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GEOLOGIC CONTROLS ON CAVE DEVELOPMENT AND THE DISTRIBUTION OF ENDEMIC CAVE FAUNA IN THE SAN ANTONIO, TEXAS, REGION

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TABLE OF CONTENTS

page

Table of contents....................ii
List of figures....................iv
List of figures under separate cover....................v
List of tables....................vi
Introduction....................1
Controls in cave development....................1
    Lithologic controls....................4
        Stone Oak area....................8
        Helotes area....................13
        Alamo Heights area....................16
        Culebra Anticline area....................16
    Structural controls....................18
        Stone Oak area....................20
        Helotes area....................21
        Alamo Heights area....................23
        Culebra Anticline area....................26
    Hydrologic controls....................29
        Edwards-Trinity (Plateau Outlier) Aquifer....................29
        Edwards (Balcones Fault Zone) Aquifer....................30
        Austin Chalk Aquifer....................38
        Epikarst....................49
    Synthesis of factors affecting cave development....................50
        Lithologic factors....................50
        Structural factors....................53
        Hydrologic factors....................53
Cave evolution and faunal speciation....................54
    Geologic evolution of the San Antonio region karst....................54
        Helotes area karst....................55
        Stone Oak area karst....................56
        Alamo Heights area karst....................57
        Culebra Anticline area karst....................57
        Interstitial zones....................58
    Distribution of cave fauna in the San Antonio region karst....................59
        Area analyses....................69
            Area #1, Government Canyon....................69
            Area #2, Helotes....................69
            Area #3, UTSA....................70
            Area #4, Stone Oak....................70
            Area #5, Culebra Anticline....................71
            Area #6, Alamo Heights....................71
        Distribution of aquatic troglobite fauna....................71
    Synthesis....................72
        Geologic and troglobite evolution....................72
        Summary of barriers to troglobite migration in the San Antonio region....................72
        Summary of speciation and endemism in karst areas of the San Antonio region....................73

TABLE OF CONTENTS (cont.)

page

Development of distribution maps of endangered cavernicole fauna....76
Conclusions and recommendations....78
Conclusions....78
Recommendations....78
Acknowledgements....79
Bibliography....80
Appendix A: Cave locations....89
Appendix B: Glossary of karst terminology....92
Appendix C: List of standard cave map symbols....97
Appendix D: Distribution maps of petitioned and endemic cavernicole fauna in the San Antonio region....98
Appendix E: Geologic time scale....99

LIST OF FIGURES

Figure page

1. Map of the San Antonio region and geologic areas............3
2. Simplified geologic map of the San Antonio region...........5
3. Stone Oak area cave elevations (1 of 2)....................9
4. Stone Oak area cave elevations (2 of 2)....................10
5. Helotes area cave elevations...............................14
6. Culebra Anticline area cave elevations.....................17
7. Cave fracture orientations, Stone Oak area.................22
8. Cave fracture orientations, Helotes area...................24
9. Cave fracture orientations, Alamo Heights area.............25
10. Cave fracture orientations, Culebra Anticline area.........28
11. Map of Madla's Cave..31
12. Map of Kamikazi Cricket Cave...............................32
13. Map of Is That All There Is Spring.........................33
14. Location of the Edwards Aquifer and its subdivisions.......34
15. Map of Pomeranian Pit......................................36
16. Map of Genesis Cave..37
17. Map of Voight's Bat Cave...................................39
18. Map of No Exit Cave..40
19. Map of Hills and Dales Pit.................................41
20. Map of Black Cat Cave......................................42
21. Map of Shot-and-a-Prayer Cave..............................43
22. Map of 2 For 1 Cave and 2 For 1 Spring.....................44
23. Map of Robber Baron Cave...................................46
24. Map of Isopit..47
25. Map of Wurzbach Bat Cave...................................48
26. Map of World Newt Cave.....................................52
27. Schematic of San Antonio region karst areas and distribution of troglobites...................61
28. Map of San Antonio region karst areas......................62
29. Distribution graph of troglobites in the San Antonio region..................................63
30. Histogram of troglobite species shared by karst areas of the San Antonio region.................64
31. Histogram of average shared troglobites in karst areas of the San Antonio region..................65
32. Histogram of troglobite species endemic to karst areas of the San Antonio region..................66
33. Endemism index: karst areas of the San Antonio region...................................74
34. Location map of Bexar County caves.........................91
35. Location of petitioned and endemic fauna distribution maps.............................98

LIST OF FIGURES UNDER SEPARATE COVER

Petitioned and endemic fauna distribution maps of the San Antonio region on 7.5' topographic quadrangle base maps:

- Bat Cave Quadrangle
- Bulverde Quadrangle
- Camp Bullis Quadrangle
- Castle Hills Quadrangle
- Culebra Hill Quadrangle
- Helotes Quadrangle
- Jack Mountain Quadrangle
- La Coste NE Quadrangle
- Longhorn Quadrangle
- San Antonio East Quadrangle
- San Antonio West Quadrangle
- San Geronimo Quadrangle
- Schertz Quadrangle
- Van Raub Quadrangle

LIST OF TABLES

Tables	page
1. Stratigraphic column of Cretaceous rocks in the San Antonio region	4
2. Caves of the Stone Oak area analyzed in Figure 3	11
3. Caves of the Stone Oak area analyzed in Figure 4	12
4. Caves of the Helotes area analyzed in Figure 5	15
5. Caves of the Culebra Anticline area analyzed in Figure 6	18
6. Cave fracture orientations of the Stone Oak area analyzed in Figure 7	21
7. Cave fracture orientations of the Helotes area analyzed in Figure 8	26
8. Cave fracture orientations of the Alamo Heights area analyzed in Figure 9	27
9. Cave fracture orientations of the Culebra Anticline area analyzed in Figure 10	27
10. Troglobites of the San Antonio region analyzed in Figures 27-33	67
11. Summary description of San Antonio region karst areas, delineated in Figures 27-28 and analyzed in Figures 29-33	68

GEOLOGIC CONTROLS ON CAVE DEVELOPMENT AND THE DISTRIBUTION OF ENDEMIC CAVE FAUNA IN THE SAN ANTONIO, TEXAS, REGION

by George Veni

Introduction

Ten ***cave*** arthropods in the San Antonio, Texas, area have been petitioned for federal listing as endangered species (Cunningham, 1992). These species are threatened by the urban expansion of San Antonio and neighboring communities onto the ***karst*** of the upper member of the Glen Rose Formation, the Edwards Limestone, and the Austin Chalk. The habitat conditions of the species in the San Antonio area is similar to that of listed arthropod cave species in the Austin, Texas, region. 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 (Elliott and Reddell, 1989; Reddell, 1991; Elliott, 1993).

The impact of urbanization 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, ergo zones of cave development and the extent of connectivity between 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 (e.g. Veni and Associates, 1988, 1992).

This investigation is modeled after a similar study for the Austin region by Veni and Associates (1992). Prior to that work, 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 San Antonio region's geologic controls on cave development, within the context of how 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 cave fauna petitioned for endangered listing, and produce maps that delineate the probable distribution of the region's ***endemic*** and petitioned cave fauna. A companion report to this study by James R. Reddell (1993) will provide faunal lists for area caves, habitat descriptions, and other related biologic information. The approximate locations of caves discussed in this report are presented in Appendix A.

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. The effects of ***lithology***, ***structure***, and hydrology are specifically addressed in the following subsections; relief and time are inherent to each discussion. A glossary of karst and related geologic and biospeleologic terms is provided in Appendix B; the first text occurrence of a glossary term is bold-printed in ***italics***. Appendix C provides a list of cave map symbols.

The study area, which includes most karst in Bexar County, is roughly divided into four geologic areas (Figure 1):

1) <u>Stone Oak area</u>: the exposure of the Edwards Limestone and upper member of the Glen Rose Formation in Bexar County between Cibolo Creek and Leon Creek;
2) <u>Helotes area</u>: the Edwards Limestone and upper Glen Rose between Leon Creek and San Geronimo Creek in Medina County 1-2 km west of the Bexar County line;
3) <u>Alamo Heights area</u>: the outcrop of Austin Chalk and Pecan Gap Chalk within the wedge-shaped ***horst*** beginning near San Pedro Park in San Antonio, which widens to about 3 km, and heads northeast to where it pinches out near O'Conner Road roughly midway between Nacogdoches Road and Interstate Highway 35;
4) <u>Culebra ***Anticline*** area</u>: the outcrops of the Austin Chalk and Pecan Gap Chalk along the Culebra Anticline, extending west from Culebra Creek to the end of the outcrops about 3 km into Medina County.

The outcrops and the units within these areas are not always continuous, and include erosional remnants and ***fault***-isolated segments. Not included in the study area are outcrops of the upper Glen Rose, Austin Chalk, and Pecan Gap Chalk where caves are not known or insufficiently known. The results of this study are used to project the likelihood of endemic or petitioned cave fauna into poorly studied areas, as illustrated on the topographic faunal distribution maps accompanying this report (Appendix D).

To date, Veni (1988) has published the most comprehensive study of caves in Bexar County. Based on that work, Bexar County area caves in the lower member of the Glen Rose Formation and within Quaternary fluviatile terrace deposits will not be considered in this investigation. The lower Glen Rose caves have a cavernicolous fauna that is distinct from the upper Glen Rose, Edwards Limestone, and Austin Chalk caves, and whose habitat is not significantly threatened by urban or other developments. The few caves which are known in the terrace deposits, while located in heavily urbanized areas, are geologically recent features and are not known to have evolved any unique or cavernicolous fauna.

