

Fisher

Sources of Shallow Saline Ground Water in Concho,
Runnels, and Tom Green Counties

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1. INTRODUCTION

Soil and ground-water salinization causing vegetative-kill areas and water-well contamination are major concerns of farmers in Texas and in many other states in the U.S. In many parts of the country a combination of natural and agricultural factors is solely responsible for salinization. In West Texas pollution hazards associated with the exploration and production of oil further complicate the problem of determining the sources of soil and ground-water contamination.

This study was restricted to the area of Concho, Runnels, and Tom Green Counties in west-central Texas (fig. 1), because (1) soil and ground-water salinization are widespread in these counties and (2) natural and manmade salinization sources may be active.

The area is characterized by hilly terrain in southern, western, and northern Tom Green County where remnants of the Edwards Plateau rise to a surface elevation of approximately 2,500 ft above sea level. Plains and river valleys cover most of the remaining area and lowest surface elevations (approximately 1,500 ft) occur in river valleys to the east. The Colorado River in Runnels County, the Concho Rivers in Tom Green and Concho Counties, and several surface-water reservoirs just west of San Angelo are the major drainage systems (fig. 1).

The average annual rainfall in the area is approximately 21 inches, which is nearly one third of the net lake evaporation.

1.1 PURPOSE AND SCOPE

Many residents of Concho, Runnels, and Tom Green Counties have blamed oil-field related activities for widespread contamination by pointing out that (a) water was of better quality before drilling for oil began and (b) locally, formerly productive land has become so salty that plant growth is limited or has ceased. Documented brine pollution, the number of oil wells, core holes, shot holes, and injection wells, the use of surface pits for brine disposal until the late 1960's, and the discoveries of brine flow from abandoned holes and leaky injection wells demonstrate the potential hazards of oil-field related pollution in the area. In addition, the area is underlain by an overpressured brine aquifer that stratigraphically overlies oil-producing horizons. Each hole drilled for oil penetrates this artesian aquifer and thus creates a potential, artificial pathway for brine movement into shallow, fresh ground water or to land surface.

Many investigators (for example, Reed, 1962; Seaman, 1969) have distinguished between oil-field pollution versus widespread pollution caused by natural conditions and by agricultural and water-well-drilling techniques. Deepening of dried-out water wells into saline parts of aquifers during severe droughts in the 1950's (many of these wells were not plugged) is one possible source of ground-water pollution. Attempts to reduce surface runoff by land terracing and unusual heavy rainfalls in the 1960's resulted in a shallow ground-water table, which in turn leads to seepage of ground water, waterlogging of areas, and subsequent salinization of soil due to evaporation. Salts that precipitate in the soil due to evaporation from the shallow water table (a) prohibit growth of non-salt-resistant plants and (b) are dissolved and flushed into ground water

and surface water after rainfall, thus spreading the pollution hazard to other areas. These processes are known to occur in the absence of any oil field activity or overpressured brine aquifers, as evidenced by hundreds of thousands of acres affected throughout the Great Plains from Texas to Montana (Miller and others, 1981).

This report is based on a short-term pilot study performed from January 1 through April 30, 1985. The study was designed to investigate whether existing data and techniques allow differentiation of salt-water sources in Tom Green, Runnels, and Concho Counties. Several methods were to be tested for their effectiveness in characterizing possible salinization sources and in detecting mixed waters. These included an inventory of water wells, construction of iso-contour maps of chemical constituents, potentiometric-surface maps, maps of base of fresh water, and plots of chemical and isotopic constituents. Water samples from water-supply wells, oil wells, and injection wells were obtained for chemical and isotopic analyses designed to establish the chemical characteristics of ground water in the area. Specifically, the effectiveness of using ratios of certain chemical constituents, such as Na/Cl, Br/Cl, and I/Cl, to determine salt-water sources, as was done in other contamination studies (for example, Richter, 1983), was to be tested. If possible, other tracers of pollution, such as stable isotopes and other minor chemical constituents, were to be identified. However, detection limits of trace and minor constituents and their relative low concentrations made it uncertain whether such tracers could be detected.

1.2 GEOLOGIC SETTING

The area is underlain by sediments of Permian to Recent age (table 1). Cretaceous rocks in southern, western, and northern Tom Green County, in southern Concho County, and in outliers in northeastern Runnels County form topographic highs bordering the area (fig. 2). Pleistocene and Recent alluvial deposits of variable thickness directly overlie Permian strata in central and eastern Tom Green County and in parts of Runnels and Concho Counties. Permian strata crop out as north-south trending belts in central Tom Green County and in northern Concho and southern Runnels County (fig. 2). These Permian strata, which dip to the west and northwest at approximately 50 ft per mi, consist mainly of red beds, bedded limestones, shales, gypsum beds, and sandstones (Willis, 1954).

Thousands of oil-related wells and holes have been drilled in the area since oil exploration started at the end of the last century. Most oil production is from Pennsylvanian strata at depths below 3,000 ft in the western and below 2,000 ft in the eastern part of the area. There is some shallow production from the Permian San Angelo Formation at approximately 1,000 ft below land surface in southwestern Tom Green County. Udden and Phillips (1911) reported on shallow oil encountered in wells within a depth range of less than 50 to 300 ft in western Tom Green County.

1.3 HYDROGEOLOGIC SETTING

No continuous major fresh-water aquifers are provided by shallow formations in the area. Although some fresh water is found in outcrop areas of Permian strata, principal aquifer units are Cretaceous limestones and alluvial deposits of Quaternary age. Locally, limestone units in Permian strata, notably the Bullwagon Dolomite in eastern Tom Green County (fig. 2), are of importance as fresh-water sources.

The occurrence of ground water in these units generally is very erratic both in quality and in quantity. Many dry holes have been drilled in the immediate vicinity of high-capacity water wells. At one location in northern Concho County a dry hole was drilled only 20 inches from a flowing well (both 100 ft deep), an indication that the ground water flows through solution channels or fractures in the aquifer.

Potable water in Permian strata is generally found only in outcrop areas whereas saline water is encountered downdip. Highly mineralized water under artesian pressure and at shallow depths occurs in the San Angelo and Blaine Formations of west-central Tom Green County (Willis, 1954). "Very salty water" associated with "some oil at depths varying from less than 50 to 300 ft below land surface" in western Tom Green County was mentioned by Udden and Phillips (1911). The presence of salt water and oil so close to the land surface, reported as early as 80 years ago, suggests that natural discharge of deep-basin brine is one source of brine movement into the shallow subsurface of the area.

The Coleman Junction Limestone aquifer (table 1) underlies the area at

depths between 3,000 ft in the southwest to approximately 800 ft in the east. This aquifer contains salt water that is approximately twice as saline as ocean water and that has the potential to flow to the land surface via natural or artificial pathways. Measurements at leaky injection wells and from drill-stem tests indicate pressures high enough to lift brine up to 700 ft above land surface if a subsurface pathway were provided (table 2). Although existing pressure data of the Coleman Junction are too sparse to allow mapping of the potentiometric surface of the aquifer, it is possible to infer from the pressures available, from driller's logs, and from the known number of flowing wells in the area that the potential of upward flow of brine exists in the Coleman Junction aquifer throughout the area.

Ground-water flow in the shallow aquifer units is governed by topography, so that flow is toward the North Concho River in northern Tom Green County, toward the northeast and north in southern Tom Green County, to the east in southern Runnels County, and to the south in northern Runnels County (Jones, 1972; Lee, in preparation). Although water levels in many wells in eastern Tom Green County show an overall increase during the last 30 years, water levels in the county are mostly 50 or more feet below land surface. In southern Runnels County, in contrast, water levels approach land surface in many wells, causing seepage at topographically low areas. Detailed areal mapping of seep-area water levels, which would help establish the relationship between changes in water-table elevation and seepage-area growth, proved impracticable due to the lack of data. Only extensive monitoring on a local basis can provide this type of information.

The base of fresh water is defined by local water-well drillers as the first occurrence of blue shale, which normally occurs between 100 and 200 ft below land surface. Driller's logs did not allow the mapping of the base of fresh water because the occurrence of salt water is documented only on a few logs. The latter is consistent with reports of local residents that their water was of potable quality when wells were drilled. Maps obtained from the San Angelo District Office of the Railroad Commission of Texas (fig. 3) show the required depths of surface casing for protection of fresh ground water in Tom Green, Concho, and Runnels Counties. These values are determined by Texas Department of Water Resources on the basis of structure maps and the depths of existing water-supply wells in the area. The values should closely approximate the fresh-water base because wells generally bottom in the blue shale and because the deepest well of the area should set the minimum depth of required surface casing. Therefore, as indicated by the map (fig. 3), the fresh-water base has a west to east trend ranging from 400 ft below land surface in the west to 100 ft in the east.

Marshall (1976) reported that probably hundreds of water wells were drilled up to 500 ft deep west of the city of San Angelo during the drought in the 1950's, and, although these wells encountered highly mineralized water, many of them were not plugged. These water wells create a pollution hazard.

2. GEOCHEMISTRY

2.1 METHODOLOGY AND RESULTS

The major sources of chemical data used in this report are the Texas Natural Resources Information System (TNRIS) and reports of ground-water quality in Tom Green County (Work Projects Administration, 1941; Willis, 1954; Lee, in preparation). From those a good data base was established for Tom Green County, including chemical analyses of ground water from 1937 through 1983. Although chloride and sulfate determinations of some water samples from Runnels County were done in 1958, the only comprehensive sampling program for the entire county was completed in 1970. Other ground-water studies in Runnels County are primarily concerned with local problems. Little data are available for the area of interest in Concho County; therefore, discussion of water chemistry is restricted to Tom Green and Runnels Counties.

In addition to data obtained from published and unpublished sources 46 water samples were taken during this study, 39 of which represent shallow water wells, and seven of which are brines from oil-field related wells and holes (table 3; fig. 4). Five of the 46 samples were collected from shallow holes drilled in seep areas. Three of these were from water wells and two from shallow holes drilled for this investigation.

To establish the characteristics of water types, sampling included (1) oil-field brines, (2) Coleman Junction brine, (3) allegedly polluted wells, (4) stock wells, (5) house wells, and (6) seep wells. Analyses for major and minor chemical constituents and for stable isotopes of oxygen and hydrogen were performed by the Bureau's Mineral Studies Laboratory and by

Coastal Science Laboratory, Austin, respectively.

Results of ^{18}O and ^2H analyses commonly permit differentiation among waters recharged to an aquifer system at different geographical locations. A difference in isotopic composition between fresh, local ground water and subsurface brines was therefore expected. Mixing of these two end members would be documented by an intermediate isotopic composition, which, in turn, could serve as a basis for determining contamination by brine.

Chemical analyses were done to establish concentration ranges of major and especially of minor chemical constituents in the water samples. Mixing of waters (for example, good-quality water with brines or seep waters) can be determined by changes in concentrations as well as ionic ratios. Therefore, the characteristics of ground water are reported as ratios and as concentrations. Concentrations are expressed as milligrams per liter (mg/L) in tables 3 through 6, and as millimoles per liter (mmol/L) in plots of chemical constituents. To convert these the following relation is used:

$$\text{mmol/L} = (\text{mg/L}) / \text{formula weight}$$

Formula weights of constituents of interest are:

	Ca	Mg	Na	HCO	SO	Cl
formula weight	40.08	24.31	22.99	61.02	96.06	35.45

Two graphical methods are used to illustrate the characteristics of ground water. The percentages of major cations ($\text{Ca}^{[+2]}$, $\text{Mg}^{[+2]}$, and $\text{Na}^{[+1]}$) and of major anions ($\text{Cl}^{[-1]}$, $\text{SO}_4^{[-2]}$, and $\text{HCO}_3^{[-1]}$) are presented in Piper diagrams (Piper, 1944). Two chemically different waters plot at

different percentages in the cation and anion fields, regardless of concentration ranges. Mixtures of these waters plot on a line connecting these end members. Evaporation of water, in contrast, does not change the position of water on a Piper diagram because the ratios between chemical constituents remain constant during evaporation.

The concentrations and ratios of individual chemical constituents are illustrated in plots of Na/Cl, Ca/Cl, Mg/Cl, (Ca+Mg)/SO₄, SO₄/Cl, and Br/Cl. Two groups of non-related waters cluster in different parts of the plot, whereas related samples approach a straight line.

2.2 DISCUSSION

The methodology used in this study has been used successfully in a salt-water study in North-Central Texas (Richter, 1983). In that study the differences in Na/Cl, Br/Cl, I/Cl, Mg/Cl and (Ca+Mg)/SO₄ ratios proved indicative for two salt-water types. (1) Salt water derived from dissolution of halite relatively close to land surface is characterized by Na/Cl and (Ca+Mg)/SO₄ molar ratios of approximately 1 and by low Mg/Cl, I/Cl, and Br/Cl ratios. (2) Salt water derived from deep-basin brines (for example, oil-field brines) is characterized by Na/Cl ratios of less than 1, (Ca+Mg)/SO₄ ratios of greater than 1, and high Mg/Cl, Br/Cl, and I/Cl ratios. In addition, stable isotopes of hydrogen and oxygen (deuterium and oxygen-18) characterized halite-dissolution brine as local, meteoric ground water. Deep-basin brines proved to be of non-local origin.

Two possible sources of saline water exist in Tom Green, Runnels, and Concho Counties: deep-basin brines and salt seeps. A goal of the study was to obtain a clear definition of deep-basin brine characteristics, similar

to those in the study mentioned above, through the use of isotopes and ratios of chemical constituents. Another goal was to see if distinct concentration ranges of Na, Ca, Mg, Br, I, SO_4 , and Cl could be determined for seeps also. It was not known, however, if and how concentration ranges differ in those two possible sources and if the concentration of dissolved solids in allegedly polluted waters (polluted either by brines or seepage water) is high enough to exceed detection limits for minor chemical constituents.

Nitrate was chosen as an additional possible tracer of pollution sources. Shallow ground water in the area typically exhibits high concentrations of nitrate due to dissolution of nitrate by water recharging through the soil zone (Kreitler and Jones, 1972). Ground water at or slightly below the land surface in seep areas, therefore, could be elevated in nitrate concentrations. Deep-basin brines, in contrast, normally do not contain appreciable amounts of nitrate.

Stable isotopes of oxygen and hydrogen in brines were expected to show higher values (more positive) than fresh ground water in the area. Evaporation of ground water from a shallow water table results in an isotopic shift toward higher values. Therefore, seep waters too were expected to be isotopically heavier than local fresh water. The magnitude of the shift and the difference between brines and seep water, however, were not known.

Ground-water flow over most of the area is through solution channels, bedding planes, and fractures. These kinds of flow paths commonly are

responsible for very erratic occurrence and erratic quality of ground water. Therefore, water sampling was done in a way that (1) a good coverage of the entire area was achieved, (2) allegedly polluted areas were sampled, and (3) if possible, more than one water sample was obtained within an individual area.

The shallow ground-water table, seepage areas, and high nitrate values in ground water are major agricultural problems in southern Runnels County (Kreitler and Jones, 1972). Evaporation from a shallow water table increases the concentration of mineral deposits and of total dissolved solids in the soil and in the water, respectively. Dissolution of these deposits during and after rainfall and subsequent flushing of the soil lead to increases in dissolved mineral matter in ground and surface water. Total-dissolved solids concentrations of more than 10,000 mg/L in ground water near seeps in Montana were reported by Miller and others (1981). As mentioned above, evaporation and rainfall change the salinity of soil and ground water, thus, the chemistry of seepage water will vary through time in proportion to length and intensity of evaporation and rainfall periods. The samples obtained in southern Runnels County during February 1985, therefore, probably are less saline than seepage water collected during and at the end of summer.

2.3 REGIONAL INVESTIGATIONS

2.3.1 Good-quality ground water

For the purpose of this study, good-quality ground water is defined solely on the basis of a chloride content of less than 250 mg/L, which equals the standard for chloride set for drinking water (U.S. Public Health Service, 1962).

Based on Piper diagrams, two types of water occur in Tom Green County (fig. 5). A Ca-Mg/HCO₃ water, the major water type, occurs predominantly in Cretaceous formations. Another facies type is a Ca-Mg/SO₄ water, the probable result of gypsum and/or anhydrite dissolution in Permian strata. In the cation and anion triangles, trends toward the center of the plots indicate some mixing between the two types. Both trends are also indicated on Piper plots of ground water in Runnels County (fig. 6). However, a more uniform Ca-Mg/Cl-SO₄ water seems to dominate in Runnels County. This is also seen in plots of Na, Ca, SO₄, and (Ca+Mg)/SO₄ versus Cl, which indicate one major trend (with low Ca/Cl, SO₄/Cl, (Ca+Mg)/SO₄ ratios) in Runnels County (fig. 7). In Tom Green County, in contrast, high (Ca+Mg)/SO₄ ratios at low chloride concentrations, and much scatter in other ratios, illustrate a second water type (Cretaceous water) and greater variability (fig. 8).

Six samples collected during this investigation turned out to have chloride concentrations of less than 250 mg/L (table 4). These fit into the general trends of good-quality ground water (figs. 7 and 8). In southwestern Tom Green County nitrate concentration are the lowest (fig. 9). Nitrate values increase toward the northeast, with the highest value

of 155 mg/L in northwest-central Runnels County (fig. 9). Br/Cl weight ratios in these waters range from 33×10^{-4} to 48×10^{-4} (table 4) (fig. 10). Isotopically these waters are not different from other ground water in the area (fig. 11).

2.3.2 Poor-quality ground water

Poor-quality ground water is defined in this study as ground water with chloride concentrations of higher than 250 mg/L, regardless of concentration ranges of other chemical constituents.

Brines

Oil-field brines and Coleman Junction brines typically are of the NaCl type (fig. 12). Molar Na/Cl ratios are close to 1 for chloride concentrations of less than 42,000 mg/L, which is characteristic of brines from the Coleman Junction aquifer (fig. 12). At Cl concentrations higher than 42,000 mg/L, which is typical for Pennsylvanian and deeper aquifers, the molar Na/Cl ratio typically is on the order of 0.75 to 0.85. A brine sample from the San Angelo oil field (sample B-7) in southwestern Tom Green County is relatively low in Cl (Cl=27,200 mg/L) and extremely low in sulfate ($SO_4=9$ mg/L) (table 3). However, this sample may not be representative of original San Angelo brine because of possible mixing with water from secondary recovery operation, which was started in this field in 1969. Nevertheless, minor chemical constituents and most ratios of chemical constituents are similar in most brines (table 3).

Two samples from a well completed in the Coleman Junction aquifer (B-2 and B-3), two samples from shallow, flowing core holes (B-4 and B-6), two

samples from leaky injection wells (B-1 and B-5), and one sample from an oil-producing well (San Angelo Formation, B-7) were collected and analyzed to define the characteristic values of minor constituents and of isotopes (table 3; fig. 4). Minor constituents, except bromide and nitrate, were generally below the detection limit (in brine or in fresh ground water) and, therefore, are not useful as tracers of possible contamination in this study. Thus, NO_3 concentrations and the ratios of Na/Cl , Ca/Cl , Mg/Cl , SO_4/Cl , and Br/Cl emerge as the defining criteria of brine characteristics. Among those, chloride and bromide are generally the best tracers because both are conservative ionic species in ground water. Sodium is not as ideal a tracer because of possible cation exchange between Ca in the water and Na in clays, which causes an increase in Na content without addition of brine.

Values of stable isotopes of oxygen and hydrogen in brines are not significantly different from values found in shallow ground water of the area and, therefore, cannot be used with certainty as tracers of contamination in this study (fig. 11). This isotopic similarity may be caused by injection of shallow ground waters during secondary recovery operations and by contact with the atmosphere or mixing with fresh water in leaky injection wells and core holes.

Seep Areas

Five water samples from three different seepage areas (fig. 13) were collected to establish characteristics of this water type (table 5). Two of the samples were collected from holes drilled during this study. Hole #7 was drilled 5 ft and hole #8 20 ft into seep #1. Both holes filled

rapidly with water up to approximately 15 inches below land surface, which represents a higher head than water in the nearby weakly flowing creek. Sample #6 was obtained from a water well (20 ft deep) approximately 200 yards from the test holes. Sample #11 was collected at a flowing well at seep #3, which, according to the owner, ceases to flow after pumping of irrigation wells uphill to the north has started. Seep #3 is just to the east of seep #2 (fig. 13). Both seeps are characterized by water standing at or slightly beneath land surface, which is approximately 3 ft above the bordering Little Concho River. Well #10 is used by the owner to lower the water table in seep #2. This well had not been pumped for several weeks before the sample was collected.

