times in correcting erroneous aquifer designations, but depth may be changed owing to the deepening or plugging back of the well. If such changes in well depth are not documented, water data may be attributed to the wrong aquifer or may falsely imply a geothermal anomaly. Several instances of an apparently unrecorded change in well depth have been diagnosed during fieldwork, leading us to infer the undetected presence of numerous such errors among the compiled water data.

In addition to its being useful as an identifier, depth also provides key information for making judgments on anomalously thermal areas, on the basis of either water temperature or BHT. In computing geothermal gradient values, it is important to distinguish the depth logged (for which a given BHT is usually cited) from the depth drilled, yet the two values may be highly divergent. Finally, well depth provides a major criterion for designating a particular thermal target.

Aquifer Designation

Aquifer designation constitutes a type of data that is compiled not from a measurement, but instead, is based on an interpretation. Such interpretations are subject to considerable uncertainty--because of geologic complexity, varying (but unknown) competence of persons making the interpretations, and nomenclatural vagaries of the stratigraphic units denoted. Nonetheless, aquifer designation is very important information; it affects our total perception of water resources, including interpretations of ground-water quality, hydrologic properties, and loci of anomalous temperatures.

We have generally accepted, on face value, aquifer designations as recorded in various files by TDWR, since most of our water-well data eventually come from that agency. TDWR employs a three-digit numeric code for specifying aquifers. There are, so designated, 439 aquifers (or permutations of aquifers where a well produces from more than a single horizon; see Appendix C for a complete listing of these codes). We have identified five aquifers for which no code-number has been thus designated and have added these to the TDWR list.

The main institutional problem with the TDWR convention stems from the difficulties inherent in classifying the diverse and complex assortment of water-bearing units in the state. Fourteen rock units constitute 7 major and 7 minor aquifers that produce most of the ground water in the state. Yet local stratigraphic complexity, minor aquifers of local extent, nomenclatural subsets, and individual wells penetrating several horizons are subsumed in 439 TDWR designated "aquifers." When nomenclatural repetition (causing a multiplication of a single genetic unit) is accounted for (see fig. 5), less than 10 percent of the 439 "aquifers" yield most of the TDWR data. For example, the Hosston/Trinity aquifer, which comprises the main geothermal water-bearing formations in Central Texas, is represented in the TDWR aquifer codes by 37 different numbers representing nomenclature changes and combinations with other water-producing strata.

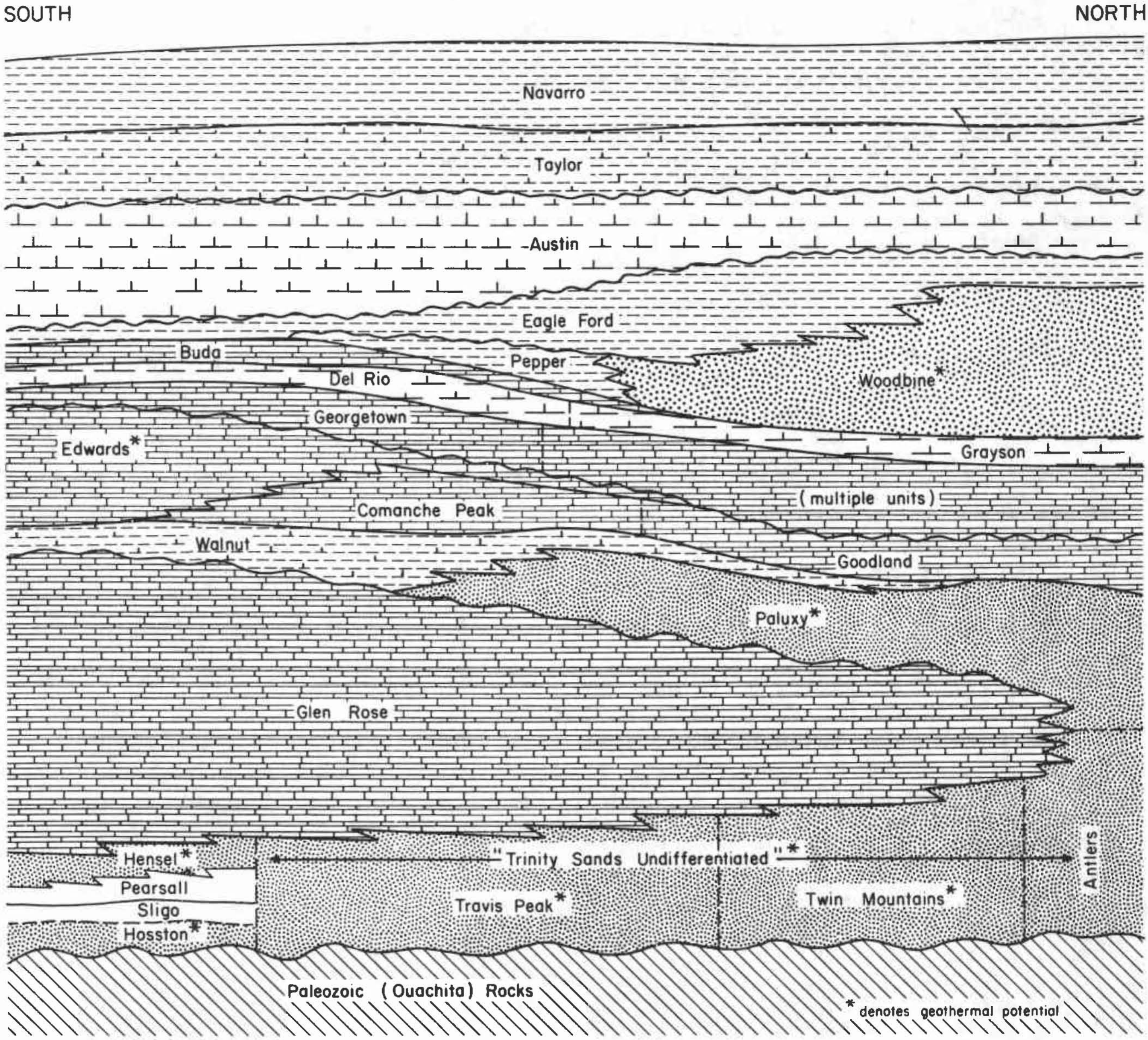


Figure 5. Example of nomenclatural complexity for Lower Cretaceous aquifers in Central Texas.

In summary, the TDWR tends to classify aquifers so as to include large and diverse units of water-bearing strata--including permutations of many, often unrelated rock units. In this way, there is no discrimination as to the finer distinctions and ambiguities of the units from which the name is derived. To resolve this, one must make a well-by-well judgment on producing horizon on the basis of whatever stratigraphic data are at hand. However, the stratigraphic data generally available for water wells are usually drillers' logs, and, as already discussed, these data are often unreliable. Data in the form of geophysical logs, cuttings, or cores provide abundant solutions to this problem, but seldom does a water well have the requisite stratigraphic raw information available for subsequent geological interpretations.

Besides ambiguities in geology and nomenclature, the condition of the well itself--its screens or perforations, casing, and the like--may alter which aquifer is actually producing water at a given location. Faulty recording of this important information is probably more common than is generally recognized, and it adds yet another variable and another level of uncertainty to subsequent interpretations.

Findings Based on Well Data

Compiled Water Temperature Data

Using publications and state agency files, we compiled selected groundwater data in order to obtain a statewide inventory of wells and springs. Documented water temperatures of wells and springs indicate low-temperature geothermal potential. We defined "thermal" water as at least 10°C above mean annual air temperature (Muffler, 1979, p. 87), that is, at least 29.4°C to 31.1°C (85°F to 88°F) for most counties in Texas. This compiled data base represents the best available (state-of-knowledge) compendium of geothermal aquifers within the state. This inventory delineates areal extent and various resource components (such as depth, temperature, TDS, flow) of these geothermal aquifers. The compiled inventory provides both a statewide catalog of known occurrences of thermal resources and a baseline for ongoing efforts at measuring water temperatures in the field. We are thereby documenting firsthand the extent and quality of geothermal resources in Texas.

Our compiled water data base includes 1,224 data points, selected by manual survey of all available sources of well data that contain water temperatures. This inventory is presented in its entirety in Appendices A and B. Appendix A is a county-by-county folio of maps showing computer-plotted locations of wells. Appendix B is a printout of selected tabular data and identifiers for each well. These appendices also contain our stratigraphic data base--that is, the inventory of logs, or cuttings, or cores that support our stratigraphic interpretations; stratigraphic data occur exclusively along the Balcones/Ouachita trend in Central Texas. The wells composing this part of our computerized listing number 1,143. Topical information sources for these stratigraphic data commonly do not contain values for water temperature, as they are usually petroleum exploration wells. They do, however, often contain BHT values that may be used to delineate areas showing geothermal anomalies.

This inventory supports our efforts to create a generalized statewide "public" map, and to maintain a nationally accessible (computerized) catalog of the resource. The creation of the "public" map is part of a cooperative program between the U.S. Department of Energy (DOE) and the National Oceanographic and Atmospheric Administration (NOAA); the computerized index (the GEOTHERM File) is a USGS effort, aimed at making raw data collected by the various DOE-sponsored programs widely available to the scientific community. Our computerized data entry and retrieval system (described in Appendix C) maintains currency of our data files and allows ready transfer of data pertinent to the "public" map and GEOTHERM File.

Another major function of the inventory is to use the presumed geographical extent and thermal, chemical, and hydrologic properties of the known resources in Texas as a baseline for establishing "target wells" for measuring water temperatures in the field. This field-oriented effort is the heart of our research.

Collected Water Temperature Data

We are now expanding the statewide inventory of geothermal waters by collecting water temperatures in the field, thus extending and refining the coverage provided by the compiled data base. By documenting additional occurrences of thermal and nonthermal water, we are able to define more precisely the geographic boundaries of the thermal reaches of geothermal aquifers, as well as their temperature attributes. Moreover, comparison of field observations with compiled temperatures enables us to evaluate and improve the quality of our compiled data. In some cases, valid temperature and locational data are made more precise; in other instances, erroneous or historical data are replaced by accurate, contemporary measurements. In either event, relevant information on the current status of wells or springs supplements the compiled data, and our own program of data-collection allows us to critique the general limitations of the compiled data base. The procedure for collecting new water-temperature data comprises two ongoing tasks: target selection and field observation.

Selection of Target Wells

The targeting process provides the field scientist with the best available location and all relevant topical data and identifiers for a selected population of potentially thermal water wells. Procedures involved in establishing candidate wells as field targets involve an algorithm (fig. 6). However, because of

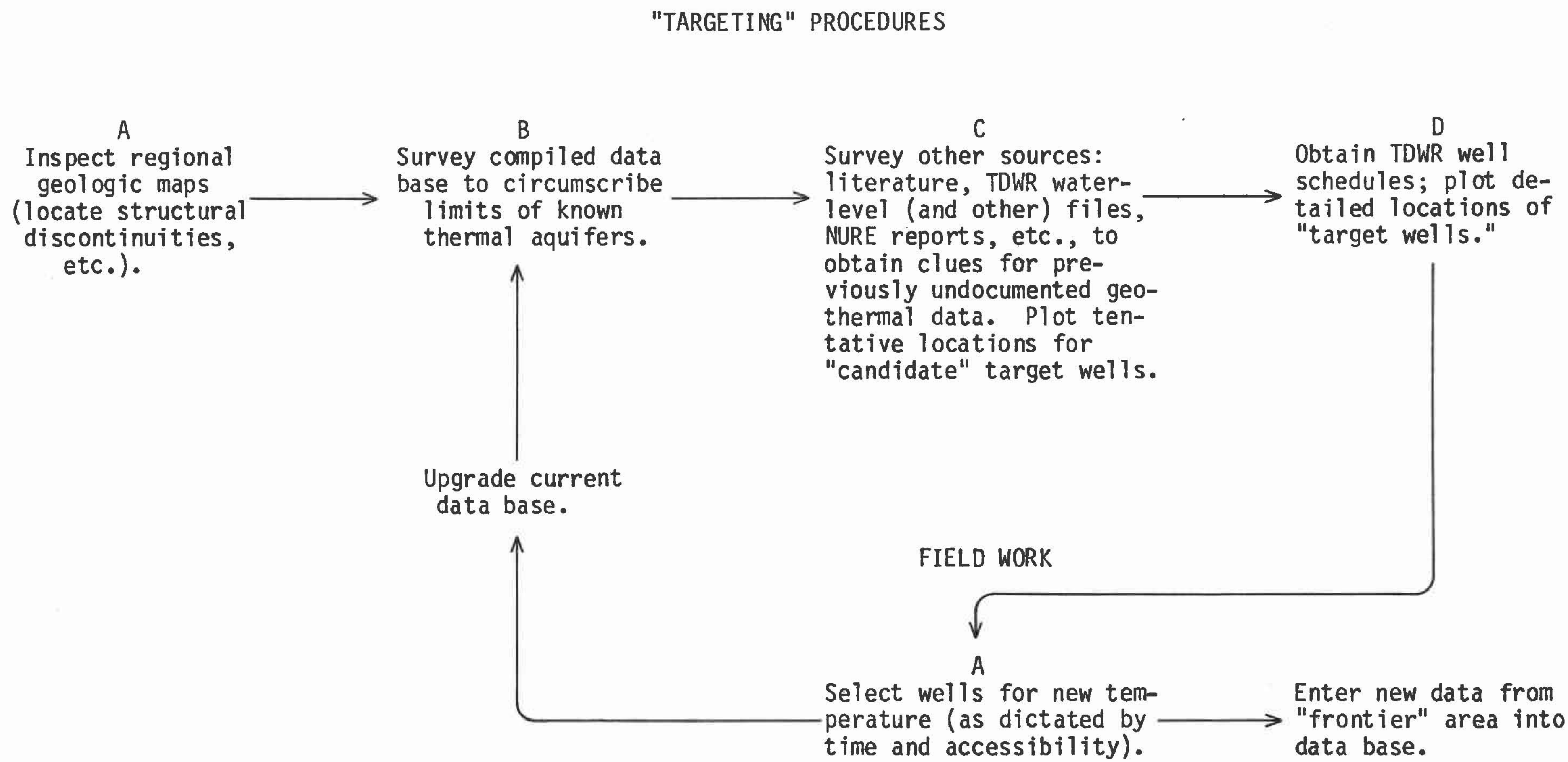


Figure 6. Algorithm for selecting target wells. Note feedback loops to the compiled data base and to the field collection of temperatures.

constraints imposed by the area that must be assessed and the size of the data population to be assayed, a much larger number of "candidates" target wells will be accessed that can actually be measured. Hence, much of the targeting involves a winnowing process to select the wells most likely to yield new information. Special attention is thus accorded wells that might prove a heretofore undocumented aquifer as having a thermal resource. Of second priority are targets that refine the geographic or topical precision of a geothermal resource that is already documented. Of third priority is the checking of suspect thermal wells--that is, those data that may be erroneously cited in current files.

Targeting is county by county, since that is how the TDWR data are stored. However, an initial part of our procedure is a regional structural/stratigraphic overview. This alerts us to any major geologic dislocations that may indicate previously undocumented geothermal potential. Such potential may exist owing to deep circulation along fault zones or upwelling of basinal waters, to cite only two possibilities. The regional perspective, thus obtained, is especially important because many counties in Texas have no water data that indicate any geothermal potential whatsoever. Yet such a potential may exist, and it may be indicated by regional structural or stratigraphic trends. The only means for accessing wells in these areas is through petroleum data including drill-stem tests, and by locating oil and gas tests that have been converted to water wells. In other words, the absence of compiled or collected geothermal data across much of the north-central plains and High Plains of Texas may be due to the local absence of such a resource. However, it might also be an artifact of the "samples" available to us, as dictated by the economics of drilling deep versus shallow wells.

Having conducted a reconnaissance of the regional geologic setting, we obtain any data that may identify potential targets. These data include mainly published reports and TDWR files. At this stage of investigation, we plot the promising data points on TDH&PT one-half scale maps. This is a very time-consuming process, but it is necessary in order to determine whether the candidate target well exists in a geothermal "frontier" area (our first priorities for investigation). This is determined by comparison to our compiled data base. Depending on local quality and quantity of existing data in a given county, we next obtain copies of TDWR well schedules in order to provide information on well completion, detailed location, and site accessibility.

Some wells may be eliminated from further consideration at this stage of investigation. Well records often show that certain wells are capped, plugged, destroyed, or otherwise inaccessible for further study. Depending on priorities, ease of access, and permission for access to the property, selected target wells may be visited in the field. During some of these visits we obtain water temperature data.

Field Observations

Our methods emphasized the collection both of water-temperature measurements as close to formation temperature as possible, and of precise well locations plotted on USGS 7.5-minute topographic maps. In the case of certain wells for which no chemical analysis could be found on record, we have measured pH, conductivity, salinity, and bicarbonate concentration in the field. We also collected water samples for laboratory analysis of sulfide and nitrate concentrations, and analysis of the major suites of anions and cations.

Field Procedures

Our first step in the course of each field trip is to contact, either by telephone or in person, water superintendents, landowners, ranch foremen, or whoever allows access to a given target well. The amount of territory that must be covered, the large number of targets for most counties, and uncertainties about who to contact generally preclude our making prior arrangements to visit most wells. Furthermore, the information provided by our sources, even by many TDWR well schedules, is often incomplete or obsolete, so that identifying and contacting the appropriate party requires interviews with City Hall personnel, storeowners, or neighbors--in other words, field work generally is needed just to locate the correct property owner. If we can contact the property owner or ranch foreman, we request access and, if necessary, permission to open a valve or start the pump; most often, our contact accompanies us and provides assistance and information.

If the well is not already flowing or pumping, we evacuate the well bore (unless the owner objects) before making measurements. We measure water temperature either downhole or as close as possible to the wellhead. We also record air temperature and other factors that might affect the measurement. Such factors include relatively low rate of discharge, distance from wellhead to measuring point, and failure to evacuate the well bore. The location of the well is plotted in the field on a 7.5-minute USGS topographic map.

Many wells have been located (that is, observed in the field) but have not yielded a water-temperature measurement. If the owner cannot be contacted (or identified), the well will not be measured unless (a) it is flowing or pumping and (b) access does not necessitate crossing a fenceline. Sometimes an owner may deny permission, or may be unwilling to start the pump in order to provide water merely for the purpose of obtaining a temperature value. The severe 1980 Texas drought prevented our obtaining numerous measurements because ranchers were reluctant to "waste" water by pumping unused wells. Wells ordinarily in use had been shut down as a result of depletion of the entire reservoir (as in Kinney County), and municipal personnel who might provide us access under normal conditions were often busy repairing pipe broken by the contraction of dry earth. Often, the owner provides access, but the well cannot be measured for other reasons: it may be destroyed, plugged, capped, or not producing water when observed. Geothermal water is often saline as well as hot, hence it is commonly destructive to croplands; similarly, dissolved hydrogen sulfide gas renders some thermal wells public nuisances. Municipal wells of this kind are obsolescent in many areas where surface-water projects are providing or are projected to provide adequate potable water supplies. Individuals often plug mineral wells because of the damage to the soil, or allow the wells to seal themselves by corrosion, or simply abandon them as the casing collapses and new wells are drilled for better water. Older wells may be destroyed regardless of water quality, as urban development makes different demands on land use; they may simply be covered by pavement, as has occurred at Terrell Wells in San Antonio, the site of a former health resort supplied by thermal ground water.

If a chemical analysis is called for, we measure pH, salinity, and conductivity with the appropriate meters; total calcium carbonate alkalinity concentration is determined by titration of 50 ml of water with 0.01639N HCl to a pH less than 4, with the actual endpoint extrapolated graphically. We collect two unfiltered 125-ml water samples in polyethylene bottles for laboratory analysis; one sample is treated with 5 ml cadmium acetate, to determine hydrogen sulfide concentration, the other with 5 ml chloroform, to determine nitrate concentration. An unacidified 250-ml sample, pressure-filtered through a 0.45 millipore filter, is collected for laboratory analysis of general anion/cation concentrations.

Equipment

If the well is flowing or pumping, we measure water temperature by immersing a standard laboratory thermometer with a range of -10° to 110°C directly in the flowing water. These thermometers are accurate within 1°C and precise within 0.25°C. If, on the other hand, the well is not producing water and is accessible to downhole measurement, that is, is open-hole, we use either a maximum-reading thermometer with a range of 0°F to 220°F, calibrated in 2°F increments, or a digital thermometer with thermistor probe manufactured by Enviro-Labs Inc., Glendale, California.

The maximum-reading thermometer is useful only when the air temperature is significantly lower than water temperature, that is, during winter months; it is attached to 2,000 ft of nylon cord, which on some occasions has snagged and prevented our obtaining a measurement. Thus, this instrument has proven to be of limited utility. The digital thermometer, on the other hand, is designed to measure water temperature with a precision of $\pm$0.05°C, regardless of air temperature; the probe is attached to 1,500 ft of cable, and is explicitly intended for the kind of field application our project calls for. We have encountered numerous problems with this instrument, however, which have cost us much time and labor; its defects of construction and design render it practically useless.

We experienced our first difficulties with the thermistor probe while attempting to calibrate the digital thermometer according to instructions provided by the probe's manufacturer. Although the calibration endpoints, 0°C and 100°C, were eventually obtained within the limits of precision, an error of 2 to 3°C persisted in the mid-temperature range, which is the range within which most of our expected thermal waters fall. Measurements of the resistance of the two thermistors in the probe itself revealed a 50 percent deviation from resistances as specified. After several months of experimentation and correspondence with the manufacturer, whose responses were typically neither prompt nor informative, we decided to use the instrument in the field despite its problems, since the heat of the summer months precludes the use of the maximum-reading thermometer, and we had established the probable error of the instrument within the thermal range.

We discovered during field work that the instrument is also poorly designed for its intended purpose. The weight exerted by 600 ft of extended cable was sufficient to destabilize the metal framework supporting the cable reel, so that the entire apparatus had to be bolted (semipermanently) to the floor of the field vehicle; the probe is no longer portable. The metal crank by which the cable is reeled up out of the hole had to be doubled in length, that is, redesigned and rebuilt, so that its mechanical advantage was sufficient for one person to rewind the cable. Even so, operation of the reel requires at least two people of average strength to pull more than 800 ft of cable out of a hole. Moreover, the device that measures how many feet of cable have been let out works only if the cable is fed through it manually; likewise, faulty reel design dictates that cable must be fed onto the reel manually during rewinding, another reason why the instrument cannot be operated by only one person.

Since water temperatures in well bores tend to equilibrate with those of the surrounding rock, it is desirable to lower the probe into unused wells as far as the cable permits (1,500 ft for our probe) in order to determine the geothermal potential of the water closest to the producing aquifer. In practice, however, obstructions in the well or irregularities in the casing generally prevent the probe from being lowered to the producing level. Open holes especially invite debris of various kinds (including, in one well, a golf putter).

Thus, as a result of many experiences with this instrument, each seeming to display additional defects of its design or conditions limiting its use, we have concluded that its application is virtually confined to open-hole wells (a) which are flowing slowly; (b) which are accessible by vehicle; and (c) where the probe may be lowered to depths of several hundred feet (and then reeled back by one person). This procedure allows us to obtain a water temperature more representative of formation temperature than are measurements made at the wellhead. But we have, to date, encountered only one well of this description among the 143 data points observed in the field.

Limitations

In some instances, water temperature may be measured, yet it may not represent formation temperature. If we are unable to evacuate the well bore satisfactorily or if a well is flowing slowly, our measurement will be considerably lower than formation temperature (a fact we note in our data base). Likewise, the amount of heat lost as water flows through pipe may be significant. If a measurement must be made of water taken from a holding tank, such measurement will probably be invalid because of the influence of ambient air temperature and solar heating. Also in a few cases, water-cooled pumps circulate pumped ground water through their cooling systems, thus contributing some recirculated (hence, cooled) water to the outflow point where temperature is being measured.

A final source of uncertainty in the collected data base relates to the previously mentioned problems of location and substantiation of well-identification. In some areas, it is not altogether clear which well is being observed. That is, if a well schedule shows one well where field observation finds two, it is not always possible to identify which well is described by the available data. Or, if a well was not targeted but is nonetheless observed in the field, it may not be possible to associate it with a well identified by state well number at TDWR. Sometimes, information may be provided by the owner, but owners' statements concerning well depth, date of completion, and the like are not always reliable. Consequently, there are a few data points collected in the field without substantiating information first compiled from our usual sources.

Status of Targeting and Field Collection as of September 1980

As of early September 1980, we have identified a total of 613 target wells in 126 counties; of all counties surveyed to date, 46 contain no target wells whatsoever (fig. 7). In addition to the target wells thus selected for possible field examination, there are 104 wells selected from DOE's NURE open-file reports. Many of these targets, however, are of relatively low priority for followup temperature measurement, because the values cited are commonly for shallow aquifers that are documented in the literature as not having anomalous temperatures and which have been monitored by NURE personnel during summer months. Hence, we presume that such values do not represent formation temperatures.

We attempted to collect temperatures from 143 wells to date (table 1). All these field data points occur along the Balcones Fault trend from Val Verde County to Falls County, including an intensive survey of the "bad-water zone" of Bexar and Atascosa Counties. Of the 143 attempted measurements, we obtained valid temperatures for 81 wells (figs. 8, 9, and 10).

Both targeting and field collection are ongoing tasks, and despite the problems enumerated here, the data thus collected are essential to the construction of a more complete statewide assessment of geothermal resources. The target wells that are not actually measured in the field remain in our files in case future workers attempt further measurements. Also, the wells that were not measured owing to their being plugged, destroyed, or otherwise inaccessible are also so noted. We feel that the failure to collect field data may sometimes be as significant as the data themselves.

Finally, just as our current state-of-knowledge based on compiled data has resulted in a "public" map showing the distribution of geothermal resources in general, the more refined data base that we are presently collecting will result in a statewide "technical" map to follow.

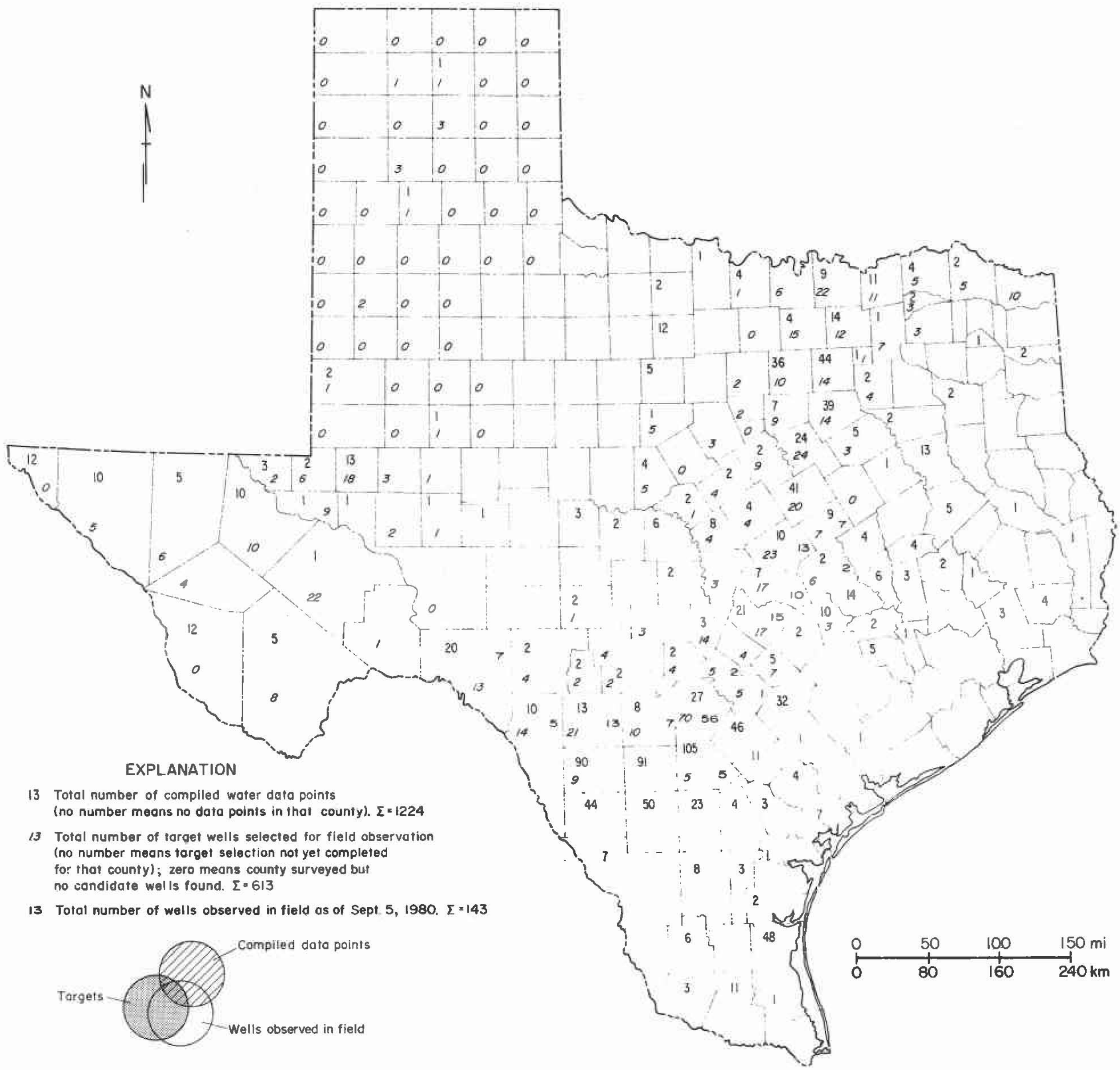


Figure 7. Status of "targeting" process in Texas as of September 1980.

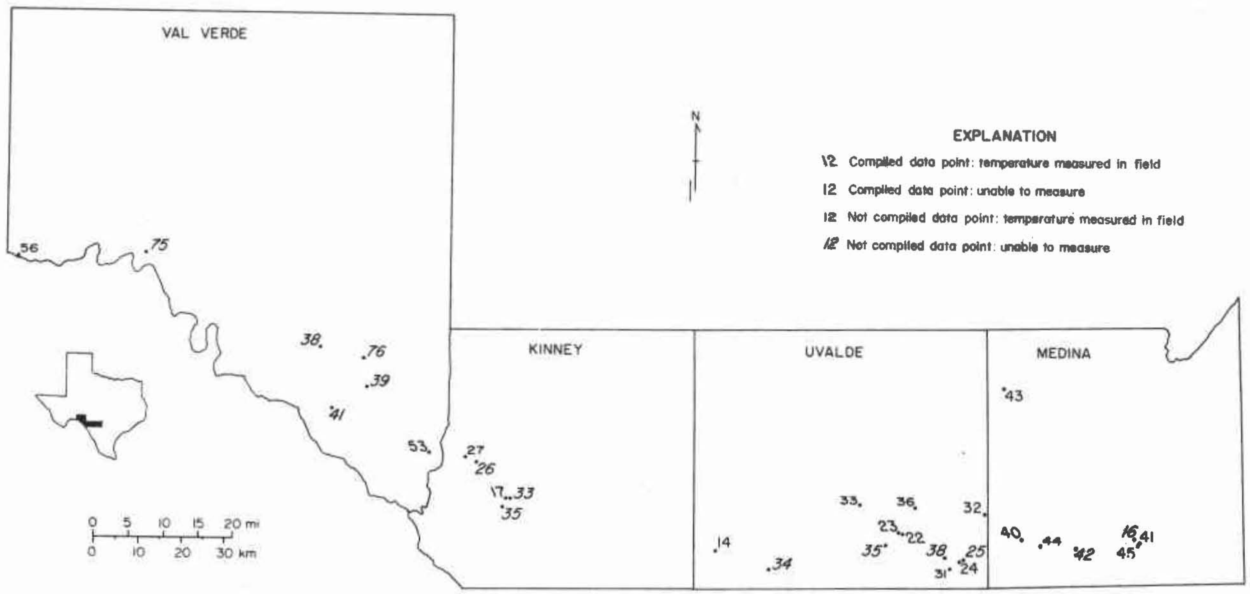


Figure 8. Field water-temperature measurement localities, southwest part of Balcones Fault Zone, as of September 1980.

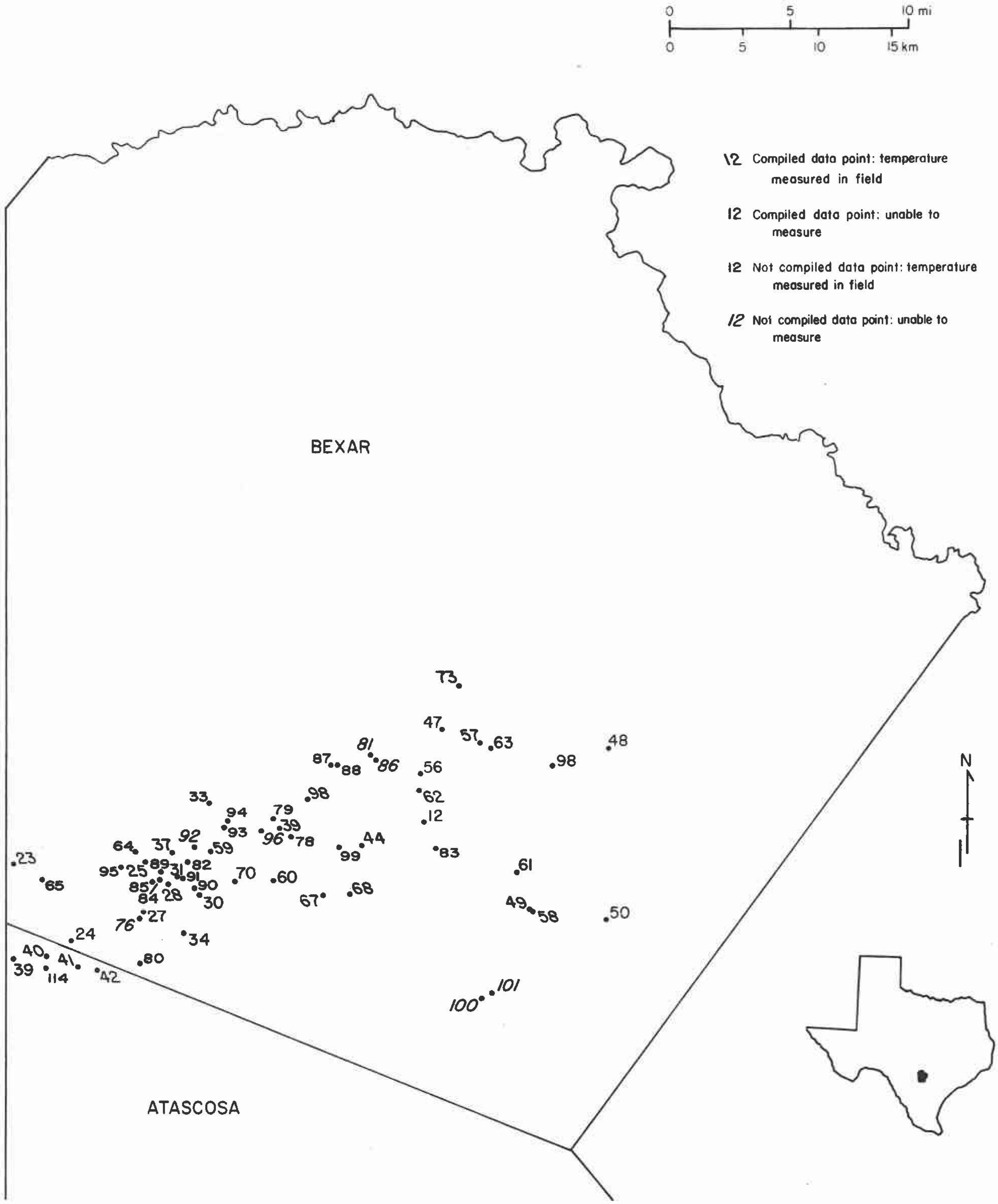


Figure 9. Field water-temperature measurement localities, Bexar and Atascosa Counties, as of September 1980.

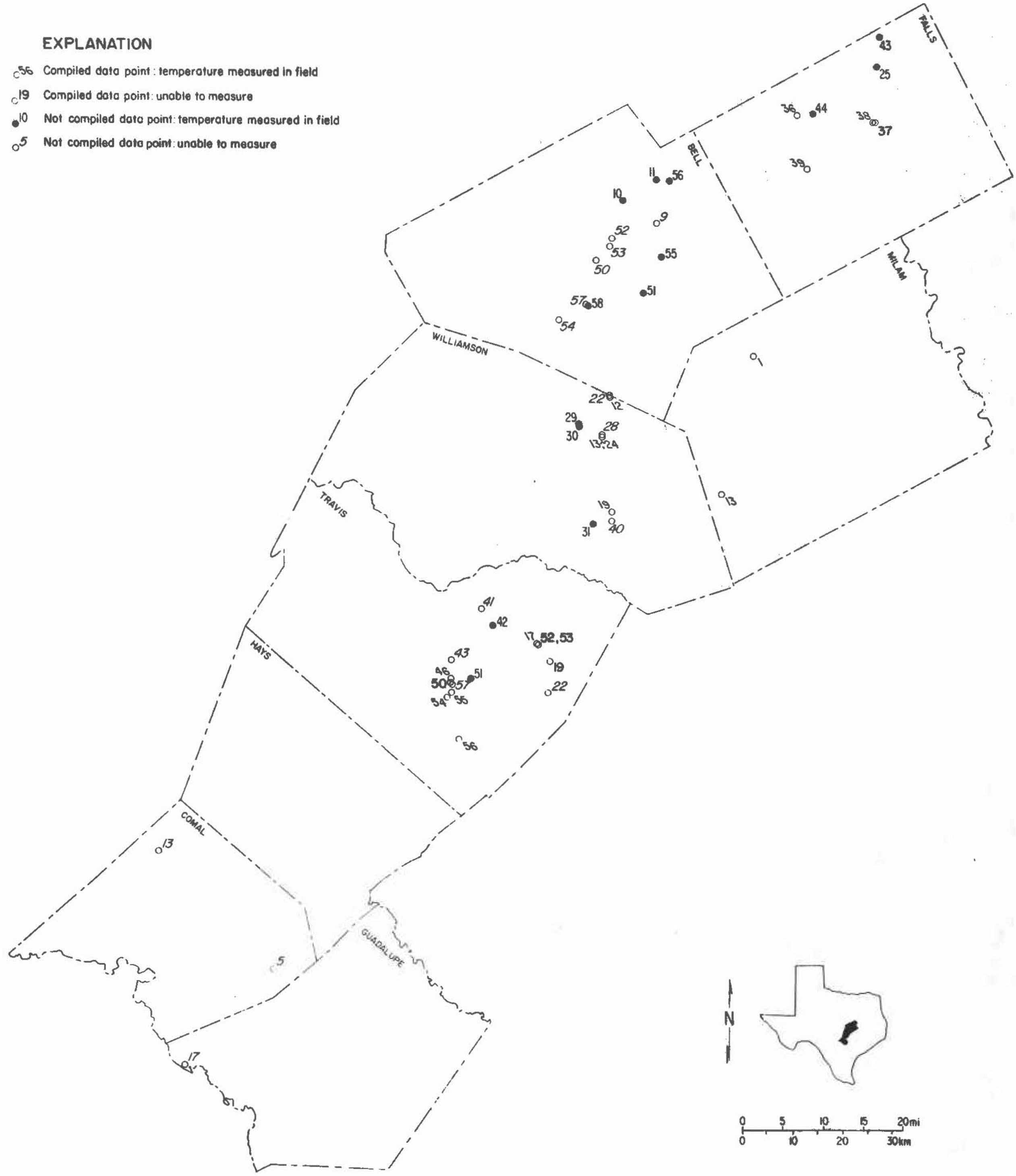


Figure 10. Field water-temperature measurement localities, central part of Balcones Fault Zone, as of September 1980.

Table 1. Wells for which temperature measurements were attempted in the field.

ATASCOSA COUNTY

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
39		see Appendix B		2,379	066	UTM
40		"		2,498	066	105.8
41		"		2,507	066	90.5
42		"		2,656	066	105.8
114	68-50-303	-	Gidley Estate	2,428	066	100.4

BELL COUNTY

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
9		see Appendix B		2,136	269	UTM
10		"		1,355	269	85.1
11		"		1,657	178	94.1
17		"		3,178	269	116.1
50	40-61-703	J. L. Myers Sons	City of Belton No. 3	1,293	269	UTM
51	58-06-102	Tx Water Wells	Bell Co. WCID No. 2 (Little River)	2,210	269	95.0
52	40-61-509	Layne Tx	City of Temple No. 3	1,261	269	UTM
53	40-61-503	J. L. Myers Sons	Brazos River Electric Coop No. 1	1,365	269	UTM
54	58-04-601	-	Paul Pirtle	2,300	269	UTM
55	40-62-501	Triangle Pump Supply	Acres WSC	2,236	269	95.0
56	-	J. L. Myers Co.	Pendleton WSC No. 2	1,828	269	97.2
57	-	-	-	-	066?	UTM
58	-	-	-	-	066?	UTM

BEXAR COUNTY

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
12		see Appendix B		4,700	066, 080, 269?	UTM
23		"		2,308	066	83.3
24		"		2,165	066	UTM
25		"		2,298	066	84.2
27		"		1,860	066	95.0
28		"		1,993	066	95.0
30		"		1,800	066	UTM
31		"		1,800	066	UTM
33		"		2,911?	066	80.6
34		"		2,226	066	UTM
37		"		2,002	066	84.2

Table 1 (continued)

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
39		see Appendix B		1,660	066	86.0
44		"		1,850	066	106.7
47		"		2,103	066	UTM
48		"		1,715	066	UTM
49		"		2,444	066	116.6
50		"		2,927	066	UTM
56		"		1,885	066	UTM
57		"		1,878	066	104.0
58		"		2,558	066	116.6
59		"		1,856	066	92.3
60		"		1,700	066	UTM
61		"		2,090	066	UTM
62		"		2,190	066	104.9
63		"		2,100	066	UTM
64	68-43-404	Burkett Drlg.	Henry Nentwich	2,285	066	80.6
65	68-42-902	J. R. Johnson	Atascosa Rural Water Supply No. 2	2,326	066	87.8
67		see Appendix B		2,355	066	110.3
68		"		-	-	104.9
70		"		4,518	178	UTM
73		"		-	-	79.7
76		"		2,055	066	100.4
78	68-44-405	Pegg Bros.	Mrs. Wm. Ripps	2,000	066	86.9 *
79	68-44-401	Fred Burkett	C. Verstuyft	1,532	066	82.4
80	68-51-102	J. R. Johnson	Frank Willis	2,363	066	108.5
81	68-44-214	J. R. Johnson	Thurman Barrett	1,285	066	UTM
82	68-43-814	-	Fritz Schneider	1,900	066	91.4
83	-	-	City of San Antonio	-	-	94.1
84	68-43-817	Pegg Bros.	Tony Constanzo, Jr.	1,949	066	95.0
85	68-43-806	Bill Pegg	Tony Constanzo, Jr.	1,887	066	84.2
86	-	J. R. Johnson	Thurman Barrett	1,662	066	UTM
87	68-44-215	J. R. Johnson	City Public Service Board No. 1	1,174	066	79.7
88	68-44-207	J. R. Johnson	City Public Service Board No. 4	1,686	066	80.6
89	68-43-815	Armstrong & Sutton	Aldridge Nursery	2,251	066	95.0
90	68-43-807	J. R. Johnson	A. A. Grothues	2,292	066	96.8
91	68-43-805	J. R. Johnson	Henry Verstuyft	2,195	066	93.2
92	-	-	R. R. Jarvis	1,850	066	UTM
93	68-43-608	J. R. Johnson	O. R. Mitchell Farm No. 5	1,683	066	84.2
94	68-43-607	J. R. Johnson	O. R. Mitchell Farm No. 3	2,068	066	85.1
95	-	-	Aldridge Nursery	2,160	066	91.4

Table 1 (continued)

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
96	68-44-407	J. R. Johnson	O. R. Mitchell Ranch	2,040	066	UTM
97	68-44-403	J. R. Johnson	Henry Krueger	1,781	066	76.5 *
98	-	-	Mrs. Francis Dullnig	2,215	066	UTM
99	-	J. R. Johnson	D. Saenz	1,767	066	103.1
100	-	Parks-Bailey	J. F. Bailey	2,000±	066	UTM
101	-	-	Joe Lamm	2,873	066	UTM
			COMAL COUNTY			
5	68-24-105	Killam & Hicks	Mrs. B. Gruene Estate	2,350	284	UTM
13	-	-	Norton Trust	480	066?	UTM
			FALLS COUNTY			
25		see Appendix B		3,764	269-080	143.6
36		"		2,708	269	89.6 *
37		"		3,378	178	UTM
38		"		3,350	178	122.0
39		"		3,295	269	135.0
43	-	J. L. Myers	Tri-County WSC No. 4	3,840	269	141.8
44	-	McClinton Drlg.	A. H. Rowan No. 1	3,002	269	118.0
			GUADALUPE COUNTY			
17	68-30-602	J. R. Johnson	Schertz Water Works	2,353	269	UTM
			KINNEY COUNTY			
17		see Appendix B		1,408	066	94.1
26	70-43-302	-	F. Beidler	1,600	066	UTM
27	-	-	Wardlaw (?)	-	-	85.1
33	70-44-801	W. S. Seward	G. A. & W. E. Woodward	1,390	066	UTM
35	-	-	Kintex Farms	-	-	UTM

Table 1 (continued)

MEDINA COUNTY

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
16		see Appendix B		5,515	178	UTM
40	69-54-501	L. W. Burell	John Farley	2,000	066	76.1
41	69-56-501	T. M. Johnson	Edwin Yanta	2,646	066	UTM
42	69-55-501	Pan American Oil	Lucian Ward	2,550	066	UTM
43	-	J. W. Roberts	Valdina Farms	2,206	180	UTM
44	-	Gulf Oil Co.	Carle (& Nester?)	2,500	066	81.5
45	69-56-507	J. R. Johnson	Fred Yanta	2,700	066	UTM

MILAM COUNTY

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
1		see Appendix B		3,448	269	129.2
13		"		2,231	213	126.0

TRAVIS COUNTY

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
17		see Appendix B		3,086	269	110.0
18		"		2,246	269	99.0
19		"		3,250	269	UTM
22		"		1,690	066	UTM
41		"		1,400	178 (269)	UTM
42		"		1,456	213, 066? 248?	80.6
43				1,975	289-319?	UTM
46		"		1,554	319	82.0
50		"		2,025	178	UTM
51		"		1,147	080	80.1
52		"		3,001	269	UTM
53		"		2,560	180	UTM
55		"		1,595	178	92.0

Table 1 (continued)

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer[†]	Collected Temp. in °F
56		see Appendix B		2,425	269	92.0
57		"		-	-	UTM
			UVALDE COUNTY			
14		see Appendix B		2,140	066	UTM
22		"		1,410	066	92.3
23		"		1,262	066	90.5
24		"		1,990	066	UTM
25		"		2,575	066	UTM
31	69-52-902	Layne Tx	Fred Woodley	2,242	066	100.4
32	-	-	A. L. Rehm	4,490	178	UTM
33	-	-	M. B. Walcott	3,030	080?	85.1 *
34	-	-	C. A. McDaniel	2,000	066	UTM
35	69-51-602	J. Roberts	Joe Hargrove	2,309	066-080	UTM
36	-	-	B. Reagan (?)	1,685	066	84.2
38	69-52-901	J. R. Johnson	Fred Woodley	2,632	066	UTM
			VAL VERDE COUNTY			
38		see Appendix B		3,502	-	UTM
39		"		1,560	066?	UTM
41		"		-	-	UTM
53		"		3,507?	066?	83.3
56		"			-	UTM
75	71-13-801	A. F. Holderman	V. B. & H. B. Ross et al.	1,213	066?	UTM
76	70-25-602	Shell Oil Co.	Elvis Stewart	2,410	070	UTM
			WILLIAMSON COUNTY			
12		see Appendix B		2,617	269	107.6
13		"		2,606	269	105.8
19		"		3,373	269	118.4
22		"		1,320	066	UTM
24		"		2,531	269	UTM

Table 1 (continued)

County No.	State Well No.	Driller	Owner	Depth (ft)	Aquifer†	Collected Temp. in °F
28		see Appendix B		2,605	269	UTM
29		"		~790	066	78.8
30		"		~790	066	78.8
31		"		1,115	066	UTM
40	58-29-605	Layne Tx	Taylor Bedding Co.	3,353	269	UTM

Explanation

† TDWR Aquifer Codes

066 Edwards Limestone or Edwards and Associated Limestones

070 Ellenburger Group

080 Glen Rose Limestone

178 Travis Peak Formation

180 Trinity Group or Trinity Sand

213 Fredericksburg Group

248 Glen Rose - Fredericksburg

269 Hosston Formation

284 Edwards and Associated Limestones
(Balcones Fault Zone Aquifer)

319 Lower Glen Rose

UTM Unable to measure

* Measurement not representative of formation temperature

Quantitative Hydrologic Data

Most identified hydrothermal resources in Texas occur in the downdip extensions of rock units that, in their shallower reaches, are important freshwater aquifers. Most of these aquifers are sandstones and limestones, which are tabular strata that dip into sedimentary basins. The hydrologic properties of these rock units--both in their shallow and deep (geothermal) reaches--are affected by (a) their primary (depositional) attributes, (b) their diagenetic history, and (c) their subsequent structural dislocations. These aspects of stratigraphic and structural history affect rock composition and overall geometry, degree of cementation or porosity augmentation (such as by dissolution), and amount of deformation (especially faulting) that forms secondary avenues for flow of underground fluids.