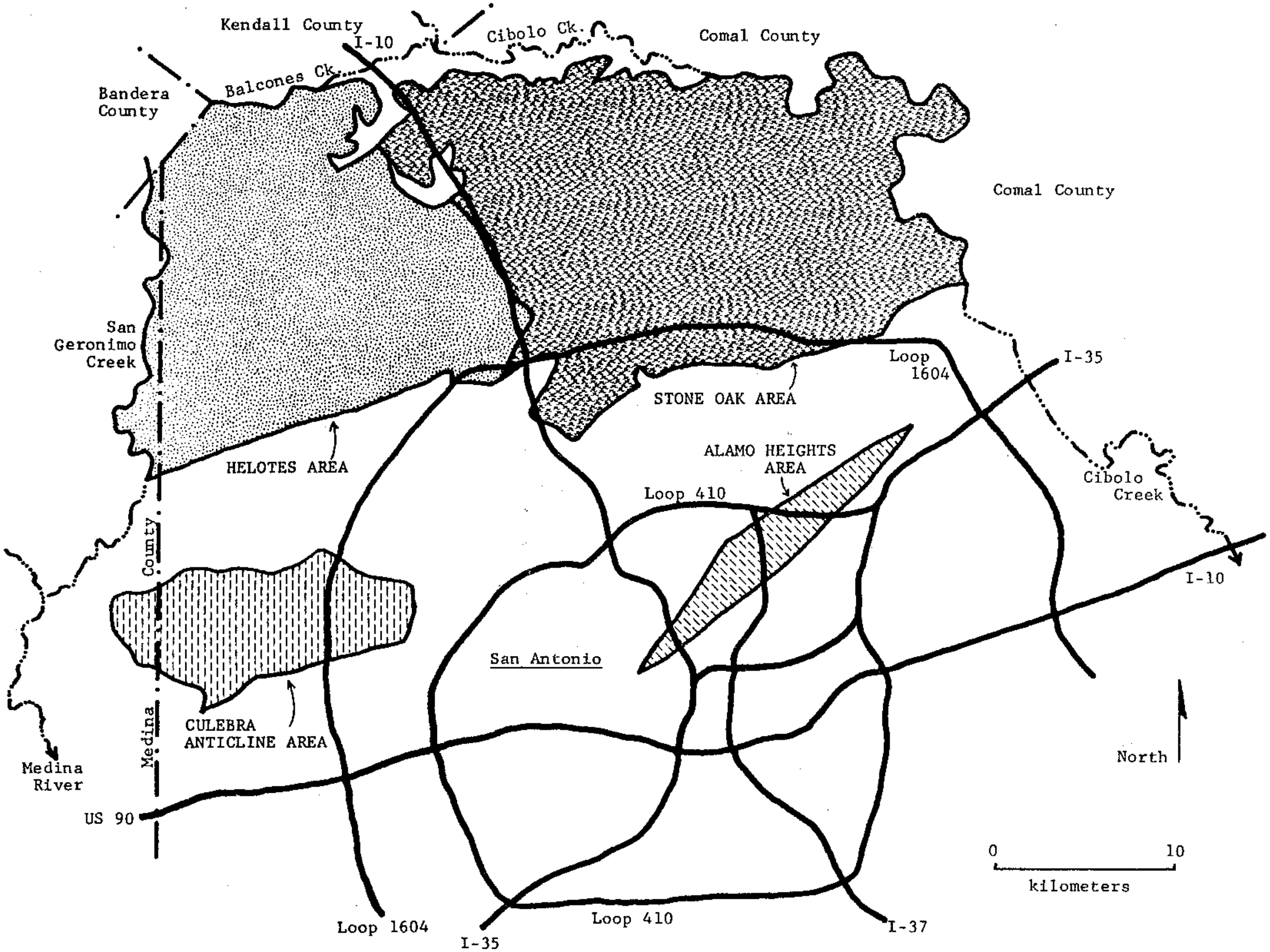


Figure 1: Map of the San Antonio region and geologic areas.

Lithologic Controls

The karstified rocks in the San Antonio region examined by this investigation are all middle to late Cretaceous in age and include the upper member of the Glen Rose Formation, the Edwards Limestone, the Austin Chalk, and the Pecan Gap Chalk. Of these units, the Edwards and Austin Chalk have the greatest number of caves. The Edwards also has the best studied ***stratigraphy*** since its ***aquifer*** is the sole water supply for the region and thus the focus of intensive research. Figure 2 provides a simplified geologic map of the study area, and Table 1 illustrates the ***stratigraphic*** relationship of the units; Appendix E contains a geologic time scale to correlate period names with actual time. Helpful stratigraphic and structural data were compiled for this investigation from several geologic maps and reports listed in the following paragraphs.

Sources of information for the upper Glen Rose include George (1947, 1952), Holt (1956), Arnow (1959), Abbott (1966), Reeves (1967), Newcomb (1971), Stricklin, Smith, and Lozo (1971), Abbott (1973), Shaw (1974), Waddell (1977), Ashworth (1983), Veni (1988), Stoker (1992), Vauter (1992), Waterreus (1992), and Veni (in review). The upper Glen Rose is a 95 m thick sequence of interbedded limestone, ***marl***, and dolomite. This unit is generally a poor cave-former except for a dolomitic horizon which ranges up to 30 m thick in Bexar County, occurring near the top of the unit. This horizon is known to extend west from the area of Natural Bridge Caverns in Comal County to at least San Geronimo Creek in eastern Medina County, and it is not known in Kendall County. The upper Glen Rose outcrops in northern Bexar County along the dissected margin of the Edwards Plateau, upstream of the Balcones Fault Zone.

The Edwards Limestone Group is the most cavernous unit in the study area. Geologic data on the Edwards are derived from George (1947, 1952), Rhoades and Guyton (1955), Holt (1956), Arnow (1959), Moore (1964), Reeves (1967), Newcomb (1971), Rose (1972), Abbott (1973), Shaw (1974), Waddell (1977), Shaw (1978), Barnes (1983), Maclay and Small (1983, 1984), Small (1986), Veni (1988), Veni and Associates (1989), Burgess (1991), Stoker (1992), Vauter (1992), Waterreus (1992), Ozuna and Stein (in review), and Small and Hanson (in review). The Edwards conformably overlays the Glen Rose Formation, and is a succession of fine to course grained limestone and dolomitic limestone. Rose (1972) subdivides the group's Kainer Formation into Dolomitic, Kirschberg, and Grainstone members, and the Person Formation into the Regional Dense, Collapsed, Leached, Marine, and Cyclic members. Maclay and Small (1984) include the Basal ***Nodular*** member as the base of the Kainer, which is equivalent to the Walnut Formation described by Abbott (1973), among others. The Basal Nodular has generally not been recognized as cavernous, but recent detailed stratigraphic studies have proven otherwise (Russell, 1987; Veni; 1988; Small and Hanson, in review). The Edwards is primarily exposed in the Balcones Fault Zone, and as caps for upper Glen Rose hills in the dissected margin of the Edwards Plateau, upstream of the fault zone. Occasional differences in cave stratigraphy between this report and Veni (1988) result from more precise and larger-scale mapping of the Edwards since that work was published.

Information on the Austin Chalk was gathered from Stephenson (1937), George (1947, 1952), Young and Marks (1952), Rhoades and Guyton (1955), Holt (1956), Arnow (1959), Pessagno (1969), Shaw (1974), Cloud (1975), Young, Barker, and Jonas (1975), Waddell (1977), Young (1977), Dravis (1979), Corbett (1982),

Figure 2 (from Veni, 1988)

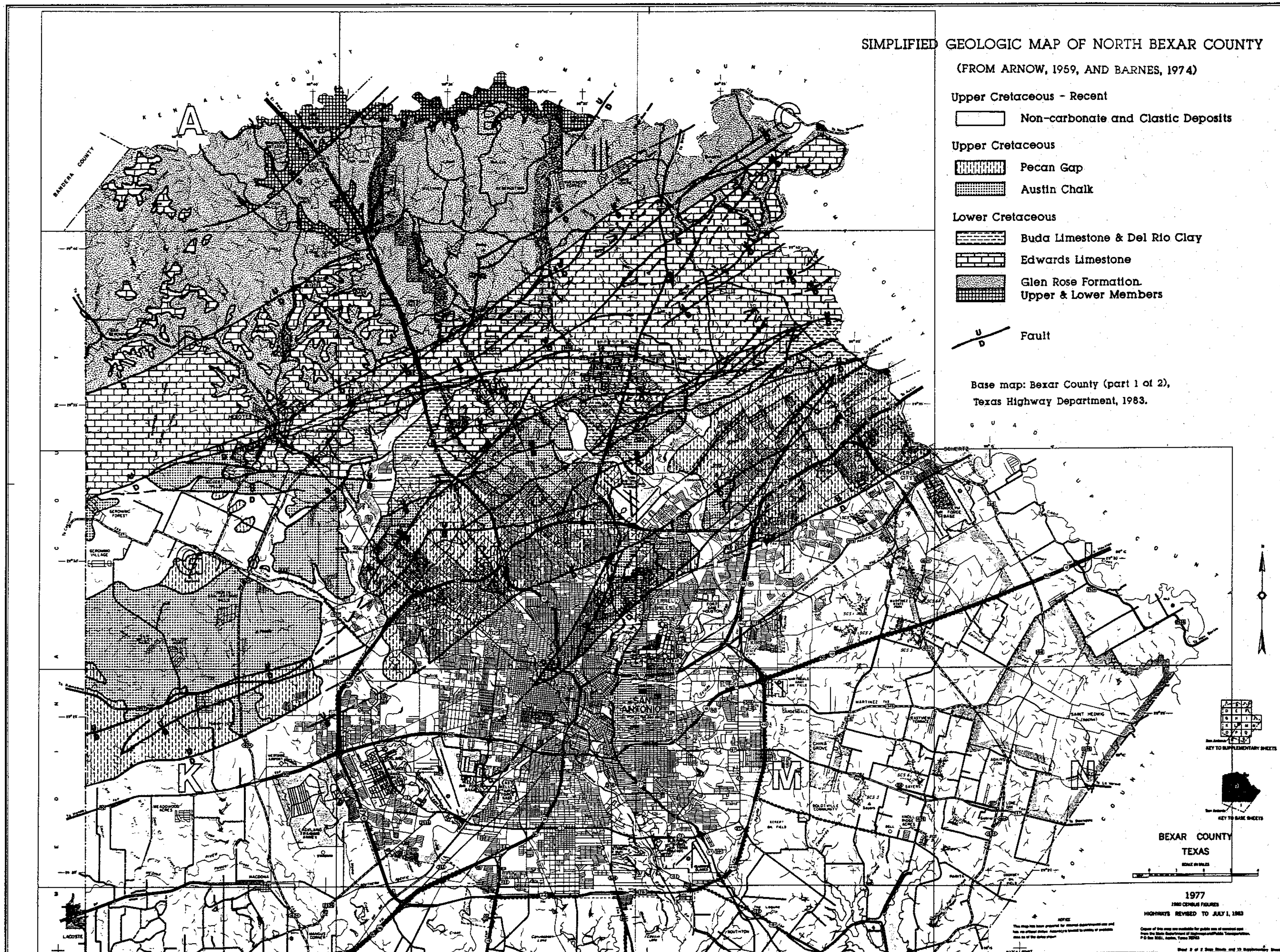


Table 1

STRATIGRAPHIC COLUMN OF CRETACEOUS ROCKS IN THE SAN ANTONIO REGION

Group	Formation	Member	Average Thickness (m)*
Taylor			
	Pecan Gap Chalk		+60.0
~~	~~~~~	~~~~~	~~~~~
Austin			40-73
	Dessau		inadequately mapped
	-----	-----	-----
	Vinson		inadequately mapped
	-----	-----	-----
	Atco		inadequately mapped
~~	~~~~~	~~~~~	~~~~~
	Buda Limestone		16.5
-----	-----	-----	-----
	Del Rio Clay		16.0
-----	-----	-----	-----
	Georgetown		0-5
~~	~~~~~	~~~~~	~~~~~
Edwards			147.1
	Person		55.7
		Cyclic	8.5
		Marine	20.0
		Leached	12.5
		Collapsed	8.6
		Regional Dense	6.1
	-----	-----	-----
	Kainer		91.4
		Grainstone	15.2
		Kirschberg	18.3
		Dolomitic	39.6
		Basal Nodular	18.3
-----	-----	-----	-----
Trinity			
	Glen Rose		165.0
		Upper	95.0
		Lower	70.0

* given thicknesses are means for the outcrop area, some variation occurs through the study area and elsewhere in Bexar County.

