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DRAINAGE-BASIN EVOLUTION AND AQUIFER DEVELOPMENT IN A KARSTIC LIMESTONE TERRAIN SOUTH–CENTRAL TEXAS, U.S.A.[1]

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SUMMARY

The Edwards artesian aquifer occurs in cavernous limestones of Cretaceous (Albian) age within the Balcones fault zone in south–central Texas. The major recharge and discharge zones of the aquifer are contained within the upper reaches of three river systems: the Nueces, the San Antonio, and the Guadalupe. Within these watersheds, recharge dominates in the semiarid Nueces basin to the west while most discharge occurs farther east from wells in the subhumid San Antonio basin and from springs in the subhumid Guadalupe basin. This long-distance transfer of ground water (up to 240 km) is a result of several factors: depositional and early diagenetic history of the limestone host rock, geometry and magnitudes of fault displacement, and physiographic responses to faulting.

The loci of greatest discharge from the aquifer occur in an area that was exposed subaerially with concomitant porosity enhancement due to dissolution of limestone during late Early Cretaceous time. This area also was subjected to the greatest fault displacement during Miocene time. Thus, faults and associated joints superimposed additional avenues for porosity and permeability development onto an area that already had considerable secondary porosity. Further determinants on aquifer properties resulted from late Tertiary and Quaternary drainage evolution in response to faulting along the Balcones trend. The strike of the fault zone lay at acute angles to the courses of the main trunk streams in the ancestral Guadalupe and San Antonio River systems, whereas in the Nueces basin the trend of the fault zone was normal to the courses of the main streams. Thus, as a fault-line scarp began to form in the eatern basins, scarp-normal streams were incised rapidly into northwest-trending canyons. These steep-gradient streams captured the eastward-flowing major streams in the easten watersheds. These pirate streams incised into the aquifer at the lowest topographic levels within the region because of: 1. The sudden acquisition of extensive catchment areas in a subhumid area; and 2. Steep stream gradients that reflected the larger fault displacement in the east. The low topographic points of discharge became the loci of major springs.

Recharge is dominant in the Nueces basin mainly because streams cross permeable limestone units at higher topographic levels than in the San Antonio and Guadalupe basins. The topographic characteristics of the Nueces watershed resulted from a combination of diverse factors: lesser fault displacement, no major stream piracy, and less vigorous erosion because of a semiarid climate.

KEY WORDS Karst hydrogeology Recharge Stream piracy Spring discharge

INTRODUCTION

Karstic tablelands and highly dissected limestone terrains are the dominant landforms from the south-eastern Edwards Plateau to the Balcones fault zone in south–central Texas (Figure 1). These areas are

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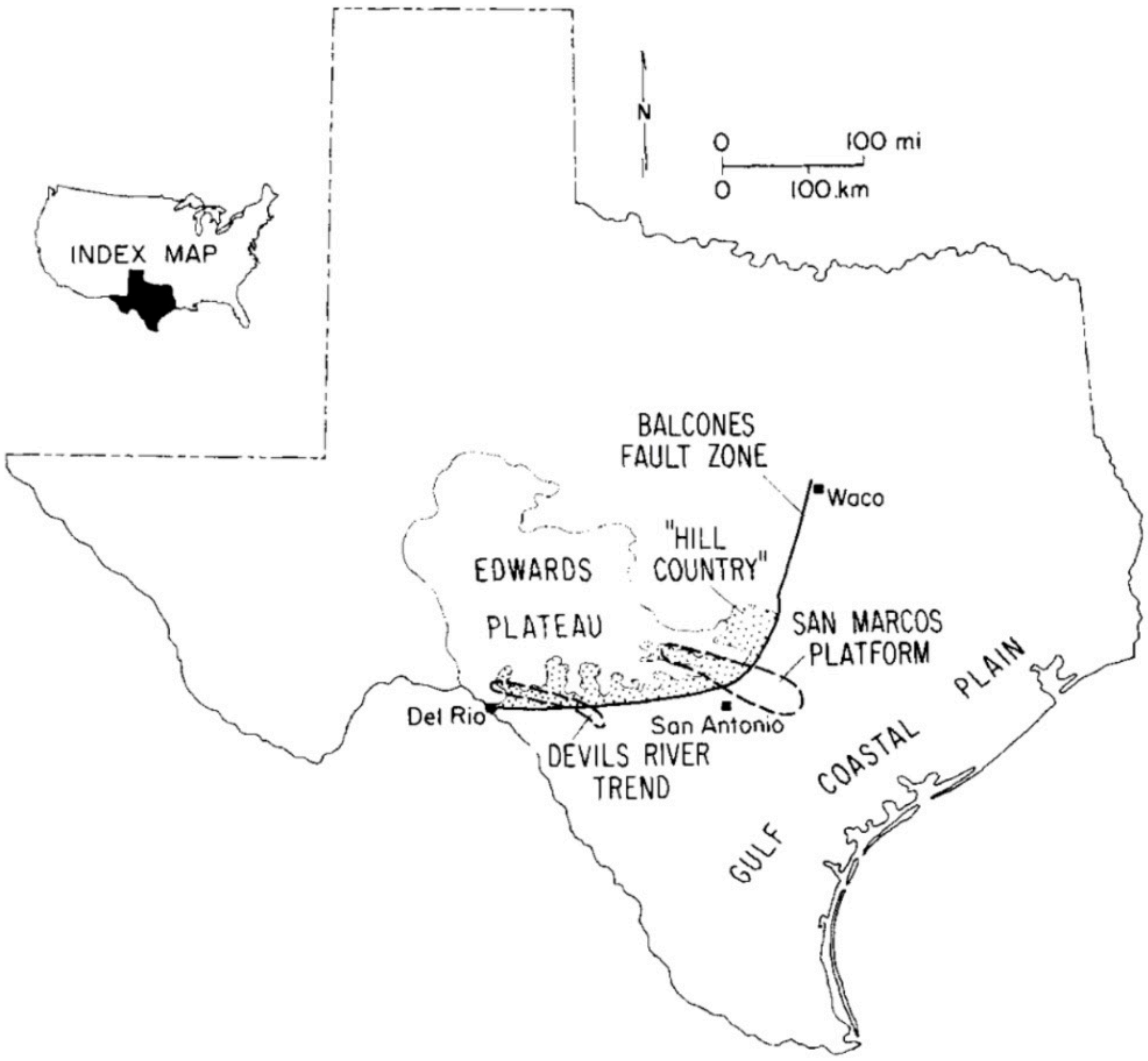


Figure 1. Regional physiographic and structural features, central Texas

drained by three river systems: the Nueces, the San Antonio, and the Guadalupe (Figure 2). Together, the upper reaches of the three drainage basins constitute an important hydrogeologic entity; they include the catchment watersheds, the recharge areas, and the discharge points for the central segment of the Edwards artesian aquifer. This central segment, delimited by the river-basin divides in Kinney and Hays Counties, is part of a larger cavernous limestone system that extends for over 400 km along the Balcones fault zone from Val Verde County on the Mexican border to Bell County in north–central Texas. The central part of the aquifer constitutes the main water supply for a region that includes the city of San Antonio and a population of more than one million people.

Previous studies (Sayre and Bennett (1942); Pettit and George (1956); Arnow (1963); Klemt and coworkers (1975)) have shown that interactions occur on a regional scale between surface streamflow and ground-water levels in the aquifer. It is reasonable to suppose that these interactions also occurred during earlier developmental stages of both the aquifer and the surface drainage network. The thesis proposed here is that within larger structural geologic and climatic controls, physiographic development near the Balcones fault zone predetermined both geographic configuration and magnitudes of recharge and discharge in the Edwards aquifer.

It is the purpose of this paper to examine the current regional geologic, physiographic, climatic, and hydrologic conditions existing in the upper parts of the Nueces, San Antonio, and Guadalupe drainage basins. Based on an integration of these conditions, hypotheses are proposed that account for regional recharge–discharge relations in which the bulk of recharge occurs in the western part of the central aquifer segment while the majority of discharge occurs in the east. It is proposed that these relations are in large measure due to stream piracy that chiefly affected the San Antonio and Guadalupe watersheds.