We have already assessed the overall lithic and structural attributes of those major Cretaceous aquifers that produce geothermal waters along the Balcones/Ouachita trend (Woodruff and McBride, 1979). In this previous survey, we delineated the general locations of major depositional systems and component facies for the various aquifers, and we ascertained the areal extent and amount of displacement of faults affecting them. The combination of these two lines of investigation resulted in our selecting the Hosston/Trinity Sands, the Paluxy Sand, and the Woodbine Sand for continued assessment. We selected these rock units on the basis of their importance as aquifers in their relatively shallow reaches, their local production of warm waters, and their lithic properties conducive to the maintenance of sustained aquifer yield in their downdip (geothermal) reaches. That is, for each of these aquifers, we delineated thick, dip-oriented sand trends that provide avenues for downdip migration of ground water; moreover, we accorded special attention wherever these dip-oriented sand geometries persist to sufficient depths for possible thermal enhancement of ground water. The structural "overprint" has proven to be an additional factor of importance to the location of geothermal resources. Down-to-the-basin, normal faulting, in particular, abets geothermal potential because of the marked increase in the depth (hence, temperature) of an aquifer within a short lateral distance. Likewise, enhanced hydrologic communication down or across fault planes allows deep circulation of ground water, or, in some instances, faults may act as traps, preventing downward circulation of cool meteoric waters and their mixing with waters deeper within a basin; either way, anomalous temperatures may be enhanced or maintained. Structural downwarping by monoclinal folding may similarly enhance geothermal potential--even where an "average" geothermal gradient prevails; this may result from deep-seated connate waters moving updip under pressure. The interactions of thermal waters and the aquifer host rocks under these circumstances, however, commonly result in diagenetic changes and the attendant plugging of pore spaces by secondary minerals, with a corresponding decrease in permeability.

Clearly, stratigraphic and structural attributes affect the porosity and permeability of aquifers, and these hydrologic properties affect the amount of water stored and the potential for ground-water production from a particular stratum. Although hydrologic properties may be grossly estimated from geologic attributes such as sand geometry or fault location, other kinds of data must be acquired in order to obtain meaningful quantitative information that relates local aquifer (lithic) properties to safe, sustainable well yields. These data generally involve the controlled pumpage of a well during a specified period of time and the measurements of changes in water level in response to this pumpage. Field operations that provide these raw hydrologic data are termed pump tests; only these tests allow us to properly assess and manage an aquifer. In short, porosity and permeability are generally not measured directly in the process of assessing the hydrologic properties of an aquifer. Instead, the various types of pump tests provide empirical data for depicting different hydrologic attributes. These tests depend on firm knowledge about the well bore itself and the aquifer penetrated; if firm data are not available, then assumptions must be made, but the quality of interpretations is lessened accordingly.

Hydrologic Attributes Tested

We attempted to obtain data that bear on three main hydrologic parameters: hydraulic conductivity, transmissivity, and storage coefficient. These parameters are related to Darcy's Law, in which a section of aquifer is depicted in terms of water yield as a function of hydraulic gradient and the cross-sectional area of the part of the aquifer examined, with allowances made for properties of the porous medium and the fluid by means of a constant. It may be expressed:

$$\underline{Q} = - \underline{KiA},$$

where:

$\underline{Q}$ is well discharge (expressed in volume [L^3] per unit of time [T]);

$\underline{K}$ is a constant of proportionality, termed hydraulic conductivity;

$\underline{i}$ is hydraulic gradient (the change in hydraulic head with depth); and

$\underline{A}$ is cross-sectional area (expressed in L^2).

The minus sign is a convention representing the negative function on a Cartesian graph between head plotted on the abscissa, and the elevation of the depth of the well plotted on the ordinate.

Hydraulic conductivity, also called coefficient of permeability, is the quantity of water that will flow through an aquifer cross section of 1 ft^2 under a hydraulic gradient of unity. From the Darcy equation, it is clear that hydraulic conductivity has dimensions of velocity, or L/T. In the English system $\underline{K}$ is commonly expressed in gal/day/ft^2.

Transmissivity is defined as the rate at which water will flow through a vertical strip of an aquifer 1 ft wide <u>and extending through its entire</u>

saturated thickness, under a hydraulic gradient of unity (Johnson Division, 1975, p. 102). Hence, transmissivity (T) is related to hydraulic conductivity (K) by

$$T = Kb,$$

where:

b is the saturated thickness of the aquifer;

T has dimensions of L^2/T and is expressed in gal/day/ft.

Storage coefficient (S) is the volume of water released from storage per unit area of the aquifer, per unit decline of head (Freeze and Cherry, 1979, p. 60). It is a dimensionless term that has values with magnitudes ranging from 10^{-1} to 10^{-2} for water-table aquifers to magnitudes of 10^{-3} to 10^{-5} for artesian systems. In other words, for a given change in head, much more water will flow from a water-table system than from an artesian system.

Values for all three parameters, K, T, and S, may be obtained in the field by conducting pump tests of wells. However, assessment of these tests presupposes certain conditions. For example, in obtaining S, proximity of an observation well penetrating the same horizon as the pumping well is required. Where these conditions are not met or are uncertain, either gross qualifying assumptions must be made or an evaluation simply cannot be made at that locality. There are similar constraints on data used to compute K and T.

As with the data on water temperature, our findings depend on compiled data, thus, we are at the mercy of the quality and quantity of data at hand. In brief, compiled pump-test data are of several types, and they have different degrees of veracity. For example, many of our interpretations are based on "specific capacity" tests that are run for a brief period by the driller shortly after a well is completed. These tests provide us with a crude basis for estimating T and K. Other tests include single-point drawdown tests, step-drawdown tests, and tests with one or more observation wells. In all instances, there are a number of variables that affect subsequent interpretations. Yet commonly our compilation sources provide us not with the raw data, but instead with second-hand interpretations. Since the quality of our findings (that is, the contoured values of T and K for the three aquifers studied) depends on the quality of these compiled data and interpretations, we critiqued the pump-test data bases for the three Cretaceous aquifers in Central Texas. These critiques (figs. 11A, 11B, 12, 13) qualify some of our interpretations.

Before presenting our tentative findings on the hydrologic properties of the various aquifers studied, it is appropriate to discuss factors affecting the amount, distribution, and quality of hydrologic data in general. We do this because of our utter dependence on compiled data and the fact that judgments have been made (anonymously) regarding: (1) which specific horizon is producing at a specific well; (2) well completion and development practices; and (3) vagaries of the testing process itself, including recording practices, instruments used, and interpretations of the time necessary for equilibrium to be attained.

General Problems Limiting Assessment of Hydrologic Attributes

Although there are copious data on various tests run on water wells, only some of these data may be used with confidence. Most pumping tests indicate only very generally an aquifer's hydrologic properties. Most tests are rarely able to reveal the water-yielding properties of one particular sand stratum. For heterogeneous units, such tests are not necessarily even a representative average of the properties of all the permeable units within a lithic package that is designated an "aquifer." The condition of the well and the conditions under which any particular test is run also affects the transmissivity calculated from a pumping test. Since these conditions are often unknowable after the fact, the degree to which a transmissivity value can be adjusted to account

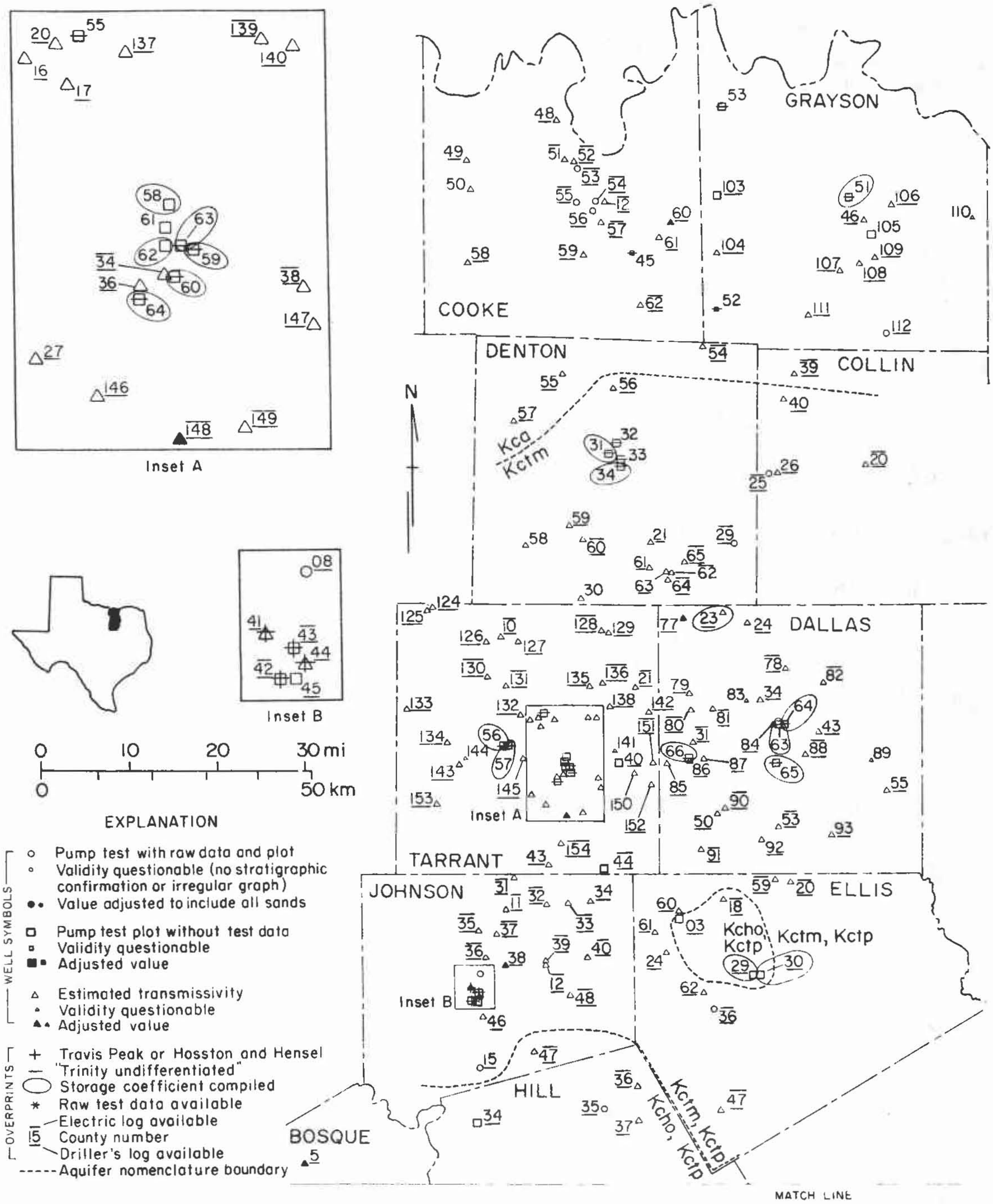


Figure 11-A. Data base for hydrologic assessment of Hosston/Trinity aquifer, northern part of study area. Note areas having different aquifer designations reflecting nomenclatural complexity of basal Cretaceous sands (see fig. 5): Kca (Antlers Formation); Kctm (Twin Mountains Formation); Kctp (Travis Peak Formation); Kcho (Hosston Formation); further aquifer designations are noted by various "overprints" as noted in figure explanation. Asterisk noted as an "overprint" refers to raw data for computing storage coefficient. Darkened well symbols indicate adjustments for partial penetration; reduced-size well symbols denote questionable data.

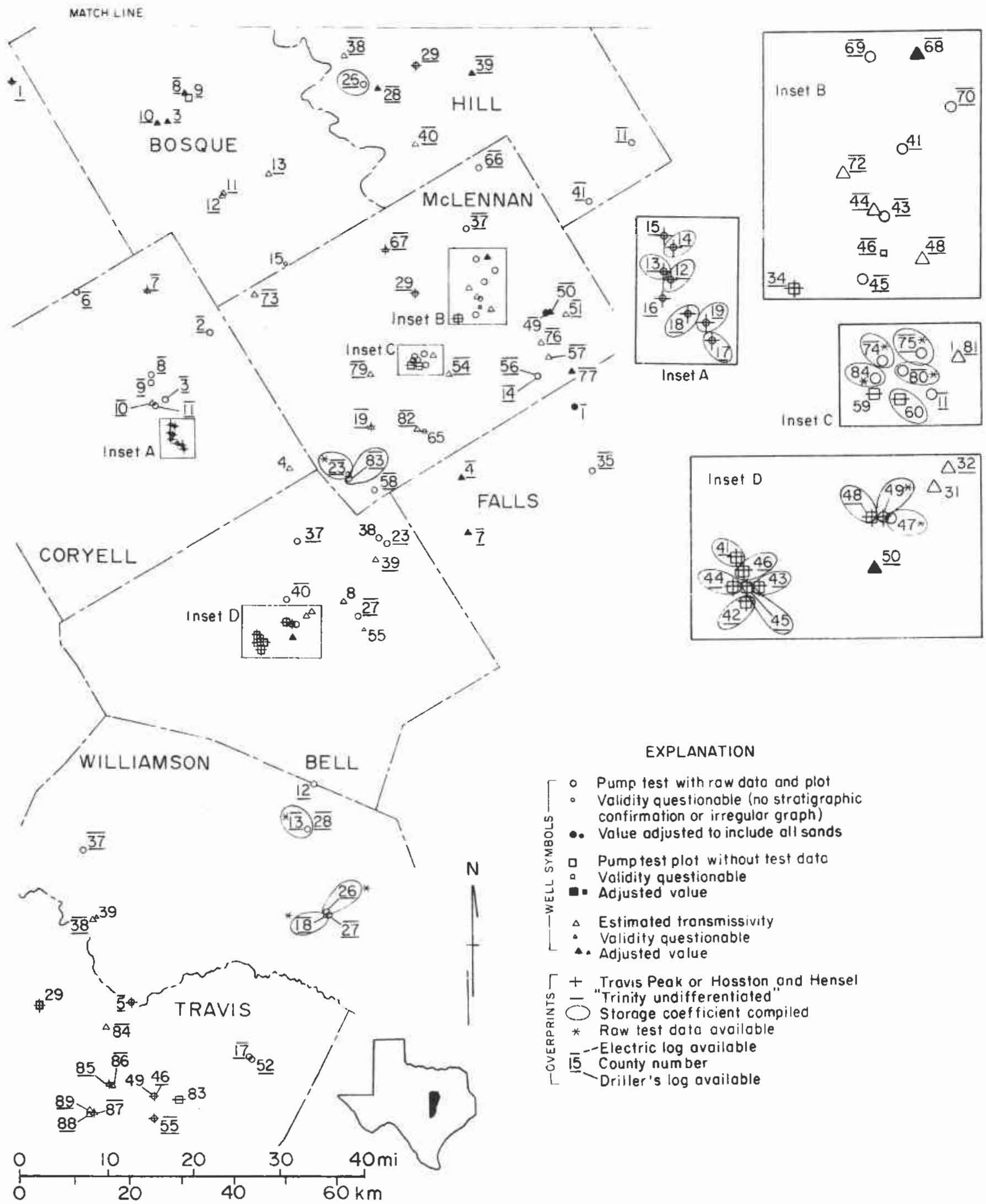


Figure 11-B. Data base for hydrologic assessment of Hosston/Trinity aquifer, southern part of study area. Unless indicated otherwise by "overprint" symbol wells are reported (by TDWR) to produce from Hosston Sand. Asterisk noted as an "overprint" refers to raw data for computing storage coefficient. Darkened well symbols indicate adjustment for partial penetration; reduced-size well symbols denote questionable data.

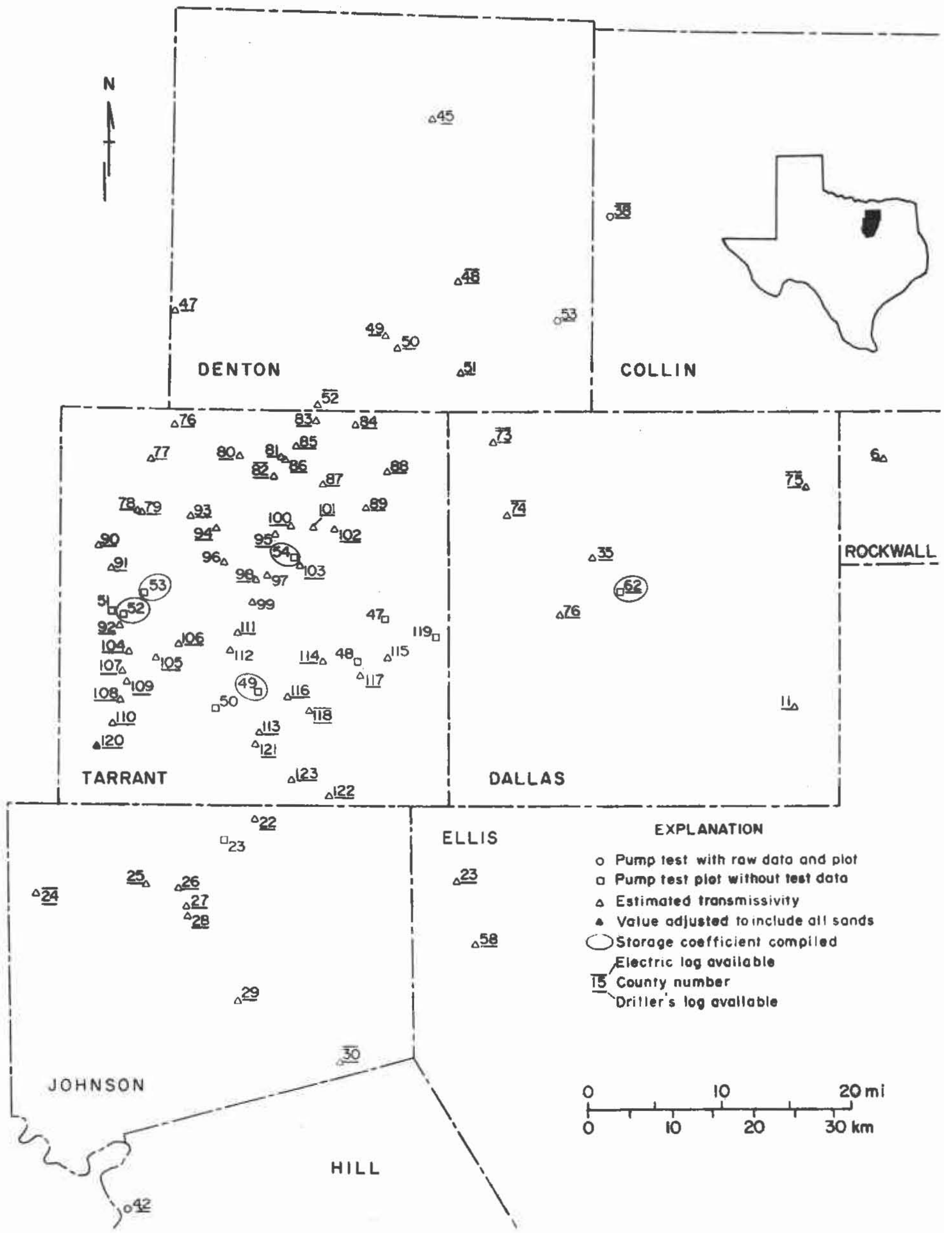


Figure 12. Data base for hydrologic assessment of Paluxy aquifer.

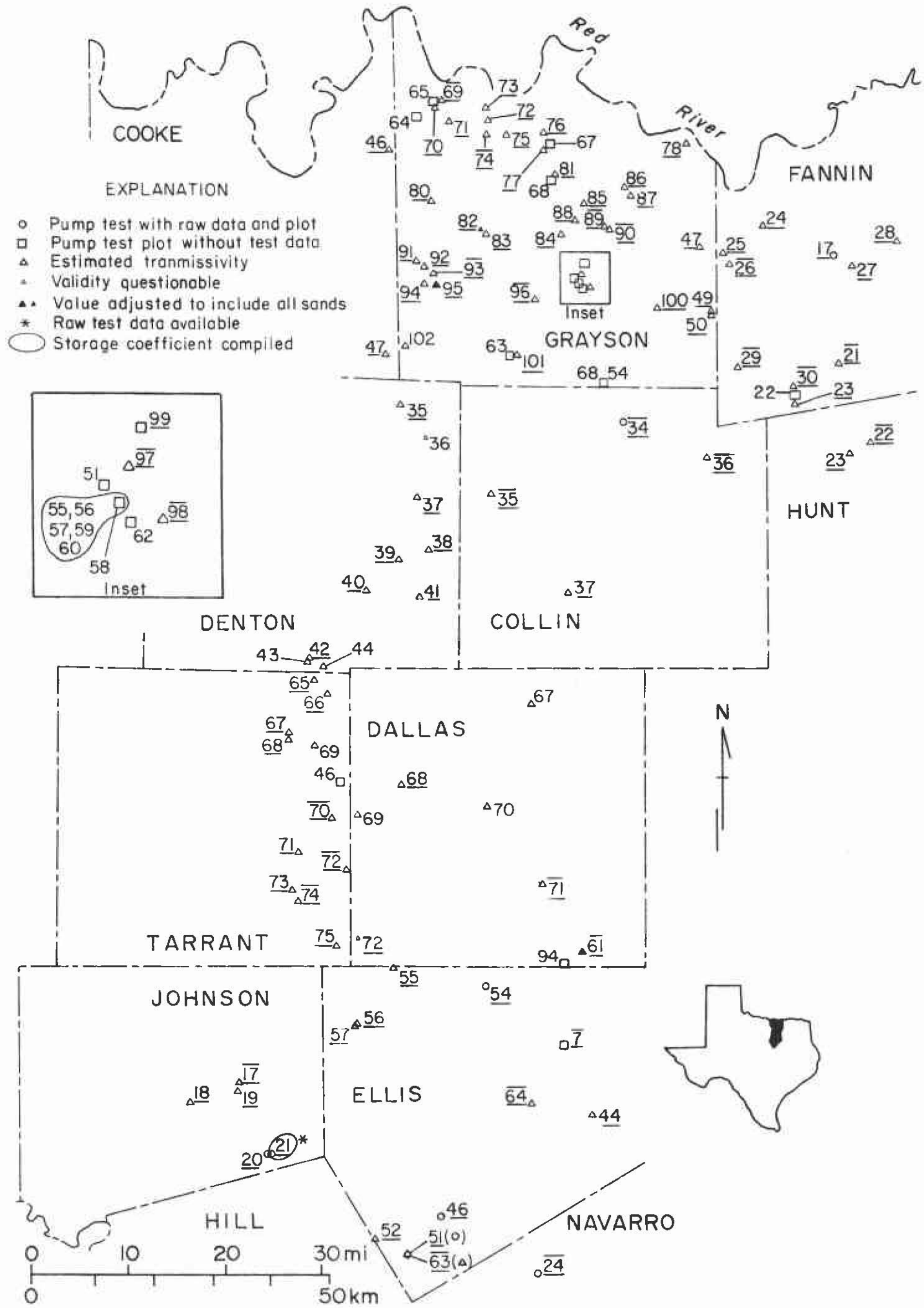


Figure 13. Data base for hydrologic assessment of Woodbine aquifer. Asterisk noted in figure explanation refers to raw data for computing storage coefficient. Darkened well symbols indicate adjustments for partial penetration; reduced-size well symbols denote questionable data.

for them is limited. However, it is important to be aware of all the provisional aspects of the data in order to keep in perspective the usefulness of transmissivity maps. In short, a regional transmissivity map is a guide, and one subject to revision whenever new or better data are acquired.

Aquifer Delineation and Determination of Producing Horizons

Pump-test theory presumes that the aquifers tested are homogeneous, isotropic, and of infinite areal extent. Clearly, clastic sedimentary deposits never meet these criteria. None of the aquifers studied are simple tabular bodies; instead they have lenticular geometries and consist of interbeds of differing composition and texture (and thus have different intraformational hydrologic attributes). Moreover, there are recognized "upper" and "lower" members of the Woodbine and the Paluxy aquifers, for example, yet the information in water-agency files on a particular well seldom acknowledges this fact. Similar situations occur for the Hosston/Trinity. Nomenclatural problems already discussed for the Hosston/Trinity (see fig. 5) spread further confusion. For instance, wells reportedly completed only in the Hensel Sand are not used in this study, whereas wells in the Hosston and Hensel Sands (or in the laterally equivalent Travis Peak Formation), as well as those completed only in the Hosston Sand, are included in the data base. This decision was based on the relative thickness and areal extent of the Hensel Sand, which in the area of concern were both small. In short, these distinctions among stratigraphic units presuppose a reasonably accurate designate of "aquifer" penetrated as reported with the pump-test data. Yet as our discussion of "aquifer designation" has already shown, such an assumption may not be valid. In fact, confusion as to which aquifer a well produces from is common, and we excluded some wells from the data base because of uncertainty about the actual producing horizon or because of production from multiple aquifers, some of which are not of interest to us. But the important fact is that we are almost always dependent on someone else's determination of producing horizon, with full knowledge that the aquifer designations themselves are often arbitrary.

Precise information on the stratum penetrated by a water well is important, because the production interval (saturated thickness) is a key factor in computing transmissivity of the aquifer. Since the clastic aquifers with which we are concerned consist of interbedded sand and shale, the actual production interval of a well is crucial in evaluating the validity of the transmissivity determined from a pump test. Within this production interval (that is, the part of the hole screened, or otherwise open to receive water) lithic interpretations of discrete sand versus shale intervals must be made on the basis of whatever data are on hand (electric logs, drillers' logs, or whatever). If data are not available on the exact production interval, or on lithic properties, the validity of the transmissivity is questionable. If the well only partially penetrates the aquifer of concern, then the transmissivity will be affected, since vertical flow as well as horizontal flow will be measured, and vertical conductivities are usually much lower than horizontal conductivities. Because of these influences we accorded considerable attention to the cited producing aquifer and the types of data available for interpreting sand/shale intervals (see especially figs. 11A-B).

Moreover, a well that terminates in a sand deposit creates a special problem, since the depth to the actual base of the formation cannot be determined except by correlation to other wells (or by extrapolation). In these wells the effects of partial penetration might be important, although it is impossible to judge quantitatively just what the hydrologic effects would be. In any event, these uncertainties cast doubt on our subsequent interpretations.

Physical Limitations of the Well

Well-completion practices clearly affect hydrologic properties, because the completion techniques define the amount of "communication" between the formation and the well. Commonly, however, the lack of reliable information on well-completion merely increases our uncertainty in dealing with the data. The performance of a well can be adversely affected by the type of "screening" or lack thereof, and this in turn is reflected in the transmissivity value determined from a pump test. The optimum screening is accomplished by matching the size of the intake slots of a well screen to the grain size distribution in the aquifer. Other methods of creating communication between the well and the aquifer include (a) using mill-slot casing, in which the openings per linear foot are fewer than in conventional well screen; (b) torch-slotting the casing before lowering it into the hole; (c) perforating the casing by "shooting" holes in it after it is in place; and (d) leaving the production interval open or uncased. A given method may not necessarily allow the best communication between the well and the aquifer; however, because the degree to which this is a problem cannot easily be quantified, the type of screening is not considered in this study, even though its influence might be significant.

Besides the conditions of well completion, subsequent well development also affects aquifer performance. Proper well development permits a well to be used at its maximum capacity with negligible head loss. It involves a process of removing fine-grained particles from the vicinity of the well bore; as a result, a highly permeable zone is created around the well. Well development is effected by allowing water discharge to grade the sediment in the aquifer (in response to water flow converging at the well), or by emplacing a permeable material (gravel) around the well screen. Well development occurs after the pipe and screen are in place; if it is not done, or done improperly or incompletely, the well will yield less water with a greater drop in water level, resulting in a lower apparent transmissivity. Since there are often no records of precisely how a well was drilled, completed, and developed, and since the amount of development needed is largely a subjective judgment, it is not possible for us to discard data on the basis of presumed improper well development. However, because well development influences the transmissivity measured at a well, it is another factor to consider when no explanation can be found for anomalously low transmissivities.

The age of the well on which a pump test is conducted may also affect the resulting (apparent) hydrologic properties. If a test is run on a new well, some development (maturation) may take place during the test, changing the apparent transmissivity of the aquifer and producing a set of data that is easily misinterpreted. If, on the other hand, the test is run on a very old well, corrosion or precipitation in the well casing can increase the head loss and decrease the apparent transmissivity of the aquifer. Bacteria can also cause plugging of screen openings and thereby decrease the apparent transmissivity. These problems, again, are not easily recognized during data collection nor are they easily quantified, but they affect our data; thus, we must take the age of the well into consideration in evaluating compiled data or in selecting sites for new aquifer tests.

Limitations of Aquifer Tests

The length of the testing period is important, because if pumping is stopped before the well and aquifer reach an equilibrium or steady-state in terms of potentiometric decline per time-interval of pumpage, then the transmissivity calculated from the data will not be the true transmissivity of the aquifer. As a rule, an artesian well should be pumped for 24 hours and a water-table well for 5 days, to ensure that an equilibrium or steady-state has been reached. Specific-capacity tests are usually run a mere fraction of this length of time, so that equilibrium probably has not been reached at the end of such tests. A public water supply well or industrial well, on the other hand, is tested more extensively, often for the requisite 24 hours or more. Sometimes the test is conducted in the form of a "step test," in which the rate of pumping is increased or decreased in discrete increments. Usually a valid transmissivity value can be calculated from these tests, but sometimes only an estimation can be made.

Recording procedures are also vital to subsequent interpretations. If, during a regular pumping test, accurate measurements are not made, verification of hydrologic equilibrium or steady-state may be difficult. The pumping may have been stopped prematurely, yet our interpretations would fail to take this into account. Graphical analyses might show a gently curving line (nonequilibrium), which could easily be mistaken for a straight line (steady-state or equilibrium). As already mentioned, if steady-state is not reached, a valid transmissivity cannot be calculated from the data.

Occasionally a pump test is run for the express purpose of determining aquifer properties; these tests are carefully done and usually result in extensive information about the aquifer. The most useful test is run using at least one observation well, in which water levels are measured as the pumping well discharges water at a controlled rate. More often, no observation wells are available, and the test involves measuring water levels in the pumping well exclusively. Such a test provides reasonably valid transmissivity values but cannot be used to calculate a storage coefficient.

The particular method of water-level measurement may impose further limitations on pump-test data. For most tests, except those run specifically to determine aquifer properties, an air line with an accuracy of 0.5 to 1 ft is used to measure water levels. During these tests, water levels are often measured at time intervals too large to allow calculation of a reasonably accurate transmissivity. Other methods of water-level measurement include using an electric sounder (E-line), constant water-level recorders, and steel tape and chalk. These devices are more precise than the air line; in general, they are used during tests run for scientific purposes and are accurate to one-hundredth of a foot.

Other conditions, such as nearby pumping wells, faults, facies changes, leakage from overlying or underlying aquitards and aquifers, or any other types of interference, may create boundary conditions that can increase or decrease the apparent transmissivity of a well. Without a precise pump test coupled with valid stratigraphic information, boundary effects may not be recognized and taken into account when calculating the transmissivity of the aquifer.

Quantity and Distribution of Data Specific to Cretaceous Aquifers in Central Texas

Heretofore, little research has been conducted on the ground-water hydrology of the aquifers in question, although Klemt and others (1975) and Hall (1976) addressed these attributes in parts of the Hosston/Trinity Sands. Their studies focus on the part of the aquifer that is most intensively used--that is, the updip areas producing fresh water. There the ground water has moderate temperatures approximating mean annual air temperatures. In the deeper reaches, there is a paucity of wells, because the ground water is considered an undesirable and expensive potable-water resource. As with our other data, the lack of well density in the thermal reaches of aquifers prevents assessments of hydrologic properties in a uniform and consistent manner.

But even under conditions where the aquifer is intensively used and well-density is high, exhaustive pump tests commonly are not run for domestic wells, because of the time and cost incurred. Some type of performance test is usually conducted, but often it is conducted only to ascertain the proper type and size of pump to be employed. Such a test entails pumping the single well at a certain rate for a specified time period and then noting total drawdown. No effort is made to determine instantaneous water-level declines during repeated, incremental time intervals as is necessary to ascertain hydrologic equilibrium of an aquifer. The only value obtained by this common type of "performance test" is specific capacity, which is pumping rate divided by total amount of drawdown at the well. Specific capacity may only indirectly indicate values for transmissivity ($\underline{T}$) and hydraulic conductivity ($\underline{K}$).

Commercial, industrial, or public-supply wells, as mentioned previously, are usually tested with more care than are individually owned wells because of their greater cost and the larger demands placed on them. Since these wells are generally located near or within population centers, the best data are clustered near population centers that do not have an established source of surface water. Rural water-supply corporation wells are another generally valid source of data; they are especially valuable because they are located away from population centers, and hence provide valid data in an otherwise generally untested area.

Two other types of aquifer performance tests are found in TDWR files: those involving both a pumping well and an observation well (or wells); and those involving a pumping well alone. Of these two types of tests, the one that yields the most reliable data involves two (or more) wells: a pumping well and at least one observation well. These kinds of tests, however, are conducted infrequently, because they demand greater proximity (less than a few thousand feet) of wells producing from the same horizon. More commonly, a single-point drawdown (or recovery) test is conducted, which, as the name implies, employs only a single well for both pumping and drawdown-measurement purposes.

For both these types of tests, the drawdown is recorded as a continuous set of measurements (during frequent time intervals). These aquifer tests that involve repeated measurements of drawdown (or recovery) as a function of well pumpage during a defined time interval provide the most useful data, because equilibrium conditions may be gauged with more confidence than simple specific capacity tests. Yet, of the data available to us, the specific capacity tests are the most numerous.

Methods

It was our intention to marshal all available data relevant to aquifer capabilities and, using these compiled data as a departure point, to conduct our own pump tests to fill in gaps. However, the same limitations that militate against a satisfactory density of compiled data for any of our other assessments also dictate that there are few wells that are not already tested in some way. Moreover, of the untested wells, few correlate easily with our existing data, because of the penetration of different horizons, unknown well completion, and similar problems. We retained a hydrologic consultant to survey our data for areas where a new aquifer test might be conducted, given the well spacing, and where data would be meaningful to our study; the consultant was also to supervise these tests. As it happened, we conducted only one pump test during this contract period, but our regional evaluation of the data base is continuing in the hope that we will locate other suitable areas for conducting similar tests.

Three categories of information provided us with compiled data for constructing maps that present hydrologic properties of the Cretaceous aquifers along the Balcones/Ouachita trend. These categories include: (1) raw pump-test data and supporting information for direct computation of transmissivities (and other parameters); (2) transmissivity values compiled from existing reports without supporting data; and (3) performance-test information from TDWR well schedules, which mostly consist of specific-capacity values.

The records of pump tests are of greatest value for our purposes, because we are thus privy to all the circumstances that affect final values and are able to draw our own conclusions regarding the validity of the hydrologic properties thus obtained. The variables that are needed to compute a valid _T_ value include: (1) an initial static water level; (2) rate(s) of discharge during the pumping of the well; (3) water-level measurements at frequent time intervals; (4) notations about interruptions or interferences during the test; and (5) salient information on well completion, including well diameter, screened interval, and the like. We employed graphical methods as described by Walton (1962) to obtain a _T_ value from these data. However, correct interpretations of these data presuppose geological interpretations (based on logs or cuttings), to ascertain the particular aquifer interval penetrated. These interpretations are limited by the same variables of stratigraphic nomenclature and lateral geologic variability that we have already discussed.

Transmissivity values (derived from any of the three source categories) that appeared anomalous were examined closely for partial penetration of the aquifer. When electric logs or detailed drillers' logs were available and partial penetration was evident, the apparent transmissivity values obtained from testing such a well were adjusted using the method suggested by Klemt and others (1975). The apparent transmissivity values were divided by the actual penetration, or the screened interval footage, in order to find a reasonable _K_ for the aquifer. This _K_ was then multiplied by the total sand thickness in the aquifer in order to compute an _adjusted_ transmissivity of the aquifer. This adjustment regarding sand thickness frequently lessened inconsistencies in the data. However, we employed this adjustment only when transmissivity values appeared anomalous, and not for the entire data base. In short, it is clear that, for hydrologic interpretations to be meaningful, correct geologic correlations of the aquifer stratum (or strata) are needed.

Finally, our having access to raw data from pump tests is necessary for us to note changes in rate of decline of water level that may relate to hydrologic barriers or to leakage from other horizons. Also interpretation of the impact of barriers depends on an adequate assessment of the geologic framework in the area of the pumping well in terms of facies changes, faults, and similar features that may constitute hydrologic boundaries. Having the raw data on hydrologic variables and aquifer (lithic) attributes allows us to obtain our own values independently. These tests are usually performed by the TDWR (or its predecessors), by the USGS, or by private consultants. Where the final results of such tests were simply compiled from the literature, we lose the ability to assess the data critically and to make our own assumptions. Yet we have been forced to use various types of compiled information because data are generally sparse, especially in the thermal reaches of the aquifers assessed (<u>see</u> the numerous qualifications of data sources and nomenclature on figs. 11A-B, 12, 13). We compiled data from reports (Myers, 1969) where a graphical construct shows relations at specific wells between drawdown and time for stated pumping rates. Although the underlying assumptions are not always evident, these graphical renderings are of higher value than simply the presentation of (say) a transmissivity (<u>T</u>) value. Yet we were obliged to use <u>T</u> values as cited, because of the absence of any other data whatsoever.

Specific-capacity tests compose the most tenuous type of data that we employed. These values are used to compute an "estimated transmissivity." Specific-capacity values allow almost no critical evaluation to correct for complicating aquifer properties; we were at the mercy of the person who conducted the performance test for a purpose quite different from ours. Nonetheless, scarcity of data on hydrologic properties demanded that we assess these data with the other values and construct with caution a composite map from such diverse bases. We computed estimated T values using specific-capacity values, well radius, length of specific-capacity test, and an estimated storage coefficient.

Estimated T values are founded on either the Theis equation (Theis, 1935) or the Thiem equation (Thiem, 1906); some estimation methods are described by Lohman (1972), Ogden (1965), Thomasson and others (1960), and Walton (1962). We chose the method developed by Theis and others (1963), because it incorporates corrections for most variables that influence the specific capacity derived from a performance test. One of the major problems with estimated values is that the precision and accuracy of the T values decrease with lower values. Hence, we are suspicious of values less than about 1,000 gpd/ft; we know only that the actual value is very low, but it is numerically imprecise.

Results

Our hydrologic data base consists of 498 wells in 21 counties along the Balcones/Ouachita trend. We assessed three sand aquifers for T and K values: Hosston/Trinity (figs. 14A and B, 15A and B), the Paluxy (figs. 16 and 17), and the Woodbine (figs. 18 and 19). But because of nomenclatural complexities and the associated proliferation of aquifer designations in TDWR files, we had to assay eight nominal aquifers (six of which are merely permutations of the Hosston/Trinity). The Hosston/Trinity extends throughout the study region from Travis County north to the Red River; both the Woodbine and the Paluxy aquifers occur within a much more limited area of North-Central Texas.

Of the 498 wells assessed, we obtained 498 values for transmissivity, 375 values for hydraulic conductivity, and 53 values for storage coefficient.

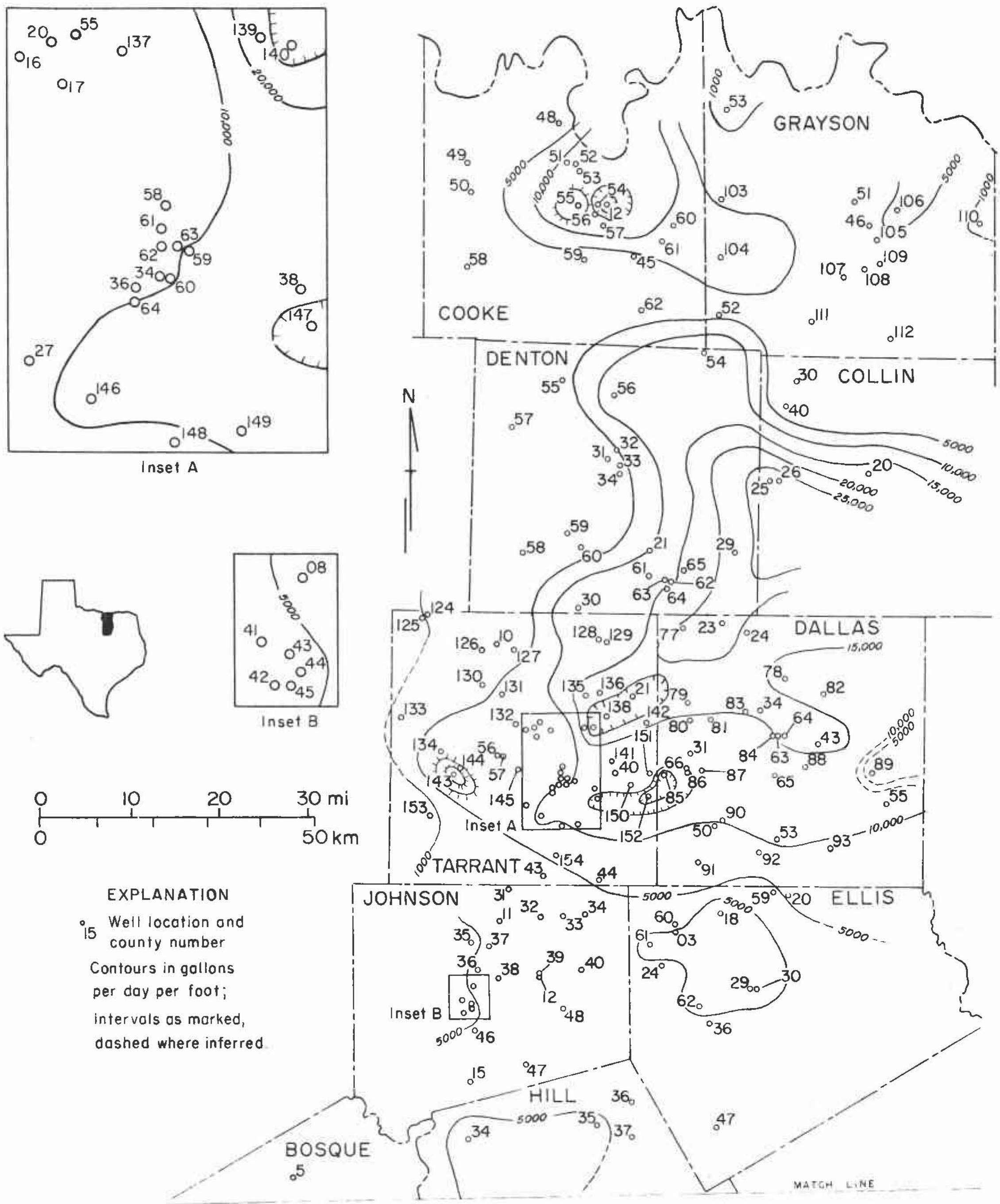


Figure 14-A. Transmissivity contours for Hosston/Trinity aquifer, northern part of study area.