----- = conformable contact
~~~~~ = unconformable contact
~~~~~

Barnes (1983), Young and Woodruff (1985), Corbett, Friedman, and Spang (1987), Veni (1988), Corbett et al. (1991), and Vauter (1992). The Austin Chalk Group in central Texas is thinnest in Bexar County with a measured thickness of 40 to 73 m, and is comprised of the Atco, Vinson, and Dessau Formations. The Austin is a fossiliferous, fine-grained to chalky limestone, whose stratigraphy in Bexar County has not been well described. Thus, thicknesses for the individual formations are not available for Table 1. Although the unit is exposed through Texas from Oklahoma to Mexico, relatively few caves are known and most occur in Bexar County.

References for the Pecan Gap Chalk include Stephenson (1937), Holt (1956), Arnow (1959), Pessagno (1969), Shaw (1974), Waddell (1977), Young (1977), Barnes (1983), Young and Woodruff (1985), and Veni (1988). This chalk to chalky marl unit outcrops with up to 60 m relief in the study area, thinning westward and pinching out in Medina County. Its outcrop in Bexar County has been described as the Anacacho Limestone (e.g. Young and Woodruff, 1985), but this report follows the mapping of Barnes (1983). The Pecan Gap Chalk extends along the southern margin of the Balcones Fault Zone through the study area. While it contains only a few caves, most of which are small and contain no significant cavernicole fauna, at least one large cave is known suggesting the Pecan Gap should not always be dismissed as a minor cave-bearing unit.

The influence of lithology on cave development can be estimated for each of the four geologic areas by plotting the elevation of the entrance, base, and main ***passage*** levels of each cave relative to known stratigraphic horizons. Although the elevations of these horizons may change across the study area, the degree of detail in their mapping makes them fairly reliable and usable references for the scope of this study. Where geologic data are insufficient for accurate stratigraphic correlations, interpretations are based solely on cave surveys and observations. It is beyond the scope of this study to field verify the stratigraphy of each cave. Some variance is expected from the caves' true stratigraphic situations, but field observations suggest little effect on overall trends interpreted from the map-based data.

The effects of lithology, 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 San Antonio region karst (Veni, in review), correlations in cave levels are interpreted as follows:

1) Most ***shaft*** entrances at similar elevations in the San Antonio 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 into an underlying unit of greater solubility or permeability.
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*** and 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). To determine the proper model to describe the development of an area's cave entrances, the upper strata must be examined.

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 lesser 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 the ***competence*** of vadose waters is exceeded where their ***hydraulic gradient*** decreases sharply at the base of the shafts.
6) ***Springs*** will often discharge along the contact of upper permeable and/or soluble strata with lower strata of lesser permeability and/or solubility. Some springs and cave ***stream*** passages are slightly below the contact due to downward incision. Discharge occurs into valleys that breach the contact, and the magnitude of discharge is proportional to the size of each spring's drainage basin. ***Artesian*** springs may rise through fractures in both ***impermeable*** and insoluble strata from deeper, groundwater-bearing formations.

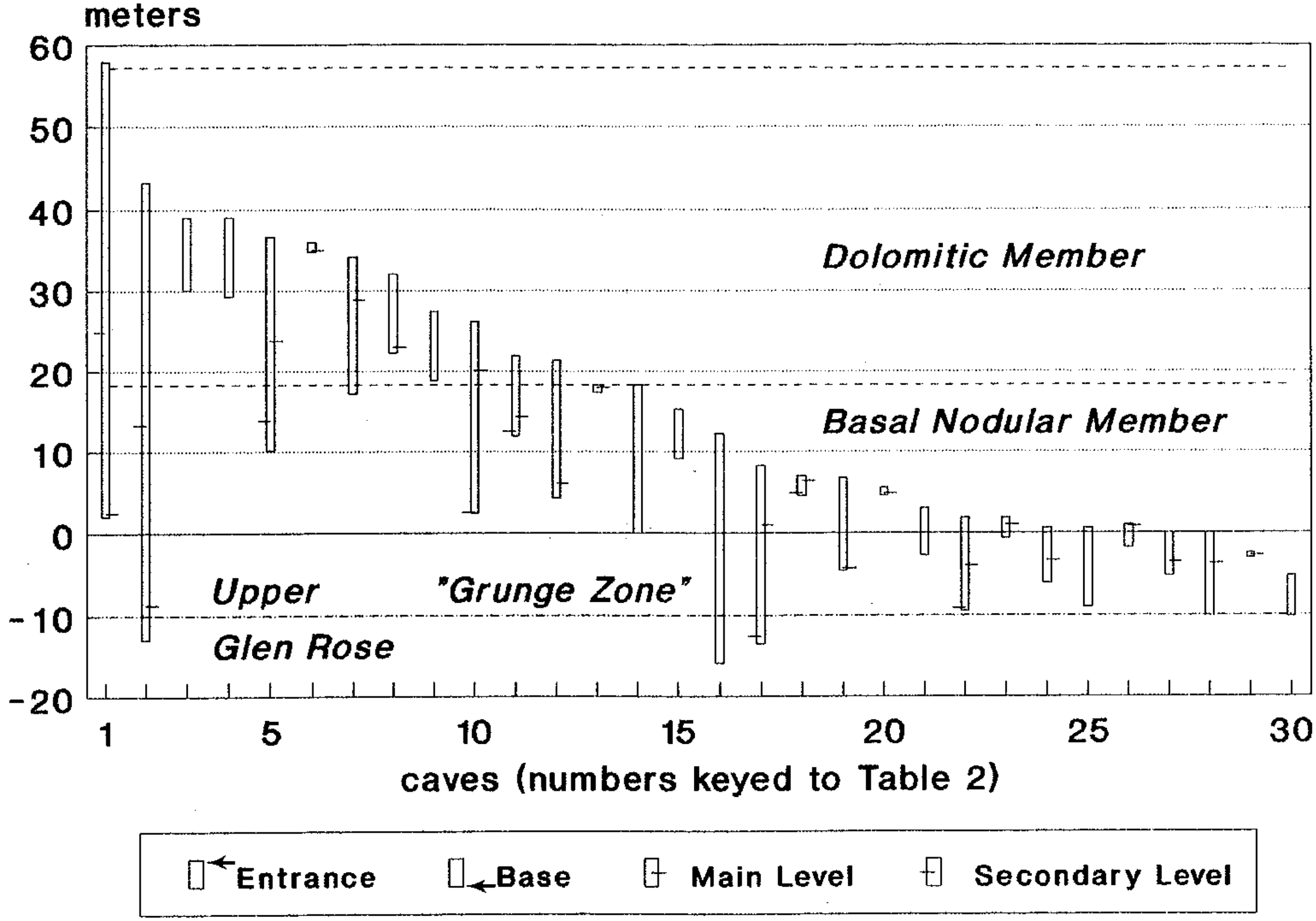
Unless otherwise cited, all cave map data and descriptions were obtained primarily from Veni (1988) or the Texas Speleological Survey files; some information was also published by Reddell and Knox (1962), and Poole and Passmore (1978). The caves selected for the following analyses are not representative of the total number of caves in each area, but of the caves with adequate elevation data to permit stratigraphic appraisals. The order of listing for caves analyzed in Figures 3 through 6 is from highest to lowest stratal elevation, an arrangement which allows easy stratigraphic correlations between the caves.

Stone Oak Area

The 60 caves included for the stratigraphic analysis of the Stone Oak area (Figures 3 and 4) are listed in and keyed respectively to Tables 2 and 3. The caves in Figure 3 are formed in the middle to lower portion of the Kainer Formation, and within the top of the upper Glen Rose. Cave morphology changes with position in this stratigraphic section. High in the section, the caves are shafts with little horizontal extent. The caves' ***lengths*** surpass their ***depths*** lower in the section within the Basal Nodular member and the upper 10 m of the Glen Rose which Abbott (1973) describes as the "grunge zone." While nodular limestone in the Edwards Group seldom supports significant cave development

