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GEOLOGIC CONTROLS ON CAVE DEVELOPMENT AND THE DISTRIBUTION OF CAVE FAUNA IN THE AUSTIN, TEXAS, REGION

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF TABLES

GEOLOGIC CONTROLS ON CAVE DEVELOPMENT AND THE DISTRIBUTION OF CAVE FAUNA IN THE AUSTIN, TEXAS, REGION

by George Veni

Introduction

Five cave arthropods in the Austin, Texas, area are federally listed as endangered species (Chambers and Jahrsdoerfer, 1988). These species are threatened by the urban expansion of Austin and neighboring communities onto the karst (see Appendix A) of the Edwards and associated limestones. Direct threats to the cave fauna are the destruction and contamination of habitat during and following urbanization; indirect threats include competition with and predation by introduced species (Biological Advisory Team, 1990).

Urban impact on cave ecosystems is largely a function of local geologic character and karst evolution. The distribution of cave fauna is fully dependent on the distribution of strata and fractures that are more susceptible to karstic dissolution, and hence cave development, and on the extent of connectivity between those caves and related conduits. Local geology thus dictates not only the distribution of cavernicole habitat but also determines the avenues for the influx of nutrients, contaminants, and competing species (Veni and Associates, 1988a and 1988b).

Unlike this investigation, prior studies correlating geology to species distribution emphasized biologic aspects. Research related to Texas caves includes work by Barr (1960), Holsinger (1967), Mitchell and Reddell (1971), Bull and Mitchell (1972), Elliott and Mitchell (1973), Barr (1974), and Elliott (1976). Non-Texas and more generalized biogeologic cave research includes studies by Christiansen and Culver (1968), Culver, Holsinger and Baroody (1973), Henry (1978), Holsinger (1978), Juberthei and Delay (1981), Peck (1981), and the detailed treatise on the evolution and ecology of cave species by Culver (1982).

The first objective of this study is to assess the region's geologic controls on cave development, within the context of how the karst evolution influenced the evolution and distribution of cave fauna. The second objective is to combine the above information with the distribution of known caves and endangered cave fauna to produce maps that delineate the probability of endangered cave fauna occurring within given areas of the Austin region.

Controls In Cave Development

The primary factors that determine the presence, size, shape and extent of caves are:

1) predominantly soluble rock;
2) fractures or other permeable zones within the rock;
3) water that is chemically undersaturated with respect to the primary soluble minerals present;
4) sufficient relief to allow the water to flow through the permeable zones before discharging at a lower elevation; and
5) time.

Generally, caves become larger, longer, deeper, and more interconnected with the greater abundance of each of the above variables. These variables can therefore be examined to delineate areas where caves and related humanly inaccessible interstitial zones occur. In the following subsections the effects of stratigraphy, structure, and hydrology are specifically addressed, with relief and time being inherent to each discussion. A glossary of karst and related geologic terms is provided in Appendix A.

The study area, essentially comprising the karst areas of Travis and Williamson counties, is roughly divided into six areas (Figure 1):

1) Georgetown-Round Rock area: the exposure of the Edwards and associated limestones east of Jollyville extending north from the Travis-Williamson county border to the Bell-Williamson county border;
2) North Austin area: the continuous Edwards and associated limestones extending southeast of Jollyville toward the Colorado River;
3) Cedar Park area: the Edwards and associated limestones exposed west and northwest of Jollyville;
4) Jollyville Plateau area: the outcrops of the Edwards and associated limestones on the Jollyville Plateau;
5) South Austin area: the Edwards outcrop south of the Colorado River to Hays County;
6) Post Oak Ridge area: the Edwards and the equivalent outcrop of the Walnut Formation on Post Oak Ridge in eastern Burnet and adjacent Travis and Williamson counties.

<u>Stratigraphic Controls</u>

The Cretaceous Edwards Limestone is the most extensively karstified rock in the Austin region. Other local formations contain consequential caves and karst features elsewhere in Texas, however, with the exception of the Walnut Formation, they generally do not have any significant caves near Austin.

A detailed review of Edwards stratigraphy is given in Moore (1964), and the regional stratigraphic column is illustrated in Figure 2. Figure 3 shows that the Edwards Limestone thins northward across the study area as the Walnut Formation thickens and increases in members and complexity. Stratigraphic and structural data were compiled for this investigation from geologic maps and reports including those of Nicholson (1947), Outlaw (1947), Culbertson (1948), Ward (1950), Arrington (1954), Atchison (1954), McReynolds (1958), Lozo, et. al (1959), McQueen (1963), Rogers (1963), Iranpanah (1964), Moore (1964), Evans (1965), Groshong (1967), Rogers (1969), Rodda (1970), Rodda, Garner and Dawe (1970), Barnes, et. al (1972), Barnes (1974), Evans (1974), Garner and Young (1976), Smith (1978), Barnes (1981), Kolb (1981), Senger and Kreitler (1984), Baker, et. al (1986), Dorsey and Slagle (1987), Land and Dorsey (1988), Baker, et. al (1990), Flores (1990), and Senger, Collins and Kreitler (1990).

The influence of stratigraphy on cave development can be estimated for each of the six subregions by plotting the elevation of the entrance, base, and main passage levels of each cave relative to the base of the Edwards Limestone. Although the stratigraphic level of the base of the Edwards does change as the

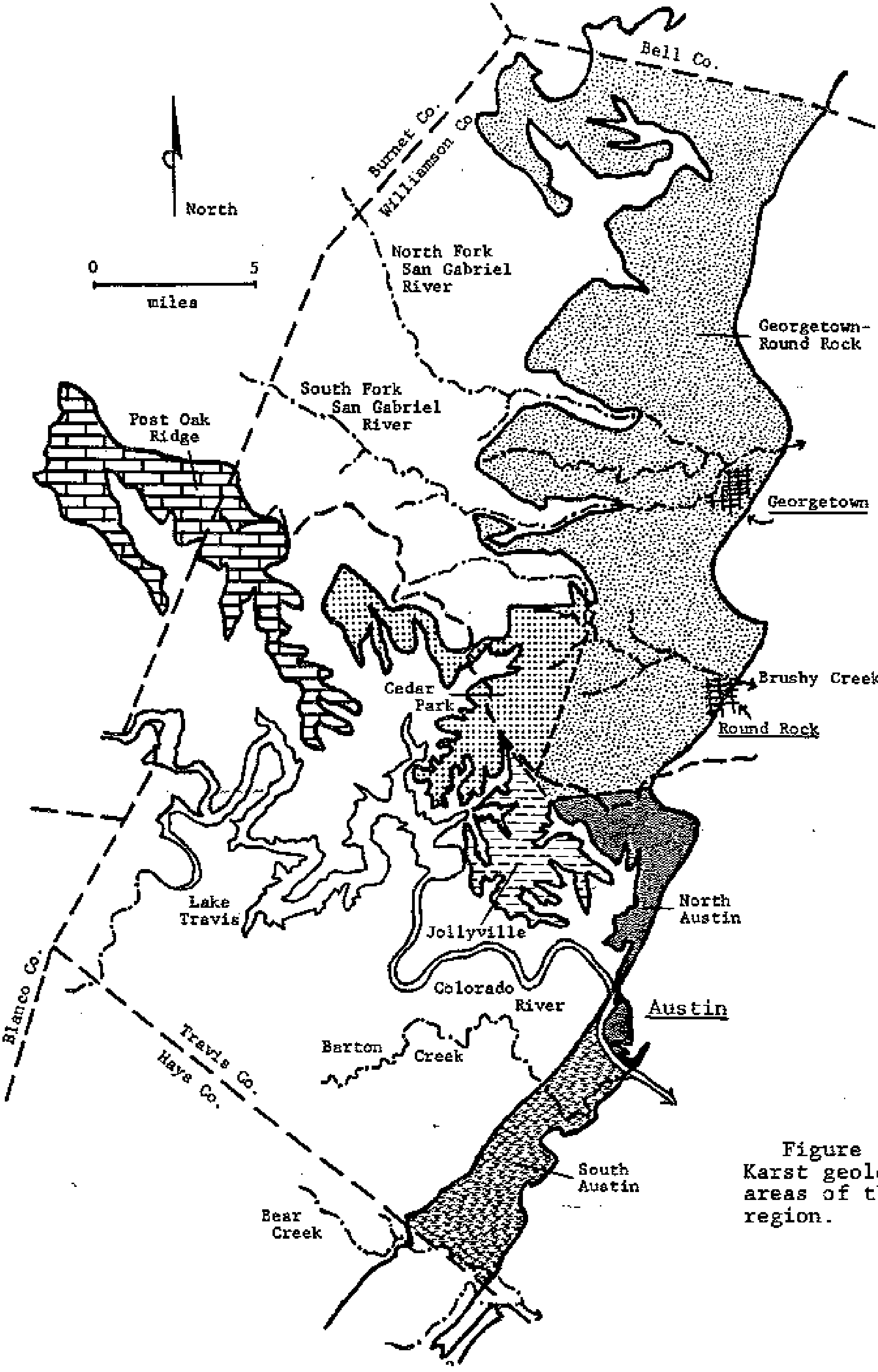
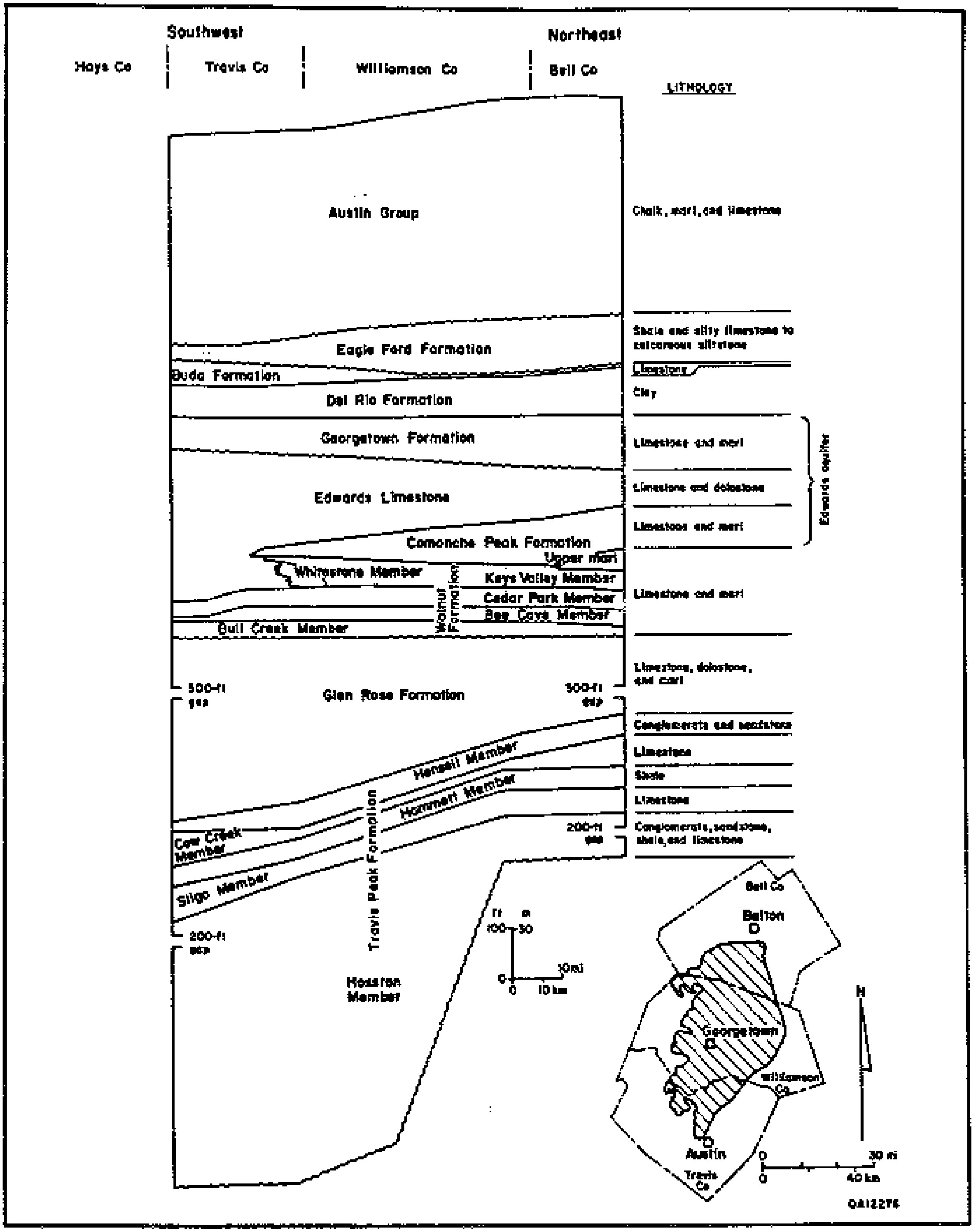


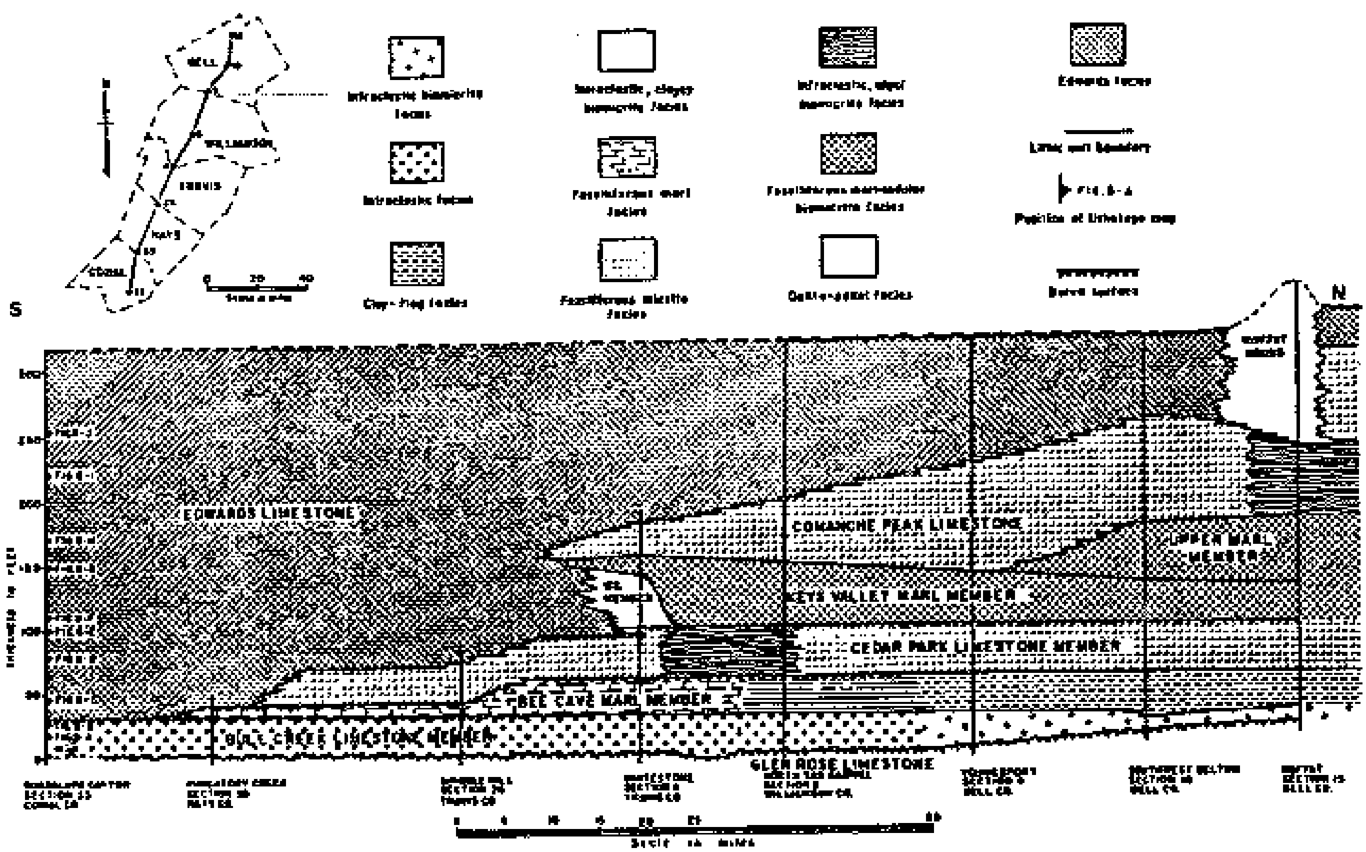
Figure 1: Karst geologic areas of the Austin region.

Figure 2 (from Senger, et. al, 1990)



Stratigraphic column of Cretaceous rocks of the northern segment of the Edwards aquifer, Austin region.

Figure 3 (from Moore, 1964)



Stratigraphic cross section; vertical facies distribution, Fredericksburg Division. Sections 26, 30, and 33 are sections 6, 9, and 10, respectively, of Moore (1961).

Walnut thickens northward, the base of the Edwards is a fairly reliable and usable datum in the region. Where geologic data are insufficient for accurate stratigraphic correlations, stratigraphic interpretations are based solely on cave surveys and observations.

The effects of stratigraphy, structure, and hydrogeochemistry on karstification are fully described by White (1988) and Ford and Williams (1989). Based on those well established characteristics of cave development and specific knowledge of the Austin area karst, correlations in cave levels are interpreted as follows:

1) Most shaft entrances at similar elevations in the Austin region indicate a stratum of relatively low permeability and/or solubility (possibly missing at the surface due to erosion) that directed surface recharge downward along permeable fractures.
2) Shaft entrances at similar elevations may also indicate a highly permeable upper stratum through which surface water rapidly infiltrates to converge at its base on top of a less permeable bed, to then flow down a permeable fracture. Entrances that are small relative to the diameter of the underlying shaft are formed in the upper stratum, while exposure of the main shaft as an entrance indicates that the upper stratum has been removed by erosion since the cave formed (Veni, 1987). In determining the proper model to describe the development of an area's cave entrances, it is necessary to examine the upper strata.
3) Shafts generally develop above the water table along permeable vertical fractures through strata with relatively low lateral permeability and/or solubility.
4) Horizontal passages generally develop in horizontal strata with high relative lateral permeability (often via bedding planes) and/or solubility; passage morphology indicates if a passage formed as a vadose stream or a phreatic conduit.
5) Lowermost reaches of caves are generally above strata of relatively low permeability and/or solubility. Horizontal passages that would be expected to extend laterally along the top of these strata may not be evident and thus inaccessible for human entry due to sediment fill; the sediments are commonly deposited as vadose stream competence is exceeded where the streams' gradient decreases sharply at the base of the shafts.
6) Springs discharge along the contact of upper permeable and/or soluble strata with lower strata of lesser permeability and/or solubility. Discharge occurs into valleys that breach the contact, and the magnitude of discharge is proportional to the size of each spring's drainage basin. Some springs are slightly below the contact due to downward incision. Artesian springs

may rise through fractures in both impermeable and insoluble strata from deeper, groundwater-bearing formations.

The solubility or permeability of strata is described relative to that of adjacent beds.

Unless otherwise cited, all cave map data and descriptions were obtained from the Texas Speleological Survey files or publications (Reddell and Russell, 1961; Reddell and Finch, 1963; Russell, 1984, 1985 and 1988). The caves selected for the following analyses are representative not of the total number of caves in each area but of the caves having adequate elevation data to permit stratigraphic appraisals. The order of listing for caves analyzed in Figures 4 through 7 is from highest to lowest elevation within the Edwards Limestone. This arrangement allows for easy stratigraphic correlations between the caves.

Georgetown-Round Rock Area

The 11 caves included for the stratigraphic analysis of the Georgetown-Round Rock area (Figure 4) are listed and keyed in Table 1. Zones of greater cave development are evident at elevations of 25-40 ft, 49-55 ft, 64-70 ft, 80-85 ft, and 95-100 ft above the base of the Edwards Limestone (Figure 4). These elevations correlate well with measured cross sections near Round Rock (Atchison, 1954); the strata of those levels are thin- to medium-bedded limestone while the intervening strata are less permeable because they are either dolomitic, marly, cherty or thick-bedded.

The density of caves diminishes significantly north of the Georgetown-Round Rock area boundary. The cause is the thinning of the limestone to about 100 ft, greater dolomitization, and increased number of marl interbeds.

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Table 1

CAVES OF THE GEORGETOWN-ROUND ROCK AREA ANALYZED IN FIGURE 4

Cave name	Number in Figure 4
Ku Klux Klan Cave	1
Man With A Spear Cave	2
Cat Cave	3
Bone Cave	4
Off Campus Cave	5
Inner Space Cavern	6
Steam Cave	7
Chinaberry Cave	8
The Lookout	9
The Bat Well	10
Riderless Cave	11

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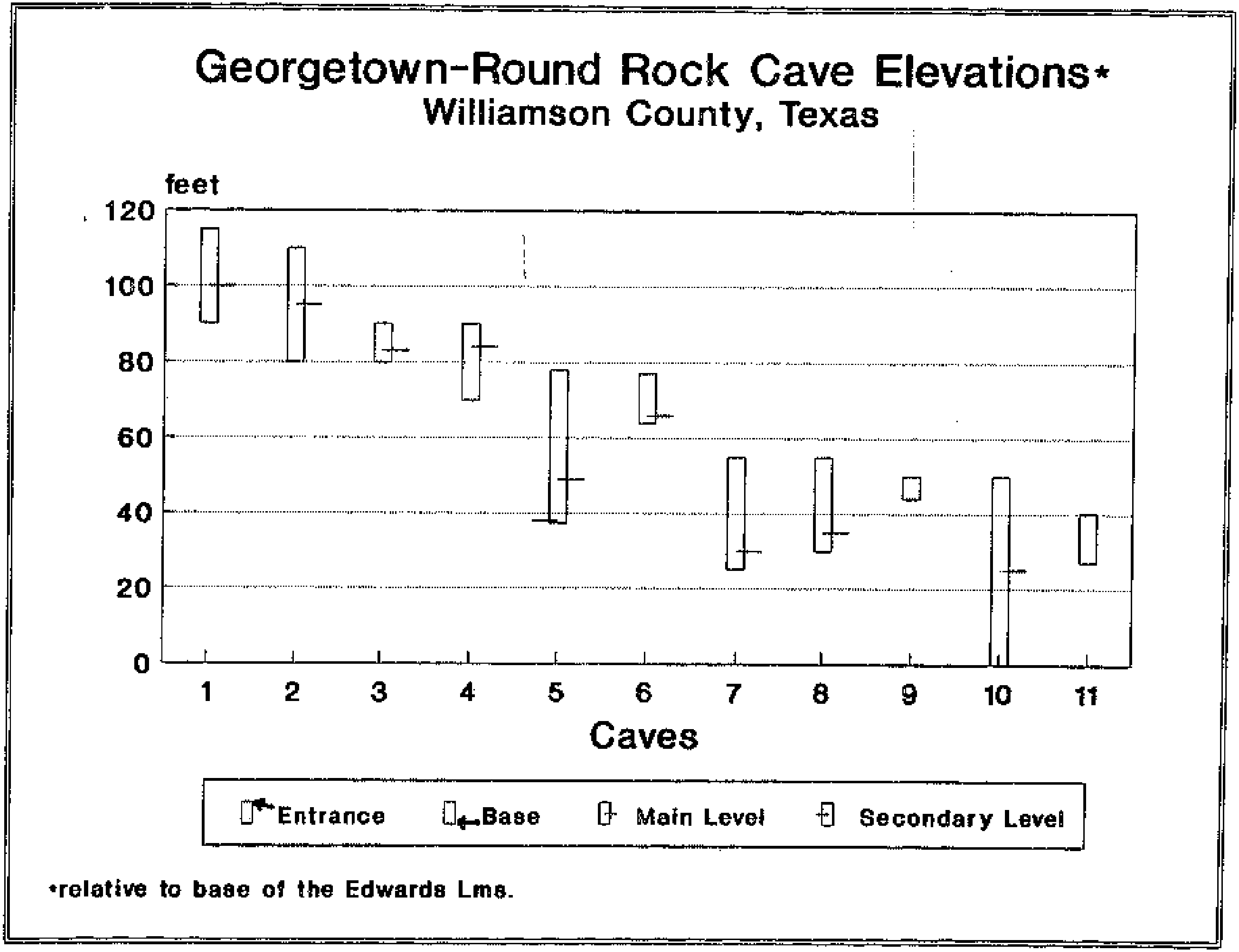

Georgetown-Round Rock Cave Elevations*
Williamson County, Texas
feet
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
Caves
Entrance
Base
Main Level
Secondary Level
*relative to base of the Edwards Lms.

Figure 4

North Austin Area

Most of the North Austin karst is in the upper portion of the Edwards Limestone. Although over 30 caves and karst features have been recorded in this outcrop, data are insufficient to accurately determine all their stratigraphic positions based solely on the available geologic maps and cave surveys.