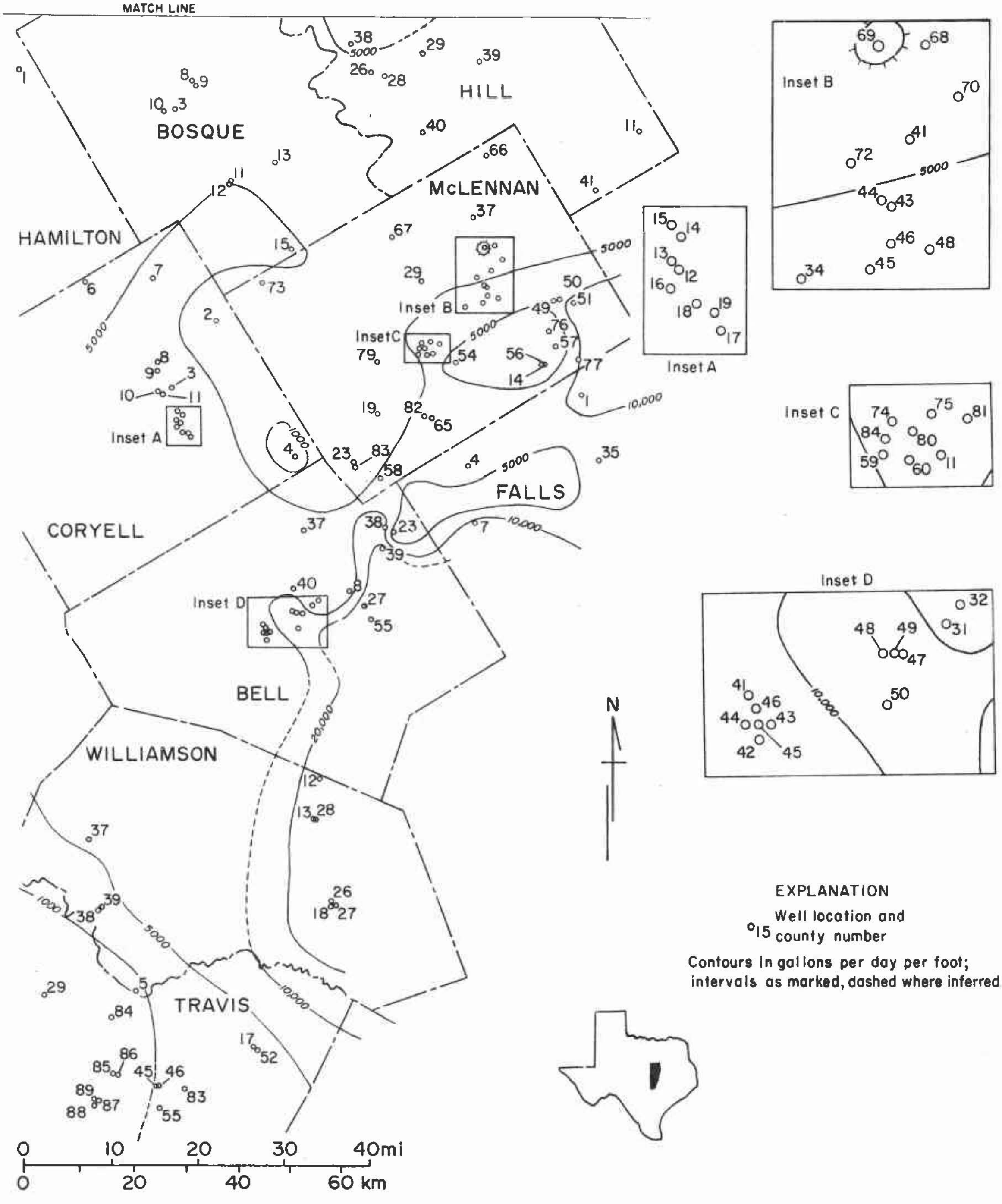


Figure 14-B. Transmissivity contours for Hosston/Trinity aquifer, southern part of study area.

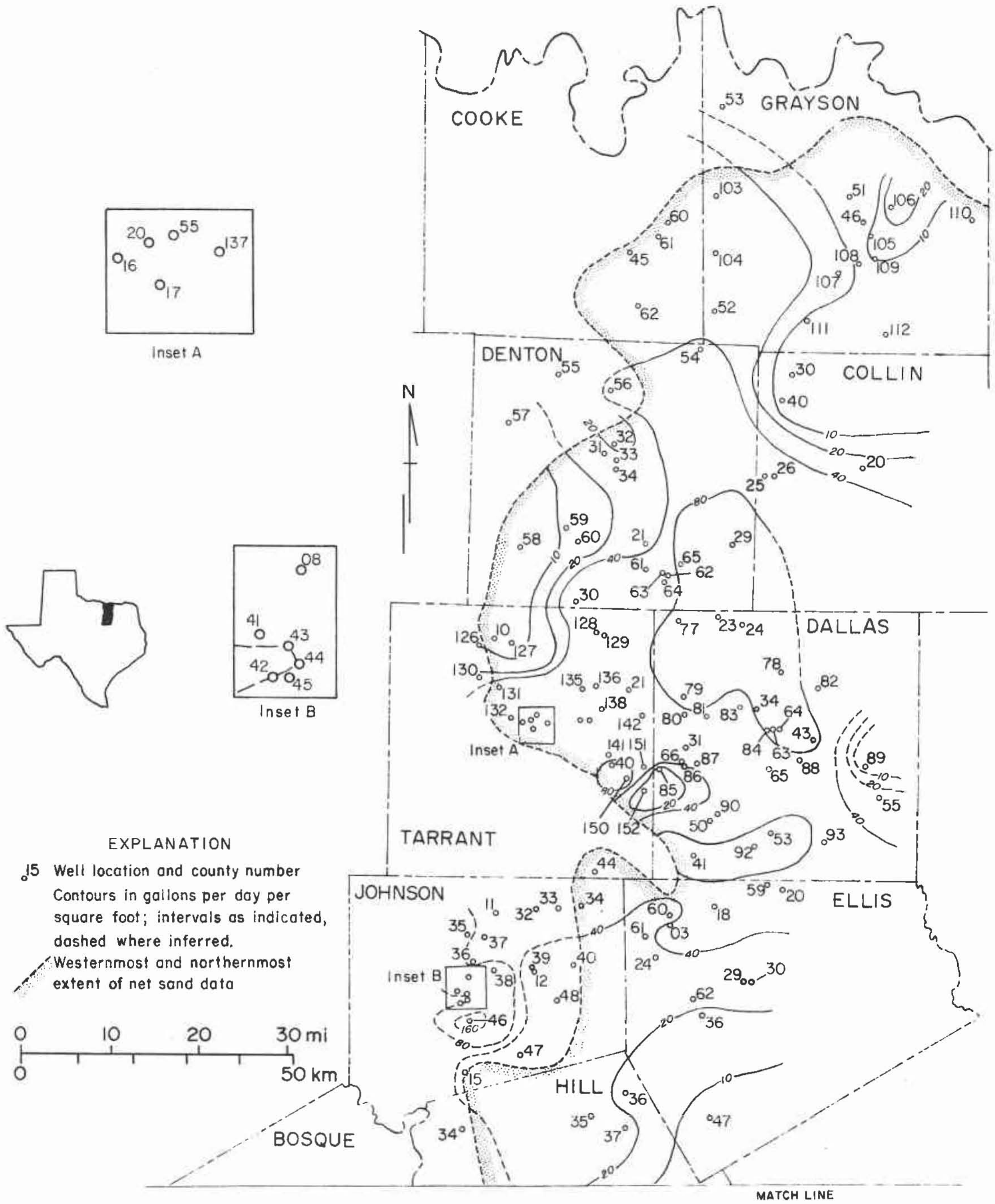


Figure 15-A. Hydraulic conductivity contours for Hosston/Trinity aquifer, northern part of study area.

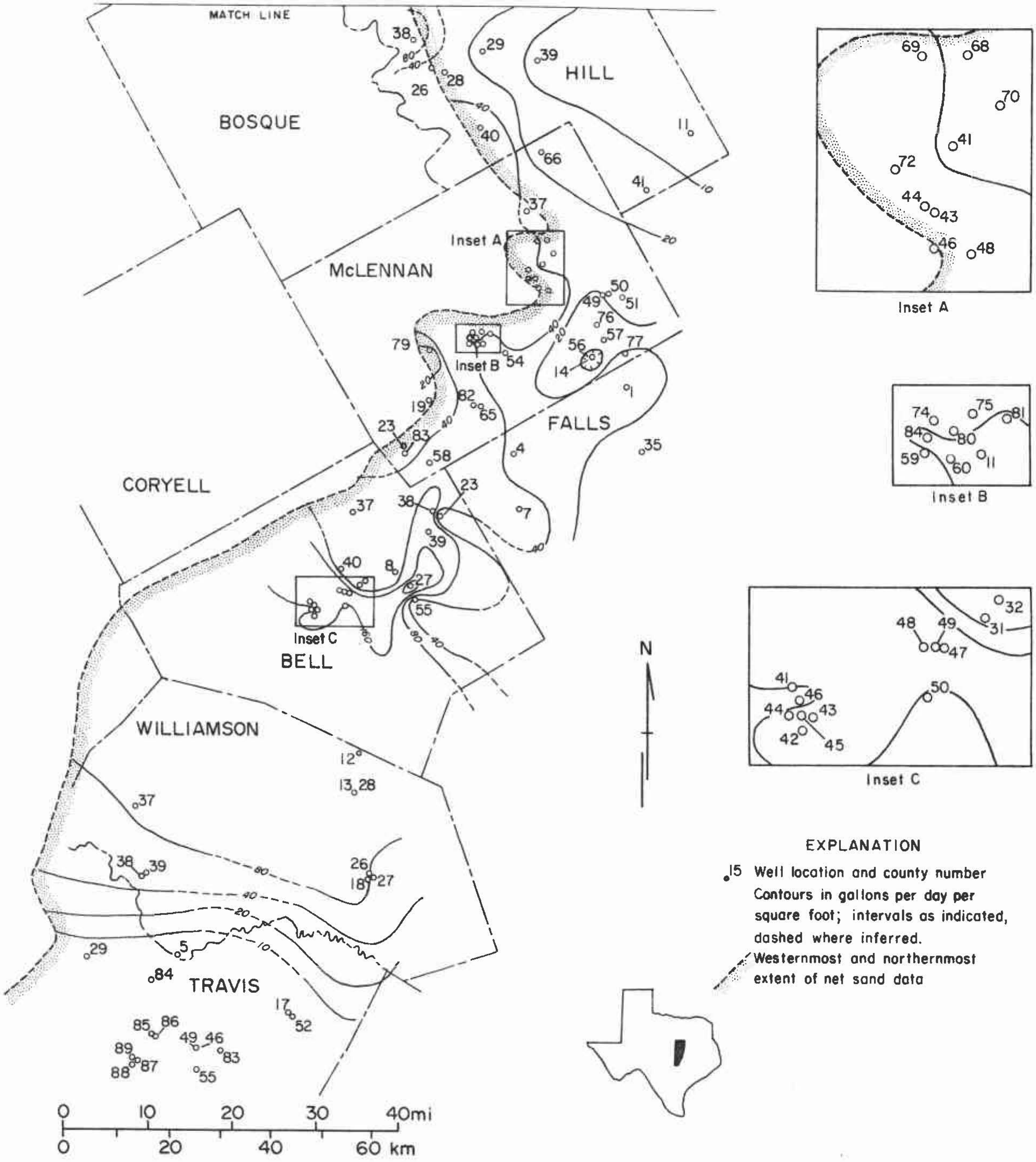


Figure 15-B. Hydraulic conductivity contours for Hosston/Trinity aquifer, southern part of study area.

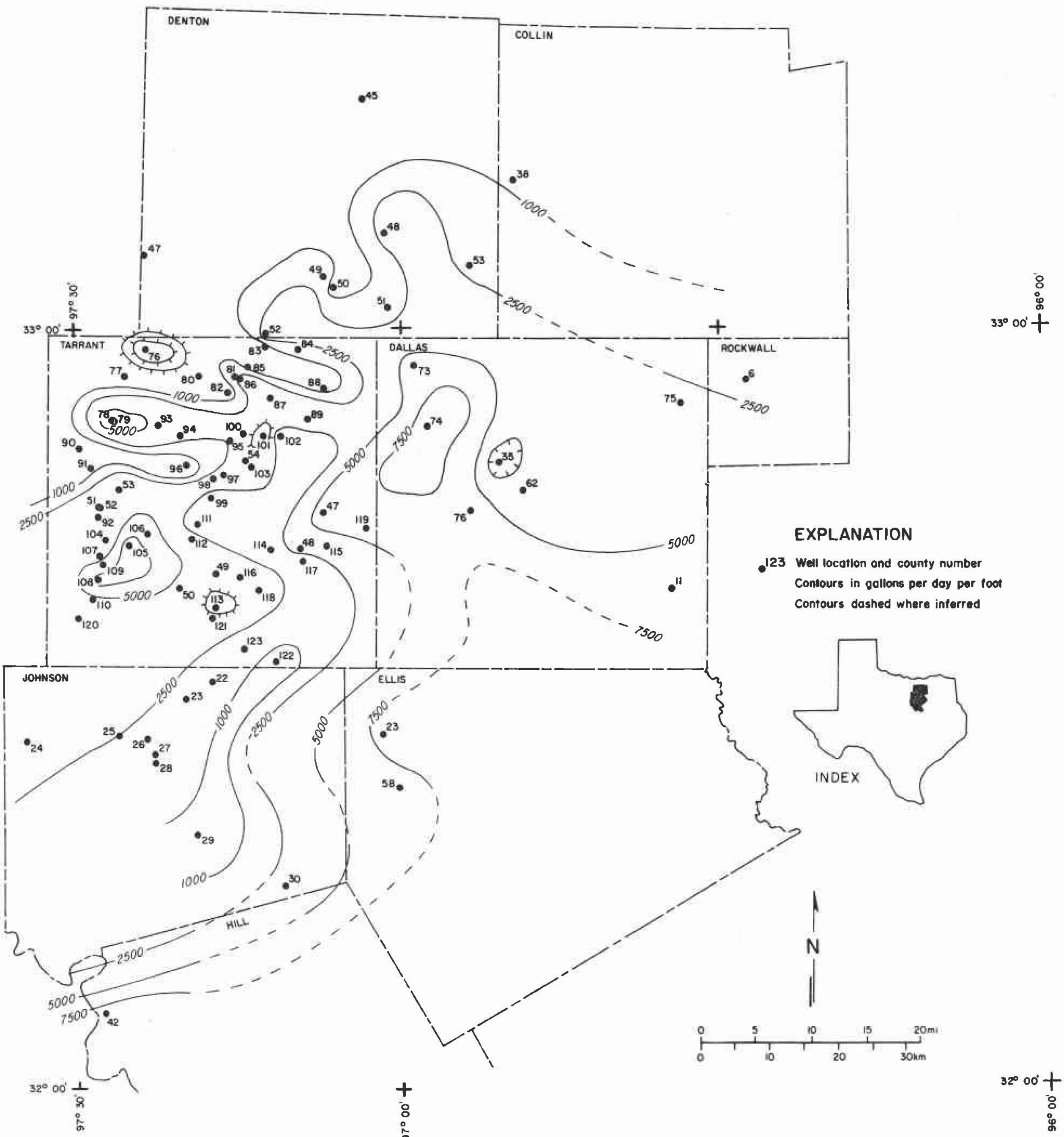


Figure 16. Transmissivity contours for Paluxy aquifer.

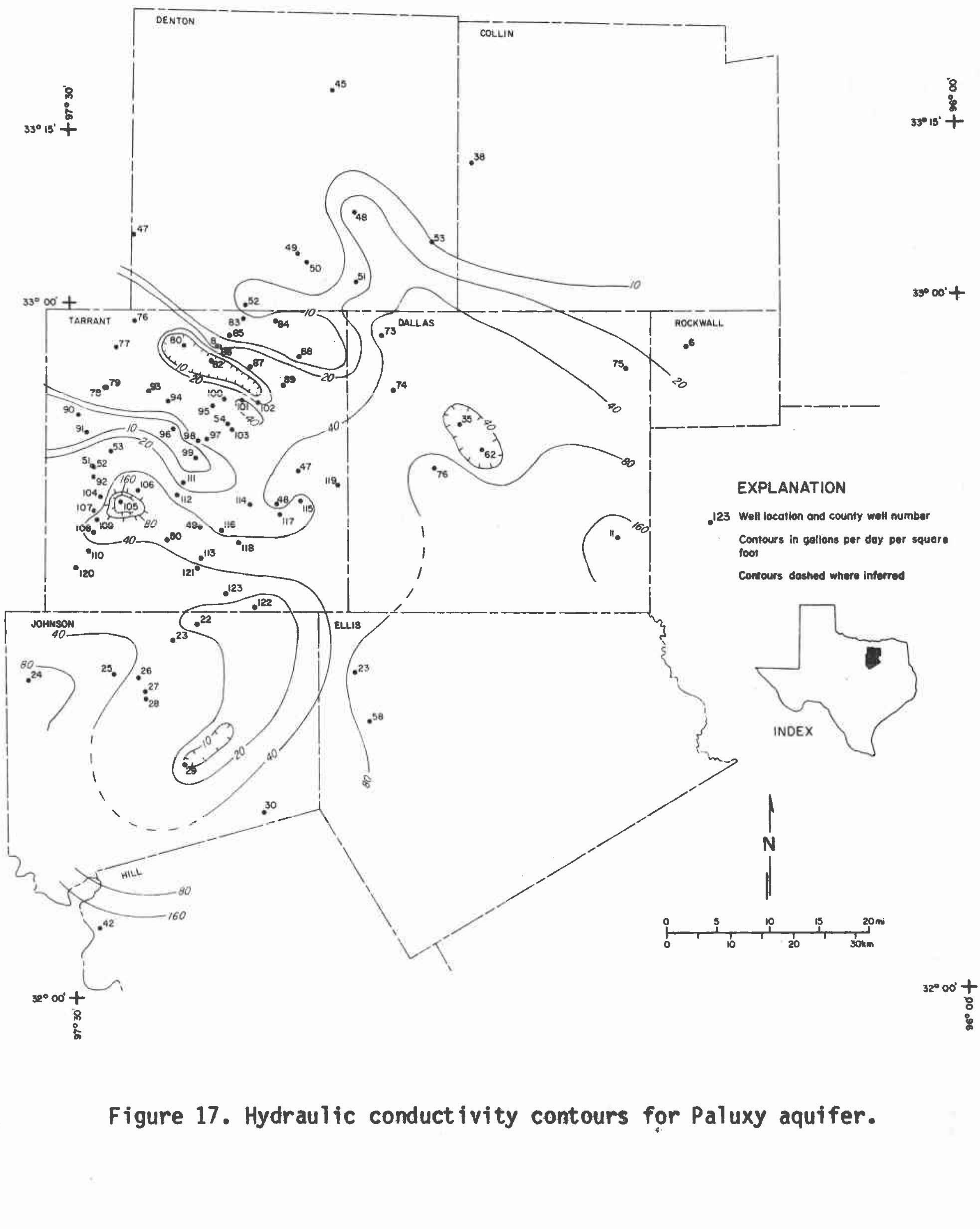


Figure 17. Hydraulic conductivity contours for Paluxy aquifer.

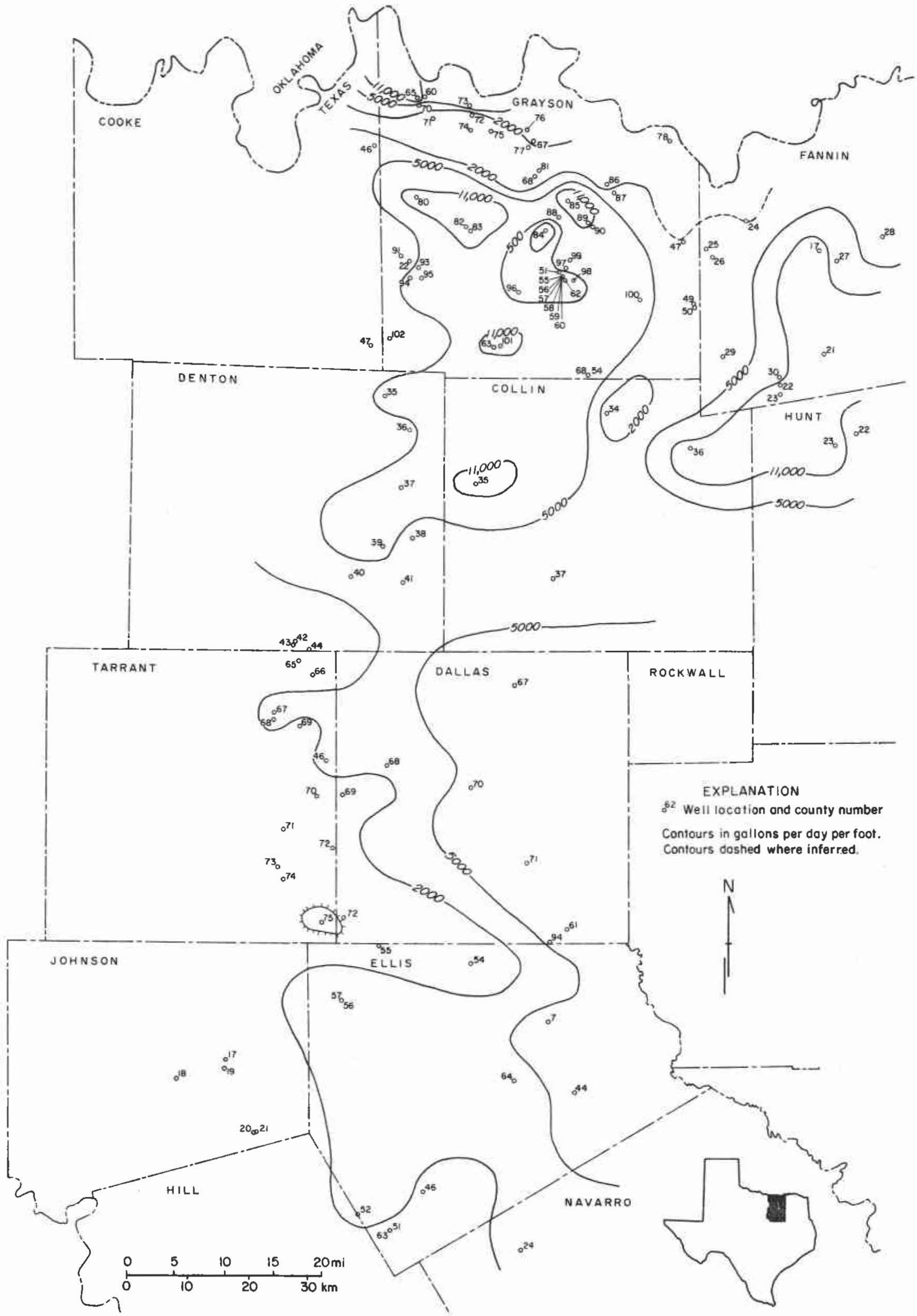


Figure 18. Transmissivity contours for Woodbine aquifer.

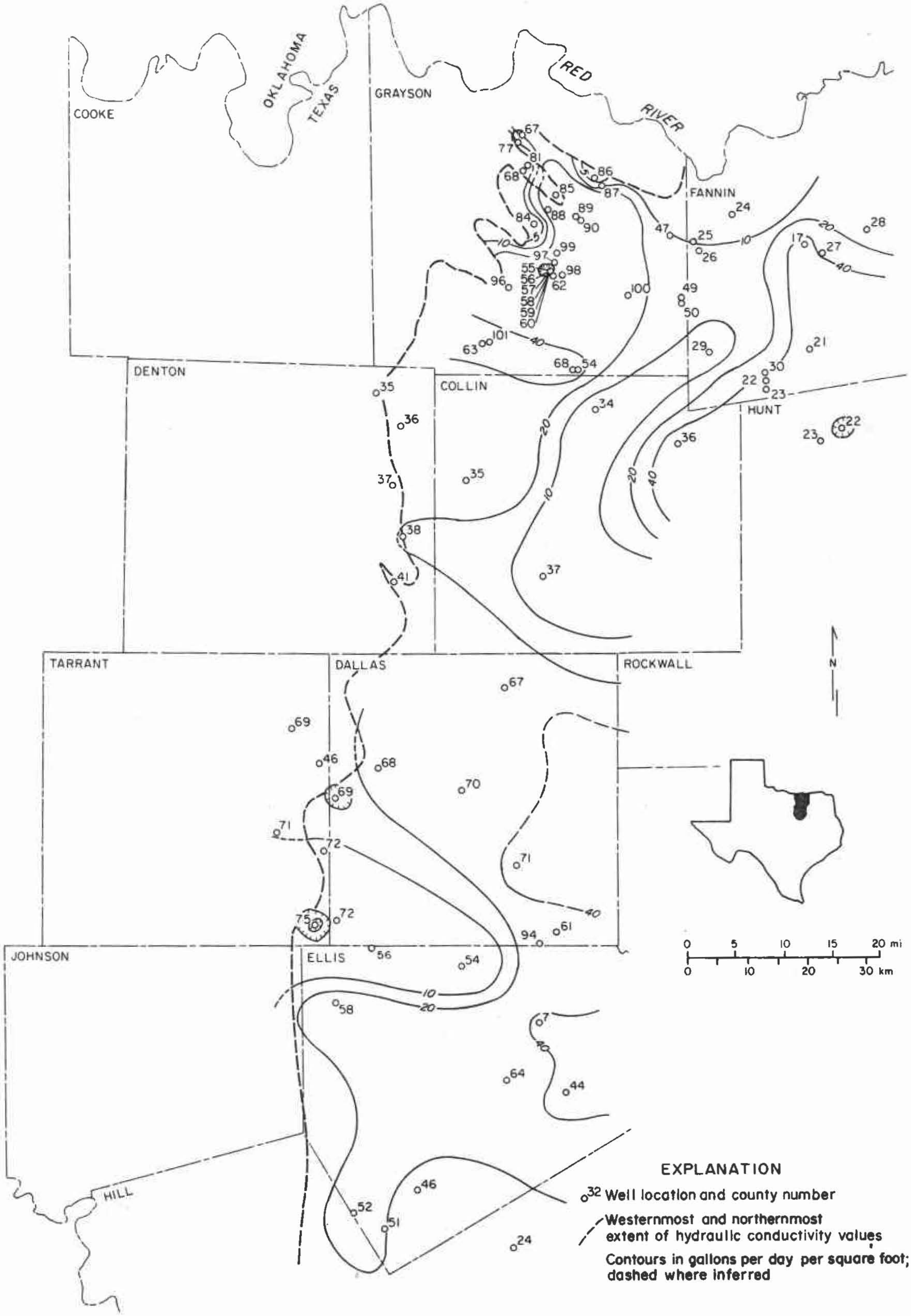


Figure 19. Hydraulic conductivity contours for Woodbine aquifer.

However, the validity of these data is based on numerous assumptions, as already discussed, owing to the source of the data. We obtained the majority of our data (336 values) from specific-capacity tests, which were, in turn, used to estimate _T_ values. The _T_ values thus obtained were divided by the saturated thickness of the aquifer to obtain values for hydraulic conductivity (_K_), thus adding a double layer of assumptions and uncertainty to our interpretations of _K_. Obtaining _K_ in this manner assumes that all sands contribute equally to production from the well tested; it presumes that only the sands are acting as aquifers; and it assumes full penetration of the aquifer, as well as a valid _T_ value. Since our net sand maps do not extend as far west or north as the transmissivity data, the hydraulic conductivity maps are of smaller areal extent than the _T_ maps. They do, however, include the prime area in which geothermal ground waters occur.

The values having highest validity--those for which we have raw data available to us--include tests of only 86 wells. The reported transmissivity values without supporting data--the data having the second highest levels of uncertainty--comprise 76 wells. Table 2 presents (in a county-by-county format) the data that underlie our findings; these data are keyed to the maps showing our interpretations (figs. 14A-B, 15A-B, 16, 17, 18, 19). These interpretations are presented as "tentative findings." They are not assessed in terms of geologic relations in this presentation; instead further evaluations of our data are part of our ongoing research. As mentioned at the outset, this report constitutes mainly a critique of the vast data base that we have compiled on Texas aquifers.

Because of the few data points (53) that support storage-coefficient (_S_) determinations, and because methods for estimating _S_ are very crude (thickness times 10^{-6}), we constructed no map showing areal differences in this parameter.

Table 2. Data base for quantitative hydrologic interpretations of Cretaceous aquifers along the Balcones/Ouachita trend.

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				BELL COUNTY						
08	40-62-102	Ralph Wilson Plastics	269	1,822	1,768-1,717	6.63	7,500	E	60	
23	40-54-601	City of Troy #2	269	1,833	1,610-1,633 1,695-1,715 1,722-1,744 1,764-1,824	4.5	3,400	P	21	
27	40-62-401	V.A. Hospital, Temple	269	2,323	2,234-2,323	14.0	46,900	P	336	
31	40-61-507	City of Temple #1	269	1,238	1,144-1,228	10.0	5,100	E	57	
32	40-61-509	City of Temple #3	269	1,261	1,160-1,260	10.0	4,700 §§	E	43	
37	40-53-505	Moffatt W.S.C. #1	269	1,192	1,075-1,192	4.5	7,700	P	70	
38	40-54-501	City of Troy #1	178	1,735	NA	NA	14,100	P	94	
39	40-54-502	Little Elm W.S.C. #1	178	2,045	1,715-1,740 1,980-2,045	4.5	22,000	E	137	
40	40-61-101	U.S. Army Corps of Engineers HQ, Belton Reservoir, Live Oak Ridge Pk.	269	1,351	1,078-1,108	6.0	5,800	P	58	
41	40-60-601	U.S. Army Corps of Engineers (Yarrell) #2	178	965	817-965	10.75	10,300	I	200	9×10^{-5}
42	40-60-801	U.S. Army Corps of Engineers (Copland) #1	289	948	665-734 836-924	10.0	9,300	I	186	4.3×10^{-5}
43	40-60-902	U.S. Army Corps of Engineers (Wilson) #2	289	965	716-786 847-934	10.75	7,700	I	154	6×10^{-5}
44	40-60-903	U.S. Army Corps of Engineers (Safley) #1	289	932	665-731 817-906	10.75	9,700	I	184	6×10^{-4}
45	40-60-904	U.S. Army Corps of Engineers (Wilson) #1	289	968	743-831 883-965	10.75	10,500	I	240	4.2×10^{-5}
46	40-60-905	U.S. Army Corps of Engineers (Yarrell) #1	289	956	673-743 825-936	10.75	7,400	I	148	5.5×10^{-5}
47	40-61-405	City of Belton-abandoned	178	1,180	NA	6.0	17,900	P	224	4.3×10^{-4}
48	40-61-403	City of Belton Old City #2	178	1,172	NA	8.0	19,600	I	245	5×10^{-4}

Explanation of symbols at end of table.

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				BELL COUNTY continued						
49	40-61-402	City of Belton #1	178	1,190	NA	8.0	18,600	P	233	2.7×10^{-4}
50	40-61-703	City of Belton #3	269	1,293	1,204-1,284	10.75	11,500 *	E	183	
55	40-62-501	Acres W.S.C. #1	269	2,218	2,118-2,125	6.63	4,700	E	31	
					2,130-2,172					
					2,182-2,189					
					2,195-2,206					
				BOSQUE COUNTY						
03	40-03-802	Tx. Parks & Wildlife	269	910	720-910	3.0	2,100 *	E		
05	32-59-405	Mobil Oil Corp. #2	269	639	607-625	4.5	1,600 *	E		
08	40-03-604	City of Meridian #4	269	758	673-758	6.63	8,500 *	E		
09	40-03-603	City of Meridian #3	269	838	735-838	8.63	9,500 *	P		
10	40-03-701	Lakeview Recreation Assoc.	269	940	800-926	6.63	4,600 *	E		
11	40-12-703	City of Clifton #5	269	942	824-934	6.63	3,600	E		
12	40-12-705	City of Clifton #6	269	1,006	920-1,000	8.63	7,200	E		
13	40-13-401	Childress Creek W.S.C. #1	269	1,172	1,044-1,064	7.0	4,100	E		
					1,078-1,088					
					1,096-1,106					
					1,110-1,120					
					1,124-1,134					
15	40-21-701	City of Valley Mills #2	178	962	NA	6.0	7,100	P		
				COLLIN COUNTY						
20	18-51-301	City of McKinney #3	312	3,412	3,110-3,410	6.63	17,400	E	35	
25	18-50-501	Tx. Power and Light #1	312	2,525	2,266-2,515	9.63	27,400	P	69	
26	18-50-502	Tx. Power and Light #2	312	2,662	2,378-2,640	9.63	26,600	E	63	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				COLLIN COUNTY continued						
34	18-44-202	City of Anna #2	200	1,559	1,300-1,328	5.5	1,900	P	8	
					1,335-1,356					
					1,360-1,365					
					1,430-1,456					
					1,496-1,506					
					1,512-1,526					
35	18-50-301	David Dobson	200	958	916-946	3.0	18,100	E	95	
36	18-45-604	City of Blue Ridge #2	200	1,900	1,760-1,792	4.0	13,000	E	45	
					1,800-1,830					
					1,836-1,878					
37	18-59-303	City of Allen #3	200	1,483	1,265-1,379	6.0	2,100	E	8	
38	18-50-504	Tx. Power & Light #3	138	1,710	1,333-1,378	6.63	800	P	3	
					1,393-1,418					
					1,460-1,504					
					1,509-1,524					
					1,542-1,567					
					1,590-1,600					
					1,612-1,631					
					1,635-1,652					
39	18-42-301	Gunter W.S.C.	272	2,180	2,060-2,180	7.0	2,300	E	7	
40	18-42-604	City of Celina #3	312	2,300	2,044-2,088	8.63	1,800	E	5	
					2,154-2,184					
				COOKE COUNTY						
12	19-23-901	City of Gainesville #6	272	904	723-782	6.63	3,700	E		
					798-890					
45	29-32-5--	NA	180	1,524	1,330-1,524	NA	4,500	I	20	
46	18-09-802	NA	200	226	215-226	5.5	2,100	E		
47	18-33-403	R. G. Sitzers	200	278	0-278	7.0	1,800	E		

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		COOKE COUNTY continued								
48	19-15-701	Richard Stark & Ken Davey	272	348	301-346	3.5	2,200	E		
49	19-21-301	Mrs. Joe Pantler	272	487	454-462 471-487	2.38	1,400	E		
50	19-21-910	Chuck Bartush	272	628	507-517 527-532 537-542 548-564	6.0	3,200	E		
51	19-23-201	Hubert Felderhoff	272	920	NA	8.0	13,100	E		
52	19-23-502	City of Gainesville (Howze) #2	272	940	560-582 598-628 651-667 687-767 790-800 828-857 877-918	8.63	14,900	E		
53	19-23-503	City of Gainesville (Howze) #3	272	912	660-690 710-795 815-910	8.63	10,600	P		
54	19-23-906	City of Gainesville #8	272	982	754-802 807-827 848-855 866-886 906-961	10.75	9,200	P		
55	19-23-805	City of Gainesville #9	272	927	629-694 707-749 760-770 805-893	10.75	21,200	P		
56	19-23-903	City of Gainesville #3	272	931	767-789 856-873 887-927	8.0	16,500	P		

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		COOKE COUNTY continued								
57	19-31-302	City of Gainvesville #7	272	997	726-766	10.75	14,500	E		
					787-797					
					806-811					
					826-846					
					868-888					
					908-978					
58	19-29-602	Buckner Baptist Benevolences	272	283	234-283	open	1,000	E		
59	19-31-501	Tx. Highway Dept.	272	860	794-846	3.0	1,800	E		
					846-860	open				
60	18-25-104	Woodbine W.S.C. #3	272	1,468	1,336-1,446	5.56	9,600 *	E	51	
61	19-32-302	Kiowa Utilities Corp.	272	1,301	1,010-1,055	10.75	8,000	E	36	
					1,065-1,105					
					1,120-1,135					
					1,200-1,210					
					1,220-1,275					
62	19-40-201	Mountain Springs W.S.C.	272	1,424	1,338-1,358	3.0	3,500	E	20	
					1,376-1,396					
		CORYELL COUNTY								
02	40-28-404	Coryell City W.S.C. #1	269	1,080	970-990	7.0	400	P		
					994-1,004					
					1,022-1,052					
03	40-35-409	City of Gatesville #5	269	916	785-875	10.75	7,800	P		
04	40-44-902	The Grove W.S.C. #1	269	1,126	1,025-1,125	7.0	500	E		
06	40-26-102	Jonesboro W.S.C. #1	269	622	574-612	7.0	4,800	P		

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				CORYELL COUNTY continued						
07	40-27-102	Turnersville W.S.C. #1	289	1,003	700-746	7.0	5,500	P		
					750-760					
					770-780					
					832-842					
					882-892					
					912-922					
08	40-35-104	Gatesville School for Boys #4	289	762	584-609	8.0	9,300	P		
09	40-35-108	Gatesville School for Boys #3	269	774	638-658	10.75	5,800	P		
					710-760					
10	40-35-403	City of Gatesville #3	269	736	620-722	10.75	9,400	E		
11	40-35-404	City of Gatesville #4	269	755	695-739		8,800	P		
12	40-35-802	U.S. Army #2	289	690	478-544	8.0	12,500 ††	P		2.8×10^{-5} ††
					632-678					
13	40-35-803	U.S. Army #3	289	721	492-516	8.0	10,300 ††	P		6.1×10^{-5} ††
					663-710					
14	40-35-804	Jack Fry #4	289	745	492-534	8.0	13,100 ††	P		5.7×10^{-5} ††
					671-737					
15	40-35-805	U.S. Army #5	289	759	537-554	8.63	5,500 ††	P		
					699-748					
16	40-43-201	U.S. Army #1	289	765	505-555	8.0	10,600 ††	P		
					697-747					
17	40-43-202	U.S. Army #2	289	772	531-599	8.0	7,600 ††	P		5.6×10^{-5} ††
					726-760					
18	40-43-206	U.S. Army #6	289	735	496-563	8.0	11,300 ††	P		
					651-718					
19	40-43-207	U.S. Army #7	289	745	517-561	8.0	9,700 ††	P		5.7×10^{-5} ††
					667-733					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
					DALLAS COUNTY					
11	33-20-803	Federal Correction Institution #2	138	2,780	2,571-2,724	6.63	6,500	E	163	
23	33-01-302	City of Dallas #47	312	2,275	1,990-2,025 2,040-2,200 2,213-2,275	9.63	19,200 ††	P	101	1.1×10^{-4} ††
24	33-02-102	City of Carrollton	312	2,515	2,245-2,290 2,330-2,455	10.75	16,700	E	88	
31	33-09-701	City of Grand Prairie #19	312	2,092	1,880-1,950 1,950-1,983 1,983-2,039	6.63	14,700	I	59	
34	33-10-401	Eastman Kodak	312	2,689	2,435-2,641	6.63	16,900	E	90	
35	33-10-402	Exchange Park Utilities #1	138	1,527	1,332-1,340 1,344-1,360 1,385-1,390 1,418-1,443 1,447-1,457 1,475-1,481 1,488-1,514	6.63	1,600	E	21	
43	33-11-703	Dallas Power & Light, Parkdale #2	312	3,180	2,963-3,003 3,013-3,043 3,048-3,178	8.63	18,000	E	95	
50	33-17-801	City of Duncanville #4	312	2,622	2,380-2,392 2,410-2,452 2,471-2,569	6.63	9,500	E	59	
53	33-18-803	City of Lancaster	312	3,091	2,904-2,908 2,932-2,936 2,998-3,013 3,064-3,068 3,078-3,088	9.63	14,800	E	93	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				DALLAS COUNTY continued						
55	33-20-401	Dallas Co. W.C. & I.D. #4, #1	312	4,110	3,851-4,041	6.63	11,300	E	93	
					4,048-4,056					
					4,073-4,083					
					4,096-4,104					
61	33-27-605	Trinity River Authority	200	1,645	1,240-1,298	4.5	6,900 *	E	36	
					1,320-1,352					
62	33-10-8--	NA	312	1,623	NA	NA	2,900	I	26	2×10^{-5}
63	33-10-8--	NA	180	2,755	NA	NA	16,300	I	86	8×10^{-5}
64	33-10-5--	NA	180	2,734	NA	NA	17,000	I	89	9×10^{-5}
65	33-18-2--	NA	178	2,883	NA	NA	12,300	I	49	5×10^{-5}
66	33-17-1--	NA	178	2,066	NA	NA	12,500	I	52	2×10^{-4}
67	33-03-404	Dallas Co. F.W.D. #15	200	1,243	NA	NA	7,600	E	38	
68	33-09-509	City of Irving #2	200	494	381-494	7.0	4,700	E	31	
69	33-16-906	A. W. Sowell #1	200	286	140-150	4.5	100	E	1	
					264-268					
70	33-10-808	Dallas Co. (Courthouse) #1	200	740	NA	7.63 **	7,500	E	29	
71	33-19-501	Dallas Co. Boys Home	200	1,044	875-1,040	5.5	9,700	E	55	
72	32-32-303	Bill Carter	200	410	330-339	4.5	1,600	E	8	
73	33-01-101	Dallas Power & Light #1	138	1,144	1,009-1,040	4.5	6,700	E	50	
					1,065-1,090					
					1,112-1,132					
74	33-09-203	Las Colinas Corp.	138	1,160	980-1,001	5.31	8,300	E	66	
					1,016-1,055					
					1,089-1,105					
					1,110-1,160					
75	33-04-801	City of Rowlett #1	138	2,658	2,460-2,633	5.5	3,300 §§	E	22	
					2,633-2,658					
76	33-09-908	Gen. Portland Cement #5	138	1,557	1,375-1,400	8.63	6,500	E	87	
					1,418-1,452					
					1,472-1,504					
77	33-01-101	City of Coppell #3	312	1,987	1,843-1,970	4.5	22,400 *	E	118	
78	33-02-904	City of Dallas #45	312	3,053	2,816-3,016	6.63	14,400	E	90	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				DALLAS COUNTY continued						
79	33-09-101	City of Irving #6	312	2,134	1,925-2,126	6.63	19,300	E	92	
80	33-09-403	City of Irving #3	312	2,117	1,924-1,942	8.63	14,400	E	69	
					1,948-1,980					
					1,985-2,051					
					2,057-2,077					
81	33-09-507	Whalen Corp. #1	312	2,250	2,102-2,125	8.63	11,900	E	63	
					2,129-2,169					
					2,173-2,214					
					2,220-2,240					
82	33-11-101	City of Dallas #43	312	3,206	2,963-3,203	9.63	12,600	E	70	
83	33-10-101	Dallas Co., Park Cities W.D. & I.D. #2	312	2,400	2,052-2,070	6.63	7,000	E	44	
					2,140-2,152					
					2,161-2,181					
					2,210-2,233					
					2,244-2,254					
					2,266-2,274					
					2,293-2,320					
					2,328-2,362					
					2,379-2,389					
84	33-10-501	Dallas Power & Light #3	312	2,735	2,567-2,734	4.5	11,300 *	E	59	
85	32-24-307	City of Grand Prairie #23	312	2,070	1,880-1,950	9.63	1,900	E	9	
					1,950-1,996					
					2,036-2,052					
86	33-17-111	L.T.V. Aerospace Corp. #5A	312	2,100	1,921-1,937	6.0	7,600	E	32	
					1,946-1,961					
					1,974-2,000					
					2,000-2,050					
					2,050-2,080					
87	33-17-203	Dallas Naval Air Station #4	312	2,118	1,992-2,115	6.63	11,300	E	45	
88	33-19-101	City of Dallas #41	312	3,076	2,844-3,064	9.63	12,300	E	59	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				DALLAS COUNTY continued						
89	33-20-101	Dallas Co. W.C. & I.D. #6, #1	312	3,840	3,612-3,840	5.5	3,200	E	8	
90	33-17-901	City of Duncanville #3	312	2,641	2,521-2,531 2,541-2,631	5.5	11,300	E	59	
91	33-25-202	City of Cedar Hill	312	2,568	2,418-2,568	7.0	7,900	E	88	
92	33-26-105	City of DeSoto #4	312	2,824	2,644-2,814	6.63	9,600	E	80	
93	33-27-205	City of Wilmer #3	312	3,572	3,322-3,442	6.0	8,800 *	E		
94	33-27-602	NA	200	1,390	1,288-1,352	NA	4,700	I	27	
				DENTON COUNTY						
21	19-64-201	Urban Services Inc.	312	1,748	1,621-1,727	3.5	10,000	E	36	
29	18-57-602	Colony M.U.D. Trinity #1	312	2,409	2,235-2,390	8.63	21,800	P	87	
30	32-07-205	Trophy Club Estates #1	312	1,424	1,291-1,391	6.63	12,700	E	73	
31	19-55-3--	NA	180	1,132	1,030-1,127	NA	4,500	I	24	
32	17-48-7--	NA	180	1,142	980-1,140	NA	3,000	I	16	
33	19-56-1--	NA	180	1,202	1,055-1,202	NA	5,000 §	I	26	
34	19-56-1--	NA	180	1,234	990-1,188	NA	4,100	P	22	
35	18-33-809	Joe Strittmatter	200	280	164-264	16.0	9,000	E	90	
36	18-41-604	Jeff Pedigo	200	330	130-330	14.0	2,900	E	23	
37	18-49-301	Michael W. Glitsch	200	420	104-181 220-309 300-420	12.0	8,300	E	83	
38	18-49-903	James B. Nix	200	380	310-380	4.5	2,000	E	18	
39	18-49-807	U.S. Army Corps of Engineers, Cottonwood Pk.	200	402	382-402	2.5	9,900	E		
40	19-64-306	Lake City Utility Authority #4	200	308	122-172 239-289	8.0	3,700	E		
41	18-57-304	Beach & Tennis Club	200	550	503-533	1.5	3,000	E	33	
42	19-64-704	U.S. Army Corps of Engineers, Twin Cave Pk. #14	200	180	105-135	2.5	500	E		