Figure 3

Stone Oak Area Cave Elevations (1 of 2)*



*relative to base of Kainer Formation

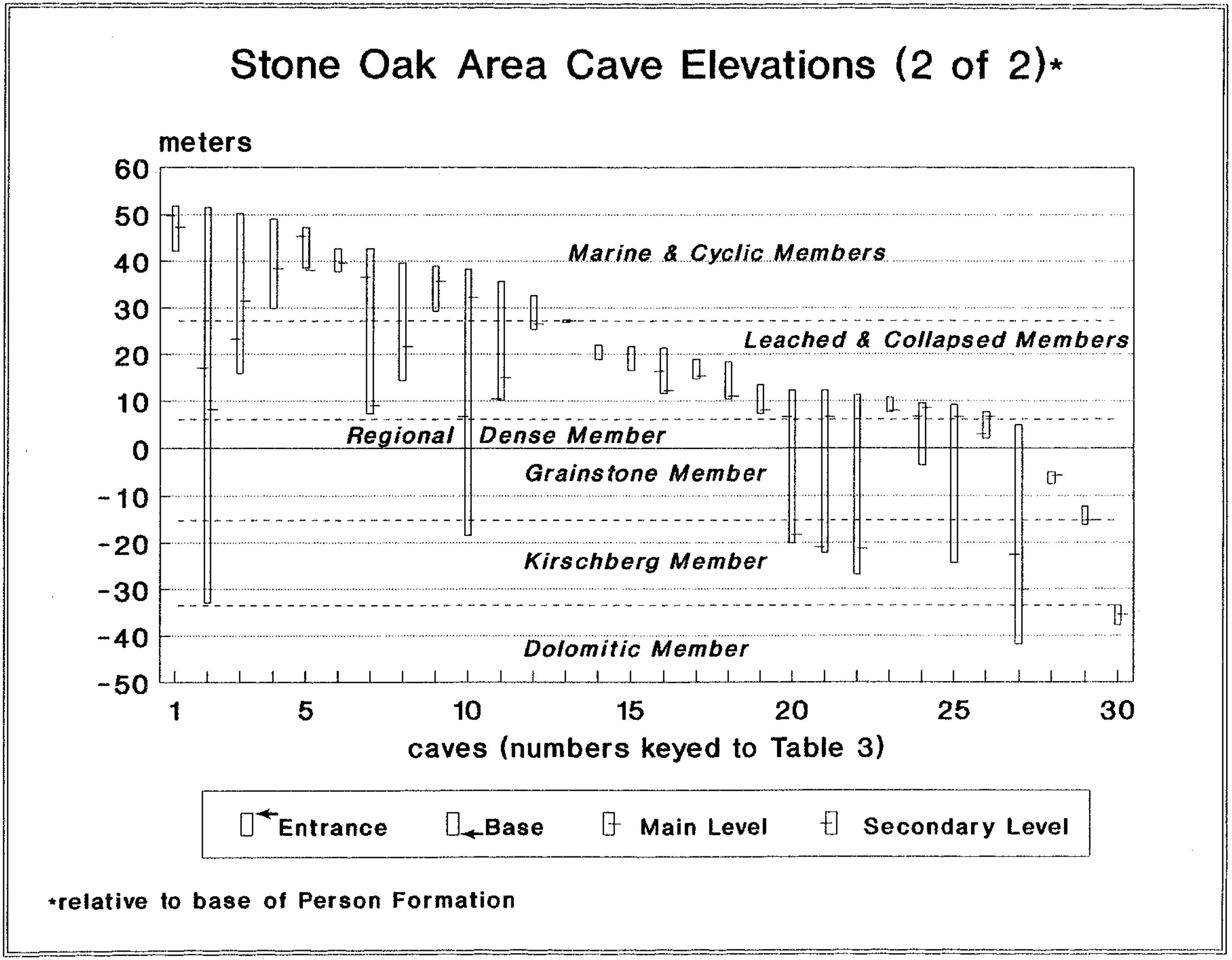

Stone Oak Area Cave Elevations (2 of 2)*
meters
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
Marine & Cyclic Members
Leached & Collapsed Members
Regional Dense Member
Grainstone Member
Kirschberg Member
Dolomitic Member
1
5
10
15
20
25
30
caves (numbers keyed to Table 3)
Entrance
Base
Main Level
Secondary Level
*relative to base of Person Formation

Figure 4

(e.g. Veni and Associates, 1992), the Basal Nodular member and the upper member of the Glen Rose contain a sufficient combination of poorly nodular limestone on nodular or marly beds to form extensive horizontal passages (i.e. groundwater flowpaths). Numerous springs that drain small upland areas also occur near the Kainer-Glen Rose contact. In addition to the cave springs in Figure 3, Cherry, Devine, Indian, and a nearby set of unnamed springs are all located on the Bulverde 7.5' topographic quadrangle within the same horizon.

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

Table 2

CAVES OF THE STONE OAK AREA ANALYZED IN FIGURE 3

Cave name	Number in Figure 3
Hairy Tooth Cave	1
Raging Cajun Cave	2
Pomeranian Pit	3
Pekingese Pit	4
Hitzfelder's Bone Hole	5
The Crawl	6
Crystal Cave	7
Elmore Cave	8
C-Section Cave	9
Elm Waterhole Cave	10
Creekbed Cave	11
Pick-Up Sticks Cave	12
Tee 2 Cave	13
Olive Pit	14
Dick White Cave	15
Cub Cave	16
Bear Cave	17
Elephant Spring	18
Hopeless Cave	19
Dam Crawl	20
Hornet's Last Laugh Pit	21
Headquarters Cave	22
2 For 1 Cave and 2 For 1 Spring	23
Ackerman's Trash Hole	24
Cave File Cave	25
Crescent Spring	26
Aue Road Cave	27
Tick 'n Delight Cave	28
Is That All There Is Spring	29
Drop And A Prayer Pit	30

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

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

Table 3

CAVES OF THE STONE OAK AREA
ANALYZED IN FIGURE 4

Cave name	Number in Figure 4
Toad Cave	1
Genesis Cave*	2
Bet-Ya-Can't-Find-It Cave	3
Cave of the Bee Spirits	4
Cave of the Woods	5
Hidden View Cave	6
Dead Deer Cave	7
Shavano Park Cave	8
Height's Cave No. 1	9
Elm Springs Cave	10
Flint Bridge Cave	11
Gandalf's Cave	12
Blanco Road Cave	13
Goonies Cave	14
Cave With Ladder In It	15
Black Cat Cave	16
Voight's Bat Cave	17
Assassin Cave	18
Council Cave	19
Poison Ivy Pit	20
Whistledrop Cave	21
Tobacco Can Cave	22
Sink Hole	23
Virgin Cave	24
Looserock Cave	25
Bailing Wire Cave	26
Corkscrew Cave	27
Cave of the Cliff	28
Cave of the Creek	29
No Exit Cave	30

* The depth illustrated on Figure 4 includes an unsurveyed 6 m deep pit located at the bottom of the cave.

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

The 30 Stone Oak area caves in Figure 4 are formed in the Person Formation and the upper portion of the Kainer. Caves within the Cyclic, Marine, Leached, and Collapsed members occur at all levels of the units and show no preferential development except immediately above the Regional Dense member. Groundwater flow and cave passages are ***perched*** above the dense member which is breached by shafts in more than half of the caves that descend within 10 m of the unit. In most caves the groundwater is perched in horizontal passages

for only 10-50 m, although the unmapped portion of Dead Deer Cave is perched an estimated 500 m before dropping past the dense member. Not all major passage levels in Figure 4 correlate precisely to the top of the Regional Dense member; some are artificially elevated by passage collapse and sediment deposition on the member.

The only other significant cavernous horizon in Figure 4 occurs below the Regional Dense member and 3-6 m into the Kirschberg member. This zone of passage development extends throughout the Stone Oak area without an obvious reason for its presence. Shaw (1974) describes that horizon, which he lists as the 282-290.5 foot level of unit 14 in the Lockhill Test Hole, as "dolomitic and very ***porous***, with scattered open fracture porosity," and with no immediately underlying ***aquitard***. Cave development usually does not occur in dolomitic or porous limestone, although selective enlargement of the open fractures may account for the passages at this level. However, since the data in Figure 4 are approximations of the levels, the passages may in fact be formed in the underlying micritic bed described by Shaw (1974). Laboratory analyses by Rauch and White (1970) found that caves in central Pennsylvania preferentially developed in micritic limestones, an affinity reaffirmed in the British Isles by Sweeting and Sweeting (1970), in southern Missouri by Dreiss (1974), and in Jamaica by Wadge and Draper (1977). This pattern probably also holds true for the Edwards Limestone in Texas.

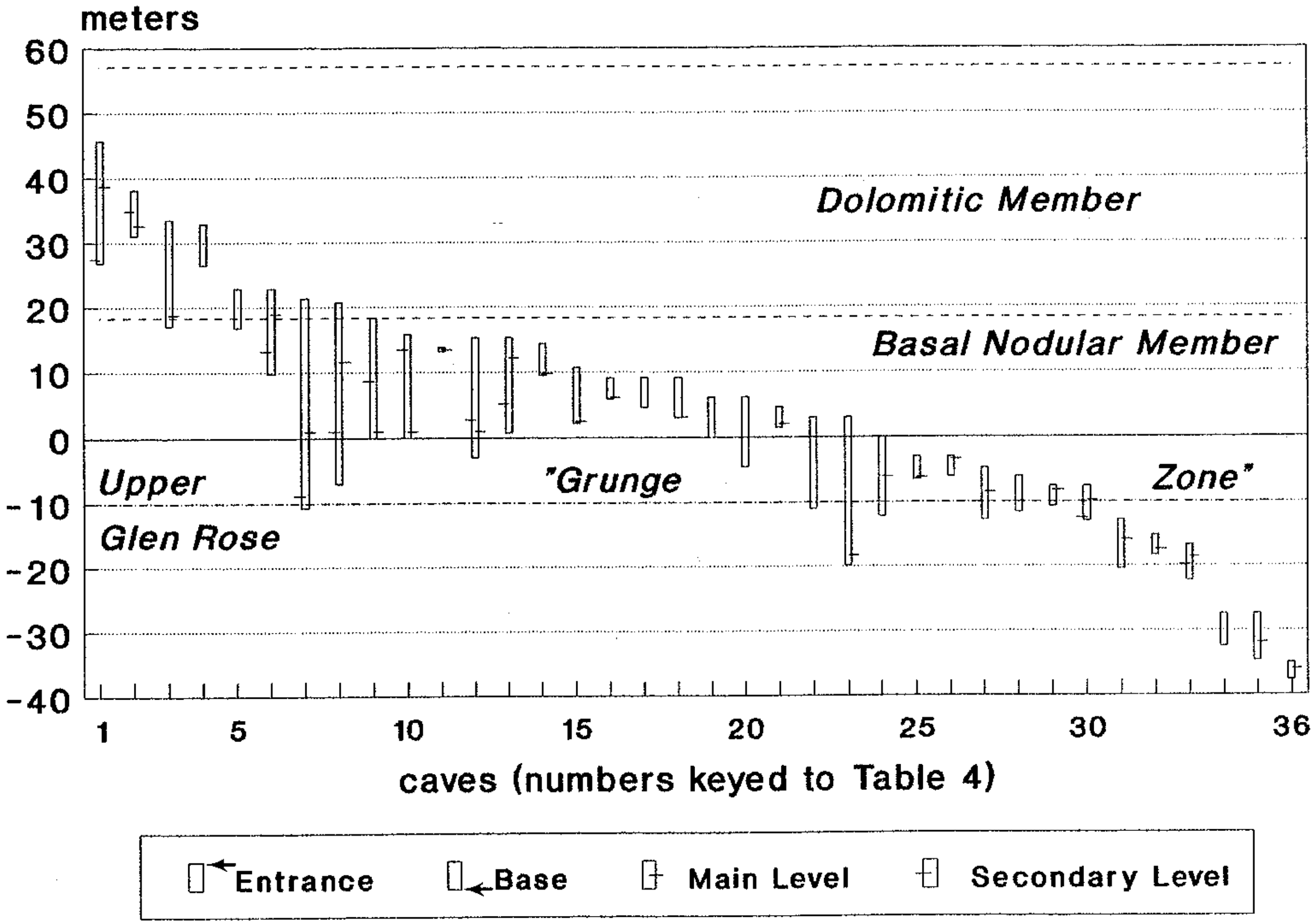
Helotes Area

The 36 caves of the Helotes area listed in Table 4 and shown in Figure 5 extend from the middle portion of the Dolomitic member down through the upper 38 m of the upper member of the Glen Rose Formation. As with the Stone Oak area caves in Figure 3, the stratigraphically higher Helotes caves tend to be shafts while the stratigraphically lower caves are horizontal passages. Most of the upper Glen Rose caves are ***paleosprings*** (e.g. Washout Cave) or intermittent springs (e.g. Christmas Cave), although some active springs are indicated on the topographic maps as low as 55 m into the formation.