The southern section of this area along its eastern fault boundary has several sediment-filled solution pits and sinkholes; Balcones Sink is accessible primarily due to extensive excavation of sediment fill. The cause and period of sedimentation has not been determined but may coincide with that of nearby Fyllan Cave or with Inner Space Cavern near Georgetown. The Fyllan deposits were determined to be over 730,000 years old (Taylor, 1982; Young, 1986), and dated deposits in Inner Space range from about 14,000-23,000 years old (Lundelius, 1985). The extensive cave sedimentation in this area probably limits the distribution of cave fauna by filling cavities which could serve as habitat and by blocking the input of organic material that would feed cavernicole fauna.

Cedar Park Area

Table 2 lists 8 caves from the Cedar Park area, where the Edwards Limestone is eroded to a thin veneer and caves form in its lower portion, commonly extending into underlying formations. Although many other caves are known near Cedar Park, they are omitted because of stratigraphic complexities. A stratigraphic analysis of the unlisted caves would require a stratigraphic survey within each one. Such a survey should also examine the eight listed caves to verify interpretations in this report.

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Table 2

CAVES OF THE CEDAR PARK AREA
ANALYZED IN FIGURE 5

Cave name	Number in Figure 5
Marigold Cave	1
Ilex Cave	2
T.W.A.S. A Cave	3
Honeycomb Cave	4
Good Friday Cave	5
Kamikazi Crack Cave	6
Grimace Cave	7
Cedar Elm Sink	8

<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

Six of the eight listed Cedar Park caves display significant horizontal development at the base of the Edwards just above the Comanche Peak Formation (Figure 5). The Comanche Peak and the underlying Keys Valley Member of the Walnut are low permeability, nodular, marly limestones that are not known to contain caves in the Austin area. The primary permeability of these units is low enough to generally retard downward groundwater movement and thus develop cave passages along the upper contact with the Edwards; however, high secondary permeabilities along fractures have formed shafts in most of the caves, some of which may extend as deep as the Whitestone Lentil (sometimes called the

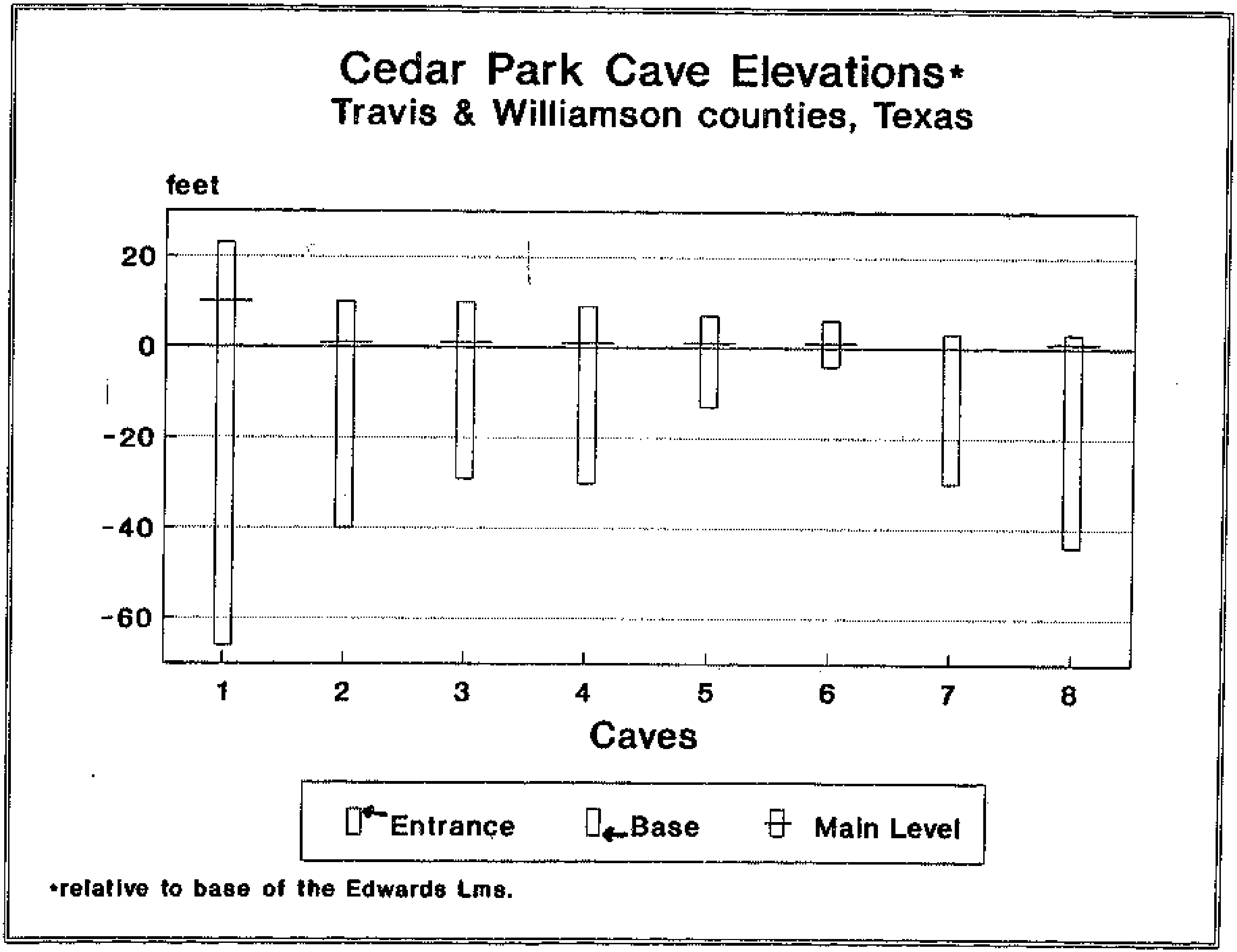

Cedar Park Cave Elevations*
Travis & Williamson counties, Texas
feet
20
0
-20
-40
-60
1
2
3
4
5
6
7
8
Caves
Entrance
Base
Main Level
*relative to base of the Edwards Lms.

Figure 5

Whitestone Member) of the Walnut Formation.

The Whitestone Lentil is divided into upper and lower units; the upper unit is an 8 ft thick, crossbedded, oolitic limestone, and the lower unit is a 34 ft thick oolitic, shell-fragment, and miliolid limestone (Barnes, et. al, 1972). Preliminary observations in the Post Oak Ridge area indicate that caves form primarily in the lower unit due to greater groundwater circulation immediately above the contact with the poorly permeable Cedar Park Member.

The varying thicknesses of units in the Cedar Park area, especially the Comanche Peak and the Whitestone, make stratigraphic interpretation difficult. Two correlations are possible based on published geologic data and the cave levels illustrated in Figure 5. The first correlation is based on the mapping of the top of the Whitestone in T.W.A.S. A Cave (Figure 6); if this correlation is correct, the cave streams in Ilex and Cedar Elm caves would then appear to be perched on top of the more permeable and cavernous lower Whitestone unit, which is quite unlikely. In this correlation model the base of Marigold Cave is just above the Walnut Formation's Cedar Park Member, a poorly permeable, slightly nodular limestone, which is dolomitic along its upper contact.

The second and perhaps more accurate correlation is to assume that the Whitestone Lentil is mislocated on the T.W.A.S. A Cave map. In this model the Comanche Peak has twice the thickness of the first model (the geologic map of Garner and Young [1976] show the formation varying from 20-40 ft thick), and the base of T.W.A.S. A Cave would instead be perched on the Comanche Peak's clayey lower unit. In turn, the streams of Ilex and Cedar Elm caves would be more appropriately perched on the marly Keys Valley Member of the Walnut Formation instead of on the Whitestone. Only Marigold Cave would then extend into the Whitestone, but its small perched stream may indicate that the Whitestone is missing in that locale and replaced by the less permeable Cedar Park Member of the Walnut. However, until the stratigraphy of the Cedar Park area has been carefully mapped on a cave-to-cave basis, neither of the above two models can be confirmed.

Jollyville Plateau Area

Adjacent to the Cedar Park area, the Jollyville Plateau lacks its neighbor's stratigraphic complexities because the Comanche Peak, Keys Valley and Whitestone units are absent, having pinched out. Consequently, all 13 surveyed caves (plus Garden of Sinks Cave and Jug Cave which were well described) are listed in Table 3 and their relative elevations illustrated in Figure 7.

The measured section of Barnes, et. al (1972, p. 72) on the Jollyville Plateau was used as the local stratigraphic reference to aid in interpreting Figure 7. The two lowermost caves in the area correlate to the three lowermost units of the section. Examination of McDonald Cave has shown it to be predominantly developed in a 3 ft layer of soft, granular, secondary limestone perched on a 13 ft section of recrystallized limestone (Veni and Associates, 1988b). Below these units is the 7 ft basal unit which, like the 3 ft layer, is also composed of soft, granular, secondary limestone. The elevation for the room at the base of Pickle Pit places it just above the elevation of the basal unit in the section. A closer measurement in the cave would probably show the room to actually be within the secondary limestone.

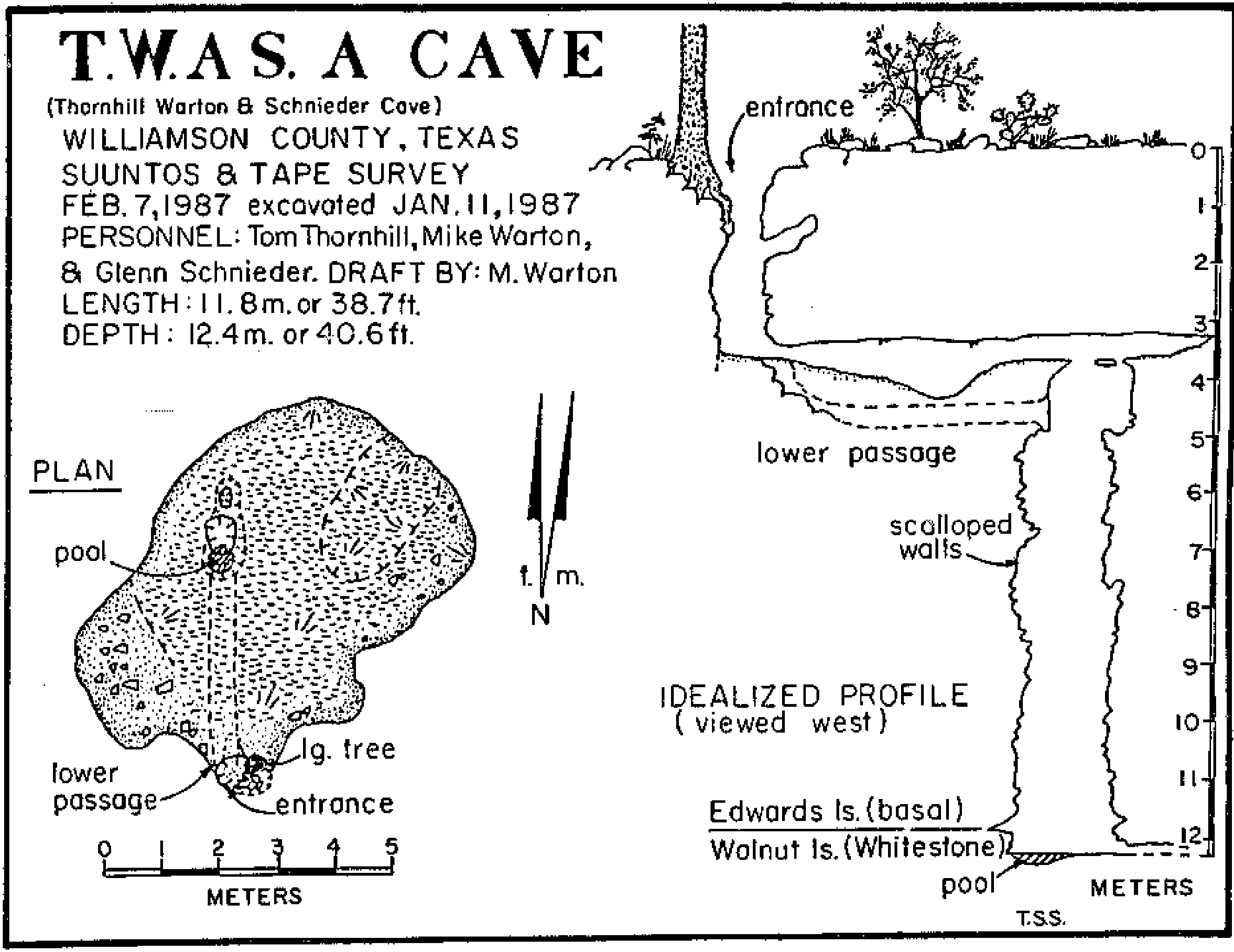
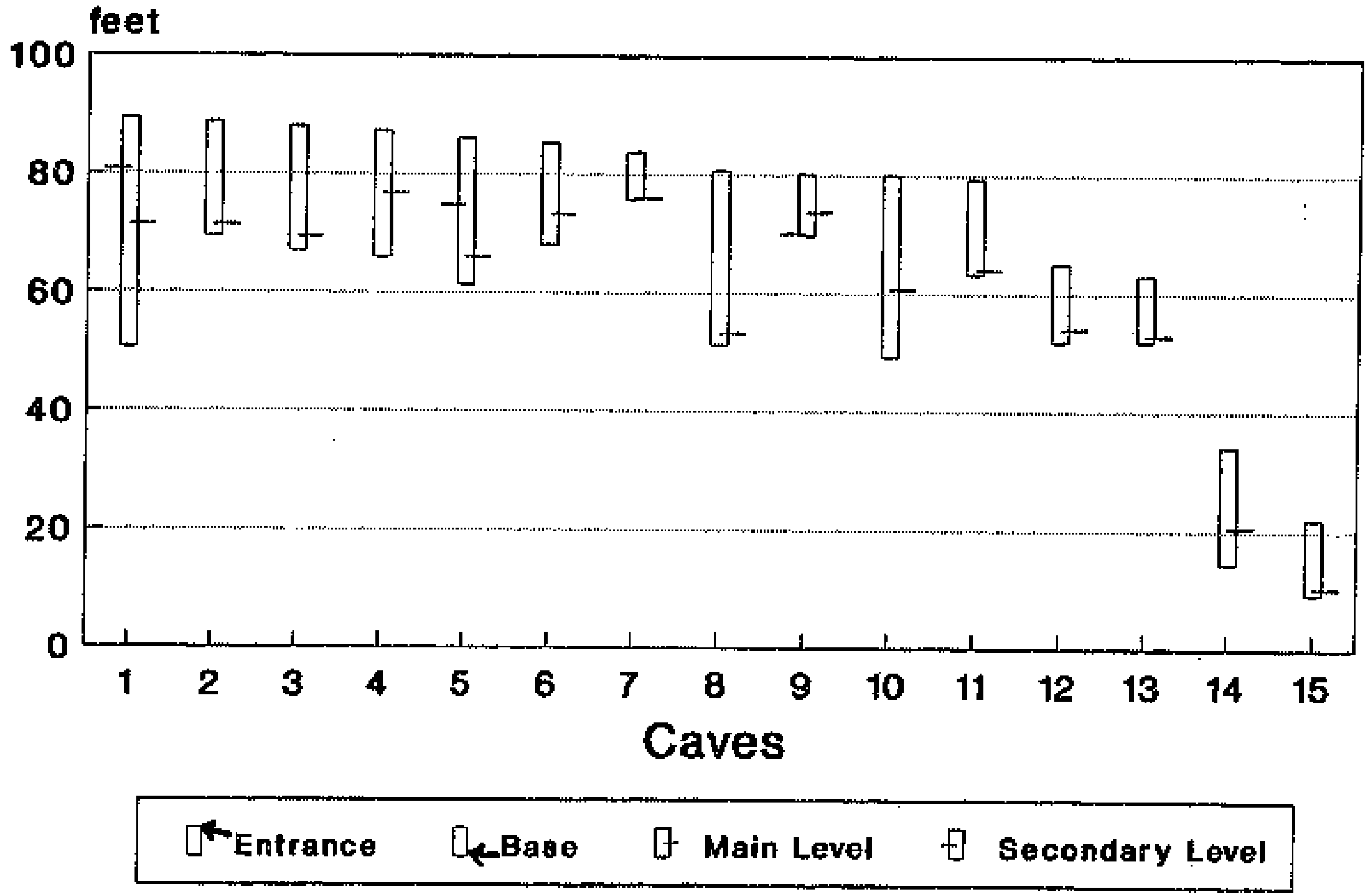


Figure 6 (from Elliott & Reddell, 1989)

Jollyville Plateau Cave Elevations*
Travis County, Texas



*relative to base of the Edwards Lms.

Figure 7

Table 3

CAVES OF THE JOLLYVILLE PLATEAU AREA ANALYZED IN FIGURE 7

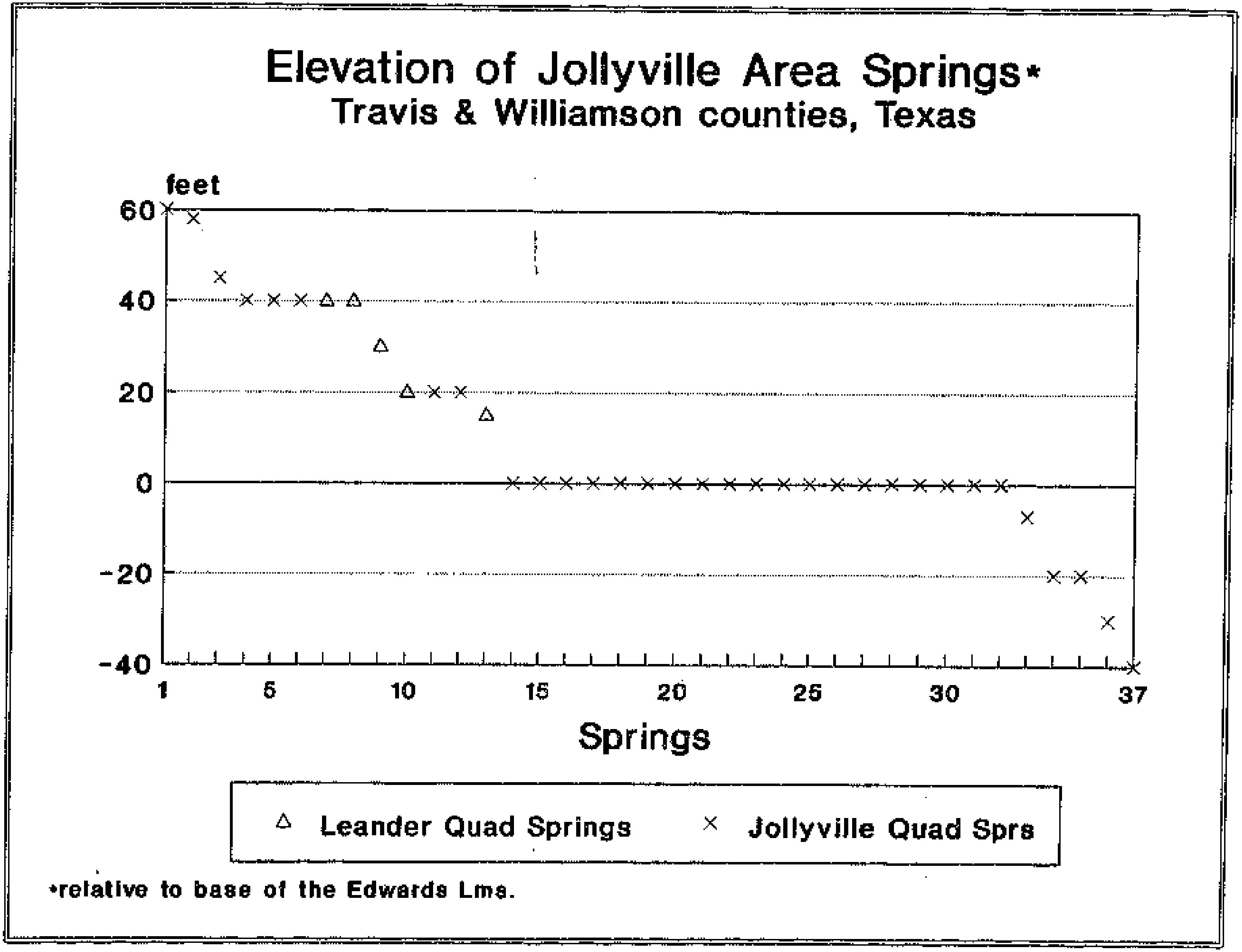
Cave name	Number in Figure 7
Kretschmarr Double Pit	1
Deer Stand Cave	2
Kretschmarr Fluted Sink	3
Gallifer Cave	4
Amber Cave	5
Tooth-Russell Cave	6
Garden of Sinks Cave	7
Kretschmarr Sink	8
Lakeline Cave	9
Kretschmarr Cave	10
Encinal Cave	11
New Comanche Trail Cave	12
Jug Cave	13
McDonald Cave	14
Pickle Pit	15

The measured section shows a dolomitic chert zone 38-48 ft above the base of the Edwards, which was first described by Veni and Associates (1988a) as a lower barrier to cave development on the Jollyville Plateau. No caves extend through this level, and three of the five caves which approach it have perched horizontal passages along the narrow 53-54 ft level. Above the 54 ft level there is no published local stratigraphic data, and the interpretations that follow are based on the cave levels in Figure 7.

The 54-66 ft level above the base of the Edwards has moderately poor lateral permeability, but the zone from 66-77 ft contains several levels of passages developed along bedding plane partings. Several cave entrances developed just below the 90 ft level probably indicate an overlying zone of lesser permeability and/or solubility which is now absent due to erosion.

The plot of 37 spring elevations in the Jollyville Plateau area reinforces the picture of greater and lesser zones of permeability given by the cave data (Figure 8). Springs selected were those shown on the Jollyville and Leander 7.5' topographic quadrangles (Table 4). All springs on the Jollyville quadrangle, plus springs not shown on the map, have been numbered according to Russell (1985). Springs of the Leander quadrangle were arbitrarily numbered 1-5.

Although most of the spring elevations were estimated from topographic maps and not field checked like most caves, four distinct boundaries to groundwater flow are evident. The lowermost level of low permeability is 20 ft below the Edwards and probably reflects the lower nodular unit in the Cedar Park Member. The most significant low permeability boundary is indicated by 20 springs perched on or cut slightly into the Walnut Formation. The third level correlates to the 13 ft thick recrystallized limestone on which McDonald Cave is



Elevation of Jollyville Area Springs*
Travis & Williamson counties, Texas
feet
60
40
20
0
-20
-40
1
5
10
15
20
25
30
37
Springs
Leander Quad Springs
Jollyville Quad Sprs
*relative to base of the Edwards Lms.

Figure 8

Table 4

SPRINGS OF THE JOLLYVILLE AREA
ANALYZED IN FIGURE 8

Spring name	Number in Figure 8
Jollyville Quad Spring J63C	1
Jollyville Quad Spring J37A	2
Jollyville Quad Spring J12A	3
Jollyville Quad Spring J22A	4
Jollyville Quad Spring J22B	5
Jollyville Quad Spring J22C	6
Leander Quad Spring 2	7
Leander Quad Spring 5	8
Leander Quad Spring 4	9
Leander Quad Spring 3	10
Jollyville Quad Spring J54A	11
Jollyville Quad Spring J13D	12
Leander Quad Spring 1	13
Jollyville Quad Spring J70A	14
Jollyville Quad Spring J80A	15
Jollyville Quad Spring J81A	16
Jollyville Quad Spring J81B	17
Jollyville Quad Spring J62A	18
Jollyville Quad Spring J62B	19
Jollyville Quad Spring J41A	20
Jollyville Quad Spring J32B	21
Jollyville Quad Spring J32C	22
Jollyville Quad Spring J13E	23
Jollyville Quad Spring J33A	24
Jollyville Quad Spring J33B	25
Jollyville Quad Spring J43A	26
Jollyville Quad Spring J43B	27
Jollyville Quad Spring J43C	28
Jollyville Quad Spring J44B	29
Jollyville Quad Spring J44C	30
Jollyville Quad Spring J44D	31
Jollyville Quad Spring J45A	32
Kretschmarr Salamander Cave	33
Jollyville Quad Spring J61A	34
Jollyville Quad Spring J72A	35
Talus Spring Cave	36
Jollyville Quad Spring J14b	37

perched, and the fourth level is along the cherty dolomitic horizon.

South Austin Area

Like the Cedar Park area, stratigraphic correlations based solely on available cave and geologic maps are difficult to make in South Austin. Not only are there several facies changes, but significant faulting in South Austin offsets the strata and is much more extensive than shown on the geologic maps. Those maps are based mainly on air photos on which faults are clearly seen where differing units are juxtaposed, but faults are often hard to see if the same formation occurs on both sides. Field research in South Austin and Smith's (1978) and Kolb's (1981) mapping indicate that the intense faulting, as mapped in the Rollingwood and Sunset Valley areas (Garner and Young, 1976), extends throughout the South Austin Edwards Limestone outcrop.