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				DENTON COUNTY continued						
43	32-08-109	U.S. Army Corps of Engineers, Murrell Pk. #10	200	150	NA	4.5	200	E		
44	32-08-203	U.S. Army Corps of Engineers, Murrell Pk. #8	200	160	NA	4.5	300	E		
45	19-48-501	3 V's Ranch	138	641	499-519 557-577 587-607	2.0	600	E	4	
47	19-61-301	Dr. Walter Miller	138	415	284-294 368-372 377-386	5.5	500	E	4	
48	19-64-304	Lake Cities Utilities Authority #2	138	978	810-820 920-957	4.5	3,900	E	26	
49	19-64-905	Bartonville W.S.C. #1	138	883	780-810 830-865	3.5	1,600	E	9	
50	19-64-403	H. C. Otis	138	747	670-700	3.5	500	E	3	
51	19-64-906	City of Lewisville #8	138	950	853-891 920-944	6.63	1,500	E	15	
52	32-07-206	Trophy Club Estates #2	138	1,314	446-480 510-515 522-568 584-596 612-626 640-686	8.63	3,000	E	18	
53	18-57-601	Colony M.U.D. #1	138	1,432	1,220-1,285 1,318-1,328 1,347-1,422	4.5	1,300	P	10	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		DENTON COUNTY continued								
54	18-33-807	City of Pilot Point #5	272	1,559	1,404-1,458	5.5	10,900	E	61	
					1,472-1,480					
					1,502-1,512					
					1,524-1,532					
					1,538-1,548					
55	19-47-102	Bolivar W.S.C. #1	272	852	740-780	3.5	4,700	E	26	
					800-840					
56	19-48-103	Green Springs W.S.C.	312	1,283	1,226-1,268	3.0	10,700	E	56	
57	19-46-801	Bolivar W.S.C.	272	900	770-796	3.0	3,100	E	19	
					816-831					
					845-855					
					860-870					
58	19-62-204	City of Justin #3	312	1,045	950-982	4.5	1,300	E	9	
					988-1,013					
59	19-63-202	Argyle W.S.C. #1	312	1,144	1,102-1,114	3.5	3,000	E	17	
					1,116-1,137					
60	19-63-204	Argyle W.S.C. #4	312	1,124	986-996	4.0	3,400	E	18	
					1,008-1,016					
					1,027-1,034					
					1,042-1,047					
					1,052-1,064					
					1,069-1,090					
					1,103-1,118					
61	19-64-502	Flower Mound Utility District No. 1, #3	312	1,747	1,648-1,695	4.0	13,200	E	43	
					1,701-1,740					
62	19-64-903	City of Lewisville #3	312	1,901	1,745-1,896	6.63	12,500	E	50	
63	19-64-903	City of Lewisville #4	312	1,900	1,750-1,800	6.63	14,000	E	51	
					1,805-1,861					
64	19-64-905	City of Lewisville #7	312	1,901	1,690-1,768	6.63	16,900 §§	E	56	
					1,773-1,860					
					1,865-1,892					
65	18-57-404	City of Lewisville #6	312	1,900	1,710-1,772	6.63	17,100	E	86	
					1,782-1,858					
					1,858-1,865					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
					ELLIS COUNTY					
03	33-33-101	City of Midlothian #3	269	2,412	2,175-2,226	7.0	5,900	I	54	
					2,235-2,335					
07	33-35-503	City of Palmer #2	200	1,522	1,330-1,390	4.0	11,300	I	54	
18	33-25-902	Sardis Lone Elm W.S.C.	269	2,762	2,565-2,581	4.0	6,000	E	50	
					2,592-2,617					
					2,632-2,650					
					2,664-2,699					
20	33-26-902	Rochett W.S.C. #2	312	3,178	2,978-3,126	6.0	9,600	E	55	
23	32-40-308	Tx. Industries #4	138	1,238	1,132-1,224	5.0	8,000	E	89	
24	32-40-606	Mountain Peak W.S.C. #1	312	2,411	2,245-2,350	4.5	4,800	E	25	
29	33-34-703	Waxahachie #3	269	2,950	NA	4.5	8,800	I	31	
30	33-34-702	City of Waxahachie #1	269	2,950	NA	6.0	9,000	I	32	
36	33-41-501	Buena Vista W.S.C. #1	312	2,606	2,450-2,456	4.5	3,600	P	15	
					2,466-2,472					
					2,480-2,489					
					2,493-2,506					
					2,516-2,520					
44	33-44-402	City of Ennis #2	200	1,821	1,722-1,821	7.0	9,900	E	62	
46	33-49-602	City of Italy #3	200	935	839-858	6.63	1,400	P	13	
					862-883					
					909-929					
47	33-49-803	South Ellis W.S.C.	312	2,700	2,573-2,630	8.63	1,400	E	5	
51	33-57-202	City of Milford #2	200	900	744-786	4.0	1,400	P	18	
					789-803					
					824-845					
52	32-56-901	Taylor Gandy	200	603	579-588	4.5	2,100	E	26	
54	33-26-802	City of Red Oak #2	200	1,171	1,085-1,111	8.0	700 ††	P	6	
					1,117-1,125					
					1,135-1,161					
55	33-25-501	Bill Nutting	200	699	662-697	4.5	500	E	3	
56	32-40-303	Tx. Industries #3	200	573	446-477	8.63	4,500	E	32	
					481-531					
					536-556					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		ELLIS COUNTY continued								
57	32-40-307	Tx. Industries #6	200	650	518-543 549-624	8.63	3,500	E	25	
58	32-40-901	Salvation Army, Camp Holblitzelle	138	1,359	1,230-1,244 1,254-1,338	8.0	5,700 §§	E	81	
59	33-26-817	Rockett W.S.C. #4	312	3,092	2,862-2,944 2,956-3,044	5.0	4,800 §§	E	44	
60	33-33-105	City of Midlothian #4	312	2,354	2,080-2,100 2,110-2,158 2,178-2,210 2,230-2,344	6.63	1,300	E	13	
61	32-40-501	Chaparral Steel Co.	312	2,150	1,966-1,996 2,001-2,030 2,035-2,081	6.0	6,700	E	35	
62	33-41-203	Bethel W.S.C., Buena Vista #2	312	2,564	2,410-2,452 2,472-2,500 2,510-2,540	5.5	6,400	E	28	
63	33-57-206	City of Milford #3	200	865	764-813 840-861	4.0	1,900	E	24	
64	33-43-101	Boyce W.S.C. #2	200	1,370	1,268-1,310 1,318-1,328	3.0	4,800	E	34	
		FALLS COUNTY								
01	39-33-604	Perry W.S.C.	269	3,651	3,458-3,526	7.0	10,800 *	P	28	
04	40-47-602	Mooreville W.S.C.	269	2,609	2,474-2,494 2,514-2,522 2,530-2,544	7.0	5,100 *	E	32	
07	40-56-102	Cego-Durango W.S.C. #1	269	2,768	2,708-2,748 2,756-2,768	8.63	10,700 *	E	59	
35	39-41-6--	T.H.S. Memorial Hospital	269	3,885	3,613-3,883	5.5	7,600 *	P	14	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		FANNIN COUNTY								
17	18-31-201	City of Bonham #5	200	1,282	1,096-1,240	8.63	10,300	P	48	
21	18-39-501	City of Bailey	200	1,595	1,530-1,580	4.5	13,400	E	56	
22	18-39-701	City of Leonard #2	200	1,690	1,523-1,673		26,400 §	I	96	
23	18-47-101	City of Leonard	200	1,605	1,502-1,581	4.5	12,600	E	46	
24	18-22-801	Morris Ballew	200	179	165-178	4.5	2,000	E	8	
25	18-30-102	Town of Savoy	200	528	508-528	5.0	2,300	E	10	
26	18-30-401	S W Fannin Co. W.S.C. #2	200	763	608-648	3.0	3,500	E	10	
					696-738					
27	18-31-602	Brotherton W.S.C.	200	1,480	1,377-1,461	3.5	6,300	E	33	
28	18-32-201	Lannius W.S.C.	200	1,454	1,368-1,395	3.0	2,300	E	15	
					1,405-1,432					
29	18-38-402	Trenton W.S.C.	200	1,588	1,492-1,518	4.5	2,500	E	9	
					1,556-1,588					
30	18-39-702	City of Leonard #3	200	1,720	1,464-1,508	6.63	8,000	E	29	
					1,550-1,606					
		GRAYSON COUNTY								
46	18-28-101	City of Sherman, R-1T	272	2,380	1,585-2,370	10.0	2,900	E	7	
47	18-29-301	City of Bells	200	709	674-705	4.0	2,000	E	10	
49	18-29-902	City of Whitewright #2	200	1,189	1,109-1,189	6.0	3,600	E	17	
50	18-29-904	City of Whitewright #4	200	1,388	1,136-1,146	4.0	2,500	E	11	
					1,154-1,167					
					1,173-1,210					
					1,242-1,252					
					1,268-1,304					
					1,317-1,328					
51	18-19-9--	NA	180	2,160	NA	NA	3,400	I	8	$2x10^{-4}$
52	18-23-3--	NA	180	1,514	1,372-1,514	NA	4,900	I	26	
53	18-09-6--	NA	180	1,021	991-1,021	NA	420	I	2	
54	18-36-5--	NA	200	1,400	1,160-1,400	NA	10,000	I	71	$2x10^{-4}$

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				GRAYSON COUNTY continued						
55	18-28-4--	NA	200	785	726-785	NA	2,300	I	11	1.9×10^{-4}
56	18-28-4--	NA	200	776	725-776	NA	2,200	I	11	9×10^{-4}
57	18-28-4--	NA	200	786	724-786	NA	2,300	I	11	1.8×10^{-5}
58	18-28-4--	NA	200	778	721-778	NA	2,400	I	11	
59	18-28-4--	NA	200	778	541-772	NA	2,400 §	I	12	2×10^{-4} §
60	18-28-4--	NA	200	2,140	NA	NA	2,400	I	12	1×10^{-4}
62	18-28-4--	NA	200	1,069	908-1,054	NA	7,900 §	I	39	
63	18-34-4--	NA	200	732	655-732	NA	14,700	I	74	
64	18-26-5--	NA	200	345	189-345	NA	7,900	I		
65	18-10-4--	NA	200	180	80-180	NA	16,700 §	I		
66	18-19-3--	NA	200	642	470-632	NA	300	I	2	
67	18-11-8--	NA	200	443	241-341	NA	2,300 §	I	11	
68	18-36-5--	NA	200	1,401	1,165-1,401	NA	7,900	I	56	
69	18-10-404	Grover Moor	200	183	100-178	8.63	7,900	E		
70	18-10-402	J. B. Rich	200	275	0-220	8.0	4,900	E		
71	18-10-408	O. L. Holder	200	324	74-324	7.0	400	E		
72	18-10-601	Tom Erikson	200	234	195-234	4.5	500	E		
73	18-10-603	Mill Creek Meadows	200	125	75-103	7.0	9,600	E		
74	18-10-903	Flowing Wells Resort	200	435	248-435	4.5	400	E		
75	18-11-702	Pottsboro School Dist. #2	200	395	382-395	4.5	400	E		
76	18-11-804	Texoma Ranch Estates	200	281	238-281	7.0	1,900	E		
77	18-11-805	Chevron U.S.A., New Mag., Unit 11-1W	200	496	180-195	8.63	500	E	3	
					252-260					
					385-395					
					405-435					
78	18-13-801	Johnnie E. McCraw	200	60	20-60	5.0	1,700	E		
80	18-18-601	Harry Lee Wright	200	479	0-479	8.63	12,000	E		
81	18-19-303	City of Dennison #1	200	620	510-620	6.0	500	E	3	
82	18-19-702	Bermico Co. #2	200	770	651-724	8.63	6,300 *	E		
83	18-19-701	Bermico Co. #1	200	772	623-639	8.63	12,800	E		
					646-658					
					670-750					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		GRAYSON COUNTY continued								
84	18-19-901	Hole Mfg. Co.	200	872	793-808 834-838	5.5	150	E	1	
85	18-20-401	City of Sherman 1-W	200	1,012	740-785 900-950	10.75	15,800	E		
86	18-20-501	W. O. Wright, Jr.	200	380	360-380	4.5	700	E	3	
87	18-20-603	Star Water Co.	200	320	250-320	7.0	4,500	E	18	
88	18-20-710	City of Sherman Fairview Sta. WB-9	200	789	718-773	8.0	7,400	E	30	
89	18-20-801	City of Sherman, Stevens 1W	200	1,025	650-700 710-730 740-780 800-895 905-980	10.75	11,200	E	45	
90	18-20-804	City of Sherman, Stevens W-2	200	1,044	570-624 638-658 790-810 834-908 966-1,034	10.75	7,600	E	30	
91	18-25-301	McDonnell Construction	200	280	250-280	7.0	1,700	E		
92	18-25-302	J. L. Welch #2	200	320	140-320	16.0	4,600	E		
93	18-25-605	Bob Light #1	200	425	0-340	14.0	7,500	E		
94	18-25-608	Manuel Carney	200	309	229-309	8.63	9,900	E		
95	18-26-401	Bob S. Light #2	200	355	235-355	16.0	9,600 *	E		
96	18-27-801	City of Sherman W-10	200	950	630-670 748-772 788-856 888-934	12.75	4,500	E	21	
97	18-28-402	City of Sherman, Woodbine #2	200	1,050	840-910 927-932 939-969	8.63	6,800	E	34	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				GRAYSON COUNTY continued						
98	18-28-403	City of Sherman, Woodbine #1	200	1,090	794-835 930-935 967-972 1,006-1,064	10.75	4,700	E	27	
99	18-28-103	City of Sherman, Tuck 1-W	200	1,023	832-912 942-1,012	10.0	5,900 ††	P	28	
100	18-29-702	City of Tom Bean #2	200	1,475	1,283-1,295 1,386-1,440 1,445-1,455	4.5	5,700	E	33	
101	18-35-402	Gunter Water Works, Home for Aged	200	730	655-730	4.5	12,500 ††	P	59	
102	18-33-204	R. B. Hunsaker	200	255	112-232	16.0	4,400	E		
103	18-17-901	City of Whitesboro #3	272	1,520	1,388-1,519	5.5	4,600	I	24	
104	18-25-601	City of Collinsville	272	1,524	1,328-1,522	5.5	8,000	E	32	
105	18-28-102	City of Sherman, Tuck Station T-1	272	2,460	1,590-2,420	10.0	4,700	I	13	
106	18-20-803	City of Sherman, Stevens T-2	272	2,307	1,464-2,206	10.75	6,100	E	22	
107	18-27-802	City of Sherman C-9T	272	2,480	1,594-2,454	10.75	3,500	E	19	
108	18-27-901	City of Sherman C-8T	272	2,460	1,670-2,450	8.0	1,900	E	8	
109	18-28-404	City of Sherman, Trinity #1	272	2,500	1,700-2,450	10.75	3,000	E	10	
110	18-29-302	City of Bells #2	272	1,680	1,326-1,577	4.5	100	E	1	
111	18-35-403	City of Gunter	272	1,666	1,491-1,511 1,516-1,537 1,542-1,563	4.0	2,000	E	8	
112	18-36-503	City of Van Alstyne	272	2,300	2,010-2,020 2,075-2,095 2,109-2,128 2,150-2,290	5.5	1,100	P	7	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				HAMILTON COUNTY						
01	40-01-401	Gordon Euhus	178	355	157-355	12.0	11,800	E		
				HILL COUNTY						
11	39-10-201	City of Hubbard #2	269	3,555	NA	10.75	4,000	P	8	
26	40-06-501	City of Whitney #3	269	1,283	1,129-1,282	6.63	2,900	P	36	2.8×10^{-5}
28	40-06-504	Hill Co. W.S.C. #1	269	1,470	1,326-1,336 1,346-1,409	3.5	2,900 *	E	32	
29	40-07-101	City of Hillsboro, Barrett Well	178	1,617	1,397-1,427 1,488-1,516 1,528-1,598	8.63	2,400	P	16	
34	32-53-902	Blum W.S.C. #1	180	934	855-910	5.5	5,600	I	56	
35	32-55-902	City of Itasca #5	269	1,835	1,745-1,835	8.63	5,200	P	35	
36	32-56-403	Files Valley W.S.C. #1	269	2,287	2,030-2,209	4.0	1,600	E	11	
37	32-56-702	Files Valley W.S.C.	269	2,240	2,080-2,233	4.0	4,100	E	27	
38	40-06-101	Lake Whitney Recreation Club #1	269	1,278	1,128-1,156 1,164-1,182 1,190-1,204 1,211-1,219 1,231-1,247	8.63	9,700	E	139	
39	40-08-501	Chatt W.S.C. #1	269	2,070	1,940-1,950 1,972-2,036	7.0	1,700 *	E	9	
40	40-15-102	Aquilla W.S.C.	269	1,485	1,380-1,480	8.63	4,000	E	44	
41	39-09-901	City of Calm #1	269	3,458	3,120-3,300	8.63	2,000	P	11	
42	32-61-103	U.S. Army Corps of Engi- neers, Noland Pk.	138	228	208-218	NA	9,300	P	233	
				HUNT COUNTY						
22	18-48-402	Webb Hill Country Club	200	2,318	2,239-2,331	7.0	4,500	E	15	
23	18-47-601	Hickory Creek W.S.C.	200	2,388	2,225-2,303	4.5	10,500	E	35	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		JOHNSON COUNTY								
08	32-37-901	City of Cleburne #12	312	1,283	961-1,062	8.0	4,500	P		
					1,090-1,115					
					1,130-1,245					
11	32-38-102	Bethesda W.S.C. #2	312	1,437	1,076-1,088	6.0	2,500	E		
					1,122-1,130					
					1,160-1,178					
					1,188-1,196					
					1,212-1,222					
					1,230-1,240					
					1,254-1,272					
					1,278-1,326					
12	32-38-901	Bethany W.S.C. #1	312	1,630	1,522-1,540	7.0	1,000	E	13	
					1,544-1,564					
					1,570-1,575					
15	32-54-101	Wallis Simpson Water Co.	312	1,215	1,137-1,215	7.0	3,400	P	34	
17	32-39-707	Don R. McNeill #1	200	178	NA	4.5	900	E		
18	32-46-209	R. B. Beasley	200	160	48-120	7.0	500	E		
19	32-47-107	Mohawk Water Supply	200	160	145-160	5.5	1,000	E		
20	32-47-806	City of Grandview #4	200	224	182-204	6.0	1,600	P		
21	32-47-803	City of Grandview #3	200	214	188-210	7.0	1,300	P		5.1×10^{-5}
22	32-30-904	E. E. Doyal	138	575	555-575	4.5	1,200	E	16	
23	32-30-502	City of Burleson #4	138	587	472-528	7.0	2,400	I	30	
					543-561					
					570-586					
24	32-36-503	Dr. Robert Shaw #1	138	400	364-370	4.5	3,000	E	100	
25	32-37-202	Community Water Co., Sundance Add't SDA #1	138	690	584-594	7.0	2,500	E	50	
					618-622					
					630-654					
26	32-37-311	City of Joshua #2	138	688	573-651	7.0	2,400	E	40	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		JOHNSON COUNTY continued								
27	32-37-602	Harvey Baker	138	623	593-623	4.5	1,700	E	28	
28	32-37-603	John Sanders	138	NA	585-595 602-626	4.5	2,300	E	38	
29	32-46-202	Liberty School District 33	138	698	675-698	4.0	500	E	10	
30	32-47-802	City of Grandview #3	138	852	802-846	6.0	3,700	E	61	
31	32-30-501	City of Burleson #2	312	1,180	1,034-1,180	6.0	1,700	E		
32	32-30-908	Bethesda W.S.C.	312	1,568	1,236-1,262 1,266-1,281 1,285-1,310 1,393-1,408 1,446-1,456 1,486-1,510 1,517-1,552	6.63	2,100	E		
33	32-31-706	Johnson Co. Rural W.S.C. #14	312	1,640	1,494-1,562	6.63	4,600	E	57	
34	32-31-805	Johnson Co. Rural W.S.C. #15	312	1,721	1,601-1,711	6.63	4,600	E	46	
35	32-37-313	Johnson Co. Rural W.S.C. #6	312	1,320	1,044-1,191 1,228-1,263	4.5	7,700	E		
36	32-37-905	Johnson Co. Rural W.S.C. #17	312	1,408	1.020-1,038 1,044-1,076 1,083-1,111 1,212-1,232 1,237-1,268 1,274-1,312 1,330-1,408	10.75	2,800	E		
37	32-38-403	Bethesda W.S.C. #6	312	1,449	1,100-1,130 1,140-1,170 1,175-1,205	7.0	3,000	E		

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
					JOHNSON COUNTY continued					
					1,225-1,230					
					1,240-1,255					
					1,305-1,365					
					1,375-1,385					
38	32-38-702	City of Keene #6	312	1,480	1,370-1,480	7.0	4,700 *	E		
39	32-38-904	Bethany W.S.C. #2	312	1,590	1,488-1,498	7.0	2,000	E	25	
40	32-39-804	Johnson Co. Rural W.S.C. #16	312	1,778	1,508-1,550	6.63	1,900	E	21	
					1,563-1,571					
					1,583-1,587					
					1,591-1,601					
					1,660-1,670					
					1,678-1,692					
					1,705-1,758					
41	32-45-301	City of Cleburne #9	178	1,265	925-1,079	8.0	6,100	E		
			269		1,106-1,200					
42	32-45-302	City of Cleburne #7	178	1,250	898-1,003	8.0	4,300	I		
			269		1,024-1,066					
					1,099-1,204					
43	32-45-304	City of Cleburne #5	178	1,274	941-1,086	8.0	2,500	I		
					1,129-1,251					
44	32-45-307	City of Cleburne #6	312	1,206	880-1,048	8.0	5,000	E		
					1,096-1,180					
45	32-45-601	City of Cleburne #11	312	1,266	895-995	8.0	7,700 §	I		
					1,015-1,165					
46	32-45-607	Texas Lime Co. #3	312	1,220	1,120-1,220	7.0	9,300	E		
47	32-46-903	Parker W.S.C. #1	269	1,612	NA	7.0	1,000	E	11	
48	32-47-103	Johnson Co. Rural W.S.C. #3	312	1,680	1,562-1,582	7.0	2,600	E	29	
					1,600-1,608					
					1,630-1,646					
					1,656-1,660					
					1,664-1,672					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				MCLENNAN COUNTY						
11	40-39-106	Midway Water Co.	269	1,828	1,727-1,827	7.0	5,700	P	46	
14	39-33-102	Texas Power & Light, Lake Creek #2	269	2,898	2,550-2,570	6.0	1,600	P	6	
					2,584-2,594					
					2,605-2,615					
					2,650-2,670					
					2,676-2,716					
					2,725-2,745					
					2,757-2,797					
					2,810-2,830					
					2,853-2,873					
19	40-38-801	Spring Valley W.S.C. #1	289	1,460	1,244-1,264	7.0	2,600	E	48	
					1,372-1,390					
					1,397-1,406					
					1,412-1,424					
					1,436-1,440					
					1,448-1,450					
23	40-46-402	City of Moody #1	269	1,494	1,333-1,487	6.0	3,500	P	28	3.18×10^{-5}
29	40-31-102	City of Waco, Blackland Flying Field #2	289	1,540	1,186-1,254	6.63	4,200	P		
					1,316-1,337					
					1,360-1,493					
34	40-31-601	City of Waco-Filtration Plant Well	178	2,046	NA	6.0	6,600 §	I	73	8×10^{-5} §
37	40-24-101	Ross W.S.C. #1	269	2,269	2,110-2,265	5.5	2,600	P	27	
41	40-24-802	Connally Air Force Base #2	269	2,370	2,178-2,368	6.0	4,200	P	34	
43	40-32-102	City of Bellmead #1	269	2,303	2,115-2,287	6.0	5,700	P	57	
44	40-32-103	City of Bellmead #2	269	2,396	2,198-2,392	6.0	6,500	E	65	
45	40-32-403	General Tire & Rubber #1	269	2,312	2,109-2,311	6.63	4,500	P	+50	
46	40-32-404	General Tire & Rubber #2	269	2,376	2,133-2,312	6.63	11,100 §	I	123	1×10^{-4} §
					2,352-2,374					
48	40-32-501	City of Waco Timbercrest #2	269	2,493	2,331-2,464	6.63	4,400	E	44	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		MCLENNAN COUNTY continued								
49	39-25-401	Texas Power & Light Co. #1	269	3,035	2,554-2,569	6.63	2,800 *	P	19	
					2,574-2,584					
					2,590-2,600					
					2,644-2,684					
					2,694-2,714					
					2,720-2,730					
					2,737-2,742					
					2,845-2,865					
					2,870-2,885					
					2,920-2,960					
50	39-25-402	Texas Power & Light Co. #2	269	2,950	2,542-2,557	6.63	6,600	E	44	
					2,574-2,584					
					2,618-2,643					
					2,650-2,680					
					2,700-2,730					
					2,762-2,772					
					2,824-2,830					
					2,864-2,890					
					2,898-2,918					
					2,926-2,946					
51	39-25-501	City of Mart #1	269	3,181	3,030-3,181	7.0	16,000 §§	E	91	
54	40-39-302	Waco Memorial Park #1	269	2,096	1,996-2,096	5.0	4,100	E	27	
56	39-33-101	Texas Power & Light, Lake Creek #1	269	2,820	2,475-2,485	6.0	2,000	E	8	
					2,499-2,509					
					2,515-2,525					
					2,537-2,547					
					2,553-2,563					
					2,574-2,584					
					2,609-2,629					
					2,653-2,733					
					2,756-2,776					
					2,788-2,808					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				MCLENNAN COUNTY continued						
57	40-33-104	Meyer Settlement W.S.C. #2	269	3,115	3,010-3,030	7.0	3,900	E	16	
					3,040-3,070					
58	40-46-801	Elm Creek W.S.C.	269	1,680	1,595-1,680	7.0	5,600	P	45	
59	40-39-1--	NA	180	NA	NA	NA	5,400 §	I	43	
60	40-39-1--	NA	180	NA	NA	NA	5,000	I	40	$8x10^{-5}$
65	40-39-7--	NA	180	1,881	NA	NA	11,500	I	82	
66	40-16-404	City of West	269	1,977	1,870-1,977	6.63	2,000	P	15	
67	40-22-605	Cross Country W.S.C.	178	1,296	1,082-1,226	8.63	1,000	E		
68	40-24-501	Pure W.S.C. #1	269	2,350	2,278-2,306	7.0	3,900 *	E	39	
69	40-24-703	McLennan Co. W.C.I.D. #2	269	2,348	2,184-2,336	7.0	11,200	P	112	
70	40-24-803	Connally A.F.B. #3	269	2,494	2,253-2,492	8.0	3,800 §	P	36	
72	40-32-104	City of Lacey-Lakeview #3	269	2,329	2,153-2,320	7.0	4,600	E	46	
73	40-28-502	Hog Creek W.S.C. Midway	269	1,194	999-1,112	4.5	3,400	E		
74	40-31-701	Water Co.	269	1,779	1,689-1,779	4.0	5,500	P	42	$6.6x10^{-5}$
75	40-31-802	Bryan-Maxwell-Bryan	269	2,040	1,904-2,009	6.63	5,000	P	42	
76	39-25-701	H & H W.S.C. #1	269	2,916	2,789-2,909	7.0	2,700	E	13	
77	39-33-202	Riesel MUD #1	269	3,531	3,390-3,455	7.0	7,900 *	E	25	
79	40-38-202	Harris Creek Country Club #1	178	1,306	1,048-1,068	8.63	1,400	E	17	
					1,074-1,094					
					1,228-1,248					
					1,252-1,258					
80	40-31-801	Midway Water Co.	178	1,828	NA	8.0	5,300	P	44	$5.98x10^{-5}$
81	40-39-101	Waco Syrian Assoc.	269	1,865	1,800-1,865	2.0	5,500	E	40	$5.98x10^{-5}$
82	40-39-702	Lorena W.S.C. #2	269	1,888	1,690-1,801	5.0	5,700	E	82	
83	40-46-403	City of Moody #2	269	1,561	1,347-1,485	6.0	3,700	P	30	$3x10^{-5}$
84	40-39-104	Midway School	269	1,872	NA	4.0	4,700	E	38	$5.94x10^{-5}$
				NAVARRO COUNTY						
24	33-59-102	City of Blooming Grove #2	200	1,603	1,402-1,514	8.63	3,100	P	19	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				ROCKWALL COUNTY						
06	33-05-401	City of Rockwall #2	138	3,342	3,242-3,342	4.5	2,300	E	14	
				TARRANT COUNTY						
10	32-06-403	City of Haslet #2	312	1,190	1,084-1,134	7	1,300	E	7	
16	32-14-609	Haltom City	312	1,130	958-978 988-998 1,020-1,090	6.63	6,900	E	69	
17	32-14-604	Haltom City	312	1,140	1,040-1,130	8.63	5,600	E	56	
20	32-14-605	Haltom City	312	1,284	1,102-1,188	8	5,100	E	41	
21	32-16-202	City of Euless, Trinity #5	312	1,781	1,649-1,679 1,701-1,738 1,740-1,781	8.63	9,300	E	39	
27	32-22-602	City of Forrest Hill, Trinity #2	312	1,288	1,051-1,078 1,087-1,093 1,109-1,118 1,131-1,140 1,197-1,233 1,245-1,267 1,279-1,286	6.63	6,800	E		
34	32-23-102	Texas Electric Survey #9	312	1,352	1,180-1,230 1,238-1,340	8.63	9,900	E		
36	32-23-404	Texas Electric Service #11	312	1,352	1,064-1,112 1,134-1,144 1,176-1,209 1,246-1,260 1,313-1,350	8.63	10,300	E		
38	32-23-307	City of Pantego #4	312	1,619	1,374-1,394 1,409-1,429 1,449-1,560	10.75	11,200	E		
40	32-24-101	City of Arlington #6	312	1,775	1,567-1,751	7	12,500	I	83	
43	32-30-605	Bethesda W.S.C. #7	312	1,526	NA	6	4,700	E		

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				TARRANT COUNTY (continued)						
44	32-31-605	City of Mansfield #4	312	1,732	1,592-1,614 1,633-1,708	6.63	6,700	I	67	
46	32-16-5--	NA	200	267	236-266	NA	2,400 §	I	30	
47	32-16-7--	NA	138	817	668-809	NA	6,100	I	68	
48	32-23-3--	NA	138	786	628-776	NA	3,900	I	43	
49	32-23-6--	NA	138	595	NA	NA	4,300	I	54	1.8×10^{-4}
50	32-22-7--	NA	138	398	NA	NA	3,300	I	41	
51	32-14-7--	NA	138	254	150-254	NA	7,500 §	I	68	
52	32-14-7--	NA	138	210	NA	NA	3,100 §	I	28	4×10^{-4} §
53	32-14-8--	NA	138	170	NA	NA	4,100 §	I	37	7.4×10^{-4} §
54	32-15-4--	NA	138	524	453-524	NA	2,700	I	23	1.2×10^{-4}
55	32-14-6--	NA	178	1,130	958-1,090	NA	6,900	I	49	
56	32-14-7--	NA	178	964	NA	NA	2,900	I		3×10^{-5}
57	32-14-7--	NA	178	964	NA	NA	2,800	I		9×10^{-5}
58	32-23-1--	NA	178	1,431	1,305-1,425	NA	9,000	I		7×10^{-5}
59	32-23-1--	NA	178	1,363	1,154-1,334	NA	11,000	I		6×10^{-5}
60	32-23-1--	NA	178	1,346	NA	NA	9,800	I		1×10^{-4}
61	32-23-1--	NA	178	1,376	1,239-1,359	NA	10,000	I		
62	32-23-1--	NA	178	1,330	1,210-1,330	NA	7,800	I		5×10^{-5}
63	32-23-1--	NA	178	1,432	690-1,432	NA	7,400	I		4×10^{-5}
64	32-23-3--	NA	178	1,352	NA	NA	15,200	I		1×10^{-4}
65	32-08-112	Fergurson	200	134	95-130	4.5	500	E		
66	32-08-505	U.S.Army Corps of Engineers, Silver Lake Pk. #16	200	197	170-190	3	1,800	E		
67	32-07-908	Bluebonnet Hills Memorial Pk. #3	200	50	20-48	6	4,800	E		
68	32-08-707	Leon Smith Kwb #1	200	240	210-235	4.5	4,900	E		
69	32-08-702	Leonard Hall	200	209	NA	6	1,500	E	17	
70	32-16-802	Ray Young	200	285	195-202 258-285 225-229 237-241 248-249	4.5	100	E		

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		TARRANT COUNTY (continued)								
71	32-23-311	R. G. Farrell	200	126	NA	4.5	1,700	E	11	
72	32-24-505	Irving L. Taggart #1	200	395	210-220 325-334	4.5	900	E	5	
73	32-23-608	Arlington Ventures Inc. #1	200	200	NA	4.5	700	E		
74	32-23-902	American Way Homes	200	308	290-300	4.5	1,700	E		
75	32-23-501	J. P. Day	200	335	172-207 302-318	7	10,800	E	62	
76	32-05-302	J. B. Lindsley, Willow Springs Golf Course, #2	138	419	305-330 340-375 395-410	6	3,300	E	25	
77	32-05-502	Quick Car Corp.	138	405	345-375	4.5	2,500	E	23	
78	32-05-801	Lake Country Estates Inc. #1	138	208	110-182	6	5,000	E	42	
79	32-05-802	Lake Country Estates Inc. #2	138	250	166-234	6	6,500	E	54	
80	32-06-504	Keller Rural W.S.C., Paluxy #3	138	690	543-564 570-576 585-606 612-652 656-669 674-678	6.63	500	E	4	
81	32-06-602	North Tarrant Co. Mun. Water Dist. #1	138	639	535-600 605-635	7	1,800	E	13	
82	32-06-606	Keller Rural W.S.C.	138	780	623-654 659-677 686-702 707-728 740-749 752-762	6.63	750	E	6	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		TARRANT COUNTY (continued)								
83	32-07-201	Keller Rural W.S.C. #4P	138	747	586-646	3	600	E	4	
					690-750					
84	32-07-301	B & D Mills Inc.	138	660	NA	4.5	1,300	E	8	
85	32-07-403	Keller Rural W.S.C. #3	138	841	714-720	7	700	E	5	
					725-748					
					760-774					
					782-806					
					812-828					
86	32-07-401	N. Tarrant Co. Mun. Water Dist. #3	138	625	522-561	7	5,900	E	42	
					564-620					
87	32-07-803	City of N. Richland Hills #1	138	757	642-752	7	4,800	E	38	
88	32-08-401	Fina	138	749	734-749	open (4.5)	600	E	5	
89	32-08-708	Leon Smith, Paluxy #2	138	859	808-813	4.5	3,100	E	26	
					818-825					
					854-858					
90	32-13-101	City of Ft. Worth Pks. Dept.	138	179	55-80	6	700	E	6	
91	32-13-405	Town of Lakeside #5	138	180	98-100	6	400	E	4	
					140-161					
92	32-13-707	City of White Settlement #5A	138	305	175-305	6	4,000	E	36	
93	32-14-111	City of Saginaw #2	138	525	266-281	7	4,800	E	40	
					326-368					
					392-402					
					410-415					
					425-435					
					466-492					
94	32-14-105	Saginaw Park Utility #1	138	428	337-385	6.63	3,000	E	25	
					400-423					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				TARRANT COUNTY (continued)						
95	32-14-304	N. Richland Hills	138	538	421-531	7	2,500	E	21	
96	32-14-512	International Mineral & Chemical	138	434	379-388 402-408 415-430	8	800	E	7	
97	32-14-606	Haltom City	138	482	NA	6	5,100	E	43	
98	32-14-608	Haltom City	138	442	306-339 371-388	8	3,000	E	25	
99	32-14-905	Haltom City	138	431	359-374	8	1,000	E	9	
100	32-15-105	N. Richland Hills #1	138	560	434-471 476-523 527-549	7	2,700	E	21	
101	32-15-102	N. Richland Hills (College Hills #4)	138	700	575-619 629-640 643-676 680-692	7	6,500	E	54	
102	32-15-207	N. Richland Hills, Hay Plant	138	682	538-558 573-576 578-595 620-640 650-660 669-677	7	1,300	E	11	
103	32-15-413	N. Richland Hills	138	629	511-541 559-580 585-624	7	4,200	E	35	
104	32-21-204	Benbrook #10	138	381	280-294 310-375	7	2,500	E	23	
105	32-21-217	Clinton Wright	138	272	NA	6.63	15,700	E	174	
106	32-21-307	Champlin Refining Co.	138	384	284-323 330-360	6.63	5,200	E	58	
107	32-21-405	Benbrook #8	138	258	193-225 232-248	6.63	3,000	E	25	
108	32-21-407	Benbrook Water & Sewer Authority #11	138	310	195-295	8	9,400	E	75	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft²)	Coefficient of Storage
				TARRANT COUNTY (continued)						
109	32-21-506	Benbrook #16	138	277	192-272	7	6,200	E	52	
110	32-21-703	U.S. Army Corps of Engineers H.Q.	138	285	264-285	2.5	3,300	E	26	
111	32-22-208	Spencer Chemical	138	451	336-368 390-413	8	1,300	E	12	
112	32-22-211	St. Joseph Hospital #2	138	515	439-441 461-471 485-497	8	2,700	E	27	
113	32-22-907	City of Everman #4	138	585	507-546 550-580	7	6,500	E	81	
114	32-23-203	Arlington Country Club #2	138	590	520-530 560-570	6	2,300	E	23	
115	32-23-309	City of Arlington #15	138	951	NA	6.63	2,900	E	36	
116	32-23-402	Redwood Estates	138	610	NA	4.5	2,600	E	33	
117	32-23-602	Dalworthington Gardens #1	138	773	672-715 734-755	6	2,200	E	27	
118	32-23-701	Kennedale #2	138	700	535-632	6	4,500	E	56	
119	32-24-202	City of Arlington #12	138	1,074	888-908 922-954 970-1,058	6	6,300	I	63	
120	32-29-102	U.S. Army Corps of Engineers Holiday Pk. #4H	138	270	230-270	2.5	3,100 *	E	28	
121	32-30-301	City of Everman #3	138	590	515-556 562-578	7	2,600	E	23	
122	32-31-501	Westside Rural W.S.C.	138	867	732-737 752-772 792-802 822-827 834-854	3	500	E	6	
123	32-31-405	Tarrant Utility Co. #2	138	780	690-775	6.63	1,800	E	23	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		TARRANT COUNTY (continued)								
124	32-05-101	Texas National Guard #A-3	312	573	482-539	8	2,500	E		
125	32-05-102	Texas National Guard #A-2	312	542	485-538	8.63	500	E		
126	32-06-404	York Construction Co.	312	1,018	872-1,018	4.5	2,500	E	10	
127	32-06-502	Keller Rural W.S.C., Trinity #3	312	1,160	1,035-1,070 1,100-1,155	7	1,600	E	8	
128	32-07-602	City of South Lake #2	312	1,610	1,500-1,573	6.63	10,800	E	49	
129	32-07-601	City of South Lake #1	312	1,649	1,522-1,548 1,556-1,610	6.63	11,500	E	46	
130	32-14-110	City of Saginaw, Trinity #2	312	1,041	876-892 904-916 932-942 954-1,016	10.75	3,800	E	25	
131	32-14-107	Saginaw Park Utility #3	312	1,105	958-978 983-1,008 1,013-1,038 1,046-1,054	8	7,400	E	49	
132	32-14-502	Magnolia Petroleum	312	1,108	950-980 990-1,020 1,030-1,070 1,080-1,100	10.75	7,700	E	77	
133	32-12-603	Harston Gravel Co.	312	568	380-420 480-564	8.63	1,300	E		
134	32-13-807	General Dynamics	312	810	561-619 679-699 714-741 749-794	6	9,000	E		
135	32-15-201	City of Hurst, #9-T	312	1,588	1,368-1,420 1,420-1,522	8.63	15,000	E	68	
136	32-15-307	City of Bedford #5	312	1,550	1,370-1,398 1,408-1,526	8.63	15,400	E	64	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
		TARRANT COUNTY (continued)								
137	32-15-412	Richland Hills	312	1,235	1,059-1,075	6.63	9,400	E	63	
					1,087-1,107					
					1,119-1,161					
					1,171-1,225					
138	32-15-604	Euless	312	1,625	1,342-1,398	8.63	12,200	E	49	
					1,432-1,447					
					1,510-1,525					
					1,540-1,600					
139	32-15-507	City of Hurst #11-T	312	1,432	1,232-1,250	8.63	17,000	E	71	
					1,260-1,275					
					1,290-1,324					
					1,331-1,428					
140	32-15-601	Bell Aircraft Corp. #1	312	1,483	1,179-1,219	8.63	11,500	E	48	
					1,240-1,250					
					1,272-1,292					
					1,329-1,339					
					1,379-1,429					
					1,440-1,450					
141	32-15-901	City of Arlington #13	312	1,654	1,414-1,471	6	9,700 **	E	51	
					1,481-1,511					
					1,525-1,568					
					1,588-1,646					
142	32-16-501	Ft. Worth International	312	1,742	1,626-1,642	8	15,000	E	60	
		Airport #2			1,656-1,742					
143	32-21-201	Texas Water Co. #1	312	1,030	770-788	6.63	17,200	E		
					828-865					
					873-880					
					900-928					
144	32-21-303	City of Westover Hills #1	312	865	713-860	7	4,000 **	E		
145	32-22-210	Great Western Food Co.	312	1,189	978-1,013	5.5	9,700	E		
					1,018-1,046					
					1,057-1,075					
					1,085-1,095					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
				TARRANT COUNTY (continued)						
146	32-22-901	City of Forest Hill #6	312	1,352	1,108-1,138	6.63	11,800 §§	E		
					1,158-1,186					
					1,192-1,202					
					1,260-1,280					
					1,290-1,335					
147	32-23-604	City of Dalworthington Gardens #3	312	1,650	1,460-1,476	5.5	9,100	E		
					1,486-1,496					
					1,512-1,526					
					1,536-1,570					
					1,578-1,630					
148	32-23-705	City of Kennedale #4	312	1,450	1,284-1,335	10.75	7,600 *	E		
					1,350-1,390					
					1,400-1,420					
					1,430-1,450					
149	32-23-802	City of Arlington	312	1,612	1,408-1,462	8.63	11,400	E		
					1,490-1,500					
					1,510-1,580					
150	32-24-109	City of Arlington #17	312	1,859	1,712-1,848	13	14,000	E	93	
151	32-24-201	City of Arlington #9	312	1,941	1,783-1,930	6	14,100	E	67	
152	32-24-501	City of Grand Prairie #24	312	2,150	1,805-1,856	8.63	2,100	E	14	
					1,856-1,958					
153	32-21-403	Benbrook #3	312	907	670-680	6	800	E		
					704-725					
					776-810					
					830-878					
					670-681					
					696-700					
					707-712					
					726-734					
					740-748					

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft²)	Coefficient of Storage
		TARRANT COUNTY (continued)								
154	32-31-104	Bethesda W.S.C. #1	312	1,551	1,248-1,268	6.63	8,900	E		
					1,298-1,308					
					1,326-1,341					
					1,371-1,396					
					1,404-1,419					
					1,434-1,494					
		TRAVIS COUNTY								
05	58-34-603	Balcones Country Club	178	1,100	980-1,100	7	30	P	1	
			269							
17	58-44-204	City of Manor #2	269	3,086	2,795-3,086	6.63	1,400	P	4	
29	58-33-403	Lake Shore Acres	178	459	446-459	6	150	I	1	
46	58-43-702	State Capitol	178	1,554	NA	NA	1,100	P	4	
			080							
49	58-43-703	Driskill Hotel	178	2,250	1,580-2,250	open	1,000	P	4	
			269			(5)				
52	58-44-201	City of Manor (new well)	269	3,001	2,941-3,001	4	1,900	P	6	
55	58-51-103	Robert Small	178	1,595	NA	8.0	2,900	P	9	
			080							
83	58-43-8--	NA	178	1,147	NA	NA	1,500	I	4	
84	58-34-802	Tx. Tumbleweed Restaurant	269	530	435-530	7	700	E	7	
85	58-42-801	West Lake W.S.C.	178	931	857-931	7	100	E	1	
			269							
86	58-42-504	West Lake W.S.C.	269	786	669-786	7	100	E	1	
87	58-42-702	Lost Creek Golf Club	178	560	420-560	6.25	800	E	3	
			269							
88	58-42-705	Lost Creek Golf Club #2	269	525	435-525	7	500	E	2	
89	58-42-706	Lost Creek Golf Club #3	269	530	435-530	7	500	E	2	

Table 2 (continued)

County Number	State Well Number	Owner, Well Number	Aquifer	Total Depth (ft)	Production Interval (ft)	Well Diameter (in)	Transmissivity (gpd/ft)	Type of Test	Hydraulic Conductivity (gpd/ft^2)	Coefficient of Storage
					WILLIAMSON COUNTY					
12	58-13-503	City of Bartlett #3	269	2,617	2,471-2,617	5	37,300	P	157	
13	58-21-203	City of Granger #3	269	2,606	2,356-2,606	5.5	24,600	P	103	7.7×10^{-5}
18	58-29-603	City of Taylor #3	269	3,335	2,749-3,335	7	44,700	P	112	1.5×10^{-4}
26	58-29-602	City of Taylor #2	269	3,308	2,961-3,308	6.63	24,500	P	61	3.58×10^{-4}
27	58-29-604	City of Taylor #4	269	3,356	2,780-2,950	6.63	28,500	P	71	
					2,950-2,970					
					2,970-3,346					
					3,346-3,356					
28	58-21-202	City of Granger #2	269	2,607	2,341-2,605	5.5	34,800	P	145	
37	58-18-401	Walter Carrington	178	510	409-510	7	5,400	P	90	
38	58-26-406	Leander W.S.C.	269	709	645-700	6.63	2,700	E	45	
39	58-26-401	Leander School	178	780	42-780	6.63	100	E	2	

EXPLANATION OF SYMBOLS, TABLE 2

Symbol	
*	Value adjusted for partial penetration
**	Validity uncertain as reported
†	Questionable aquifer designation, based on stratigraphic information
††	Value reported; confirmation not possible
#	Location uncertain
§	May not be steady-state determination, or other interferences not accounted for
§§	Regular pump test performed but data not reliable
NA	Not available

AQUIFER CODE

080	Glen Rose Formation
138	Paluxy Formation
178	Travis Peak Formation
180	Trinity Group or Trinity Sand
200	Woodbine Formation
269	Hosston Formation
272	Antlers Sand
289	Hensel-Hosston
312	Twin Mountains Formation

TYPE OF TEST

P	Transmissivity from traditional pump test
E	Estimated transmissivity calculated from specific capacity
I	Transmissivity reported; data not reliable or incomplete

WELL SCREEN OR CASING DIAMETER IN PRODUCTION INTERVAL

Decimal	Fraction
.25	1/4
.30	5/16
.38	3/8
.44	7/16
.50	1/2
.56	9/16
.63	5/8
.75	3/4
.88	7/8

open = open hole

PART II--DATA PERTAINING TO REMOTELY SENSED LINEAMENTS

General

Lineaments, which have also been called lineations, linears, fracture traces, and many other names (El-Etr, 1976), are currently the object of intense interest and some controversy. Opinions are divided among investigators, who either extol or malign the usefulness of lineaments in applications ranging from petroleum and mineral exploration (compare Halbouty, 1976, and Gilluly, 1976) to nuclear energy facility siting (compare Eggenburger and others, 1975, and Seay, 1979). Of greater importance, however, is the uncertainty which some authors have expressed concerning the objective reality of perceived lineaments. Wise (1976) acknowledged this point whimsically by defining the canons of lineament perception (or, in his words, "linear geo-art") based on "subtle, sophisticated methods of mutual delusion" (p. 635). Wise also observed that although lineaments have been noted on maps and globes for at least 150 years, it is only recently that the "art form" has truly proliferated; this he attributed to "the advent of the flying machine (which) spawned a prolific new generation of linesmen who demonstrated clearly that by squinting obliquely across air photos a great number of random lines could be drawn" (p. 635). Other "critics" have been even less charitable.

We trace most of the difficulty of investigating lineaments to three problems: (1) ambiguous terminology (that is, discrepancies and imprecision in the use of the word "lineament" and related terms); (2) inconsistent methods (for detecting and analyzing lineaments); and (3) generally low reproducibility of results. These problems inveigh against confidence in the data obtained from traditional lineament studies, and in the validity of applications of these data.

Purpose and Scope

In the current investigation we have sought solutions to these three problems. We have proposed a concise terminology, and a systematic method of perceiving and interpreting lineaments that also improves data reproducibility. These proposals draw, in part, on our review of published works on lineaments; references that are most relevant to the objectives of this study are cited in the accompanying bibliography (Appendix G).