Unlike the Stone Oak area caves, large ***chambers*** are a common feature in the upper Glen Rose of the Helotes area. They form in a medium to thick-bedded limestone and dolomitic limestone sequence which extends for about 10 m down from the grunge zone. The drainage of water from these phreatically-formed chambers resulted in collapse of the overlying and less structurally competent grunge zone beds. Examples of such caves includes John Wagner Ranch Cave No. 3, Madla's Cave, and Robber's Cave, the latter being a collapse feature that completely fills the original chamber.

The most prominent zone of cave development in the Helotes area is at the Kainer-Glen Rose contact. Waddell (1977) describes the top of the Glen Rose as a 0.3 m thick limestone bed, underlain by a 2.8 m thick dolomite and quartz arenite. This unit functions as an aquitard that promotes overlying cave development. Moderate lengths of horizontal passage also occur above the contact throughout the Basal Nodular member, mostly along non-nodular limestone beds. Little significant horizontal development is known in the area's Dolomitic member.

Helotes Area Cave Elevations*



*relative to base of Kainer Formation

Figure 5

Table 4

CAVES OF THE HELOTES AREA
ANALYZED IN FIGURE 5

Cave name	Number in Figure 5
Madla's Drop Cave	1
Hummingbird Cave	2
Hills and Dales Pit	3
Brand X Pit	4
B.J. Pit	5
Scorpion Cave	6
Logan's Cave	7
Big Bexar Cave	8
Mastodon Pit	9
Young Cave No. 1*	10
Young Cave No. 2	11
Helotes Hilltop Cave	12
Kamikazi Cricket Cave	13
Shotgun And A Prayer Cave	14
Villa Rreal's Cave	15
Mattke Cave	16
Spider Hole	17
Huesta Cave	18
Blue Hole No. 2	19
Blue Hole No. 3	20
Three Fingers Cave	21
Robber's Cave	22
Madla's Cave	23
Government Canyon Bat Cave	24
Basement Cave	25
Bandera Road Cave	26
Roan's Cave	27
Wagner Ranch Pit	28
Washout Cave	29
World News Cave	30
Crane Bat Cave	31
Some Monk Chanted Evening Cave	32
John Wagner Ranch Cave No. 3	33
Moonshine Cave	34
Christmas Cave	35
Helotes Blowhole	36

* The depth illustrated on Figure 5 includes an unsurveyed 6 m deep pit and passage located at the bottom of the cave.

Alamo Heights Area

Urbanization of the Alamo Heights area karst has sealed most of its caves. Robber Baron Cave, Roy's Cave, and The Labyrinth are the only significant caves which are currently open. All three caves are formed near the top of the Austin Chalk, but only Robber Baron was accessible for this study. The internal stratigraphy of the Austin is not well mapped in Bexar County, so discussion of the Alamo Heights and Culebra Anticline areas will not generally consider its individual formations. Geologic cross sections by Small (1986) illustrate the Austin is about 40 m thick. Corbett et al. (1991) report the Austin's basal Atco Chalk is over 22.8 m thick (assuming their "75 m" thickness is a typographical error for 75 feet), which does not seem likely based on field observations of the lithology.

The entrance to Robber Baron Cave is situated about 4.5 m below the contact with the Pecan Gap Chalk. The upper 10 m of the cave, especially the ***sinkhole*** entrance, is collapsed from a soft, clay-rich, somewhat nodular, massive, highly fractured chalk unit. All ***solutionally***-formed passages occur immediately below this unit within a hard, fossiliferous limestone. Passages occur in the Austin from 14-23 m below the top of the formation, with principal levels at -18 and -20 m. The close range of these levels makes them hard to distinguish throughout much of the cave. The Austin Chalk within the Alamo Heights horst contains the longest caves in Bexar County; Robber Baron Cave has a combined surveyed and explored length of about 1.45 km, and The Labyrinth which is presumably at the same stratigraphic level and is largely unexplored has an estimated length of at least 1 km. Both caves are ***network mazes***.

Culebra Anticline Area

In western Bexar County the Austin Chalk is exposed along the Culebra Anticline, a broad asymmetrical fold whose axis runs N65°E and plunges to the southwest. Small (1986) illustrates the Austin here is about 73 m thick, nearly twice as thick as in the Alamo Heights area. The lack of detailed geologic maps requires estimating cave levels through interpolation of anticlinal plunge, and on the ***dip*** of its limbs based on mapping by Small (1986), Barnes (1983), and Holt (1956).

Figure 6 depicts the stratigraphic situation of 23 Culebra Anticline area caves listed in Table 5. They occur as two distinct groups, one extending from 1.5-23 m and the other from 29-58 m below the top of the Austin Chalk. All caves in the lower group are clustered within a 700 m diameter area and exhibit three significant horizons of passage development. The two lowest levels are marked by the basal passages in Isopit and Wurzbach Bat Cave, respectively 57 m and 49 m below the top of the Austin. The passage in Isopit is the only known perennial cave stream in the Austin Chalk, but there is insufficient information for either level to know if they represent especially soluble units or if they are perched on insoluble beds. The third and highest level of the lower group extends from 34-37 m below the top of the Austin. This level is the most prevalent, noted in the morphology of several caves, and correlates to underlying clay-rich seams of up to 10 cm thick. However, with the exception of Wurzbach Bat Cave, the horizontal extent of these passages is generally <8 m.

The upper Austin group includes caves at the eastern and western-most outcrops on the anticline. Like the lower group, most of the caves are simple

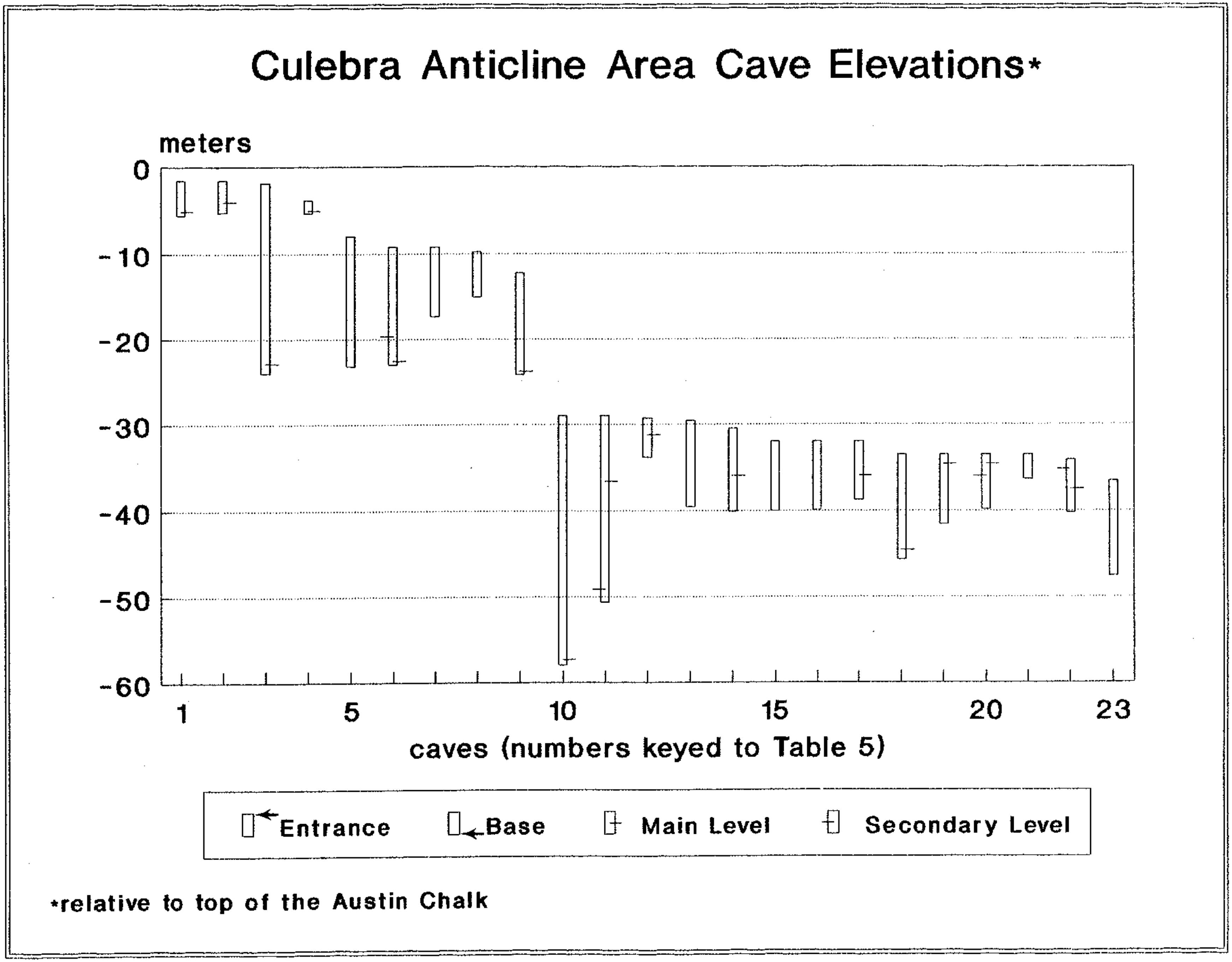

Culebra Anticline Area Cave Elevations*
meters
0
-10
-20
-30
-40
-50
-60
1
5
10
15
20
23
caves (numbers keyed to Table 5)
Entrance
Base
Main Level
Secondary Level
*relative to top of the Austin Chalk

Figure 6

shafts with little horizontal extent. Exceptions are caves near the top of the Austin, and those at levels 23 m deeper. Underwater Cave, Stevens Ranch Cave No. 1, and KKYX Cave display extensive horizontal development 5 m below the top of the Austin. They are perched on a 3 m thick unit which probably has a higher clay content, below which caves again occur. The caves which reach 23 m below the top of the Austin are likely perched on a 5 m thick clay-rich unit. Stevens Ranch Cave No. 2 has nearly 400 m of passages developed at this level, including passages with perched water.

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Table 5

**CAVES OF THE CULEBRA ANTICLINE AREA
ANALYZED IN FIGURE 6**

Cave name	Number in Figure 6
Underwater Cave	1
KKYX Cave	2
Stevens Ranch Cave No. 2	3
Stevens Ranch Cave No. 1	4
Droll Cave	5
Game Pasture Cave No. 1	6
The Two Raccoon Cave	7
Cave of the Skinny Snake	8
King Toad Cave	9
Isopit	10
Wurzbach Bat Cave	11
Molar Hole	12
Carcass Cave	13
Braken Bat Cave	14
Womly Pit	15
Cave of the Bearded Tree	16
Thurman's Cave	17
Cave of the Half Snake	18
World Newt Cave	19
Cave of the Mad Machete	20
Niche Cave	21
Chimney Cricket Cave	22
Fence Post Hole	23

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

Structural Controls

The dominant structural feature of the San Antonio region is the Balcones Fault Zone (Figure 2). The fault zone is formed along the ***homoclinal*** hinge between the relatively flat-lying strata of the Edwards Plateau to the northwest 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 San Antonio region are as much as 180 m, but most major fault displacements are only about 15 m. Many faults with less than 3 m of throw do not appear on geologic maps due to difficulty in mapping them. Although several reports map and describe the general faulting of the San Antonio region, structural analyses are few. Detailed information on ***joints*** and folds is rare. Based on field experience and the limited joint studies, the following discussions assume that most joints in the study area parallel the fault trends.