GEOLOGIC SETTING

Events that occurred during two time intervals were of critical importance for integration of subsurface and surface drainage systems: 1. During the Cretaceous Period when the Edwards Limestone was deposited,

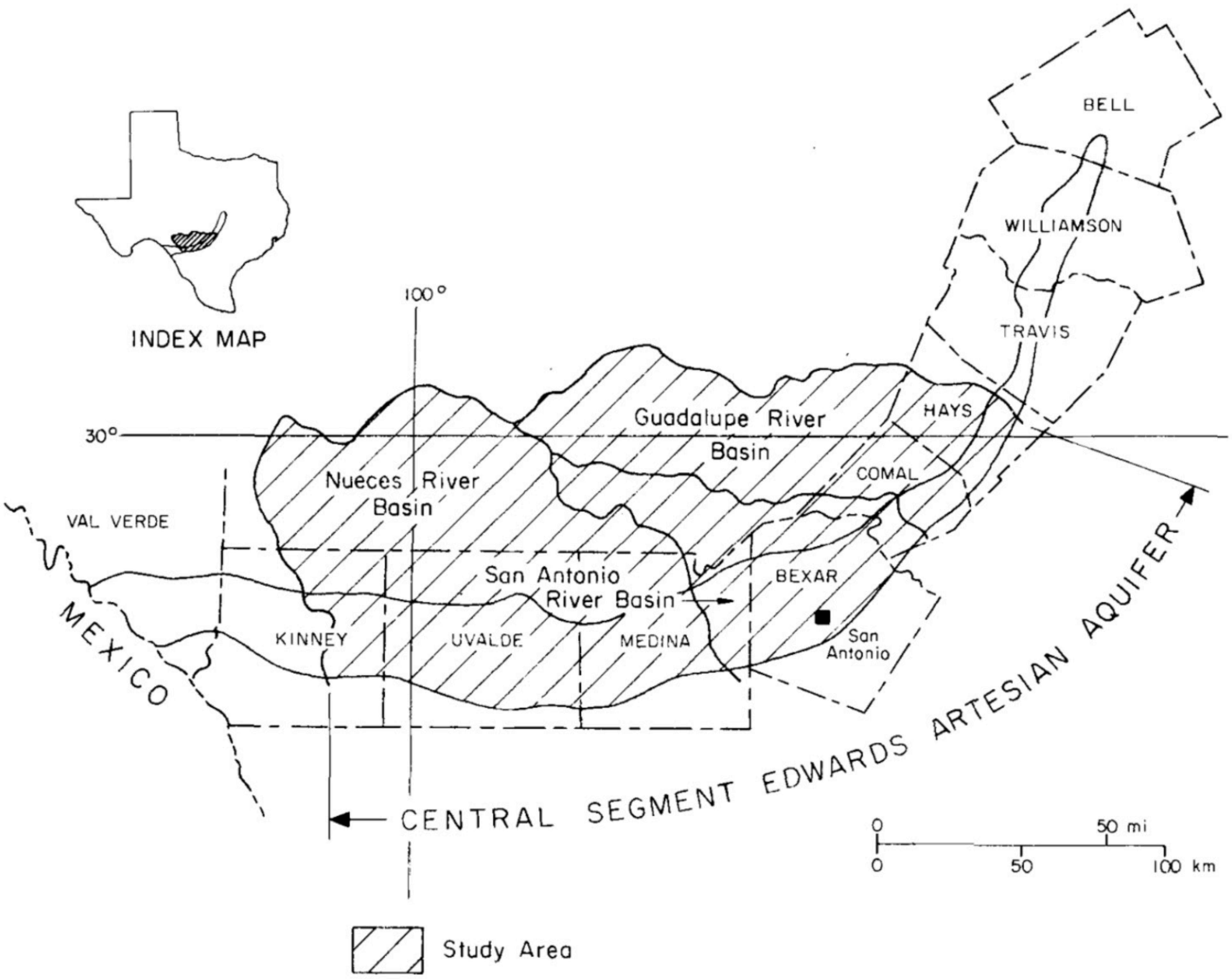


Figure 2. Location map showing study area that includes the upper parts of the Nueces, San Antonio, and Guadalupe River basins, and the central segment of the Edwards artesian aquifer

exposed subaerially, and buried; 2. During the Miocene Epoch when major episodes of Balcones faulting occurred, and the Edwards Limestone was exhumed.

Most aquifer development ultimately occurred within rocks of the Edwards Group that were deposited on the San Marcos platform and in the Edwards-equivalent limestones of the Devils River trend (Figure 1). According to Rose (1972), the San Marcos platform acted as an area of lesser subsidence upon which about 150 m of shallow marine and tidal flat sediments accumulated during the Albian Stage (Cretaceous). At the same time along the Devils River trend, roughly 300 m of grainstone and rudist boundstone were formed. Subsequent uplift along the northwest-trending axis of the San Marcos platform resulted in more than 30 m of the uppermost Edwards Group being removed by erosion during late Early Cretaceous time. This subaerial erosion was accompanied by pore space enlargement and cavern development resulting from meteoric water circulating in these carbonate rocks. Thus the part of the Edwards Group that makes up the present aquifer in Bexar, Comal and Hays Counties was on the San Marcos platform and received significant enhancement of porosity during Cretaceous time (Rose (1972, p. 55)). Notably, this is where discharge dominates today. The parts of the aquifer in Medina, Uvalde and Kinney Counties where recharge dominates at present were southwest of the axis of uplift and apparently received little, if any, solution enlargement of porosity during the Cretaceous. During the remainder of Early Cretaceous and throughout Late Cretaceous time the entire region was covered by shallow marine shelf waters. Deposition of argillaceous and micritic sediments resulted in the Edwards Group being covered on the San Marcos platform by 260 m of low-permeability rock. This burial sealed off the Edwards Group and precluded the circulation of ground water necessary to further increase porosity.

The region of the present-day Edwards aquifer was lifted above sea level near the close of Cretaceous time by the slow upwarping of the northwestern margin of the subsiding Gulf of Mexico. Continued deformation gave a generally southeastward dip to the sedimentary rock units in central and south Texas. At this time, deeply circulating ground water might have augmented earlier developed porosity, but as pointed out by Abbott (1975, p. 258) this ground-water system would have been largely static, having no means for egress. This would have resulted in chemical equilibration between host rock and the waters contained therein in chemical equilibration between host rock and the waters contained therein, thus preventing extensive cavern development at that time.

The dominant geologic feature presently seen in the region is the Balcones fault zone, a system of *en echelon*, mainly down-to-the-coast, normal faults that extend about 545 km from Del Rio on the Mexican border to near Waco in north–central Texas (Figure 1). The strike of individual faults within the study region is predominantly northeast–southwest, but the overall structural alignment subtly changes to a more east–west trend in the southwestern part of the region (Figure 3). Total stratigraphic displacement decreases from east to west. In Comal County total displacement is as much as 520 m (DeCook (1963)), resulting in a fault-bound exposure of Edwards Limestone between alternating beds of limestone, dolomite, and marl of the older Glen Rose Formation on the upthrown side of the fault system, and the less resistant chalk, clay, and marl units of younger Cretaceous age on the downthrown side. Juxtaposition of these diverse rock types resulted in compartmentalization of the aquifer into a belt less than 40 km wide that includes most of the recharge and discharge areas within the eastern basins. However, farther west, in Uvalde County, total displacement is only 215 m (Welder and Reeves (1962)). Because of this lesser fault