Sampled seep waters are high in Ca, SO₄, and NO₃ (table 5). Ratios of Ca/Cl, Mg/Cl, SO₄/Cl, and Br/Cl in these waters range from 0.38 to 0.70, from 0.22 to 0.38, from 0.20 to 1.05, and from 33×10^{-4} to 42×10^{-4} , respectively, and therefore, are higher than those of brines underlying the area. Nitrate concentrations in four samples exceed 100 mg/L, which reflects dissolution of nitrate by water in the soil zone.

During evaporation, the ratio of chemical constituents remains constant, that is, on plots of one chemical constituent versus another the line connecting evaporated waters has a slope of 1. Seep samples approach this slope in plots of Ca, Mg, and SO₄ versus Cl (fig. 14), indicating evaporation rather than mixing of different waters as the cause of salinization. The slope of these trends points away from brine values. Evaporation is also indicated in the Br/Cl ratio. The range of Br/Cl ratios in seep waters (33×10^{-4} to 37×10^{-4}) overlaps with the range of

Br/Cl in fresh water (33×10^{-4} to 48×10^{-4}), thus, the ratio is constant for increasing chlorinity (fig. 10).

The isotopic composition of samples #6, #7, #8, and #10 shows these waters to be isotopically heavier than most of the waters sampled during this investigation (fig. 11). This too suggests evaporation from a shallow water table.

Ground water

A. Previously collected data

Two chemical facies define poor-quality ground water in Tom Green County: (1) Ca-Mg/SO₄-Cl water and (2) NaCl water (fig. 15). Mixing between these is indicated in those samples that form a straight line between the different water types. A change in water type through time is not indicated (fig. 15). In Runnels County only one major chemical facies is distinguishable: Ca-Mg/SO₄-Cl water (fig. 16). In the Runnels County plots the cation triangle of good-quality ground water is similar to that of poor-quality ground water (figs. 6 and 16). The anions have shifted toward the SO₄-Cl side of the triangle, but have not become dominated by Cl quite as much as in Tom Green County. Therefore, cation and anion distributions indicate less mixing of NaCl water in Runnels than in Tom Green County. In the latter county the cation and anion triangles of poor-quality ground water differ from those of good-quality ground water, indicating that mixing of different waters governs water chemistry in Tom Green County (figs. 5 and 15).

Plots of chemical constituents [Na/Cl, Ca/Cl, Mg/Cl, and SO₄/Cl] for Tom Green and Runnels County are similar for most chemical constituents (figs. 17 and 18). The scatter in the plots is also fairly widespread, indicating the presence of non-related waters in Tom Green County (fig. 17).

B. Data collected during this investigation

Samples from 33 water wells collected during this study have chloride concentrations in excess of 250 mg/L (table 3). Molar ratios of Na/Cl in these follow the major trends seen in previous plots, with ratios of approximately 1 (fig. 14). This trend includes the seven brine samples collected during this study. Two trends are indicated in plots of Ca, Mg, and SO₄ versus Cl (fig. 14): (1) The trend high in Ca, Mg, and SO₄ is represented mainly by samples collected in Runnels, Concho, and eastern Tom Green County and points away from values typical for brines and toward salinization values. (2) The trend low in Ca, Mg, and SO₄ points toward brine values and is made up of samples mainly derived from the western half of Tom Green County (figs. 14 and 19).

Nitrate concentrations in the sampled waters generally increase from southwest to northeast (fig. 20). Cretaceous waters and samples in the southwestern part of Tom Green County contain the lowest concentrations sampled, whereas concentrations in excess of 100 mg/L were measured in samples from northeastern Tom Green and in southern Runnels County.

Ratios of Br/Cl predominantly fall within and between the ranges of brines and seep waters. Ratios above 30×10^{-4} indicate fresh water or water mixed with seep water, whereas ratios of less than 30×10^{-4} suggest

mixing with brine (fig. 10).

Poor-quality ground water varies over a wide isotopic range (fig. 21). Other than the local influence of water from Lake Nasworthy in southwestern San Angelo (samples #27 through #29), no trends or regularities can be inferred from the analyzed isotopes.

Two water samples from Runnels County (#2 and #4; fig. 14) do not follow the general trend of ground water in that county. These two samples instead follow the trend that is characteristic of ground water from the western half of Tom Green County, which suggests pollution by deep-basin brine rather than by seep salinization.

2.3.3 Iso-chloride maps

Changes in chlorinity through time and space are illustrated in iso-chloride maps for Tom Green (figs. 21 and 22) and Runnels County (fig. 23). These maps were put together from previously available data and are limited in that (1) different wells were used for different time periods and (2) data covering several years of sampling had to be combined to contour a second map for Tom Green County. Therefore, only large-scale variations and generalized interpretations can be considered.

Chloride values in Tom Green County for 1940-41 show that most of the county produces water of relatively low chloride content (fig. 21). This is true especially for areas of Cretaceous outcrop (fig. 2), where chloride concentrations typically are less than 100 mg/L. Chloride values are generally higher (>250 mg/L) in the center and eastern parts of the county, where ground water flows through Permian and Pleistocene strata (fig. 21).

High chloride concentrations were measured in nine wells, suggesting point discharge of salt water. Contours typically are stretched west to east, coinciding with the direction of ground-water flow (Lee, in preparation). This suggests contaminant transport from a point source along the flow paths of ground water. Areal salinization is indicated in central and eastern Tom Green County, where high chloride concentrations are more widespread.

Chloride concentrations for the years 1950, 1969, and 1983 were combined to contour a second map for Tom Green County for comparison (fig. 22). With the exception of a localized increase in chlorinity in the south-central part of the county, no changes in chlorinity can be inferred during the 40-year period. Comparison of figures 15 and 21 shows that many of the ground waters in 1940-41 were already NaCl waters.

Chloride concentrations in Runnels County vary from 100 to 3,000 mg/L (Jones, 1972). High chloride values are measured consistently over wide areas, especially in the southern part of the county (fig. 23), which suggests that areal salinization plays a more dominant role in Runnels than in Tom Green County. Leaching of aquifer material, natural areal discharge of deep brine aquifers, long-term effects of brine disposal in surface pits, and evaporation are possible sources. Little or no ground water is used in western and eastern Runnels County, as indicated by the total absence of values in those areas.

2.4 SITE-SPECIFIC INVESTIGATIONS

Two sources of poor-quality ground water were defined in the previous section on the basis of Ca/Cl, Mg/Cl, SO₄/Cl, Br/Cl, and NO₃/Cl ratios. Those sources are (1) discharge of brines from deep brine aquifers and (2) evaporation from a shallow water table. Brine characteristics were found predominantly in samples obtained in the western half of Tom Green County (table 6). Salinization in the shallow subsurface dominates in Runnels, Concho, and eastern Tom Green Counties (table 6).

2.4.1 Pollution by brines from the deep subsurface

Pollution by brines is indicated in two waters from Runnels County (#2 and #4, table 6). Both samples were obtained in areas close to producing oil wells. Well #2 produced drinking water for 15 years before suddenly turning salty 10 years ago. Well #4, drilled several months ago, in contrast, has produced salt water (from 35 ft below land surface) since it was drilled.

Wells #3 and #5, which were the subject of contamination complaints in the past, do not indicate brine pollution (table 6). At the present time these wells produce Ca-SO₄ water typical for the area. However, there is reason to believe that both wells were polluted when sampled in 1970 (#5 in this study = #578 in Jones, 1972) and in 1984 (sample #3b, sampled by owner) (table 7). Ratios of Ca/Cl, Mg/Cl, and SO₄/Cl suggest mixing of NaCl brine with local ground water in the previously sampled waters. Well #5 probably was polluted by an injection well approximately 20 yards away. Brine injection at this well did not occur during the last couple of months prior to sampling. Well #3 and a neighbor's well suddenly became salty during spring of 1984, after having produced drinkable water for nearly 20

years. Both wells (1) became salty at about the same time, (2) are known for producing more water than nearby water wells, and (3) were back to normal-quality conditions when tested during this investigation. The confined nature of pollution and the rapid changes in water quality suggest that a salt-water plume may have passed these wells through a distinct, highly permeable zone.

Pollution of wells #35 and #39 (fig. 4) is indicated in all ratios of chemical constituents (table 6). Simple arithmetic mixing of 5 percent brine from well B-6 (fig. 4) and 95 percent of relatively fresh water from well #34 results in a chemical composition that is very similar to that of #35 (table 8). That the potential of upward flow of brine and of consequent mixing of brine with fresh water exists in the area is documented by studies of leaky injection and oil wells and by a flowing brine well just southeast of well #35 (Ross, 1978). Well #39 has produced salt water since it was drilled approximately 30 years ago. This well is completed in the Blaine Formation (table 1) at 216 (?) ft below the land surface, which is far deeper than other wells in the area from which chemical analyses are available. Possible mixing of a NaCl brine with fresh water is indicated by arithmetic mixing of samples B-6 and #39 (fig. 4) (table 8). Mixed at a ratio of 74:26, the resulting chemical composition is very close to that of #39 in Na, Cl, Ca, K, and NO_3 concentrations.

2.4.2 Pollution within the shallow subsurface

Whenever the water table is close to the land surface, two possible mechanisms can cause increases in mineral content of ground water: (1) Evaporation leads to increases of all chemical constituents at approximately the same proportions (1:1) and (2) Water passing through the soil zone leaches nitrate out of the soil.

An increase in chlorinity and a decrease in SO_4/Cl ratio in well #17 relative to nearby wells #16 and #18 (table 3) may be interpreted as possible pollution by NaCl water. However, the Na/Cl ratio is lowest in #17 and the NO_3/Cl ratio is relatively constant in the three samples. This indicates that the increase in chloride content is associated with an increase in NO_3 , but not in Na. Therefore, leaching of mineral matter in the soil zone rather than mixing with a Cl water is responsible for the poor quality of sample #17. NO_3/Cl ratios in samples from eastern Tom Green County ($\text{NO}_3/\text{Cl}=0.17$ to 0.28) fall within the range of ratios of seep waters ($\text{NO}_3/\text{Cl}=0.18$ to 0.37), suggesting the same kind of pollution in all these waters.

2.4.3 Limitations

For the purpose of contamination studies the absolute concentration of chemical constituents is of major importance when ratios of chemical constituents are being used. At high concentrations different salt-water sources usually are defined within relatively narrow ranges for ratios of specific constituents. Mixing with fresh water normally widens these ranges progressively with decreases in salinity. Also, chemical reactions within the water or between the water and the aquifer material (dissolution and precipitation of mineral matter) has a more pronounced effect on ion

ratios at low concentrations than at high concentrations.

Well #32 contains one of the lowest concentrations of chemical constituents sampled during this study. Ratios of chemical constituents in the water do not indicate pollution by NaCl brine. A strong hydrogen sulfide odor that periodically is noticed in the well, however, is one indication of contamination. Other indications are (1) erratic changes through time from a Ca-HCO₃ water to a NaCl water (for analyses see Ross, 1979), (2) nearby water wells are not affected by changes in quality, (3) one leaky oil well and one leaky injection well did exist in the area in 1979 approximately 1 mi to the southeast of well #32, and (4) in another well approximately 2 mi to the southeast of well #32 the same changes from a Ca-HCO₃ water to a NaCl water were recorded. This indicates that ground water in the area flows along distinct pathways, such as fractures and solution channels, and that one of those pathways may connect the two water wells with a leaky oil well. The relative contribution of NaCl water is too low, however, to enable detection of contamination using ratios of chemical constituents.

The magnitude of change caused by contamination is also important in ground water of higher mineral content. Contamination in small quantities may affect ratios only slightly and, therefore, may not document a shift from one characteristic range of ratios (for example, the characteristic range of Ca-SO₄ water) to another (for example, the range of NaCl water). Sample #21, for example, is nearly identical to sample #20 (table 3). Sodium and chloride, however, increase by 4.37 and 4.55 mmol/L, respectively (molar Na/Cl ratio of increase = 0.96 = molar Na/Cl ratio in

Coleman Junction brine). Also, the increase in chloride is accompanied by a decrease in NO_3 . Therefore, samples #20 and #21 probably both represent mixtures of fresh water with NaCl water, whereby the ratio of fresh water to NaCl water is higher in #20 than in #21. This slight difference cannot be picked up in regional applications of ratios of chemical constituents because ranges of ratios normally are too wide. The source of NaCl water is not known.

Contamination of fresh water by Coleman Junction brine can be caused by (1) natural discharge of brine and (2) discharge through man-made pathways. Contamination by oil-field brine can be caused by leaky production and injection wells and by brine disposal pits that were in widespread use in Texas prior to the mid and late 1960's. The application of chemical constituents ratios on a regional basis permits determination of contamination caused by brines but does not provide a basis for identification of the mechanisms responsible for contamination. The latter must be evaluated during site-specific investigations using geochemical and non-geochemical techniques.

3. CONCLUSIONS

- (1) Good-quality ($Cl < 250$ mg/L) ground waters in Tom Green and in Runnels County are of the Ca-Mg/HCO₃ or the Ca-Mg/SO₄ type.
- (2) Poor-quality ($Cl > 250$ mg/L) ground waters in Tom Green and in Runnels County are of the Ca-Mg/SO₄-Cl or NaCl types.
- (3) Deep-basin brines are of the NaCl type with low Ca/Cl, Mg/Cl, SO₄/Cl, and Br/Cl ratios.
- (4) Seep waters have Ca/Cl, Mg/Cl, SO₄/Cl, and Br/Cl ratios that are higher than those observed in deep-subsurface brines. Evaporation of shallow ground water in agricultural salinization areas results in 1:1 molar increases in the Ca/Cl, Mg/Cl, SO₄/Cl, and Br/Cl ratios.
- (5) Seep areas generally have high nitrate concentrations, whereas deep-basin brines have very low nitrate concentrations.
- (6) In this study, the stable isotopes ¹⁸O and ²H did not provide reliable tracers of water types. This is because brines were not isotopically enriched as has been observed in other areas of the state and because the isotopic composition of some brines may have been altered by secondary recovery operations.
- (7) In Tom Green County, the chemical composition of the poor-quality ground water appears to result from the mixing of good-quality water with NaCl brines. Piper plots show a trend toward a NaCl water. Ratio plots of

Ca/Cl, Mg/Cl, and SO₄/Cl also trend toward brine values. The presence of high-chloride waters in Tom Green County is not new. High-chloride waters were present as early as 1911; however, the mechanism of this brine pollution remains unknown.

(8) In Runnels County, there appear to be two causes of deterioration of water quality. Some poor-quality waters result from evaporation of ground water, probably in seep areas. These waters characteristically have high Ca/Cl, Mg/Cl, SO₄/Cl, and Br/Cl ratios. Other poor-quality waters result from the mixing of NaCl brines with fresh ground water. These waters have low Ca/Cl, Mg/Cl, SO₄/Cl, and Br/Cl ratios.

(9) The potential for ground-water evaporation and salinization increases as the water table becomes shallower. A salinization source for low-quality ground water should be more prevalent in Runnels County and eastern Tom Green County, where the water table is generally shallower, than in western Tom Green County.

(10) Differentiation among salt-water sources by use of chemical constituent ratios is most successful at high concentrations of dissolved ionic species. At low concentrations, ratios of chemical constituents are governed by the ratios of constituents in fresh water and by reactions between water and aquifer material. This causes an overlap of ratios and, therefore, masks characteristics of salt-water sources.

(11) On a regional basis, application of Ca/Cl, Mg/Cl, SO₄/Cl, and Br/Cl ratios and of NO₃ concentrations allowed differentiation between salt-water

pollution derived from surface salinization (evaporation of shallow ground water) and pollution derived from mixing of good-quality ground water with NaCl subsurface brines.

Four possible sources exist for the NaCl brines: (1) natural discharge of brine, (2) leakage through production, injection, or abandoned and unplugged wells, (3) brine disposal pits that were in use prior to the late 1960's, and (4) unplugged water wells that were drilled into saline parts of aquifers. There are indications that all four mechanisms were or are active. These sources could not be differentiated geochemically in this reconnaissance study. More detailed investigations, including other geochemical techniques as well as site-specific studies, are needed to determine the relative importance of each of these brine sources.

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Table 1: Generalized chart of stratigraphic units in Concho, Runnels, and Tom Green Counties.

SYSTEM	SERIES	FORMATION (Member)
Quaternary	Recent	Alluvium
	Pleistocene	Leona
Cretaceous	Comanchean	Blaine
		San Angelo
Permian	Leonardian	Choza
		Vale (Bullwagon Dolomite)
	Wolfcampian	Arroyo (Standpipe Limestone)
		Coleman Junction
Pennsylvanian		

Table 2: Bradenhead pressures of Coleman Junction Aquifer in Runnels County (from RRC files, San Angelo District Office).

Lease	Bradenhead Pressure	Remarks
W.P. Gardner (05514)	45 psi	
"" (03555)	15 psi	injection well (discontinued)
R. Parker (03206)	125 psi	
G. Pruser (03844)	75 psi	
J.W. Wetzel (02582)	25 psi	
R. Vancil (05986)	100 psi	possible hole in casing
C.T. Michaelis (03466)	80 psi	
E.D. Michaelis (04176)	5 psi	
Estes Estate (06661)	120 psi	
Sue Baggett (06673)	20 psi	
G.A. Henninger (03168)	20 psi	
"" (04594)	40 psi	
L.W. Henninger (02781)	10 psi	
""	40 psi	
E.F. Vogelsang (02889)	65 psi	
E.C. Lindemann (03266)	80 psi	
"" (03354)	80 psi	
"" (03550)	112 psi	
M. Holliday E. (03652)	20 psi	
A.M. Wiley (02827)	20 psi	

Table 3: Chemical and isotopic analyses of brines and shallow ground water in Tom Green, Runnels, and Concho Counties.