Russell (1975) was the first to correlate stratigraphic zones to cave development in the Austin area by observing that several caves, including Airman's Cave which is by far the most extensive cave in Travis County, were developed about 20 ft below the top of the Edwards Limestone. Rodda (1970) describes that zone as a 6-10 ft thick layer of dolomite, dolomitic limestone, and a thin solution collapse zone. Airman's Cave is formed in the solution collapse zone and is confined between the dolomitic beds.

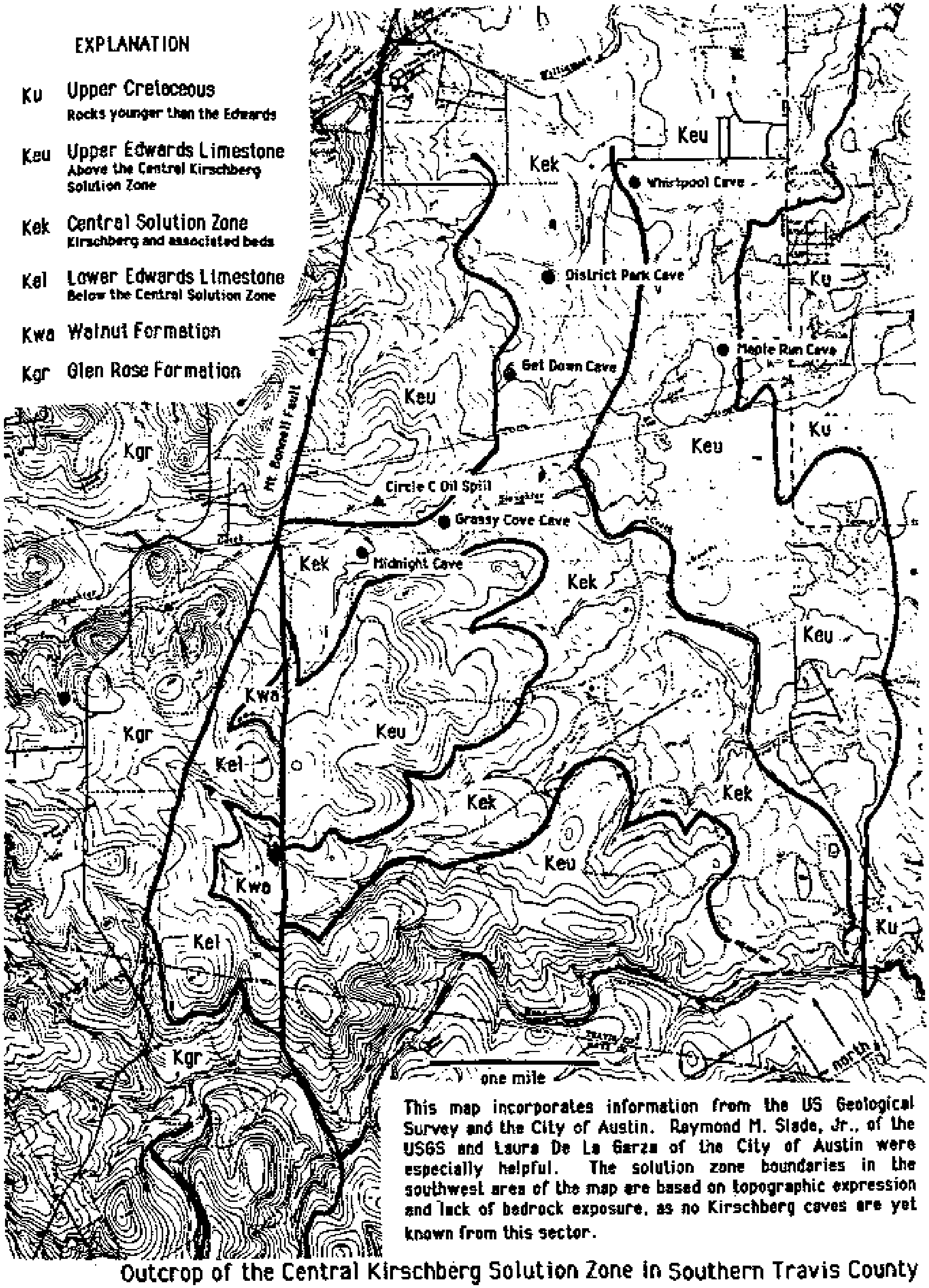
In 1987 Russell continued his study of Austin area cave stratigraphy based on in-cave mapping of Edwards Limestone units. He determined that many of the major South Austin caves occur in what he describes as the "Central Solution Zone." Some of these caves include Cave X, District Park Cave, Flint Ridge Cave, Get Down Cave, Grassy Cove Cave, Midnight Cave, and Whirlpool Cave. The Central Solution Zone is equivalent to Rodda's (1970) Member 2 of the Edwards Limestone, although Rodda indicates that the underlying 20 ft thick upper unit of Member 1 to be the most cavernous zone. Keith Young (personal communication, 1987) expressed some reservations about Russell's stratigraphic interpretations, but until the area is studied in more detail Russell's geologic map of South Austin (Figure 9), Smith's (1978) map of northeastern Hays County, and Kolb's (1981) map of the Signal Hill quadrangle are the standards used in this investigation.

Post Oak Ridge Area

Speleologic work on Post Oak Ridge began recently and several caves have been located. The ridge is capped by a 110-130 ft thick section of the Walnut Formation, including the Whitestone Lentil (Barnes, 1974, shows the southern part of the ridge as the Walnut-equivalent Edwards Limestone). Preliminary observations show that the caves develop shaft entrances at the top of the upper member of the Whitestone and often extend into the lower member. Most of the caves are shafts, solutionally enlarged along fractures, which end in sediment fill.

The morphology of the Post Oak Ridge caves indicates that the lower member of the Whitestone is probably more soluble than the upper member. Jack's Joint and Simons Water Cave are the only caves with significant horizontal extent and both are at the bottom of the Whitestone; however, most of their extensive development in the lower member is due to being perched on the underlying Cedar Park Member.

Figure 9 (from Russell, 1987)



Outcrop of the Central Kirschberg Solution Zone in Southern Travis County

Although the Walnut Formation extends continuously for more than 100 miles to the north, the cavernous Whitestone Lentil pinches out within Post Oak Ridge just south of the South Fork of the San Gabriel River. Moore (1964) indicates the Whitestone is also present north of the North Fork of the San Gabriel River, roughly along Highway 183 from Briggs in Burnet County southeast to Andice in Williamson County. Barnes (1974) only shows the Keys Valley and Cedar Park members in that location but does not include the Whitestone. This area should be considered potentially cavernous and requires field examination, but the lack of known caves or karst features suggests that Barnes' map may be the more accurate in determining potential areas of cavernicole habitat.

Structural Controls

The dominant structural feature of the Austin area is the Balcones Fault Zone (Figure 10). The fault zone is formed along the homoclinal hinge between the relatively flat-lying strata of the Edwards Plateau to the west and the more steeply dipping strata in the Gulf of Mexico Basin to the southeast. The fault zone is characterized by a series of *en echelon* normal faults, mostly downthrown toward the Gulf. Individual fault displacements in the Austin region are as much as 600 ft, but most major fault displacements are only about 50 ft. Many faults with less than 10 ft of throw do not appear on geologic maps due to difficulty in mapping them (Rodda, 1970).

Faulting in the Austin area displaces and juxtaposes the units previously described in the stratigraphy section. The faults can also serve as sites of preferential groundwater flow. Kastning (1977) discusses how faults can have positive, negative or neutral effects on groundwater flow and cave development, and illustrates all three processes within just one cave (Natural Bridge Caverns) located within the Balcones Fault Zone 60 miles southwest of the study area (Kastning, 1983). However, Veni (1985; 1988b) finds that even in the most intensely fractured portion of the fault zone, in the Bexar County area, fewer than 0.5% of the caves are formed along faults. Bexar County caves are predominantly developed along joints, which are more numerous and generally more permeable than faults. Although faults are described in most regional geologic reports as the primary sites of groundwater recharge and cave development, those assessments are not based on extensive field investigation and the fractures found associated with caves are often mislabeled faults based on ill-informed expectations and inadequate examination.

A second aspect of geologic structure that affects cave development is the attitude of the beds. Palmer (1977) shows that groundwater flow and cave development occur down-dip in the vadose zone and along strike in the phreatic zone. Although most beds in the Austin region are nearly horizontal, their slight dips will influence cave formation.

The following discussion on the effect of structure on regional cave development compares fracture orientation and attitude of bedding with local cave orientation to determine:

1) the fracture sets most prone to cave development;
2) the tendency for passages to develop along either strike or dip in the given areas.

Figure 10: Major faults of the Balcones Fault Zone in the Austin region (from Baker, et al, 1986)

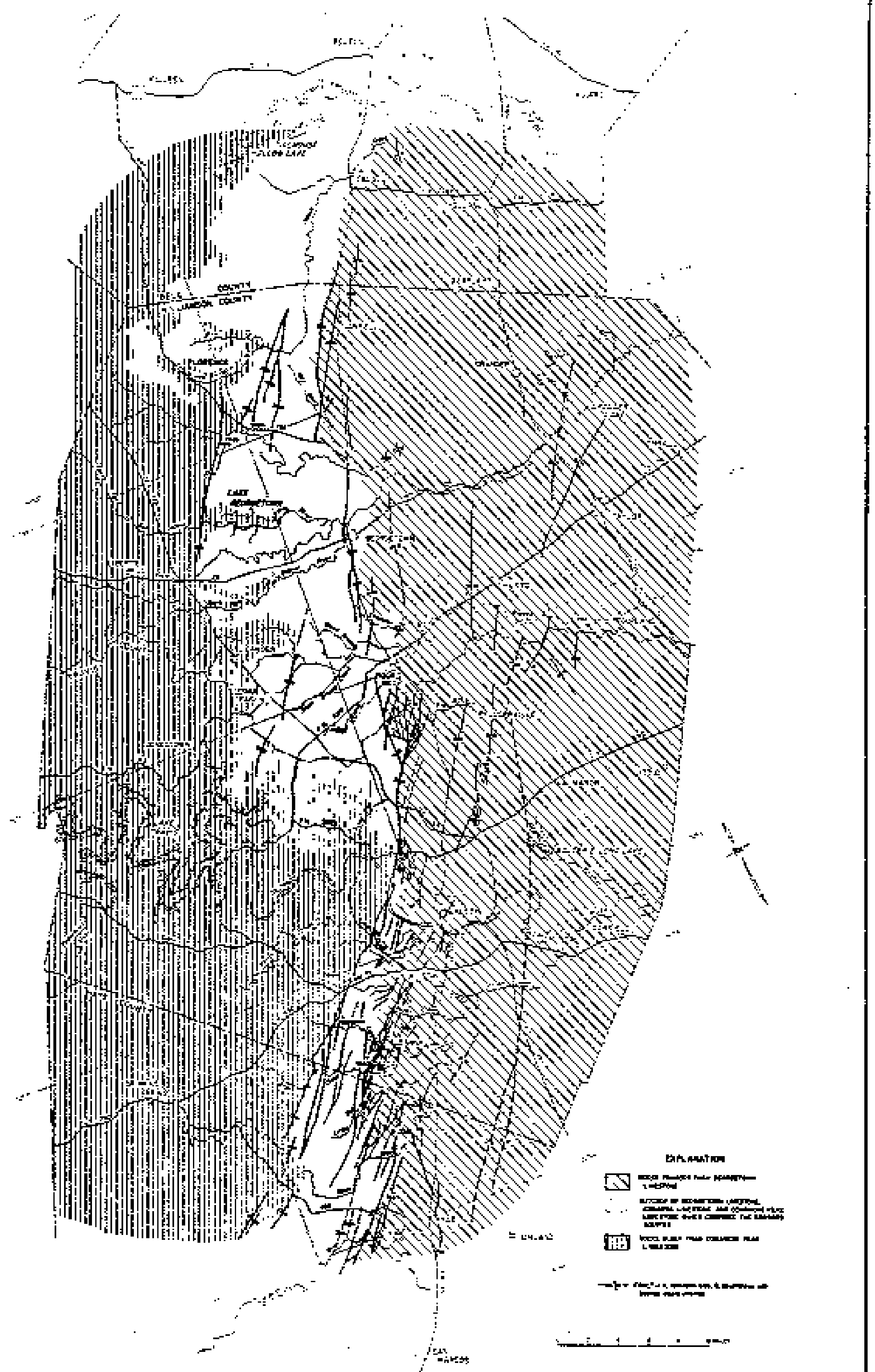


Figure 2
Hydrogeologic Map

Fracture orientations in caves are based on available cave surveys. Most such surveys are lacking in geologic detail and do not identify or measure fractures. However, in some cases cave morphology clearly indicates the presence of a fracture and may occassionally be used to estimate the fracture's bearing. The following analysis of fractures includes fractures measured in caves, known fractures in caves whose orientations were extrapolated from the cave maps, and some fractures implied by passage orientation and cave morphology (used only where morphology gives high confidence in the actual existence and probable bearing of such fractures). Although several fractures with the same trend may intersect a cave, a total count of fracture-guided passages was not made for this report. In the following tables each fracture occurrence refers to the primary trend of a fracture or fracture set along which an entire cave or its major passages have formed. Any secondary trend is also counted as a single fracture occurrence. To display the relative significance of the fracture bearings, the numbers in Tables 5-9 and Figures 11-15 have been converted to show the percent of the total fractures that occur within 20° increments.

Except for two caves in the South Austin area, no faults are reported within caves of the Austin region; based on my field investigations I have assumed that practically all of the cave fractures are joints. The majority of cave maps examined for fractures are drawn to magnetic north; a uniform correction of 7° has been applied to these maps to approximate true north.

Georgetown-Round Rock Area

Senger, Collins and Kreitler (1990) review the structural data of the Georgetown-Round Rock area and describe the major Balcones faults as being oriented between 0-40° and the minor faults mainly between 340-40° and to a lesser extent between 70-120°. Not surprisingly, joints of the area were noted to parallel the faults and trend mostly between 80-120° and also from 340-20°. Sixty percent of the faults examined were found to be filled with calcite and were generally impermeable to groundwater flow, and were thus unlikely sites for cave development.

Table 5 lists the 14 caves studied in the Georgetown-Round Rock area with their primary and secondary fracture orientations. Figure 11 illustrates the preferential development of caves in the area along the above-described 340-40° and 70-120° joint sets. Like the joint sets, the primary fracture orientations are between 80-140°, roughly perpendicular to the Balcones Fault Zone, and accounting for more than 50% of the orientations recorded. The less dominant fracture set is parallel to the fault zone between 0-39°, and accounts for about 32% of the fractures.

The easternmost caves seem to favor development along fractures parallel to the major faults. This phenomenon can be explained by the combination of the following two factors:

1) fractures parallel to the Balcones Fault Zone tend to increase in permeability with increased proximity to the fault zone;
2) regional groundwater is known to flow down-dip (west to east) toward the fault zone, then flow along strike (north-south) adjacent to the major faults (it is not

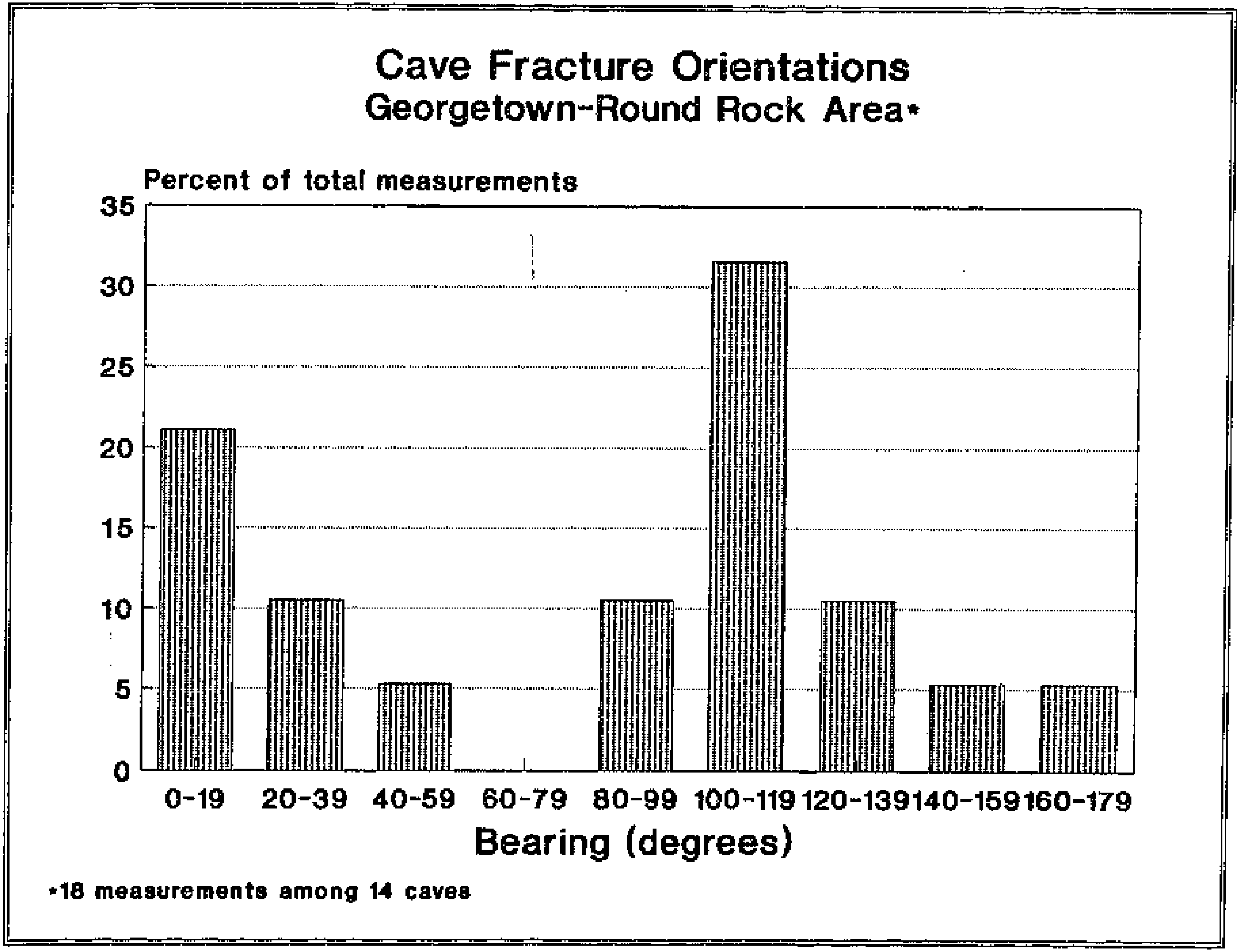

Cave Fracture Orientations
Georgetown-Round Rock Area*
Percent of total measurements
35
30
25
20
15
10
5
0
0-19
20-39
40-59
60-79
80-99
100-119
120-139
140-159
160-179
Bearing (degrees)
*18 measurements among 14 caves

Figure 11

known if higher fracture permeability promoted strike-ward groundwater flow, or if the groundwater increased fracture permeability along the fault; it is likely the two factors interacted reciprocally).

This setting promotes differential enlargement of fractures and caves within the regional aquifer, with the highest solutional activity focused along the permeable fractures and groundwater confluences of the Balcones Fault Zone.

Regionally, the beds dip roughly 1° to the east and strike north-south, but some local variations occur near and between fault blocks (Atchison, 1954; Senger, Collins and Kreitler, 1990). None of the caves investigated are within the present phreatic zone, however, their morphology and orientation to bedding indicate that many were formed under phreatic conditions. Inner Space Cavern is the best example of a phreatically developed cave in the Georgetown area. Other examples include Chinaberry Cave, Steam Cave, and Coffin Cave. Beck Ranch Cave is an excellent example of a down-dip fracture-guided passage joining a strike-oriented phreatically formed conduit. Caves farther up-dip from the fault zone are generally smaller and display more vadose features, indicating that area caves are poorly integrated and feed down-dip into the well-integrated major conduits along the fault zone.

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Table 5

CAVE FRACTURE ORIENTATIONS OF THE GEORGETOWN-ROUND ROCK AREA ANALYZED IN FIGURE 11

Cave name	Fracture bearings in degrees: Primary	Secondary
Beck Ranch Cave	108	
Bone Cave	54	
Brown's Cave	154	
Chinaberry Cave	4	112
Clark Cave	2	
Cobb Caverns	80	
Coffin Cave	2	39
Great Mud Cave	136	
Inner Space Cavern (Kastning, 1983)	10-20	90-100
Jacob's Well	121	
Lindsey Cave	108	
Off Campus Cave	179	
Steam Cave	29	108
The Bat Well	118	

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North Austin Area

Fracture orientations of the North Austin area are similar but not as prominent as those of the Georgetown-Round Rock area. Of the five caves listed in Table 6 and illustrated in Figure 12, nearly 40% of the fractures are oriented 100-119°. The significance of other fracture orientations is unknown due to the low number of available data points.

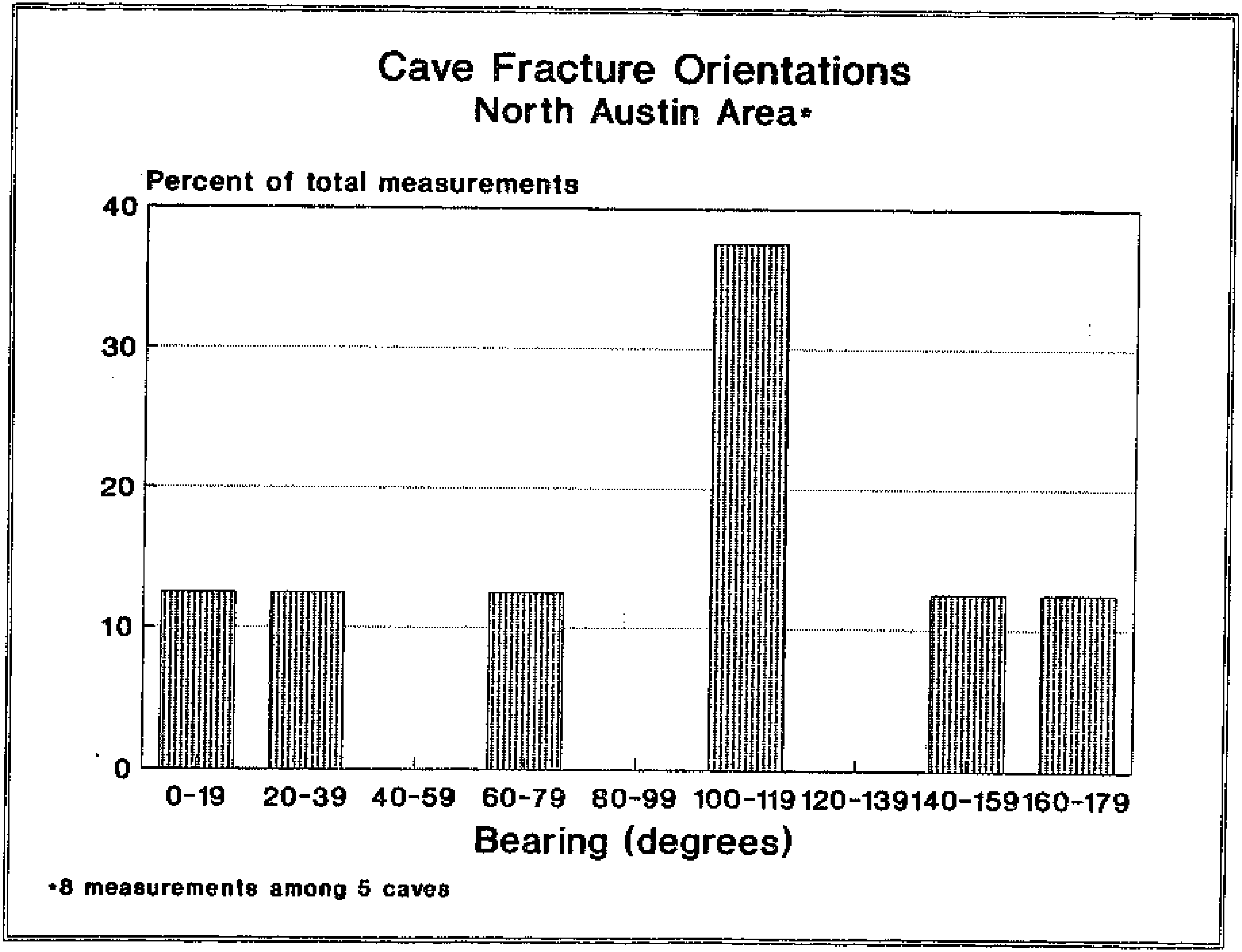
Cave Fracture Orientations
North Austin Area*
Percent of total measurements
40
30
20
10
0
0-19
20-39
40-59
60-79
80-99
100-119
120-139
140-159
160-179
Bearing (degrees)
*8 measurements among 5 caves

Figure 12

<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

Table 6

CAVE FRACTURE ORIENTATIONS OF THE NORTH AUSTIN AREA ANALYZED IN FIGURE 12

Cave name	Fracture bearings in degrees: Primary	Secondary
Balcones Sink	37	119
Dead Dog Cave #1	178	
Dead Dog Cave #2	100	7
Salamander Cave	60	140
Spoon Cave	115	

<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>

As in the Georgetown-Round Rock area, the caves closest to the fault zone are oriented along parallel fractures (e.g., Balcones Sink), and the more distant caves are developed along perpendicular fractures. The effects of strike and dip are not as clear in the North Austin area but are probably the same as in Georgetown-Round Rock.