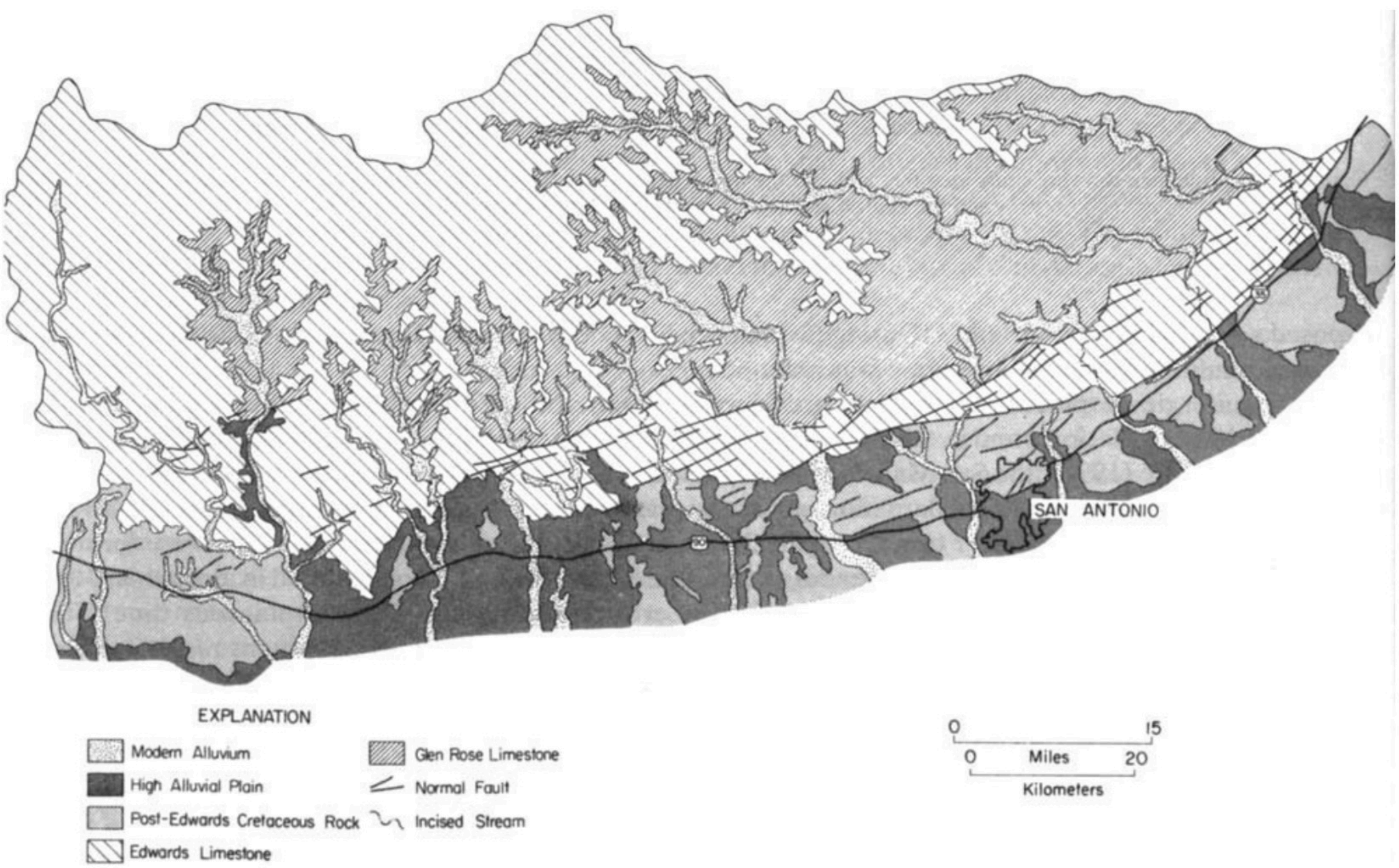


Figure 3. Generalized geologic map of study area (modified from Geologic Atlas of Texas, Virgil Barnes, project coordinator)

displacement, the Edwards Limestone crops out continuously across much of the Nueces basin, so that the aquifer is not confined to a narrow outcrop belt.

Major episodes of faulting probably occurred primarily during late Early Miocene (Young (1972)), as evidenced by the abundance of reworked Cretaceous fossils and limestone fragments in the fluvial sandstones (calclithite) of the Oakville Formation (Wilson (1956); Ely (1957)). This fault displacement markedly affected surface and subsurface drainage evolution by: 1. Controlling cavern development through creation of fracture porosity; 2. Establishing the impetus for heightened erosional activity of streams; and 3. Providing gross lateral boundaries for the aquifer host rock in the eastern river basins.

CLIMATE AND PHYSIOGRAPHY

In the western part of the region the climate is semiarid, with mean annual rainfall as low as 48 cm in some areas (Figure 4). This, coupled with high evaporation rates, has resulted in lesser streamflow and erosional potential of western streams compared to streams in the subhumid eastern basins.

An escarpment occurs along the main line of displacement within the Balcones fault zone, and it separates the low-relief terrain of the Gulf Coastal Plain from the ruggedly dissected hill country terrain to the north and west. The Balcones escarpment is less pronounced in the Nueces basin (60 m stratigraphic offset) compared to the escarpment in the San Antonio and Guadalupe watersheds (185 m offset). The highest topographic elevations within the study area occur in the headward reaches of the westernmost part of the Nueces watershed; likewise, the component rivers of the Nueces system cross the Balcones escarpment at generally higher elevations than do streams within the San Antonio and Guadalupe basins (Figure 5).

Component streams of the San Antonio and Guadalupe basins—notably Medina River, Cibolo Creek, and Guadalupe and Blanco Rivers—flow in their upper reaches in a roughly eastward direction, the projection of which is at an acute angle to the strike of Balcones faulting. Where these streams cross the resistant limestone in the fault zone there is an abrupt change in course to a trend roughly perpendicular to the fault-line scarp. Associated with these abrupt elbow turns there is incision into steep walled canyons. Asymmetrical drainage basins also occur, and there are relict erosional and depositional features on drainage divides near the elbow turns.