Well No.	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	Br	NO ₃	δ ¹⁸ O	δD	Na/Cl	Ca/Cl	Mg/Cl	SO ₄ /Cl	NO ₃ /Cl	(Br/Cl)*10 ⁻³
===== (all analyses in mg/L) =====										<= /oo>	<=====mmol ratios=====>					<=====weight ratios=====>	
BRINES--																	
B-1*	2,310	1,120	25,700	75	136	4,080	41,900	70.8	< 1.	-3.0	-30	0.95	0.05	0.04	0.03	0.00	16.9
B-2#	1,940	1,059	22,500	111	1	2,310	38,000	70.2	< 1.	-2.5	-28	0.91	0.04	0.04	0.02	0.00	18.5
B-3#	2,500	1,122	22,900	80	164	4,170	38,300	70.9	< 1.	-2.5	-28	0.92	0.06	0.04	0.04	0.00	18.5
B-4*	4,530	5	31,600	260	985	3,750	51,600	93.5	< 1.	-4.0	-32	0.94	0.08	0.00	0.03	0.00	18.1
B-5*	1,605	1,110	7,440	18	141	3,390	15,500	37.2	< 1.	-4.1	-38	0.74	0.09	0.11	0.08	0.00	24.0
B-6*	2,400	881	26,100	349	412	3,930	41,200	83.4	< 1.	-4.2	-31	0.98	0.05	0.03	0.04	0.00	20.2
B-7*	931	696	15,600	213	548	9	27,200	56.7	< 1.	-5.3	-36	0.98	0.05	0.03	0.00	0.00	20.2
GROUND WATER																	
# 1	113	35	173	3	294	108	166	0.9	155.	-4.5	-26	1.61	0.60	0.31	0.24	0.93	48.2
# 2	255	216	1,140	9	211	378	2,330	5.5	< 1.	-4.4	-34	0.75	0.09	0.14	0.06	0.00	23.6
# 3	335	138	269	3	414	940	452	1.8	5.	-4.2	-31	0.92	0.66	0.45	0.76	0.01	39.3
# 4	1,172	524	1,790	3	279	1,092	5,130	3.8	1.	-4.1	-29	0.54	0.20	0.15	0.08	0.00	7.2
# 5	731	198	249	5	327	1,815	595	2.4	32.	-3.7	-29	0.65	1.09	0.49	1.11	0.05	38.7
# 6*	350	115	295	2	200	591	699	2.5	149.	-3.8	-28	0.65	0.50	0.24	0.31	0.21	34.3
# 7*	319	154	305	3	261	567	723	2.5	128.	-3.9	-29	0.65	0.39	0.31	0.28	0.18	34.6
# 8*	299	137	289	3	211	501	685	2.4	158.	-3.7	-29	0.65	0.39	0.29	0.27	0.23	35.0
# 9	414	339	512	2	291	1,485	983	3.2	57.	-4.3	-34	0.80	0.37	0.51	0.55	0.06	31.5
# 10*	202	82	245	2	257	249	454	1.6	169.	-3.5	-30	0.83	0.40	0.27	0.20	0.37	33.0
# 11*	585	192	633	5	276	2,115	735	3.1	< 1.	-4.8	-36	1.33	0.71	0.38	1.05	0.00	42.2
# 12	129	108	218	2	387	251	343	1.6	121.	-4.7	-29	0.98	0.34	0.46	0.27	0.35	46.6
# 13	369	50	271	3	200	223	720	2.5	165.	-4.2	-35	0.58	0.46	0.10	0.10	0.23	33.3
# 14	273	764	952	13	264	2,415	1,460	8.5	30.	-5.2	-34	1.01	0.16	0.77	0.61	0.02	57.5
# 15	525	123	178	4	243	1,008	516	0.2	147.	-5.2	-33	0.53	0.90	0.35	0.71	0.28	3.9
# 16	252	82	169	3	218	270	461	1.9	115.	-4.3	-32	0.57	0.49	0.26	0.21	0.25	39.0
# 17	359	128	334	2	228	174	980	3.3	229.	-4.3	-34	0.53	0.33	0.19	0.07	0.25	33.7
# 18	229	96	143	3	258	167	454	2.0	115.	-4.1	-25	0.49	0.50	0.31	0.14	0.25	41.8
# 19	189	62	114	1	362	156	236	1.0	98.	-3.8	-28	0.74	0.71	0.39	0.24	0.41	42.4
# 20	185	118	91	2	288	474	205	0.8	35.	-5.0	-35	0.68	0.80	0.84	0.84	0.17	39.0
# 21	188	115	192	2	304	465	367	1.4	28.	-4.6	-30	0.81	0.46	0.46	0.46	0.07	38.1
# 22	212	111	233	2	363	258	482	2.0	131.	-5.0	-35	0.75	0.39	0.34	0.20	0.27	39.4
# 23	157	64	156	3	321	261	184	0.8	20.	-4.4	-32	1.31	0.76	0.51	0.52	0.11	43.5
# 24	669	242	369	12	438	2,040	639	1.5	< 1.	-4.3	-30	0.89	0.93	0.55	1.16	0.00	23.5
# 25	268	97	243	4	214	161	735	2.7	125.	-4.1	-31	0.51	0.32	0.19	0.08	0.17	36.7
# 26	452	152	363	4	202	192	1,310	4.4	87.	-3.9	-36	0.43	0.31	0.17	0.06	0.07	33.6
# 27	181	50	391	1	313	284	573	1.9	29.	-0.5	-8	1.05	0.28	0.13	0.18	0.05	33.2
# 28	448	139	732	2	310	402	1,622	4.7	173.	-2.2	-16	0.70	0.25	0.13	0.09	0.11	28.4
# 29	536	177	744	3	292	386	1,970	5.6	43.	-2.4	-28	0.58	0.24	0.13	0.07	0.02	28.4
# 30	385	124	386	5	192	131	1,230	4.3	63.	-4.1	-28	0.48	0.28	0.15	0.04	0.05	35.0
# 31	188	69	232	3	461	113	479	1.3	8.	-3.5	-29	0.75	0.35	0.21	0.09	0.02	27.1
# 32	73	30	259	8	379	180	211	0.7	2.	-5.0	-38	1.89	0.31	0.21	0.31	0.01	33.2
# 33	90	41	113	3	297	128	161	0.6	2.	-3.4	-31	1.08	0.50	0.37	0.29	0.01	37.3
# 34	212	89	422	4	399	318	712	2.2	29.	-3.6	-28	0.91	0.27	0.18	0.17	0.04	30.9
# 35	498	185	1,770	12	333	432	3,380	6.9	43.	-4.3	-35	0.81	0.13	0.08	0.05	0.01	20.1
# 36	560	263	978	13	206	462	2,650	6.2	41.	-4.4	-34	0.57	0.18	0.15	0.07	0.01	23.4
# 37	519	223	220	7	232	753	1,060	4.5	46.	-4.8	-33	0.32	0.44	0.31	0.26	0.04	42.4
# 38	290	192	284	2	293	225	976	3.2	13.	-4.6	-37	0.45	0.26	0.29	0.09	0.01	32.8
# 39	921	491	7,185	86	250	2,070	11,630	9.9	13.	-5.3	-38	0.95	0.07	0.06	0.07	0.00	8.4

-- The sources of brines are not known with certainty. According to RRC San Angelo District Office personnel samples B-1 through B-4 most likely represent brines from the Coleman Junction brine aquifer.

* leaky injection wells with flow from bradenhead

flowing well completed in Coleman Junction aquifer; sample B-2 was obtained after 10 minutes of flow, sample B-3 was obtained after 1.5 hours of flow.

S flowing core holes, both approximately 100 feet deep

possibly affected by water flooding; producing oil well, E.D. Jones #A2, Gulf Oil Corp., Atkinson West (San Angelo) oil field

* Seep sample

Table 4: Chemical analyses of good-quality ground water.

Well No.	Ca	Mg	Na	K	CO ₃	SO ₄	Cl	Br	NO ₃	$\delta^{13}C$	δD	Na/Cl	Ca/Cl	Mg/Cl	SO ₄ /Cl	NO ₃ /Cl	(Br/Cl) * 10 ⁻⁴
	← all analyses in mg/L →									‰	‰	mmol ratios				weight ratios	
# 1	113	35	173	3	294	108	166	.9	155.	-4.5	-25	1.51	0.50	0.31	0.24	0.33	48.2
#19	189	62	114	1	362	156	236	1.0	98.	-3.3	-28	0.74	0.71	0.39	0.24	0.41	42.4
#20	185	118	91	2	298	474	205	.3	35.	-5.0	-35	0.68	0.90	0.34	0.34	0.17	39.0
#23	157	64	156	3	321	261	194	.3	20.	-4.4	-32	1.31	0.76	0.51	0.32	0.11	43.5
#32	73	30	259	3	379	180	211	.7	2.	-5.0	-38	1.89	0.61	0.21	0.31	0.01	33.2
#33	90	41	113	3	297	128	161	.6	2.	-3.4	-31	1.08	0.50	0.37	0.29	0.01	37.3

Table 5: Chemical analyses of seep waters in southern Runnels County.

Well No.	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	Br	NO ₃	δ ¹⁸ O	δD	Na/Cl	Ca/Cl	Mg/Cl	SO ₄ /Cl	NO ₃ /Cl	(Br/Cl) × 10 ⁻⁴
	← (all analyses in mg/L) →									← ‰ / ‰ →	← mmol ratios →				← weight ratios →		
# 6	350	115	295	2	200	591	699	2.5	149.	-3.8	-28	0.65	0.45	0.24	0.31	0.21	34.3
# 7	319	154	305	3	261	567	723	2.5	128.	-3.9	-29	0.65	0.39	0.31	0.29	0.18	34.6
# 8	299	137	299	3	211	501	685	2.4	158.	-3.7	-29	0.65	0.39	0.29	0.27	0.23	35.0
#10	202	82	245	2	257	249	454	1.6	169.	-3.5	-30	0.83	0.40	0.27	0.20	0.37	33.0
#11	585	192	633	5	276	2,115	735	3.1	< 1.	-4.8	-36	1.33	0.71	0.38	1.05	0.00	42.2

Tab.6 Possible brine pollution indicated by ratios of chemical constituents (x). The mechanisms of brine pollution are not known.

Well No.	Name	Ca/Cl	Mg/Cl	SO ₄ /Cl	Br/Cl	NO ₃ /Cl	Remarks
Runnels County							
1	Belk						low-cl water
2	M. Werner	x	x	x	x	x	located next to oil well
3	Halfman					x	possibly polluted in 1984
4	Black		x	x	x	x	located next to oil wells
5	Matschek						possibly polluted in 1970
6	Hoelscher						house well next to seep area 1
7	Hoelscher						5 ft deep
8	Hoelscher						20 ft deep
9	Lisso						
10	Lange						seep well
11	Fischer					x	flowing seep well
Concho County							
12	Hoffman						
13	Dirschke		x				
14	K. Werner					x	
Eastern Tom Green County							
15	Scott						
16	Hoelscher						
17	R. Hoelscher			x			
18	Friend						
19	Music						low-Cl water
20	Schriever						low-Cl water
21	Schriever						
22	Sefcik						
23	Beatty						
24	Jost				x	x	
Western Tom Green County							
25	Stanford			x			
26	Fairview S.			x			
27	S. Hoelscher						
28	McCoulskey	x					
29	Baxter	x		x	x(?)	x	salt-water well
30	Block		x(?)	x			
31	Wash. School			x	x	x	
32	Richter						low-Cl water with H ₂ S odor
33	Bates						low-Cl water
34	Johnson						
35	Mair	x	x	x	x	x	possibly polluted by brine from San Angelo Formation
36	Book		x(?)	x	x	x	
37	Rose						
38	Taylor			x		x	
39	Glas	x	x	x	x	x	

Tab.7 Previous chemical analyses of wells #3 and #5
(all analyses in mg/L).

Well No.	Owner	Date	Ca	Mg	Na	SO ₄	Cl	NO ₃
#3b	Halfman	8-84	630	275	1050	940	2900	-
#5*	Matschek	70	1010	322	1020	1390	3100	10

b sampled by Mr. H. Halfman

* from Jones, 1972

Tab.8 Hypothetical mixtures of brine with fresh water (mg/L).
 For brine and fresh-water analyses (100 percent) see
 table 3.

Well No.	(%)	Ca	Mg	Na	K	SO ₄	Cl	Br	NO ₃
#34	95	201	84	400	4	302	676	2	27
B-6	5	120	44	1305	17	196	2060	4	0
total		321	128	1705	21	498	2736	6	27
#35	100	498	185	1770	12	432	3380	7	43
#38	74	207	142	210	1	166	727	2	10
B-6	26	624	229	6786	91	1020	10700	21	0
total		831	371	6996	92	1186	11427	23	10
#39	100	921	491	7185	86	2070	11630	10	13

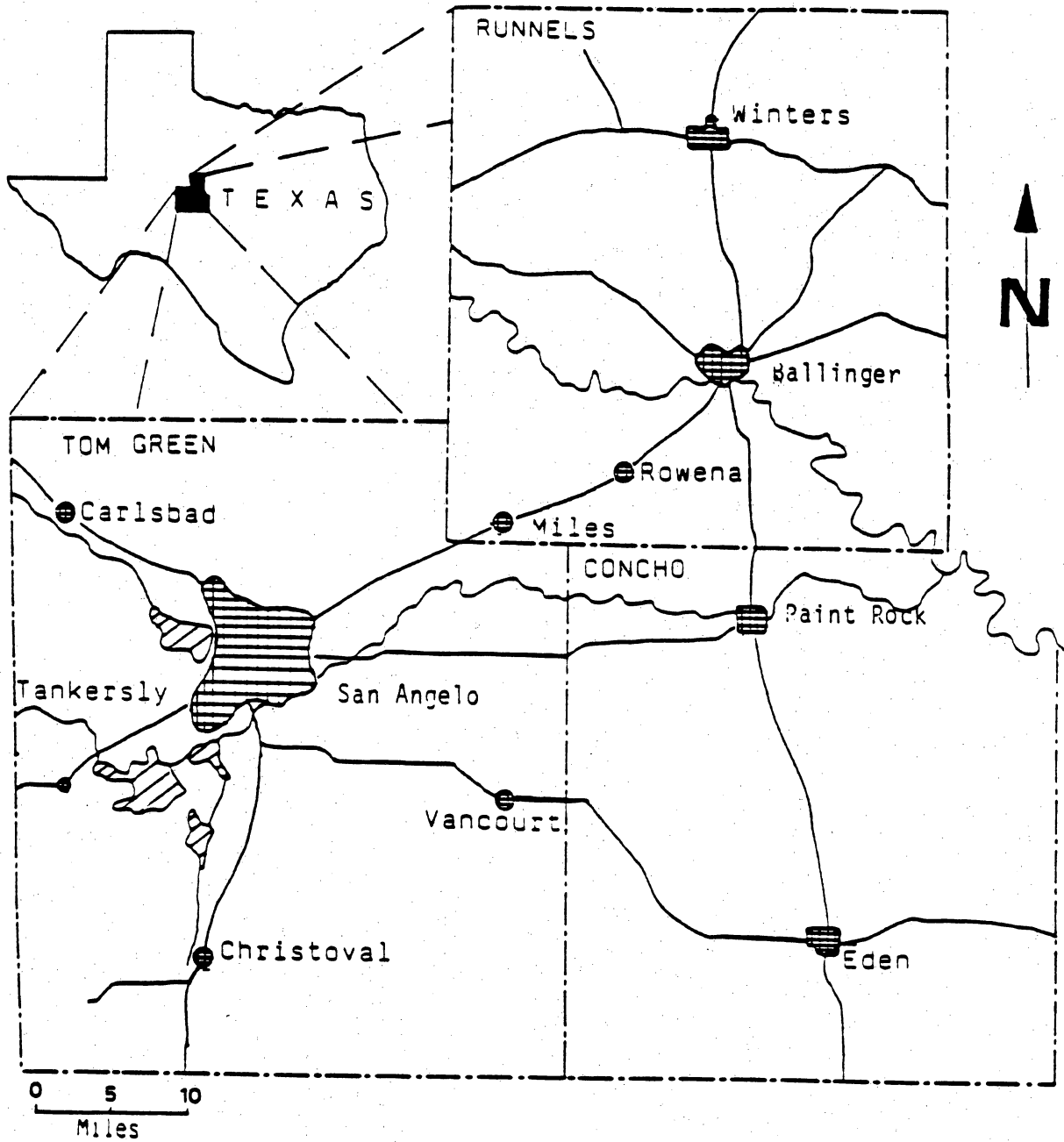


Fig.1 Area location map.

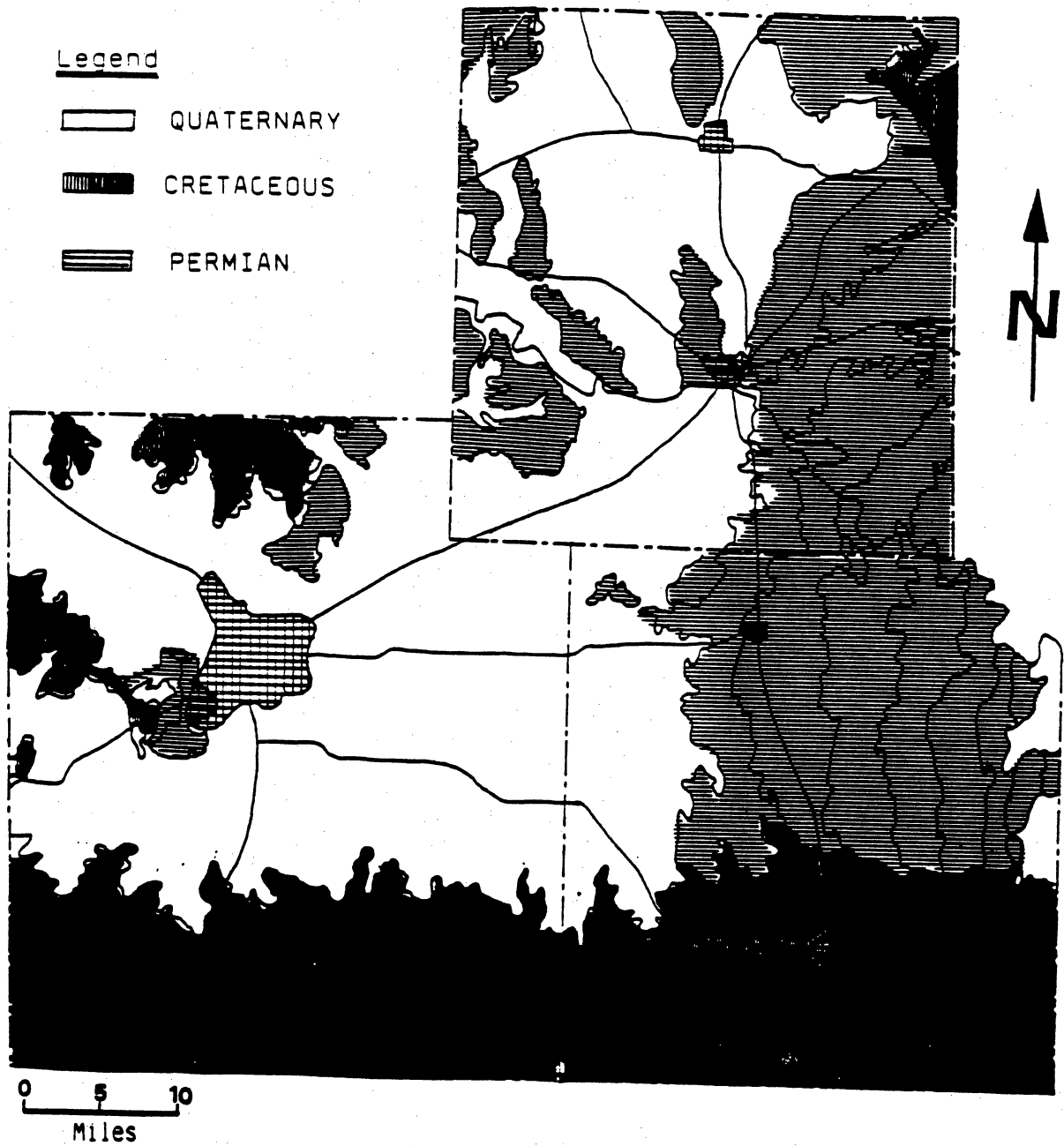


Fig.2 Generalized geologic map (from Barnes, 1975 and 1976).

Legend

250 Required depth of surface casing in feet below land surface

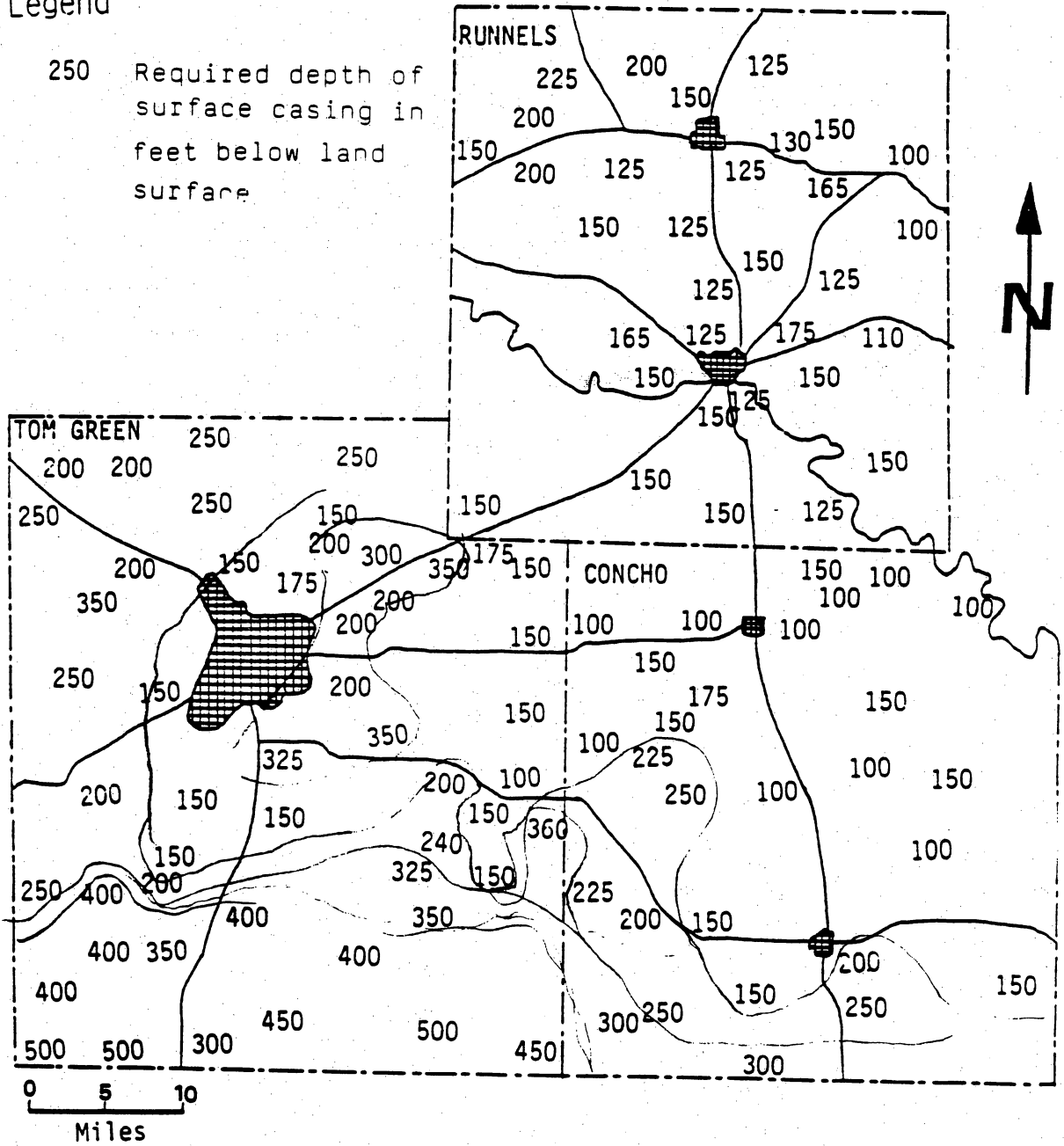


Fig.3 Required depths of surface casing for protection of fresh-water aquifers (from RRC files, San Angelo).