Jollyville Plateau and Cedar Park Areas

The Jollyville Plateau and Cedar Park areas have been combined in this analysis due to their structural similarities. They are situated 6-9 miles west of the main Balcones faulting, but numerous small faults still cross the areas. Rogers (1969) mapped 36 faults related to the Balcones system bearing 20-36° and a nearly perpendicular secondary set of 43 faults bearing 142-158°. With the exception of the Cedar Park Fault, which has 65 ft of displacement and is the only fault shown in Barnes' (1974) map, all of these faults are very minor, having an average 10 ft of displacement and often as little as 3 ft. Although many faults have been mapped in this area, it is relatively undeformed when compared to areas nearer the Balcones Fault Zone; the highly detailed level of mapping has revealed faults that normally go undetected or unreported in other areas.

The Jollyville Plateau area has a dominant joint set bearing 130-140° with 58% of all readings within 135° $\pm$20° (Dunaway, 1962). Field observations by Veni and Associates (1988a) reveal a secondary joint set bearing an average 20° and air photo lineations bearing around 50° and 135°. Evans (1965) found that 60% of the joints around Cedar Park range from 20-70°, with a secondary joint set closer to the Jollyville bearings of 110-160°.

The fracture orientations of 11 Jollyville-Cedar Park area caves are listed in Table 7 and illustrated in Figure 13; their correlation to the measured joints and faults is poor. Sixty percent of all cave fractures trend 60-105°, a range where very few joints or faults have been observed. Field observations indicate these fractures are very minor and weakly guide cave development, and would most likely be missed by standard geologic mapping projects.

The significant presence of caves along these weak fractures indicates that cave development is occurring more as a response to either favorable stratigraphic zones and/or hydraulic gradients than to fracture permeability. Of these two possibilities, stratigraphy would be the more likely influence. None of

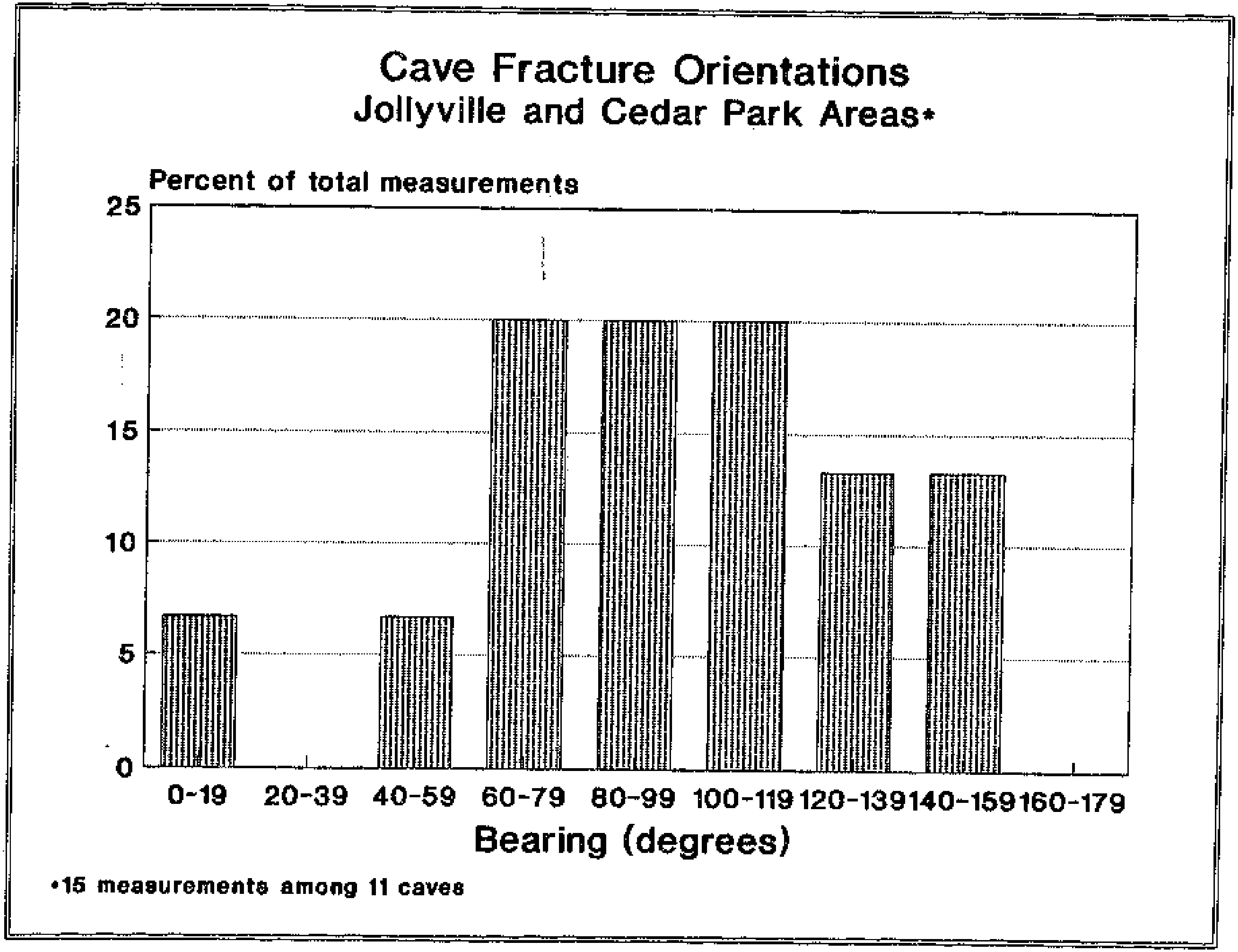
Cave Fracture Orientations
Jollyville and Cedar Park Areas*
Percent of total measurements
25
20
15
10
5
0
0-19
20-39
40-59
60-79
80-99
100-119
120-139
140-159
160-179
Bearing (degrees)
*15 measurements among 11 caves

Figure 13

the listed caves have sufficient horizontal extent to be significantly affected by regional or local hydraulic gradients; lower parts of many caves are sediment-filled, disguising any gradient impacts. Similarly, the effect of strike and dip cannot be assessed due to the limited horizontal development. However, these analyses on fractures and stratal attitude should be repeated after the stream caves of the Cedar Park area have been surveyed.

Table 7

CAVE FRACTURE ORIENTATIONS OF THE JOLLYVILLE & CEDAR PARK AREAS ANALYZED IN FIGURE 13

Cave name	Fracture bearings in degrees: Primary	Secondary
Amber Cave	90	
Deer Stand Cave	70	
Good Friday Cave	70	
Kamikazi Crack Cave	90	103
Kretschmarr Cave	15	105
Kretschmarr Double Pit	126	
Kretschmarr Salamander Cave	126	
Kretschmarr Sink	111	
Link's Cave	97	
Marigold Cave	52	140
McDonald Cave	60	144

South Austin Area

Most faults in the South Austin area trend 30-60° and secondarily at 10°. Net slip for most of the faults is generally less than 50 ft, but faults with less than 10 ft of displacement are usually not shown on geologic maps. Joints in the northern section of the South Austin area are oriented nearly the same as those in the Jollyville Plateau-Cedar Park area at 40° and secondarily at 135°, but become parallel to faulting in the southern section at 60° with secondary joint sets oriented between 90-100° and 110-130° (Rodda, Garner and Dawe, 1970; Smith, 1978; Kolb, 1981).

Fracture orientations of 14 South Austin caves are listed in Table 8 and compiled on Figure 14. Nearly 41% of the caves are formed along fracture trends of 40-59°, with little preferential development for other orientations not parallel to Balcones faulting. This correlation confirms the impact of the Balcones Fault Zone on cave development in the South Austin area.

The South Austin area is the only one in the Austin region known to have caves that either intersect faults or are developed along them. Cave X ends at the Mount Bonnell Fault, the largest fault in the region, which juxtaposes the cavernous Edwards Limestone with the noncavernous upper member of the Glen Rose Formation (Russell, 1974). The south end of Goat Cave also ends at a fault, but one with only 10 ft of displacement (Woodruff and Slade, 1984). A passage near the base of Flint Ridge Cave is developed along a small fault (Russell, 1988);

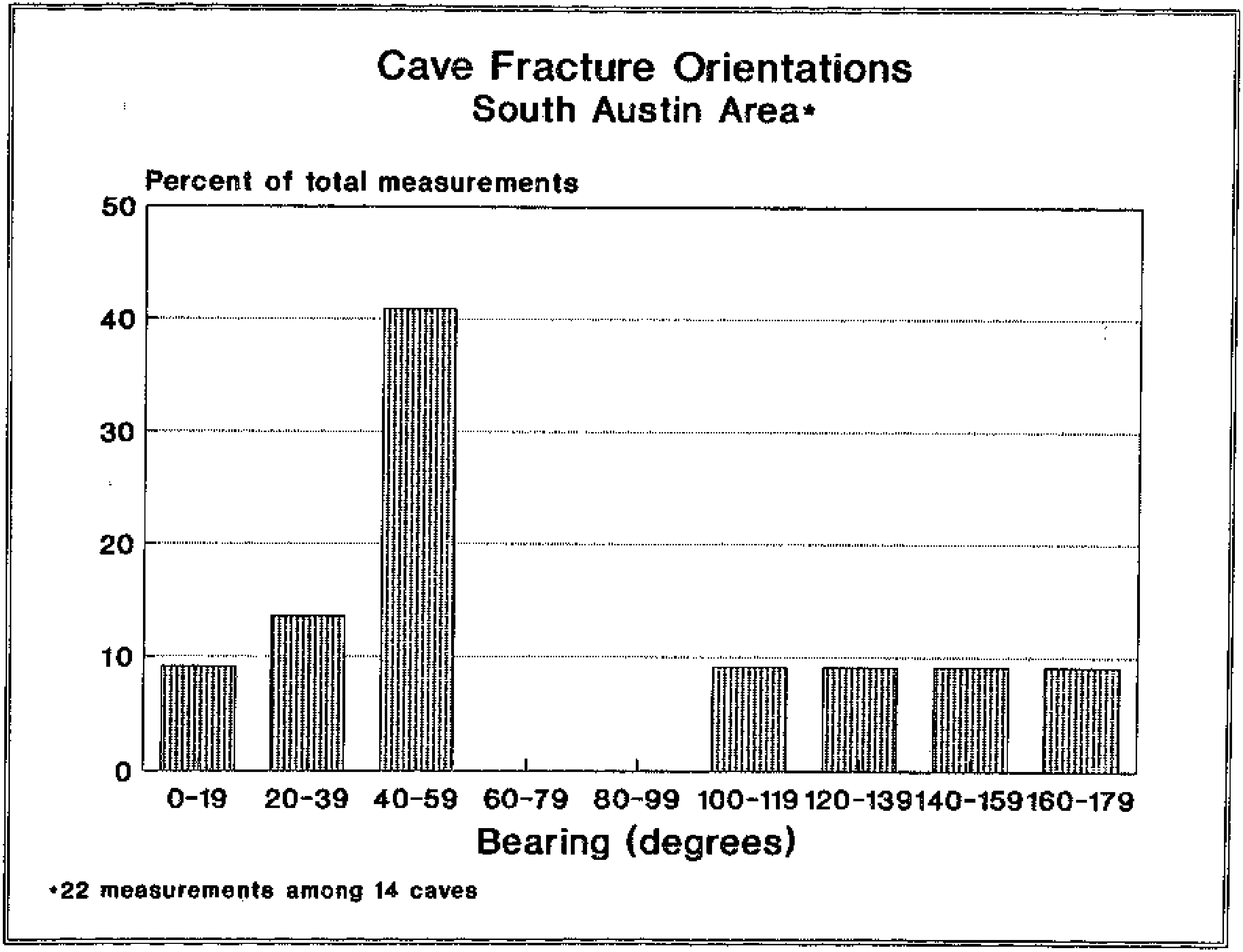
Cave Fracture Orientations
South Austin Area*
Percent of total measurements
50
40
30
20
10
0
0-19
20-39
40-59
60-79
80-99
100-119
120-139
140-159
160-179
Bearing (degrees)
*22 measurements among 14 caves

Figure 14

passages near the rear of Airman's Cave parallel faults and the Poetry Passage is developed along a fault with a measured 3 ft of displacement (Russell, 1975).

<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<<>>

Table 8

CAVE FRACTURE ORIENTATIONS OF THE SOUTH AUSTIN AREA ANALYZED IN FIGURE 14

Cave name	Fracture bearings in degrees: Primary	Secondary
Airman's Cave	44	0
Bandit Cave	52	127
Barker Bat Cave	104	
Barton Skyway Cave	22	50
Bee Creek Cave	42	12
Broken Straw Cave	173	
Cave X	59	
Cave Y	58	
District Park Cave	128	42
Goat Cave	31	
Grassy Cove Cave	38	111
Midnight Cave	178	
Sand Burr Cave	158	56
Whirlpool Cave	152	55

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Several South Austin caves are formed along tensional fractures along the upper bends of monoclines, simple drag folds that may split into faults. Some of these caves include Airman's Cave, District Park Cave, Get Down Cave and Goat Cave. Attitudes of the strata vary considerably in the immediate vicinity of faults, and even though the regional dip is a gentle 20 ft per mile (Rodda, Garner and Dawe, 1970), local variations prevent a regional evaluation of attitude on cave development. Down-dip cave development is implied where vapors were detected in caves as far as 1.7 miles down-dip from a South Austin oil spill (Russell, 1987); however, to conduct a regional assessment on the impact of bedding attitude on cave development, more data is needed from individual caves.

Post Oak Ridge Area

Little information has been published on the structural geology of Post Oak Ridge. Barnes (1974, 1981) illustrates the area as being structurally undeformed, with no major faults and dips less than 1° to the east. Iranpanah's (1964) geologic evaluation of the Burnet area included the far northwest corner of Post Oak Ridge; he found that joints predominantly trending 90-110°. Evans (1965) also conducted studies near Post Oak Ridge, but within central Williamson County, and found similar joint orientations in its vicinity.

Fracture orientations of 12 Post Oak Ridge caves are listed in Table 9. These orientations were measured during the mapping of the caves and all the fractures were identified as joints. Figure 15 shows that 50% of the fractures trend 100-119°, with most of the remaining fractures bearing east or southeast. These orientations are concordant with the apparent joint pattern of the area and

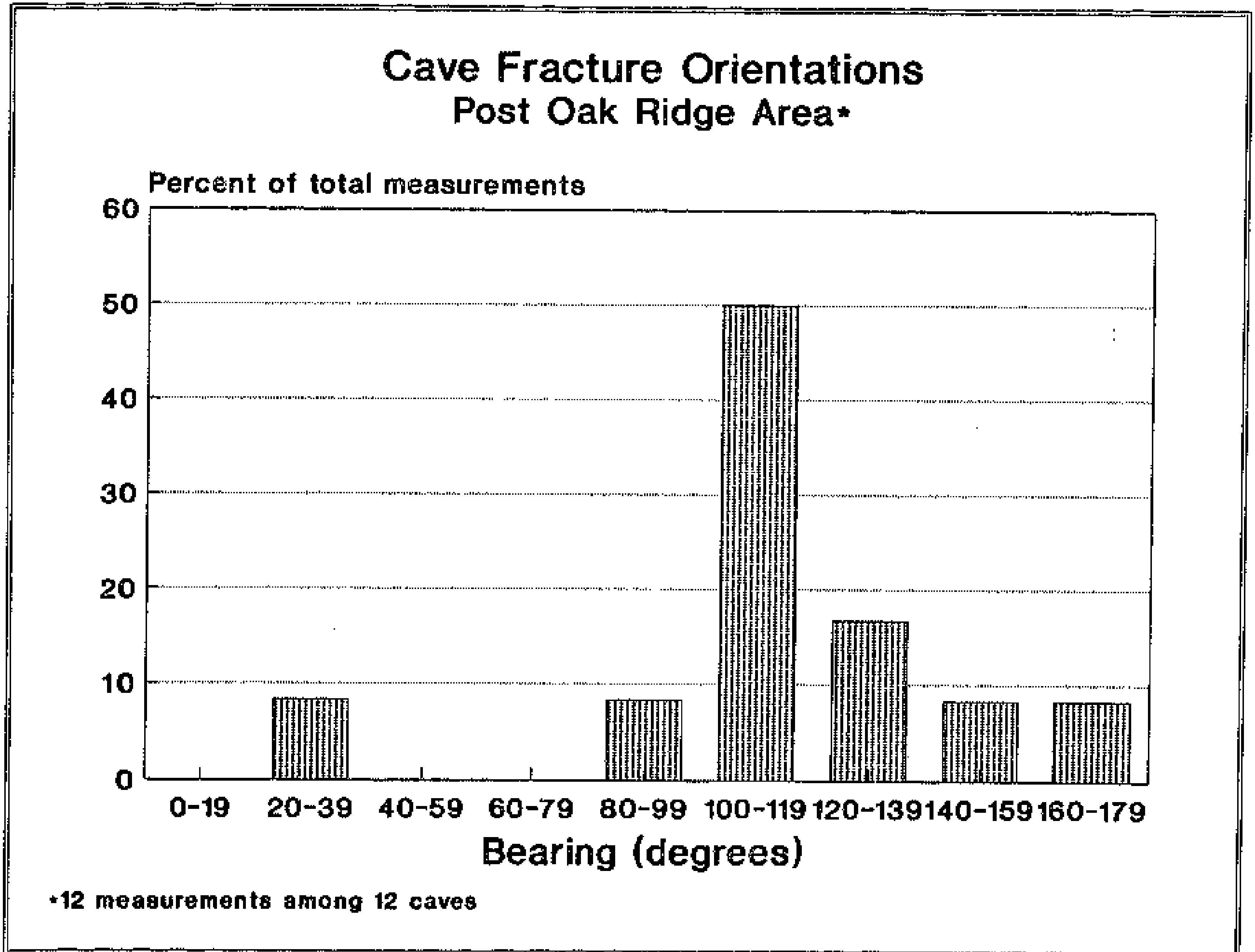
Cave Fracture Orientations
Post Oak Ridge Area*
Percent of total measurements
60
50
40
30
20
10
0
0-19
20-39
40-59
60-79
80-99
100-119
120-139
140-159
160-179
Bearing (degrees)
*12 measurements among 12 caves

Figure 15

represent solution of fractures bearing down-dip. The stream passage in Simons Water Cave heads northeast along strike, and it is probable that other cave streams in the ridge would also be strike-oriented.

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Table 9

CAVE FRACTURE ORIENTATIONS OF THE POST OAK RIDGE AREA ANALYZED IN FIGURE 15

Cave name	Fracture bearings in degrees: Primary	Secondary
Persimon Sink	165	
Simon Says Sink 1	100	
Simon Says Sink 2	115	
Simons' 1174 Sink	120	
Simons' Pretty Pit	90	
Simons' Rattlesnake Well	100	
Simons' Roadside Sink	132	
Simons' Shin Oak Sink	140	
Simons' Snake Pit	100	
Simons' Squeeze Down Pit 1	100	
Simons' Squeeze Down Pit 2	20	
Simons' Squirm Around Cave	105	

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Hydrologic Controls

Stratigraphy and geologic structure are the prime factors that determine local aquifer development, however, in a karst aquifer the morphology and extent of cave development also varies according to the local hydrologic regime. Palmer (1975, 1991) describes how maze caves form as a result of back-flooded, ponded, or slow-moving groundwater. Veni (1988a) examines the differences in conduit morphology between caves developed in gravity-drained unconfined aquifers and deep artesian aquifers.

The incision of surface streams through the aquifer is also an important factor in cave and aquifer evolution. The effect of stream valleys depends on their depth and number; deeply cut valleys produce drainage outlets for aquifers, promote groundwater circulation, and lower water tables. Extensive stream development however, can fragment and drain an aquifer into parcels with little groundwater productivity. As water levels descend, air-filled caves are left behind as relicts of the hydrologic regimes that created them. The study of these relicts is useful in assessing the paleohydrology of an aquifer, cave interrelationships, and in modeling current aquifer development below the current water table.

Five basic cave types occur in the Austin region and each reflects the current or past hydrologic processes that formed them:

1) Phreatic chambers: formed below the water table as singular voids with no extensive passages or connections to other caves.

2) Phreatic conduits: generally horizontal passages that formed below the water table and received water from several recharge points for transmission toward discharge points (springs).
3) Vadose caves: usually shafts or high-gradient caves developed above the water table that recharged (transmitted) water to the aquifer.
4) Transitional caves: originally phreatic chambers or conduits but modified into vadose recharge sites.
5) Spring caves: caves from which groundwater spills to the surface.

The above cave types are actually parts of a hydrologic continuum, and a single cave may display more than one of the listed qualities.

The following sections describe the two karst aquifers in the Austin region. Both are developed in the Edwards Limestone but differ considerably in hydrologic character.

Edwards (Plateau Outlier) Aquifer

The Edwards (Plateau) Aquifer extends over most of the Edwards Plateau region and is areally one of the largest aquifers in Texas. Stream dissection along the plateau margin has left several Edwards-capped erosional outliers with similar aquifer hydraulics (eg. Post Oak Ridge on Figure 1). Some of these outliers are stratigraphically continuous with the Edwards Limestone that recharges the Edwards (Balcones Fault Zone) Aquifer. Maps of the fault zone aquifer recharge zone are drawn based on the continuous exposure of the Edwards Limestone because potentiometric mapping is inadequate. Outlier areas like the Jollyville Plateau (Figure 1), where groundwater flow discharges in nearby valleys, are thus improperly included within the recharge zone of the fault zone aquifer.

The Edwards (Plateau Outlier) Aquifer is a term adopted here to refer to the continuous and discontinuous sections of the Edwards Limestone functioning as unconfined aquifers that are gravity-drained to nearby valleys. Isolated hills capped by Edwards Limestone are the readily identifiable discontinuous sections of this outlier aquifer. Other portions of the aquifer include stream-dissected peninsular outcrops of the Edwards Limestone within or extending from the Balcones Fault Zone; in the Austin region the Jollyville Plateau is the best known example.

Though areas such as the Jollyville Plateau have lateral continuity with the Edwards Limestone of the fault zone aquifer, their local hydraulic gradients are so steep that practically all recharge discharges at springs and seeps around the plateau margin. Thirty-two springs have been identified around the Jollyville Plateau (Table 4); although a water budget has not been calculated, their total discharge probably equals nearly all of the Plateau recharge. Typical of the plateau outlier aquifer, the Jollyville springs have either seasonal or very low discharge due to their small recharge area, and the phreatic zone is seldom thick enough to be mapped or to provide water to wells.

Caves of the plateau outlier aquifer are typically small and can be classified as either phreatic chambers, vadose shafts, or springs. Gallifer Cave

(Figure 16) is an example of a phreatic chamber, whose ceiling collapsed as water table decline removed buoyant support. The size and elevation of Gallifer and other similar caves demonstrates a former short-lived, slow-flow phreatic zone in the Edwards Limestone that was at least 90 ft thick, and the lack of vadose features indicates a rapid drop in the water table. The vadose shafts and springs are more recent karst features, formed after the drop in water table. Their small size results from a lack of preferential recharge and discharge sites; many permeable openings compete for the little water available.

The presence of significant cave streams under Buttercup Creek in Ilex Cave and neighboring Cedar Elm Sink is anomalous for the Edwards (Plateau Outlier) Aquifer. This concentration of surface and groundwater flow is probably due to local complex facies relations of the Edwards Limestone, Comanche Peak Formation, and the Whitestone, Keys Valley and Cedar Park Members of the Walnut Formation. Discharge from these caves is probably farther down Buttercup Creek in or along the Walnut Formation outcrop.

Edwards (Balcones Fault Zone) Aquifer

The Edwards (Balcones Fault Zone) Aquifer is the hydrologic system within the Edwards Limestone in the Balcones Fault system. The aquifer is divided into four segments (Figure 17): San Antonio, Barton Springs, Northern Balcones, and Washita Prairie (Yelderman, 1987). The segments are separated respectively by a drainage divide, incised valley, and gap of Edwards Limestone outcrop within the fault zone.