Faulting in the San Antonio region displaces and juxtaposes the units previously described in the stratigraphy section. Kastning (1977) discusses how faults can have positive, negative or neutral effects on groundwater flow and cave development, and illustrates all three processes within Natural Bridge Caverns, located within the Balcones Fault Zone 3 km northeast of the study area (Kastning, 1983). However, Veni (1985; 1988) finds that even in Bexar County, the most intensely fractured portion of the fault zone, 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 many regional geologic reports as the primary sites of groundwater recharge and cave development, those assessments are not based on extensive field investigation. The joints that are associated with most 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 San Antonio region are nearly horizontal, their slight dips 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; and
2) the tendency for passages to develop along either strike or dip in the given areas.

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 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 or tertiary trend is also counted as a single fracture occurrence. To display the relative significance of fracture bearings, data in Tables 6-9 have been converted to percent in Figures 7-10 to show the proportional total of fractures that occur within 20° increments.

The only caves of the San Antonio region known to be intersected by faults are Stevens Ranch Cave No. 1 and possibly Stevens Ranch Cave No. 2 on the Culebra Anticline, and Genesis Cave and possibly Crystal Cave in the Stone Oak area. Based on extensive field investigations, the following sections assume that practically all cave fractures are joints. The majority of cave maps examined for fractures are drawn to magnetic north; a uniform correction of 8.5° has been applied to these maps to approximate true north.

Stone Oak Area

The largest of the four karst areas in the San Antonio region, Stone Oak has the greatest structural variation. Within Bexar County and the Stone Oak area specifically, the Balcones Fault Zone arcs from a predominantly N60-70°E trend west of San Antonio to a N30-50°E trend northeast of San Antonio. Faults along the outer (southern and eastern) margin of the fault zone are consequently more closely spaced and include ***reverse*** and ***antithetic faults***.

Newcomb's (1971) study of Bat Cave Quadrangle at the eastern end of the Stone Oak area found most joints parallel the major Balcones faults with a primary mode of N50-65°E and have a secondary perpendicular mode of N40-50°W. The joints in the Edwards Group are near vertical, and joints in the upper Glen Rose dip 60-70°. At the west end of the Stone Oak area, mapping by Shaw (1974) shows most faults running N65-80°E. Faulting throughout the area intensifies southward, and faults decrease in length from several kilometers to <1 km. The longer faults average N55°E (Abbott, 1973), while the short faults' mean trend is N45°E (Burgess, 1991).

Table 6 lists the 33 caves studied in the Stone Oak area with their primary and secondary fracture orientations. Figure 7 illustrates the preferential development of caves in the area along the above-described 40-79° and 140-159° joint sets. However, while 51% of the fractures are oriented in these directions, the remaining 49% display little preferential development. This broad distribution of cave fracture orientation reflects the intense and multi-directional fracturing of the area.

Close examination of Figure 7 and Table 6 reveals that the largest, longest, and deepest caves of the Stone Oak area occur along the fractures parallel to the Balcones trend. This distribution indicates that joints related to Balcones faulting are the most permeable in the area. The secondary 140-159° joint set only occurs in small caves, or guides small segments of moderate-sized caves.

Strata in the Stone Oak area generally dip <1° to the southeast, and strike is usually parallel or subparallel to the major Balcones faults. Local instances of greater dip or different strikes occur within some small fault blocks or by drag next to major faults. Only Cueva Cave, measured in beds striking N84°W and dipping 3°S (Veni, 1988), has been noted in such a setting. The difficulty in measuring low dips is exacerbated by most caves having relatively short explored horizontal extents, which prevents assessment of the impact of strike and dip on cave development. The 70 m long middle section of Corkscrew Cave appears to run down-dip, but insufficient field data precludes verifying this hypothesis. Additionally, since strike and the main fracture trends are so similar, distinguishing between the two is often difficult.

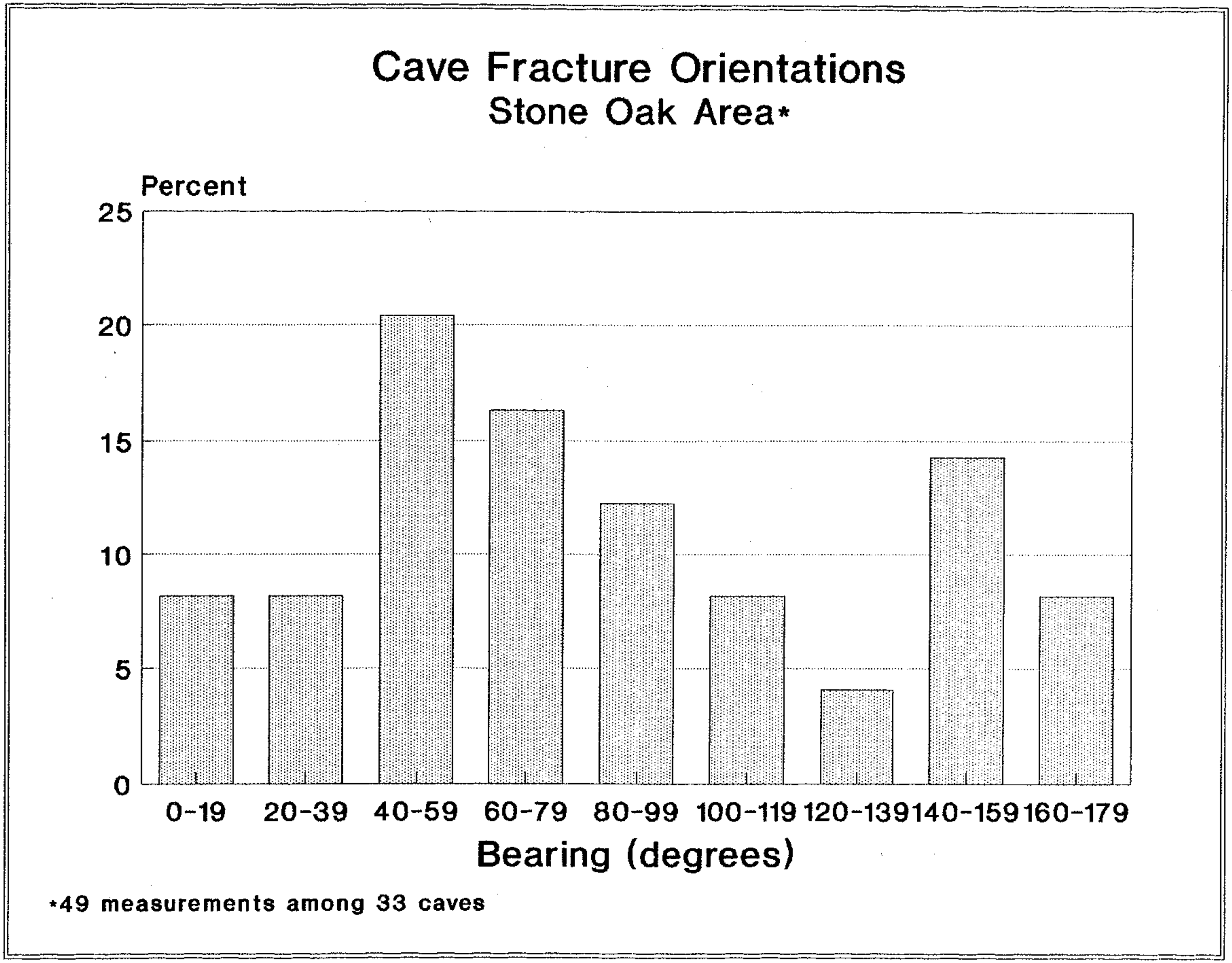
Table 6

CAVE FRACTURE ORIENTATIONS OF THE STONE OAK AREA ANALYZED IN FIGURE 7

Cave name	Fracture bearings in degrees: Primary	Secondary
Ackerman's Trash Hole	62.0	
Aue Road Cave	98.5	161.5
Bailing Wire Cave	79.0	149.0
Bet-Ya-Can't-Find-It Cave	70.0	150.5
Black Cat Cave	98.5	
C-Section Cave	148.5	
Cave File Cave	97.5	
Cave of the Creek	49.0	144.5
Cave of the Woods	152.5	84.5
Corkscrew Cave	61.5	
Crescent Spring	89.0	
Dam Crawl	23.5	
Dead Deer Cave	40.5	165.5
Dirtwater Cave	77.5	
Drop and A Prayer Pit	165.0	
Dynamite Cave	156.0	
Elm Springs Cave	33.0	128.5
Elmore Cave	108.5	
Elm Waterhole Cave	52.5	1.0
Flint Bridge Cave	10.0	100.0
Friesenhahn Cave	64.5	
Gandalf's Cave	43.0	
Genesis Cave	41.0	112.5
Hairy Tooth Cave	42.0	
Hidden View Cave	78.5	54.5
I Think Its A Cave	53.5	
Looserock Cave	18.5	
No Exit Cave	133.5	75.0
Poison Ivy Pit	57.5	109.5
Prayer To Oztotl Cave	153.5	38.5
Tick n' Delight Cave	1.5	87.5
2 for 1 Cave/2 for 1 Spring	35.5	
Woods End Cave	58.5	178.5

Helotes Area

The karst of the Helotes area can be divided into northern and southern sections relative to the Balcones Escarpment, which is dramatically demarcated in this part of Bexar County by the Haby Crossing Fault. Most of the Helotes caves and karst lie north of the fault, and are primarily developed in the Dolomitic member of the Kainer Formation or in stratigraphically lower units. The southern



Cave Fracture Orientations
Stone Oak Area*
Percent
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)
*49 measurements among 33 caves

Figure 7

Helotes karst is far smaller in size, and its few known caves have formed in the middle to upper portion of the Person Formation.

Structural studies by Waddell (1977) show that beds north of the escarpment dip south an average 0.75°, and south of the escarpment average dip increases to 1.6°. Waddell also found that north of the escarpment most faults trend N75°E ±25°, changing slightly to a mean N80°E ±35° to the south. Turk et al. (1972) examined area joints and discovered 40% are parallel to the major faults, while the remaining 60% are somewhat evenly distributed along other compass directions.