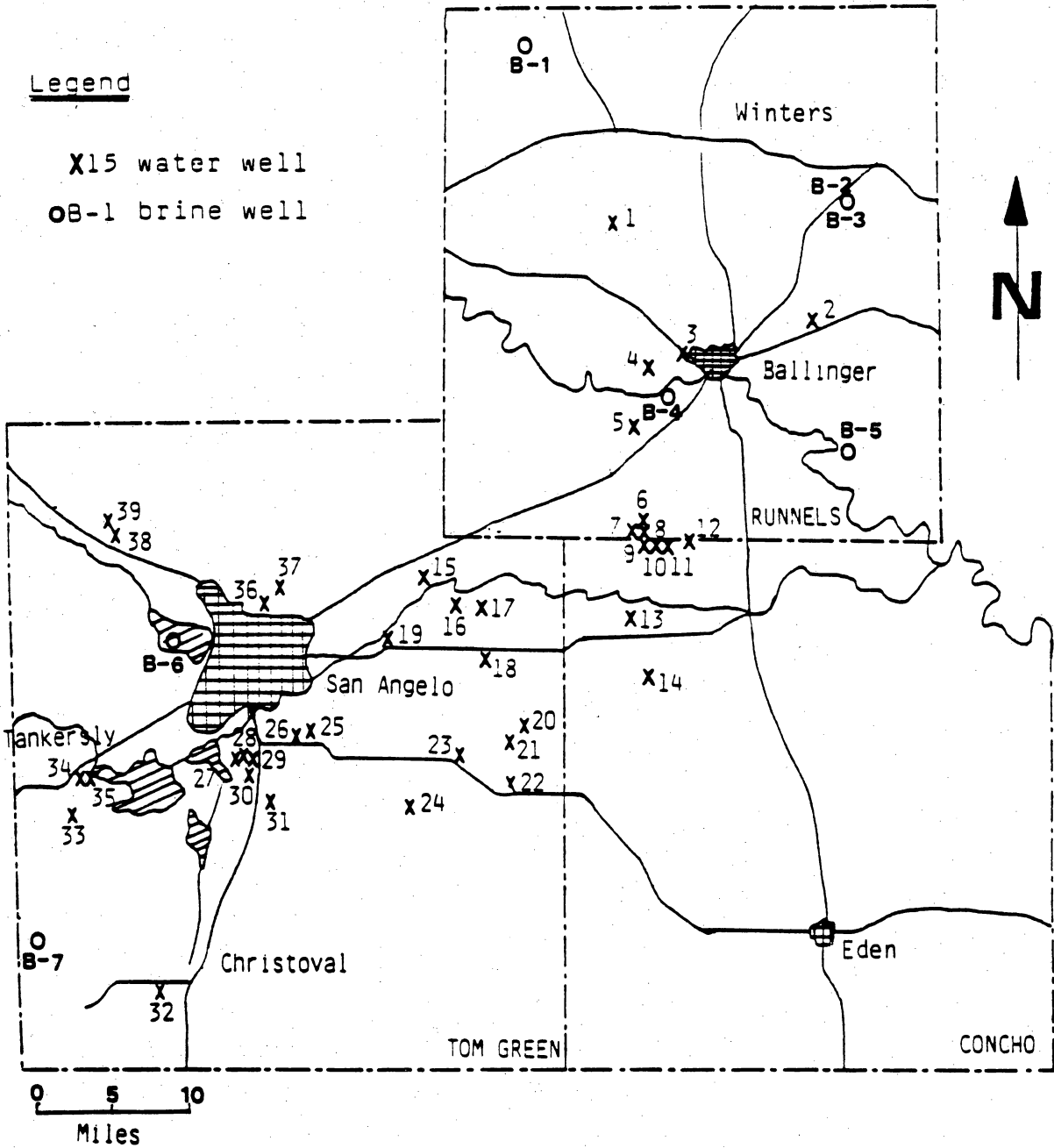


Fig.4 Well location map.

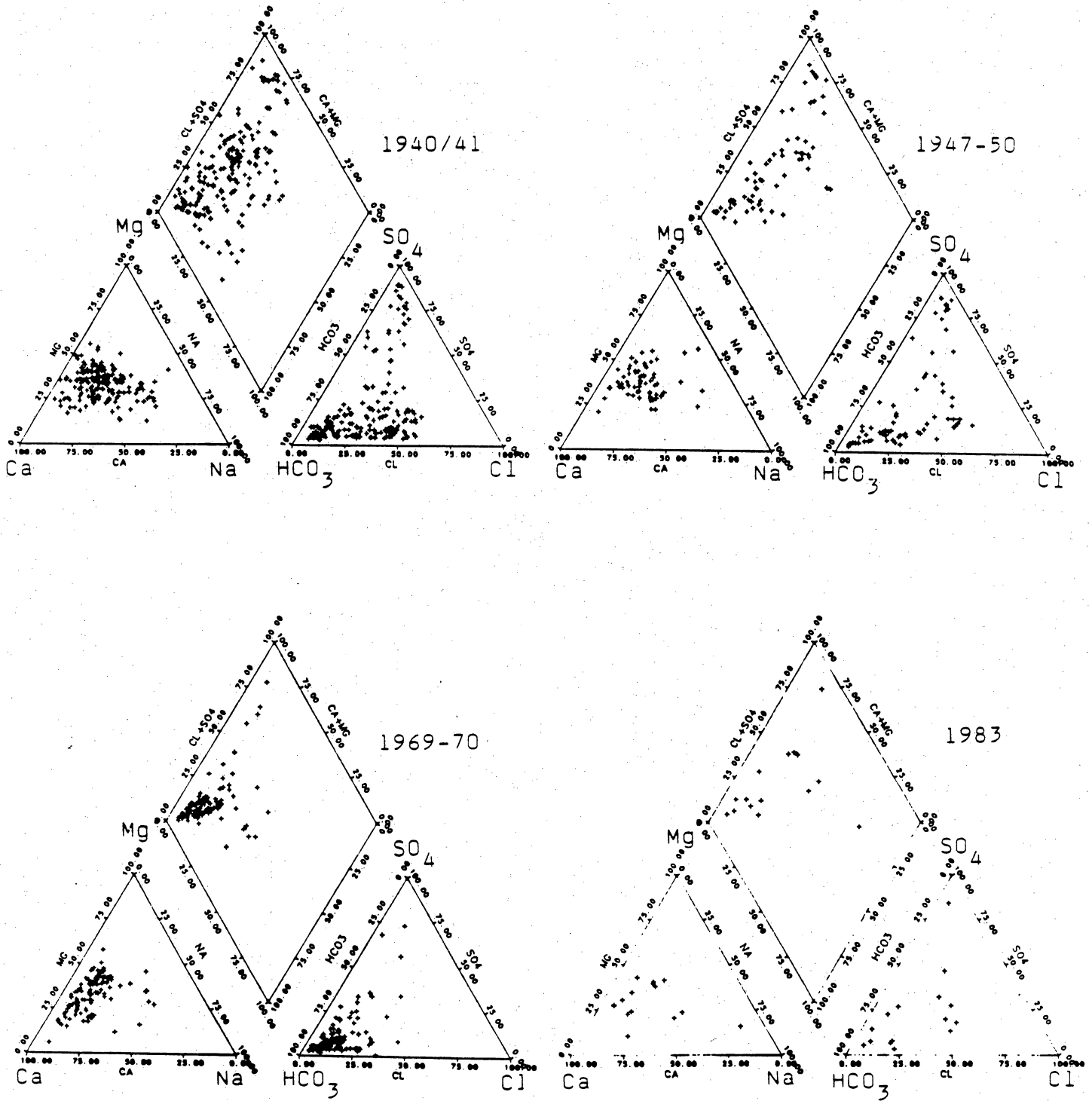


Fig.5 Piper diagrams of good-quality ground water (Cl less than 250 mg/L) in Tom Green County for the years 1940/41, 1947-1950, 1969-70, and 1983.

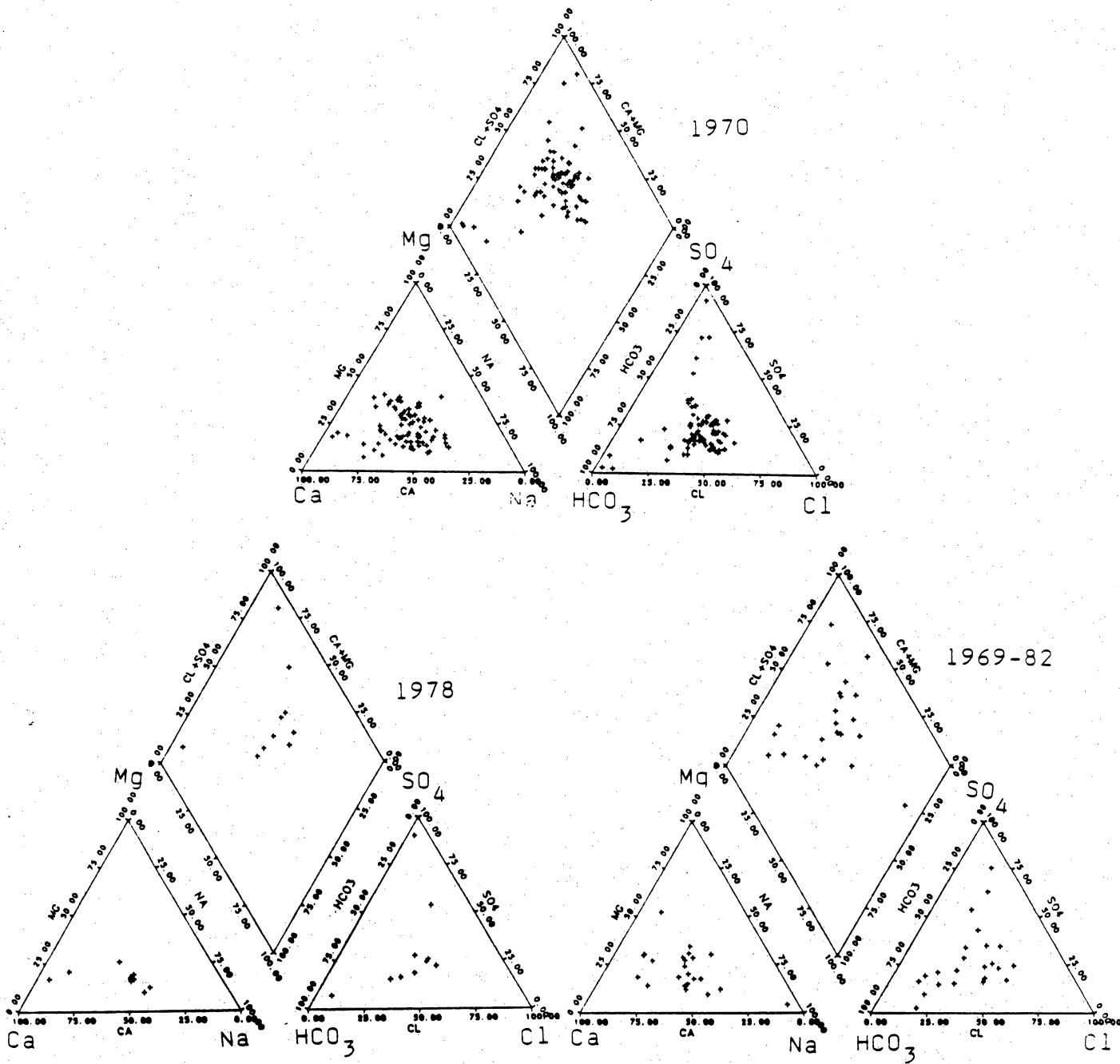
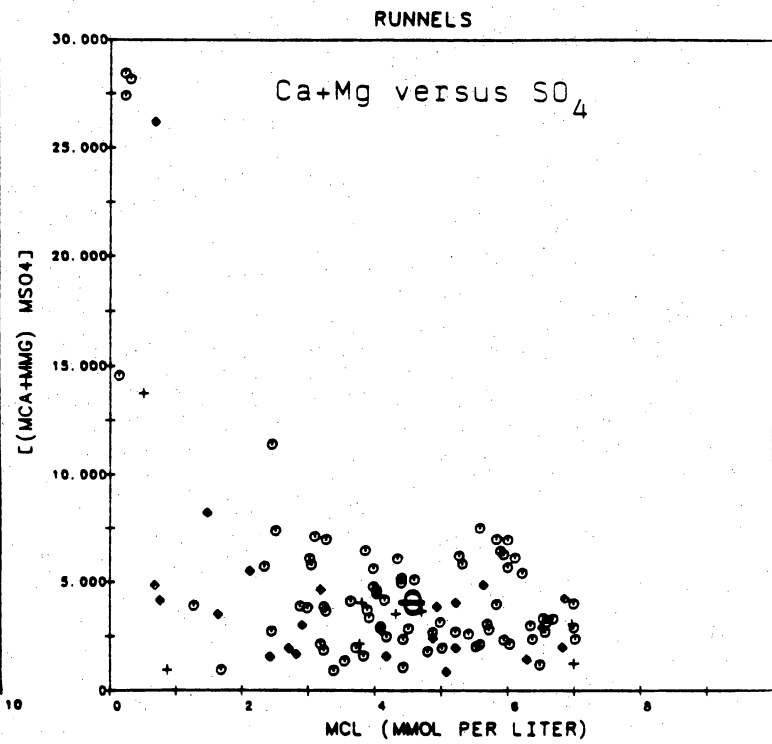
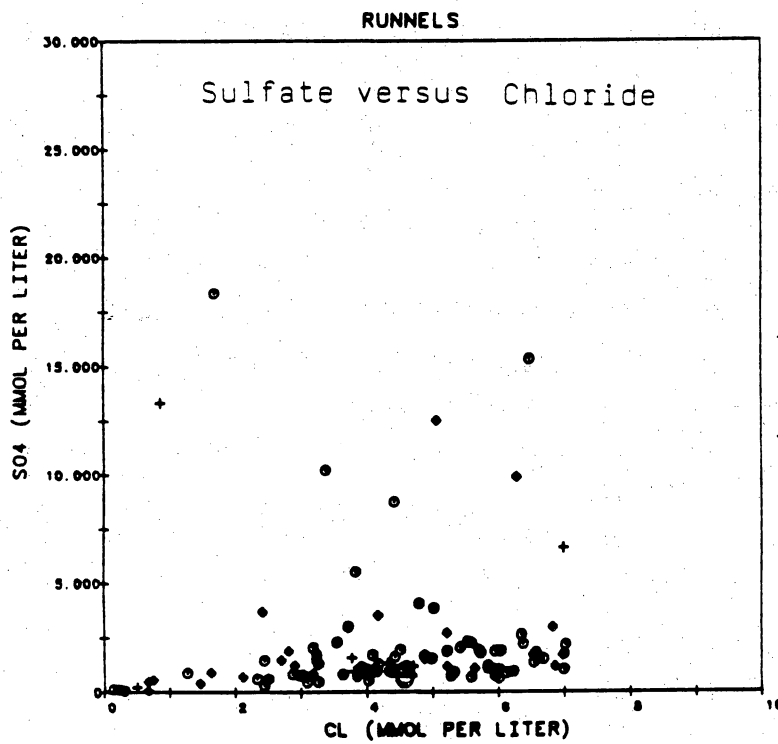
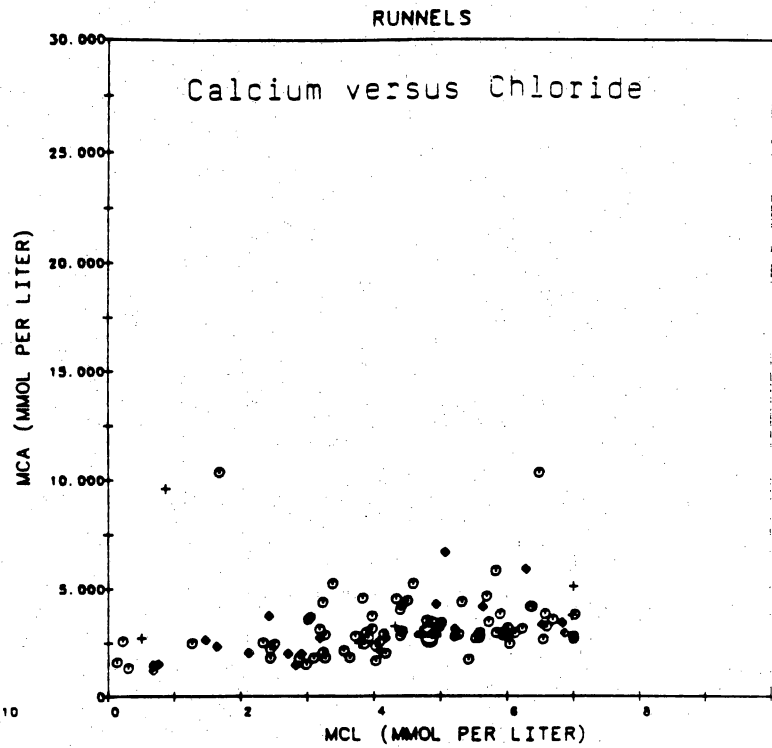
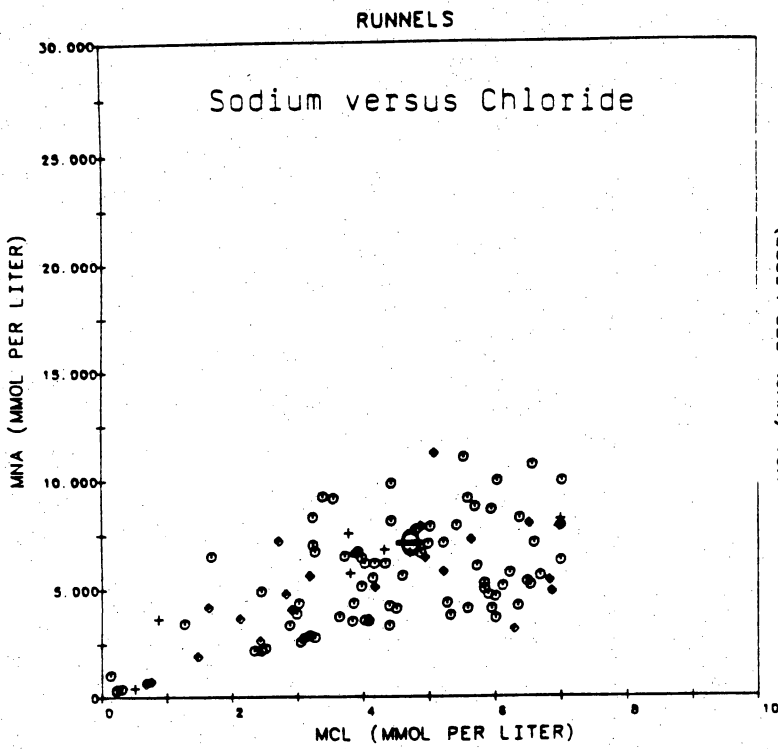