Baker, et. al (1986) review the hydrogeology of the Austin region, which includes the Barton Springs and Northern Balcones segments of the Edwards (Balcones Fault Zone) Aquifer. The segments are divided by the deeply incised valley of the Colorado River which flows through Austin. The segments also approximate respectively the boundaries of the South Austin area and the combined Georgetown-Round Rock and North Austin areas.

The Northern Balcones and Barton Springs segments of the fault zone aquifer can each be divided into four zones: drainage or contributing zone, recharge zone, artesian or confined zone, and saline zone. The drainage zone is the upgradient non-Edwards area whose streamflow reaches or crosses the recharge zone, the exposure of Edwards Limestone within the fault zone where water enters the fault zone aquifer. The artesian zone is that area where the Edwards Limestone is down-faulted into the subsurface and its groundwater is "confined" between upper and lower less permeable formations. The aquifer's largest springs occur where groundwater rises up fractures to discharge in stream valleys that intersect the potentiometric surface. The "bad water line" is the arbitrary downgradient boundary of the artesian zone with the saline zone, where total dissolved solids in the groundwater exceed 1,000 mg/l. Groundwater flow in both aquifer segments is generally down-dip (eastward), then along strike northward.

The recharge and artesian zones of the Northern Balcones Segment of the Edwards Aquifer respectively average 7-8 miles and 5-7 miles wide, about twice the width of those zones in the Barton Springs Segment. Balcones faulting intensifies southward, and the aquifer narrows proportionately as faults increase in number and in average displacement; consequently, the hydraulic gradient

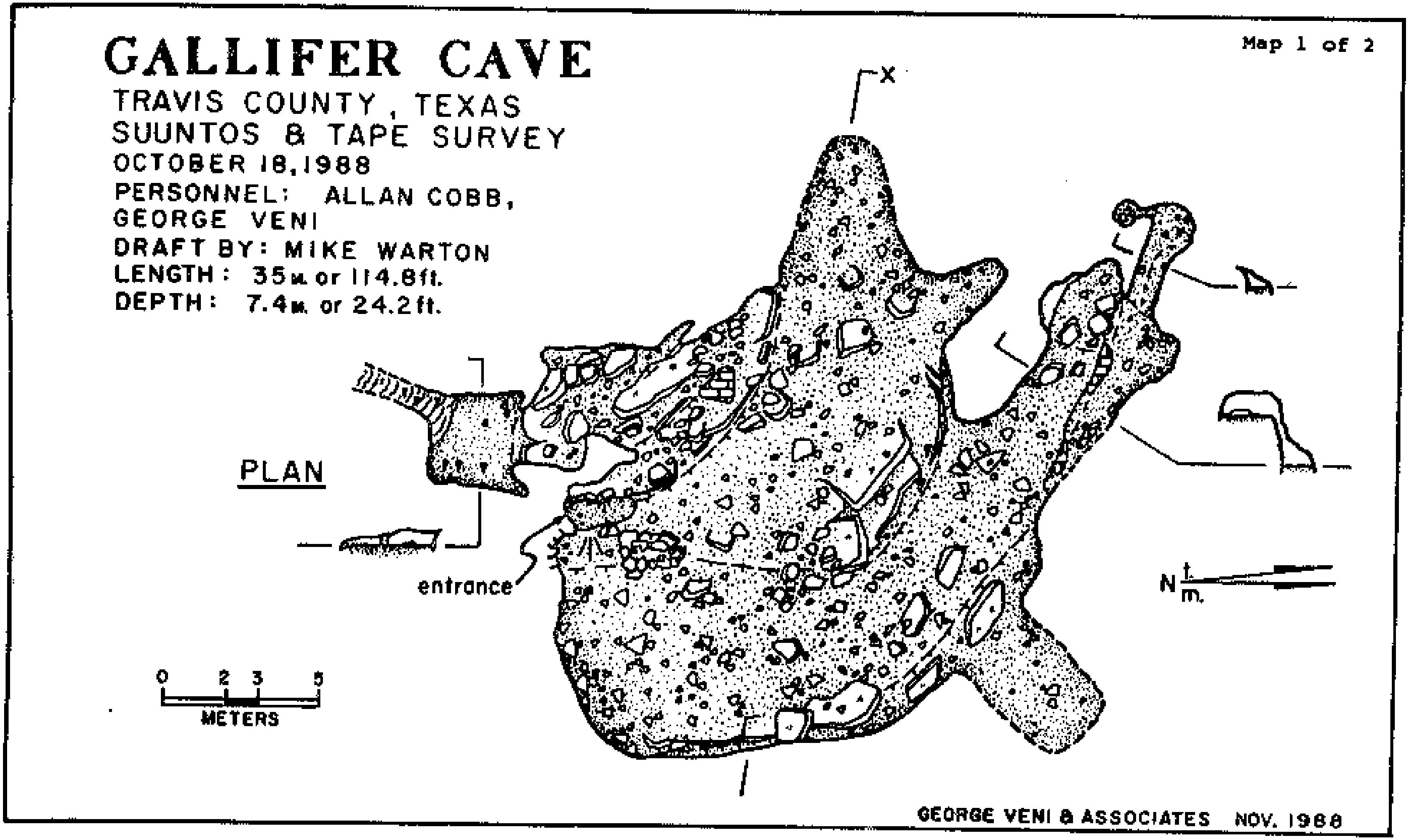


Figure 16 (from Veni and Associates, 1988a)

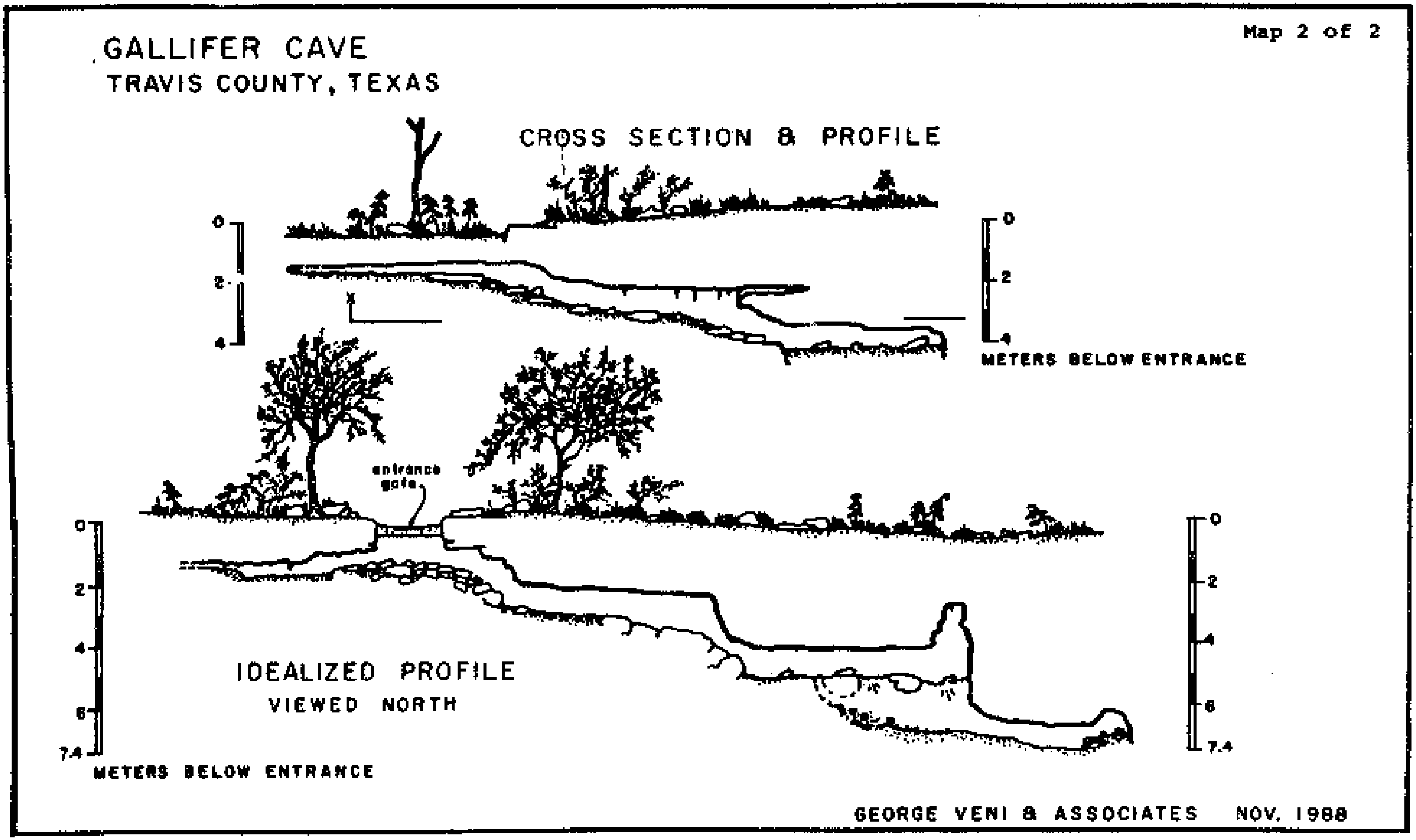
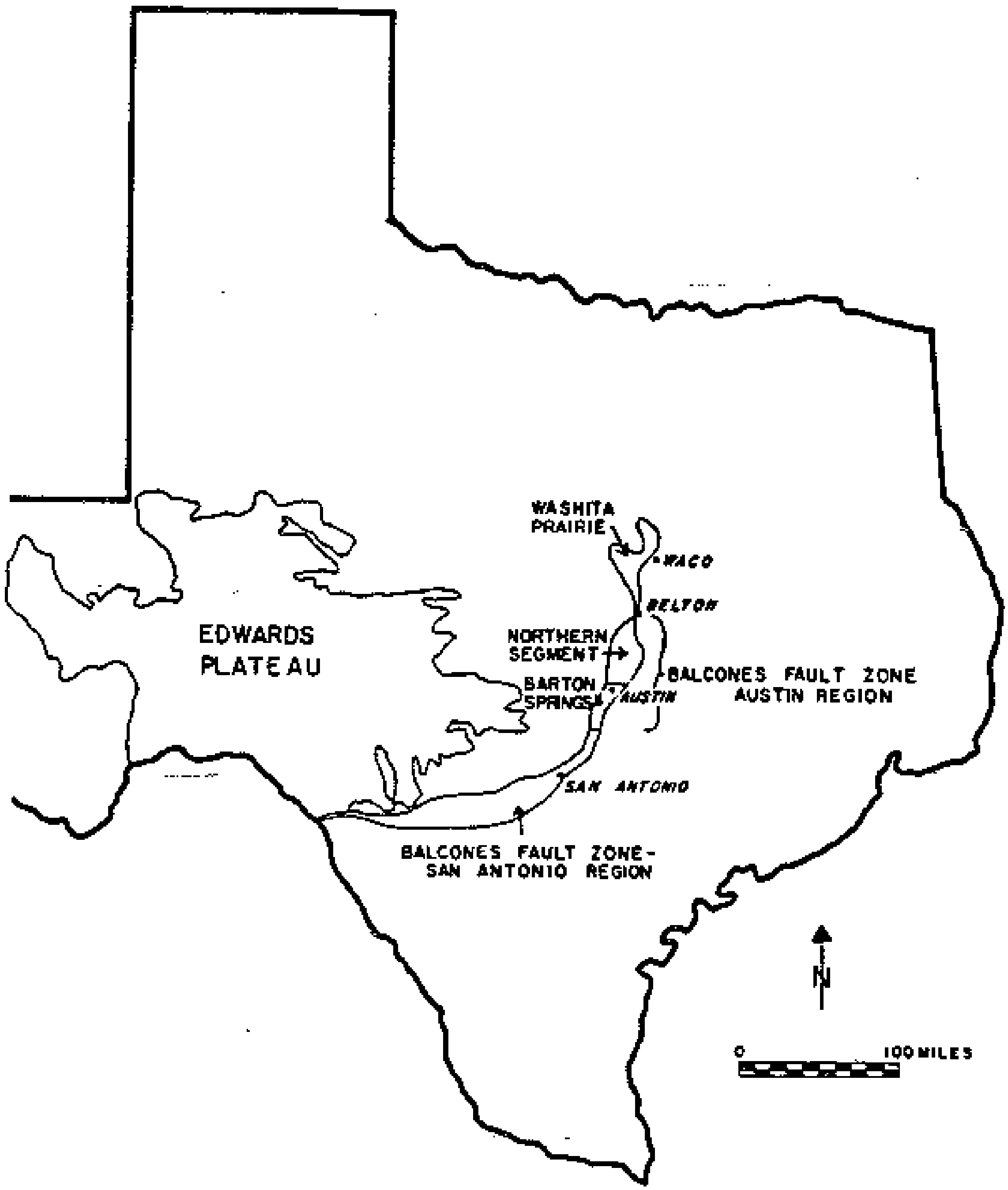


Figure 16 (continued)

Figure 17
(from Yelderman, et al, 1987)



Location of the Edwards aquifer and its subdivisions.

across the Barton Springs Segment becomes much steeper than in its northern counterpart. Depth to water also increases to the south as the Edwards Limestone thickens; the Northern Balcones Segment averages 60-80 ft to water, nearly half the depth of the Barton Springs Segment (Baker, et. al, 1986, Figure 20). These contrasting hydrogeologic factors affect cave development in the Austin fault zone aquifer segments as follows:

1) Barton Springs Segment caves are generally deeper and shafts are more common due to the steeper hydraulic gradient and thicker limestone section;
2) the steep hydraulic gradient of the Barton Springs Segment results in deposition of coarser sediments in caves than in caves of the Northern Balcones Segment;
3) caves of both aquifer segments extend through essentially all the Edwards Limestone sections, breaching impermeable strata via permeable vertical fractures;
4) fractures, especially faults, are more likely to guide the development of caves and passages in the more intensely fractured Barton Springs Segment than in the Northern Balcones Segment;
5) shafts deeper than 40 ft are uncommon due to the thinning of the Edwards Limestone in the Northern Balcones Segment and due to preferential down-dip flow along highly soluble and permeable strata (such as the Central Solution Zone) in the Barton Springs Segment;
6) horizontally extensive recharge caves in the Barton Spring Segment may have initially been phreatic but have developed into predominantly vadose conduits;
7) few basal Edwards Limestone caves or passages are known in the Barton Springs Segment recharge zone because:
    a) few caves extend to that level,
    b) passages are occluded by sediments where high hydraulic gradients suddenly decrease, and
    c) time has been insufficient to form many significant conduits as base level has dropped rapidly in geologic and recent time;
8) the presence of large horizontal phreatic conduits in the Northern Balcones Segment indicates a long-term stable base level, and/or a zone of groundwater mixing where the solution capacity of groundwater is increased (Clement, 1989); and
9) episodic partial reflooding of the Northern Segment conduits indicates a geologically recent and/or slow drop in base level to elevations only a short distance below many of the caves.

Cave Evolution and Faunal Speciation

The origin and evolution of cave-dwelling animals is dependent on the occurrence and evolution of caves, and on conditions that would cause surface-dwelling creatures to retreat underground. Speciation occurs as cave habitat becomes available or attractive, and as incipient cave dwellers begin to diverge genetically from their epigean ancestors. As species become increasingly cave-adapted, their ability to survive on the surface decreases until they evolve into obligatory cave dwellers, or troglobites. Speciation continues as caves and karst areas become fragmented by geologic processes and cavernicole populations become isolated, unable to cross the intervening non-cavernous areas. Several such isolated (endemic) species have been federally listed as endangered. A clear understanding of the origin and distribution of these species requires an analysis of their cavernous habitat and its geologic evolution.

Geologic Evolution of the Austin Region Karst

The geologic history of the Austin region karst begins with the deposition of the Edwards and associated formations during the Cretaceous Period (see Appendix C for geologic time scale). The first episode of karstification and cave development occurred during the late Early Cretaceous when the San Marcos Platform was uplifted and subaerially exposed, resulting in the erosion of as much as 100 ft of the upper Edwards Limestone in the southern part of the region. By the Late Cretaceous, however, sea levels rose to bury the Edwards under a thick sequence of carbonate and fine-grained clastic sediments (Rose, 1972).

During the very Late Cretaceous or Early Tertiary, the Edwards Plateau was lifted above sea level, and cavities within the Edwards Limestone were slowly drained of sea water and filled with meteoric water. The Edwards Limestone was completely covered at that time, and there was little groundwater movement due to the lack of discharge points, except for some upward seepage along fractures. Consequently, Edwards groundwater reached chemical saturation, and little dissolution was possible to increase porosity and permeability.

Ely (1957) determined that in the Early Miocene, prior to Balcones faulting, some streams had incised to near the top of the Edwards Limestone. Abbott (1975, 1984) found that by the Middle Miocene the Edwards would have been exposed enough to provide discharge sites for its groundwater and that initial karstic conduits had developed along fractures to these sites. Increased stream downcutting subsequent to Balcones faulting increased the hydraulic gradient, which increased flow along the conduits to the springs and further increased conduit size and permeability. As erosion exposed more of the Edwards Limestone, more water was recharged into the aquifer through the early but well-established conduit system.

Surface stream systems along the Edwards Plateau margins were also affected by the Balcones faulting. Eastward flowing meandering rivers were incised into the plateau, and headward erosion of new streams oriented perpendicular to the fault zone pirated some of the rivers from their original courses. Streams that once served as discharge points for the aquifer were altered to recharge areas after their flow had been captured and they could not erode their beds as deeply as neighboring streams to reach the water table

(Woodruff, 1977 and 1984; Woodruff and Abbott, 1979).

Jollyville Plateau Area Karst

The absolute ages of the Austin region caves cannot be accurately determined within the scope of this investigation, but many will probably correlate with levels of incision of the Colorado River and its tributaries. The phreatic caves of the Jollyville Plateau and the current western margin of the Edwards Limestone are certainly the oldest caves in the Austin region, one possible scenario is that they date to the Early Miocene. The caves are relicts of a low-velocity groundwater system that lacked the volume, chemical aggressiveness, and/or time to develop major conduits. This type of aquifer system existed in the Jollyville area during the time the Colorado River began cutting into the Edwards Limestone about 20 Ma (million years ago).

A second possible scenario is that the Jollyville caves are as young as Early Pliocene. As the Colorado River began to fully breach the Edwards, flow through the limestone increased due to the steepened hydraulic gradient and greater recharge as the Edwards exposure increased. During such a period, a phreatic conduit system could have developed that was better integrated than the low-velocity system implied by the observed phreatic chambers. Consequently, these caves would not be isolated chambers but parts of a more extensive and interconnected cave system now blocked off by collapse. Gallifer, Tooth, and Root caves are the major known phreatic caves on the Jollyville Plateau, but several nearby collapse sinkholes also known within the same stratigraphic horizon indicate that it is more cavernous than is readily apparent (Veni and Associates, 1988a).

The age of this second Jollyville cave origin scenario can be estimated by the average rate of incision for the Colorado River. Extrapolating from Figure 13 of Baker, et. al (1986), the top of the Edwards Limestone on the Jollyville Plateau would have had an elevation of 1,250 ft. During the onset of Balcones faulting 20 Ma, the Colorado River would have been situated near the top of the Edwards; an average incision rate of 38.5 ft/My (million years) would allow the Colorado to reach its current 480 ft elevation. Based on that rate, for the Jollyville caves to have formed according to the second scenario the Colorado River would have cut to near the base of the Edwards by about 12.5 Ma.

The time periods for both scenarios are far older than most confirmed dates for Texas caves, but a 90 ft thick phreatic zone in the Jollyville Plateau was needed to create its caves; such a zone could not exist once the Edwards Limestone had been fully cut by the adjacent Colorado River. Wetter climates and the slight dip away from the river could have extended the presence of a thick phreatic zone but not for any significant period.

Groundwater drained out of the Jollyville Plateau (and its caves) as the Colorado River incision resulted in steeply dissected plateau margins. Many of the phreatic caves collapsed without the buoyant support of water; if any vadose features developed during the water withdrawal they were hidden by the breakdown. However, vadose caves began to develop as favorable solution zones were eroded and exposed to the recharge. One such area contains the Amber Cave group of 4 caves and 9 sinkholes (Veni and Associates, 1988a). Abundant permeable fractures compete equally for available recharge so there is little preferential development among these caves. Although they intersect and have some horizontal development in the permeable zone that contains the older phreatic caves, these caves are shafts that lacked a local water table and developed laterally only atop impermeable zones. Most of these small caves are likely very recent features, probably dating to about the end of the Pleistocene.

Northern Balcones Segment Karst

The Cedar Park, North Austin, and Georgetown-Round Rock areas have a similar and interrelated history of karst aquifer development and are considered together here as parts of the Northern Balcones Segment of the Edwards (Balcones Fault Zone) Aquifer.

The first caves to develop in the Northern Balcones Segment were formed during low velocity phreatic conditions, similar to what existed in the Jollyville Plateau prior to the development of spring outlets that allowed vigorous groundwater circulation. San Gabriel Spring was probably the first major spring to discharge from the aquifer, followed in turn by Berry Spring and Salado Spring to the north. As spring outlets developed, groundwater circulation increased and the elevation of the water table decreased, draining phreatic chambers such as McNeil Bat Cave.

The timing of the development of the first Northern Balcones Segment springs has not been determined, but the San Gabriel Spring is certainly the oldest. The North and South Forks of the San Gabriel River are the largest and most deeply incised streams crossing the Northern Balcones Segment of the Edwards Limestone. The downcutting of the rivers through the Edwards Limestone and groundwater capture by San Gabriel Spring prevented much groundwater from migrating into the Edwards Limestone north of the river. Although the lithology becomes less favorable for cave development to the north, this groundwater capture probably accounts for the significant decrease in the size and number of caves in northern Williamson County.

Most of the Northern Segment caves (both north and south of the San Gabriel River) are vadose-modified phreatic conduits that run down-dip toward the Balcones Fault Zone. The caves formed initially under phreatic conditions concurrent with the development of the springs. Groundwater that approached the fault zone turned to flow along strike toward the springs and enlarged fractures parallel to the fault zone. Groundwater in some caves and springs located near the deeply cut margin of the Edwards Limestone along the Colorado River, flowed up-dip to discharge into the Colorado due to the steep hydraulic gradient. These caves are generally very small because of their small drainage basins.

Continued downcutting by the San Gabriel and related rivers has steadily lowered the water table in the Northern Balcones Segment, leaving many caves in the vadose zone. The master conduits along the Balcones Fault Zone became vadose stream caves, but some caves up-gradient in the outcrop were abandoned in favor of new routes to the water table. Abbott (1984) places the earliest opening of the caves to the surface during the Sangamon interglacial (120-140 ka [thousand years ago]) based on evidence from fossils, although most vertebrate fossils found in area caves date from about 30 ka to the present (Lundelius, 1986). Harmon's (n.d.) radioisotope dating of speleothems in Inner

Space Cavern indicate that vadose conditions existed in the cave at least as early as 57 ka ±13 ka or 52 ka ±6 ka.

Currently, the water table for the aquifer is several feet below many of the master conduit caves like Beck Ranch Cave and Inner Space Cavern, but after periods of high recharge the water table may rise and partially reflood them. However, overall flow through these conduits is lost, and many have been filled by resultant sediment aggradation. While the main groundwater flow has been generally diverted to conduits forming deeper in the limestone in response to stream incision, climatic changes have resulted in a recent period of surface-stream aggradation. Hall (1990) describes nearly 7 m of aggradation in the North Fork of the San Gabriel River, which began about 5 ka and ended abruptly at 1 ka. The San Gabriel has since returned to its previous level, but it is not certain if the subsequently raised water table had any significant impact on cave development in the area.

South Austin Area Karst

Karst aquifer evolution in the South Austin area is similar in many respects to the Northern Balcones Segment:

1) phreatic chambers formed by slow-moving groundwater, later drained by spring development along the downcutting Colorado River;
2) down-dip flow from the recharge zone; and
3) strike flow along fractures near the eastern margin of the outcrop to the spring outlets.

The main differences from the northern aquifer are less development time and more intensive faulting.

Using the 38.5 ft/My incision rate for the Colorado River, incision of the Edwards Limestone east of the Mount Bonnell Fault began roughly 6 Ma. The overall exposure of the Edwards outcrop is probably much more recent south of the Colorado River. The outcrop of the northern aquifer is continuous with the Edwards Plateau outliers and so at least its up-dip sections have been exposed for some time. The initially slow input of recharge, even without well established discharge points, may have been instrumental in creating its large conduits over a greater time period.