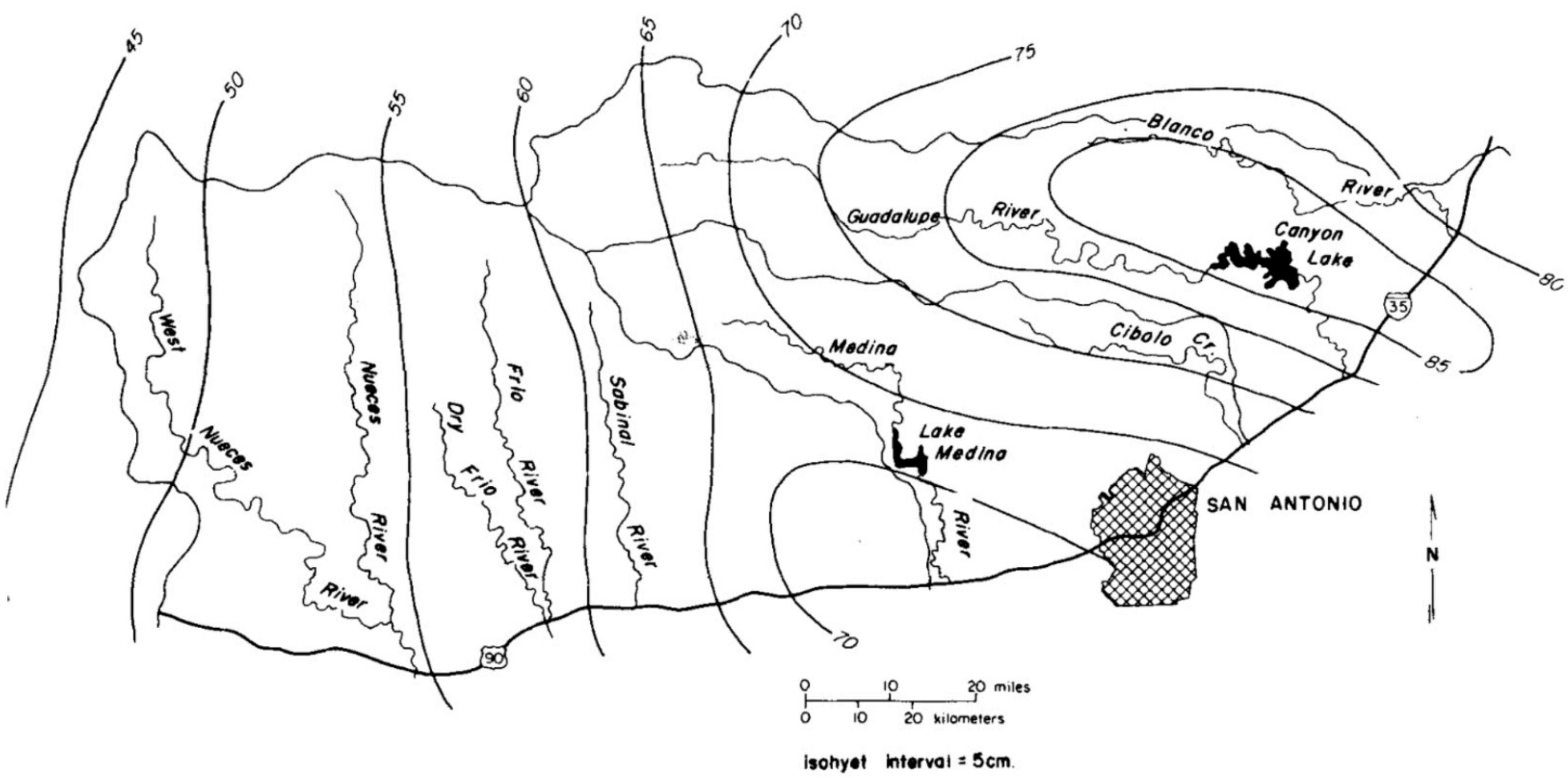


Figure 4. Mean annual precipitation (in centimetres) within study area

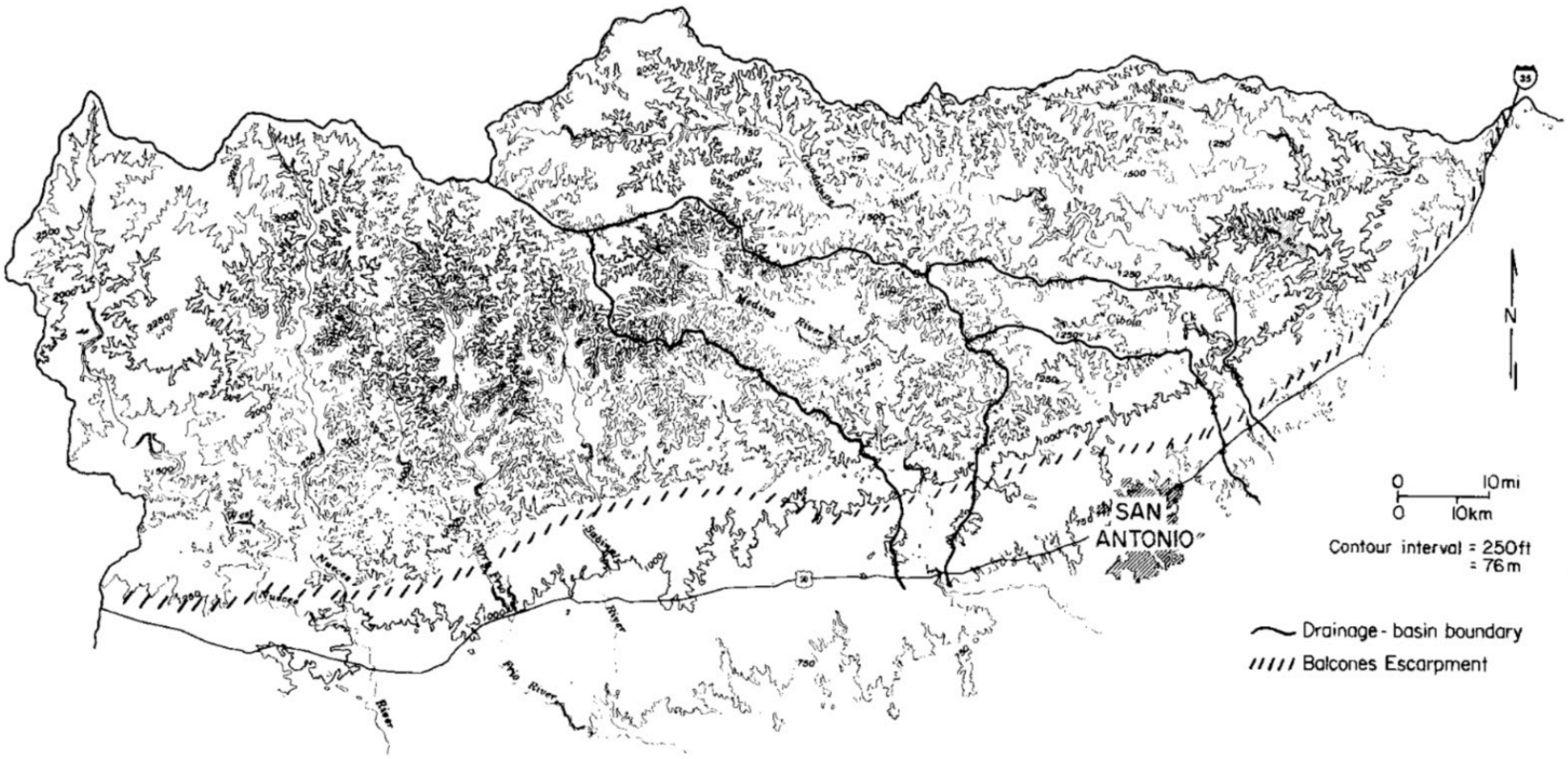


Figure 5. Generalized topographic map of study area showing major drainage divides and the Balcones escarpment

In the Nueces basin, streams trend throughout their entire upper courses in a generally southward direction. More extensive alluvial plains exist south of the main fault line in the Nueces basin than in the areas near the escarpment to the northeast (Figure 3). Also, streams of the Nueces system have generally broader alluvial valleys throughout their reaches, despite the fact that they transect large outcrop areas of resistant limestone strata that have overall properties similar to rocks occurring in those parts of the San Antonio and Guadalupe basins where steep-walled canyons have been eroded and where little or no alluviation has occurred.

Woodruff (1974; 1977) has postulated that stream piracy occurred in the upper reaches of the San Antonio and Guadalupe basins as a result of streams with steeper gradients eroding normal to the Balcones fault zone. No piracy of such large magnitude is evidenced in the Nueces basin. There are no elbow turns, asymmetrical basins, or relict fluvial features on divides between major streams. Thus, it is presumed that component streams of the Nueces system have flowed generally southward throughout their developmental history (Figures 6A, 6B, 6C).

HYDROLOGIC SETTING

The Edwards aquifer is generally considered to consist of two components—an unconfirmed (water-table) aquifer upstream from the main Balcones fault-line scarp, and a confined (artesian) aquifer within the eastern and southeastern part of the fault zone. Recharge to the water-table aquifer results from precipitation occurring throughout much of the Edwards Plateau (Figure 1). This ground water moves toward the southwest down the regional dip of the aquifer, discharging through myriad seeps and springs that provide base flow for component streams in the Nueces, San Antonio, and Guadalupe basins (Figure 7). The surface streams sustained by this spring-derived base flow eventually cross the highly fractured, cavernous limestones in the Balcones fault zone where infiltration into the confined aquifer occurs. Underflow directly into the confined aquifer without water being discharged first as surface flow accounts for about 6 per cent of recharge into the Edwards aquifer (William B. Klemt (written communication, 1977)). This underflow is probably especially important in the western part of the Nueces watershed. There, continuous exposures of Edwards Limestone allow underground hydraulic communication to occur throughout an area from the Edwards Plateau to the Balcones escarpment.

Most recharge occurs in two types of terrain—stream bottoms underlain by faulted or cavernous limestone, and low-relief terrain underlain by karstic limestones. Of these the more important is where streams cross permeable limestone. These recharge zones along bottomlands are especially apparent because stream discharge decreases through these reaches; dry or nearly dry streambeds are commonly incised into bedrock, and there is a concomitant attenuation of alluvial deposits.