We tested and refined our methods in a pilot study, in which we used six Landsat band-5 images (black-and-white positive prints reproduced at a nominal scale of 1:250,000). These images depict most of Central Texas and small areas of northern Mexico. The pilot study was conducted to evaluate the efficacy and validity of our procedures, and served as the foundation for our larger investigation of lineaments seen in 51 images covering the entire state. Appendix E contains maps representing these lineaments (more than 31,000) keyed to the Landsat images in which the lineaments were perceived. The quality, extent of coverage, and other characteristics of each Landsat image used in this study are summarized in Appendix F. The lineaments, thus depicted, are not an end, a finished product. Instead, we view these mapped features as data to be analyzed and interpreted. For much of Texas these data remain in "raw" form awaiting further examination and interpretation.

Our primary goal is to investigate the possible relations between lineaments and known low-temperature geothermal resources in Texas. On the basis of examination of geothermal data in Central Texas and lineaments perceived in that area, we propose that a clear but often complex correlation exists. Lineaments serve mainly to define the structural context of these resources; thus, a study of lineaments aids in exploration for low-temperature geothermal waters by locating structural anomalies, such as zones of enhanced (fracture induced) permeability or areas of fluid upwelling (moving up-structure).

Review of Terminology

Whenever a field of scientific inquiry grows very rapidly with input from several disciplines, the technical jargon in use in that field may become complex and confusing; this has been especially true with the study of lineaments. The evolving use of the word "lineament" and of various, generally inappropriate synonyms was first reviewed by Lattman (1958), and later by El-Etr (1976) and O'Leary and others (1976, 1979). More recently, significant contributions toward a concise, modern nomenclature have been made by Burns and others (1976), Burns and Brown (1978), and Huntington and Raiche (1978), although these authors failed to provide a system of terminology which was both internally consistent and broadly applicable.

Part of the difficulty of investigating lineaments arises from confusion in the application of the word "lineament." Two authors may use the term to refer to line types which are generically incompatible. In contrast, lines that are essentially homologous may be called different names by different authors. These problems were reviewed in depth by O'Leary and others (1976) but have not been entirely resolved in more recent studies.

For example, Gilluly (1976, p. 1507) reported that linear surface-features as much as 100 mi (161 km) wide have been called lineaments, a practice which is inconsistent with other interpretations (<u>see</u> Burns and others, 1976, p. 269).

Similarly, "lineament" has been used to mean a perceptually discrete linear figure in some studies (for example, Burns and Brown, 1978), and an entire population of parallel to nearly parallel ("subparallel") lines in others (for example, Brock, 1957a).

The "linearity" of lineaments has also been questioned. O'Leary and others (1979, p. 575), following the precedent of Gary and others (1972, p. 408), defined lineaments as lines which may be either straight or "slightly curved," but did not attempt to determine an acceptable limit on, or even a means of assessing, the degree of curvature. Huntington and Raiche (1978, p. 147) stated that curvature is a valid property of lineaments but treated each perceived curve as a continuous aggregation of "straight line segments" for statistical purposes. The terms "curvilinear element" (Seay, 1979, p. 36) and "curvilineament" (O'Leary and others, 1979, p. 575) were introduced to distinguish "circular or subcircular" and "distinctly arcuate" lines from "straight" lineaments, although the distinction is apparently subjective and thus complicates the nomenclature unnecessarily.

Many other examples of conflicting definitions are available. The term "lineament" was restricted to presumed structural alignments of regional to worldwide extent by Hills (1953, p. 48) and by others, but has also been used (for example, Collins and others, 1980, p. 12) to refer to features whose lengths approach the lower practical limit of resolution of most large-scale aerial photographs, that is, a few hundred feet or less. Well-meaning attempts have even been made (by Lattman, 1958; El-Etr, 1976; and others) to define different terms for linear patterns differentiated solely on the basis of length. Thus, figures whose scale-equivalent length is one mile or more would be called lineaments whereas shorter but otherwise identical figures would be fracture traces (Lattman, 1958, p. 569). Unfortunately, these efforts have certain conceptual and practical weaknesses and serve only to further encumber an already cumbersome nomenclature. Some of this nomenclature, however, warrants review here in order to introduce the terminology that we employ.

O'Leary and others (1976) argued convincingly in favor of the word "lineament" over other possible terms for use in denoting features of the type considered in the current investigation. O'Leary and his co-workers demonstrated that "lineation"--one of the words sometimes considered synonymous with or superior to "linéament" (for example, El-Etr, 1976)--is actually a term best used to describe any internal structural alignment in igneous, metamorphic, or sedimentary rocks (compare American Geological Institute, 1962, p. 290; also Gary and others, 1972, p. 408-409). Lineations, as discussed by O'Leary and others, are too small to be depicted on most maps. O'Leary and others (1976) would also restore the word "linear" to a grammatically correct, exclusively adjectival sense rather than to the nominative sense occasionally ascribed to the term (for example, Gary and others, 1972, p. 408: "linear (tectonic)"; and Gross, 1951, p. 79, as cited by O'Leary and others, 1976, p. 1464). We have followed these conventions.

But beyond acceptance of the name "lineament," we diverge from conceptual and practical standards for use of the term that were proposed by O'Leary and others (1976); we even ascribe "lineament" to a different origin. O'Leary and others (p. 1463) stated that the word "lineament" was introduced by Hobbs (1904a), who was indeed an early champion of "the importance of the directional element in topographic development" (p. 484). However, Dana (1863) used the term "lineament" in referring to "(prevalent trends) in the courses of the Earth's feature-lines" (p. 39). Dana devoted many pages to this topic in the

1863 (and subsequent) editions of his Manual (see especially p. 19-21 and p. 29-39). Dana did not, however, define "lineament," and used the word in a restricted sense that is inadequate for most contemporary applications. We therefore concur with Hodgson (1976), who stated that "Hobbs can truly be said to be the father of modern lineament studies" (p. 9), and we continue to look to Hobbs for guidance in the proper use of this term.

Hobbs did not rigorously define the word "lineament" in these works although a somewhat poetic allegory does appear on p. 227 of Hobbs's 1912 publication: "significant lines of landscapes which reveal the hidden architecture of the rock basement and described as lineaments...They are the character lines of the Earth's physiognomy." Hobbs did provide an adequate working description on which to base subsequent studies, and more importantly, a description of his method. As noted by Gilluly (1976, p. 1507), Hobbs's original (1904a) observations were of linear trends or alignments appearing on topographic and geologic maps; his subsequent field investigations of joint and fault trends simply demonstrated approximate agreement with regional lineament patterns he had noted previously. Hobbs himself (1904a, especially p. 484-488, plates 45 and 46, and fig. 2; 1904b) was explicit in this matter. Hobbs (1904a) also recognized the all-important scale-dependence of lineament perceptions: "lineaments, which may appear rectilinear on the maps, may be so only in proportion as the scale of the map is small" (p. 486; see also his fig. 1). These statements suggest that lineaments must be regarded as figures that are entirely dependent for expression on the medium in which they are represented.

This interpretation is also implicit in Hobbs's awareness that lineaments are not expressions of any particular class of earth features such as faults.

His (Hobbs's) thematic mapping revealed lineaments seen as topographic, geologic, and hydrologic alignments with equal frequency. In fact, a single lineament may be defined by several themes simultaneously. Hobbs (1904a, p. 486) referred to this tendency as the "composite nature of extended earth lineaments":

> From the existence of several types of lineaments, it is to be expected that one which is manifested for a greater or less distance upon the earth's surface as a distinct type--say a scarp--may be continued as another type--let us say a drainage line--and this again may be extended by a third--it may be as a 'fall line' which intersects lines of drainage, and this again by a geologic boundary, et cetera.

Hobbs (1904a) also reported his "observation made in smaller areas (i.e., on larger scale maps) that the course of a (lineament) is not straight, but made up of a great number of straight elements composing a series of zigzags" (p. 486). These remarks illustrate Hobbs's acceptance of a complex and occasionally obscure relationship between lineaments perceived on maps and correlative surface elements.

The important conclusion to be drawn from these remarks is that Hobbs regarded lineaments as lines apparent on maps (and on other representations of the earth's surface) but not necessarily on the ground, even if there were perfect correspondence between lineaments and identifiable linear elements of topography and geology as seen on the ground. The perception of a lineament at a particular location is thus largely dependent upon the means and scale of representation of the surface features. A single lineament clearly is not, in every case, represented in exactly the same way (that is, with the same apparent length, orientation, width, and the like) on a map and on the ground. Moreover, a lineament perceived on a map, aerial photograph, or other image may not be detectable at all on the ground. To presuppose one-to-one correspondence is to invite error and data ambiguity. It is certainly not correct, however, to conclude from these statements that lineaments are somehow unrelated to geological phenomena; the geologic relevance of lineaments (and of lineament studies) is not compromised in the least by an appearance of imperfect correlation with surface elements.

Many investigators including Hobbs have at least occasionally appeared to use the term "lineament" to refer interchangeably to (1) a linear surface element, and (2) a linear pattern perceived in a map or other kind of image. This equivocal usage has impaired the general understanding of lineaments, particularly those with vague or complex affinities to surface features. Since there already exists a generic terminology for geologic and topographic features--for example, escarpment, fault, joint, mountain range, stream reach, stratigraphic contact, and coastline--we find no justification for substituting the word "lineament" for these features simply because they are linear. Surface expressions which appear to be linear or aligned can be described as such; thus we would simply note a linear stream segment, a line of hills, or an alignment of joints or veins. We do, however, recognize a great need for a term with which to refer to intriguingly linear patterns noticed in maps or aerial photographs. In some cases, we can account succinctly for a line detected in an aerial image, for example, by noting that the line coincides or is correlative with (say) a linear element of topography. But there often are imprecise or even no apparent agreements between the image figure and depicted surface elements; clearly, a general term is needed that does not denote any particular surface affinity.

There is considerable precedent for using the word "lineament" in this context. Billings (1972, p. 419) regarded "lineament" as "a negative term, meaning that the exact cause (or surface affinity) is unknown (although) the term may be used even if the cause is well established." Brock (1957a) expressed almost the same view in another way; he observed that:

> The suggestion of a recent author, that a certain well-defined lineament is not in fact a lineament because it contains intermittent stretches where faulting cannot be observed, points to a need for a clearer definition (of "lineament"). Had faulting been observable continuously the phenomenon would surely have been called simply a fault and not a lineament (p. 130).

Brock (1957b) reiterated this notion in his reply to discussion of this paper:

> Lineaments in their nature involve a number of different things and are manifested in many ways. Confusion of origins is inevitable. If one could disentangle the origins the need for the term lineament would disappear. What emerges in the meantime is an unexpected relationship between (for instance) an established tectonic feature and others (i.e., other geologic or topographic features, as suggested by their lying along the surface projection of a lineament) which were hitherto thought fortuitous (p. 173).

Similar conceptions of lineaments were held by Allum (1966, p. 31), Lattman (1958, p. 569), and Gary and others (1972, p. 408) in regard to "photolineaments" or "photogeologic lineaments." As stated previously, the premier works on lineaments, by Dana (1863) and Hobbs (1904a), seem to convey much the same idea.

A linear figure that is perceived in an image or other representation (such as a map, globe, or relief model) of the surface (or of some other datum, such as a subsurface horizon if the map depicts subsurface structure) should simply be noted on that base. An attempt may then be made to interpret the perceived figure by appropriate means to determine which, if any, identifiable elements of the corresponding landscape are wholly or partly correlative. Such a procedure avoids many unnecessary methodological complications and conceptual pitfalls, and is implicit in our definition of "lineament."

Definition

Our major objectives in providing yet another definition of the term "lineament" are: (1) to avoid confusion with unnecessary and grammatically incorrect synonyms such as "lineation" and "linear"; (2) to ease or eliminate conceptual entanglements by clearly divorcing a "perceived" lineament from those surface elements (if any) with which it is presumed or interpreted to be correlative; and (3) to facilitate use of practical methods for detecting, representing, analyzing, and interpreting lineaments.

Lineament: a figure (either simple or composite) that (1) is perceived in an image (or other factual representation) of a solid planetary body (Earth or other); (2) is linear and continuous; (3) has definable end points and lateral boundaries; (4) has a relatively high length/width ratio and hence a discernible azimuth; and (5) is shown or presumed to be correlative with planetary elements whose origin is geologically controlled. Structural control may be detected or inferred in the absence of contraindications but is not assumed at the outset.

Discussion of Definition

A figure is a discrete, internally consistent (but not necessarily internally uniform) component of the larger pattern of figures within a map, photograph, or model (fig. 20). The pattern may contain an unspecified number and combination of different or similar figures. This use of the word "figure" is consistent with the sense in which Burns and Brown (1978, p. 163) used "discrete feature." A simple figure is internally uniform in terms of its perceptible properties (such as tone, contrast, texture, and relief). A composite figure exhibits a distinctive combination of mutually compatible but nonuniform properties. Properties of lineaments are dependent upon the scale at which the planetary body is represented and may appear to change if the scene is represented at a different scale or by a different kind of image.

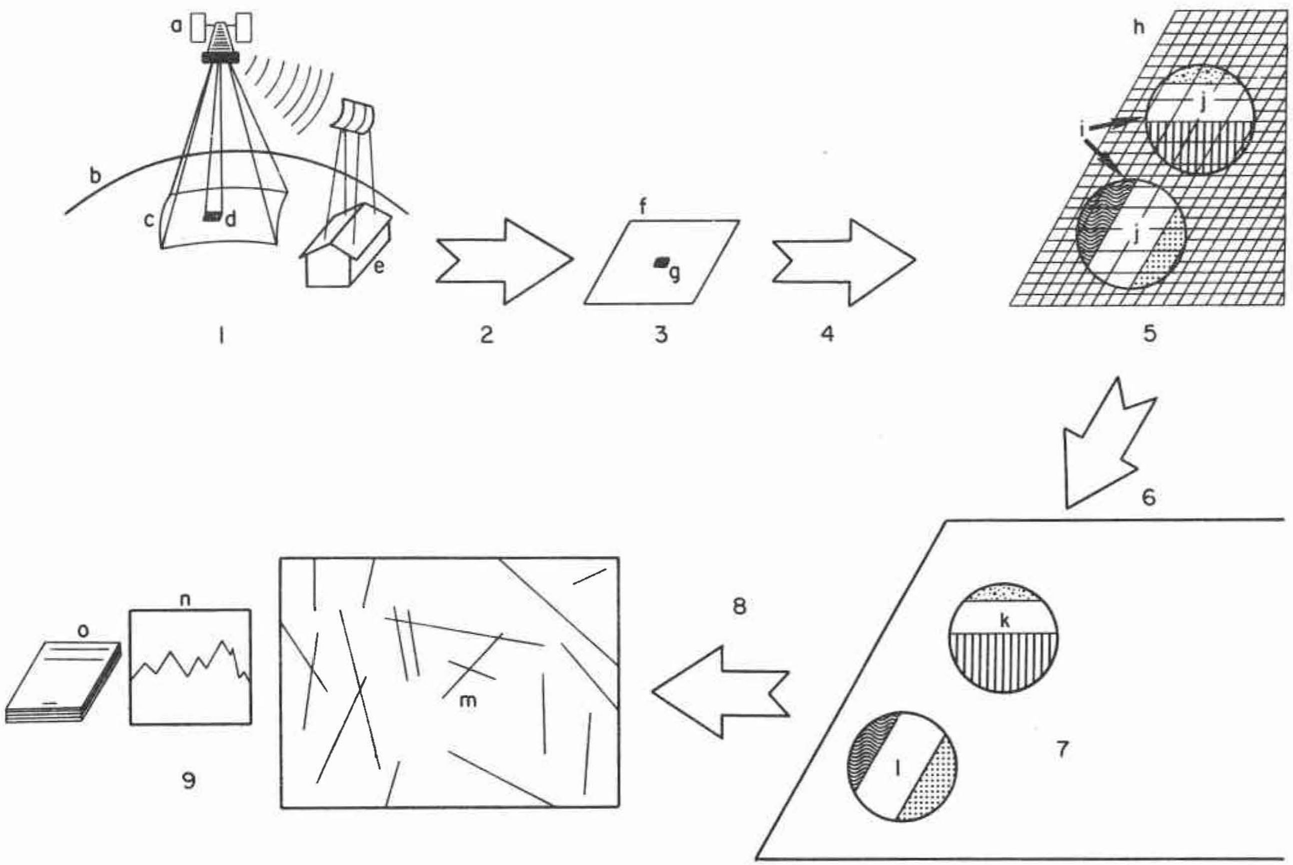


Figure 20. Landsat imagery and the perception and interpretation of lineaments.

(1) Imagery-data acquisition: (a) Landsat (on station above scene); (b) Earth; (c) scene; (d) IFOV (instantaneous field of view); (e) imagery data receiving/processing facilities. (2) Imagery-data processing. (3) Image (hard copy): (f) image; (g) pixel (picture element representing IFOV reflectance). (4) Figure perception. (5) Perceived figures: (h) pixel; (i) magnified pixels (composing linear figures); (j) linear figures. (6) Figure interpretation. (7) Interpreted figures: (k) road ("false" lineament); (l) fault zone (lineament). 8) Mapping and statistical analysis of lineaments. (9) Lineament data and analyses: (m) lineament map; (n) lineament statistics; (o) reports and applications.

We make a clear distinction between a figure in a planetary image and the features represented by the figure. Thus, a lineament exists only within an image. It may or may not correspond to recognizable planetary features. One cannot observe a lineament on the ground; instead, we can visit an area represented by a lineament and may perhaps note linear surface features or other characteristics with which the lineament appears to be correlative.

The figure is perceived in an image (fig. 20). Perception ensues spontaneously and may involve both cognitive (conscious) and passive (unconscious) awareness. This process is thus subject to a variety of influences not entirely under the conscious control of the observer. The observer's capacity to perceive figures accurately and systematically can, however, be improved through training and experience.

The image or other factual representation of a planetary body with which we are here interested includes topographic and bathymetric maps; geologic maps (surface, subsurface, structural, or other); aeromagnetic, radiometric, and gravimetric maps; aerial photographs (mosaics, individual prints, and stereo pairs); scanning radar and satellite images (color, false-color, black-and-white, and the like); and the machine-processed digital displays of these remotely sensed data. (Lineaments are also perceived in images of planets other than Earth, see Katterfeld, 1976.) Since a lineament may correspond to several surface features simultaneously (such as a linear fault-line escarpment bounding a linear stream channel), these features might be represented independently on several thematic map and image bases. However, imperfect correlation of these figures may be real or the result of error or oversight. During the analysis process the interpreter should determine the source and significance of such discrepancies. An example of this problem was described by Sabins and others (1980), and an analogous situation was discussed by Harrison (1963).

The figure must be linear and continuous. Use of the adjective "linear" denotes "straightness" or absence of curvature. In our definition, an apparently curved or arcuate figure cannot be considered a lineament, and we see no compelling reason for reintroducing the term "curvilineament" or its equivalent. Instead, we generally find that apparent curves (in earth images) which are otherwise like lineaments comprise a series of "chords" each of which is straight and internally continuous (uninterrupted along its length). Lineaments are also continuous with respect to azimuth, so that a break in the orientation of an apparent figure along its length indicates that two or more figures are present. However, a family or "zone" of lineaments can curve, in aggregate. Both linearity and continuity are among the properties that are clearly dependent upon the scale and type of image in which the lineament is perceived.

The figure must also have definable end points and lateral boundaries, a relatively high length/width ratio, and hence a discernible azimuth. A lineament is linear and continuous over some finite interval of length. Thus, although lineaments are often subtle figures, we must be able to specify discrete end points between which we perceive the figure and beyond which we do not. The distance between these points is the figure length. Figure width is determined by the positions of lateral boundaries beyond which the figure does not extend. The figure may have essentially no width if the lineament is defined by the line of separation between two distinguishable pattern areas within the image. In any event, the figure must be much longer than it is wide (although the width may vary slightly along its length). This fact makes it possible to determine the angular relationship (in the plane of the image) between the figure and a geographic meridian, that is, the figure's azimuth.

Lineaments are distinctive among all other image figures because they can be shown or presumed to be correlative with planetary elements (whose origin...). Although we define lineaments as linear figures in images (rather than linear geologic or topographic features themselves), each lineament is presumed unless contraindicated to correspond to some physical manifestation of geologic (and, in particular, structural) control. Even if we are unable to demonstrate a positive correlation between a lineament and recognized geologic features, we presume such a relation exists in order to prevent arbitrary exclusion of figures correlative with previously unrecognized features.

At least two questions must be answered in any investigation of lineaments: (1) are perceived linear figures real? and (2) if real, are they geologically significant? These questions are implicit in our definition of "lineament". Table 3 is an interpretive key which poses the questions systematically; both must be answered affirmatively before a figure can be called a lineament. Affirmation of a lineament can be based on a demonstrative finding or, in the absence of such evidence, on considered presumption, but affirmation is mandatory.

We verify the relationship between lineaments and geologic features in part by the process of elimination. Of the set of all linear figures noted on a map or image, some can be removed from further consideration because they represent either perceptual aberrations (illusions) or artifacts of the imaging process itself, such as: scan line stripes in Landsat images; film imperfections; inconsistencies in print exposure; and cartographic or projection anomalies (see fig. 21, Section A). Of the population of linear figures which remains, some

Table 3. Interpretative key to lineaments perceived in terrestrial maps or images.

LINEAR FIGURE		LINEAMENT
Is the perceived linear figure real?	If real, is the linear figure geologically significant?	
No: Figure represents (1) an artifact of the imaging process, or (2) an illusion (perceptual anomaly). Fig. 1, Section A).	No: Figure represents (1) a cultural feature that is not coincident with linear topography (Fig. 1, section B), or (2) a geomorphic feature that reflects neither stratigraphic nor structural controls (Fig. 1, section C).	Figure meets all criteria enumerated in the definition of "lineament"; properties of the lineament can be measured and analyzed (Fig. 1, sections D-F).
Yes: Figure represents (1) a physical feature on the planet or (2) an apparently real figure of undetermined origin or affinity. (Fig. 1, sections B-F).	Yes: Figure represents a geologic or topographic feature that reflects (1) stratigraphic and/or structural controls (Fig. 1, sections D and E), or (2) undetermined but presumably structural control in the absence of other plausible interpretations (Fig. 1, section F).	

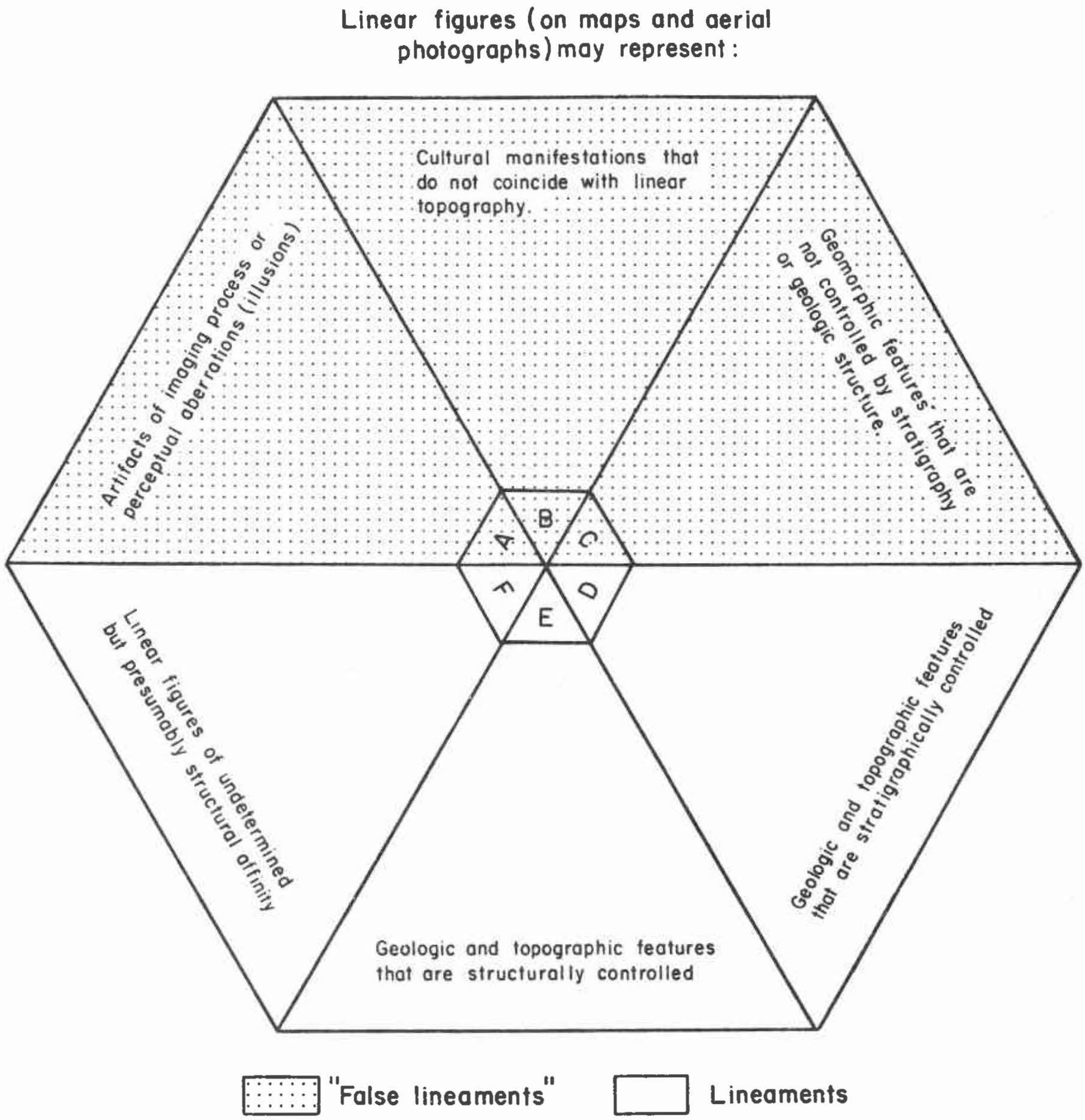


Figure 21. Possible affinities of linear figures.

Explanation of Figure 21. Possible affinities of linear figures.

Examples

A: Scan line stripes (in Landsat images), clouds and cloud shadows (appearing in aerial and orbital photographs), scratches or creases in photographs, cartographic errors, projection anomalies, illusory perceptions of spurious figures, coincidental alignments of pixels (in Landsat images).

B: Roads, rail lines, canals, pipelines, fencelines, seawalls, trails of herd animals. Note that some cultural features may coincide with topographic alignments, particularly if the topography forms a barrier, thereby restricting land use except along preferential corridors.

C: Drumlins, dunes, and snow drifts, longshore bars, aggregate patterns of frozen ground polygons, tornado pathways. Note that many geomorphic features are expressions of stratigraphic or structural controls (D and E, below).

D: Stratigraphic contacts (within and between formations), resistant- and recessive-weathering beds, chemically and/or physically unique beds (whose properties result in distinctive patterns of groundcover and pedogenesis).

E: Faults, joint sets, folds and flexures, aligned igneous intrusions and volcanoes, aligned salt or shale diapirs, geophysical (geomagnetic, radiometric, or gravimetric) anomalies.

F: Particularly large or anomalously oriented figures which appear to represent patterns on or within the planet, that have not previously been detected but which defy alternate interpretation.

may include features not related to geology (such as clouds or cloud shadows), whereas others may constitute lineaments.

The planetary elements with which lineaments are shown or assumed to be correlative are those whose origin is geologically controlled (and in particular, structurally controlled). Section B of figure 21 depicts the subset of perceived linear figures which correspond to cultural manifestations (such as roads, rail lines, canals, etc.). Ordinarily, these figures are eliminated from candidacy as lineaments whenever they are recognized. However, some care must be exercised in evaluating such figures because the pattern of cultural features may be controlled by topographic barriers that restrict land use except along preferred corridors.

The remaining population of linear figures is divided between those which are correlative with geologic and topographic elements (sections C through E of fig. 21) and those to which no probable correlation can be ascribed (section F). Section F may include linear figures representing previously undetected geologic structures ranging from local to perhaps global extent, or may simply indicate "ghosts" (poorly defined representations) of cultural or other surface features. Great care should be taken in interpreting those figures having uncertain affinity.

Figures that are thought to correspond to geologic or topographic expressions must also be carefully evaluated, because a variety of geomorphic processes may produce linear topographic elements. Yet the location, size, and orientation of drumlins, transverse dunes, longshore bars and beaches, and mud flows may in some instances (perhaps often?) be controlled by local bedrock geology and its structural overprint. But geomorphic processes do not invariably reflect stratigraphic or structural controls, and there is little reason, in this context, to give further consideration to these kinds of features and their corresponding figures; that is, they are not lineaments in the sense in which the term is here employed (fig. 21, section C).

Less clearcut is the distinction between figures representing stratigraphic patterns little affected by geologic structure (section D of fig. 21), and those correlative with identifiable structural elements (section E). Section D may include depictions of contacts between gently dipping beds cropping out in a low-relief terrain (for example, cuestas typical of the Gulf Coastal Plain of Texas), as well as other resistant or recessive beds. Regional structure certainly governs the expression of stratigraphic units, but the linear figures of section D do not themselves depict primarily structural elements.

Some linear figures (fig. 21, section E) do indeed correspond to structurally controlled topography and to more subtle expressions of geologic structure. Geologic structure is expressed in many forms: fault-line escarpments, joint patterns, fault breccia zones, folds and flexures, salt domes, and intrusive igneous bodies (such as dikes). These geologic and topographic elements may be represented as distinct figures on maps and other images, and commonly, the figures may be perceived as lineaments. Lineaments are presumed to be correlative with structural elements; however, they may not correspond precisely to structural patterns shown on conventional geologic maps. Such discrepancies are expected; the disagreement may be less than that between two independently prepared geologic maps of a given area, as noted by Harrison (1963).

Unfortunately, many investigators have assumed that all linear figures represent structural features, although Hobbs (1904a, p. 485) deplored this view:

> While believing that the greater number of rectilinear features (lineaments) have their origin either in planes of jointing or in faulting, there appears to be no advantage but serious disadvantage in giving this implication to the term. The term as here used is nothing more than a generally rectilinear earth feature.

Hobbs later (1912, p. 227, for example) compromised this interpretation, but did not specifically rescind his earlier remarks. O'Leary and others (1976, p. 1467) retained some of Hobbs's original perspective while stating that a lineament is a figure which "...presumably reflects a subsurface phenomenon." In this regard we agree with O'Leary and his co-workers. Gary and others (1972, p. 408) also defined "lineament (tectonic)" in a manner consistent with Hobbs (1904a), but their description is more ambiguous. If Gary and others (1972) had simply combined their definitions of "lineament (lunar, photo, and tectonic)" and applied them to any solid planetary body, the result would be an internally consistent definition very similar to that which we propose.

Method

Overview

We can perceive linear figures in virtually every kind of map or image; and, when definitive criteria are met, we call these figures lineaments. In this investigation, we are primarily concerned with lineaments perceived in photographic images derived from Landsat multispectral scanner (MSS) responses in spectral band 5 (wavelengths of 0.5 to 0.6 micrometers). Appendix F describes the Landsat system, the factors governing image quality and characteristics, and our image selection criteria. Each image used in this study is a "standard product" black-and-white photograph printed positively on a paper base. Nominal image scale is 1:250,000. Each image area is nearly square, being approximately 72.4 cm (29.2 in) on a side.

Fifty-one images were needed to represent the entire state of Texas (fig. 22). They were selected from hundreds of available images, on the basis of (1) image quality; (2) percentage of cloud coverage; and (3) date of acquisition of image data. Images covering the border areas of Texas also depict parts of all four U.S. states contiguous with Texas, four states of northern Mexico, and a large area of the Gulf of Mexico beyond the chain of coastal barrier islands.

There are limitations on the usefulness of the Landsat MSS image base because the images are photographically reconstructed mosaics of "picture elements" or "pixels." Each pixel represents the surface reflectance from an IFOV (instantaneous field of view), and is denoted as a gray tone representing that reflectance value. Whenever the reflectance from contiguous IFOVs is very similar, the tones of corresponding adjacent pixels will be identical or nearly so. Thus, the adjacent pixels will appear to represent parts of a single ground feature. However, many variables affect reflectance. A single IFOV is typically the site of one or more: (1) soil and vegetative cover types; (2) land uses; (3) active geologic processes (for example, mass movement, seasonal flooding, ground-water recharge); (4) topographic features (such as, hill, valley, plain); and (5) geologic formations, any one or all of which may affect reflectance. Moreover, the size of the smallest surface feature that can be detected uniquely is that of the "effective IFOV" which is 4424 m^2 or approximately 1.1 ac. Obviously, the interpreter must acknowledge and anticipate the effects of multivariate controls on the expression, distribution, and continuity of even a single figure type in an image.

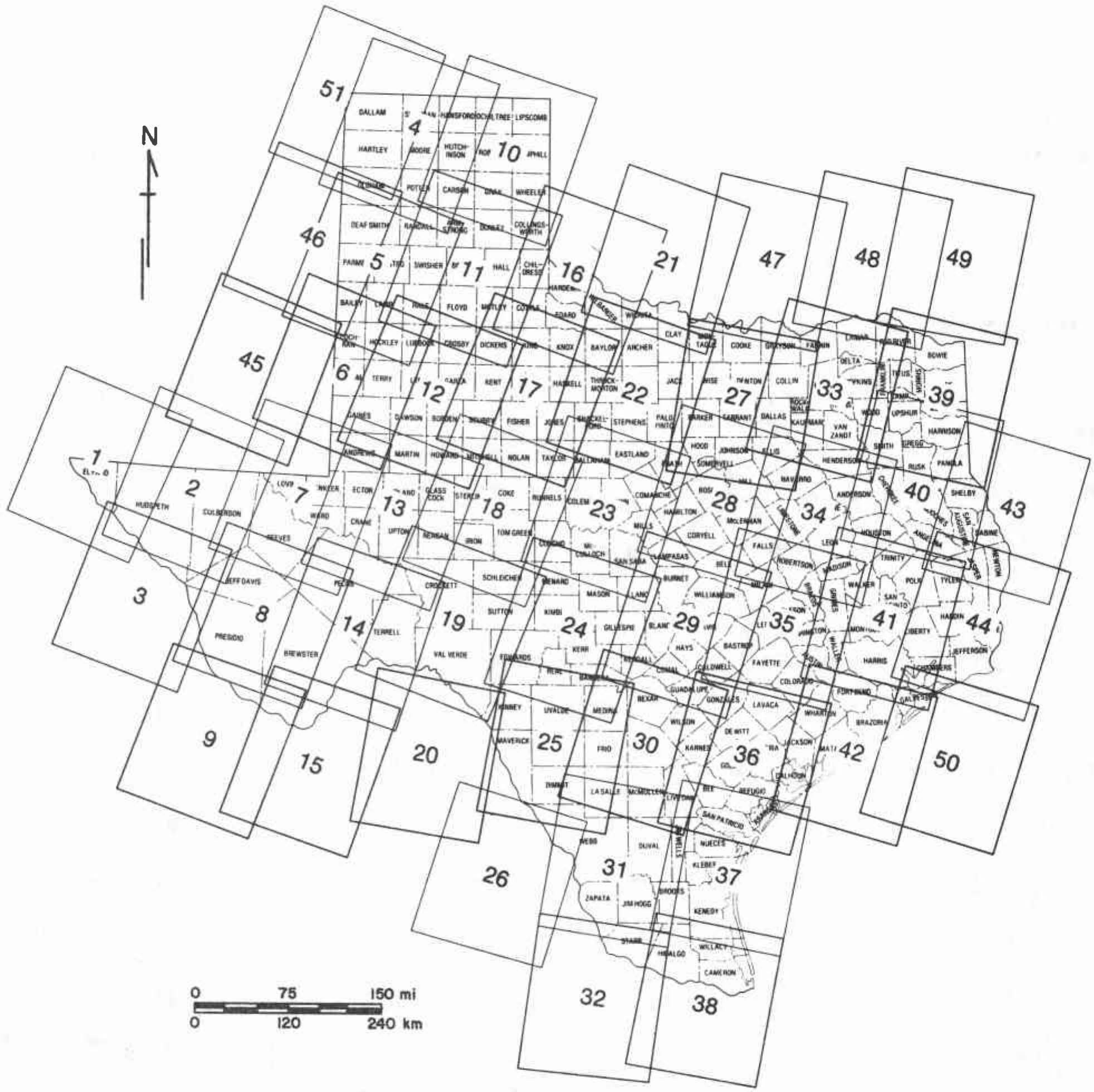


Figure 22. Index map of Landsat imagery coverage of Texas.

Review of Lineament-Detection Methods

Many investigators have proposed and tested methods of investigating lineaments. The choice of method has often been dictated by the available image type and the objectives of the investigator. For example, Dana (1863) noted lineaments and other natural alignments on very small scale planimetric maps which he later used in promulgating his theory of a "system in the courses of the Earth's feature-lines" (p. 29). Hobbs (1904a) first observed and measured the azimuths of lineaments on shaded relief maps (scale 1:7,033,000 or 111 miles to the inch) depicting drainage networks and coastlines. He later visited the areas represented on these maps to determine what, if any, relationship existed between the map lines and corresponding surface features, and found them to be in general agreement (see also Hobbs, 1911).

Within a few years after Hobbs's report, air travel completely revolutionized the study of lineaments, beginning with the work of Rich (1928), who suggested that aerial photographs could be used to investigate joint patterns. The use of stereo pairs of vertical aerial photos for relief perception was well established when Kaiser (1950) discussed the structural significance of lineaments observed in this manner. The first systematic treatment of lineaments based on aerial images was that of Lattman (1958). He reviewed much of the literature then available that described lineaments, and proposed both a "standard" nomenclature and techniques for studying lineaments in stereo images and aerial mosaics. He provided a cogent (but, unfortunately, genetic) definition of "lineament" and suggested constructive procedures for perceiving these figures, including enforcement of a recommended maximum viewing time to help the observer avoid fatigue.

Trainer (1967) was the first to study lineaments statistically when he proposed "an objective method of investigating the areal abundance of fracture traces (lineaments) seen on aerial photographs" (p. C184). He argued in favor of "a uniform duration of search, in time per unit area," noting that "the rate of discovery of the traces decreases logarithmically with time." He also defined an index of (lineament) abundance and an intersection frequency value which could be contoured and used to infer "near- surface fracture porosity of the rock" cropping out in his study area. Trainer acknowledged concern over the reproducibility of his results, noting that "problems of subjectivity (are) inherent in the interpretation of aerial photographs." He also observed that "It is impossible to find all the fracture traces on a given (image) in a practicable period of time" (p. C185).

Few investigators have given more than tacit recognition to the problem of reproducibility in interpretations of lineaments. Some, including Kreitler (1976), have attempted to resolve the problem by conducting "juried" viewing sessions in which experienced observers view the evidence (that is, the image) simultaneously. When an interpreter perceives a linear figure, he marks or directs another in marking its end points on the image. Verification of the figure is sought immediately from the other interpreters; they must also perceive the figure and confirm its "natural" origin through inspection and by exercising professional judgment. Unless so confirmed, the figures are eliminated by removing the end point markings. Confirmed figures were retained in the data pool as lineaments without further interpretation, although subsequent investigation of selected lineaments was undertaken to determine whether they represented active fault traces. Such a method, of course, may be questionable because of the suggestive influence of one interpreter on another.

A different approach to the problem was propounded by Podwysocki and others (1975). These investigators sought to minimize or eliminate "the effect of operator variability and subjectivity in lineament mapping...by use of several machine processing methods" (p. 885). They compared independent interpretations of an MSS band 5 Landsat image by four observers, and related these results to those of another group; a "large amount of variability" was found. Podwysocki and his co-workers then attempted to use two machine-aided mapping techniques, to simulate directional filters: (1) an edge enhancement algorithm and (2) "a television (analog) scanning of an image transparency which superimposes the original image (with) one offset in the direction of the scan line (p. 885)." Although these methods created similar products, they were found to introduce processing artifacts which were mistaken for lineaments. Moreover, both methods still relied on an interpreter to detect and interpret linear figures within the image, so that even if the image had been faithfully enhanced, the presumed subjectivity of the interpretation would not be eliminated or materially reduced. The same remark is equally applicable to most other automatic processing systems for mapping lineaments, if they require decisions by interpreters after image enhancement is done, as described by Maffi and Marchesini (1964), Robinson and Carroll (1977), and McGuire and Gallagher (1979).

Elaborate methods for evaluating the reproducibility of lineament interpretations have been proposed by Burns and others (1976), Burns and Brown (1978), and Huntington and Raiche (1978). Some investigators have analyzed both the figures within images and the process whereby figures are detected in a complex image by means of machine-augmented procedures. Burns and others (1976) defined coefficients of reproducibility among populations of lineaments; they stipulated that the lineaments must have unit (single pixel) width. Burns and Brown (1978) refined this procedure by measuring reproducibility of digitized lineaments on a pixel-by-pixel basis. Huntington and Raiche (1978) described the degree of correlation or similarity among lineament interpretations, stated in terms of the lineaments' "primary characteristics": (1) location; (2) orientation; (3) length; and (4) curvature. A drawback common to all of these procedures is extensive mathematical manipulation of the lineament data. Moreover, the tests served only to check the relative agreement among multiple interpretations of a single image. Most investigators have been more concerned with the agreement between lineaments and corresponding geologic features. For example, Trexler and others (1978) compared lineament patterns perceived in several types of images with gravity and aeromagnetic maps. Lineaments perceived in aerial and orbital images were found to correspond very well to the geophysical indicators. Landsat (band 5) images proved to be particularly useful for obtaining a regional geologic overview.

Other investigators have had mixed success in their efforts to develop an accurate, practical means of perceiving and analyzing lineaments. In spite of this record, some of these methods are exceedingly creative, including the following notable examples: use of photos of side-illuminated raised plastic relief maps to enhance linear topography (Wise, 1969); use of transmitted rather than reflected light to view an image (Lattman, 1958); and enhancement of satellite images by rotational photographic exposure of unexposed negative film through overlaid positive and negative transparencies (Lawton and Palmer, 1978). Although none of the procedures summarized here seem completely adequate, each contains useful elements and has in some way influenced the development of our own method.

Pilot Study and Development of Method

Our method of studying lineaments incorporates many of the procedural strengths, and avoids some of the weaknesses, of a number of previous investigations such as those just reviewed. We were also heavily influenced by our larger goal, to investigate possible relationships between lineaments and warm ground-water resources in Texas through regional syntheses. With this application of lineament data in mind, we designed our methods to (1) be uncomplicated and readily testable, (2) give objective, reproducible results, and (3) provide a geographically consistent data base.

We outlined a preliminary approach and tested it in a pilot study. This study focused on an area having local geothermal resources and complex geologic structure: the Ouachita structural trend and Balcones-Luling-Mexia-Talco Fault Systems of Central Texas. We tested a variety of techniques for perceiving and interpreting lineaments, and we assessed reproducibility of our results. Also, we tested the degree of correlation of the figures perceived on Landsat images with defined patterns on geologic and topographic maps. The results of this pilot study guided the development of our method of investigation for the entire state.

Perception and Interpretation of Figures

As mentioned earlier, we consider lineaments mapped in this project to be "raw data." In other words, they constitute simple observations that need to be screened through various conceptual "filters" before meaningful associations may be made with other representations of the "real world." In short, the data need to be "massaged" before expansive hypotheses are generated.

Nonetheless, a level of interpretation is made at the time the lineaments are perceived; this is similar to the eye-to-brain interpretive steps that experienced field geologists practice in describing an outcrop. Geologists record raw data (observations), but the data are, in the process of being recorded, also being interpreted; that is, salient information is being segregated from background "noise." General characteristics of black- and-white photographic images that may affect this process are described in table 4.

Discussion of the various interpretive steps in perceiving lineaments and then fitting these perceptions into a meaningful geologic context involves two operations: (1) "background segregation," for eliminating those figures which bear no obvious relation to the figure type of interest (and are, therefore, regarded as part of the image background); and (2) "template matching," for refining the examination, to ensure that a given figure meets the criteria or "template" by which the class is defined. To a large extent, these steps are almost inseparable. However, background segregation is most directly influenced by image quality and scale, and this operation is conducted almost exclusively when the image is initially viewed and the figures (lineaments) are perceived. "Template matching" is a process that is only, in part, simultaneous with background segregation; and this involves mental paradigms that are employed in discerning lineaments. An example of such a mental paradigm is the instantaneous application of our definition of lineament, to wit: is a given figure straight and continuous?

On the other hand, part of the template-matching operation is a mechanical process of mensuration and is conducted after the data are in hand (that is, after the perceptions are made). This mechanical process involves measuring length, width, azimuth, and the like, and is akin to the later interpretative stages where the lineaments are correlated to other data pertaining to the solid earth in a given area.

Table 4. General characteristics of black-and-white photographic images.

Tone:	"Each distinguishable shade variation from black to white" (Reeves, 1974, p. 2107). "...A measure of the relative amount of light reflected by an object and actually recorded on a black-and-white photograph..." (Ray, 1960, p. 6-7). Tone is also related to object color (hue, value or lightness, and chroma or saturation).
Texture:	"...The visual impression of roughness or smoothness created by some objects..." (Estes and Simonett, 1974, p. 875). Reeves (1974, p. 2106) defined texture as "...the frequency of change and arrangement of tones," but to this should be added an observation by Colwell (1952, p. 538) who noted that the appearance of texture "...is produced by an aggregate of unit features too small to be clearly discerned individually on the photograph." Obviously, texture is strongly influenced by image scale and resolution.
Pattern:	"In a photoimage, the regularity and characteristic placement of tones or textures" (Reeves, 1974, p. 2096). Ray (1960, p. 9) noted that if figures (within the image) "...that make up a pattern become too small to identify (interpret), as on small-scale photographs, they may then form a photographic texture." (The importance of scale and resolution are again obvious.) Pattern recognition is an important aspect of interpretation, and breaks in an otherwise continuous pattern are as informative as the pattern itself.
Association:	The persistent tendency of some figures to appear in company of one another in images. Association is not the repetition of tones and textures in a fixed pattern but is instead the recurrence of a particular combination of figure types as in a set. Strandberg (1967, p. 4) remarked that figures can often be interpreted from the "company they keep."
Shape:	The perceived form of a figure as defined by its periphery (either a sharp boundary or a zone of transition). Apparent shape is controlled in part by vantage point and viewing distance; i.e., shape varies with perspective. In landscape images, figure shape may also be affected by shadows cast from or across correlative surface features.
Size:	The relative or absolute dimensions (linear and areal) of a figure. The size (including relief and volume) of correlative landscape features, as well as the distance between features can be measured or estimated from the figure size and placement if the image scale is known. Size is an important aid to figure identification since competing interpretations of identity can be evaluated with regard to size appropriateness. The lower limit of image resolution defines the smallest discernible figure, while image scale defines the upper size limit.
Convergence of indicators:	The use of two or more properties in combination to interpret a figure. Both the existence of complementary indicators and the absence of contraindicators are valuable guides to interpretation. Convergence of several lines of corroborative evidence greatly increases confidence in an interpretation.

NOTE: These definitions apply to the terms as they are used in regard to remote sensing.