The Barton Springs Segment of the aquifer has little evidence of significant phreatic conduits except at its lower elevations such as at Airman's Cave. Airman's was probably part of an early spring system which later developed into Barton Springs. This precursor Barton Springs discharged into the Colorado River near the location of the modern springs, but incision of the river and lowering of the land surface caused the springs to migrate to a lower elevation while continuing to discharge along the same fracture set. Meanwhile, Barton Creek was being pirated from the southwest toward the springs (Woodruff, 1984) with Airman's Cave significantly contributing to the sapping that encouraged the northeastward deflection of the creek. Airman's was eventually truncated by the creek and shortened headward to its present extent. Russell (1975, 1984) notes case-hardened breakdown blocks in the cave that formed during the period of intermittent discharge when flow through the cave was being abandoned as the water table descended more than 100 ft to its present level at Barton Springs.

Most caves in the South Austin area were developed in the vadose zone, some being modified phreatic chambers and conduits. These caves have small conduits, easily blocked by clastic sediments, with limited and often difficult access for human study, but they are nonetheless effective for groundwater recharge. Human access into the deeper portions of the aquifer is also hampered by hydrostratigraphic barriers resulting from changes in lithology and faulting. The character of conduit development along the water table is poorly known throughout all segments of the Edwards (Balcones Fault Zone) Aquifer due to similar limited accessibility, but a study of well records in the San Antonio Segment indicates that conduits averaging 5-6 ft in height occur at depths of about 60 ft below the water table. These caves are believed to have formed by the mixing corrosion of adding recharge water to resident groundwater (Albert Ogden, personal communication, 1986), a process which could also account for the large conduits of the Northern Balcones Segment.

Post Oak Ridge Area Karst

The caves on Post Oak Ridge are very recent features, having formed soon after the erosional removal of the overlying Keys Valley Member of the Walnut Formation. Their development is certainly Pleistocene in age and probably dates from the late Pleistocene. The caves are vadose shafts and streams, and there is no evidence of older, pre-existing, phreatic caves in the area. Based on the knowledge that the ridge is a narrow plateau outlier with no significant water table and that its caves are mostly solutionally enlarged vertical fractures, its geologic history is probably similar to the recent history of the Jollyville Plateau.

Interstitial Zones

Most of this report has focused on the caves of the Austin region, only implying the existence, extent, and importance of the interstitial zone. Henry (1978) defined the interstitial zone as voids within sediment banks of streams, voids in the underflow of streams, and voids in the vadose zone. In this report the interstitial zone is more broadly defined as the small, humanly impassable, solutionally enlarged voids that provide potential habitat for cave-dwelling species in the areas between caves. The zone generally extends from caves in the form of micro-conduits that feed in some of the water which forms the caves. Types of interstitial areas include solutionally widened bedding planes and fractures, anastomosed bedding planes and fractures, honeycomb solution zones, non-cemented collapse or fault brecciated areas, and porous cave sediments. The interstitial zone also includes caves that have been near-completely filled with sediment.

Much of the interstitial zone is characterized by the diffuse flow component of karst aquifers (White, 1969). Its most intensive development occurs adjacent to horizontally extensive caves and where cavernous limestone crops out at the surface. The interstitial zone is laterally extensive near caves because caves are sites of flow-path convergence and because groundwater is injected when caves flood. The exposure of cavernous limestone at the surface allows for vertical interstitial development via solutionally enlarged fractures, which can interconnect with horizontal interstitial zones and horizontal caves. In the phreatic zone, the interstitial zone is the extensive and permeable system that supplies most groundwater to wells.

Based on study and observation throughout the Austin region, the interstitial zone is vertically and laterally extensive throughout all the karst areas. If permeable sections of the limestone are continuous between given areas, even if no caves are known, it is possible that the conduits of the areas are interconnected by interstitial micro-conduits. In some cases the interstitial zone may not hydrologically connect certain caves, but it could provide an avenue of movement between those caves for some cave-dwelling species.

The hydrologic bounds of the interstitial zone around a cave can be approximated to determine the range of water inflow to the cave which could contain nutrients or contaminants (Veni and Associates, 1988a and 1988b). Such an assessment requires a detailed survey of the cave, measurement of its interface with the interstitial zone, and consideration of the fractures, solution zones, attitude of the beds, and hydrologic conditions that affected the origin and development of the cave.

The biologic bounds on faunal migration through the interstitial zone are determined by food availability. The minimum width of interstitial voids for a significant cavernicole fauna is probably 5-10 mm; this width corresponds to the threshold of turbulent groundwater flow that could carry nutrients to cave species. Although some species can traverse smaller openings, the lack of food probably restricts their migration. Collins (1989) found fracture and bedding plane widths in the Georgetown Limestone, which is not known to have a cavernicole fauna, to be generally less than 1 mm, while widths in the Edwards Limestone range from "a few millimeters to a few centimeters" and support a rich cavernicole population. Similar findings were made in Europe where cave fauna was found to generally inhabit voids greater than 1 mm in width (Juberthei and Delay, 1981).

Caves without natural entrances and of both relatively shallow and deep depth have been encountered during Austin area construction and well drilling; with respect to cavernicole fauna, some caves have been biologically active while others are biologically sterile. The sterile caves have at least one of two characteristics in common:

1) all fractures or openings to the caves are less than 5-10 mm wide or otherwise filled with fine clay or secondary (speleothem) calcite;
2) the caves are situated under an impermeable formation.

While the first factor may physically restrict access by cave fauna, both factors impose restrictions by greatly limiting nutrient input. These factors may also explain why certain caves with natural entrances lack significant troglobite populations. Surface-foraging trogloxenes, such as cave crickets, can travel from one cave entrance to another; on the other hand, if troglobites cannot enter a cave via the interstitial zone, their inability to survive on the surface prevents them from entering via the cave entrance.

In most cases, caves and naturally-filled sinkholes are foci of nutrient and water input into the subsurface and thus are foci of subsurface biologic activity. As caves become drier during extended seasonal periods without precipitation, cave species probably retreat into the interstitial zone where there is less food but greater moisture (Elliott and Reddell, 1989).

Distribution of Cave Fauna in the Austin Region Karst

The distribution of endangered cave fauna in the Austin region was first illustrated by Elliott and Reddell (1989) and was updated by the Biological Advisory Team (1990). The following discussion will consider the region's specific geologic barriers to the distribution of troglobites based on spatial analyses of 38 troglobite species; although other troglobites are also known, these species are those limited to the Austin region. Table 10 lists the 38 species and their relative degrees of troglobitic development (i.e. physiologic adaptation to being obligate cave dwellers). The following analyses are based on all 38 species, not just those listed as endangered, because an endangered listing often includes the consideration of factors that have no bearing on the natural distributions of species (e.g., human activities which threaten species' survival).

The distribution and speciation of cave fauna is dependent on geologic barriers to migration and on biologic constraints on evolution. As mentioned early in this report, segregation of fauna results in speciation, but other biologic factors are also important in analyzing speciation and distribution, including:

1) the time of the species' retreat to the subsurface environment;
2) the epigean distribution of the ancestral species; and
3) rates of selection and genetic mutations of the species.

The analysis of such biologic factors is beyond the scope of this report but they are introduced since they are integral to the following geologic distribution analyses.

Geologic barriers to the migration of troglobites are stratigraphic, structural, or hydrologic. The primary stratigraphic barrier is the simple lack of cavernous rock, but others include impermeable layers within an otherwise cavernous sequence. Structural barriers are usually coupled with stratigraphic barriers through fault juxtaposition of cavernous and noncavernous units. Hydrologic barriers vary according to the needs of the species in question; terrestrial species have a downward limit at the water table, which serves as the upper limit for aquatic species. Conditions that decrease the input of moisture or nutrients into a cave beyond the organisms' ability to survive are also barriers.

The areas where it is easiest to define zones of limited cavernicole distribution are isolated hills, or "islands," of limestone, such as those of West Lake Hills or those adjacent to the Jollyville Plateau. Beyond this type the distribution of species becomes more subtle and complex.

Figure 18 is a schematic representation of the Austin region illustrating 11 karst areas, their physiographic and geologic boundaries, and their troglobite species. The karst areas are based on the geologic areas examined earlier in this report, but with further subdivision of the South Austin, North Austin, and Georgetown-Round Rock areas. The karst areas are numbered 0-10 and are keyed to Table 11, which includes area descriptions. Figure 19 has the actual outlines of each area.

Table 10

TROGLOBITES OF THE AUSTIN REGION ANALYZED IN FIGURES 18-24*

No.	Species name	Troglobitic development
1.	*Cicurina (Cicurella)* new species 1	high
2.	*Cicurina (Cicurella)* new species 2	high
3.	*Cicurina (Cicurella)* new species 3	high
4.	*Cicurina (Cicurella)* new species 4	high
5.	*Cicurina (Cicurella)* new species 5	high
6.	*Cicurina (Cicurella)* new species 6	high
7.	*Cicurina (Cicurella)* new species 7	high
8.	*Cicurina (Cicurella)* new species 8	high
9.	*Cicurina (Cicurella)* new species 9	high
10.	*Cicurina (Cicurella)* new species 10	high
11.	*Cicurina (Cicurella) buwata* Chamberlin and Ivie	high
12.	*Neoleptoneta anopica* (Gertsch)	high
13.	*Neoleptoneta concinna* (Gertsch)	high
14.	*Neoleptoneta devia* (Gertsch)	high
15.	*Neoleptoneta myopica* (Gertsch)	low+
16.	*Eidmannella reclusa* Gertsch	high
17.	*Aphrastochthonius* new species	high
18.	*Tartarocreagris* sp. nr. new species 1	low
19.	*Tartarocreagris* new species 1	low
20.	*Tartarocreagris* new species 2	high
21.	*Tartarocreagris infernalis* (Muchmore)	high
22.	*Microcreagris reddelli* (Muchmore)	high
23.	*Microcreagris texana* (Muchmore)	high+
24.	*Texella* new species 1	low to high+
25.	*Texella* new species 2	low
26.	*Texella mulaiki* Goodnight and Goodnight	high
27.	*Texella reddelli* Goodnight and Goodnight	low+
28.	*Speodesmus* new species	high
29.	*Rhadine austinica* Barr	high
30.	*Rhadine noctivaga* Barr	high
31.	*Rhadine persephone* Barr	low+
32.	*Rhadine russelli* Barr	high
33.	*Rhadine subterranea* (Van Dyke)	high
34.	*Rhadine subterranea mitchelli* Barr	high
35.	*Rhadine subterranea subterranea* Barr	high
36.	*Batrisodes (Excavodes)* new species 1	medium
37.	*Batrisodes (Excavodes)* new species 2	high+
38.	*Texamaurops reddelli* Barr and Steeves	high+

*data courtesy of James R. Reddell
"+" denotes federal listing as an endangered species

Figure 18: Schematic profile of Austin region karst areas and the distribution of troglobites (species numbers keyed to Table 10).

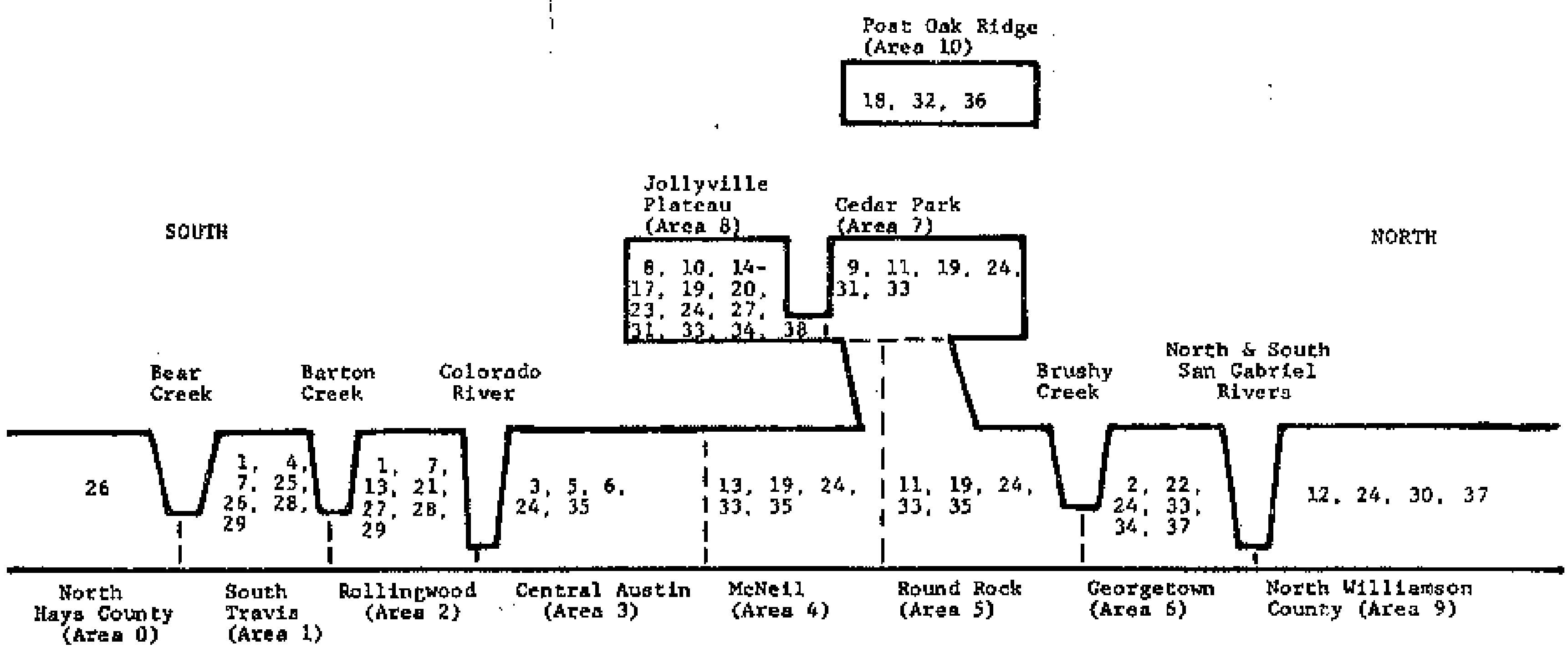


Table 11

SUMMARY DESCRIPTION OF AUSTIN REGION KARST AREAS, DELINEATED IN FIGURES 18-19 AND ANALYZED IN FIGURES 20-24*

No.	Karst area	Descriptions and boundaries
0.	North Hays County	Bounded to the north by Bear Creek, southern boundary undetermined; possibly drainage divide of the San Antonio and Barton Springs segments of the Edwards Aquifer. Limestone thinning due to erosion on San Marcos Arch. Intensely faulted.
1.	South Travis County	Bounded to the south by Bear Creek and to the north by Barton Creek. Intensely faulted area.
2.	Rollingwood	Bounded to the south by Barton Creek and to the north by the Colorado River. Intense faulting. Area of discharge from Barton Creek Segment of aquifer.
3.	Central Austin	Bounded to the south by the Colorado River and to the north by thin section of Edwards Limestone near the McNeil area. Intense to moderate faulting.
4.	McNeil	Bounded by narrow exposure of Edwards Limestone near east end of Travis-Williamson County line along Edwards outcrop. Moderate to intense faulting.
5.	Round Rock	Bounded to the north by Brushy Creek and to the south and west near the Brushy Creek drainage divide. Moderate faulting.
6.	Georgetown	Bounded to the south by Brushy Creek and to the north by the San Gabriel River. Moderate faulting. Groundwater discharge area along San Gabriel River.
7.	Cedar Park	Bounded by area of complex stratigraphy. Little faulting.
8.	Jollyville Plateau	Bounded by connection of plateau to other Edwards outcrops along Travis-Williamson County line. Little faulting.
9.	North Williamson Co.	Area north of San Gabriel River; northern boundary undetermined, probably near Williamson-Bell County line where limestone thins and becomes marly. Little to moderate faulting.
10.	Post Oak Ridge	Isolated exposure of Whitestone Lentil of Walnut Formation along ridgetop. Little faulting.

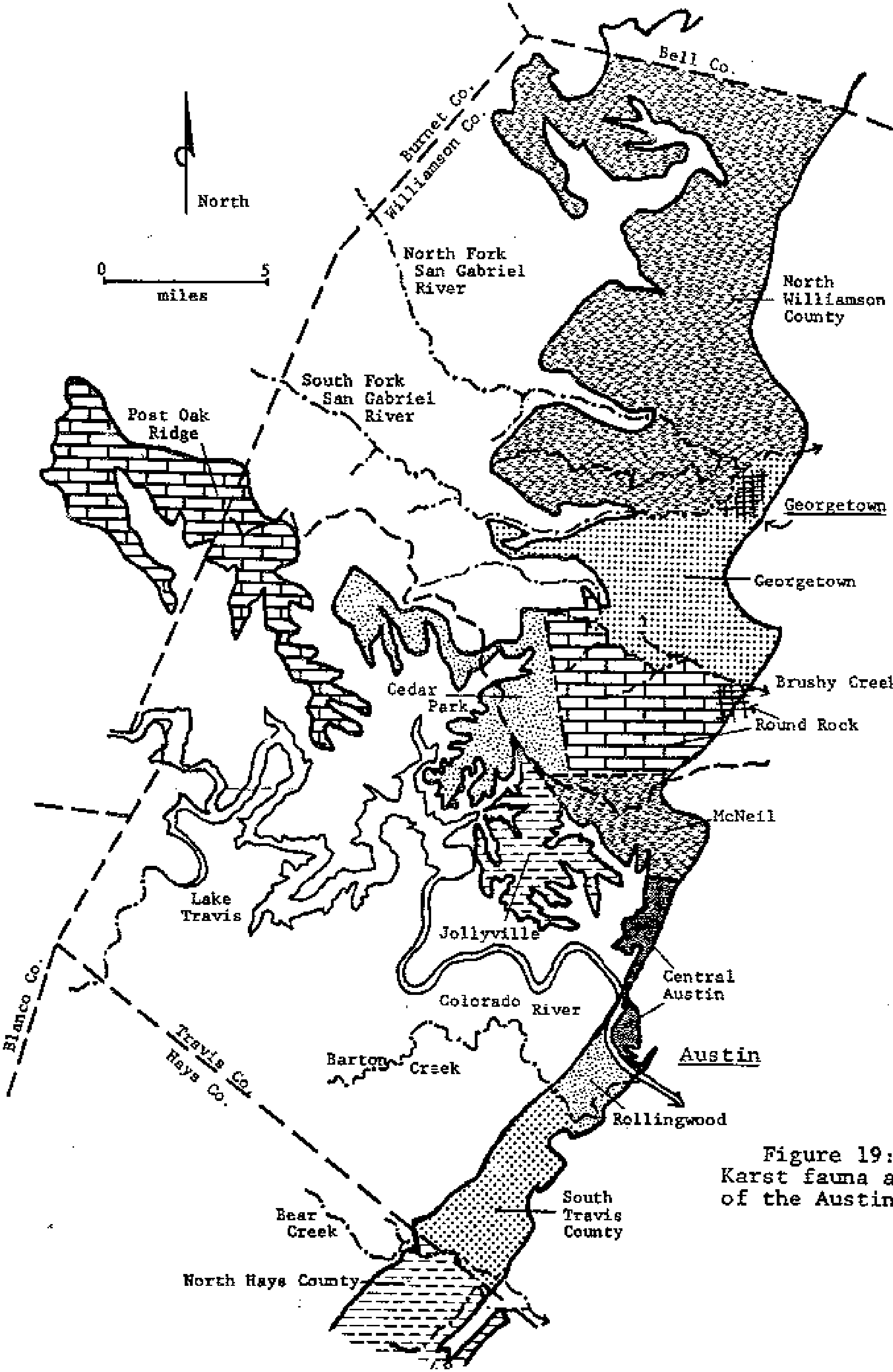


Figure 19:
Karst fauna areas
of the Austin region.

Figures 20-23 schematically illustrate the distribution of the 38 troglobites in the Austin region. Figure 20 shows the specific species that occur in each karst area; connecting horizontal lines correlate their mutual presence among areas. The lack of connecting lines for a species indicates it is restricted to the one karst area. The limits of the horizontal lines indicate probable barriers to species migrations. The areas included within the lines indicate areas which have no significant barriers to migrations. Areas that are crossed by some lines and not by others reflect developing or recently developed barriers where there has been insufficient time for speciation of all the listed troglobites.

Figures 21 and 22 illustrate the percentage of species each area has in common with other areas. Shown in Figure 21 are the specific comparisons of shared species that each area has with each of the other areas. Figure 22 is an average of all the comparisons obtained by summing the Figure 21 percentages and dividing by 10, the number of neighboring karst areas. Figure 23 provides a similar but somewhat "mirror image" view to faunal distribution by plotting the percent of species known from each area which are endemic (only occur) in those areas. As will be discussed in further detail below, areas that have a relatively low percentage of species in common with other karst areas, or conversely a high percentage of endemic species, are bounded by effective geologic barriers or restrictions to troglobite migration. While further collection and study of troglobites in the Austin region will modify the numbers of Figures 20-23, the detailed level of biospeleologic investigations in the region suggests that most of the current figures will remain as close approximations.

The following discussion frequently uses the terms "barrier" and "restriction" in assessing troglobite migration. Barriers refer to features or zones which cannot be crossed by troglobites, such as areas where cavernous rock is absent. Restrictions are features or zones that allow limited migration of troglobites. The limits will usually be either spatial, such as the narrow ridge of cavernous rock connecting the Jollyville Plateau to the main Edwards outcrop, or temporal, when the intermittent drying of some streams allows the migration of terrestrial troglobites.

Area Analyses

AREA #0, NORTH HAYS COUNTY:

The area south of Bear Creek in North Hays County has not been well studied biologically or geologically for this investigation. Only one of the 38 considered species, *Texella mulaiki*, is known to occur in that area and is otherwise only known from the South Travis County area. The species has been found as far as San Marcos, which implies that the thinner limestone section along the San Marcos Arch and the drainage divide between the San Antonio and Barton Creek segments of the Edwards Aquifer are not barriers to troglobite migration. Data are insufficient to define the restrictions that may exist in this area.