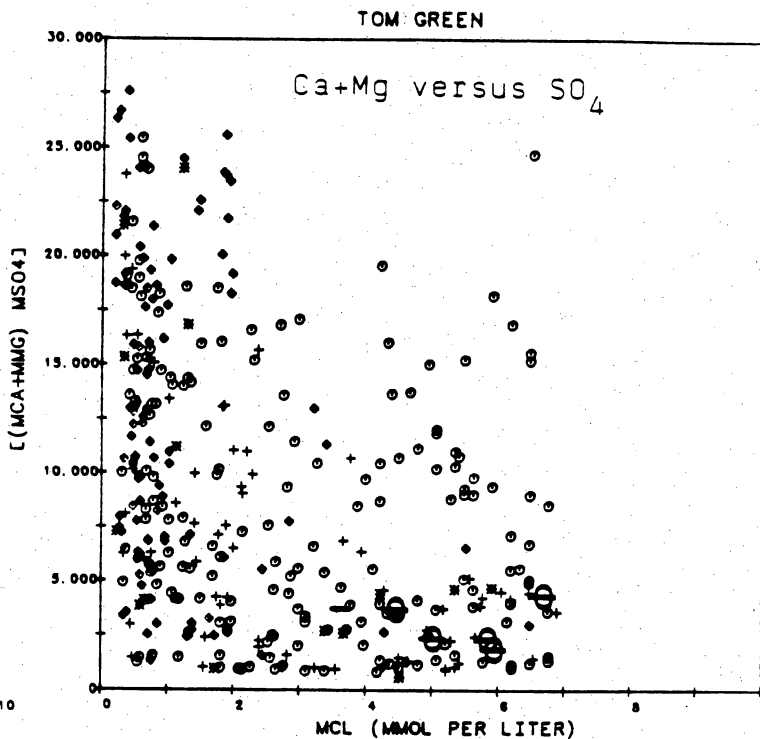
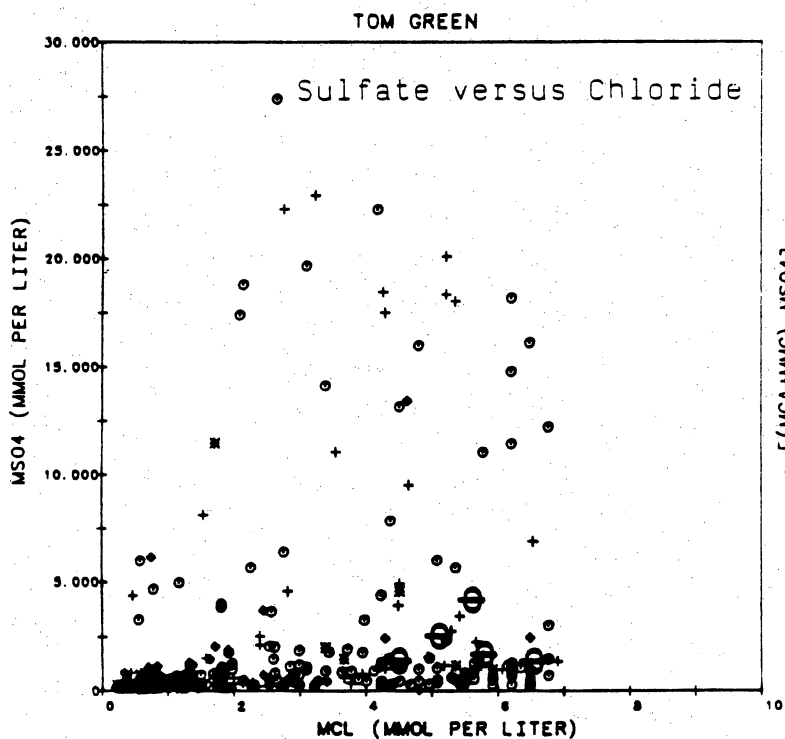
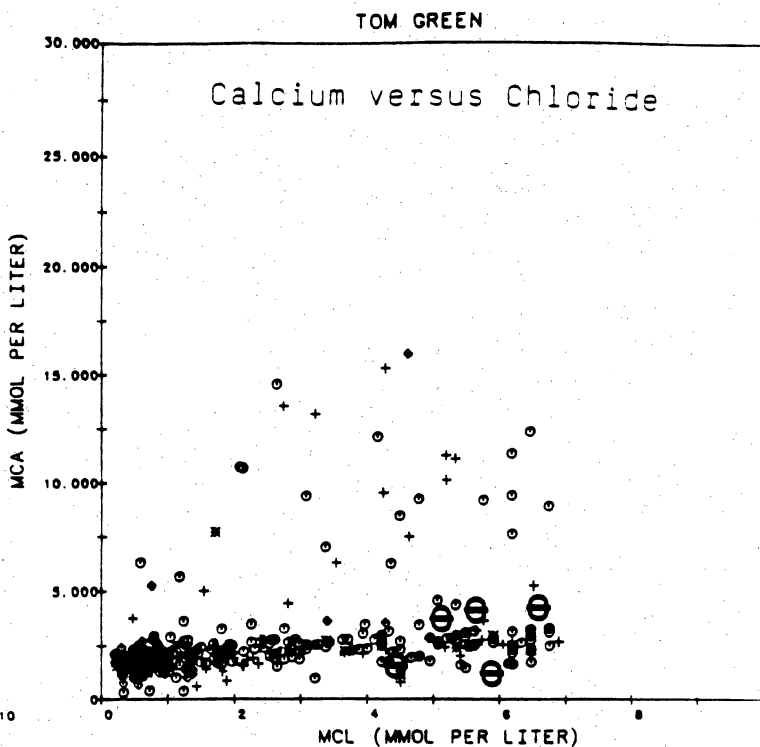
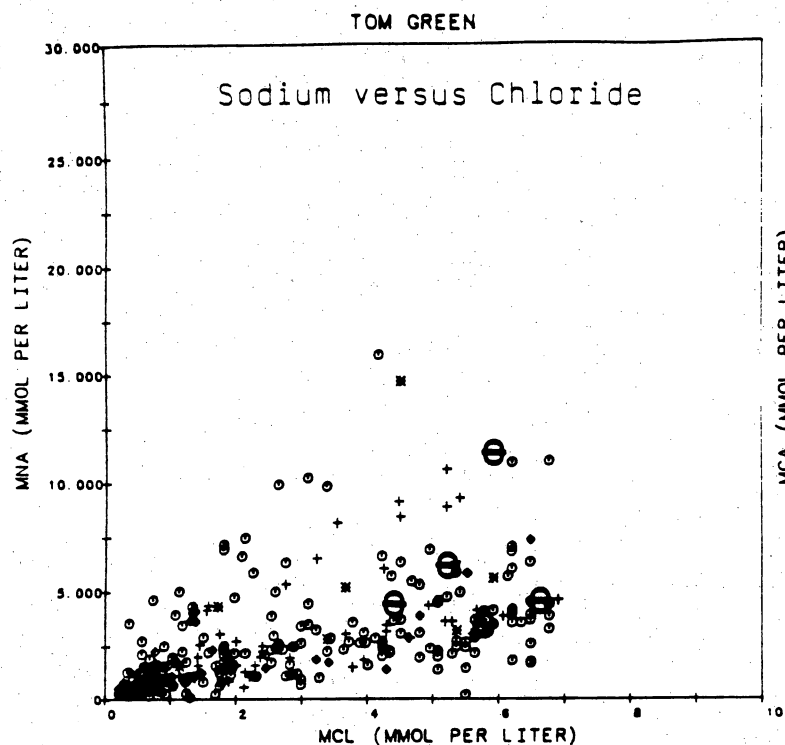
Fig.6 Piper diagrams of good-quality ground water (Cl less than 250 mg/L) in Runnels County for the years 1970, 1978, and 1969-82 (excluding 1970 and 1978).



LEGEND

- 1970
- ⊕ 1978
- ◆ 1969-82
- ⊖ this study

Fig.7 Chemical constituents of good-quality ground water (Cl less than 250 mg/L) in Runnels County.



LEGEND

- | | | | | | |
|---|---------|---|---------|---|------------|
| ○ | 1940/41 | ◆ | 1969-70 | ⊖ | this study |
| + | 1947-50 | ✱ | 1983 | | |

Fig. 8 Chemical constituents of good-quality ground water (Cl less than 250 mg/L) in Tom Green County.

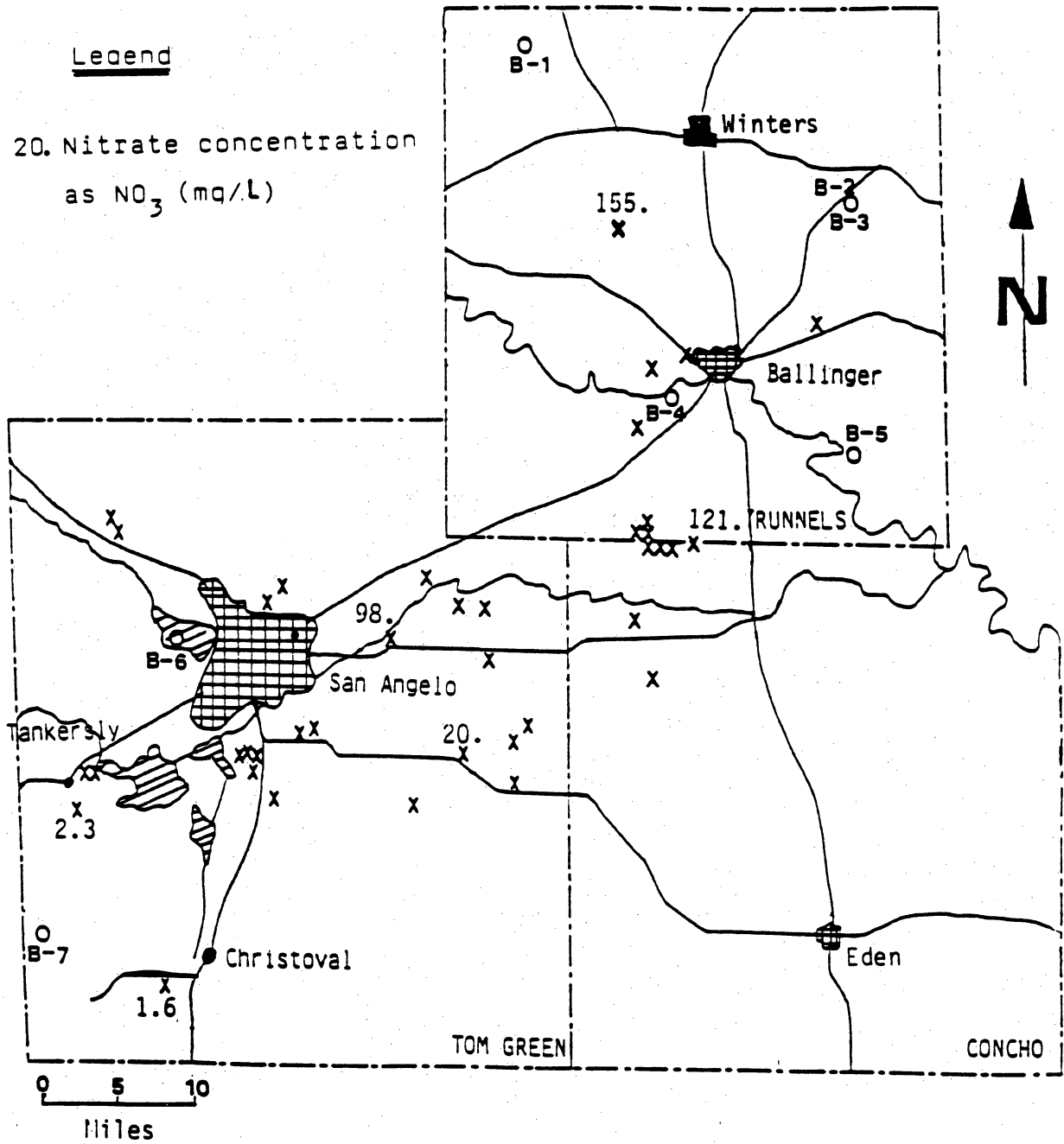


Fig.9 Nitrate concentrations in good-quality ground water, Tom Green and Runnels Counties.

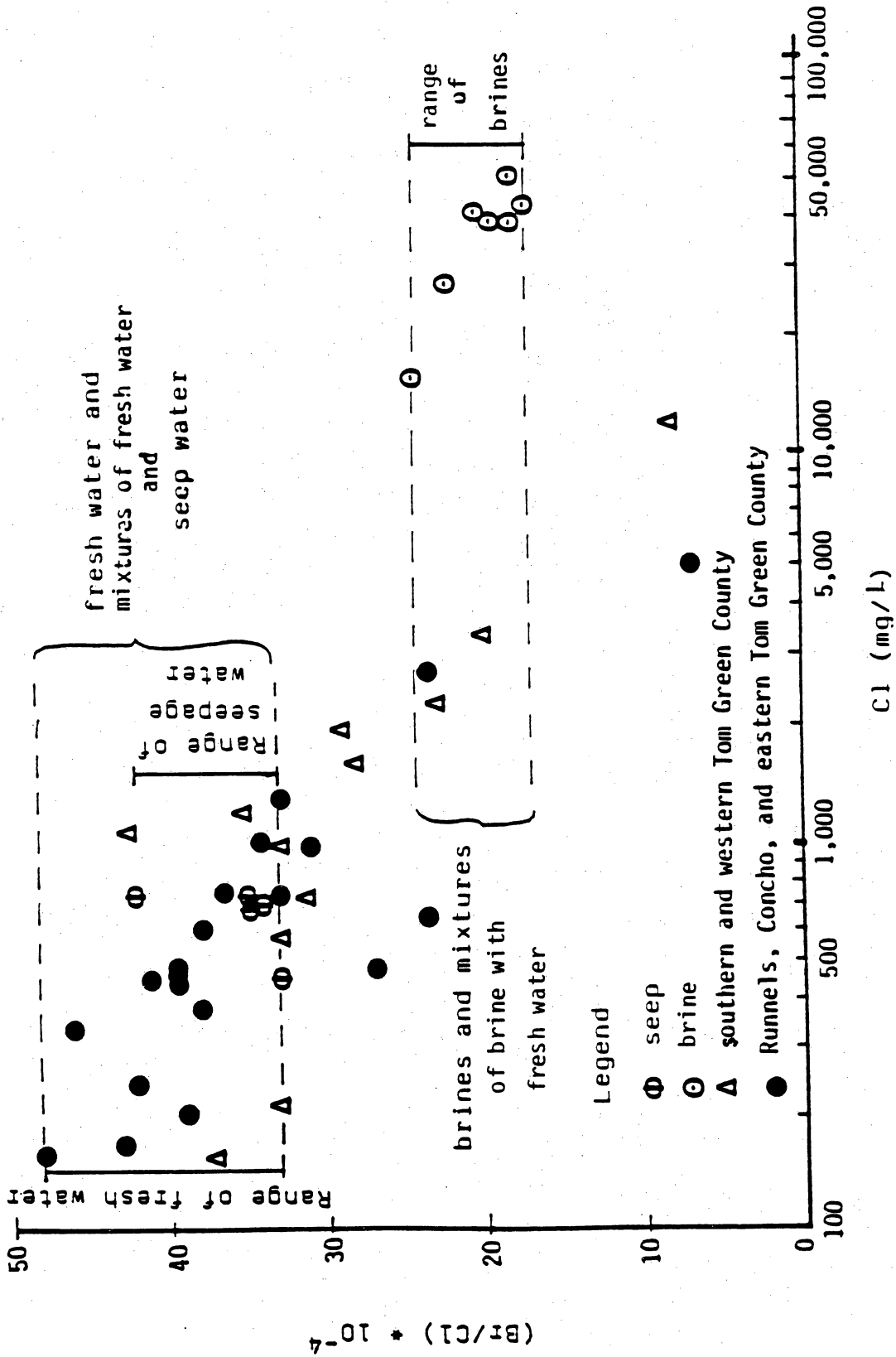


Fig.10 Br/Cl ratios in brines and ground water in Tom Green, Runnels and Concho Counties.

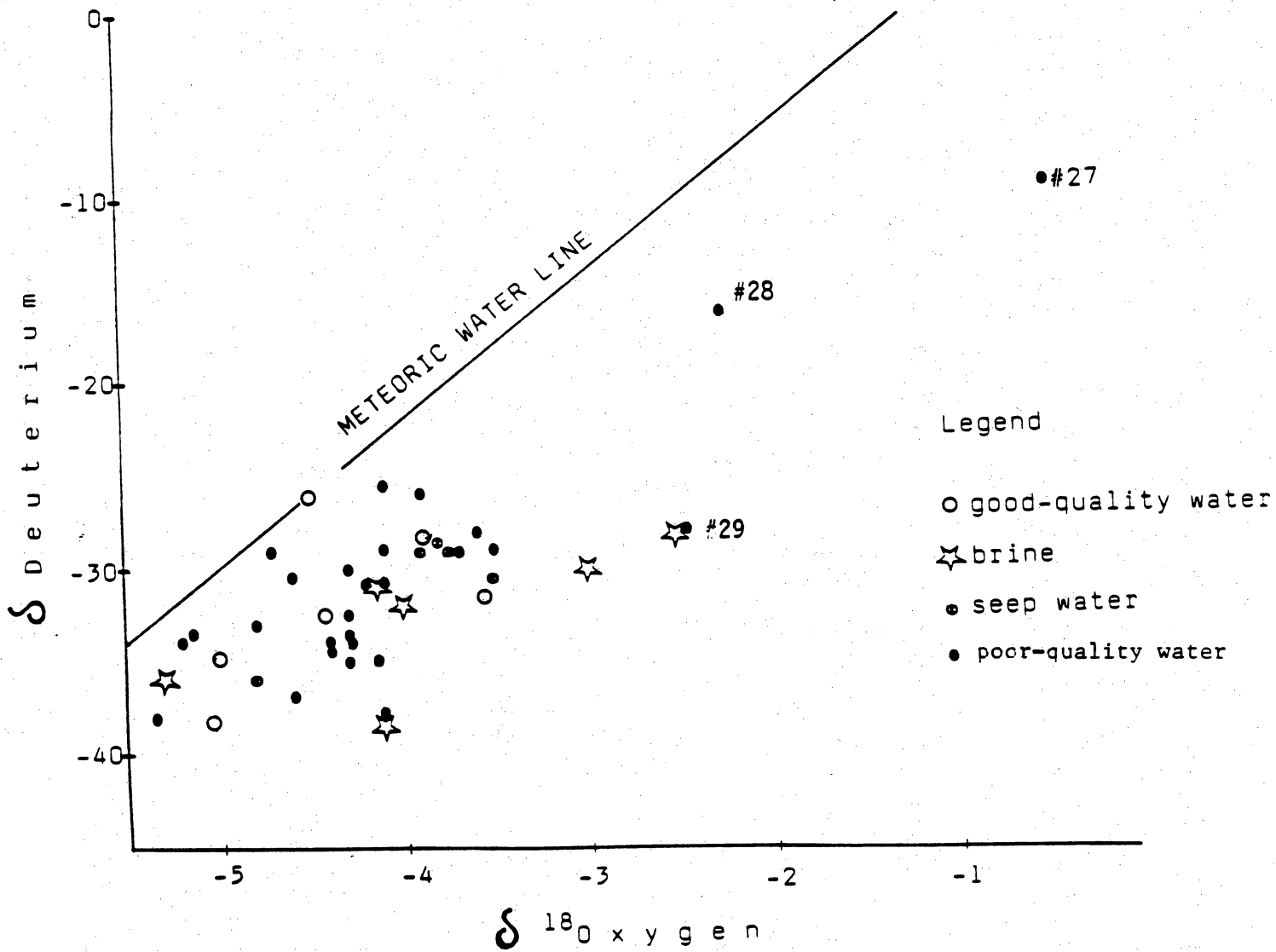


Fig.11 Isotopic composition of brines and ground water in Tom Green, Runnels, and Concho Counties.