In short, figure perception is an interpretation of the image, whereas template matching is an interpretation of the figures perceived on an image. The initial (conceptual) part of template matching (involving mental templates) are discussed here under method, whereas we discuss the use of graphical templates for mensuration purposes as a part of the interpretive "findings."

Background segregation involves scanning an image and immediately partitioning it into parts that appear to contain linear figures from background areas which do not. No effort is made at this stage to measure properties of the figures (such as length, width, or azimuth), or to determine whether the figures are correlative with geologic or topographic features. But during this step a trained observer (1) avoids figures that are artifacts of the imaging process (including scratches, scan line stripes, and exposure flaws); and (2) reduces the number of figures corresponding to manifestations of land use (that is, figures obviously representing cultural features). Elimination of culturally related figures, however, should be done conservatively at this stage because some cultural features lie along topographic elements (for example, a fault-line escarpment) which may be expressed as lineaments.

Initial template matching involves instantaneously comparing features on an image to preconceived attributes that suggest lineaments. Examples include identifiable stimuli or "cues" that suggest figure linearity and continuity. In black-and-white Landsat images, the most important cues are (1) boundary contrast, (2) background contrast, and (3) apparent relief (fig. 23). A contrast boundary is an essentially one-dimensional border between contiguous portions of the image that differ in tone or texture. A figure defined by background contrast is two-dimensional, although its width might in some cases be no greater

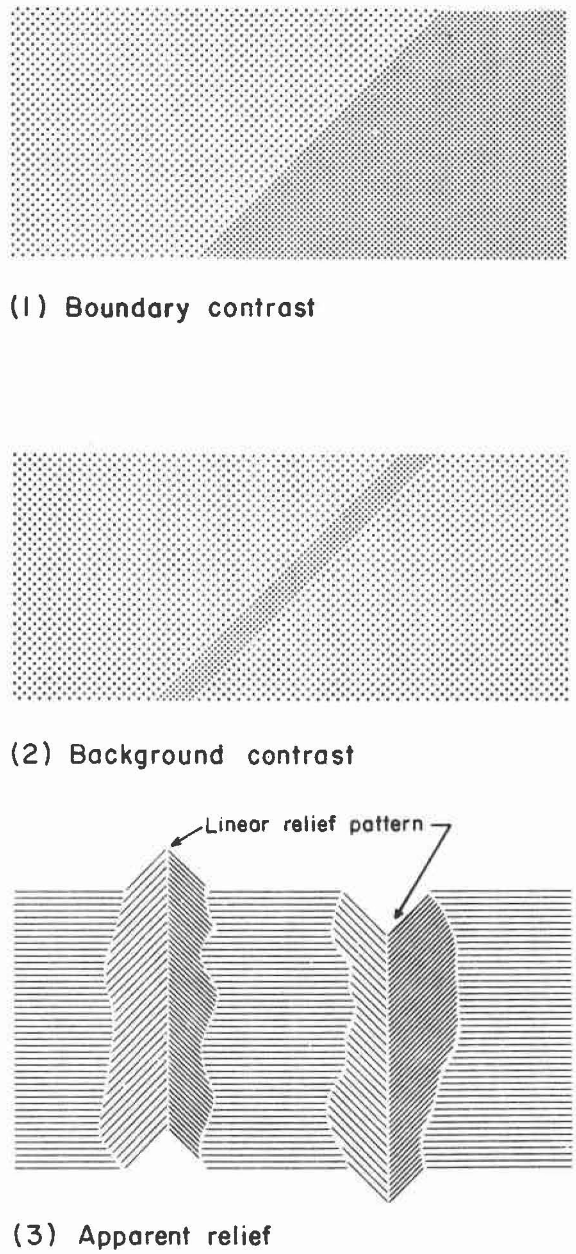


Figure 23. Cues to perception of lineaments.

than that of a single pixel; the figure is perceived as a line whose tone or texture contrasts with that of its background. Apparent relief is the seemingly three-dimensional quality of a figure, corresponding to topographic relief on the depicted surface. Until recently, relief data could not generally be obtained by using conventional Landsat images alone; however, relief can now be perceived in many images using a technique we developed during the present study.

Basic Procedure

We chose six images for the pilot study. Our basic procedure required three observers to examine each Landsat image independently for two 30 minute periods. The end points of perceived linear figures were marked on the Landsat images with grease pencils. After an observer's second session, an assistant carefully traced the indicated figures in colored pencil onto a piece of translucent film held in registration with the image corners. The assistant recorded salient information, such as the scene name and number, the observer's name, and the number of figures perceived during each session. Once the transferral of data from the image was complete, the image was thoroughly cleaned with rubbing alcohol and allowed to dry before the next observer began his examination. For convenience of ultimate cartographic rendition, separate film sheets were prepared for each of the three observers' markings (both sessions) on each image.

Reproducibility

When all six of the pilot study images had been examined in this manner by the observers, the three film sheets for each image were overlaid and precisely registered. Instances of agreement among the observers' marks were tallied and formed the basis for statistical comparisons. "Agreement," for our purposes, was defined as the partial or complete superimposition of two or three observers' figure tracings. To be in agreement, the tracings had to have very nearly the same azimuth (2 or 3 degrees maximum deviation) and to overlie or very nearly overlie one another (within a few line widths). A small degree of imprecision was permitted because of the possible introduction of minute positional errors during the transfer of figures from the image to film, and because two observers may on occasion mark opposite sides of the same figure if it has sufficient width. The lengths of figures in agreement were not necessarily the same since partial overlap was permitted.

As shown in table 5, our preliminary results were not immediately encouraging in terms of reproducibility. Simple agreement was typically quite low, ranging from 7.7 to 14.4 percent of the total number of figures denoted on an image by all three interpreters. The fact that Observer I consistently scored the highest percentage of agreement, even among these low values, was of considerable interest, prompting further evaluation of the available data. Tables 6 through 11 revealed the cause of Observer I's higher agreement percentages to be an artifact of the large total number of figures denoted by him on each image. In fact, Observer I frequently noted more than 50 percent of the entire population of figures detected by all three observers.

When the figures perceived by only two interpreters are compared and their agreement is expressed as a percentage of the number of figures seen by them individually, the percent of agreement is generally much higher, ranging to a maximum of 52.1 percent in our pilot study (tables 6 through 11). This is a much more respectable value, implying a significant level of reproducibility in the independently derived data; this value is also much higher than the agreement reported by Burns and others (1976) and Podwysocki and others (1975), for

Table 5. Agreement among independent observations made during the pilot study.

Observer number[2]		Scene number[1]					
		23	24	25	28	29	30
I	a	78	74	55	86	75	59
	b(%)	14.1	14.4	10.1	13.8	11.4	11.0
II	a	70	56	43	73	66	51
	b(%)	12.7	10.9	7.9	11.7	10.0	9.6
III	a	48	40	42	61	69	50
	b(%)	8.7	7.8	7.7	9.8	10.4	9.4
		553	514	544	623	660	534

Total number of linear figures perceived in each image (all observers).

[1] See Appendix F. Images are referenced by nominal scene number.
[2] I - C. M. Woodruff, Jr.; II - S. C. Caran; III - G. E. Smith.
[a] Number of linear figures in agreement with figures perceived by one or both of the other observers.
[b] Percentage of agreement with the total number of figures perceived in an image.

Table 6. Agreement among independent observations of the image of scene number 23.

Observer number[1]		Observer number[1]						
		I	II	III	I + II	I + III	II + III	I + II + III
I	a		50	28	50	28	78	78
	b(%)		34.7	37.8	10.4	6.8	35.8	14.1
II	a	50		20	50	70	20	70
	b(%)	14.9		27.0	10.4	17.1	9.2	12.7
III	a	28	20		48	28	20	48
	b(%)	8.4	13.9		10.0	6.8	9.2	8.7
	c	335	144	74	479	409	218	553

Table 7. Agreement among independent observations of the image of scene number 24.

Observer number[1]		Observer number[1]						
		I	II	III	I + II	I + III	II + III	I + II + III
I	a		45	29	45	29	74	74
	b(%)		45.0	47.5	9.9	6.9	45.4	14.4
II	a	45		11	45	56	11	56
	b(%)	12.8		18.0	9.9	13.3	6.7	10.9
III	a	29	11		40	29	11	40
	b(%)	8.3	10.8		8.8	6.9	6.7	7.8
	c	351	102	61	453	421	163	514

[1] I - C. M. Woodruff, Jr.; II - S. C. Caran; III - G. E. Smith.

[a] Number of linear figures perceived by an observer (horizontal row), that agreed with figures perceived by other observers (vertical column).

[b] Percentage of the total number of linear figures perceived by observers (vertical columns) that agreed with figures perceived by another observer (horizontal row).

[c] Total number of linear figures perceived by an observer (vertical column).

Table 8. Agreement among independent observations of the image of scene number 25.

Observer number[1]		Observer number[1]						
		I	II	III	I + II	I + III	II + III	I + II + III
I	a		28	27	28	27	55	55
	b(%)		27.2	50.0	5.7	6.1	35.0	10.1
II	a	28		15	28	43	15	43
	b(%)	7.2		27.8	5.7	9.8	9.6	7.9
III	a	27	15		42	27	15	42
	b(%)	6.9	14.6		8.6	6.1	9.6	7.7
	c	387	103	54	490	441	157	544

Table 9. Agreement among independent observations of the image of scene number 28.

Observer number[1]		Observer number[1]						
		I	II	III	I + II	I + III	II + III	I + II + III
I	a		49	37	49	37	86	86
	b(%)		26.3	52.1	8.7	8.5	33.5	13.8
II	a	49		24	49	73	24	73
	b(%)	13.0		33.8	8.7	16.7	9.3	11.7
III	a	37	24		61	37	24	61
	b(%)	9.8	12.9		10.8	8.5	9.3	9.8
	c	376	186	71	562	437	257	623

[1] I - C. M. Woodruff, Jr.; II - S. C. Caran; III - G. E. Smith.
[a] Number of linear figures perceived by an observer (horizontal row), that agreed with figures perceived by other observers (vertical column).
[b] Percentage of the total number of linear figures perceived by observers (vertical columns) that agreed with figures perceived by another observer (horizontal row).
[c] Total number of linear figures perceived by an observer (vertical column).

Table 10. Agreement among independent observations of the image of scene number 29.

Observer number[1]		Observer number[1] I	II	III	I + II	I + III	II + III	I + II + III
I	a		36	39	36	39	75	75
	b(%)		17.8	25.8	7.1	2.2	21.2	11.4
II	a	36		30	36	66	30	66
	b(%)	11.7		19.9	7.1	14.4	8.5	10.0
III	a	39	30		69	39	30	69
	b(%)	12.7	14.8		13.6	2.2	8.5	10.4
	c	307	202	151	509	458	353	660

Table 11. Agreement among independent observations of the image of scene number 30.

Observer number[1]		Observer number[1] I	II	III	I + II	I + III	II + III	I + II + III
I	a		30	29	30	29	59	59
	b(%)		22.6	35.4	6.6	7.2	27.8	11.0
II	a	30		21	30	51	21	51
	b(%)	9.4		25.6	6.6	12.7	9.7	9.6
III	a	29	21		50	29	21	50
	b(%)	9.1	15.8		11.1	7.2	9.7	9.4
	c	319	133	82	452	401	215	534

[1] I - C. M. Woodruff, Jr.; II - S. C. Caran; III - G. E. Smith.
[a] Number of linear figures perceived by an observer (horizontal row), that agreed with figures perceived by other observers (vertical column).
[b] Percentage of the total number of linear figures perceived by observers (vertical columns) that agreed with figures perceived by another observer (horizontal row).
[c] Total number of linear figures perceived by an observer (vertical column).

example, who applied special machine processing techniques in an effort to increase agreement.

In reviewing our data, we found that the agreement percentage values were, of course, heavily influenced by the absolute number of figures perceived by an interpreter. For example, there were 20 instances of agreement between the figures denoted by Observers II and III on the image of scene number 23 (table 6). These 20 figures represent 27.0 percent of Observer III's total (74) for that image. In this same example, which is representative of the pilot study as a whole, Observer I denoted 28 figures that were also perceived, at least in part, by Observer III; this corresponds to 37.8 percent of Observer III's total figure count (74). Observer I perceived a greater number of figures than did Observer II, and more of Observer I's figures agreed with those of Observer III than did the figures perceived by Observer II. It is apparent, then, that as the number of figures perceived by an interpreter increases, the incidence of agreement with the perceptions of others also increases. One might readily conclude that, given sufficient time, a diligent interpreter could effectively reproduce the observations of other interpreters, even if many additional figures were also perceived in the process. This idea is supported by comparisons among various combinations of the interpreters' observations (tables 6 through 11).

Originally, the effects noted above led to the speculation that two 30-minute viewing periods per observer were perhaps insufficient. That is, the total number of linear figures that an interpreter might ultimately perceive would be significantly greater than the number seen in 60 minutes. This would imply either that (1) there are an essentially infinite number of linear figures in an image (which would argue against their possible structural significance), or (2) there are many linear figures but their number is effectively finite (suggesting that our somewhat arbitrary choice of 60 minutes' total viewing time per interpreter, 3 hours of viewing time in all, might simply be inadequate. If the number of figures perceived per period by a single observer remained relatively constant through a number of repetitive viewing sessions, we would conclude that premise 1 (infinite population) had been supported. If, instead, the number of figures per viewing period decreased through several sessions, we would conclude that premise 2 (finite population) was confirmed. We tested these opposing hypotheses but recognized that the devotion of more than three man-hours per image to figure perception, when a total of 51 images had to be examined, would have been impractical. For the same reason, we limited our extended test of lineaments perceived during repeated time intervals to two images, those of scenes 24 and 29. The quality of these images is comparable and their image data was acquired on successive days.

Our testing procedure required two of us to examine the same two images repeatedly. The number of figures perceived during each half-hour session was plotted (fig. 24), and this clearly depicts a trend in the rates of figure perception. The shapes of the curves are very similar despite the absolute difference in the number of figures seen by each observer. Some fluctuation in the rates was noted (see fig. 25) but the overall pattern is one of diminishment. Although neither observer reached zero perceptions on these images, both seemed to be approaching either an effective asymptote or a precipitous decrease in the rate of figure perceptions per 30-minute session (to 20 to 40 percent of the initial rates) within three (Observer II) to six (Observer I) hours. This meant that the number of possible figures is probably finite. Each population of

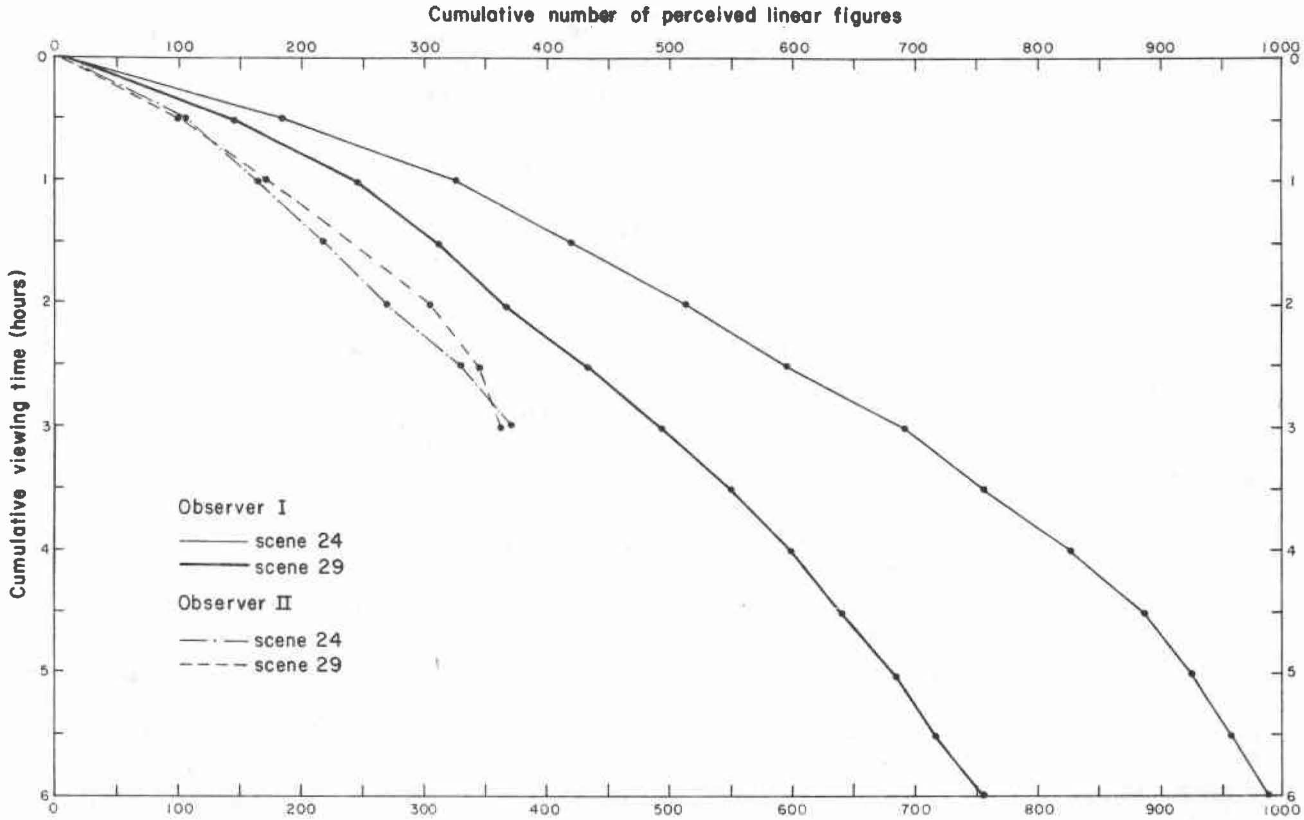


Figure 24. Trends in the cumulative number of figures perceived during repetitive viewing sessions.

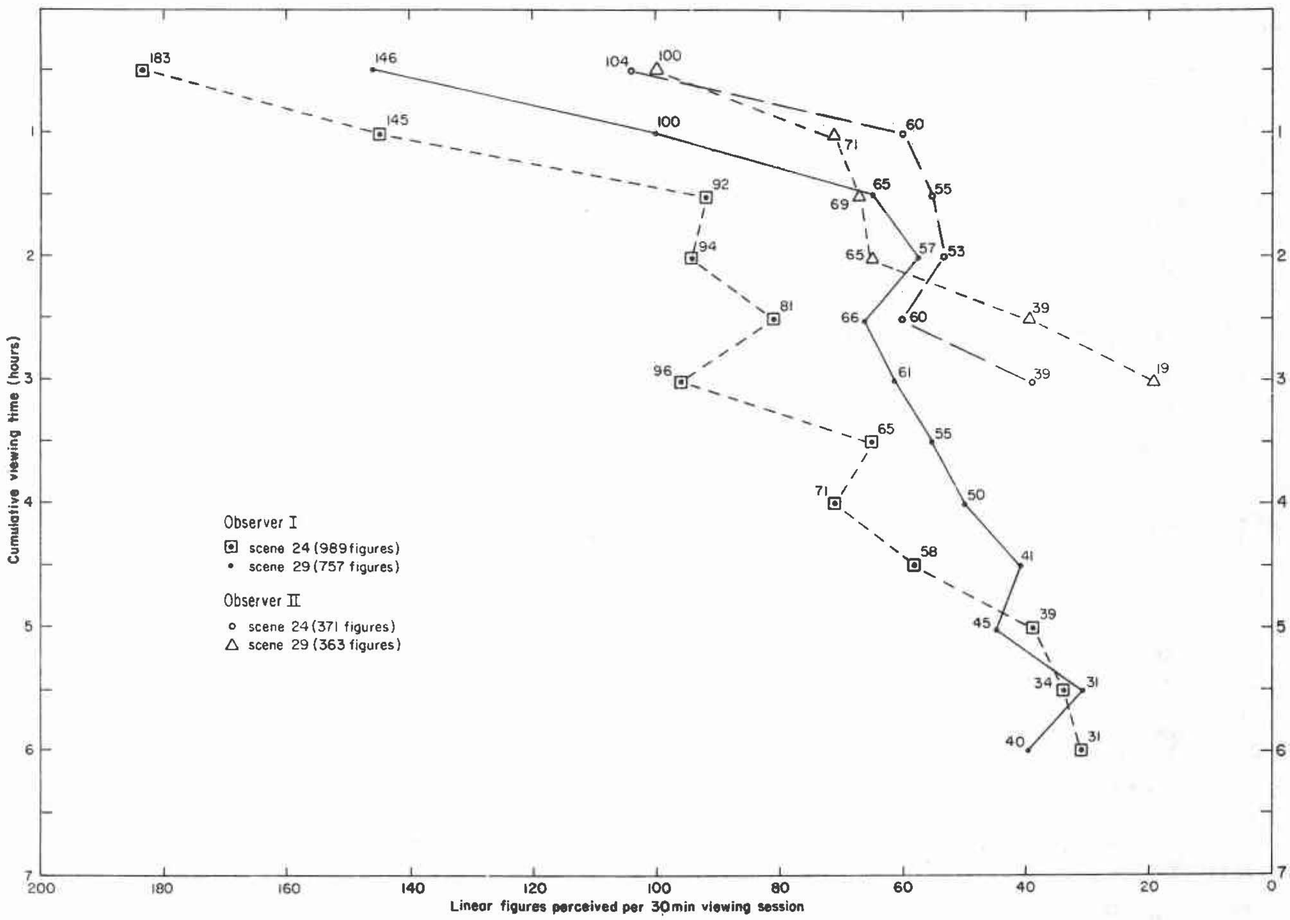


Figure 25. Trends in the number of figures perceived per session during repetitive viewing sessions.

perceived figures was thus assumed to be more nearly "complete" and accurately representative of that image, permitting a more meaningful comparison of individuals' perceptions.

Table 12 illustrates the absolute and percentage agreement of the repetitive observations of Observers I and II. Direct comparison of these observations is somewhat misleading in that the total time required for substantial reduction in the number of figures perceived per session differed between the observers (six hours for Observer I, three hours for Observer II). However, it is unlikely (given his low rate of perception after three hours) that the level of agreement would have changed significantly even if Observer II had also examined each image for six hours. The agreement shown in table 12 is comparable to that in tables 6 through 11; this suggests that while some evidence implies possible convergence of independently derived figure populations as population size increases, there may in fact be perceptual and conceptual differences between observers that would prevent complete agreement. In any event, a study based on observations by three interpreters (one hour each) per image is more efficient and possibly gives more objective results than does a study based on the observations of one or two observers, each of whom devotes three to six hours viewing time to each image. The total number of figures perceived in three hours by three observers (one hour each) is approximately equal to the average of two observers' totals during repetitive observations (compare tables 7, 10, and 12), and is therefore representative of the potential maximum population of figures in an image. The use of three observers, each devoting a total of one hour of viewing time to each image, thus has two distinct advantages over other possible approaches: (1) the population of data is representative of the image and is readily obtained; and (2) the data user can be

Table 12. Agreement between repetitive observations by independent interpreters.

Observer number[1]

		Scene number 24 (Junction, Texas) I	Scene number 24 (Junction, Texas) II	Scene number 29 (Marble Falls, Texas) I	Scene number 29 (Marble Falls, Texas) II
I	a		106		135
I	b(%)		29.3		37.5
II	a	106		135	
II	b(%)	11.2		17.8	
	c	947 (6 hr)	362 (3 hr)	759 (6 hr)	360 (3 hr)

[1] I - C. M. Woodruff, Jr.; II - S. C. Caran.
[a] Instances of agreement between observers.
[b] Percentage of agreement (percent of total number of figures perceived by an observer, vertical column).
[c] Total number of figures perceived by an observer (vertical column) and his total viewing time.

confident of the reproducibility of the data since agreement among the three observers' data is at least comparable to if not greater than that of a single observer's repetitive data, and overall reproducibility is relatively high.

We therefore concluded that our original examination format was quite adequate overall, although we did establish certain additional guidelines to help unify the interpretive effort. These procedural modifications included the adoption of a consistent definition and working understanding of lineaments seen in Landsat images. It also seems clear that each observer should be directed to scan the entire image during an examination, denoting first those linear figures that are most obvious and then moving to more subtle figures, to ensure selection of a population of figures representative of the image as a whole. These procedures and guidelines appear to fulfill our objectives by permitting (1) meaningful integration of the observations of three workers, each following a prescribed method; (2) maintenance of fixed viewing periods and conditions; and (3) prevention of feedback among the observers that would sacrifice the indepedence (and presumed objectivity) of their observations prior to the analysis of the lineaments themselves.

Correlation with Geologic and Topographic Features

Our method for investigating lineaments did not end with the perception of linear figures. We also determined whether the figures were correlative with recognizable features of the solid earth. Linear figures can be interpreted by either (or both) of two procedures: (1) by direct determination, whereby the interpreter makes his best assessment of a figure's identity on the basis of information derived directly from the image; and (2) by correlation with map symbols, identifiable patterns in aerial or orbital photographs, or features recognized in the field. We have relied on map correlation (using standard geologic and topographic maps), augmented by direct determination where figure identity was equivocal or our maps were inadequate.

Since we had traced our perceived linear figures onto nearly transparent film, an assistant simply overlaid the individual film sheets on selected maps at the same scale. Instances of apparent correlation were recorded, and denoted on the film. For our purposes, "correlation" pertains to the complete or partial coincidence of linear figures with mapped features (geologic or topographic). Unfortunately, small differences in the scales of the images (and their film overlays) and the geologic and topographic base maps with which the film sheets were compared prevented perfect registration (see Appendix F). The correlation values cited in tables 13 and 14 are, therefore, somewhat conservative. In addition, the regional scale (nominally 1:250,000) of the base maps did not permit depiction of many small surface features (such as certain hills and valleys, or minor drainages) that were clearly evident on the Landsat images. For example, of the 947 figures perceived by Observer I during repetitive examinations of the image of scene number 24, 81 (8.6 percent) figures could be correlated with mapped stream reaches (table 13). Yet at least 121 of Observer I's figures were clearly seen to correspond to streams when the image was reinspected; the resulting increase in the incidence of correlation (table 13) would raise Observer I's total (column F) to 199 instances or 21 percent. Even more impressive results were obtained when Observer II's repetitive annotations of the image of scene number 29 were reinspected: among his 360 figures, the incidence of correlation with linear stream reaches could be increased from 35 to 100, raising the total incidence of correlation to 156 or 43.3 percent

Table 13. Correlation of repetitive observations with mapped surface features (scene number 24).

Observer number[1]		Feature type[2] A	B	C	D	E	F	G
I	a	41	17	4	28	81	159	947
	b(%)	4.3	1.8	0.4	3.0	8.6	16.8	(6 hr)
II	a	20	10	3	13	100	138	362
	b(%)	5.5	2.8	0.8	3.6	27.6	38.1	(3 hr)

Table 14. Correlation of repetitive observations with mapped surface features (scene number 29).

Observer number[1]		Feature type[2] A	B	C	D	E	F	G
I	a	55	21	13	27	195	286	759
	b(%)	7.3	2.8	1.7	3.6	25.7	37.7	(6 hr)
II	a	21	9	14	35	33	91	360
	b(%)	5.8	2.5	3.9	9.7	9.2	25.3	(3 hr)

[1] I: C. M. Woodruff, Jr.; II: S. C. Caran.

[2] A: fault-line; B: interformation contact (not faulted); C: bedding strike (bed or intraformation contact); D: topographic feature or alignment (other than stream); E: stream reach; F: incidence of correlation (one or more features); G: total number of linear figures perceived by an observer, and his total viewing time.

[a] Instances of correlation of linear figures with the indicated feature type.

[b] Percentage of the total number of figures perceived by an observer.

(table 14, column F). Informal reinspection of these images revealed that many more of the figures could also have been reasonably identified as surface features.

Thus we feel that our method of studying lineaments has practical value; it permits meaningful expansion of the data base available to geologists employing more traditional means of investigation. The method is simple and readily testable; it ensures an acceptable level of reproducibility; and it provides geographically consistent data over large areas. We used this method in our examination of all 51 images covering Texas.

Summary of Method

We summarize our method of investigating lineaments as a series of simple steps. In practice, several of these steps are often performed simultaneously, as interpreters and assistants completed different phases of the investigation with different images. We attempted to standardize many aspects of the study to ensure completeness and data compatibility; this effort began with the acquisition of a uniform image base, and has continued into the preparation of this report. At the same time, we have tried to make or maintain opportunities for original observations, particularly in regard to the perception and interpretation of image figures and our applications of the lineament data. This approach has been fruitful, providing the organizational stability needed to complete the study while allowing us sufficient flexibility to pursue less conventional lines of inquiry.

(1) All viewing sessions were conducted in a large room that provided both artificial lighting and large north-facing windows; thus, illumination was held

relatively constant throughout the study. Distractions and noise were minimized in the work area during observation periods. A timer equipped with a bell chime was used to mark the passage of these periods.

(2) A Landsat image was placed on a table large enough to permit rotation of the image through 360 degrees. The observer (also known as the interpreter) was able to examine the image from any distance, direction, and viewing angle.

(3) The time was set for 30 minutes (shorter periods in some cases; see Appendix F) as each session began. An interpreter, working alone, examined the image throughout this period, marking both end points (with arrowheads pointing toward the center of the figure) of perceived linear figures thought to be lineaments. Marks were made on the image itself to ensure precise denotation of the figures as perceived.

(4) The observer used a grease pencil of a specified color to denote the figures; the color referred to the ordinal number of the session underway, that is, first, second, or (in the case of the repetitive sessions) "nth." A soft eraser was used to correct marking errors and a straight edge was occasionally used for checking the linearity of a figure.

(5) Once a viewing session had begun it was completed without interruption. The observer was directed to scan the entire image and denote figures that were most obvious before marking those of a more subtle appearance. Our definition of "lineament" and the concepts outlined in our discussion of figure perception were mentally invoked as keys for selecting appropriate figures.

(6) At the sound of the chime the viewing period ended. The observer marked no other figures until the next session unless he had denoted only one of a figure's end points when the timer chimed; in such case he was permitted to mark the second.

(7) After an observer's second (or nth, in the case of repetitive sessions) examination of an image, an assistant prepared the translucent film overlay that would become a permanent record of the observer's perceptions. This film sheet covered the entire image area. Reference marks corresponding to the image corners, and latitude/longitude tic marks traced from the image margins, were denoted on the overlay to facilitate precise registration. The observer's name and the number of the corresponding scene were also written on the overlay sheet.

(8) The assistant carefully traced the indicated figures onto the overlay, which was held in proper registration. Figures perceived by the observer during all examinations of that image were transferred to the same overlay. As they were traced, the figures were counted. The number of figures per session and the time when each session began were recorded in a data log for each observer and image.

(9) Once all data had been transferred from the image, an assistant removed all grease pencil and other extraneous marks using rubbing alcohol. When the image had dried thoroughly it could be used by another observer and the observation process was repeated.

(10) After all three observers had completed steps 1 through 8, interpretation of the image's figures could begin. An assistant overlaid the annotated film sheets on topographic and geologic maps (nominally 1:250,000-scale) of the scene, noting instances of correlation (including correlation with cultural features, such as roadways). Small discrepancies in registration were common; these resulted from minor scale and projection differences between the Landsat image and the base maps. Other possible sources of error affecting the

location, length, and azimuth of the linear figures included imprecise denotation of end points by the observer and incorrect transferral of figure annotations to the film overlays by the assistant. The assistant was able to improve the fit locally by sliding the overlay to keep it in near registration as widely separated figure lines were checked.

(11) If a figure (as indicated on the overlay) appeared to correspond to a cultural feature whose location was not controlled by topography or other natural constraints, that line on the overlay was flagged for later removal. Since our regional-scale base maps did not depict every cultural feature in the area, the assistant, usually in consultation with the observer of a questionable figure, occasionally had to make a determination of a figure's identity based entirely on a reexamination of the image. In general, we exercised a conservative reluctance to remove figure annotations if there was doubt about either their identity or possible topographic control of the corresponding feature. Comparison of the figures with mapped cultural patterns effectively constituted a second interpretation of the figures, since each observer had attempted to avoid figures obviously depicting man-made features (as well as figures representing geomorphic features lacking direct structural control).

(12) When all three of an image's overlays had been checked in this manner, they were ready for cartographic rendition. The marks on the overlays were traced onto a single positive film base by a cartographer; lines of different weights were used to symbolize the three observers' figures. The composite film base was then used in printing our lineament maps (Appendix E), which are keyed to the Landsat images themselves and to the approximate latitude and longitude of the scene. (Note: After completion of the pilot study, E. J. Thompson replaced G. E. Smith as Observer III; Thompson also served as the assistant who traced

and checked the perceived figures, including his own. To preserve his objectivity, Thompson completed his examinations of each image before Observers I and II, and generally checked the figures under Observer II's supervision.)

Findings

Overview

We employed our method of mapping lineaments on 51 Landsat images covering Texas (Appendix E). The more than 31,000 linear figures perceived in these images (fig. 26) constitute items of unrefined data suitable for interpretation and analysis. However, it is very time consuming to satisfactorily determine the relation of so many image figures to planetary features over so large an area. Parts of Texas are shown on 52 topographic maps at a scale of 1:250,000; there are 38 geologic maps covering parts of Texas at this scale. Our study area also extends beyond Texas into contiguous states of the United States and Mexico where geologic map coverage at the desired scale is even less complete. The enormity of the task and the incomplete map base prevented map comparisons of linear figures outside of our six scene pilot study area. Linear figures noted on the remaining 45 images were interpreted by reinspection of the images by two observers. This procedure proved satisfactory for our regional assessment of the data, but a more detailed comparison, with both topographic and geologic maps, would be needed to apply the data locally.

As the discussion of the definition makes clear, lineaments may correspond to any of a variety of surface features, or may suggest no recognizable associations with any surface element. Lineaments are generally subtle figures; in some instances, they and their properties may be perceived differently by independent observers, or by a single observer on different occasions. Their

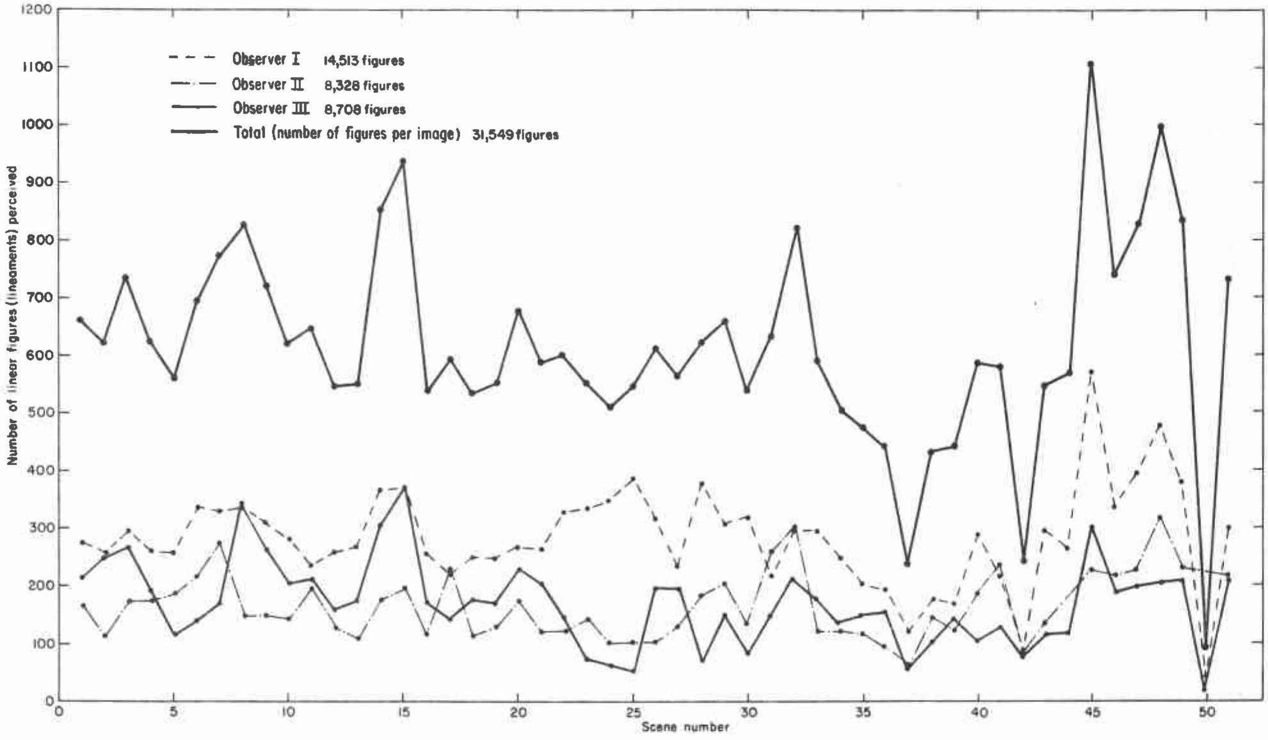


Figure 26. Number of linear figures perceived in each Landsat image covering Texas.

seemingly incongruous characteristics make lineaments difficult to define, and present unique problems of perception and interpretation. However, perception and interpretation of linear figures and lineaments in Landsat images are founded on a few basic assumptions. One assumes that the Landsat multispectral scanner collects valid reflectance data, that variations in data returns are linked to differences among features within the scene; hence, the data can be processed to produce an image that is representative of the scene.

Figure Interpretation

As mentioned previously, perceived figures exist only within the image; their relevance with respect to the ground is a matter for subsequent interpretation. Figures that match a graphical template--and hence, are to some extent quantifiable--can generally be assessed in terms of their possibly correlating with geologic features. However, the interpreter must bring to bear in this endeavor: (1) knowledge of the imaging process (see Appendix F); (2) familiarity with landforms, land use patterns, and geologic processes in the area surveyed; and (3) a capacity to detect or infer meaningful patterns of association within complex or ambiguous images.

Suffice it to say, the Landsat system of imagery employs a process that is subject to numerous variables. Incident sunlight is reflected to different degrees by the various landforms and surface materials in a scene, affecting both the intensity and spectral composition of the reflected light. Thus, the intensity of the reflectance in each spectral band is affected by all of the different terrain and ground-cover conditions across the scene. Variations in the reflectance "signatures" may be controlled by angle and aspect of slope, surface wetness and roughness, and the type, density, and color of surface material (for example, vegetation, soil, water, ice, pavement, and bare rock). These tonal patterns define the figures that one perceives in viewing an image; they are expressions of multiple, highly variable surface characteristics. The perceived figures are thus polygenetic (that is, representative of any of several factors simultaneously). Also the perception of figures on Landsat images may be impeded by (1) poor quality sensor data; (2) incomplete or faulty data processing; and (3) image defects. Yet even when image quality is excellent, the correspondence between figures and surface features is necessarily imperfect. The image is a representation, not a replication, of the scene.

Direct assessment of linear figures involves the use of graphical templates which may be employed to measure a variety of attributes of lineaments as an adjunct to the process of correlating these data to existing geologic features.

<u>Template Matching--Measurement of Figures Perceived as Lineaments</u>

We have already discussed the distinction between mental (or conceptual) templates used in perceiving a figure, and graphical templates used to measure the figure once it is perceived. A graphical template is a model of the figure type. It is a tool designed for making direct comparisons among individual figures, by allowing us to measure and evaluate linear figures in terms of the diagnostic properties of lineaments. The key measurable properties that are the embodiment of our definition of "lineament" include: (1) contrast (background, boundary); (2) length; (3) width; (4) linearity; (5) continuity; (6) azimuth; (7) azimuth deviation; and (8) apparent relief. Of course, linear figures that exhibit these properties (that is, figures that match these templates) must be interpreted further to determine if there is apparent affinity with geologic features. Other measurable properties of lineaments (such as, location, density, and intersection) are also of interest but do not require special templates for their assessment. We used the graphic templates selectively during our pilot study; extensive use was not generally practicable because of the very large number of linear figures examined during the course of our investigation.

An example of using a graphical template to aid in assessing the degree of correlation with a geologic feature is the comparison of azimuths between (1) a linear figure (thought to be a lineament) perceived in a Landsat image, and (2) a fault-line, as shown on a geologic map. If we, in fact, have perceived this on-ground feature, there should be a near-coincidence of the two measurements, but the figure need not correspond precisely to the fault as mapped. It may nonetheless have affinity with some related geologic feature even if we fail to detect the relation.

Thus, in measuring the perceived linear features we meet two objectives of interpreting lineaments: (1) we determine (either by direct corroboration or by elimination of other plausible explanations) whether a figure appears to represent a geologically controlled feature; and (2) we identify and characterize the feature with which the figures are thought to be correlative. This bipartite approach to lineament recognition assures full exercise of necessary checks and balances with respect to the "reality" of a feature. We also acquire quantitative information about the figures individually and in aggregate, so that we might discern both "families" of lineaments, and anomalous lineament patterns that are inconsistent with prevailing mapped geologic features.

Tonal Contrast

Tonal contrast is the perceptible difference in tone between contiguous figures. Contrast defines linear figures in images as either: (1) a line of generally narrow but definite width whose tone (and, in some cases, texture) differs from that of its background or surroundings; and (2) a one-dimensional boundary separating areas of different tones. So important is this property that background and boundary contrast are two of the major cues whereby linear figures are initially perceived in black-and-white Landsat images.

Strandberg (1967, p. 3) reported that a person with normal vision can distinguish as many as 128 intermediate gray tones plus black and white in an image. Landsat images are constructed from 15 tones plus black (U.S. Geological Survey, 1979, p. AE-9 and -12). All or part of this tonal series is reproduced in the margin of each Landsat image. Figure 6 is a representation of a tonal scale used in our study. We employed a scale consisting of five equal tonal increments between black and white end members; this was used as an objective standard for comparative measurements of both tones and contrast.

The seven tonal steps that compose our scale are arrayed along each axis of the scale and juxtaposed in pairs so that each tone is matched with every other. Since the tones are numbered sequentially from 1 to 7 (white to black) on both axes, contrast is described as the absolute value of the numerical difference between the numbers corresponding to adjacent tones. Thus, the contrast ranges from 0 (white on white and black on black) to 6 (white on black). Equal numerical expressions of contrast across the range from 1 to 5 can be obtained in several ways. For example, a contrast value of 2 is obtained from tone pairs 2 and 4, 5 and 7, and any other combinations of numbers between 1 and 7 whose difference is 2.

Although the tones are separated by equal increments of density, low contrast values of 1 or 2 are more readily distinguishable when the lighter tones are contrasted. Related phenomena have been discussed by Lindsay and Norman (1972, p. 177, 181-185). Their observations suggest that with increasing incident light intensity, the perceived brightness of tones lighter than medium gray increases while darker tones seem darker. When these tendencies are combined with the natural "edge enhancement" that occurs whenever contrasting tones are juxtaposed, the perceived contrast between lighter tones is effectively "stretched." Also, the monotonal chips used in constructing our contrast scale were mounted on white paper; the light background appears to have further increased sensitivity of the eye to contrast between the lighter tones.

Our contrast scale was used as a template in the following manner. Tones along or on either side of an apparent lineament in an image were compared with the scale. We noted the contrasting tone pair in the scale which most closely matched the tones in the image. The tone numbers and numerical contrast value (tonal difference), as defined here, could then be read directly. These characteristics are easily compared among figures across the image. The interpreter uses the scale to calibrate his perceptual threshold, since the contrast must meet or exceed some effective minimum to allow perception of figures. However, a linear figure with high contrast is not necessarily more likely to be interpreted as a lineament than one with minimum perceptible contrast, since many other recognition criteria must also be met. These factors highlight the all-important connection between stimulus and response and the need for an effective language and method for relating one to the other, as we have attempted to do here.

Length

By our definition, a lineament must have finite, that is, determinable, length. This provision is intended to help prevent inclusion of figures too vaguely defined to warrant interpretation. The interpreter is forced to delineate the figure precisely, on the assumption that figures which cannot be so delineated may be excluded without loss of meaningful data.

The procedure followed in the present study required the interpreter to denote a perceived linear figure by carefully marking its end points. By so doing, the interpreter defines the figure's length (and azimuth; see below) before actually measuring it. The length could then be measured directly using an ordinary scale read to the nearest millimeter or 0.1 inch (rounding up or down when necessary). Length is also one of the factors used in determining linearity and continuity.

Width

A lineament must have finite width or lateral extent, as well as finite length. The lineaments in an image may differ in individual width, and even a single lineament's width may vary at points along its length. Width ranges from that of a point (or, in Landsat images, a pixel), near the lower limit of resolution, to several millimeters. The corresponding distance on the ground will also vary, in relation to image scale. For example, a lineament 2 mm (0.08 in) wide on a Landsat image at a scale of 1:250,000 represents an area 500 m (1640.5 ft) wide on the ground.