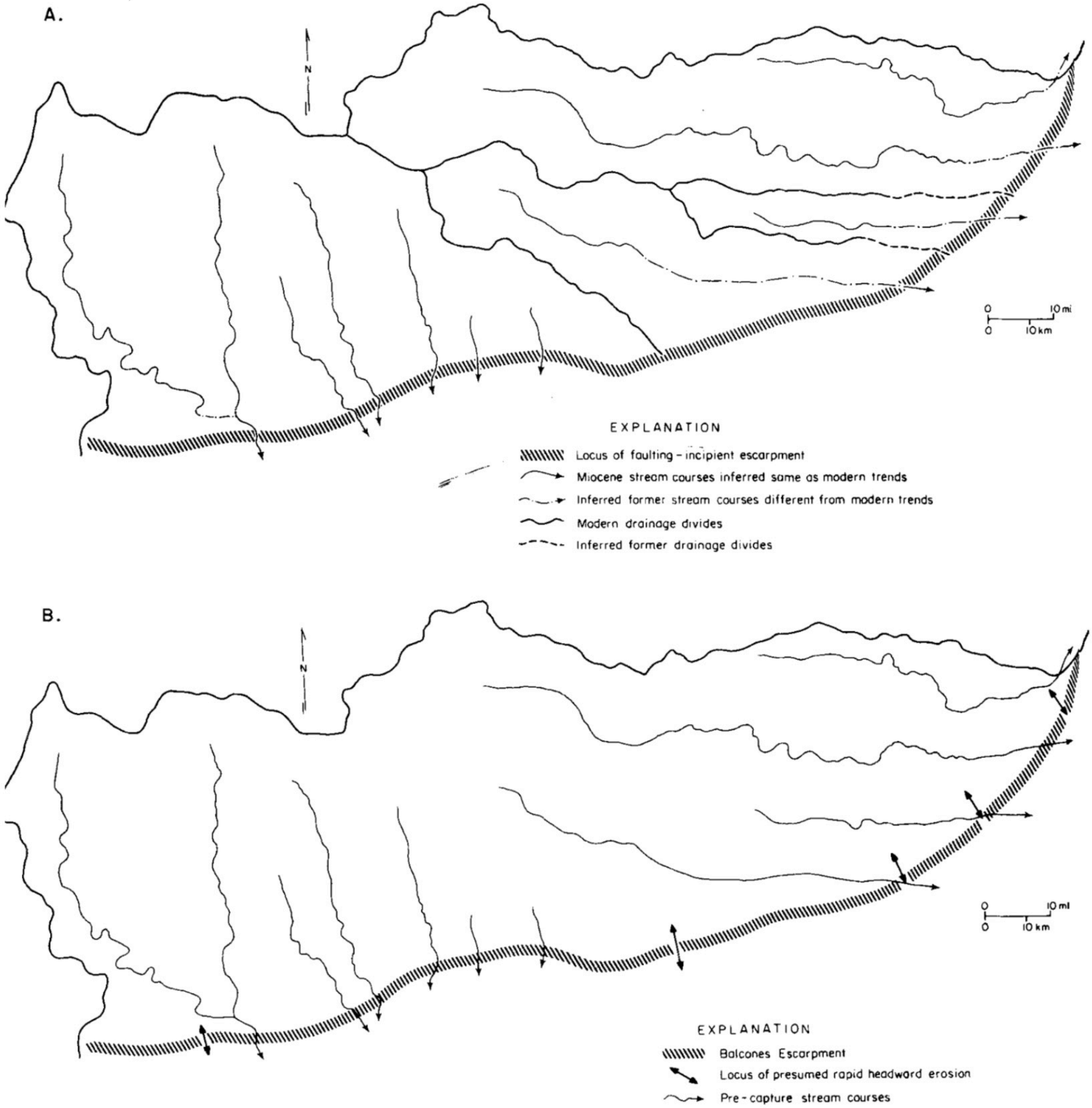
The local importance of recharge through stream bottoms is illustrated by comparing flow values for Guadalupe and Nueces Rivers. Guadalupe River, draining 3932 km^2 where it crosses the Balcones escarpment, has a mean flow of 10·54 m^3/s, which is about three times larger than the combined discharge of the Nueces and West Nueces Rivers where they flow together south of the fault zone (they have a watershed of 5043 km^2 with a mean discharge of 3·12 m^3/s). These differences in streamflow are due in part to rainfall deficiencies and increased rates of evaporation, but recharge is probably the main process responsible for these differences as indicated where the two Nueces Rivers, converge below the recharge zone. There their basin areas increase 74 per cent while their total discharge *decreases* 59 per cent (U.S. Geological Survey (1974)). No major recharge-loss is included in the Guadalupe River water budget (Table I), which is significant in demonstrating the self-ramifying processes active in this limestone aquifer. Where water is maintained predominantly in surface flow, more stream erosion and thus incision can occur; where water infiltrates underground, not only is there a lessened amount available to perform surface erosion, but because of soluble bedrock, recharging waters enlarge their flow paths, thus ensuring further underground infiltration.

About 55 per cent of the estimated annual recharge into the central segment of the confined aquifer occurs in the western part of the region supplied by the component streams of the Nueces basin (Table I). Most natural discharge occurs from springs along the Balcones escarpment—notably from Comal Springs and San Marcos Springs in the Guadalupe River basin (Figure 7). Most well discharge occurs in the San Antonio areas, and well pumpage is increasing with growing population demands. Total discharge from wells now often exceeds total discharge from springs (Klemt and coworkers (1975)).

Discharge values for wells and springs in the eastern part of the study area imply that porosity and permeability are best developed near the distal end of the ground-water flow system—in the areas farthest removed from the major loci of recharge. The role that caverns have played in this increased porosity is indicated by studies of caves in both the vadose and phreatic zones. A county-by-county enumeration of vadose caverns conducted by the Texas Speleological Survey documents an increase in the number of caves from west to east along the Balcones fault zone. As of August, 1977, there were 22 surveyed caves in Kinney County, 63 in Uvalde County, 38 in Medina County, 81 in Bexar County, 92 in Comal County, and 86 in Hays County. Thus, caves surveyed in the recharge zone number 123 compared to 259 in the distal (discharge) end of the fault zone (R. Fieseler (written communication, 1977)). Similarly, caverns have been shown to be major conduits for ground-water flow in at least part of the artesian aquifer; blind catfish have been found in waters discharged from wells as deep as 610 m (2000 ft) in the San Antonio area (Hubbs (1971)). Also, a notable cave fauna exists in the waters of San Marcos Springs (Tupa and Davis (1976)). Thus, several lines of evidence indicate that cavernous porosity is well developed and interconnected. The arcuate path of the Balcones Faults runs 240 km in a least-distance path from the western drainage divide in Kinney County to San Marcos Springs; some ground water travels at least this far.

STATEMENT OF PROBLEMS

The general geologic, physiographic, and hydrologic conditions within the study area pose problems with: 1. Why there was an initial impetus for transfer of water from the semiarid west to the subhumid eastern part of the region; 2. Why the largest single (integrated) basin in the region, that of the Guadalupe River proper (23 per cent of all three basin areas), contributes insignificant amounts of recharge where it crosses the fault zone; and 3. Why the eastern river systems incised more vigorously into lower topographic levels to create initial discharge sites (potentiometric base level) that controlled aquifer development. These problems can be resolved by considering surface drainage evolution and aquifer development as two facets of a holistic picture.



DRAINAGE-BASIN EVOLUTION

Stream piracy provides a key to deciphering the evolution of surface drainage in the region. The gross geometrical evidence for stream piracy in the Guadalupe and San Antonio River basins exists (Figure 5), but the presumed piracy events are perhaps as old as early Neogene. Thus, no clear-cut response is expected in present stream regimens or deposits, nor is any such response observed. Any evidence for this piracy must occur only on the drainage divides, yet fluvial deposits on drainage divides underlain by resistant

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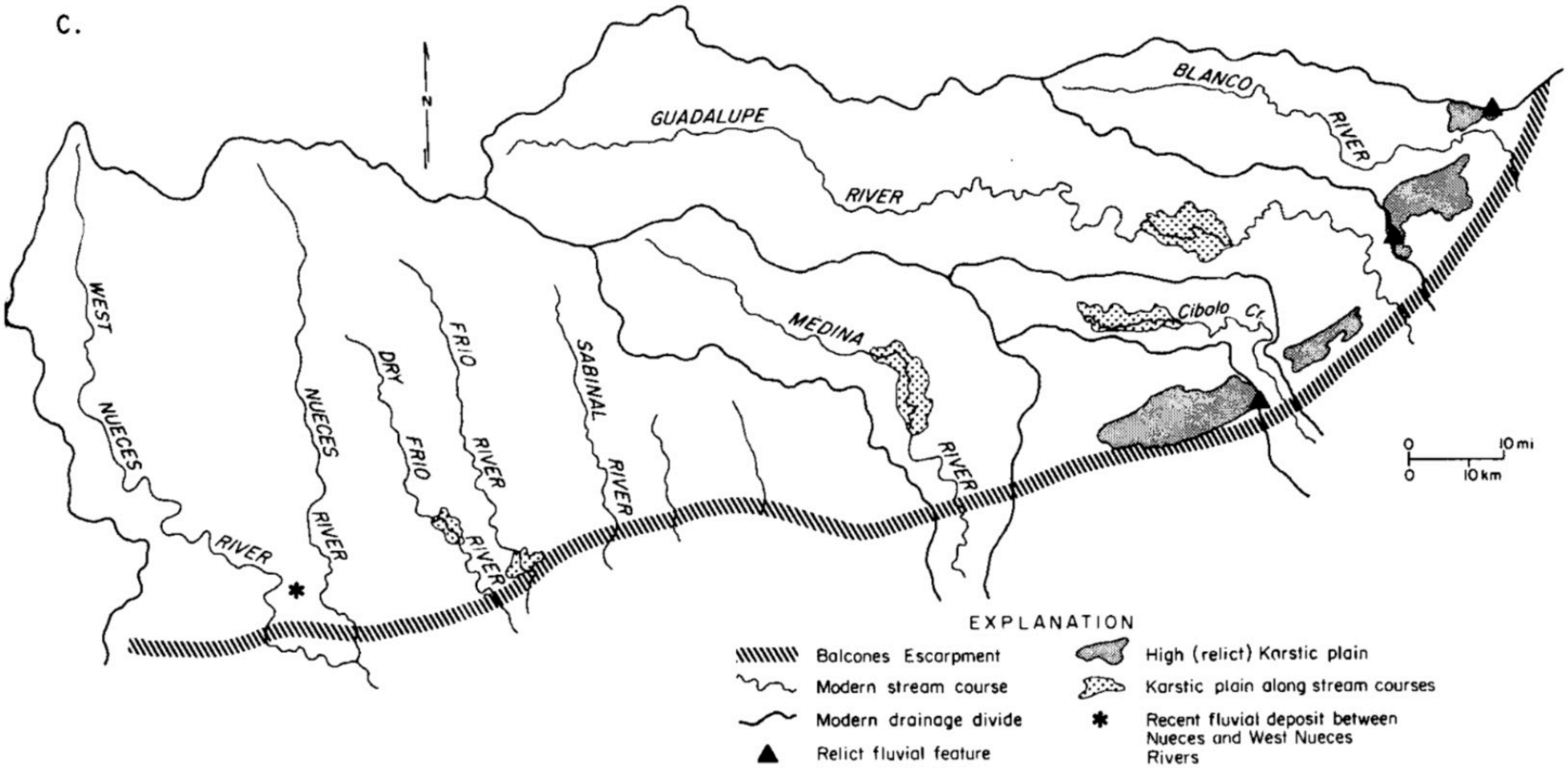