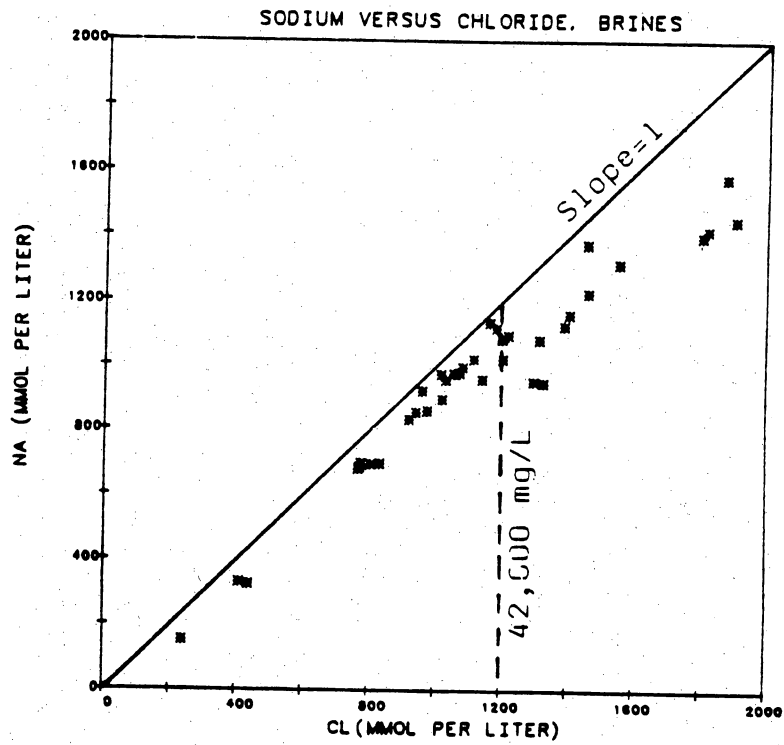
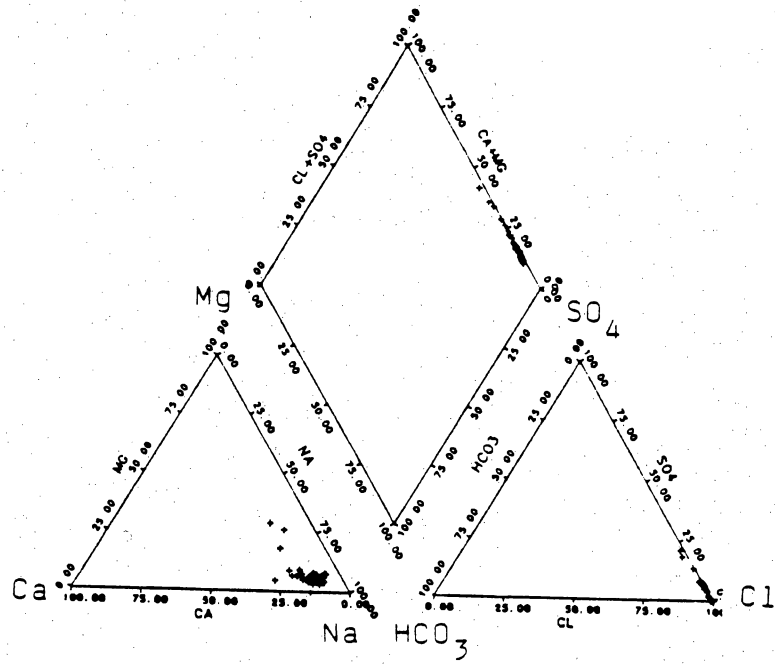


Fig.12 Piper diagram and Na/Cl ratios of brines underlying Tom Green, Runnels, and Concho Counties (chemical data from Core Laboratories, Inc., 1972, and from this study).

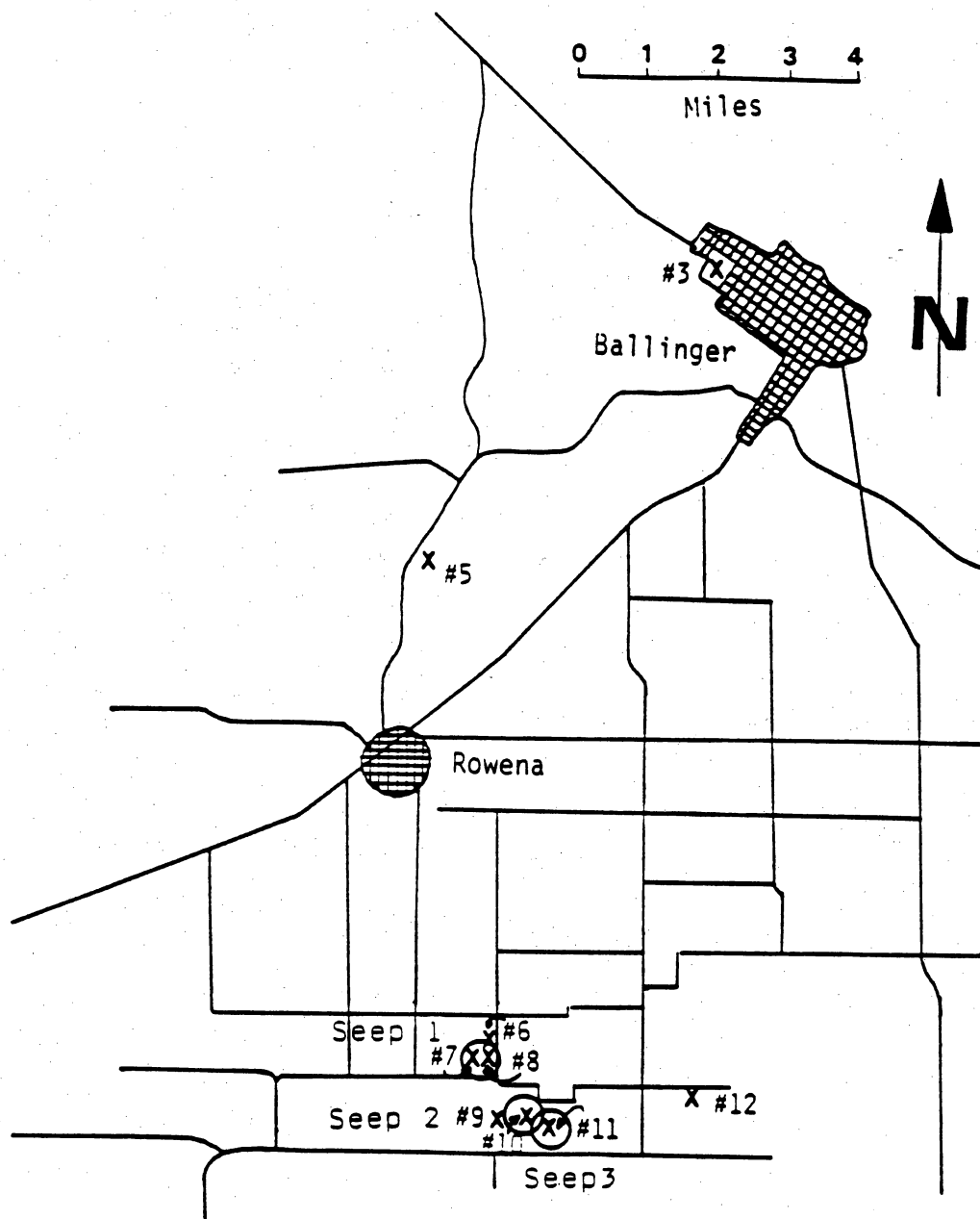
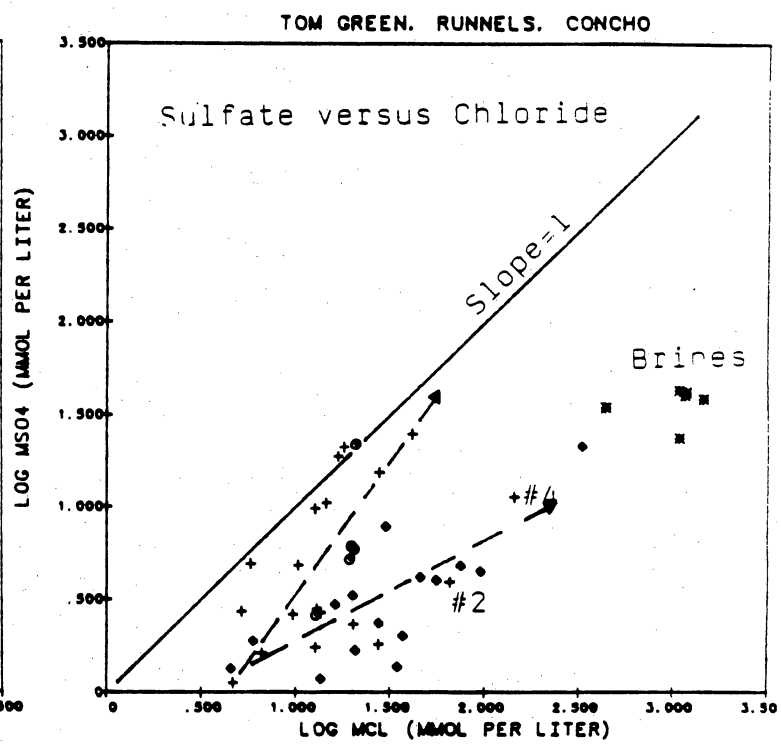
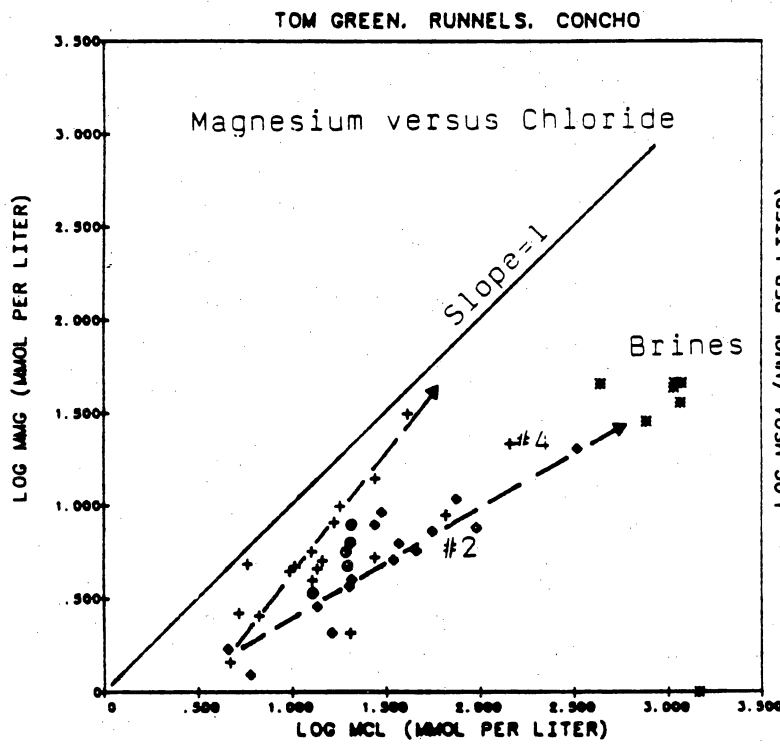
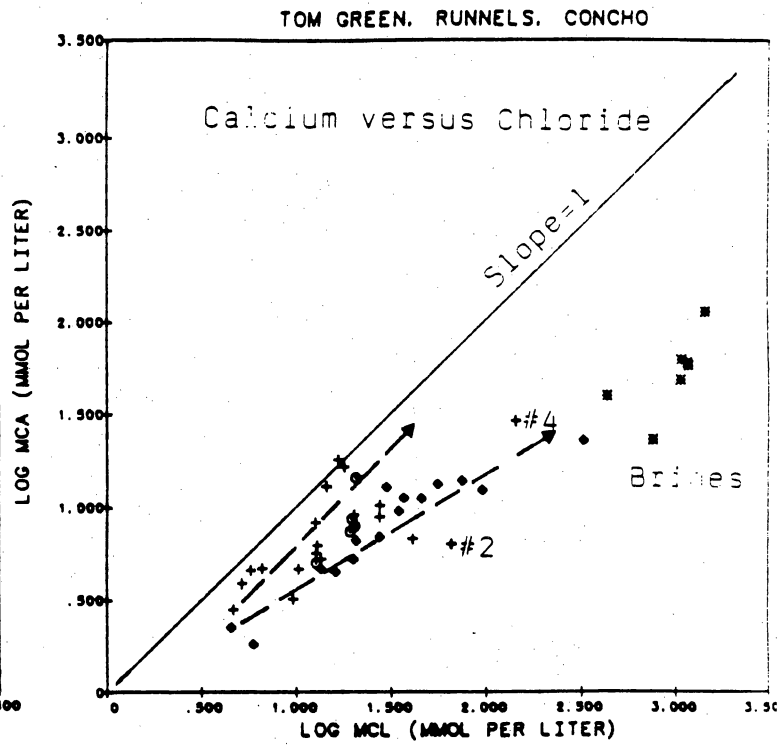
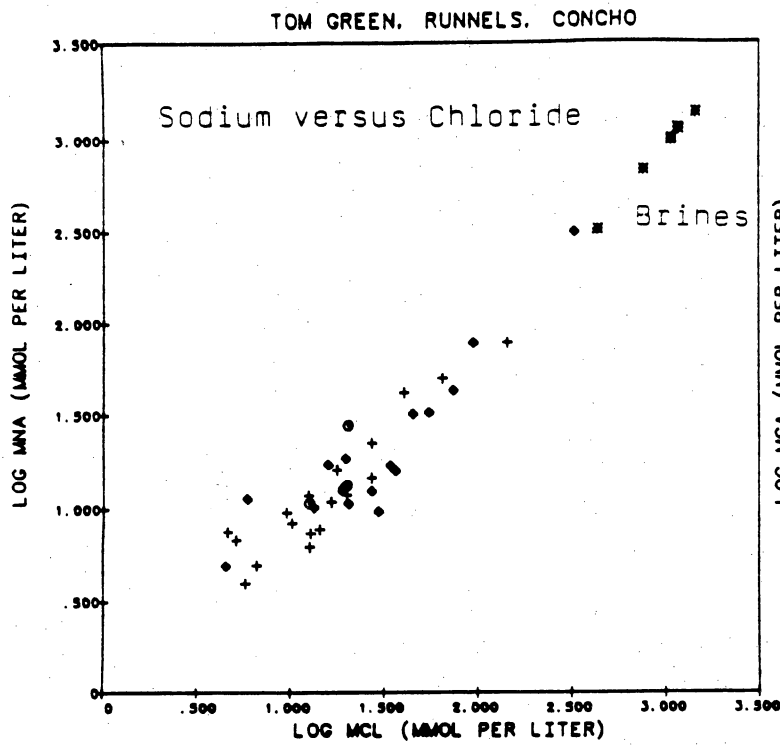


Fig.13 Location map of seepage areas in southern Runnels County where water samples were obtained (see table 3).



Legend

- | | | | |
|---|--------|---|---|
| ○ | Seeps | + | Runnels, Concho, and eastern Tom Green County |
| * | Brines | ◊ | southern and western Tom Green County |

Fig.14 Chemical constituents in ground water from Tom Green, Runnels, and Concho Counties. Samples from seep areas and the eastern half of the study area point away from values typical of subsurface brines in the area.

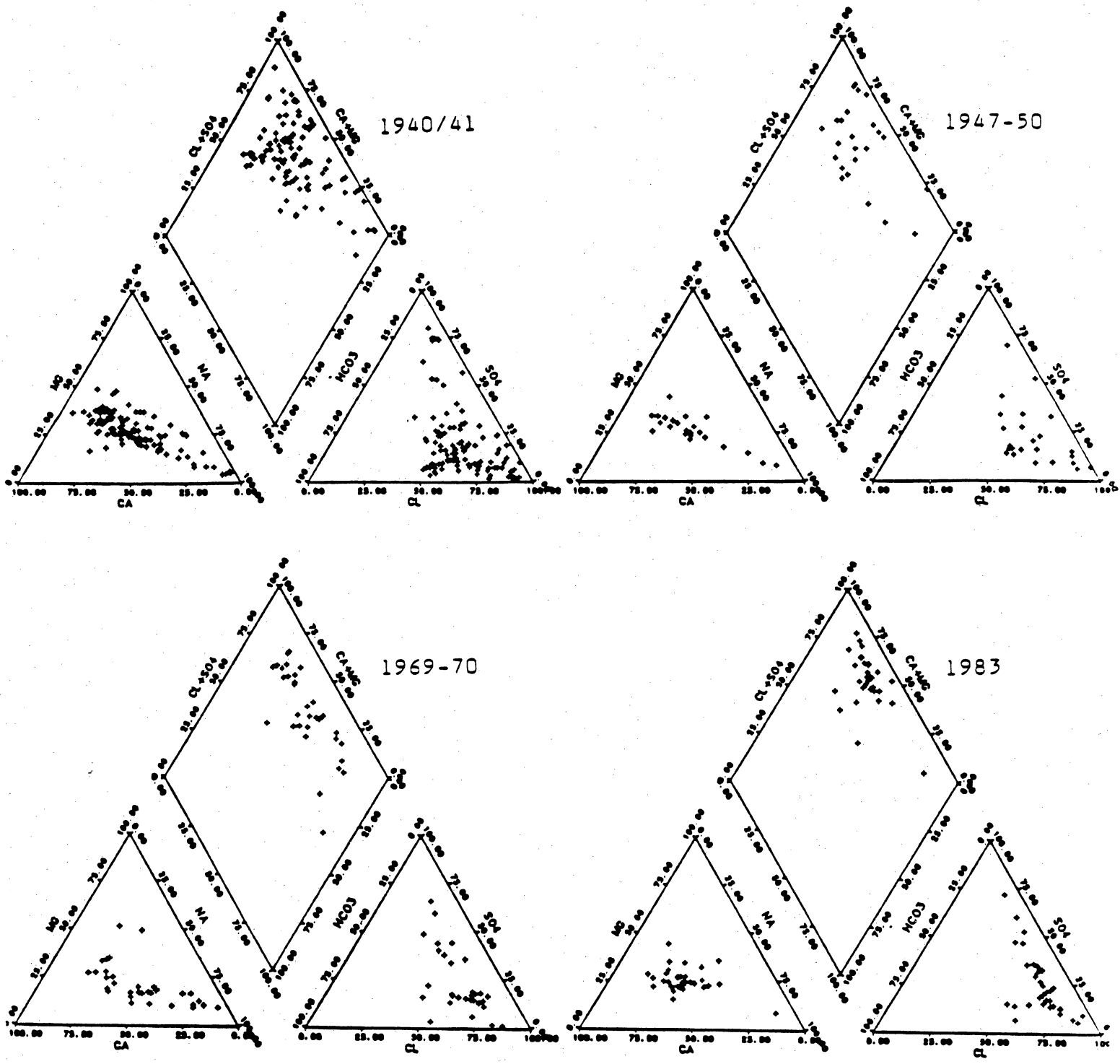


Fig.15 Piper diagrams of poor-quality ground water (Cl greater than 250 mg/L) in Tom Green County.