The orientations of fractures that guide cave development in the Helotes area are listed in Table 7 and displayed in Figure 8. Only Post Hole is located south of the Balcones Escarpment; the remaining 17 caves occur to the north. Little preferential development along fracture sets is evident in the area. The single greatest concentration of similar orientations is the 0-19° range with only 18%, and only 26% of the caves or cave segments are formed along Balcones-parallel fractures. This scattered development of caves along varying orientations partly reflects the joint pattern described by Turk et al. (1972). Closer examination shows the development of caves down local steep hydraulic gradients. Many of the caves are perched paleosprings or their upgradient sections, and they formed by draining to nearby deeply incised valleys. Hydraulic gradients in the topographic ridges are perpendicular to the valleys. Consequently, Helotes area caves formed by solutionally enlarging fractures oriented down those gradients. The nearly horizontal attitude of the beds facilitates cave development in the varying directions along the steepest local gradients.

Alamo Heights Area

The two major faults which define the Alamo Heights horst are the dominant structural elements of the Alamo Heights area. The western fault points almost north, but turns to run at N23°E along most of its southern half, and turns to N57°E along its northern half. The eastern fault bears a mean N47°E. The faults have respective average displacements of 75 and 110 m. In the central section of the horst Corbett et al. (1991) found joints are generally vertical and trend N40°E, while north in the abandoned Longhorn Cement Quarry joints dip 10-30° and on average bear N20°E. The beds within the horst are almost horizontal, but their exact attitude has not been closely measured.

Structural data is available only for seven Alamo Heights area caves (Table 8). Except for the San Antonio Spring, these caves display some of the best fracture control in the San Antonio region with nearly all passages oriented along joints. The percentages in Figure 9 are somewhat misleading due to the small sample size, but after considering the orientations against the caves' locations, their preferred development along the dominant joints is clear. In the southern half of the horst, these joints are parallel to the adjacent major faults. San Pedro Park Spring at the southern tip of the horst is guided by a near north-south fracture; Robber Baron Cave and TMI Cave in the horst's central section are primarily formed along joints averaging about N40°E. The dominant joints in the northern portion of the horst do not parallel the nearby faults, but The Labyrinth is formed along the N20°E joints. Salado Creek Water Cave is situated between the north and central sections of the horst, and its guiding joint runs

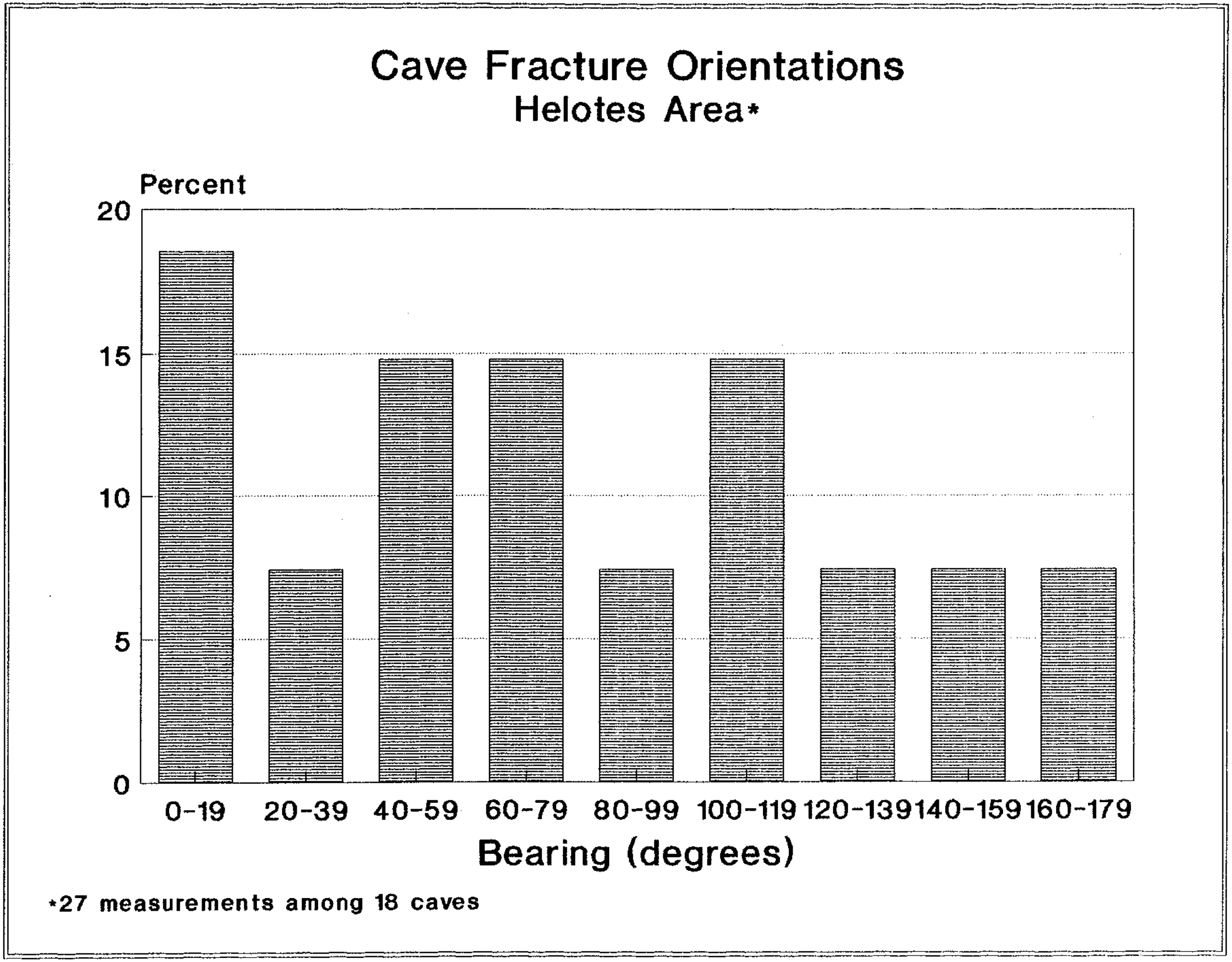
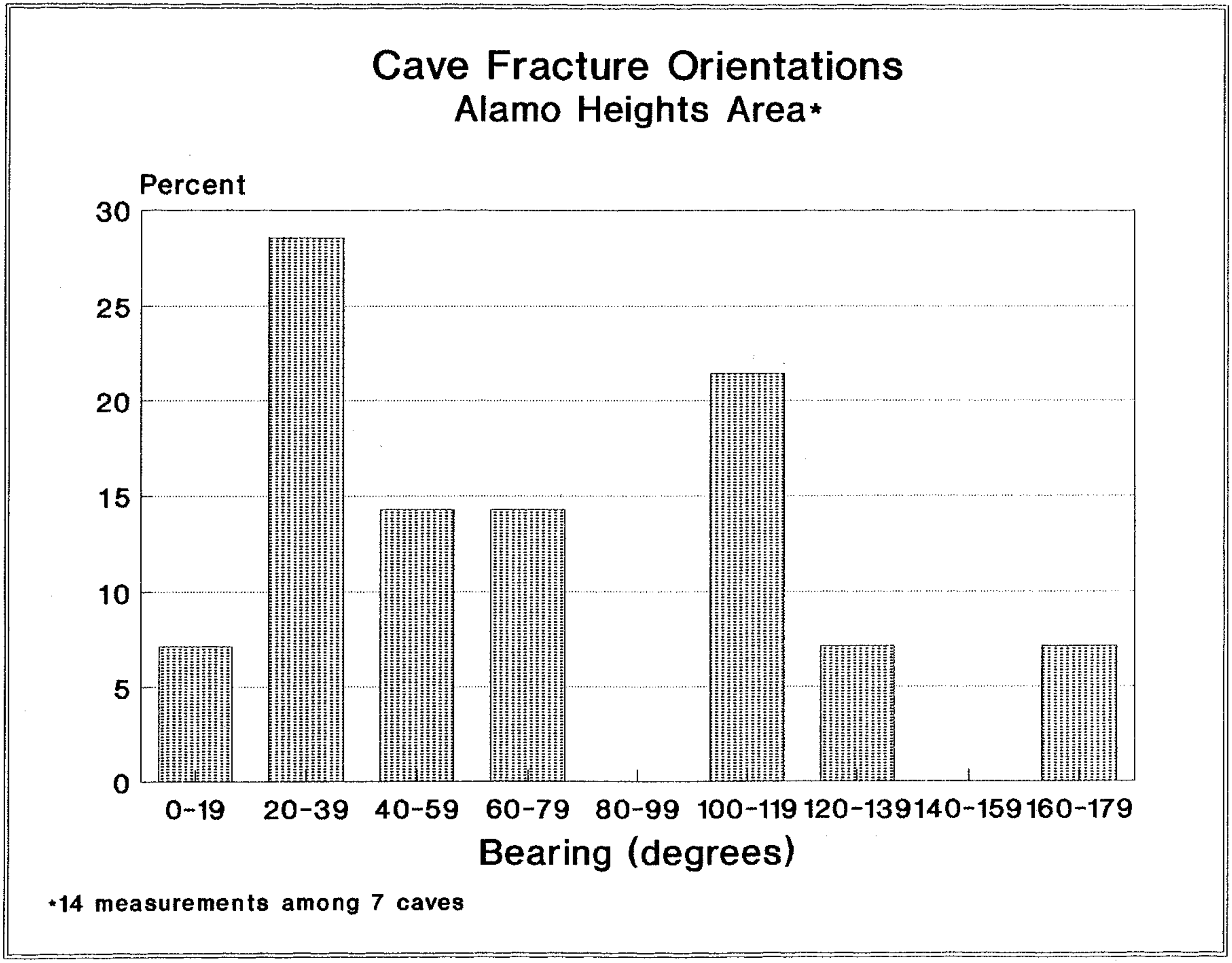

Cave Fracture Orientations
Helotes Area*
Percent
20
15
10
5
0
0-19
20-39
40-59
60-79
80-99
100-119
120-139
140-159
160-179
Bearing (degrees)
*27 measurements among 18 caves

Figure 8



Cave Fracture Orientations
Alamo Heights Area*
Percent
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)
*14 measurements among 7 caves

Figure 9

Table 7

CAVE FRACTURE ORIENTATIONS OF THE HELOTES AREA ANALYZED IN FIGURE 8

Cave name	Fracture bearings in degrees: Primary	Secondary
Big Bexar Cave	18.5	105.5
Blue Hole No. 1	145.5	
Brand X Pit	68.5	
Christmas Cave	99.0	
Gladsam's Cave	177.0	73.5
Helotes Blowhole	55.0	
Helotes Hilltop Cave	10.0	40.0
Hills and Dales Pit	5.5	90.0
John Wagner Ranch Cave No. 3	36.5	
Kamikazi Cricket Cave	104.5	17.5
Logan's Cave	110.5	20.5
Mastodon Pit	46.5	
Mattke Cave	112.0	174.5
Post Hole	74.5	148.5
Scorpion Cave	124.0	
Some Monk Chanted Evening Cave	8.5	
World News Cave	124.0	65.5
Young Cave No. 1	52.0	

on an appropriate intermediate azimuth. Secondary and tertiary fracture orientations in the more extensive caves are near-perpendicular to the main trends. Roy's Cave is mainly developed along these less dominant fractures, although much of the cave has been destroyed by quarrying, and the extant segment may not accurately represent its development.