Figure 6. Schematic illustration of drainage-basin evolution as related to Balcones faulting and subsequent stream piracy: A. Pre-faulting stream net and drainage-basin geometry; B. Locations of pirate streams eroding headward normal to Balcones escarpment; C. Modern stream net and drainage-basin geometry; also relict and modern karstic plains, and locations of relict fluvial features on divides

bedrock in a highly dissected terrain are highly susceptible to erosion. Nonetheless, scattered fluvial features do occur on uplands in the hill country, and notably, these features occur on drainage divides near some of the abrupt elbow turns in present streams (Figure 6C). The point is worthy of emphasis. The *only* river-laid deposits that occur in the uplands of the hill country exist in areas that would be predictable from regional geometrical features assuming that piracy occurred! Furthermore, the geometry and topographic position of fluvial gravel deposits on the Coastal Plain support the geometrical evidence seen in stream-nets and drainage-basins. This is done by extrapolating depositional trends on the Coastal Plain 'upgradient' to relict fluvial features on drainage divides as demonstrated by Woodruff (1977, p. 487).

Preservation of fluvial features in the hill country is associated spatially with upland karstic plains delineated in a regional mapping effort by the Bureau of Economic Géology (Wermund and coworkers (1974)). Karstic plains have afforded avenues for subsurface infiltration of water rather than the channelling of most incident precipitation into surface drainage courses. Because of gentle slopes, resistant bedrock, and predominant subsurface infiltration of water on these karstic plains, the drainage density is low (Woodruff (1975, p. 25)). Thus, karstic plains are an ideal locality for the preservation of relict landforms.

The hydrogeologic significance of karstic plains relates to inferred changes in locations and magnitudes of recharge and discharge. Modern low-lying karstic plains in the study area are the loci for the 'recharge caverns' of Thrailkill (1968). High rates of recharge probably once occurred in the eastern as well as the western basins, as evidenced by karstic plains and the large number of vadose caves, on the eastern divides. Although the loci of discharge of these waters can only be inferred, an eastern river (such as the Guadalupe) would have had a somewhat lessened discharge and lower erosion rate due to water losses into the cavernous aquifer—this despite a larger catchment area and a presumed higher rainfall rate compared to basins farther west.

Lowering of base level due to piracy plus high surface discharges from the subhumid Guadalupe River basin combined to produce the highest erosion rates of the entire region. In terms of downcutting, this river has acted as would be expected from its erosional capabilities; it is deeply incised. Thus, if any stream in the region should have a thoroughly dissected basin, with maximum hillslopes and minimum hilltops, it should

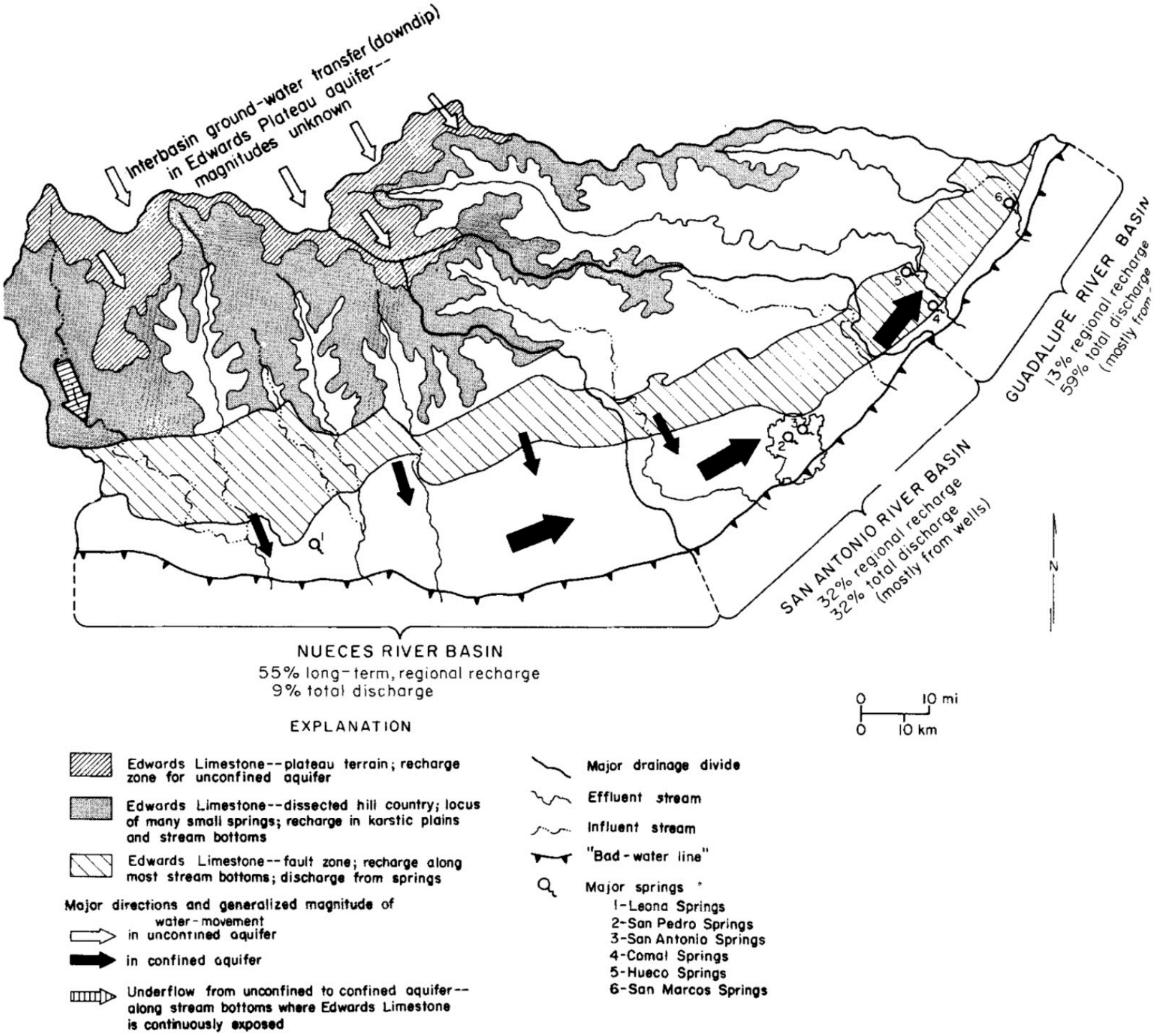

Figure 7. Generalized hydrologic setting of study area; note especially the distinct geographic separation of the Edwards Plateau aquifer from the Edwards (fault zone) aquifer in eastern basins, while in the west no distinction occurs because of continuous outcrops of Edwards Limestone

be Guadalupe River. Yet, the most completely dissected basins occur within the Nueces system, and the most extensive upland karstic plains occur in the Guadalupe watershed. This seems to indicate either drastic changes in underlying bedrock or differences in prior drainage history. Bedrock is the same regionwide, but stream piracy affords a means for explaining this observed result. The deep incision by Guadalupe River ultimately accomplished two things: 1. Erosion provided topographically low points for spring discharge that became established as base levels toward which most of the artesian aquifer flowed, and 2. Incision occurred at such a high rate that most of the upper aquifer levels were completely breached, and discharge from the aquifer (instead of recharge into it) became the major process.