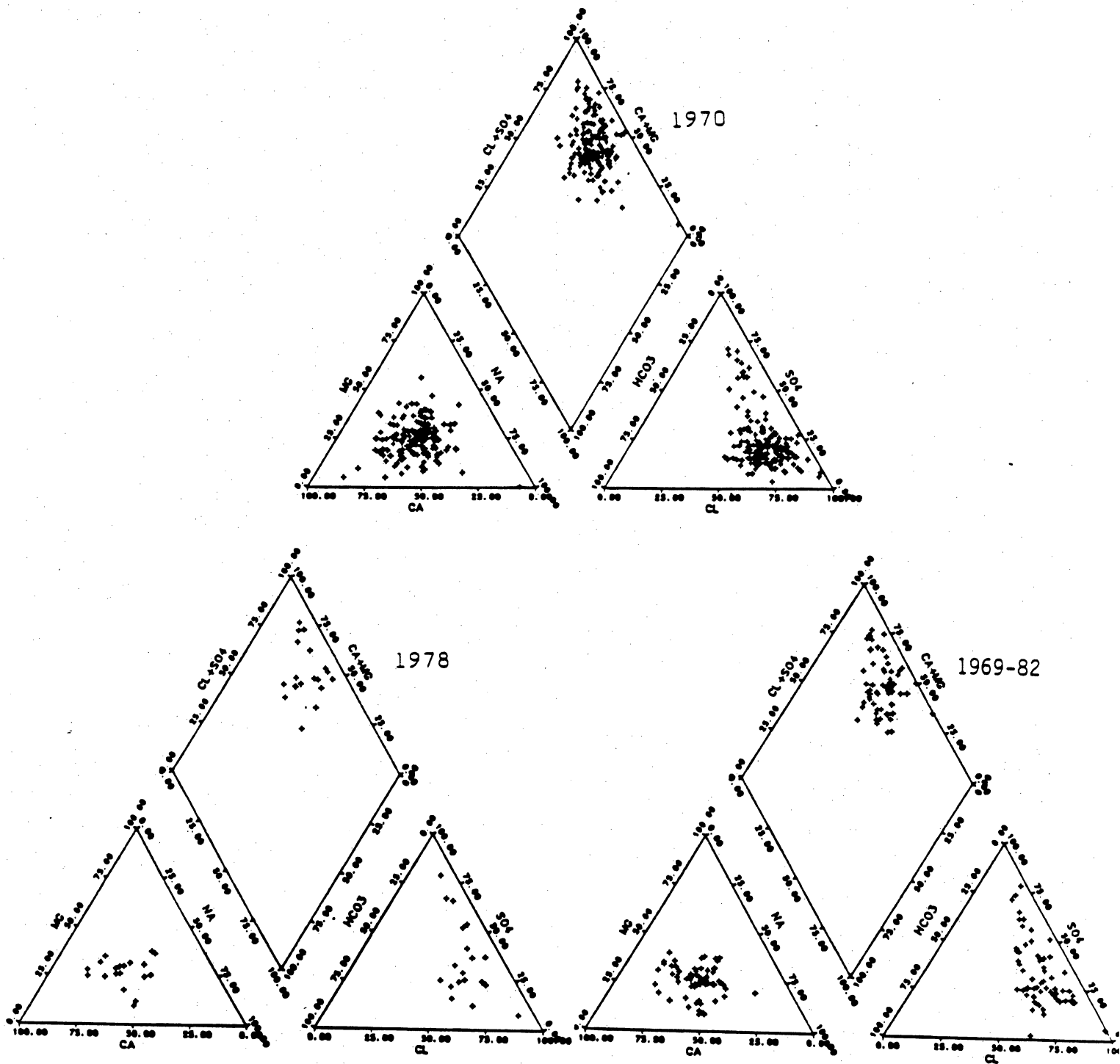
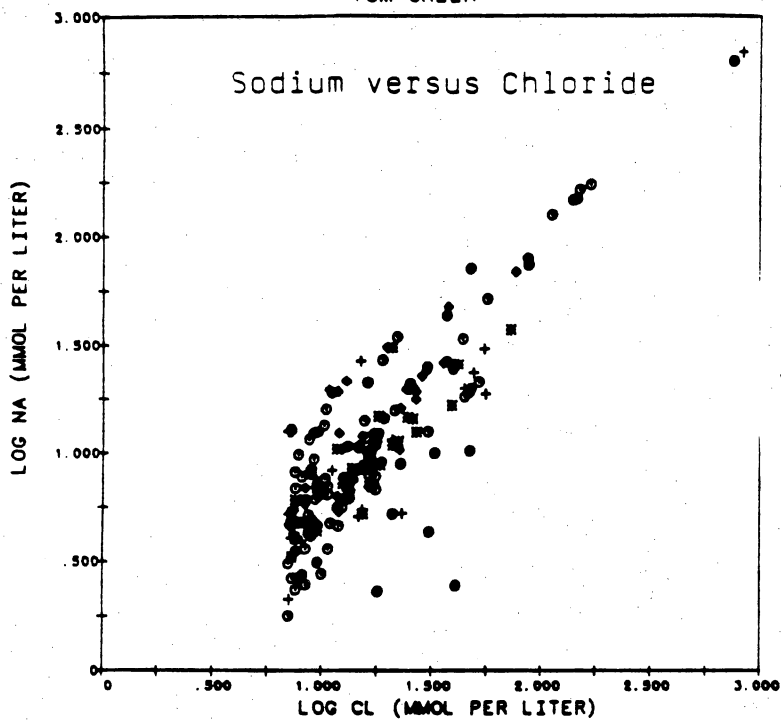
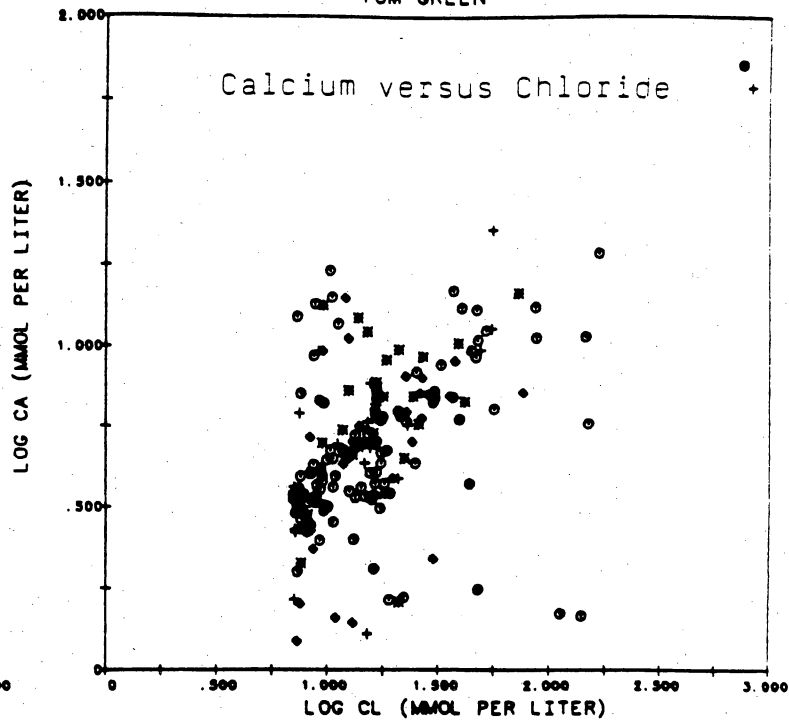


Fig.16 Piper diagrams of poor-quality ground water (Cl greater than 250 mg/l), Runnels County.

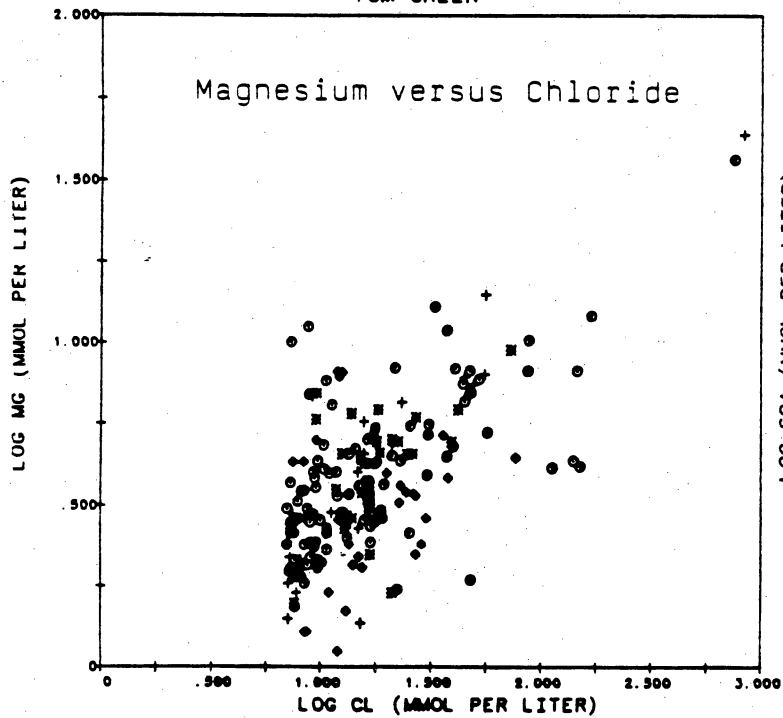
TOM GREEN



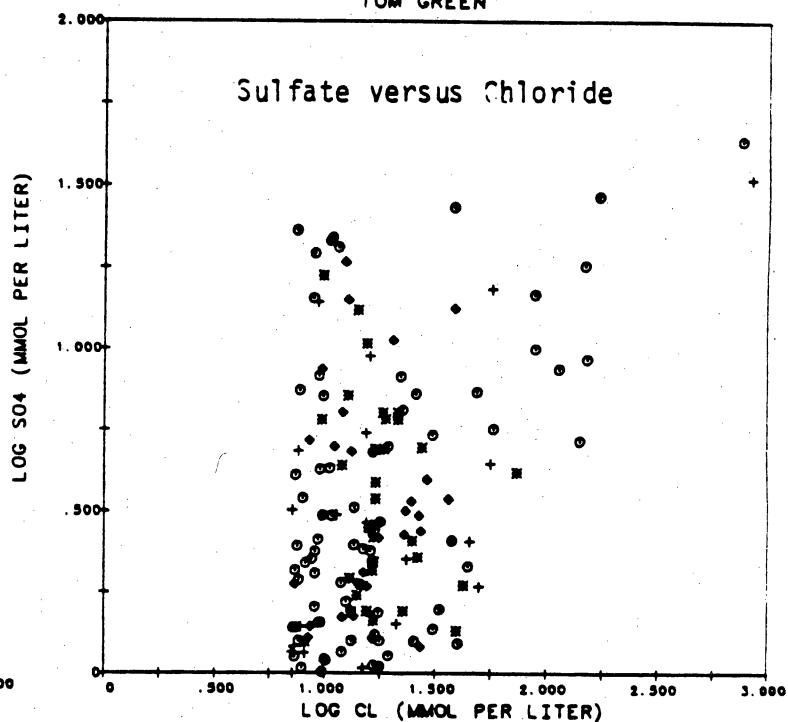
TOM GREEN



TOM GREEN



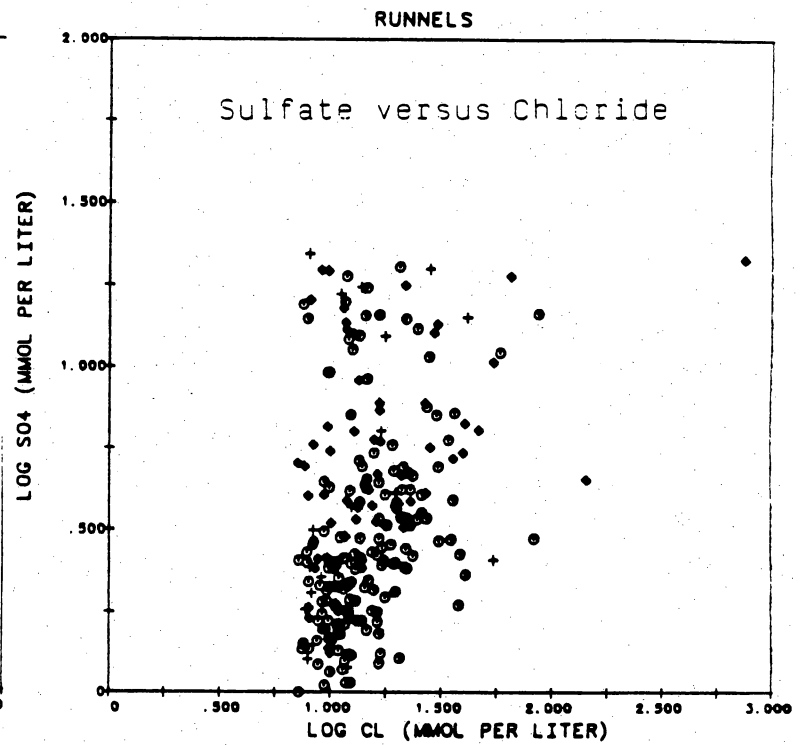
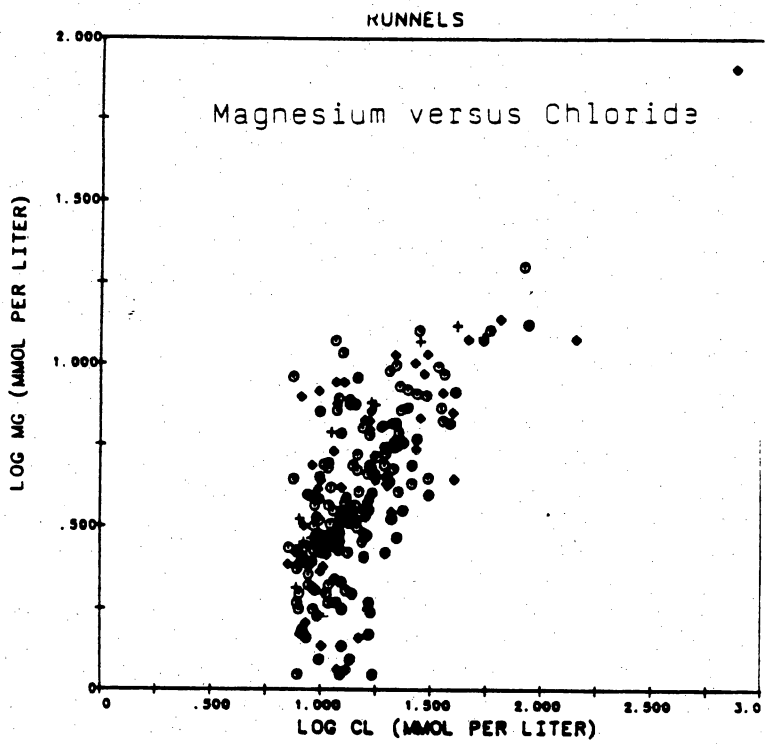
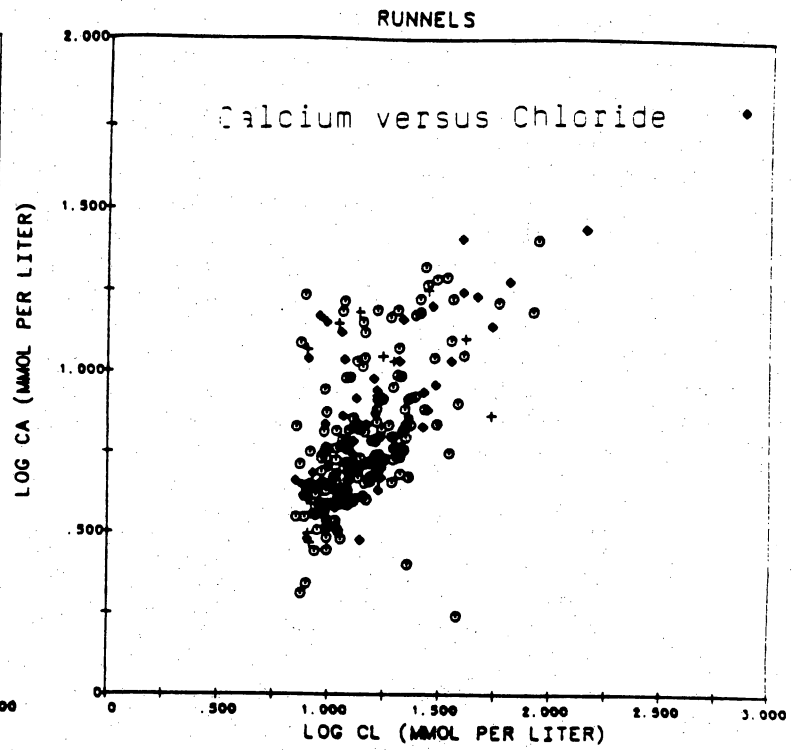
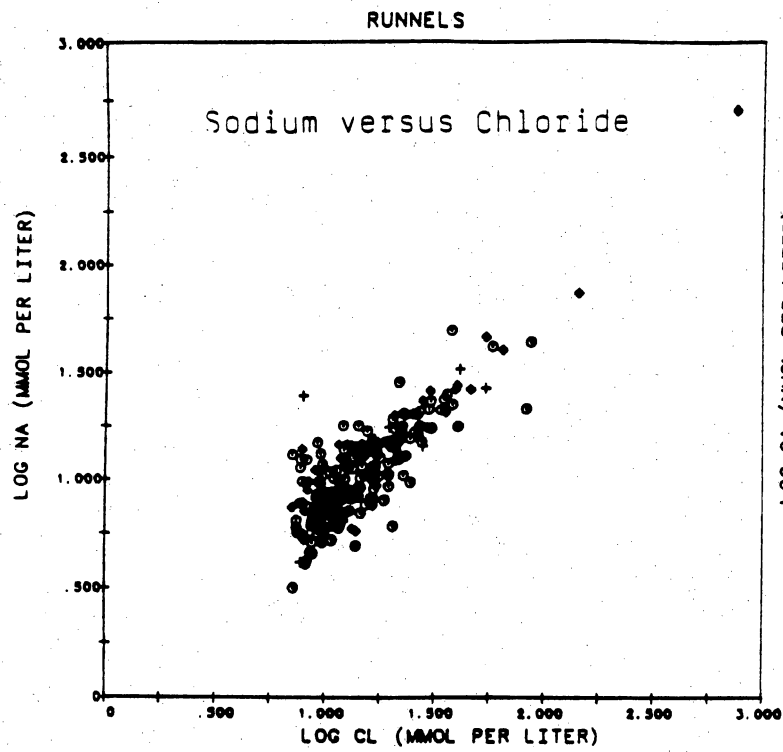
TOM GREEN



Legend

- 1940/41
- ◇ 1969-70
- + 1947-50
- * 1983

Fig.17 Chemical constituents in poor-quality ground water (Cl greater than 250 mg/L) in Tom Green County.



Legend



1970



1978



1969-82

Fig.18 Chemical constituents in poor-quality ground water (Cl greater than 250 mg/L) in Runnels County.