In the present study lineament width was measured with a scale like that shown in figure 27. The variable and somewhat poorly defined widths of some lineaments militated against use of a simple linear scale like that used for measuring length. Instead, we employed the following procedure for determining lineament width: (a) figure 27, which was printed on a transparent plastic sheet was superimposed on the image over the apparent lineament; (b) beginning

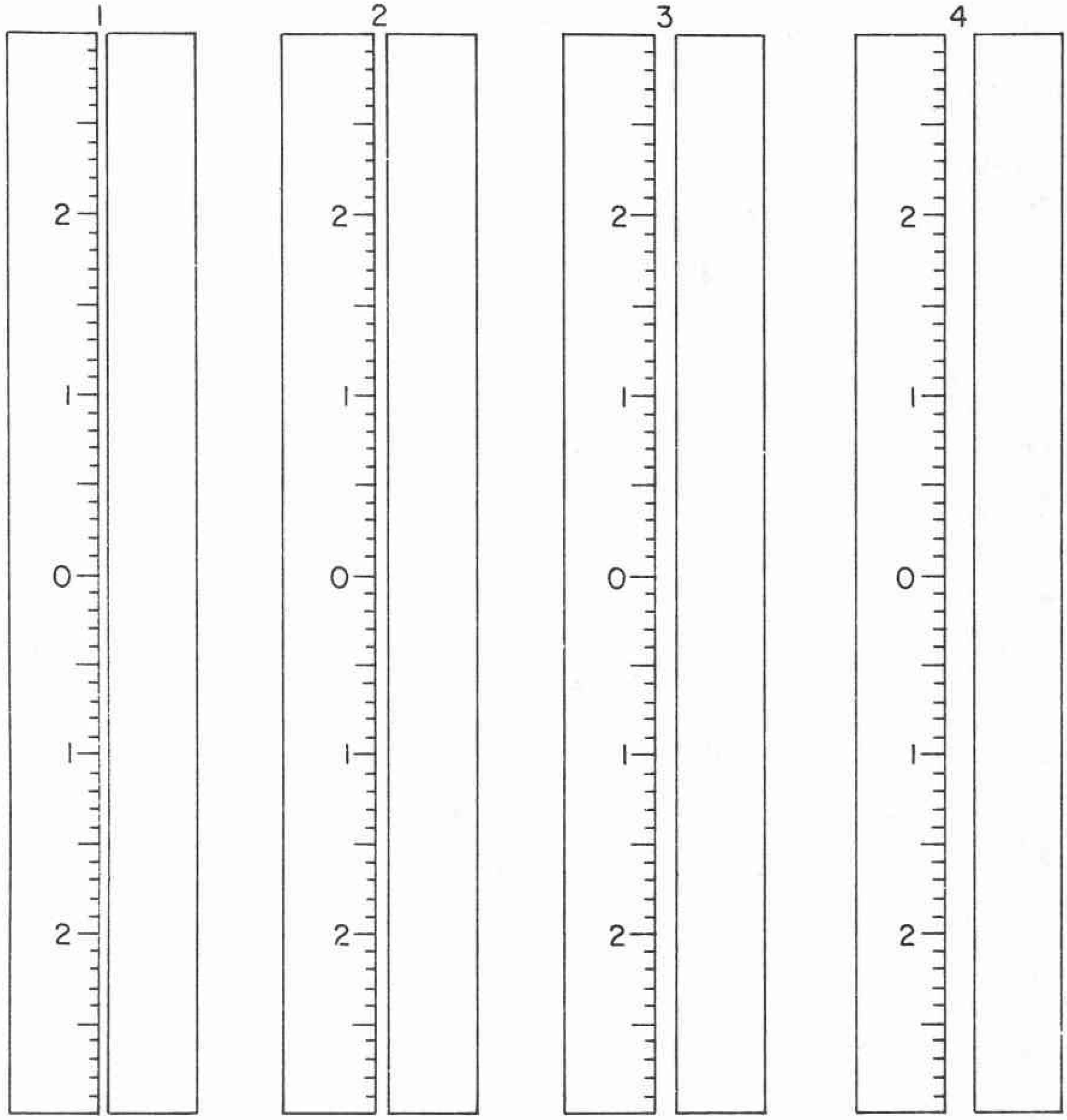


Figure 27. Figure width and linearity scale: length units are inches; width increments are millimeters.

with the widest gap, we attempted to span the apparent width of the lineament, then moved to successively narrower gaps as necessary until the widest part of the lineament just fell within the interval; and (c) we recorded the number (the width of the gap in mm) corresponding to the widest part of the lineament. We were careful to measure only one lineament at a time, since even closely spaced, parallel lineaments should be measured separately. Occasionally, parallel lineaments bound a zone or band that might be mistaken for a single broad lineament. Transition zones between tonally or texturally differentiable areas of the image may also occasionally resemble wide lineaments.

Linearity

Linearity is a measure of the extent to which a figure is linear, that is, that it has the appearance and characteristics of a straight line: (1) a high ratio of length (L) to width (W), L/W, where L>>W, W>0; and (2) an unvarying azimuth (azimuth variation is measured directly as "azimuth deviation," discussed below). By this definition, linearity is the antithesis of curvature. Some investigators (for example, Gary and others, 1972, p. 408; and O'Leary and others, 1979, p. 572) define lineaments as lines that are either straight or slightly curved, but provide no accepted limit on or even a means of assessing curvature. Others such as Huntington and Raiche (1978, p. 147) state that curvature is a valid property of lineaments but, in fact, treat curves as "straight line segments" for statistical purposes.

We find no theoretical justification for and considerable methodological disadvantage in these practices. Our own experience argues against the necessity of mapping apparently curved figures as lineaments, despite the fact that earth structures, such as faults, display curved strike directions. As mentioned in our definition, a lineament that seems to curve can be discerned as two or more discrete linear intervals or chords of the composite arc. Furthermore, lineaments are much more easily studied if perceived as straight lines, which can be defined by two end point locations and an azimuth value, or by the center point location, length, and azimuth. Finally, we are convinced that the pioneers who introduced the term and the concept of a lineament--Dana (1863), Hobbs (1904a), and those early investigators cited by Hodgson (1976)--intended to restrict use of the word "lineament" to applications wherein a straight, narrow line was perceived. Thus, where a curve is evident we describe it as a family of discerned straight-line segments.

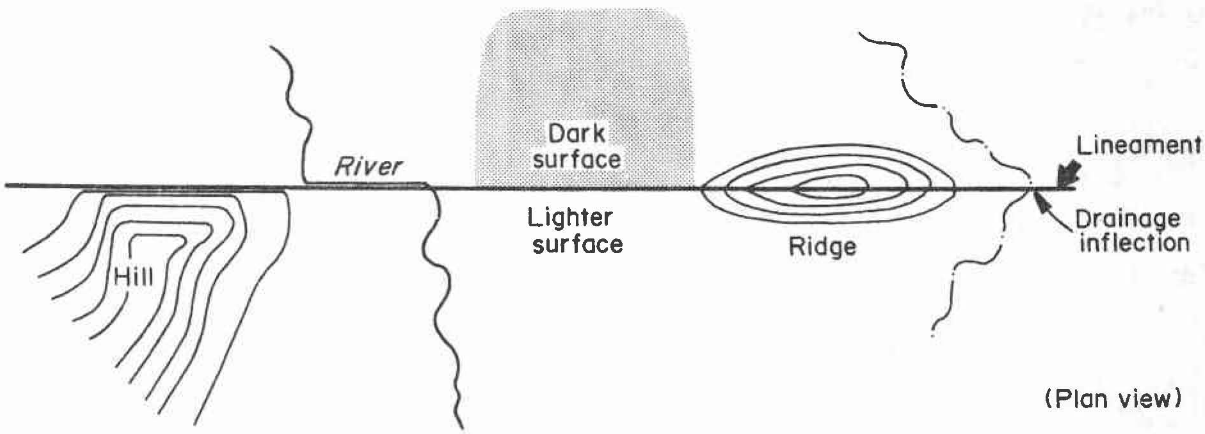
Figure 27 may be used as a template for figure linearity as well as for width and length. When printed on a transparent sheet, the part of the scale that has the appropriate gap width is now used to determine that figure's linearity. The scale is superimposed on the image figure so that the "0" (zero) mark is at either end; if the figure is perfectly linear its entire length should just fit within the gap. (Measurement of figures more than three inches in length is performed in increments.) Perfect linearity of the figure is assigned a value of 10; if, however, the apparent lineament crosses either of the lines forming the gap, linearity is imperfect (<10) and the apparent figure may in fact be two or more lineaments with slightly different azimuths. That is, if the maximum width of the apparent figure as measured previously is correct, an observed discrepancy can only be accounted for by a difference or deviation in the linearity of part of the "figure" as originally perceived.

When a deviation in linearity is noted, the length of that part of the original figure lying within the gap is measured; this measurement is the inscribed length. Linearity is the ratio of the inscribed length (IL) to the overall length (L) as measured previously, multiplied by ten, or 10(IL/L). In practice, minor deviations can be tolerated, such that the linearity rating of every lineament need not be 10. Certainly, however, the ratings should approach 10, particularly for very long figures, since the absolute length of the deviated portion of the "figure" may be significant even if the ratio is high.

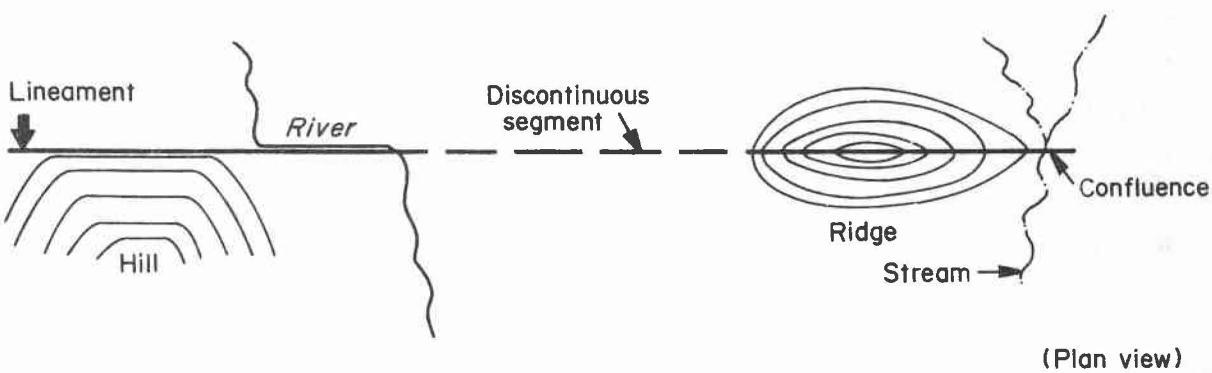
An exceptional condition arises when the width of the figure varies significantly along its length. Even under these circumstances, the gap corresponding to the maximum width should be used to determine the linearity of the figure. In general, a lineament of varying width should be considered a discrete entity only when both of its ends and a large part of its total length lie within the gap. A relatively short, diffuse segment between the ends will not adversely affect the interpretation of the figure or the determination of its linearity.

Continuity

In Landsat images, figure continuity is the persistence of linkages between individual pixels or tonal areas along the full extent of a figure. Landsat images afford a synoptic view of very large, irregular surfaces that is not otherwise readily attained. Numerous landscape features are depicted in a single image; any geographic continuity among seemingly discrete features is evident (fig. 28). Thus, a figure image will often be delineated by two or more cues along its length. Part of the figure may be perceived as a contrast boundary between contiguous tonal or textural areas, another part as a line of apparent relief (for example, a ridge line, valley, escarpment), and still another as an



(a) Continuous or nearly continuous composite lineament.



(b) Discontinuous composite lineament.

Figure 28. Continuous and discontinuous composite lineaments.

actual line, denoted by tonal contrast. Each cue may represent the expression of a different surface feature. If the features are judged to be manifestations of natural processes, the linear figure may be a lineament, either a simple lineament if only one surface feature is represented, or a composite lineament if the figure is continuous between two or more features (fig. 28a). The composite nature of some lineaments, which was discussed by Hobbs (1904a), does not impair the continuity of these lineaments.

We measure continuity by comparing the overall length (L) of an apparent lineament to its uninterrupted length (UL), in the ratio 10(UL/L). Overall length was measured previously and was confirmed or adjusted during the determination of figure linearity. The uninterrupted length is the total length of continuous segments of the figure. The value of the ratio should approach 10; a large difference between the determined continuity value and the ideal suggests that the apparent single lineament is, in fact, two or more colinear figures (fig. 28b). Determination of continuity is not immune to subjective influences affecting in particular an observer's perception of "uninterrupted length." The observer should be conscious of this fact.

Azimuth

Figure azimuth is the orientation of a linear figure with respect to geographic north. Azimuth of linear figures on Landsat images is easily measured with a transparent circular protractor, using the geographic "tic marks" in the image margins for reference. The north-south axis of the protractor is oriented with the center point of the protractor placed over the figure. The point of intersection of the figure with the graduated rim of the protractor is noted (0 to 359 degrees). This intersection constitutes the figure's azimuth.

Azimuth Deviation

Azimuth deviation of a "linear" figure is a change in azimuth noted anywhere along the length of the figure. Azimuths must deviate whenever figures have imperfect and, in particular, low linearity. Deviations in azimuth that are on the order of 5 to 10 degrees might be expected, and may be sufficient to justify division of the figure at the point of inflection. The scale shown in figure 29 can be printed on a transparent base and used for measuring azimuth deviations. Either the vertical or horizontal (0 degree) axis is aligned with the image figure and then moved from one of the figure's end points to the other; observed angular deviations are measured directly.

Apparent Relief

Prior to the current investigation, relief (apparent differences in altitude across a scene) was seldom analyzed with Landsat imagery. Unlike vertical aerial photographs, Landsat images have a limited capacity to evoke the perception of depth by conventional interpretive techniques; this is because the Landsat system does not provide synoptic stereo coverage. Aerial photographic surveys are generally designed to afford 60 percent overlap (endlap) between successive images along a flight line, and 10 percent or more lateral overlay (sidelap) between images acquired from contiguous flight lines. In contrast, endlap in the Landsat system is generally held to less than 5 percent, while sidelap varies (because of convergence of the orbital paths toward the poles) from 14 to more than 85 percent between the equator and polar regions, respectively. At 30 degrees north latitude for example, sidelap is nominally 26 percent; Texas lies between approximately 26 and 36 degrees north latitude. Thus, the amount of overlap in coverage of scenes within the state is inadequate for stereoscopic viewing of large image areas.

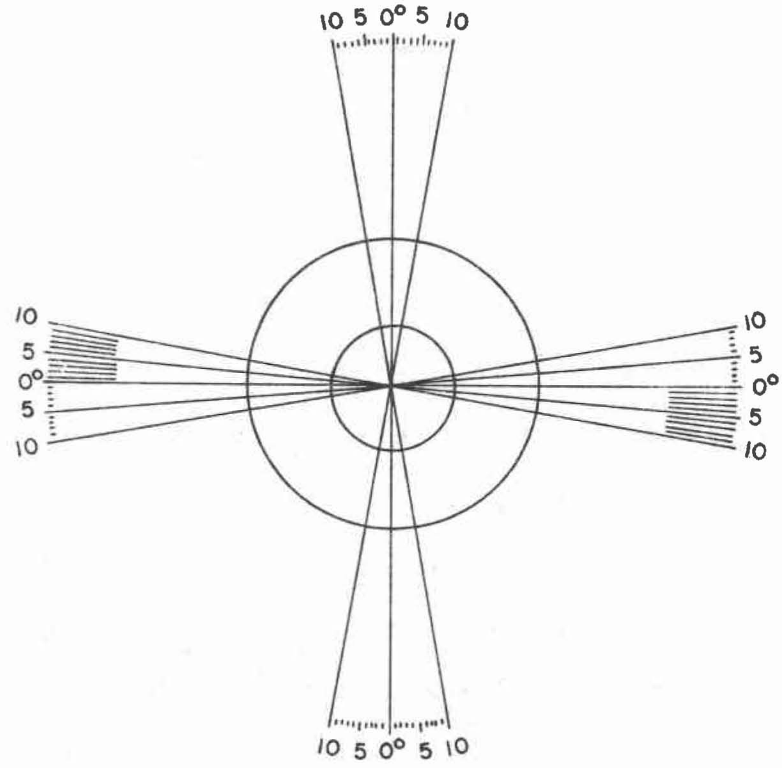


Figure 29. Azimuth deviation scale.

Raju and Parthasarathi (1977) used repetitive Landsat 1 images of a single scene to perceive relief with a conventional mirror stereoscope. Small shifts in the orbital path through time created effective parallactic displacement (difference in the position of points of reference relative to other points in the two images) that was sufficient to impart perceptible relief. This effect, along with an incidental sidelap of 94 percent between the repetitive images, permitted practical stereoscopic examination of most of the image area. However, image quality discrepancies and seasonal differences (such as variations in cloud cover, snow cover, and vegetative or soil reflectivity) between repetitive images significantly impairs application of this method.

Batson and his co-workers (1976), on the other hand, noted that "A strong stereoscopic effect can be introduced into Landsat pictures by displacing image details by varying amounts as a function of their known relative elevations" (p. 1279). Digital image processing techniques were thus employed to create synthetic parallax. In this way, a pair of conjugate images could be prepared from reflectance data collected on a single imaging date, eliminating the probable tonal mismatch of repetitive images. Unfortunately, this technique has several disadvantages: in addition to the sophisticated equipment and methods needed to manipulate the satellite data in this manner, the technique introduces various artifacts within the image (caused by interpolation between contours), and emphasizes discrepancies in registration that can produce some "disconcerting effects, such as streams climbing out of their banks and crossing ridges, (which) will compromise the usefulness of Landsat stereograms" (Batson and others, 1976, p. 1283).

Our methods of perceiving relief in Landsat images require no special equipment, introduce no vertical exaggeration, artifacts, or registration errors, and involve examination of only one image at a time so that scene changes between repetitive imaging dates are not troublesome. In its simplest form, the technique requires the interpreter to examine an image resting on a horizontal surface from a low oblique angle (20 to 30 degrees above the image plane), with one eye closed, along a line usually from west to east. If there is appreciable relief across the image in the viewing direction, and if image quality is high, the effect of apparent relief is comparable to that seen with a stereoscope when examining stereo image pairs, but without vertical exaggeration. The effect may not be immediately apparent, necessitating slight changes in viewing angle (to the surface) or direction. The perception of relief in this manner is probably linked to a system of perceptual stimuli in which binocular vision provides negative feedback (competing stimuli) that normally permits recognition of a flat surface. Without this feedback (that is, when the image is viewed monocularly), the perceptual system can be "misled," giving the appearance of relief; fortunately, the apparent relief is in fact representative of the actual topographic differences across the scene. The validity of the effect can be verified by comparing (1) perceptions of elevation changes along a line between two widely separated reference points on the image, to (2) changes along a corresponding line denoted on a topographic map covering the same area at the image scale.

Examination of the image along the same view line but from the opposite direction (that is, looking from east to west) usually produces the appearance of "negative topography." Viewing direction is thus important, apparently because of our inherent expectation that shadows will fall toward rather than away from us in aerial images (Strandberg, 1967, p. 14). This expectation probably stems from the fact that if a solid object (for example, a mountain) in our field of view casts a shadow that falls away from us, we would expect the object to impede our view of the shadow. When we see all of a shadow (shadows generally extend outward from the base of an elevated object as the angle of illumination decreases), we assume that the shadow is falling toward the observer.

In Landsat images, dark tones may occasionally be mistaken for shadows, producing anomalous effects such as both negative and normal relief perceptions at different points along the same view line. However, since we know the direction of solar illumination (time of imaging and cardinal directions are printed on each Landsat image), we can effectively compensate for this illusion. For example, all Landsat images used in thus study were morning images, indicating that illumination was from the east; thus, we examined the images by looking from west to east across each. We assume this position, to fulfill expectations that shadows should fall toward us, away from the direction of illumination. Where we noted apparent inconsistencies in the relief perceived along a particular line of view we were able to correct our perceptions from our knowledge of the direction of sunlight. We made an exception to the practice of viewing images along a west-to-east vector when a depicted landscape feature was so oriented relative to sunlight that shadows from that feature did not fall toward the observer looking from west-to-east, as when a steep, north-facing escarpment is illuminated from the east. In such a case, the image was viewed from whatever direction produced the sensation of shadows falling toward the observer. In this way, we avoided the illusion of relief inversion. Illumination direction is essentially fixed among Landsat images of a given scene because the time of transit of the satellite over that location is relatively constant (see Appendix F).

A simple variation on this technique was also discovered during our investigation. Images were photographed with slide film from the same viewing direction and at the same look angle used when we perceived apparent depth on an image monocularly. Relief was very apparent in the projected transparency when we viewed it, with both eyes, from a distance of approximately 20 feet or more. This phenomenon apparently occurs because humans are effectively monocular from this distance, as noted by Gregory (1966, p. 53). The view thus obtained is similar to our "perceiving" earth-surface relief from the window of an airplane.

Perceptual Biases and Limitations

It is important to avoid image figures that are similar yet unrelated to lineaments as we have defined them here. Various biasing factors served either to obscure otherwise perceptible, valid lineaments, or to create the illusion of linear figures of the type we would call lineaments. There are three general classes of biasing factors: (1) artifacts of image quality; (2) cultural manifestations; and (3) selected geomorphic patterns.

Image Quality

Good image quality is of the highest importance in studies of lineaments. Areas of poor contrast and dull resolution in Landsat images are unlikely to yield perceptual information or cues needed for recognition of lineament figures. Scratches, streaks, and other defects in an image may closely resemble linear figures. Prominent scan-line stripes may also be mistaken for lineaments; or they may so bias the interpreter that he will select no linear figures oriented parallel to the scan lines. Haze, clouds, and cloud shadows may also obscure or create linear patterns and thus hamper the interpretation.

Cultural Manifestations

Cultural manifestations may often impose troublesome biases, as well. Many of the figure properties characteristic of lineaments are also indicative of transportation routes and other linear cultural features (Lewis and others, 1969, and Simonett and others, 1969). Land use, particularly in urban and extensively cultivated areas, may so alter the landscape that little information about the underlying surface is conveyed by the image. Cues that might have led to the perception of lineaments are destroyed or overwhelmed by patterns that are meaningless for our purposes. Man-made lakes and reservoirs cover vast areas of the state, thus obscuring the land surface locally (although the shorelines of these impoundments are topographically controlled and thus may suggest natural linear patterns). In place of cues reflecting natural alignments we find depictions of linear roads, railways, canals, fencelines, utility corridors, and stabilized shorelines. Brush clearing, tilling, grazing, irrigation, lumbering and forestry, dredging, and surface mining may likewise produce features on the ground such that, when depicted in Landsat images, they are surprisingly like lineaments. While most of these figures can be recognized and eliminated, the interpreter must exercise restraint since the cultural overprint may coincide with surface patterns (for example, topographic alignments) that may, in fact, be lineaments.

Geomorphic Features

Perhaps the most misleading sources of biases by interpreters are those geomorphic features that are linear and yet reflect the influence of only superficial or transitory processes. That is, they are not immediately subject to geologic controls. Depiction of these features in an image can hinder the interpretation of "true" lineaments, whose origin is attributed to the expression of these geologic controls. Hindrance may be felt in either of two ways: (1) if figures representing purely surficial geomorphic features (those related to atmospheric or hydrospheric variations but without known structural or stratigraphic affinities) are interpreted as lineaments, the data will be spurious; or (2) if the interpreter recognizes the surficial nature of a linear image-pattern he may develop a negative bias, preventing an impartial interpretation of other similar figures. In either case, the validity of the data base could be compromised.

There are many kinds of linear geomorphic features which, when depicted in Landsat images, are very similar in appearance to lineaments, but which do not satisfy all criteria under our definition. Glacial and alpine regions contain many such features, including drumlins, aligned kames and kettles, terminal and lateral moraines, and aggregate or megascopic patterns of frozen ground polygons and frost-heaved topography (Washburn, 1980). Desert and steppe areas contain yardangs (Blackwelder, 1934) and wind-erosion scarps (Shawe, 1963); longitudinal, transverse, and oblique dunes (Cooke and Warren, 1973) and seasonal snowdrifts; and radiating drainage patterns on alluvial fans and pediments (Blissenbach, 1954). Coastal regions develop cheniers, distributary drainage networks on deltas, longshore bars and barrier islands, biogenic patch reefs (in bays and estuaries), and linear bay and channel margins (Price, 1947). The linear appearance of these features in images may also be reinforced by vegetative growth and land use patterns. Yet for any of these features, active faulting may play a role in controlling their orientation in some areas.

All of these geomorphic features are linear and of natural origin. However, the immediate causation of linearity in these examples may be solely attributable to the action of stream erosion or deposition, gravity, winds, tides, and currents along preferred azimuths without reliance on overriding stratigraphic or structural controls. For this reason, figures depicting these features should be evaluated with care whenever they are perceived and interpreted.

Analysis of Lineaments

Lineaments and Geothermal Resource Assessment

The primary purpose of this study is to investigate possible relationships between lineaments and low-temperature geothermal resources in Texas. Although we mapped lineaments throughout the state (Appendices E and F), the comparison of these results with the known distribution of warm ground water was conducted only in the Central Texas region, along the Balcones/Ouachita trend. It is in this area that the resource is best known and of greatest potential value (Woodruff and McBride, 1979).

Our analyses to date constitute only a pilot survey of associations among lineaments and various attributes of geothermal aquifers. Yet, this cursory investigation suggests that correlations do exist. For most of Texas, the "raw data" (that is, the perceived lineaments) await detailed interpretations regarding geothermal (or other resource) applications.

Review of Prior Applications

Our bibliography (Appendix G) cites relatively few examples of the direct use of lineaments for geothermal resource exploration and assessment. It is a topic that has received serious attention only in the past two decades. Previously, the significance of lineaments has not been pursued rigorously; lineaments have been viewed more as curiosities than as subjects for systematic inquiry, at least in this country. Thus, it is not surprising that the convergence of studies that apply lineament interpretations to geothermal potential has been somewhat limited in English-language research literature.

One of the first works on this subject is that by Rogers (1843), who described the linear distribution of thermal springs in the Appalachian Mountains of Virginia. Rogers clearly recognized "the connection of springs of this class with the structural features of the district." He also stated that virtually all of the 56 springs he had studied "issue from the lines of anticlinal axes, or from points very near such lines" (p. 331). While Rogers never mentioned lineaments, his frequent remarks concerning the "linear arrangement" (for example, p. 341) of thermal springs can be construed to imply the existence of natural alignments; these might well be depicted as lineaments.

An unpublished report in Italian by the Centro Ricerche Geologiche (1969) described what was perhaps the earliest attempt to actually investigate lineaments in connection with geothermal resource exploration. The report was among those listed as references by Cataldi and Rendina (1973, p. 116), but was not mentioned in their text and was unavailable for inspection during our study. Cataldi and Rendina were themselves pioneers in the development of the Alfina (Italy) geothermal field, which they discovered, in part, by studying lineaments perceived in aerial photographs. These investigators employed a number of exploration techniques in addition to lineament analyses and relied on the convergence of available evidence to direct exploratory drilling. However, recognition of the possible correlation of lineaments with structural features controlling the geothermal resources was a major finding of their investigation. They studied lineaments in two contexts, regional and local, using aerial photographs. Regional reconnaissance defined the gross boundaries of the area of interest; localized prospecting then defined the selection of test sites on the basis of implied "fracture density."

An earlier study by Todoki (1970) related lineament patterns to a known geothermal resource area in Japan. Todoki assumed that structural fracturing was related to stress conditions indicative of anomalous heat flow at a shallow depth. He regarded lineaments as expressions of major fracture patterns, and inferred that lineaments were predictably associated with geothermal resources. Lineament analysis could thus be applied in the manner suggested by Cataldi and Rendina (1973), for: (1) regional geothermal reconnaissance; and (2) local resource exploration.

Although Muffler (1976) did not discuss lineaments, and Lattman and Parizek (1964) did not mention geothermal resources, all three probably would have concurred with Cataldi's and Rendina's two-fold approach. Muffler discussed the dual nature of tectonic and hydrologic controls on geothermal resources. He related resource distribution to variations in reservoir properties within appropriate tectonic settings, involving generally those in which heat flow is greatest. Much of Muffler's discussion was devoted to major "hot" geothermal resources, rather than the comparative low-temperature ground waters of our Central Texas study area. However, the same general convergence of suitable reservoirs along zones of (relict?) tectonic discontinuities is generally responsible for the geothermal resources in the relatively low heat flow region of the eastern United States (Renner and Vaught, 1979; Tillman, 1980).

Lattman and Parizek (1964) formulated the "concept that fracture traces (lineaments) reflect underlying fracture concentrations and are useful as a prospecting guide in locating zones of increasing weathering, solutioning and permeability" (p. 73). They used this observation to relate lineaments to the occurrence of "cold" (non-geothermal) ground water in folded and faulted carbonate rocks with interbedded sandstones. They compared yields of wells in central Pennsylvania to mapped lineaments perceived in aerial photographs, and found that well yield varied in relation to the proximity of fracture traces. These investigators then conducted caliper surveys to determine whether lineaments reflected underlying zones of increasing permeability. The data clearly suggest that such relations exist in their study area; it also appears that selective weathering and solution within these higher permeability zones were, in fact, responsible for the surface expressions perceived as lineaments in aerial photographs.

One of the most ambitious attempts to correlate lineaments and geothermal resources was that by Trexler and others (1978), who combined the use of a variety of imagery at various scales, along with geophysical data. Trexler and his co-workers favored the use of several image types (including Landsat, SKYLAB, and low sun angle photography). These data were designed to achieve regional reconnaissance and site-specific exploration. Their intensive studies in known resource areas within Nevada demonstrated "relationships between geothermal activity and the intersection or disruption of major lineament trends." These findings were generally corroborated by Parr (1978) who analyzed (on a purely statistical basis) lineaments and distribution of rock types at the ground surface in relation to geothermal resources in Nevada.

Lineaments as Related to Structural Features in Central Texas--Tentative Findings

The concentration of geothermal wells and springs in Central Texas clearly suggests geographic relations between geothermal resources there and the region's major structural/tectonic features. Our investigation of lineaments in the area suggests that the pattern of lineaments is also closely correlative with the distribution of structural features. In this manner, lineaments also correlate with potential geothermal resources. The Balcones/Ouachita structural trend (fig. 30) constitutes a persistent hinge zone that affected deposition of Cretaceous aquifer units. Moreover, subsequent structural events (including faulting, continued downwarping across the hinge, volcanism, and salt withdrawal and diapirism) further altered the regional hydrologic system, in ways conducive to the formation of geothermal resources. As already discussed, fault zones (figs. 31 and 32) constitute possible avenues for deep circulation of ground water, or they may be barriers restricting flow. Also, downwarped strata and major depositional system changes such as occur across the hinge zone, may provide pathways for upwelling of deep, warm, basinal waters. Upwelling may also occur in the vicinity of piercement structures such as igneous plugs and salt domes; this process is evident in the role played by these structures in trapping hydrocarbons. Major tectonic features of the region are also associated with geothermal gradient anomalies. Although genetic relationships are suggested among tectonic features, geothermal anomalies, and warm-water-bearing aquifers, none are proven. Since lineaments often coincide with structurally disturbed areas, they thus may be used to infer the presence of geothermal resources.

Lineaments, Lineament Zones, and Lineament Areas

Ten Landsat images (scene numbers 24, 25, 27 to 30, 33 to 35, and 39) cover the Balcones/Ouachita trend of Central Texas (fig. 33). In our examination of these images we perceived more than 5,000 lineaments (see Appendices E and F). We evaluated the lineaments individually and compared their distribution with features shown on topographic and geologic maps of the region. However, for purposes of this discussion and ease of correlation we found it necessary to combine adjacent, essentially continuous or parallel lineaments to form "lineament zones" (figs. 34 and 35), in order to reduce the number of lineaments to more manageable and cartographically practical proportions. Each zone includes two or more lineaments along with narrow intervening gaps. The lineament zones are not always linear; their width and length are variable; and they are somewhat subjectively defined. Nevertheless, aggregation of the individual lineaments in this manner was extremely helpful, particularly for simplifying comparisons with other thematic maps.

We further consolidated the lineament patterns in each image by denoting areas in which the individual lineaments and lineament zones exhibited relatively uniform properties (length, azimuth, continuity, and density). The resulting "lineament areas" (figs. 34 and 35) are internally uniform and externally heterogeneous in terms of their predominant properties; therefore, the lineaments and lineament zones within a single lineament area can be generally treated as a unit. Like the lineaments and zones, the lineament areas generally conform to the regional geology as it is represented on maps illustrating conventional structural/tectonic interpretations. The lineament patterns and their combinations into "zones" and "areas" also compare favorably to the regional and local trends of geothermal gradient values.

Geothermal Gradients

We used measured BHT values and depths from wells to calculate geothermal gradients. The gradient calculation also requires adjustment of BHT by subtraction of the mean surface air temperature at each control point, which is assumed to equal the mean surface ground temperature at each locality. Our data consist of otherwise uncorrected bottom-hole temperatures and depth measurements from approximately 5 to 20 wells per county. Data from wells shallower than about 1,000 ft were generally omitted, since such data often reflect highly variable surface influences essentially unrelated to actual earth temperatures.

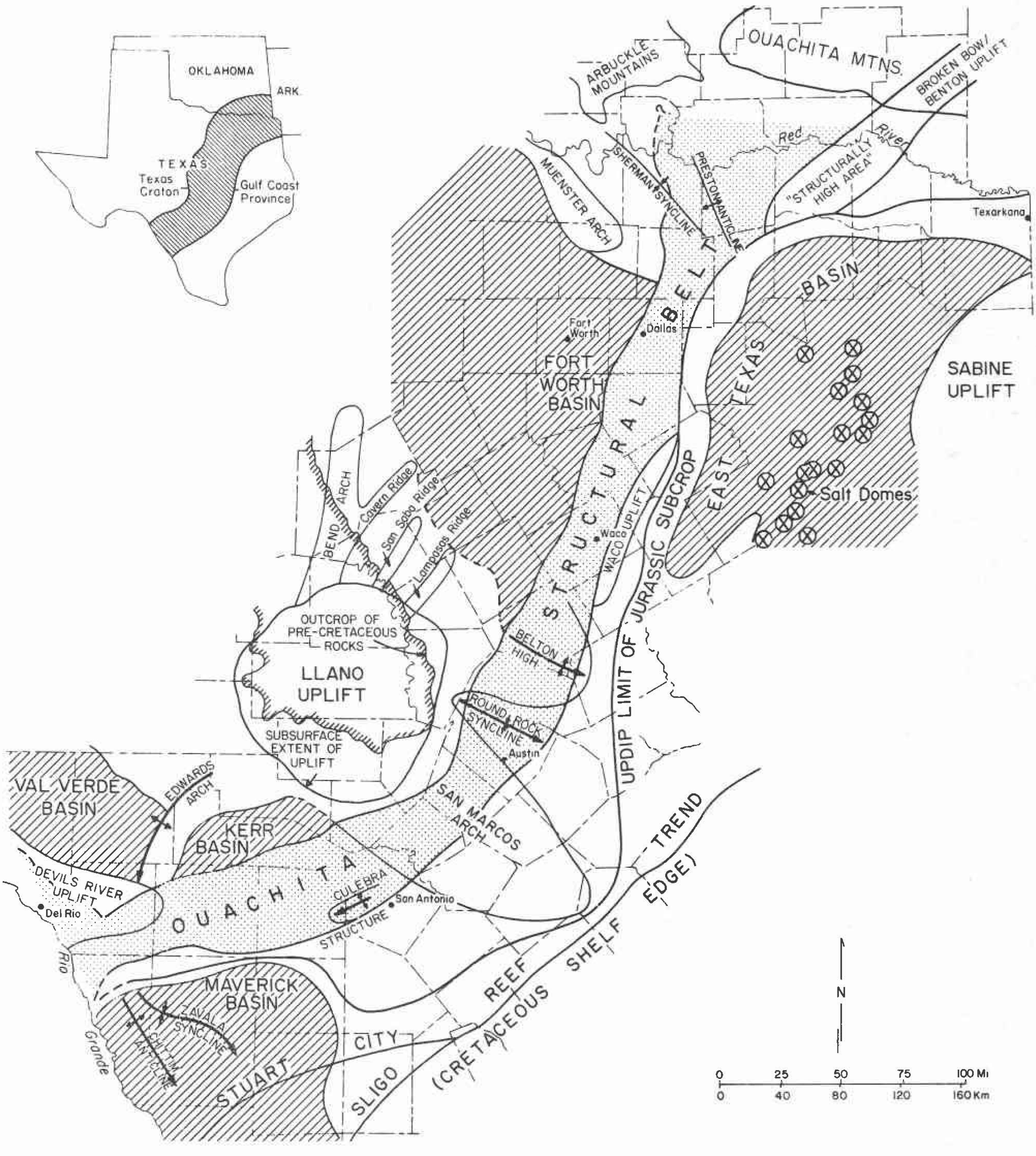


Figure 30. Major structural/tectonic features associated with the Ouachita System, Central Texas Region (after Flawn, 1961, Sellards and Hendricks, 1946, and others cited in text).

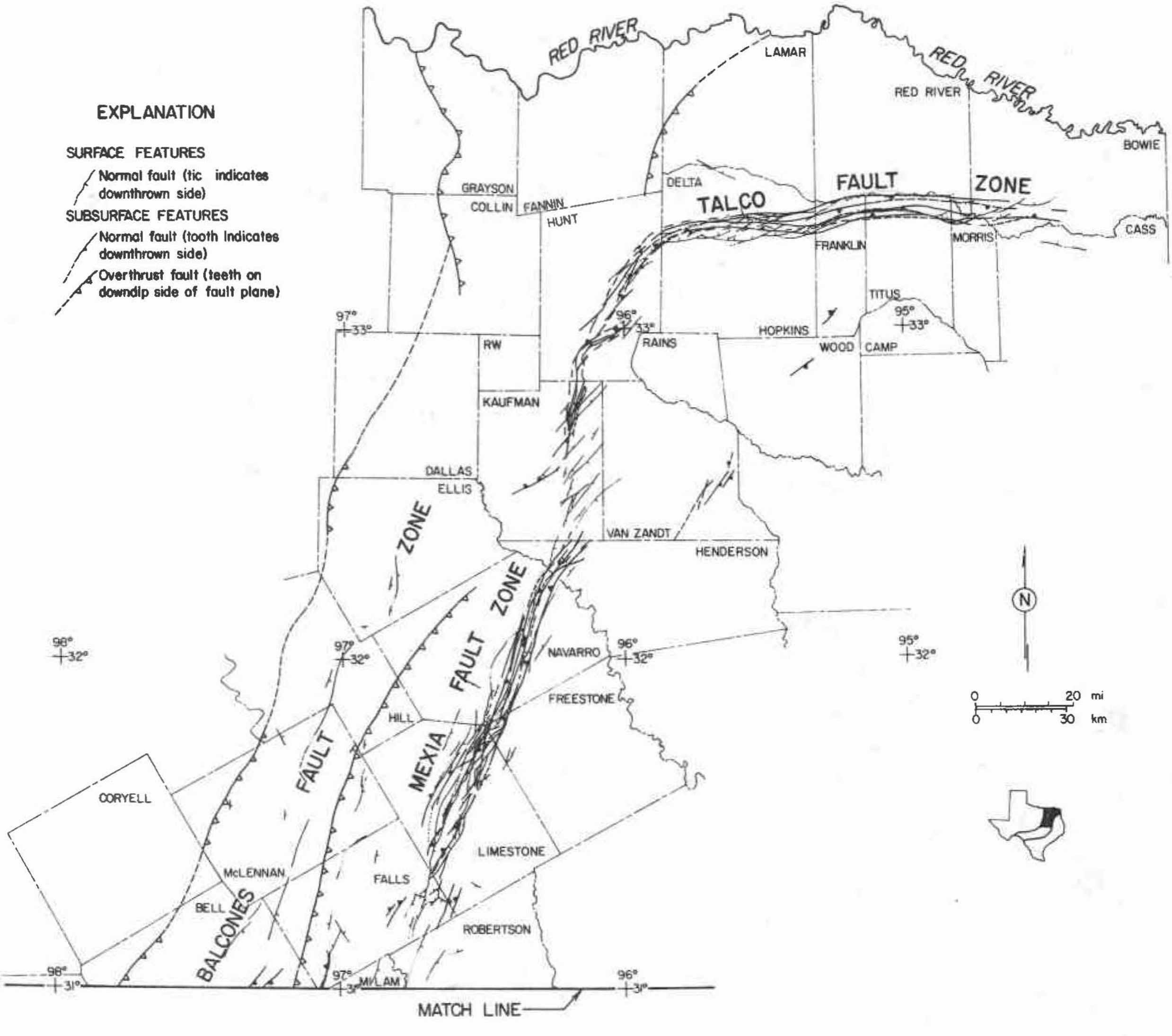


Figure 31. Faults and fault zones of the Central Texas Region, northern part (surface faults from Bureau of Economic Geology geologic atlas series; thrust faults from Flawn, 1961, plate 2).

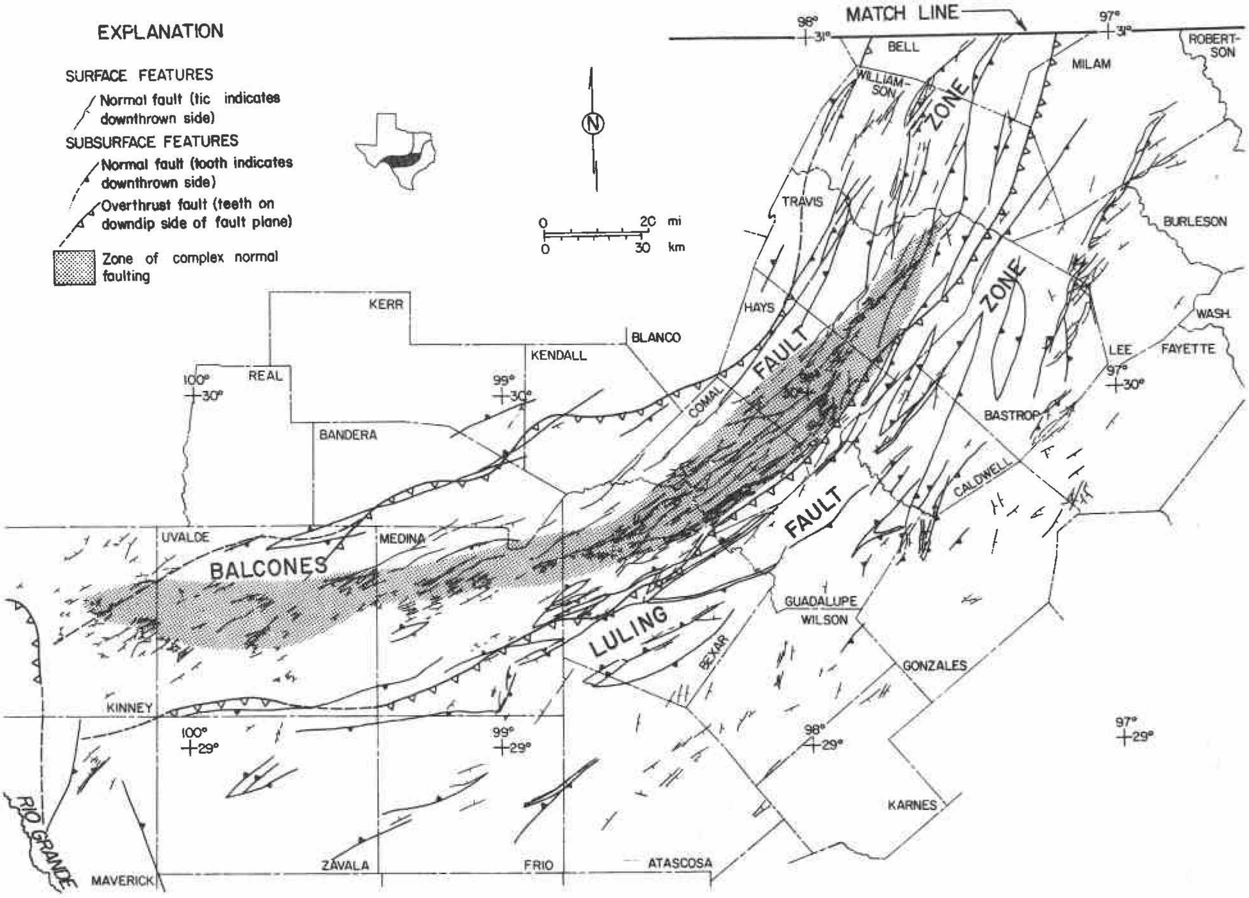


Figure 32. Faults and fault zones of the Central Texas Region, southern part (surface faults from Bureau of Economic Geology geologic atlas series; thrust faults from Flawn, 1961, plate 2).

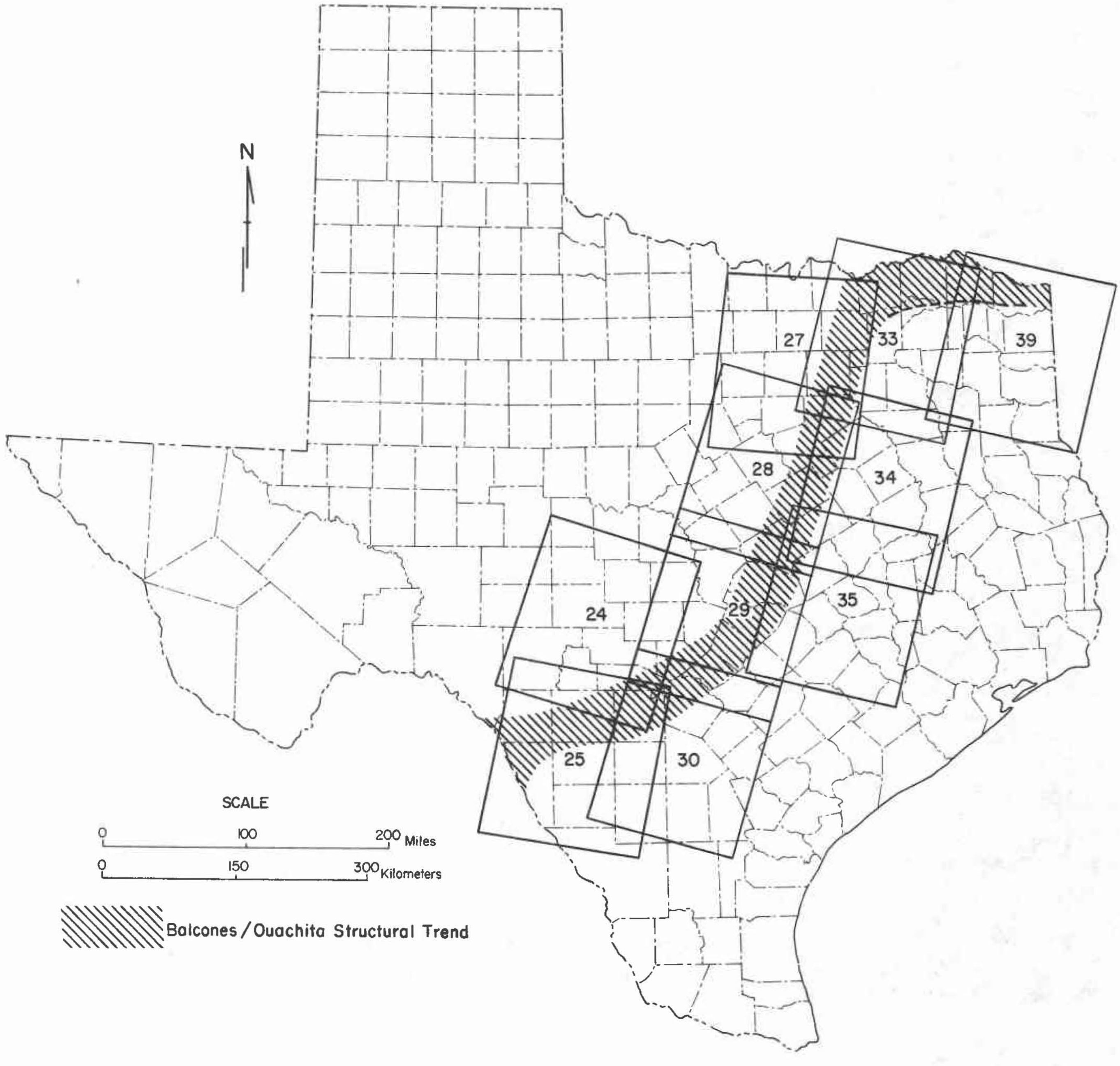


Figure 33. Landsat imagery coverage of the Ouachita/Balcones-Luling-Mexia-Talco structural trend (east of Rio Grande) in Texas.

From this temperature-depth data we calculated geothermal gradient values by the following formula:

$G = (T_Z - T_O) / z$, where:

G = geothermal gradient value at a point;

T_Z = recorded bottom-hole temperature (°F) at depth, z;

T_O = mean ground surface temperature, expressed by mean air temperature at the surface (°F);

z = bottom-hole depth (in ft) ÷ 100.

Gradient values are thus given as temperature change per 100 ft of depth (°F/100 ft).