AREA #1, SOUTH TRAVIS COUNTY

Six of the 38 Austin region cave species have been identified in the South Travis County area. Figures 20 and 21 indicate that four of the six species are shared with the Rollingwood area, and their distribution does not extend south into North Hays County or north of the Colorado River. The southward limit should not be considered a significant restriction and may largely be an artifact

Distribution of Troglobites in the Austin Region

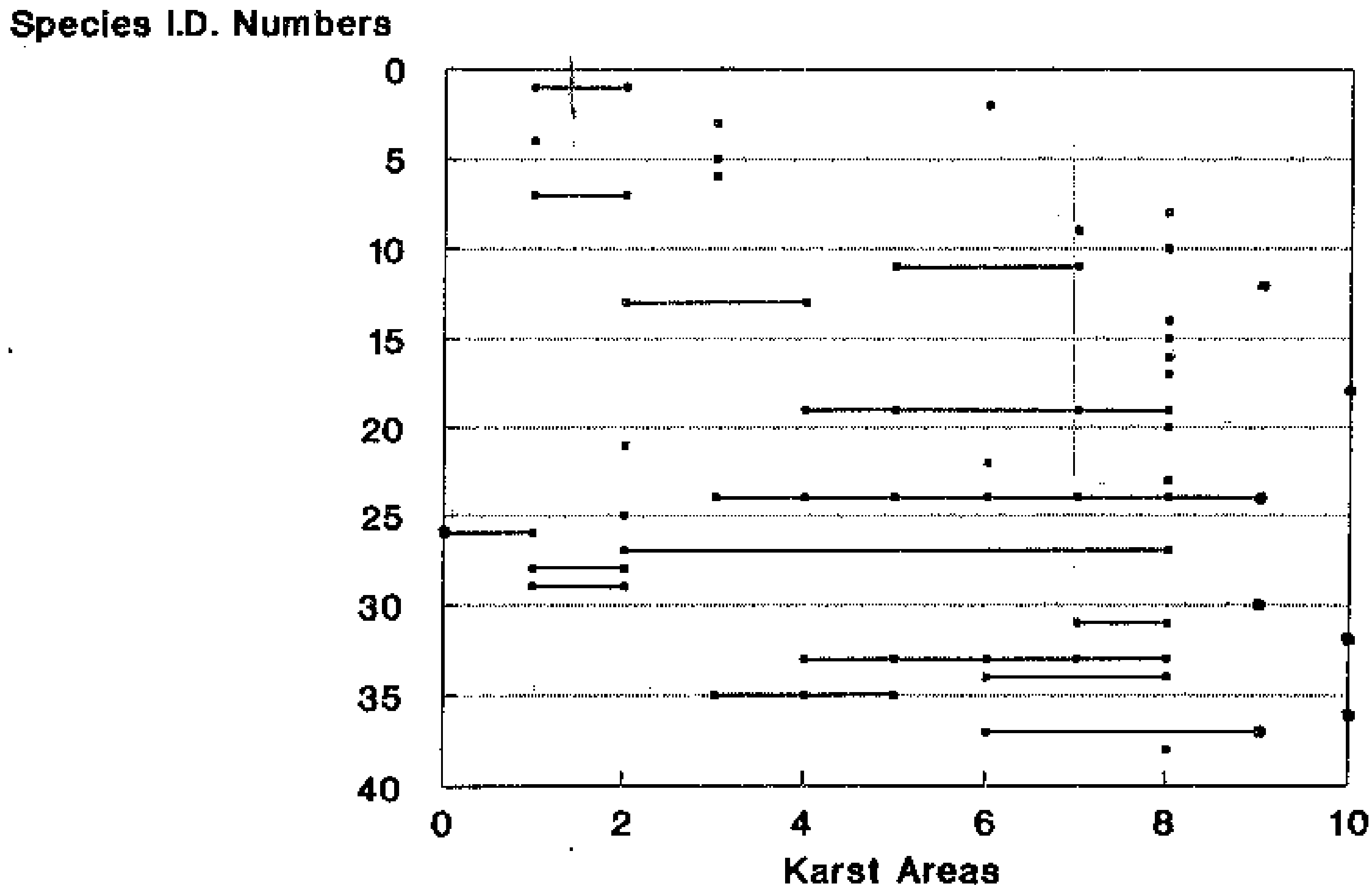
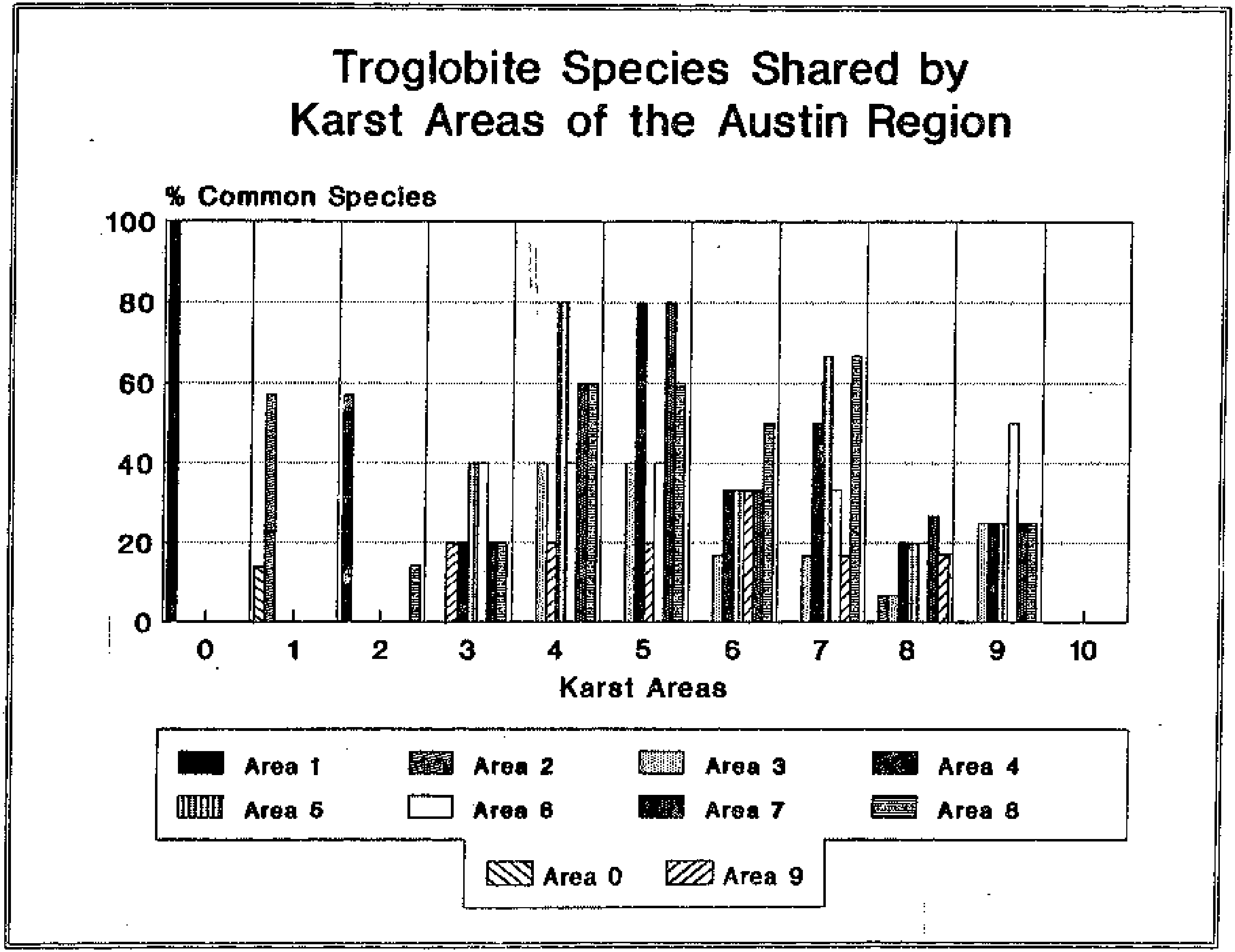


Figure 20



Troglobite Species Shared by
Karst Areas of the Austin Region
% Common Species
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
Karst Areas
Area 1
Area 2
Area 3
Area 4
Area 5
Area 6
Area 7
Area 8
Area 0
Area 9

Figure 21

Average of Shared Troglobites in Karst Areas of the Austin Region

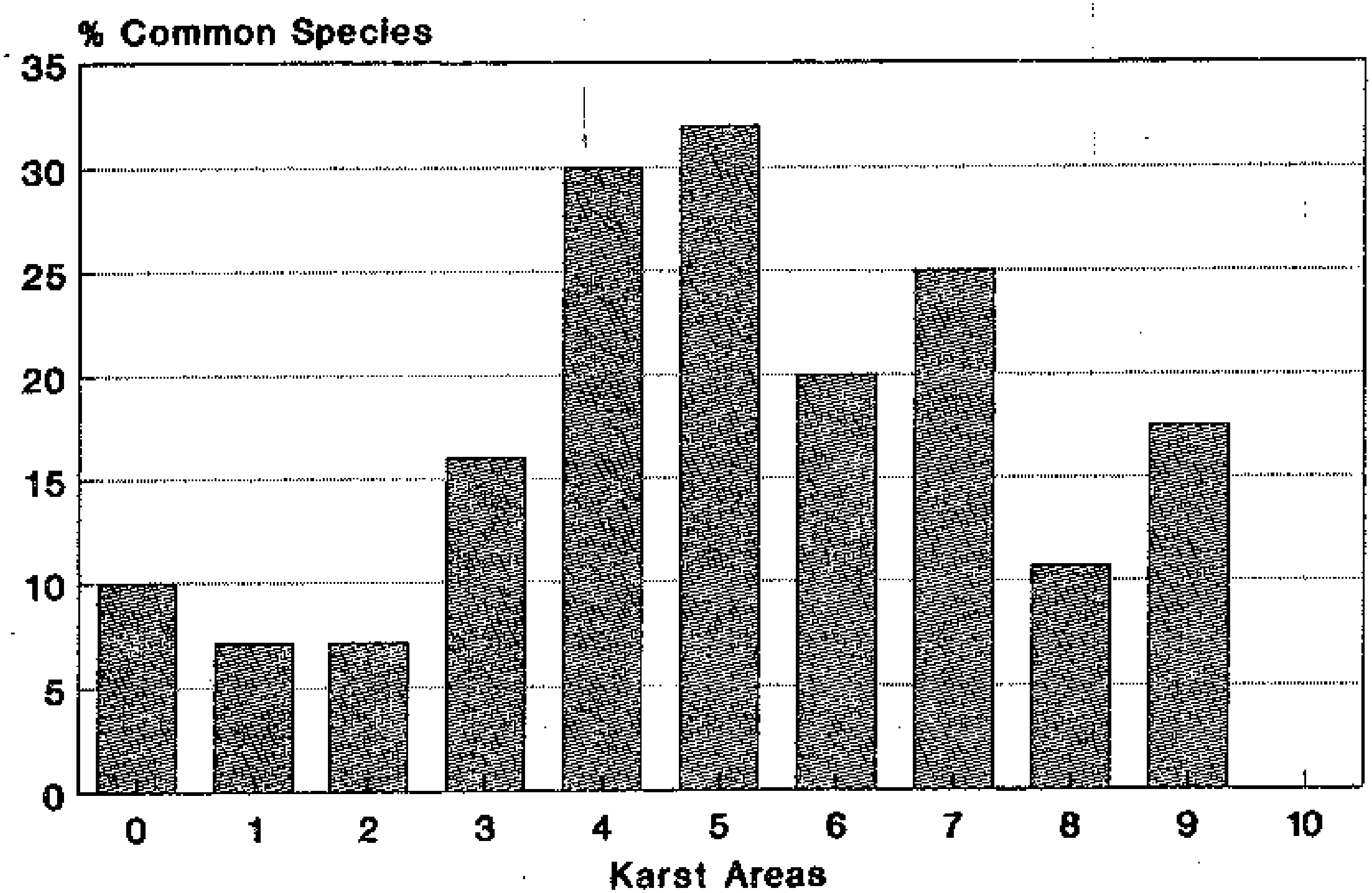


Figure 22

Species Endemic to Karst Areas of the Austin Region

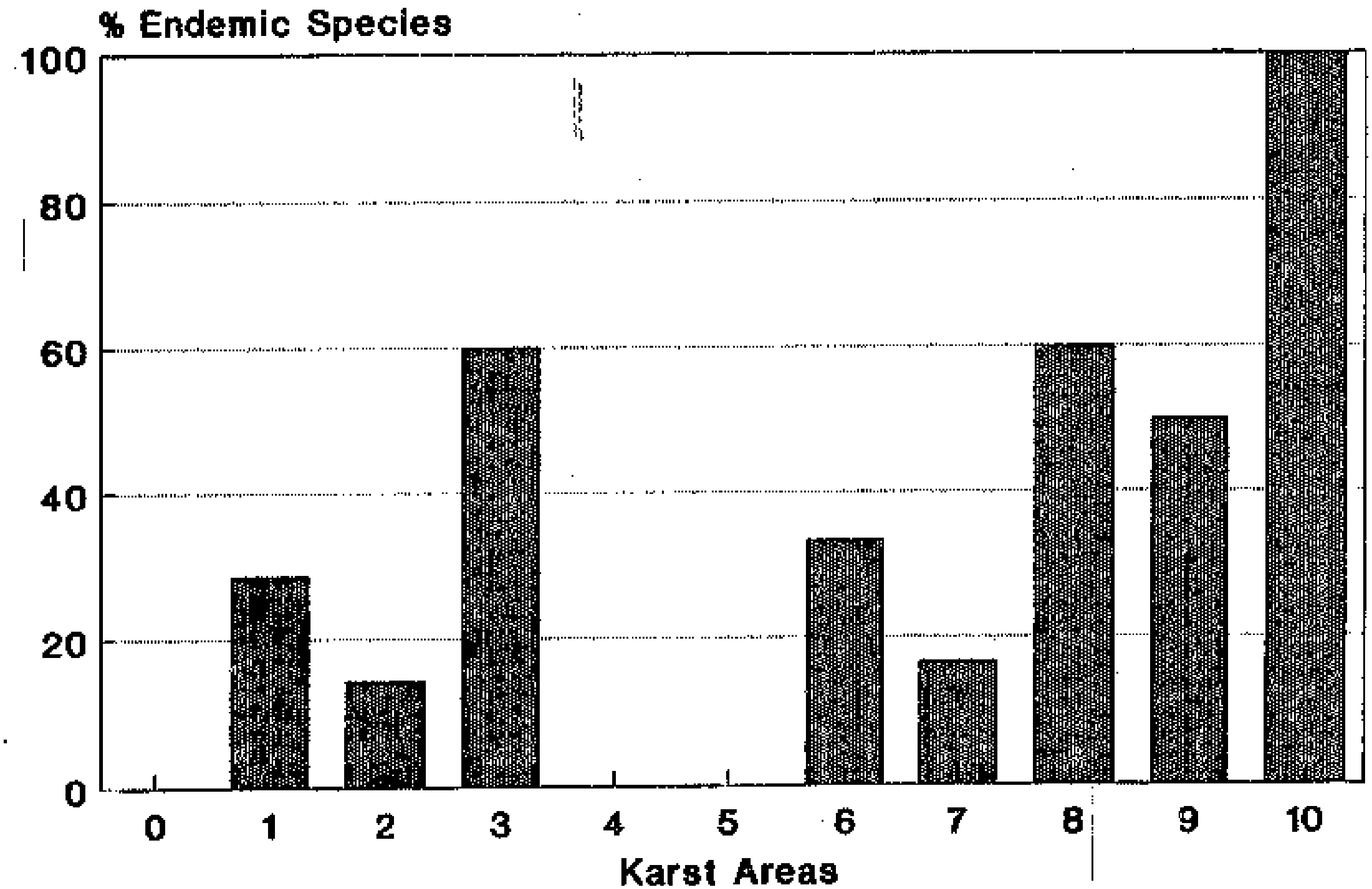


Figure 23

of few cavernicole collections in the North Hays County area; however, the Colorado River is a significant restriction to migration.

The deep incision of the Edwards Limestone by Barton Creek and extensive nearby faulting could present some restrictions between the South Travis County and Rollingwood areas through the removal of cavernous rock, cementation along faults, or by stratal juxtaposition. Elliott's (1976) detailed investigation of the *Speodesmus* genus suggests Barton Creek restricts migration of the millipede. This investigation supports Elliott's theory, finding that half of the species known in the Rollingwood area are not found south of Barton Creek.

AREA #2, ROLLINGWOOD

Of the 8 species known from the Rollingwood area, 4 occur south of Barton Creek in the South Travis County area, 2 are only known from Rollingwood, and 2 others also occur north of the Colorado River: *Neoleptoneta concinna* and *Texella reddelli*. These species occur close to the river and may reflect either recent migrations across the river or evolution from epigean or trogloxenic ancestors which inhabited that area. Prior to the modern damming of the Colorado River, terrestrial cave species could have migrated across the river valley during dry climatic periods and/or when the baseflow of the Colorado sank into the upstream section of the Edwards Limestone to create a traversable vadose outcrop. Nonetheless, the river is a formidable restriction to troglobite migrations when it is considered that of the 10 and 28 investigated species found respectively on its south and north, only two species are common to both sides.

The distribution of *T. reddelli* suggests migration across Bull Creek between the Jollyville Plateau and Central Austin areas. *T. reddelli* is a recent troglobite found only in Rollingwood and on a nearby lobe of the Jollyville Plateau. It is likely that *T. reddelli* and *N. concinna* migrated across the river during the same time period; however, *T. reddelli* was probably not fully troglobitic and was able to cross the non-karst Bull Creek valley whereas the more troglobitically advanced *N. concinna* could not.

AREA #3, CENTRAL AUSTIN

The above explanation of *T. reddelli*'s distribution indicates that it should be also found in the Central Austin area. All 5 species known from this area are from Cotterell Cave and do not include *T. reddelli*. The lack of faunal collections from other caves in this area is due to natural sedimentation and especially from urbanization which has covered many caves. The fact that 3 of the 5 species in Cotterell Cave are unique to that site implies that the sedimentation, as well as faulting and stratal juxtaposition which also occur in the Central Austin area, are important restrictions to troglobite migration.

AREA #4, McNEIL

All 5 troglobites identified in the McNeil area also occur in other areas. Figures 20 and 21 show that this area has 80% of its species in common with the Round Rock area, 60% with both the Cedar Park and Jollyville areas, 40% with Central Austin, and 20% with Rollingwood. Faulting and thinning of the Edwards Limestone in the McNeil area poses no apparent restriction to the migration of troglobites.

AREA #5, ROUND ROCK

This area is very similar to McNeil, having nearly all troglobites in common, but also sharing 80% of its 5 species with Cedar Park, 60% with Jollyville, 40% with Georgetown, and 20% with North Williamson County. The diversity of fauna in the Round Rock and McNeil areas indicates they exist at the junction of more biologically restricted areas.

The Round Rock area has no significant restriction to migration toward Cedar Park and the Jollyville Plateau, however, Brushy Creek restricts migration toward Georgetown as does the San Gabriel River toward North Williamson County. Of the 22 species that occur in the area of continuous Edwards Limestone between the Colorado River and Brushy Creek, 3 occur north of Brushy Creek and only 1 occurs north of the San Gabriel. These restrictions result from the thin exposure of the Edwards Limestone along the stream valleys, coupled with the phreatic zone occupying much of the remaining section; these factors form vadose zones as thin as 19 ft and 25 ft under each valley (Baker, et al., 1986) for the migration of terrestrial troglobites. The effective zone of migration could be even more restricted if strata unfavorable to cave development occur in those narrow vadose sections.

AREA #6, GEORGETOWN

Six troglobite species occur in the Georgetown area. Two occur only within this area, three extend south of Brushy Creek and become generally well distributed as far south as the Colorado River, and one species extends north of the San Gabriel River to the North Williamson County area. Faulting is less intense than in the southern areas and does not obviously restrict troglobite migration; Brushy Creek and especially the San Gabriel River form the significant restrictions.

AREA #7, CEDAR PARK

The complex stratigraphy of the Cedar Park area was expected to develop restrictions to cavernicole distribution but Figures 20 and 21 show that at least 50% of its species occur in the McNeil, Round Rock, and Jollyville Plateau areas. Apparently, while the stratigraphy is complex, there are sufficient sections of cavernous rock to allow terrestrial troglobite migration. The stratigraphy may pose significant restrictions in certain sections of the Cedar Park area, but they cannot be identified or assessed at this level of investigation. Facies changes of the Edwards Limestone to noncavernous rock is a barrier to northward troglobite migration, and the removal of the limestone by erosion in stream valleys forms a barrier to the southwest.

AREA #8, JOLLYVILLE PLATEAU

The greatest number of troglobites in the Austin region occur on the Jollyville Plateau. This is the oldest karst area of the region and consequently has had the longest time for troglobite evolution. Species from the Plateau occur in more areas of the region than do those from any other karst area, although total percentage of shared species is low. Many of the troglobites in the region may have originally evolved on the Plateau and migrated to other areas as caves began to form. Downcutting of stream valleys later separated the karst areas and speciation occurred. The lack of cavernous rock in these valleys forms barriers to troglobite migration around the Plateau, except for the north end. In this locale the Plateau is connected to the main body of the Edwards

Limestone by an "isthmus" of Edwards measuring 0.62 miles wide and no more than 60 ft thick. This narrow band of limestone can restrict the migration of cave fauna, but it clearly cannot prevent it.

AREA #9, NORTH WILLIAMSON COUNTY

This area is the northern end of the continuous outcrop of Edwards Limestone north of the Colorado River. Few caves are known, and as the Edwards becomes more dolomitic and gains marl interbeds northward, it consequently becomes less cavernous. There has been relatively little biologic study of cavernicoles in this area but 4 have been identified; two are only known from this area, one also occurs just south of the San Gabriel River, and the other is widespread as far as the Colorado River. The San Gabriel River forms a major restriction to migration and the northward decreasing cavernous nature of the Edwards Limestone forms a troglobite barrier possibly near the Williamson-Bell County line.

AREA #10, POST OAK RIDGE

Three of the 38 troglobites listed in Table 9 have been identified on Post Oak Ridge. The species occur in an "island" habitat within the recently exposed and erosionally isolated outcrop of the Whitestone Lentil. These species cannot migrate beyond the erosional barrier and are not known from the other Austin karst areas. While not all troglobites on Post Oak Ridge are expected to be endemic following further study, a high percentage of them should be.

Distribution of Aquatic Troglobite Fauna

Little is known of the aquatic troglobite fauna of the Austin region, largely due to a lack of access via caves to the water table. One noted exception is under Buttercup Creek in the Cedar Park area, where an underground streams exist in Ilex Cave and Cedar Elm Sink. These cave streams are probably interconnected but are otherwise isolated from groundwater in the Northern Balcones Segment aquifer. This stream flow is apparently confined to the area under Buttercup Creek and discharges to the surface somewhere south of Cedar Park. Isolation of the stream has allowed for the speciation of a newly discovered *Eurycea* sp. of salamander. The similar isolation of the Simons Water Cave stream on Post Oak Ridge may also yield new troglobites.

Migration and speciation of aquatic cave fauna is restricted in ways similar to terrestrial troglobites. Species will tend to congregate near caves where food may be washed in, and speciation can occur within non-connected strata or fault blocks. The lack of cavernous rock will form barriers, as will the lack of a significant water table. Terrestrial and aquatic fauna will not always share the same restrictions and barriers; the major difference is that aquatic fauna may be able to cross streams like the Colorado River, via subriver conduits, which would block the migration of terrestrial troglobites. A more detailed analysis of the distribution of aquatic troglobites is beyond the scope of this investigation, requiring in-depth study of the species and the areas where they occur.

Synthesis

A synthesis of the geologic and biologic troglobite distribution data must address 3 topics: geologic history and troglobite evolution, barriers and restrictions to troglobite migration, and areas of greater speciation.

Geologic and Troglobite Evolution

The Jollyville Plateau is the oldest karst area in the Austin region and is consequently the habitat for the region's most advanced and diverse group of troglobites (Table 9, Figures 18 and 20). Many of these species may have migrated to other areas as more limestone was exposed by erosion and began to form caves. The Jollyville species, probably as ancestral troglophiles to the present troglobites, extended south of the Colorado River and into the Central Austin area; downcutting of the river and Bull Creek soon created nonkarst barriers between these areas.

Exposure of the Edwards Limestone in the recharge zone of the Edwards (Balcones Fault Zone) Aquifer created broad unrestricted areas for troglobites to migrate and evolve. It is possible that the northern Edwards was exposed more recently based on its less evolved karst and fewer troglobites; however, *Texella* n. sp. 1 becomes more troglobitically advanced to the north. This apparent contradiction to the geologic age of the area is probably related to biologic factors promoting greater troglomorphism in *Texella* within the northern locales.

During the middle to late Pleistocene, incision of stream valleys across the Edwards outcrop began to restrict faunal migrations and promote speciation. The wetter Pleistocene climates would have also restricted the migration of terrestrial troglobites by raising water levels in the aquifers and eliminating the narrow vadose zones that currently exist under some stream valleys. Stream incision at this time separated Post Oak Ridge from the other karst areas, with karst development occurring near the end of the Pleistocene as the Whitestone Lentil became exposed.

Summary of Barriers to Troglobite Migration in the Austin Region

Troglobite migration in the Austin region is limited by two types of barriers and three types of restrictions.

The primary barrier is the lack of cavernous rock. This barrier delimits the Austin karst areas to the southeast where the Edwards Limestone is buried under younger sediments and has not been exposed to the surface, to the northwest where the Edwards has been removed by erosion, and to the northeast where it essentially becomes a noncavernous rock. The secondary barrier is the Colorado River. Of the 38 Austin region species, only 2 occur on both sides of the river and are likely relicts of an earlier time when migration across the river was possible. Although the Edwards has not been fully dissected along the river, there is no opportunity for migration of terrestrial species, especially now while the river is dammed.

The most significant restriction to troglobite migration is stream incision into the Edwards outcrop. Second only to the Colorado River, Brushy Creek demonstrably limits the migration of the most cave species. The San Gabriel

River is probably as effective a restriction as Brushy Creek, but most troglobites have been blocked by Brushy Creek and few remain to assess the river's impedance to northward migration. Barton Creek also seems to restrict the migration of some species, but its effectiveness is probably enhanced by intense local faulting. Bear Creek is a potential restriction to migration, but more biologic collections are needed to ascertain its importance.

The second most significant restriction to troglobite migration is stratigraphic and encompasses those locales where poorly permeable and poorly soluble sections of the Edwards Limestone are exposed at the surface. These locales yield few caves and poorly developed interstitial zones. Those conduits that exist usually have no significant access to the surface and have few nutrients for cavernicole fauna. Several such locales are in the Austin region, however, the scope of this investigation does not allow for the detailed stratigraphic mapping needed to identify them. The Central Austin area is bounded by sediment-filled caves and probably by such poorly karstified zones.

The least important restrictions are those created by faults, where cavernous rock is juxtaposed against or sandwiched between noncavernous rocks. Cave X ends at the Mount Bonnell Fault where it encounters the upper Glen Rose Formation, but overall distribution of troglobites is not obviously affected by faulting. Minor fault restrictions probably occur and may be evident after the fauna of more caves has been studied.

Summary of Speciation and Endemism in Karst Areas of the Austin Region

The degree of troglobite speciation is determined by barriers and restrictions to migration, and by the amount of time for species evolution since the development of those barriers and restrictions. Figures 22 and 23 illustrate the percentage of species distributed between and endemic to the Austin region's karst areas. Both figures are needed to assess endemism and are combined in Figure 24 to create an endemism index.