Part of the aquifer system draining to San Marcos Springs apparently does extend beneath Guadalupe River, and the Edwards Limestone crops out along a short reach of this deeply-incised river. Yet, as noted previously (Table I), no long-term recharge is shown to have occurred for Guadalupe River. This anomaly may be explained by the relatively small cavernous area within the part of the aquifer that underlies Guadalupe River and that feeds the San Marcos Springs underground catchment area. That is, the pore space beneath Guadalupe River may be essentially full of water under normal climatic conditions, and only during extreme drought conditions might this cavern system be able to accept recharge from Guadalupe River. This thesis is substantiated to some extent by the lesser fluctuations of discharge from San Marcos Springs during times of drought compared to the normally larger Comal Springs (Brune (1975)). Further substantiation is provided by analysis of tritium data (Pearson, Rettman and Wyerman (1975)) indicating that the water flowing from San Marcos Springs is younger than the water discharged from other major springs. This implies a significant admixture of water recharged from the southwest in a separate, local cavern system parallel to the main aquifer (Abbott (1977a)).

DEVELOPMENT OF THE EDWARDS AQUIFER

As soon as the Edwards Limestone was breached by pirate streams, pent-up ground water was released from the proto-aquifer, thus beginning the engrainment of the flowpaths of ground water moving toward these low-elevation discharge points (Figure 8C). Continual region-wide ground-water circulation developed as component streams of the Nueces system exhumed the structurally higher Edwards Limestone in the western basins (Figure 8D). Downcutting was less rapid there because of lesser fault displacement, because there was no piracy-initiated increase in discharge, and, presumably, because the climate was drier then, as now. Ultimately, broad expanses of limestone were exposed along stream courses within the Nueces River basin at relatively high topographic elevations, and these areas became the main loci of recharge.

Interconnection among the drainage catchment areas by fault-generated fracture systems allowed long-distance interbasin ground water transfer from the topographically higher western areas to the lower, more permeable discharge points to the northeast. This set in motion the continuously circulating, self-ramifying ground water flow system that converged toward the loci of the few springs. Thus, the initial discharge sites became the 'drains' for the aquifer, drawing on waters throughout the several drainage basins that encompass more than 17,965 km^2.

It has been pointed out by Sayre and Bennett (1942) and by Arnow (1963) that the apparent potentiometric gradient of the confined aquifer is perpendicular to the trend of faulting, whereas the main direction of flow is parallel to the strike of the fault zone. This seeming anomaly is explained by the structural control of cavern development wherein the main transmission of ground water occurs in large conduits (pipe flow) developed and enlarged by solution along, or subparallel to, the trace of major faults (Figure 9). Abbott (1975) pointed out that this apparent anomaly is actually a problem of scale; if wells were sufficiently close together then the correct potentiometric gradient could be shown to be parallel to fault trends. Abbott proposed further that the regional scale relations between aquifer thickness (150 to 200 m) and aquifer extent along strike (280 km in central segment) indicate that individual trends in porosity development, whether interparticle or cavernous, are insignificant compared to overall water-transmitting properties of the complete aquifer body. Thus, considered in its entirety, the Edwards Limestone in the fault zone behaves like a nearly homogeneous, porous, permeable medium—a master conduit for transmission of water.

The ancient engrainment of the aquifer helps explain noteworthy features of the present Edwards aquifer system such as the paucity of springs and the origin of the 'bad-water line'. Although the Edwards (fault zone) aquifer is about 400 km long there are only about a dozen large springs discharging from the system (Sayre and Bennett (1942)). Only six of the major springs occur in the 280 km long central segment: Leona Springs in Uvalde County; none in Medina County; San Antonio and San Pedro Springs (4 km apart and rising along the same fault) in Bexar County; Comal and Hueco Springs in Comal County; and San Marcos Springs in Hays County (Figure 7). These springs issue forth at progressively lower elevations to the northeast, and all but Leona Springs occur near major pirated streams. They probably discharge from enlarged lower-level conduits of initial flow systems honed to the earliest discharge sites. That is, the loci of discharge probably migrated to progressively lower topographic levels dictated by the changing base levels

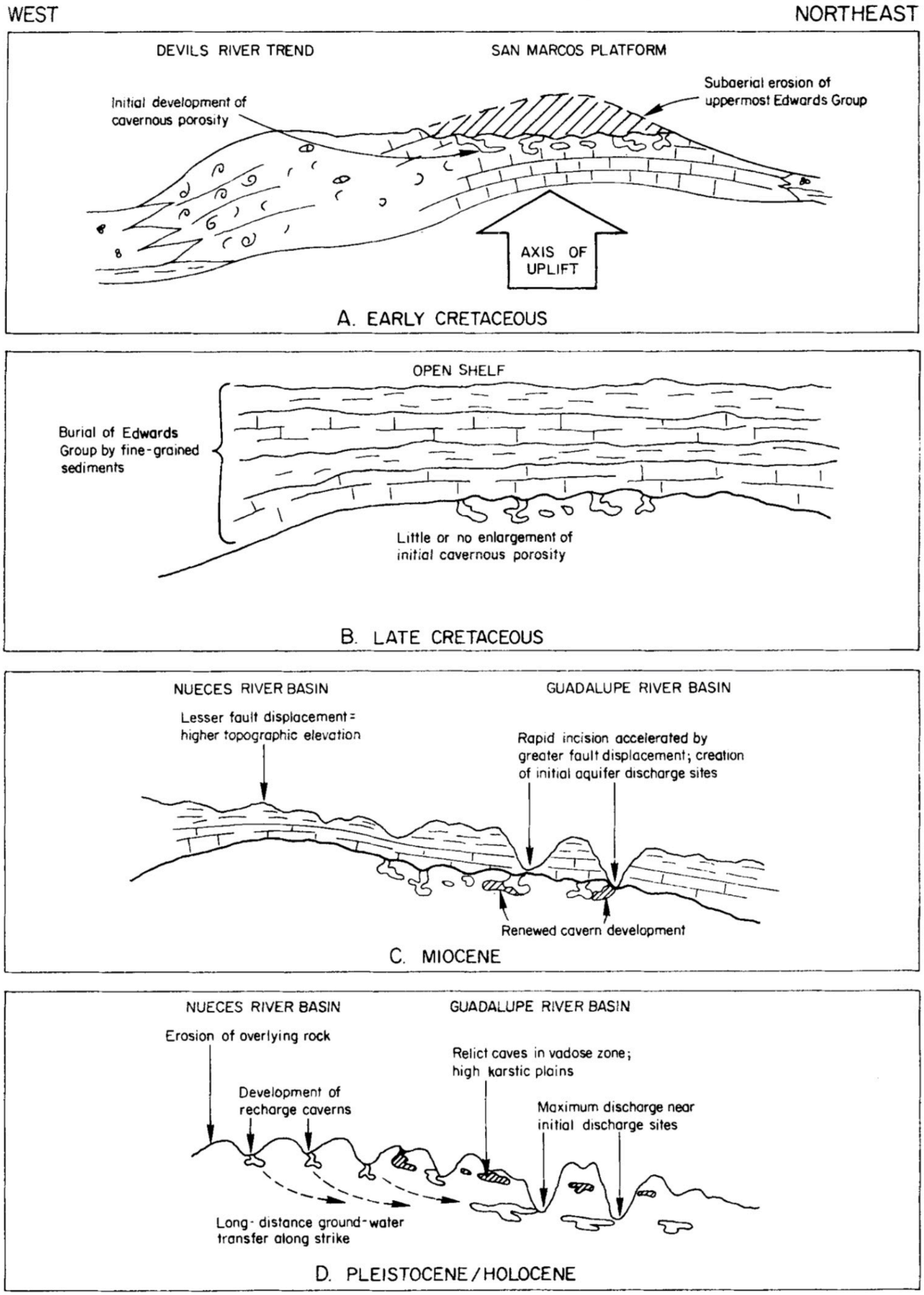

Figure 8. Schematic cross sections showing sequential development of the Edwards Aquifer (modified from Rose (1972) and Abbott (1975))