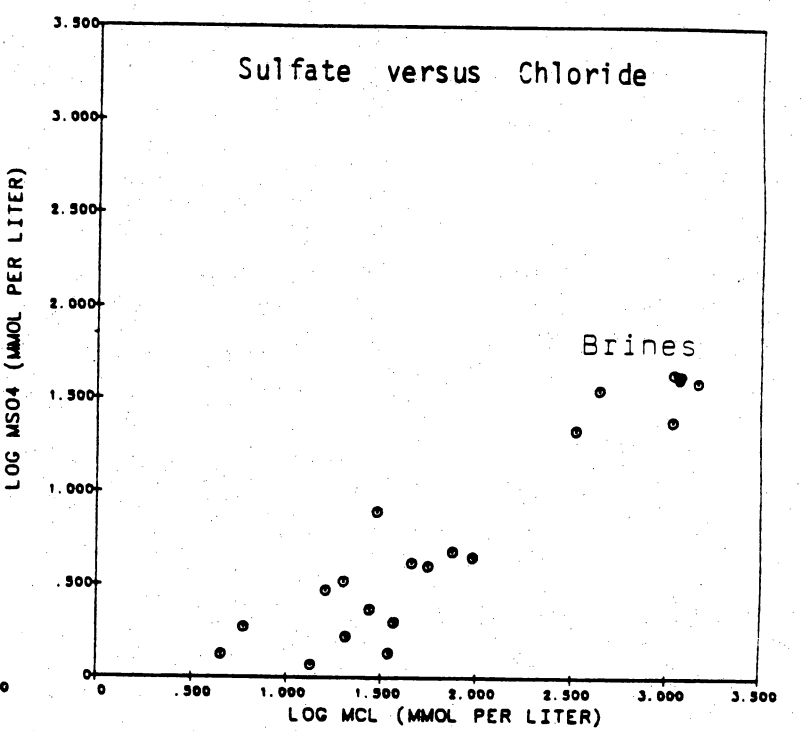
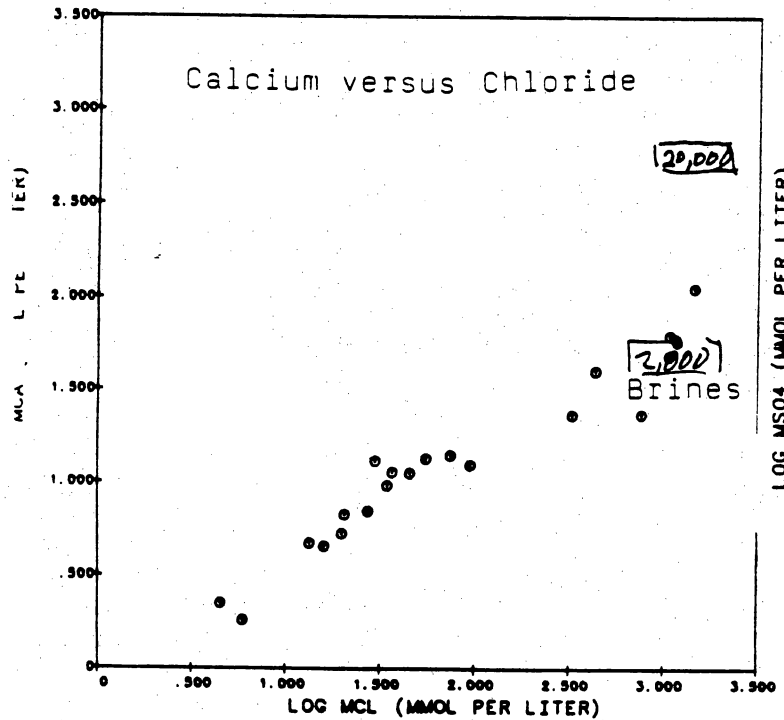
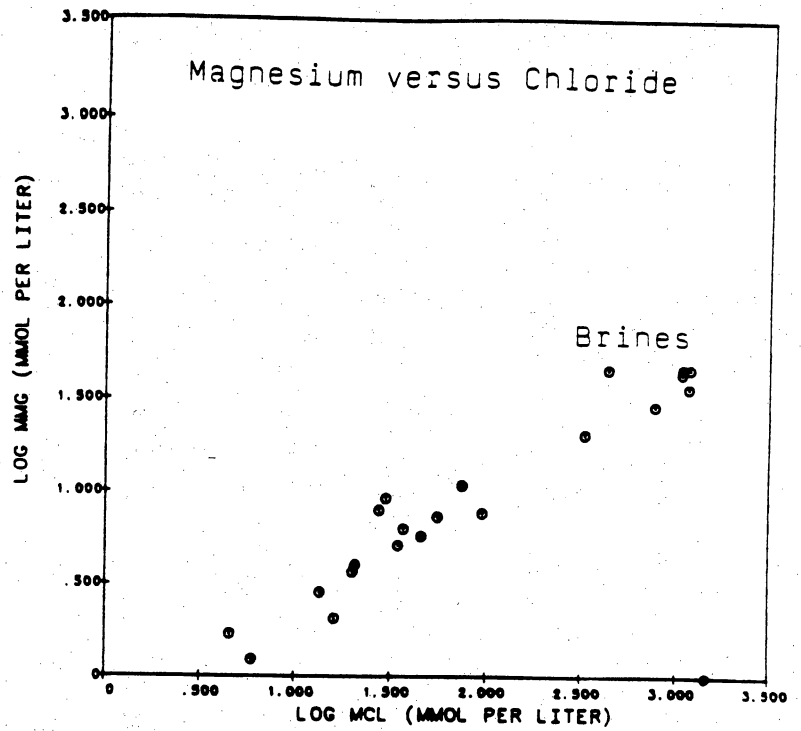
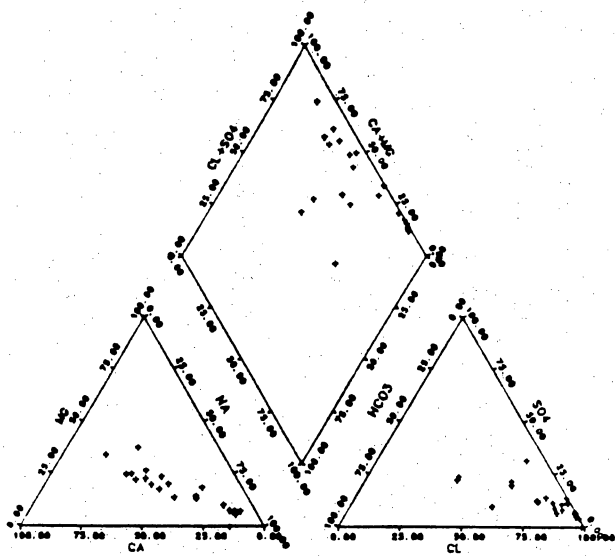


Fig. 19 Piper diagram and plots of chemical constituents for ground water in southwestern Tom Green County and for brines from brine aquifers underlying Tom Green, Runnels, and Concho Counties.

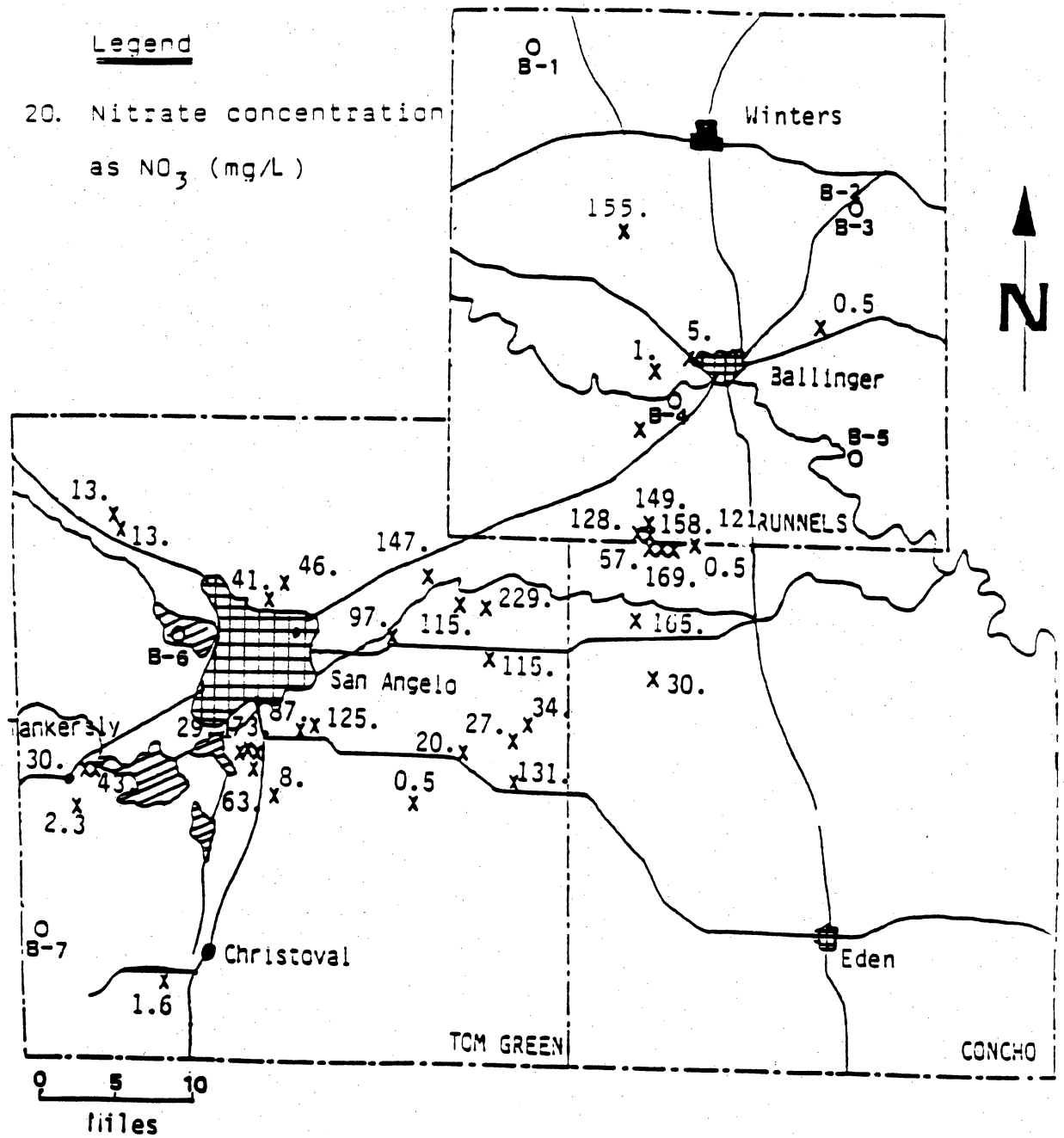


Fig.20 Nitrate concentrations in ground water in Tom Green, Runnels, and Concho Counties.

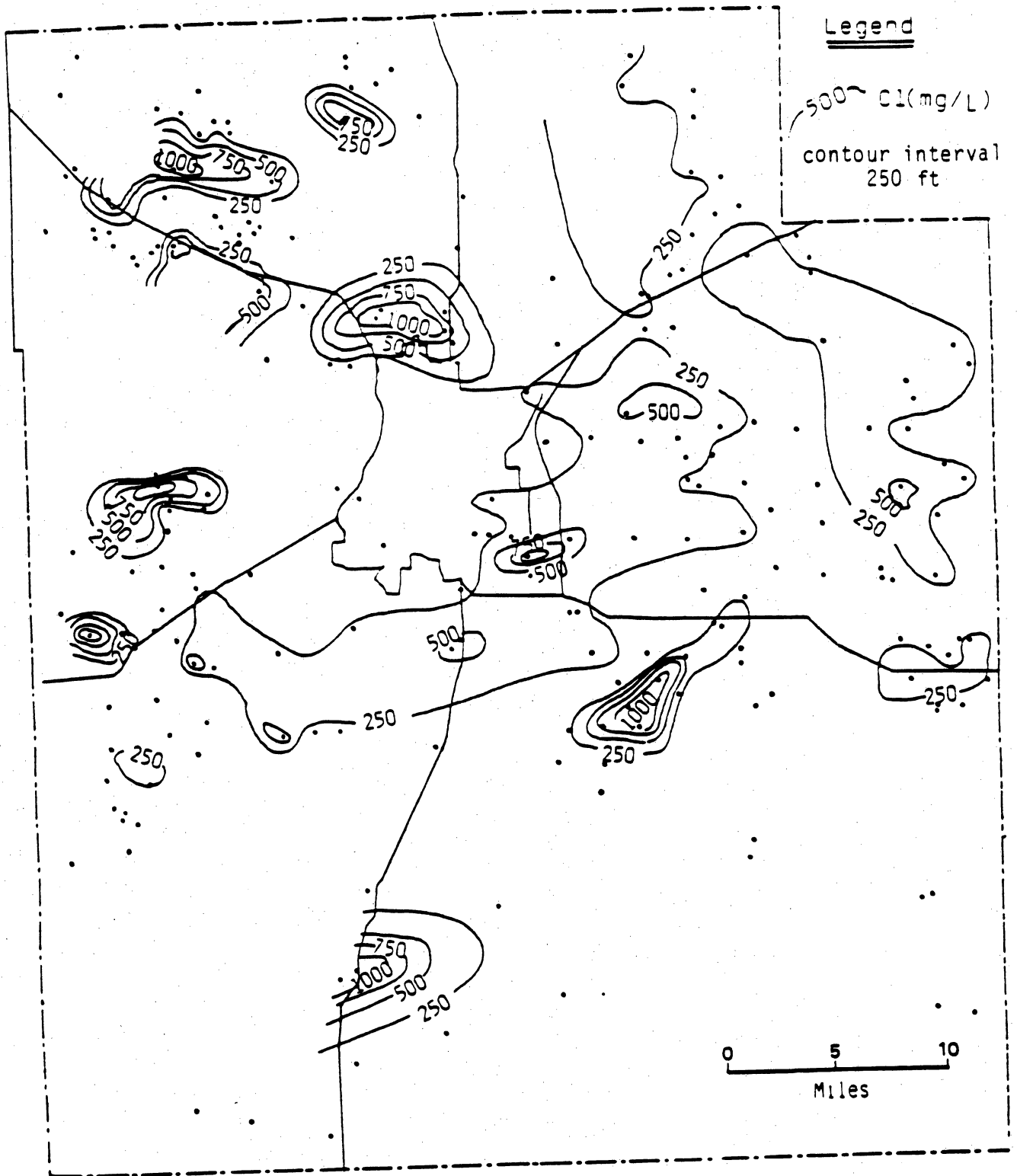


Fig.21 Iso-chloride map of ground water in Tom Green County,
1940-1941.

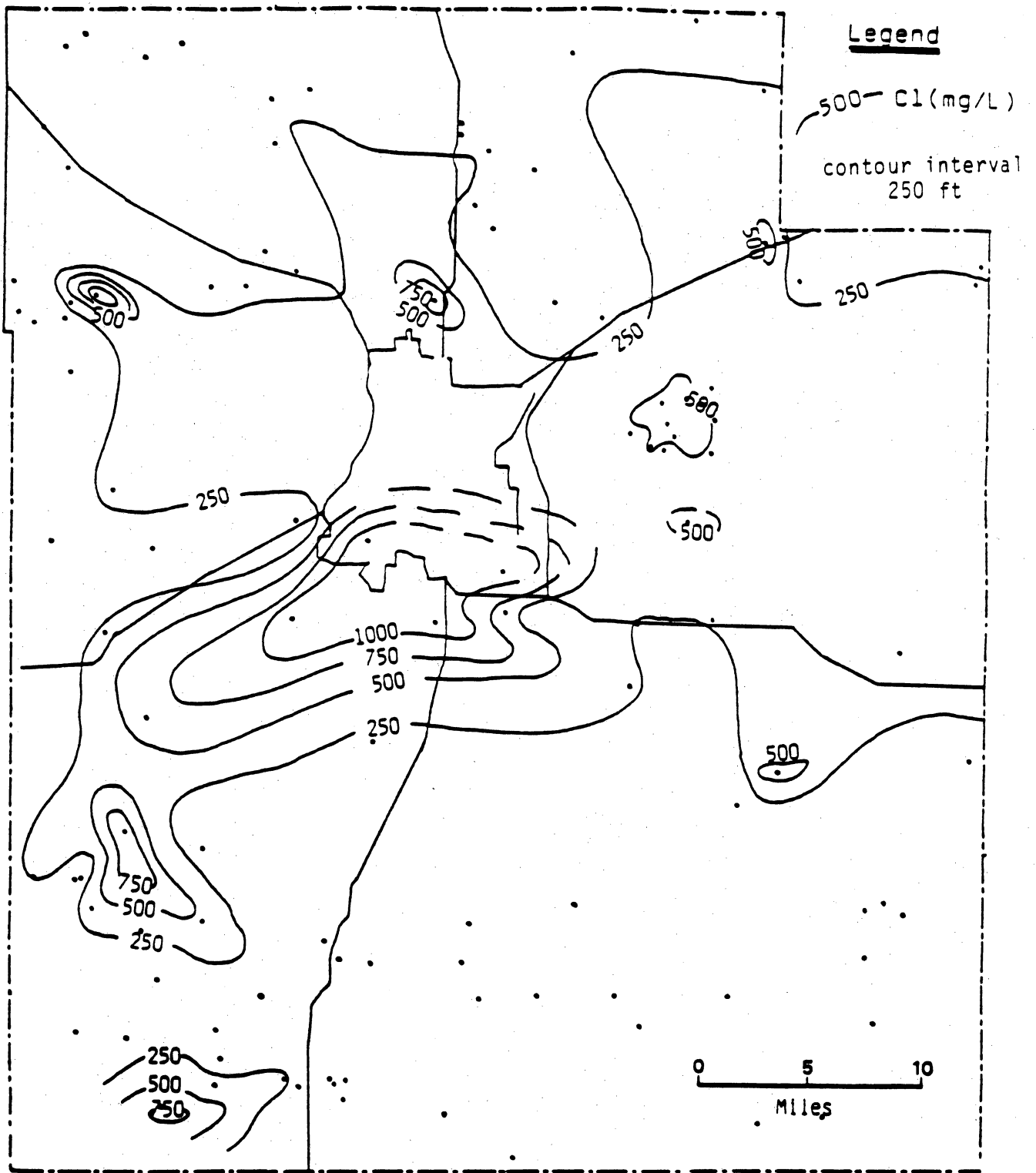


Fig.22 Iso-chloride map of ground water in Tom Green County, 1950, 1969, and 1983.

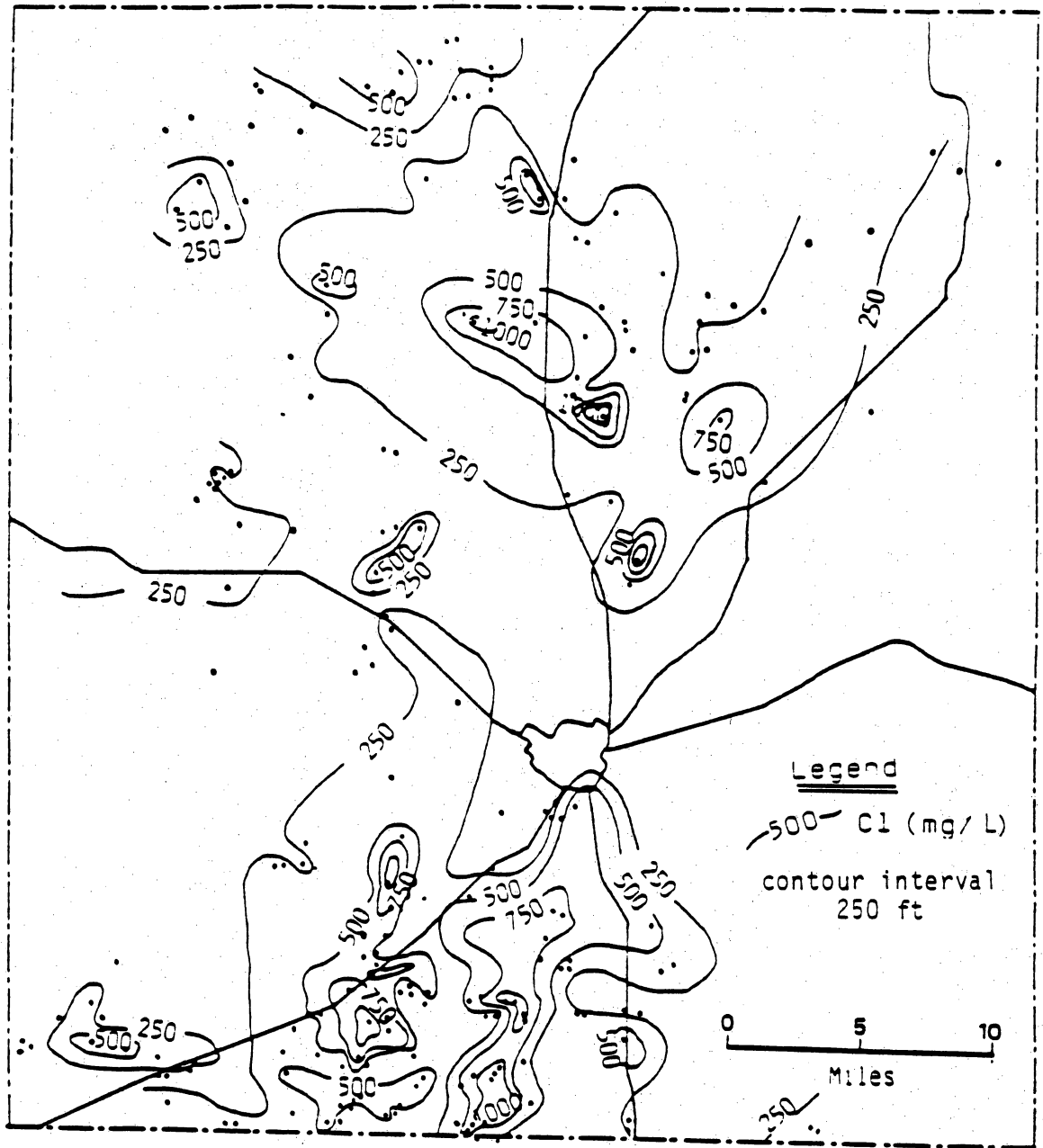


Fig.23 Iso-chloride map of ground water in Runnels County, 1970.