Using these data, we constructed contours on our map of gradient values at control wells by interpolating geothermal gradient "isograds" (equal gradient contour lines) throughout our Central Texas study area. These isograd maps (figs. 36 and 37) are presented for comparison to our maps of lineaments, lineament zones, lineament areas, and major structural/tectonic features of the region.

Correlation with Structures

As expected, lineaments correlate strongly with structures that are known to have surface expression. When we perceive a lineament we are actually seeing a tonal representation of surface reflectance related to vegetation, soils, and topography; these surface characteristics are often influenced by structural features such as folds, faults, and joints. What is surprising is the coincidence between individual lineaments, as well as lineament zones and areas, and buried structural features. Along the entire Ouachita trend in Texas, transverse zones are almost invariably associated with major structural features. These deep-seated structures and tectonic features include, for example, strata affected by subtle regional warping, buried uplifts, buried igneous plugs and

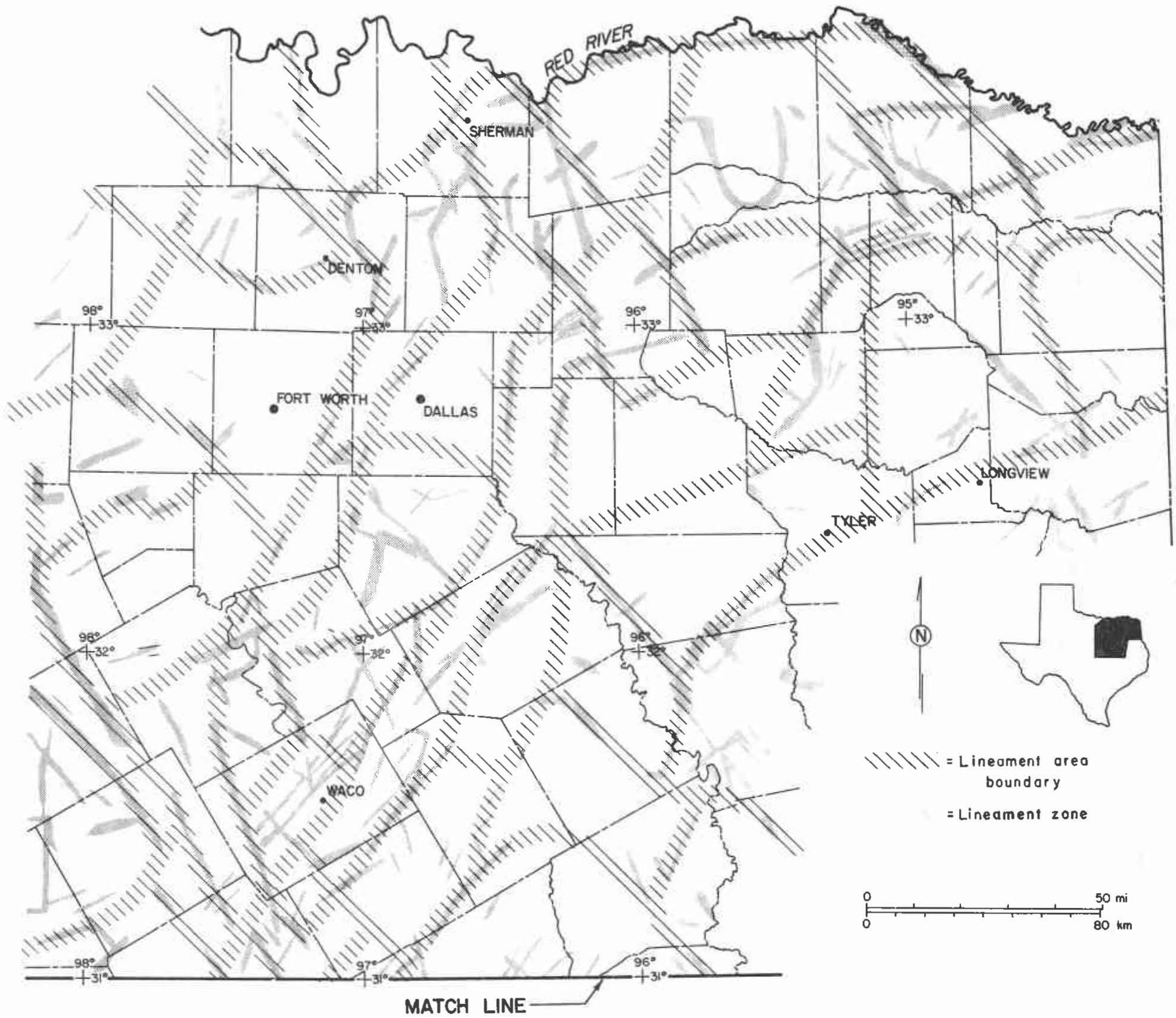


Figure 34. Lineament zones and lineament areas of the Central Texas region, northern part.

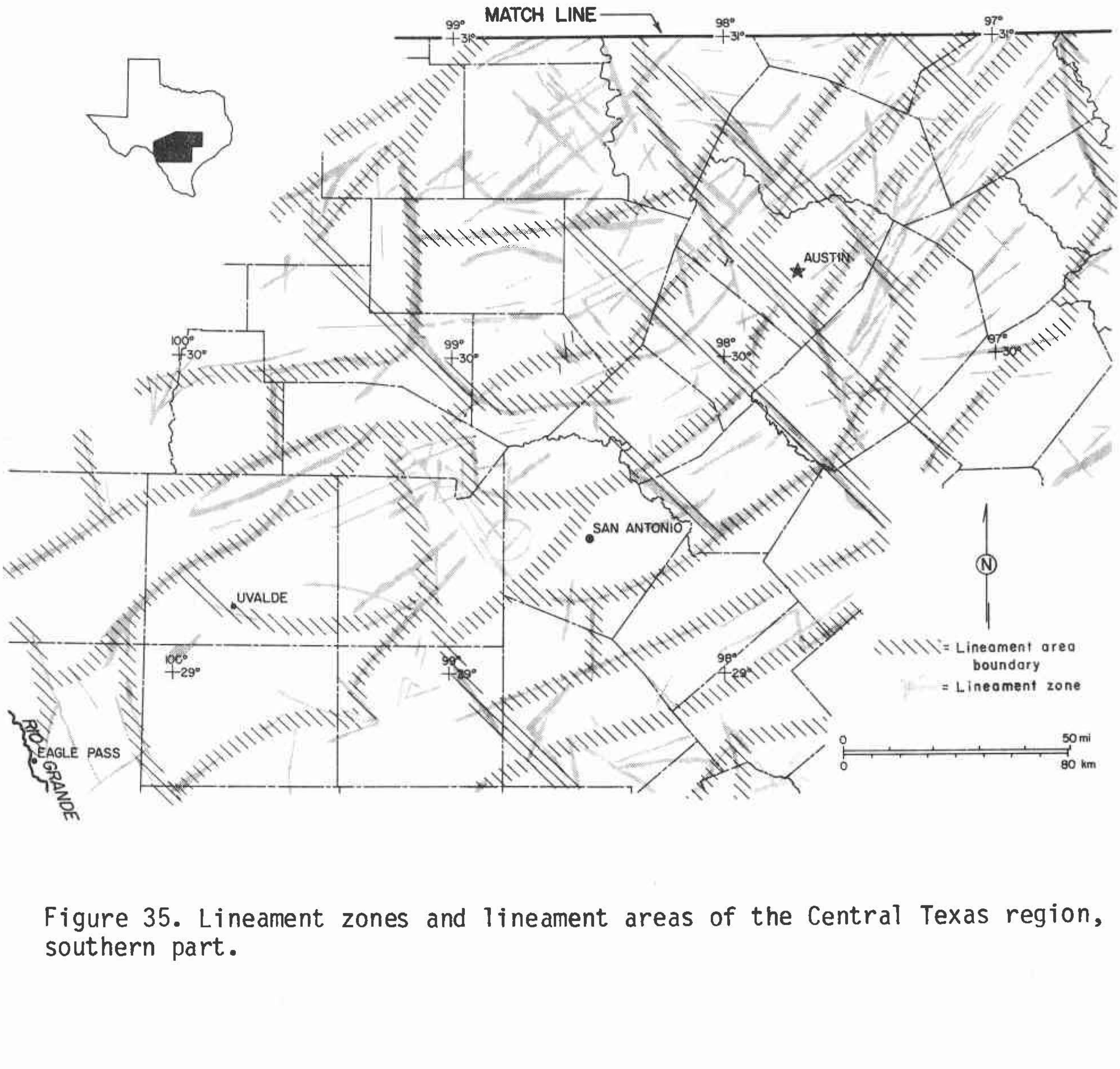


Figure 35. Lineament zones and lineament areas of the Central Texas region, southern part.

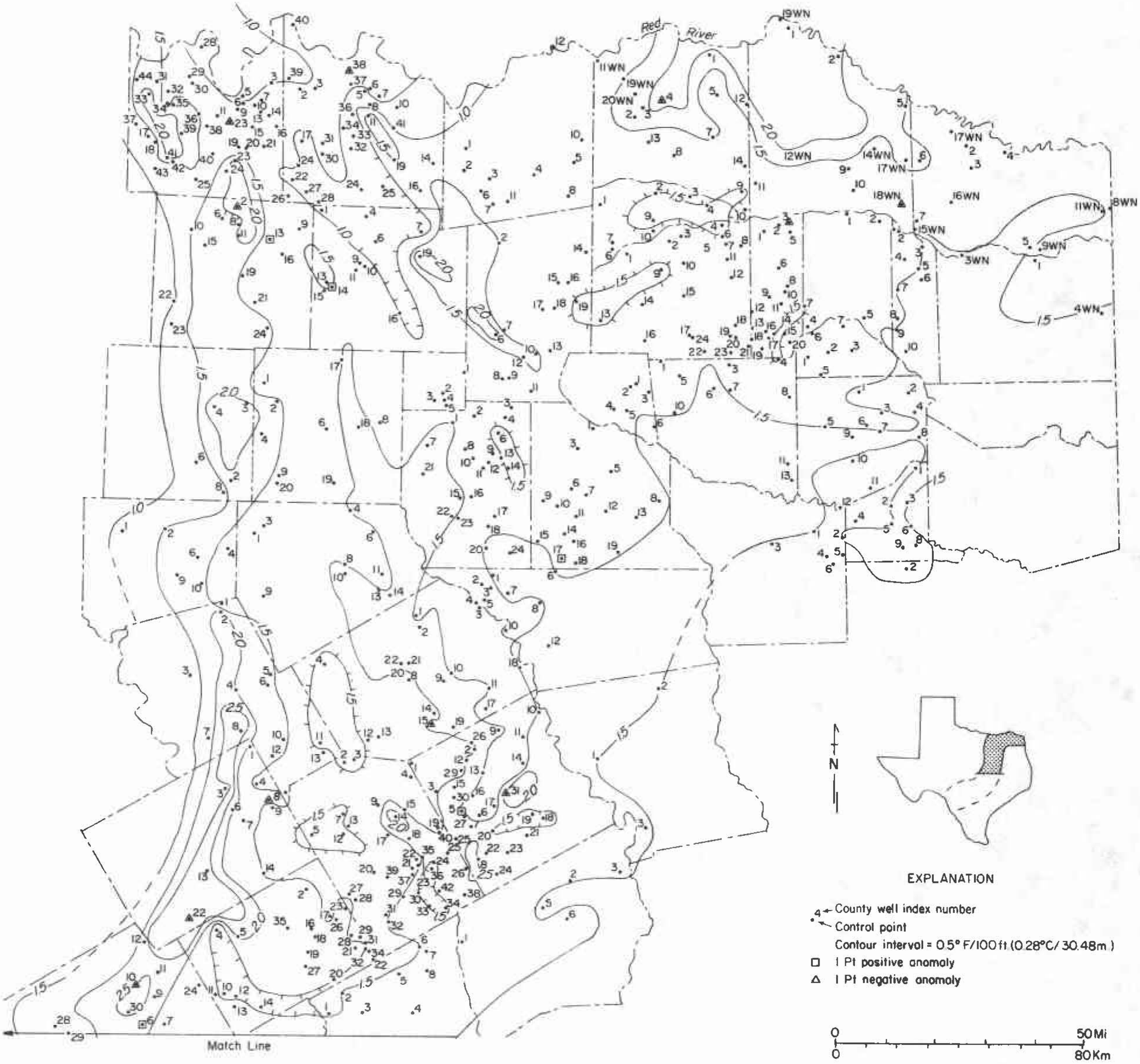


Figure 36. Geothermal gradient contour map of the Central Texas region, northern part.

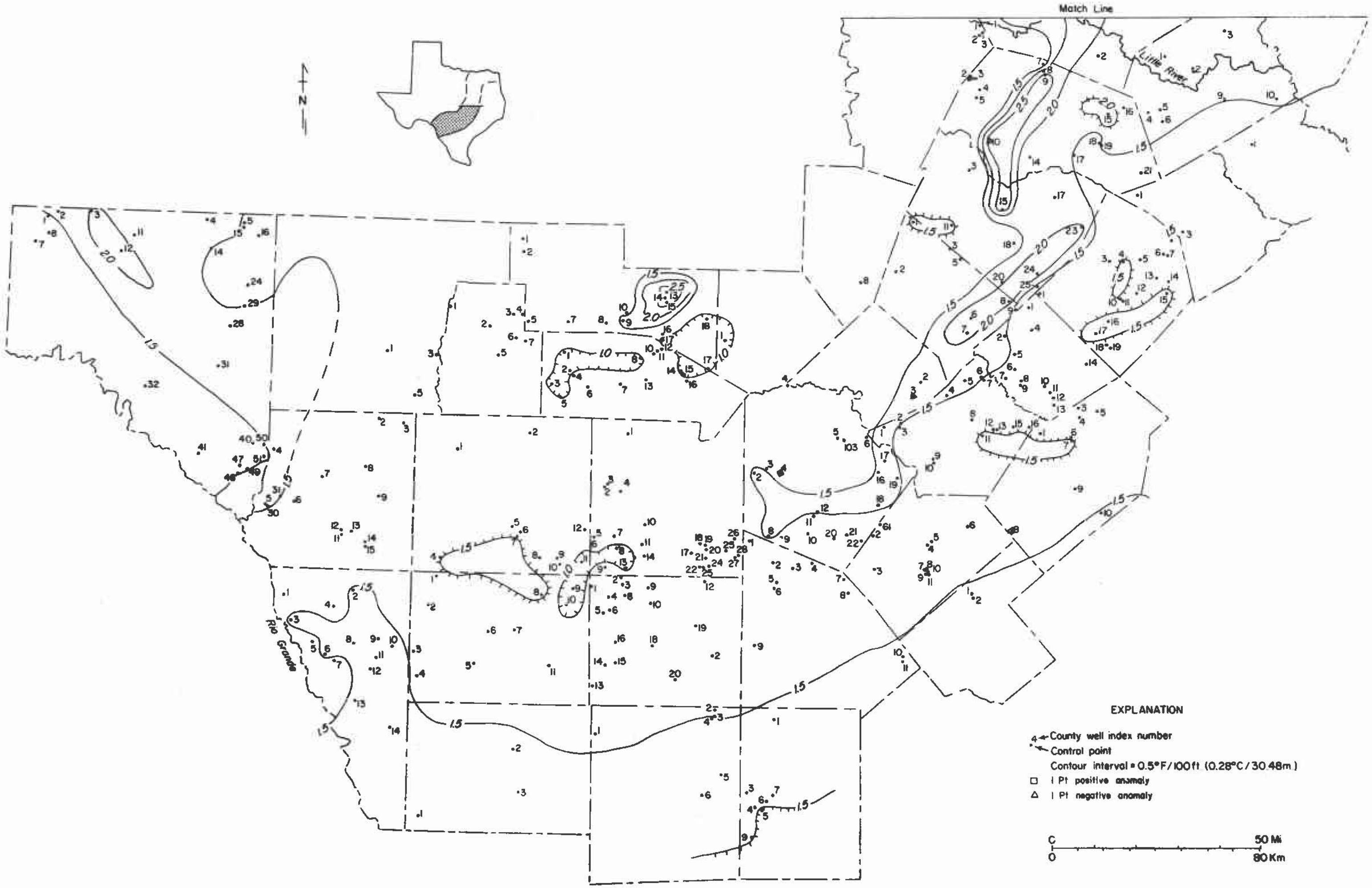


Figure 37. Geothermal gradient contour map of the Central Texas region, southern part.

salt diapirs, subsurface folds and fault zones (both thrust and normal faults), and loci of stratigraphic pinchout. Few mechanisms for surface expression of such features are known, yet apparently we have detected major subsurface structures across our survey region by their association with lineaments.

Northern Part of Region

The northern part of the Central Texas region, as here defined (figs. 31, 34, and 36) extends northward and northeastward from 31 degrees north latitude in Burnet, Bell, Falls, Milam, and Robertson Counties to the Red River. This area covers the northern half of the Ouachita structural belt in Texas and much of the East Texas Basin (fig. 30). Obvious gaps in the lineament pattern coincide with Dallas and other cities in the area because intensive urban land use obscures the kinds of natural surface features that might be perceived as lineaments when represented in Landsat images.

In the northern part of the Central Texas region, known surface features that are correlative with lineaments include the Mexia and Talco Fault Zones, which define the northern and most of the western margins of the East Texas Basin. The fault zones are outlined by nearly continuous lineament zones and coincide with a series of lineament areas. Most of the individual lineaments that we perceived along the Talco Fault Zone are associated with linear drainage reaches and tributaries of Cypress Creek and Sulphur River. The lineaments are generally oriented oblique to the overall structural trend. However, in aggregate, the lineaments form a nearly continuous band that coincides with the overall strike of Talco Fault Zone, especially along the Delta-Hopkins county line. Individual faults bear much the same relation to the fault zone as a whole. The Mexia Fault Zone is suggested in a similar manner by oblique lineaments and lineament zones in Navarro and Limestone Counties. A group of isolated geothermal gradient highs and isograd deflections follows both fault zones where they correspond to the edges of the East Texas Basin. Thus, gradient anomalies also coincide with the major lineament anomalies.

The highest gradient values in the area (2.5°F/100 ft of depth) occur within the northern part of the Balcones Fault Zone; these anomalies may result from heat convection via ground-water circulation from depth along faults and fractures. Relatively few surface faults of the Balcones system have been mapped in the northern part of the Central Texas region (fig. 31), although the number is probably higher than is now known, as evidenced by the concentration of lineaments along the extension of the Balcones Fault Zone. Lineament zones and area boundaries are correlative with the fault system as a whole and with many of the individual faults. The Balcones faults appear to terminate to the north at a point coincident with a minor transverse (approximately perpendicular to the regional strike) lineament zone and lineament area boundary in central Ellis County (approximately 50 km or 31 mi south of Dallas).

Major transverse lineament zones are present at several points along the Balcones and Luling-Mexia-Talco Fault Zones. With perhaps few exceptions they appear to coincide with structural features such as platforms, anticlines, or synclines previously known mainly from subsurface data. Most of these features cross the regional fault zones, as do the transverse lineament zones. The Belton High - Moffatt Mound trend (Cleaves, 1972; and Amsbury and others, 1977) in northern Bell County is an example of a structure of this type. The Mound is a northwesterly trending area of "anomalous thickness variations and rapid facies changes" (Amsbury and others, 1977, p. 4) in the Edwards Formation. The Edwards abruptly trebles in thickness across the Mound and changes laterally from miliolid wackestones and grainstones to oolite pellet grainstones diagnostic of local high-energy shoaling adjacent to a shallow marine shelf sequence. However, the Edwards Formation is exposed over only part of this area, implying that the lineaments with which the structure is coincident represent the surface expressions of subsurface features. Interestingly, a prominent northwestward offset of the general trend of the Balcones Fault Zone near the boundary between McLennan and northern Bell Counties (approximately 40 km or 25 mi south-southwest of Waco) is associated with the transverse lineament zone and lineament area boundary that marks the northern margin of the Belton High.

Another example of a major transverse structure is the Preston Anticline in Fannin and Hunt Counties; a prominent transverse lineament zone appears to be the surface expression of the anticlinal axis, whose location, azimuth, and length are precisely correlative with those of this lineament zone. The axis also appears to form the eastern boundary of a complex pattern of geothermal isograd highs and lows extending southeastward from the Red River and the Arbuckle Uplift of Oklahoma along the Sherman Syncline.

An area of high gradient is coincident with the axis of the Sherman Syncline (or Marietta-Sherman Basin) at a sharp bend in one of the inner thrust faults of the Ouachita overthrust system. Another area of anomalously high geothermal gradients occurs southeast of the syncline along a projection of its axis. This high anomaly extends southward and southeastward along the same azimuth following a projection along the flank of the syncline. The high gradient area terminates to the southeast at the Talco Fault Zone on the margin of the East Texas Basin in an area described by Crosby (1971) as having a prominent positive gravity anomaly. Gradient lows occur along the southwest flank of the Sherman Syncline and are deflected northwestward (up the regional dip) across the trough of the syncline. The syncline is also suggested by the pattern of lineaments, but in a complex manner primarily involving the faulted limbs rather than the axis of the fold (see Bradfield, 1959, fig. 1; and Sellards and Hendricks, 1946).

An elongate lineament pattern (including transverse zones) similar to those that characterize the Preston Anticline and Sherman Syncline is seen in Lamar, Delta, Red River, and Bowie Counties in extreme northeast Texas. The lineament areas here appear to correspond to the "structurally high area" (Flawn and others, 1961, plates 1 and 4) associated with the Broken Bow/Benton Uplift north of the Red River. The western and part of the eastern lobes of a two-lobed geothermal isogradient high in Lamar and Red River Counties are coincident with this structure. The axis of the western lobe also follows an outer thrust fault of the Ouachita overthrust. The eastern lobe extends in a southeasterly direction and is not obviously related to any major structure. However, this gradient lobe does correspond very closely to an intersecting pattern of lineament zones. Throughout the region, isolated high and low gradient anomalies are almost invariably found at concentrations of intersecting lineament zones.

Concentrations of long, intersecting lineament zones also coincide with alignments of salt domes, particularly those in the southwestern part of the East Texas Basin in Henderson, Anderson, Smith, and Freestone Counties (Anderson and others, 1973, fig. 1). The 1.5-degree geothermal gradient contours also seem to be deflected by this group of domes and to roughly outline it.

Nearby, in Limestone and western Freestone Counties, a cluster of isolated gradient high and low anomalies traces the southwestern closure of the East

Texas Basin, whereas a less regular pattern of isograds is seen elsewhere in the basin. Basins throughout the region exhibit the same general tendency to be flanked by isolated geothermal gradient anomalies (both high and low) but to enclose broad, undistinguished gradient trends in their interiors. Another example of this tendency is the narrow, featureless, roughly north-south gradient high that crosses the Fort Worth Basin. This isograd pattern extends northward from the Balcones Fault Zone in southern Hill County to the Muenster Arch and from there northwestward along the axis of the arch.

The Muenster Arch is one of several uplifts in the region involving Precambrian to Late Paleozoic rocks. In Montague, Cooke, and Denton Counties, it is well defined by both isolated and extended, northwest-trending high geothermal gradient anomalies. The structure also corresponds to an elongate, northwest-trending lineament area. In fact, a fault that actually forms the western boundary of the arch in southwest Cooke and northwest Denton Counties appears in detailed comparison to precisely coincide with a lineament zone (Bradfield, 1959, p. 56, 57, 62, 62; and Flawn and others, 1961, p. 142-143, plate 2).

The Waco Uplift in Falls, McLennan, Hill, Limestone, and Navarro Counties is bounded on the west by a Ouachita thrust fault in the Paleozoic subcrop just east of Waco (Nicholas and Rozendal, 1975, p. 193, 212). The eastern limit of this structure coincides with a lineament zone and a boundary of a lineament area. This coincidence occurs from the point where the lineament zone intersects the thrust fault at the southern end of the uplift to the point of near intersection of the thrust and lineament zone at the northern end of the uplift. The southern end of this uplift also coincides with a transverse, southeast-trending lineament zone.

Transverse lineament zones exhibit a similar pattern of correlation with the Cavern, San Saba, and Lampasas "Ridges" (uplifts?) seen on structural maps and extending northeastward from the Llano Uplift into Comanche, Hamilton, and Coryell Counties, Texas (Belforte, 1971, p. 6, 27-36). The set of nearly parallel transverse lineament zones that trend southeastward of Waco is bounded laterally (to the southwest) by the distal ends of the San Saba and Lampasas Ridges in Hamilton and Coryell Counties, and appears to terminate to the northwest at the longer Cavern Ridge in Comanche County. These lineament zones also mark the approximate southern boundary of the Fort Worth Basin.

Southern Part of Region

The southern part of the Central Texas region as we define it (figs. 32, 35, and 37) extends southward and southwestward from 31 degrees north latitude in Burnet, Bell, Falls, Milam, and Robertson Counties to the Rio Grande on the southwest, and to Dimmit, La Salle, and McMullen Counties on the south. This area covers the southern half of the Ouachita structural belt and part of the Maverick Basin. As in the northern part of the region, we found several instances of apparent correlations among geothermal isograd patterns and major structural features, lineaments, lineament zones, and lineament areas.

The extensive Balcones and Luling Fault Zones are demonstrably correlative with lineament patterns, as are individual faults. The complexity of these fault zones in the southern part of the region is seen in the highly fragmented appearance of the lineament areas, although coincidence of the fault zone boundaries and lineament areas is imperfect. Lineament patterns suggest the existence of many more faults in the region than are presently recognized.

The areal distribution of geothermal gradient values also generally aligns with the trends of the Balcones and Luling Fault Zones, across which there are marked deflections of the isograds at several points. Isolated high and low gradient areas are distributed between the fault zones, and fall partly within or at the inner margin of the Luling Fault Zone. However, the highest gradient values (in excess of 2.5°F/100 ft of depth) in the southern part of the region are found in the Balcones Fault Zone in Travis and Williamson Counties; other anomalies approximately trace the basinward thrust fault of the Ouachita trend in several counties. Two small low-gradient anomalies are roughly coincident with the inner (landward) thrust fault in Bandera and Kerr Counties, but these two areas of low geothermal gradient may be related to recharge or other hydrologic effects in the Lower Cretaceous carbonate terrane south of the Llano Uplift.

The Balcones and Luling Fault Zones cross the most extensive platform in the Central Texas region, the San Marcos Arch. Both the arch itself and presumed flank areas to the northeast and southwest are well expressed as lineament zones and areas, particularly by the long transverse zones. Transverse zones mark the axis and margins of the arch, and both the density and orientation of other lineament zones vary sharply at these breaks.

Deflections of the geothermal gradient contours coincide with the San Marcos Arch. The northwestward offset of the 1.5 degree isograd near the northern boundary of Bexar County coincides with the southwestern flank of the arch. Isolated high gradient areas are concentrated across and along the structure, and the 1.5, 2.0, and 2.5° isograds are offset or terminate along its northern boundary at the edge of the Round Rock Syncline. Identical offsets occur at the northern edge of the syncline. These offsets and terminations also coincide with the positions of transverse lineament zones.

The Chittim Anticline along the west side of the Maverick Basin coincides with a transverse lineament zone having precisely the same azimuth and location as the anticlinal axis. Even the slightly asymmetric flanks of the structure (as shown by Sellards and Hendricks, 1946) are expressed by the configuration of lineaments. A prominent northwestward deflection of the 1.5°F/100 ft isograd in Maverick County along the Rio Grande may also be related to the Chittim Anticline.

The margin of the Maverick Basin is correlative with lineament patterns only on its east side. The lack of coincidence elsewhere may be due to our oversimplified representation of the basin margin, when compared with that of Loucks (1977, especially fig. 3); however, the quality of the Landsat image (scene number 25) covering this area is comparatively low, a factor that is probably equally significant (see Appendix F). The extent of the Kerr Basin is more compatible with the lineament areas as shown (fig. 35).

Another small anticline, the Culebra Structure occurs in the San Antonio vicinity, and it is expressed as a lineament zone although the type of expression is quite different from that seen elsewhere. The Culebra Structure is a small, southwest-plunging anticline (Sellards, 1934, p. 55; and Sellards and Hendricks, 1946) that coincides with a circular lineament zone along the Bexar-Medina county line (fig. 35; see also Appendix E, scene number 30). The axis of this structure and faults associated with it coincide precisely with part of the subsurface Ouachita thrust fault as mapped in these counties by Flawn and others (1961, plate 2); according to their interpretations, a small, southwestward bend in the thrust fault coincides with the edge of the circular lineament zone.

Two large uplifts in the area (both of which are flanked by platforms or anticlines) are at least reasonably coincident with lineament zones and areas. The Llano Uplift as shown in figure 30 includes the outcrop area of Precambrian and Paleozoic rock units as well as the approximate subsurface extent of the uplift. Lineament zones coincide with the Paleozoic and Precambrian outcrop areas and not with the uplift's subsurface extent; this is most apparent when larger scale maps are used for this comparison. The Devils River Uplift in the southwestern part of the region is also shown in figure 30 (after Flawn and others, 1961, fig. 2); however, this rendering of the uplift corresponds in no more than a general way to lineament area boundaries (fig. 35).

The thrust faults of the Ouachita structural belt and the updip limit of the Jurassic subcrop are two major tectonic breaks that extend across Central Texas, into both the southern and northern parts of the region as we divide it. The thrust faults are only generally correlative with the pattern of lineament areas; their comparison with the lineament zones (figs. 34 and 35) increases the incidence of correlation although complete coincidence is neither evident nor expected. This is because there are uncertainties in the location of the thrust fault trend where deep well control is insufficient for detailed mapping (note the dash symbols in plate 2 of Flawn and others, 1961).

Correlation of lineaments with the updip limit of the Jurassic subcrop is even less evident; yet this feature marks the approximate gulfward edge of the Ouachita trend. This subcrop limit defines a locus of initial infilling of the ancestral Gulf of Mexico basin. This, in turn, was controlled by the structural discontinuity at the eastern of the Ouachita trend. This discontinuous geometrical relation between Ouachita "basement" and Jurassic subcrop is seen in the coincidence of the subcrop limit with the northern and northeastern margins of the Maverick Basin and the eastern flank of the Chittim Anticline. This pinch-out also coincides with the Mexia and Talco Fault Zones and thus with the western and northern margins of the East Texas Basin. Each of the major platforms, anticlines, or synclines that approach or cross the regional fault zones (and are expressed as long, transverse lineaments) appears to terminate at the pinch-out line.

Lineament-Based Exploration

Our comparisons of lineaments, structures, and geothermal gradients disclose numerous examples of evident correlation, thereby demonstrating that even subsurface structures may have discernible, albeit subtle, expression as lineaments on regional-scale imagery. From a synthesis of our observations we have learned to recognize structures by their lineament patterns, and from structural affinities, we can tentatively delineate areas having potential geothermal resources.

We have noted certain geographic associations, with probable genetic implications, among the prominent structures of the Central Texas region. Many of the major platforms, anticlines, and synclines lie immediately basinward from major uplifts, and probably result from basement "salients," related to the foundered Ouachita belt, since these same large transverse folds extend across the principal fault zones. Except for the Sabine Uplift, the pre-Cretaceous history of which is enigmatic (Sellards, 1934, p. 45; and King, 1975, p. 230), major uplifts flanking the buried Ouachita trend involve Precambrian to Late Paleozoic rocks. These uplifts (but not the Sabine) are found to the north and west of the thrust belt. Deep depositional basins, long filled, separate the major uplifts on the craton side of the Ouachita belt, while similar basins to the south and east separate the anticlines, platforms, and shallow synclines that surround the uplifts. Recognition of these associations facilitates structural interpretation based on analysis of lineaments.

Structural Interpretation of Lineament Patterns

Despite the frequency of correlation with structures, each lineament map was initially seen as a nearly undecipherable montage. We recognized instances of probable affinity when lineaments and structures were geographically convergent, but we were not able to confidently predict structural relations of lineaments in other areas, or to resolve apparent conflicts with our structural/ tectonic data base. Gradually, however, we began to qualitatively characterize the lineaments in terms of their length, intersection angles (perpendicular, oblique, subparallel, parallel), and relative densities. This approach has vided a means of grouping the lineaments on the basis of similar characteristics. We note recurring patterns of association among the lineaments, both individually and in combination as lineament zones and areas. Moreover, each type of association appears to be correlative with a particular kind of structure. If this conclusion is true, our method of lineament analysis could prove useful for exploration for any resource whose distribution reflects structural control. Specifically, positive structures have long been sought by geologists exploring for oil and gas. This is because of the basinal hydrodynamics causing upwelling of fluids that have been "prepared" at requisite depths (temperatures), and which then migrate updip to a suitable trap. Similar factors generally act on hydrothermal fluids, and this has possible bearing on metalliferous deposits and geothermal resources.

We initially classified the lineament patterns on a morphometric basis as described, without resorting to genetic interpretations. We then determined whether the resulting classes were consistently correlative with structures throughout the region. If the correlation was consistent a class became a "model" (table 15) by which we could extend our interpretations. Each of these lineament models corresponds to one or more particular kinds of structures, and to characteristic geothermal gradient patterns (table 16). Table 17 summarizes the relations among the structures, isogradient trends, and the lineament models that we consider structurally diagnostic, as exemplified by the major structures of the Central Texas region.

Relation to Geothermal Aquifers

Aquifer properties are often directly related to structurally controlled deposition, local fracturing, affording enhanced permeability and fault compartmentalization of an aquifer by faulting. Warm ground-water resources are related to structures and are best understood in their structural context. For example, at Hot Springs, Arkansas, steeply dipping and highly fractured novaculite beds afford avenues for deep circulation (and thus heating) of meteoric waters. Lineament analysis provides a means of studying the structural features that control warm water resources and can, therefore, be applied to geothermal exploration.

However, localized resource assessment and exploration requires a more detailed investigation than does a regional overview. Lineament patterns and structural features that are precisely correlative when mapped at a scale of 1:250,000 (approximately 4 mi per inch or 2.6 km per cm) may be widely disjunct when examined at a larger scale (that is, with finer resolution). Although site-specific exploration requires the same types of comparisons and

Table 15. Lineament Models

(1)	High-density, short to moderate length, parallel to subparallel lineaments and lineament zones, composing rectangular lineament areas whose long axes are approximately parallel to the regional strike.
(2)	Low-density, long, perpendicular and parallel lineaments and lineament zones, composing square to rectangular lineament areas grouped end to end perpendicular to the regional strike.
(3)	Variable-density, short to moderate length, perpendicular and parallel lineament and lineament zones, composing square to rectangular lineament areas (generally with well-defined perimeters).
(4)	Very low density, long, oblique lineaments and lineament zones (generally well-defined) composing irregularly shaped lineament areas.

Table 16. Geothermal Gradient Contour Patterns

(1)	Closely-spaced isograds composing elongate highs parallel to the regional strike.
(2)	Sharply to slightly offset isograds (usually two or more, roughly parallel) generally following the local strike.
(3)	Comparatively small isolated highs and/or lows generally following the local strike or a structural axis.
(4)	Extended, virtually featureless isograds (one or two together) generally following the local strike.

Table 17. Comparison of structural/tectonic zones to lineament patterns and geothermal gradient features.

Structure	Lineament Model	Isogradient Pattern	Example
Zone of normal faults	1	1	Balcones and Luling-Mexia-Talco Fault Zones
Platform, anti-cline, or syn-cline	2	2 (sharp) along flanks, axis; 3	San Marcos Platform, Chittim Anticline, Sherman Syncline
Uplift	3	2 (sharp) along flanks, axis; 3	Muenster Arch, Devils River Uplift
Basin	4	3 (margins); 4	Forth Worth and East Texas Basins
Salt domes (several)	4	2 (slight)	Domes in western Anderson and southern Henderson Counties

interpretations needed for regional studies, promising findings at the regional scale must be carefully reevaluated to be applicable in a local context. The need for precise correlation at the local level necessitates greater attention to discrete surface and subsurface features than is generally required for regional studies.

Brushy Creek Lineament--An Exploration Model

We tested the applicability of lineament analysis for geothermal resource exploration in an area known to have produced warm ground waters in Central Texas. The area chosen includes parts of Bastrop, Bell, Lee, Milam, Travis, and Williamson Counties, and small parts of several adjacent counties (fig. 38). This is the area of overlap between our Landsat image of scene number 29 (see Appendix F) and the Austin AMS topographic quadrangle map at 1:250,000-scale. The resulting area is an irregular polygon.

We mapped lineaments across the entire image covering this polygon (see Appendix E), and delineated the particular area of interest. We then compared the enclosed lineament pattern with several independently prepared maps depicting relevant themes: linear drainage reaches and other linear topographic features (or alignments of features) (as shown on the topographic map); linear stratigraphic contacts (ostensibly unfaulted) and all surface faults (after a geologic map of the area by Barnes, 1974); two buried thrust faults through the area (after Flawn and others, 1961, plate 1); and normal faults on various subsurface horizons (after Woodruff and McBride, 1979). In addition to each of these themes, we plotted the distribution of Cretaceous volcanic centers ("igneous plugs") in the area, including those known only from unpublished drilling records as well as those seen at the surface or reported in the literature (fig. 38). Many of the buried volcanoes are sites of oil production, with

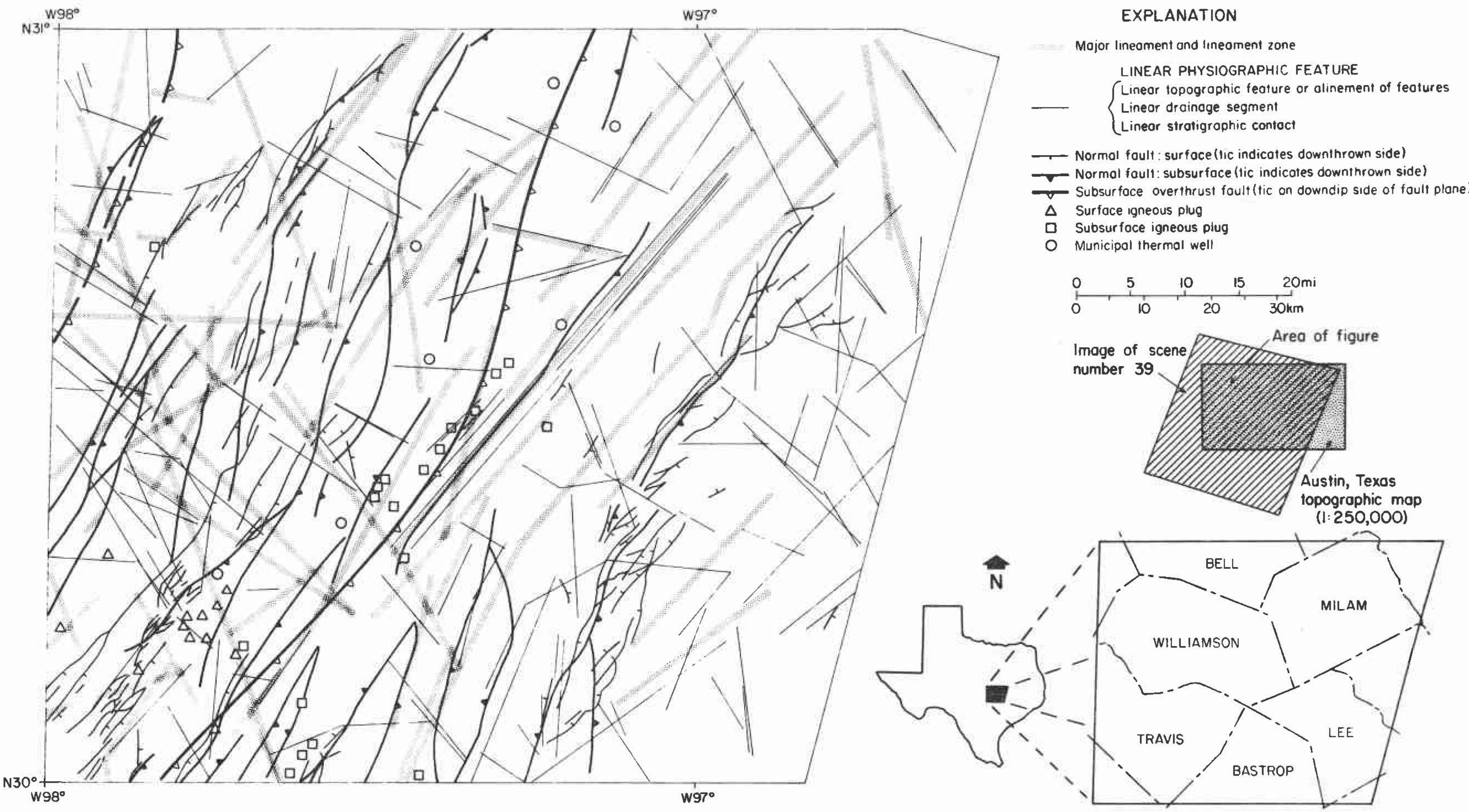


Figure 38. Surface and subsurface geological features associated with the Brushy Creek Lineaments.

altered tuff and ash deposits and associated "beach rock" facies acting as reservoirs. The locations of municipal water supply wells (whether abandoned or operational) that have yielded warm waters (90°F, 32°C or greater) are also shown. Exposed geologic units in the area include Comanchean and Gulfian Cretaceous limestones and marls (northwestern half of the map area), Lower Tertiary marls and clastic rocks (southeastern half of the area), and Upper Quaternary terrace units and alluvium (narrow bands extending generally easterly across the area).

Figure 38 shows complex (and imperfect) correlations between lineaments and other themes; the lack of coincidence of various features may be in part due to the difficulty in registering independently prepared thematic maps. Especially noteworthy is the cluster of northeast-southwest lines near the center of the figure, extending northeastward from the bend in the outer (easternmost) thrust fault. Correlative linear features represented by this cluster include a drainage reach (Brushy Creek), a sharp topographic break (northwest-facing cuesta), a stratigraphic contact (Eocene Midway-Eocene Wilcox Groups, only locally mapped as a fault contact), and normal faults mapped on several subsurface horizons. Several buried volcanic centers and two thermal wells also lie along and near the trend. We have chosen to call the three closely spaced, parallel lineaments that coincide with this trend the Brushy Creek Lineaments (Thompson and others, 1981).

In the vicinity of the Brushy Creek Lineaments, a geothermal explorationist seeking optimal drilling sites would first note the presence of thermal wells, which establishes the existence of warm water resources in the area. The fact that the wells lie within a northeast-southwest band across the middle of the figure area generally supports the concept of regional structural-stratigraphic controls on the resource since this is the regional strike direction and the band generally corresponds to the Gulfian Cretaceous terrane. Within this band, however, the distribution of thermal wells is seemingly random; but because these are municipal wells their locations are controlled by other factors affecting community siting in the area in addition to the actual distribution of the resource.

Other evidence of structural control includes the convergence within this lineament zone of linear stratigraphic contacts (between lithologically dissimilar units), subsurface normal faults, and buried volcanic centers aligned along the general extent of the Brushy Creek Lineament. In the absence of contraindications, the explorationist might then justifiably conclude that the exposed units had indeed been faulted. The subsurface faults control the geothermal resource locally, probably by providing a hydrologic barrier or by providing a convection conduit for deep basinal ground waters upward to relatively shallow aquifers.

The explorationist would attempt to maximize the heat content of ground water to be brought into production, but also to minimize drilling depth and attendant costs. Based on the location and depth of nearby producing wells, the choice of a drilling site would be a point near but on the west side of the Brushy Creek Lineament zone. Such a site would permit drilling into the deepest, and in all probability, the warmest part of the aquifer, before crossing the normal fault (east side down) that is coincident with the lineament zone. Both of the thermal wells in the immediate vicinity of the zone are located in this position. Of course, many other factors influence the siting of geothermal wells and our discussion is intended to illustrate only part of the decision process that would actually be required. One other important consideration, for example, is that of ground-water quality, since high salinity and other problems may reduce the value of an otherwise usable resource.

Other Methods of Exploration

Lineaments have been used in other ways for resource exploration. Wertz (1976), for example, emphasized the importance of lineament intersections in mineral exploration. He described his concept of an intricate relationship between lineaments perceived in images of different scales and the migration pathways for mineralizing fluids. Trainer (1967) defined an "index of (lineament) abundance" and "intersection frequency" values which could be contoured and used to infer "near-surface fracture porosity of the rock" (p. C184) cropping out in his study area. A similar but less formal approach was earlier described by Lattman and Parizek (1964) who felt that "fracture traces" (lineaments) reflect fracture concentrations in bedrock and are useful as a prospecting guide in favorable areas of relatively high permeability. Trexler and others (1978) demonstrated geothermal resources and the intersection or disruption of major lineament trends in certain areas of Nevada having known hot springs. Each of these techniques might provide useful data on which to base or support an exploration program. Our own investigations may, in the future, incorporate some aspects of these procedures.

Summary of Lineament-Based Exploration

Individual lineaments often coincide with discrete structures such as faults or fold axes and with structurally controlled facies boundaries. More extensive regional structural trends are generally correlative with entire families of lineaments or with breaks in the predominant lineament pattern.

Although we might expect lineaments to correspond to exposed structural elements, we also find many instances of convergence of lineaments with subsurface features that are not known to have conventional surface expression. Lineaments that are perceived in remotely sensed images are necessarily related to surface features capable of creating variations in surface reflectance, hue, or relief, even when these features are not recognized. The demonstrated correlation of lineaments with subsurface features suggests the existence of poorly understood mechanisms for propagating an inherited structural grain through superjacent strata. By this hypothesis, empirical evaluations of structural patterns can be considered an acceptable basis for resource assessment and exploration.

ACKNOWLEDGMENTS

This report represents an attempt to obtain meaningful information from a vast population of raw data. Potentially, the data population comprises all petroleum wells and all water wells in Texas, a number probably exceeding 500,000. In fact, only part of these wells provide information for our purposes, that is, for the assessment of geothermal potential throughout the state.

This report was prepared for the U.S. Department of Energy, Division of Geothermal Energy, under Contract No. DE-AS07-79ID12057. This report has resulted from a team effort among workers assigned to the project. It also entailed close coordination with other sectors within the Bureau of Economic Geology. Foremost in the support of this research have been the computer services staff under the direction of Mike Roberts. The formidable task of transforming the massive report and appendices into a presentable product has fallen on the cartographic, editorial, and word processing staffs, under the direction of J. W. Macon and D. F. Scranton, for cartography; S. V. Doenges, for editing;

and L. C. Harrell, for word processing. I especially thank A. R. Masterson and M. C. Pemberton for reading and editing the entire report.

I also acknowledge the ongoing cooperation of the Texas Department of Water Resources for providing access to their various data files and for base maps. The Texas Department of Highways and Public Transportation has also provided maps that we used in locating water wells. The U.S. Geological Survey provided access to their data files; especially helpful in locating wells and springs issuing from the Edwards Limestone was Ted Small of the San Antonio USGS office. We also thank the many people--private landowners, municipal employees, and corporate representatives--who provided access to wells and springs for our collection of water-temperature data.

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