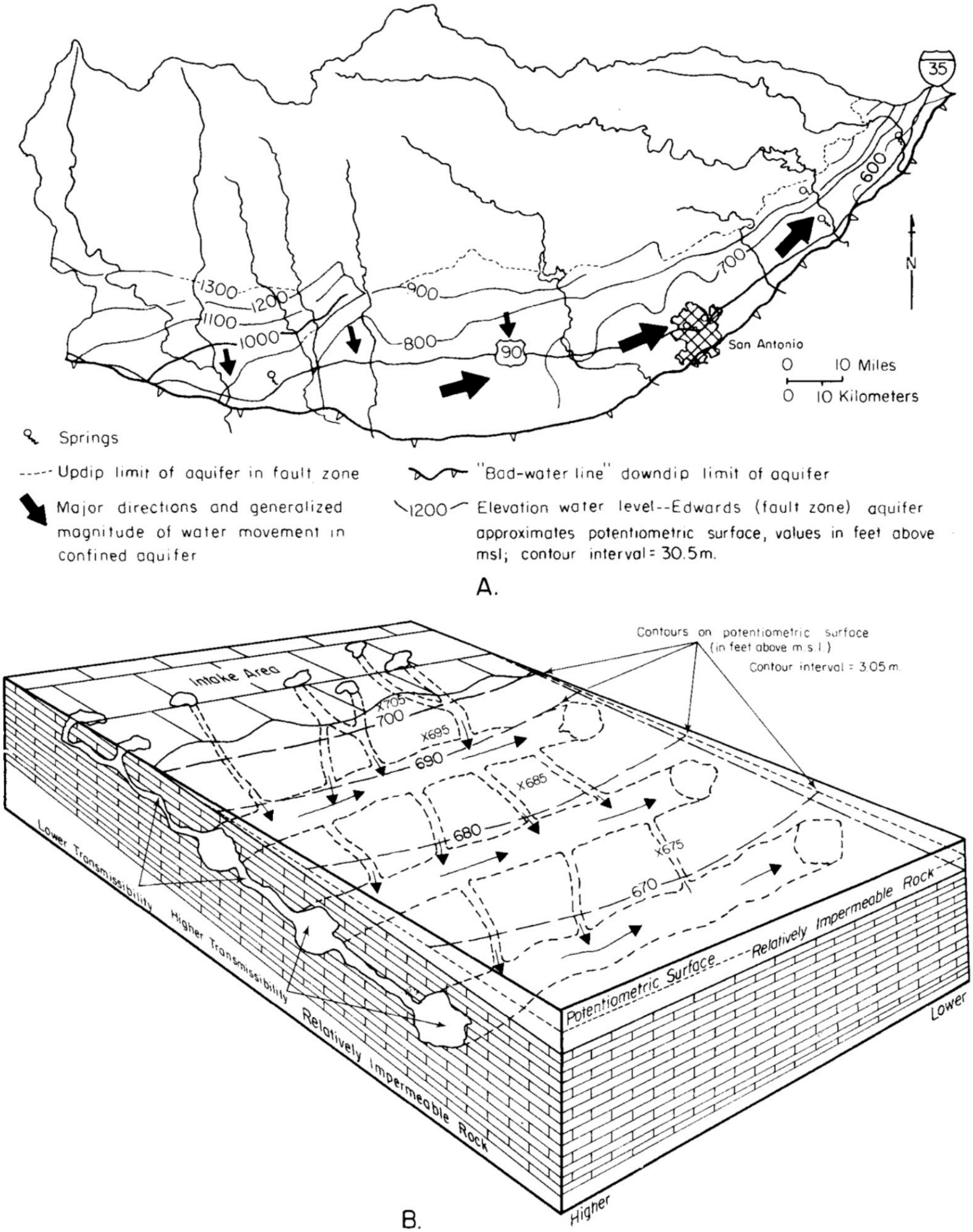

Figure 9. Potentiometric surface of the Edwards artesian aquifer: A. Water levels and directions of ground-water flow in central segment of the aquifer (after Klemt and coworkers (1975)); B. Possible explanation for flow perpendicular to apparent potentiometric gradient (modified from Arnow (1963))

of pirate streams. The general lowering of interfluvial areas and exposure of the Edwards Limestone over large areas have not caused more springs because the plumbing system was engrained long ago toward the few original discharge sites. The southeastern boundary of the aquifer is a 'bad-water line' that separates the potable water of the cavernous, high-yield aquifer from the high salinity water on the downdip side (Figure 7). Although the 'bad-water line' is roughly parallel to the trend of Balcones faulting, its detailed course disregards fault and facies boundaries. It can be understood as the solution-engrained original flow boundary of ground water that moved toward the earliest discharge sites. The assumption that it is a hydraulically-controlled boundary provides a good approximation of the downdip limit of Edwards Limestone aquifer originally affected by the subtle draws of low elevation springs.

Cavern development has been and continues to be greatest near the northeastern, or distal, end of the central segment of the Edwards aquifer. This is indicated by the larger number of vadose caves surveyed, by greater well and spring yields, and by higher transmissibilities (Klemt and coworkers (1975)). Yet this does not fit the general concept which holds that dissolution is concentrated near recharge sites where ground water is least saturated with respect to calcite and dolomite and thus is most aggressively able to form caverns. If this common view of cavern formation held for the Edwards artesian aquifer, then the cavern systems in Uvalde and Medina Counties should be more highly developed, and yields from springs and wells should be greater there. Following the same line of reasoning, the cavernous development in Bexar, Comal, and Hays Counties should be much less developed than they actually are, because ground-water that has travelled a long distance should be saturated or supersaturated with respect to calcite and dolomite and hence unable to accomplish any dissolution of carbonate rock. If the ground water had been mostly saturated during the developmental history of the aquifer, then caverns in the eastern areas would be poorly developed, and yields from wells and springs would be low. Since the caverns are best developed near the distal end of the ground-water system, then clearly the ground water passing through Bexar, Comal, and Hays Counties has primarily been undersaturated with respect to calcite and dolomite.

The modern ground-water is at least seasonally undersaturated, as shown by negative saturation indices calculated for calcite and dolomite from well and spring water samples near Comal, San Marcos, and Hueco Springs by Pearson and Rettman (1976) and Abbott (1977b). The mechanism that maintains at least seasonal undersaturation in the ground water appears to be the mixing-of-waters effect explained by Thrailkill (1968). Introduction of recharge, even if it is saturated or supersaturated, may cause undersaturation in the main ground water body if the recharge is cooled upon entering or if it is mixed with water in equilibrium with a lower partial pressure of carbon dioxide. The necessary process is the addition of carbon dioxide into the main ground water body which thus permits further carbonate rock dissolution. Maintenance of water undersaturation over the long distances within the confined Edwards aquifer must be due to the introduction of high-volume vadose flows recharged through sinks in stream bottoms in Bexar and Comal Counties, such as the karstic plains that lie along Cibolo Creek and Medina River (Figure 6C). Although the recharge supplied by Cibolo, Dry Comal, and other creeks crossing the middle part of the aquifer comprises less than one-third of the water in the aquifer, its delivery occurs at strategic points that promotes undersaturation.

Significant recharge throughout the whole system occurs primarily as vadose flows through a relatively small number of stream bottoms. Because rainfall in the region commonly occurs as downpours from convective thunderheads, much of the recharge occurs rapidly and is undersaturated with respect to calcite and dolomite. When the aquifer system is viewed in scale with its great extent, few springs, and small number of recharge streams it appears to be a long, thin tabular container with few entry and exit points.

In summary, the regional potentiometric gradient extends across the outcrop area of the Edwards Limestone from northwest to southeast down the regional dip. However, most artesian ground water flows through cavern systems parallel to the Balcones faults which are at right angles to the apparent regional potentiometric gradient. In effect the Edwards Limestone is like a tabular container inclined to the southeast, but fluid flow is stopped at the permeability barrier (container wall) expressed as the 'bad-water line'. The discharge sites created by the pirate streams are analogous to pulling plugs from the northeastern edge of the southeastward-inclined container. Water runs to these exit points rather than down the regional slope.

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