The endemism index is created by subtracting the percent of average shared troglobites in each area from the percent of endemic species. Areas having positive index values are prone to containing isolated and speciated troglobite populations due to migration barriers and sufficient time for animal evolution. Negative index values imply that few of the barriers or restrictions to migration, which would promote endemism, exist in the area.

Post Oak Ridge (area 10) plots on the index as the area of greatest endemism; all of its troglobites are restricted to that area (Figure 23), and hence none are found in other karst areas (Figure 22). In contrast, the McNeil and Round Rock areas (areas 4 and 5) have no endemism; no troglobites are restricted to those areas.

The Jollyville Plateau and Central Austin areas have moderate levels of endemism. Both areas are sites of early troglobite development and have effective barriers and restrictions to troglobite migration. North Williamson County also has a moderate degree of endemism caused by the incision of both Brushy Creek and the San Gabriel River. However, Brushy Creek alone is a less effective restriction from the unspeciated Round Rock area; consequently, the

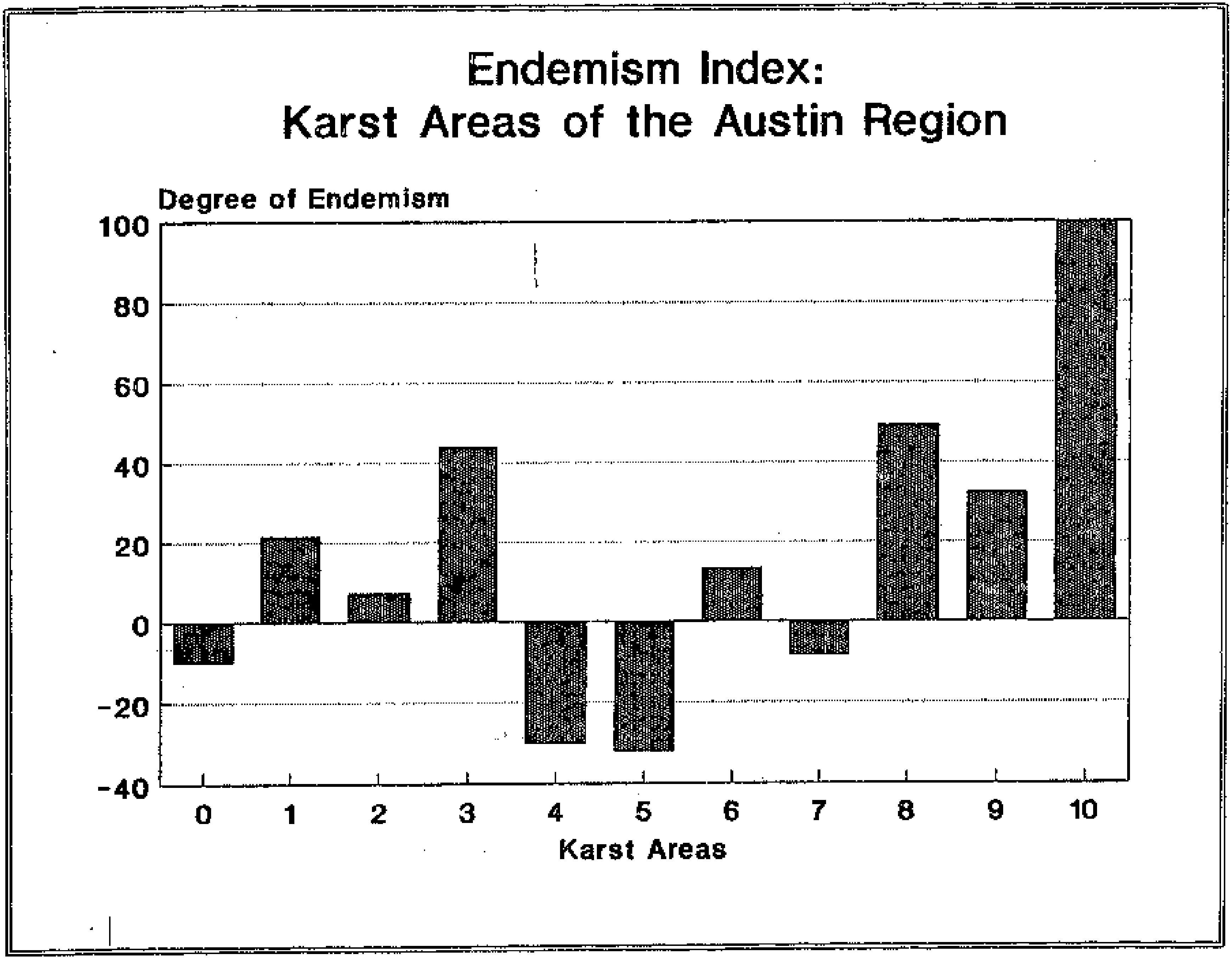

Endemism Index:
Karst Areas of the Austin Region
Degree of Endemism
100
80
60
40
20
0
-20
-40
0
1
2
3
4
5
6
7
8
9
10
Karst Areas

Figure 24

Georgetown area has a low degree of endemism. The low degrees of endemism in the South Travis County and Rollingwood areas is probably due to the relative youth of the karst. The negative endemism value for the North Hays County area is based on only one species and should not be regarded as accurate until more data are collected and analyzed. Conversely, the Cedar Park area has been well studied biologically, and its negative index value is probably valid.

Based on the endemism analysis of the Austin karst areas, degrees of endemism are classified as follows:

- -100 to -61: High non-endemism. Areas with no restrictions to migration; biologically homogeneous with other areas. Example: very young karst with fauna that has not evolved significant troglobite populations.
- -60 to -31: Moderate non-endemism. Areas with minor restrictions to migrations which cause no apparent reductions in biologic homogeneity with other areas. Example: limestone plain with shallow, seasonally active streams recharging a deep water table.
- -30 to 0: Low non-endemism. Areas with restrictions to migration in which there are some minor differences in species distribution while there is overall biologic homogeneity with other areas; also areas where there has been insufficient time to speciate since the development of restrictions. Example: limestone terrain with low to moderate stream dissection (Round Rock, McNeil, and Cedar Park areas).
- 0 to 30: Low endemism. Areas with significant restrictions or minor barriers to migration; biologically distinct from, yet similar to other areas; also areas with major barriers to migrations where speciation has recently begun to affect local fauna. Example: limestone terrain where streams cut through most of the limestone section (South Travis and Rollingwood areas).
- 31 to 60: Moderate endemism. Areas significantly bounded by barriers to migration, but where limited migration may still be possible; biologically distinct but with several species in common with other areas. Example: peninsular limestone-capped ridges that connect to the main outcrop by narrow reaches of limestone (Jollyville, Central Austin, and Georgetown areas).
- 61 to 100: High endemism. Areas bounded by barriers to troglobite migrations; biologically distinct from other areas with few, if any, common species; species have troglobitically advanced

since the development of migration barriers. Example: isolated limestone caprocks surrounded by nonkarst terrain (Post Oak Ridge).

The endemism index provides a means of overall comparison of the barriers and biology of a region's karst areas. The area boundaries can be redefined and the endemism index recalculated to better delineate the barriers to species migration. The actual significance of the index levels is tenuous due to limited sampling in many of the karst areas, but they do provide generalities that may be useful in the assessment and management of those areas and their cave species. Threats to survival are the primary factors considered in listing species as endangered. The limited range of endemic species makes them more vulnerable to threats, so areas with positive index values are more likely to contain troglobite species that may be considered for listing.

The index for the Austin region, plotted on Figure 24, indicates that the South Travis County, Rollingwood, Central Austin, Georgetown, Jollyville Plateau, North Williamson County, and Post Oak Ridge areas are speciated zones where endemic troglobites may exist which could qualify for endangered or threatened listing due to their limited distributions. The McNeil, Round Rock and Cedar Park areas are nonspeciated zones. The status of the North Hays County area requires further research.

Species that inhabit nonspeciated areas are not necessarily ineligible for endangered or threatened listing just because they have a negative index value by occurring in neighboring areas. The three nonspeciated zones are undergoing extensive urbanization which could have serious detrimental effects on the cave organisms and the habitats they depend upon. In contrast, while Post Oak Ridge has a high endemism value, the current lack of threat to the fauna makes it unlikely that the species will gain endangered listing.

The endemism index of Figure 24 only considers terrestrial troglobites; an analysis of aquatic troglobites would require the calculation of a different index. In such an index the Cedar Park area would show a greater endemism tendency due to greater isolation of its aquatic fauna.

Development of Distribution Maps of Endangered Cavernicole Faunal

Cavernicole faunal distribution maps are drawn on 7.5' USGS topographic quadrangles to indicate areas of greater or lesser probability of encountering federally listed, endangered cave species in the Austin region. The maps were prepared by overlaying a composite of each quadrangle's geology, distribution of caves, and distribution of cave fauna, then considering the controls on cave development reviewed earlier in this report. Appendix D lists the topographic base maps and illustrates the areas they cover. Due to the size and total bulk of the maps, they accompany this report under a separate cover.

Four zones are indicated on the maps:

Zone 1: areas known to contain endangered cave fauna;
Zone 2: areas having a high probability of suitable habitat for endangered or other endemic

invertebrate cave fauna;

Zone 3: areas that probably do not contain endangered cave fauna; and

Zone 4: areas which do not contain endangered cave fauna.

Due to the complexities of karst, especially the interstitial zone where much of the cave fauna abides, it is impossible to predict with certainty the areas where the endangered fauna may reside (except, of course, for Zone 1 where the animals have been observed or Zone 4 which is largely noncavernous rock). Where endangered species are present, the Zone 1 areas are delimited based on known speleogenetic, hydrologic or stratigraphic factors that indicate continuity of the zone's karst and no restrictions to its fauna.

The four map zones serve as well-considered guidelines for use in future planning. Any development of the zones should require:

Zone 1: U.S. Fish and Wildlife Service federal permit prior to development, following a detailed cave biology and hydrogeology study to determine the impact of the proposed development and means of groundwater and species mitigation.

Zone 2: an intensive investigation to search for and determine the presence or absence of endangered cave species; if endangered species are found the land is rezoned as Zone 1; if no endangered species are found, a detailed Zone 1 type cave biology and hydrogeology study should be conducted to mitigate the impacts of development in case the species do occur but could not be located.

Zone 3: an investigation to search for and determine the presence of endangered cave species; if endangered species are found the land is rezoned as Zone 1; if endangered species are not found, and pending approval of the investigating biologist, no further biologic or hydrogeologic study is needed.

Zone 4: no action.

Conclusions and Recommendations

Conclusions

The karst of the Austin region can be described as 6 distinct geologic zones, which can be subdivided into 11 biogeologic areas. Analysis of the regional geology and troglobite distribution shows good correlation between geologic history and the migration of cave fauna. These correlations can generally be determined and applied to species management through the development and interpretation of a endemism index. Conclusions from the index for the Austin region include that the Post Oak Ridge, Jollyville Plateau and Central Austin areas are speciated zones, and the McNeil, Round Rock and Cedar Park areas are nonspeciated zones. While useful as a predictive and management tool, the endemism index is not and should not be the sole basis in assessing the endangered status of species; habitat requirements and threats to species survival must also be considered.

Recommendations

Deficiencies in this investigation result from limited data available for certain areas or aspects of study. Following are recommendations for further geologic research into areas that lack sufficient data to conduct adequate assessments.

1) The Cedar Park area is the most stratigraphically complex locale in the Austin region. The impact of the stratigraphy on cave development and faunal distribution can only be fully understood by mapping the strata on a cave-to-cave basis, coupled with hydrologic tracing to determine local aquifer flow patterns.
2) The outcrop of Edwards Limestone in north Williamson County needs to be evaluated to determine the actual limitations on cave development and the boundary on the northward distribution of endangered cave fauna.
3) An investigation similar to that in recommendation #2 is needed in the Hays-Travis County area to determine the southern boundary of endangered cave fauna in the Austin region.
4) A study on the stratigraphic occurrence and interconnection of caves in the South Austin area is needed to better determine the distribution of endangered cave fauna. Extensive faulting in the area precluded a detailed analysis during this investigation.
5) A biogeologic study of the aquatic troglobite fauna of the Austin and Edwards Aquifer Region is needed to understand its occurrence, distribution, potential areas of occurrence, and potential threats by groundwater contamination or withdrawal.

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APPENDIX A

Glossary of Geologic and Karst Terminology

Aggradation: The process of building up a surface by deposition.

Anastomoses: Small interconnecting conduits that fork and rejoin, usually along bedding planes and joints.

Aquiclude: Rocks or sediments, such as shale or clay, that do not conduct water in significant quantities.

Aquifer: Rocks or sediments, such as cavernous limestone and unconsolidated sand, that store, conduct, and yield water in significant quantities for human use.

Aquitard: Rocks or sediments, such as cemented sandstone or marly limestone, that transmit water significantly more slowly than adjacent aquifers and that yield at low rates.

Artesian: Describes water that would rise above the top of an aquifer when intersected by a well; sometimes flows at the surface.

Base level: The level to which drainage gradients (surface and subsurface) are adjusted, usually a surface stream or relatively impermeable bedrock. Sea level is the ultimate base level.

Bedding plane: A parting plane between two distinct bedrock layers.

Breakdown: Rubble and boulders in a cave resulting from collapse of the cave ceiling.

Cave: A naturally occurring, humanly enterable cavity in the earth, at least 5 m in length and/or depth, and where no dimension of the entrance exceeds the length or depth of the cavity (per the definition of the Texas Speleological Survey).

Cavernicole: A species of animal that spends at least part of its life cycle in the subterranean environment.

Conduit: A subsurface bedrock channel formed by groundwater solution to transmit groundwater; often synonymous with cave and passage, but generally refers to channels either too small for human entry, or of explorable size but inaccessible.

Confined: Pertaining to aquifers with groundwater restricted to permeable strata that are situated between impermeable strata.

Dip: The angle that joints, faults or beds of rock make with the horizontal; the "slope."

Endemic: Biologically, refers to an organism that only occurs within a particular locale.

Epigean: Pertaining to species living on the surface of the earth.

Facies: The aspect, appearance, and characteristics of a unit of rock or sediment, usually reflecting the conditions of its origin.

Fault: Fracture in bedrock along which one side has moved significantly with respect to the other.

Homoclinal hinge: The axis of a single, uniform bend in strata.

Impermeable: Does not allow the significant transmission of fluids.

Interstitial zone: Conduits of an aquifer and/or cave which are too small for human access; can be located both above and below the water table. Generally used to describe a type of habitat for cavernicole fauna.

Joint: Fracture in bedrock exhibiting little or no relative movement of the two sides.

Karst: A terrain characterized by landforms and subsurface features, such as sinkholes and caves, that are produced by solution of bedrock. Karst areas commonly have few surface streams; most water moves through cavernous openings underground.

Meteoric water: Water that occurs or is derived from the atmosphere.

Nodular: Composed of nodules (rounded mineral aggregates).

Passage: An elongate portion of a cave; usually a conduit for groundwater flow.

Permeable: Allows the significant transmission of fluids.

Permeability: Measure of the ability of rocks or sediments to transmit fluids.

Phreatic: The area below the water table, where all voids are normally filled with water.

Pit: A vertical cavity extending down into the bedrock; usually a site for surface water flow into the subsurface, but sometimes associated with collapse.

Porosity: Measure of the volume of pore space in rocks or sediments as a percentage of the total rock or sediment volume.

Potentiometric surface: An imaginary surface to which underground water confined in pores and conduits would rise if intersected by a borehole. See water table.

Recharge: Natural or artificially-induced flow of surface water to an aquifer.

Relict karst: Karst formed by processes unrelated to present geologic conditions and not buried by younger sediments.

Resurgence: Discrete point or opening from which groundwater flows out to the surface; a spring. Strictly speaking, a return to the surface of water that had gone underground.

Room: An exceptionally wide portion of a cave, often at the junction of passages; commonly indicative of either the confluence of groundwater flowpaths or of slow, nearly ponded, groundwater flow.

Shaft: See pit.

Sink: See sinkhole.

Sinkhole: A natural depression in the earth's surface caused by solution and/or collapse of the bedrock.

Solution: The process of dissolving; dissolution.

Speciation: The process of developing new species through evolution.

Speleothem: A chemically precipitated secondary mineral deposit (eg., stalactites and stalagmites) in a cave; usually calcite but can include gypsum.

Spring: See resurgence.

Stratigraphic: Pertaining to the charactistics of a unit of rock or sediment.

Stream caves: Caves formed by and functioning as channels for underground flowing water.

Strike: The direction of a horizontal line on a fracture surface or a bed of rock; perpendicular to dip.

Sump: A cave passage that descends below the surface of flowing or standing water.

Troglobite: A species of animal that is restricted to the subterranean environment and which typically exhibits morphological adaptations to that environment, such as loss or reduction of eyes and pigment and elongated appendages.

Troglomorphism: The development of troglobite characteristics.

Troglophile: A species of animal that may complete its life cycle in the subterranean environment but which may also be found on the surface.

Trogloxene: A species of animal that inhabits caves but which must return to the surface for food or other necessities.

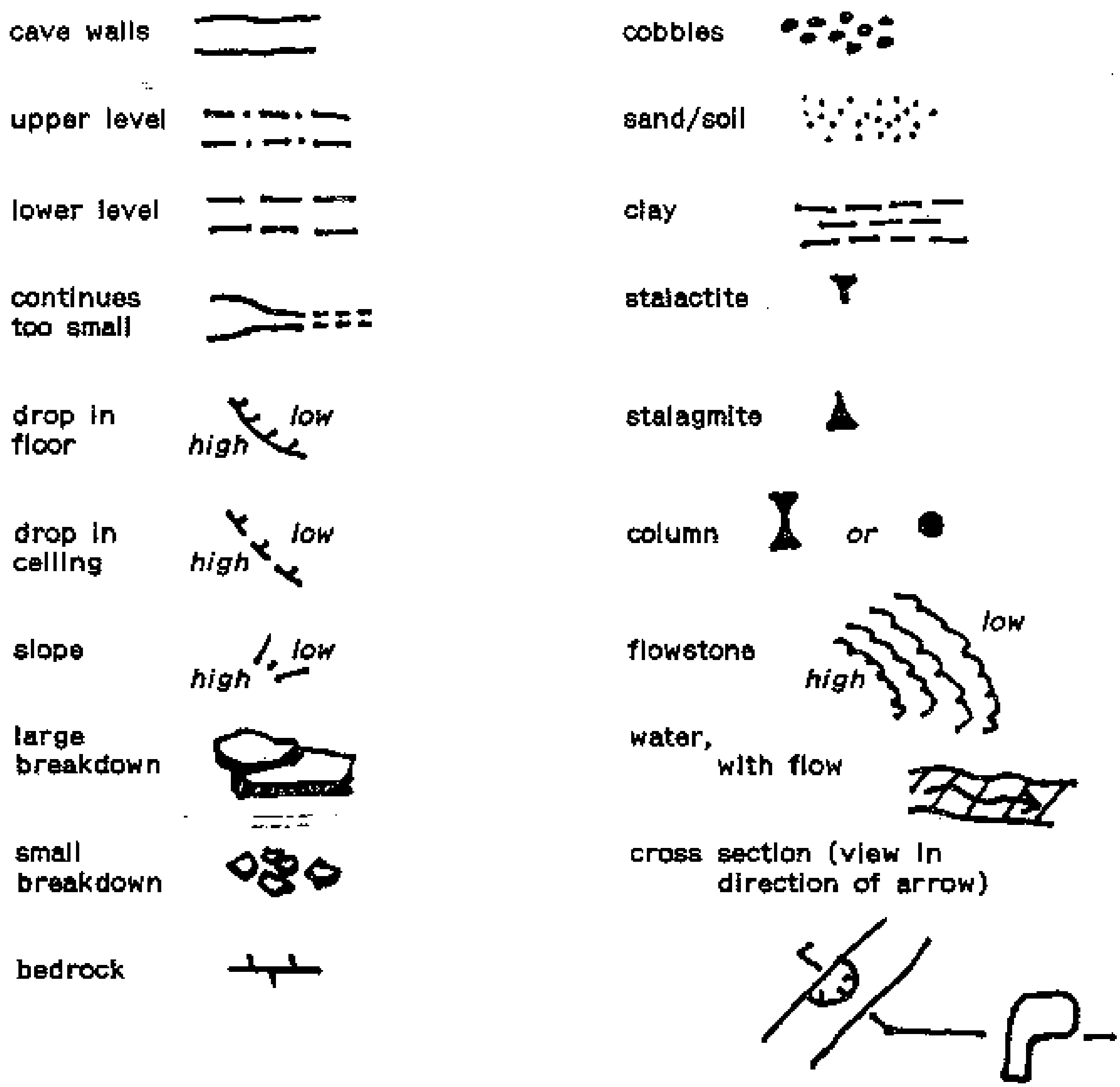
Unconfined: Pertaining to aquifers having no significant impermeable strata between the water table and surface.

Vadose: Pertaining to the zone above the water table where all cavities are generally air-filled, except during temporary flooding.

Water table: The boundary of the phreatic and vadose zones. A potentiometric surface but used only in unconfined aquifers.

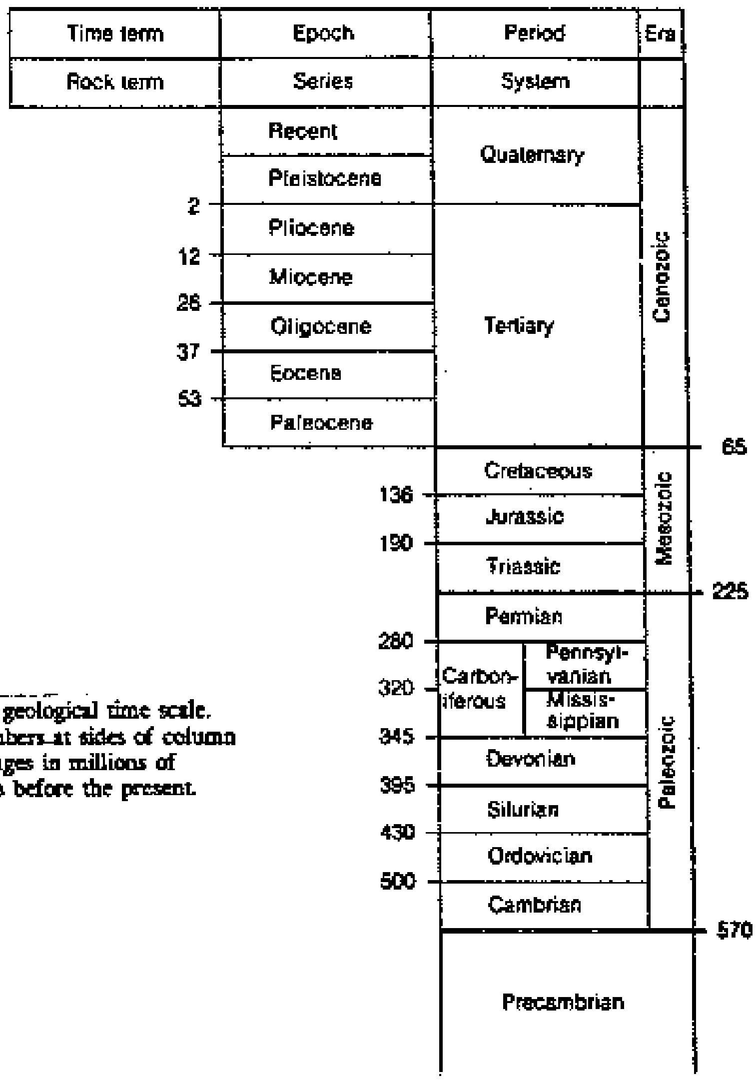
APPENDIX B

Standard Cave Map Symbols



APPENDIX C

Geologic Time Scale
(from Press and Siever, 1978)



The geological time scale. Numbers at sides of column are ages in millions of years before the present.

APPENDIX D

Distribution Maps of Endangered Cavernicole Fauna in the Austin Region

The known and probable distribution of endangered and endemic cave fauna in the Austin Region is illustrated on 22 U.S. Geological Survey 7.5' topographic maps. The maps are listed below and their locations are keyed to Figure 25. Due to the size and total bulk of the maps, they accompany this report under a separate cover.

Austin East
Austin West
Bertram
Briggs
Cobbs Cavern
Ding Dong
Florence
Georgetown
Jarrell
Jollyville
Leander
Leander NE
Liberty Hill
Mahomet
Mansfield Dam
Nameless
Pflugerville West
Oak Hill
Round Rock
Signal Hill
Travis Peak
Youngsport

Figure 25

	Briggs	Ding Dong	Youngsport	
	Mahomet	Florence	Cobbs Cavern	Jarrell
Bertram	Liberty Hill	Leander NE	Georgetown	
Travis Peak	Nameless	Leander	Round Rock	
	Mansfield Dam	Jollyville	Pflugerville West	
		Austin West	Austin East	
	Signal Hill	Oak Hill		