Culebra Anticline Area

Little structural data have been published about the Culebra Anticline. Holt's (1956) maps show the anticline is slightly asymmetrical, dipping 2.5°N and 2.7°S; the southern limb is truncated by a N71°E fault, downthrown about 90 m to the south. The anticline's axial trend of N65°E can also be interpreted from Holt's maps. Less detailed mapping by Barnes (1983) suggests the anticline extends from Medina County into Bexar County with no significant changes.

Table 9 and Figure 10 present fracture data for 24 caves in the Culebra Anticline area. About 33% of the caves are oriented between N40-59°E, more than twice as many as any other direction. The significance of this orientation is not clear since data are not available on the area's primary joint trend. Most of the known caves follow the crest of the anticline, but since they don't follow fractures parallel to the N65°E axis which are expected to be the most permeable (e.g. Kiersch and Hughes, 1952), their structural location may not be an important

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Table 8

CAVE FRACTURE ORIENTATIONS OF THE ALAMO HEIGHTS AREA ANALYZED IN FIGURE 9

Cave name	Fracture bearings in degrees: Primary	Secondary	Tertiary
Robber Baron Cave	35.0	75.0	120.0
Roy's Cave	72.5	161.5	27.0
Salado Creek Water Cave	31.0		
San Antonio Spring	116.5		
San Pedro Park Spring (West)	7.5		
T.M.I. Cave	47.5	110.5	
The Labyrinth	20.0	100.0	44.5

Table 9

CAVE FRACTURE ORIENTATIONS OF THE CULEBRA ANTICLINE AREA ANALYZED IN FIGURE 10

Cave name	Fracture bearings in degrees: Primary	Secondary
Black Widow Pit	57.5	
Braken Bat Cave	56.5	
Caracol Creek Coon Cave	76.5	38.5
Carcass Cave	63.5	
Cave of the Half-Snake	138.5	52.5
Cave of the Mad Machete	109.5	52.0
Cave of the Skinny Snake	88.5	22.5
Chimney Cricket Cave	104.0	49.0
Droll Cave	100.5	35.5
Forked Pit Cave	142.5	
Game Pasture Cave No. 1	33.5	93.5
Grave Marker Cave	50.5	
Isopit	72.0	51.0
King Toad Cave	142.5	
KKYX Cave	129.0	
Molar Hole	68.0	
Pot-Bellied Stove Cave	30.5	
Screaming Meemies Pit	52.5	98.5
Stevens Ranch Cave No. 1	64.5	128.5
Stevens Ranch Cave No. 2	49.5	90.0
The Two Raccoon Cave	151.5	48.5
Underwater Cave	154.0	
World Newt Cave	48.0	
Wurzbach Bat Cave	40.5	153.5

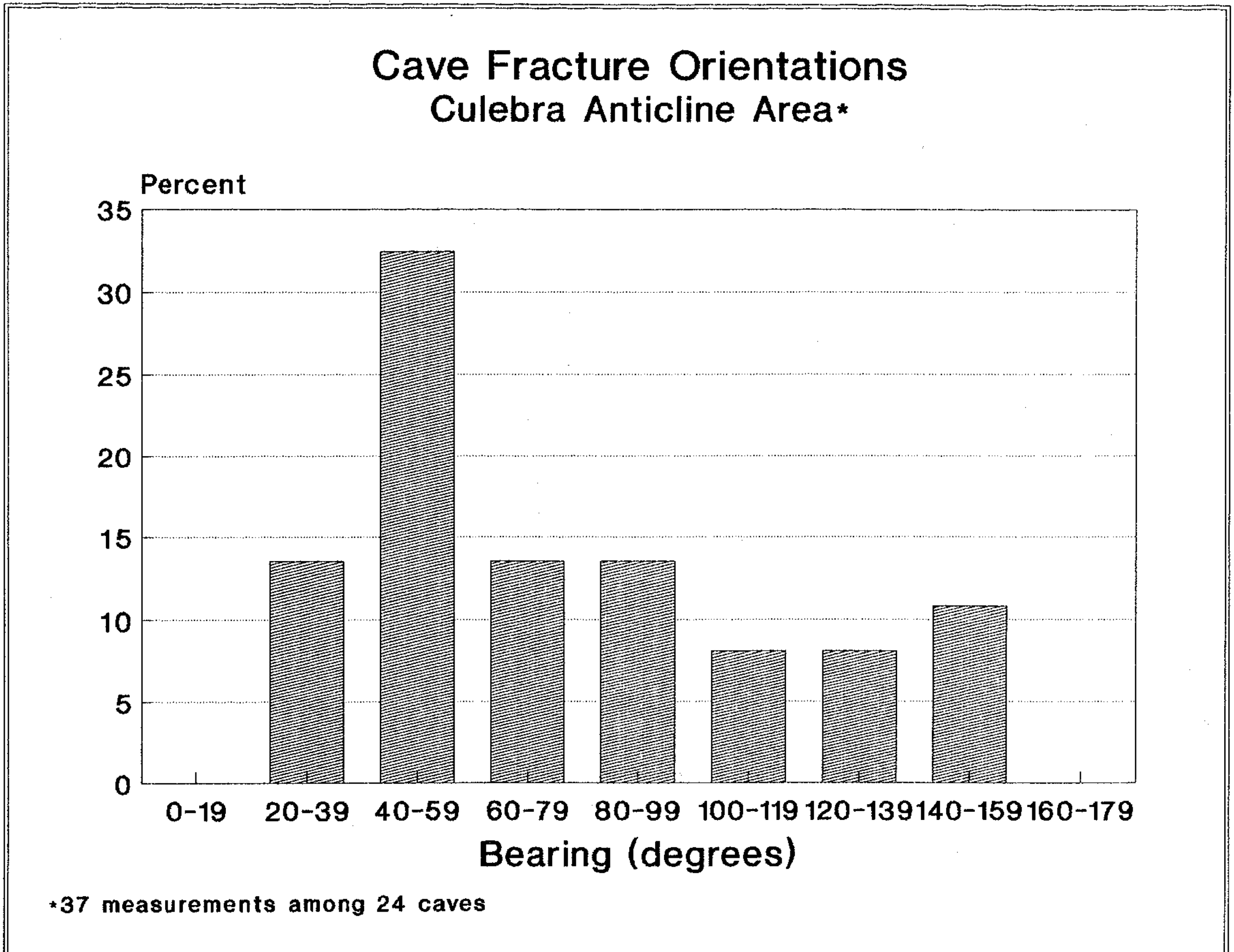

Cave Fracture Orientations
Culebra Anticline Area*
Percent
35
30
25
20
15
10
5
0
0-19
20-39
40-59
60-79
80-99
100-119
120-139
140-159
160-179
Bearing (degrees)
*37 measurements among 24 caves

Figure 10

factor in their orientation. More research on the area's fracture trends is needed to provide detailed and definitive conclusions about its caves.

Hydrologic Controls

Lithology and geologic structure are the prime factors that determine local aquifer development, but in a karst aquifer the morphology and extent of cave development also varies according to the local hydrologic regime. Palmer (1975, 1991) described how maze caves form as a result of back-flooded, ponded, or slow-moving groundwater. Veni (1993) examined the differences in conduit morphology between caves developed in free-flow ***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. However, extensive stream development 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 and cave interrelationships, and in modeling current aquifer development below the modern water table.

Five basic cave types occur in the San Antonio region, and each reflects the current or past hydrologic processes that formed them (Veni, 1988):

1) Phreatic chambers: oval, circular or irregular-shaped cavities that formed by slow-moving groundwater below the water table as singular voids with no extensive passages or connections to other caves.
2) Phreatic conduits: generally linear, 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 water to the aquifer.
4) Transitional caves: originally phreatic chambers or conduits, modified into vadose recharge sites.
5) Spring caves: conduits which spill groundwater to the surface.

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

The following sections describe four karst groundwater systems in the San Antonio region. Two are developed in the Edwards Limestone and Glen Rose Formation, one in the Austin Chalk, and one occurs in all stratigraphic units.

Edwards-Trinity (Plateau Outlier) Aquifer

The Edwards-Trinity (Plateau) Aquifer extends over most of the Edwards Plateau region and is one of the largest aquifers in Texas. Stream dissection along the plateau margin has left several Edwards-capped erosional outliers with similar aquifer hydraulics (e.g. locales within the Helotes area as in Figure 2).

Some hydrologically similar areas are not completely dissected from Edwards Limestone that recharges the Edwards (Balcones Fault Zone) Aquifer. Maps of the fault zone aquifer's recharge zone are drawn based on the continuous exposure of the Edwards, because ***potentiometric*** mapping is inadequate. Therefore, the northern peripheries of that recharge zone are often improperly included within its boundaries, when in fact those areas function as outliers where groundwater flow discharges in nearby valleys.

The Edwards-Trinity (Plateau Outlier) Aquifer is a term first used by Veni and Associates (1992) 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. The outlier aquifer includes portions of the upper member of the Glen Rose Formation that are hydrologically connected to the modern or pre-***denuded*** Edwards outcrop.

Though locations such as the fringes of the Helotes area and the northeast portion of the Stone Oak area 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. Nine springs have been identified from both the Helotes and northeastern Stone Oak areas. Typical of the plateau outlier aquifer, these springs have either seasonal or very low discharge due to their small recharge areas, and the phreatic zone is seldom thick enough to be mapped or to provide water to wells. No tracer tests or water budget calculations have been performed to delineate the drainage basins or hydrologic character of any of these springs.

Caves of the plateau outlier aquifer can be classified as either phreatic chambers, vadose shafts, or springs. Madla's Cave (Figure 11) is an example of a phreatic chamber whose ceiling collapsed as water table decline removed buoyant support. While most plateau outlier caves are typically small, the size and elevation of Madla's and other similar caves demonstrates a former long-lived, slow-flow phreatic zone along the Glen Rose - Edwards contact whose water table was at least 60 m above the modern valley floor. Although most phreatically-formed features are obscured by collapse, the lack of ancient vadose features in these caves indicates a rapid drop in the water table that likely coincides with the rapid incision of the surface valleys. The vadose shafts and springs are smaller and 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 available water. Kamikazi Cricket Cave (Figure 12) is an example of a well developed plateau outlier vadose cave, and Is That All There Is Spring (Figure 13) is a typical small, seasonally active spring.

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 14): San Antonio, Barton Springs, Northern Balcones, and Washita Prairie (Yelderman, 1987). The segments are separated respectively by a drainage divide, an incised valley, and a gap of Edwards Limestone outcrop

Figure 11 (from Veni, 1988)

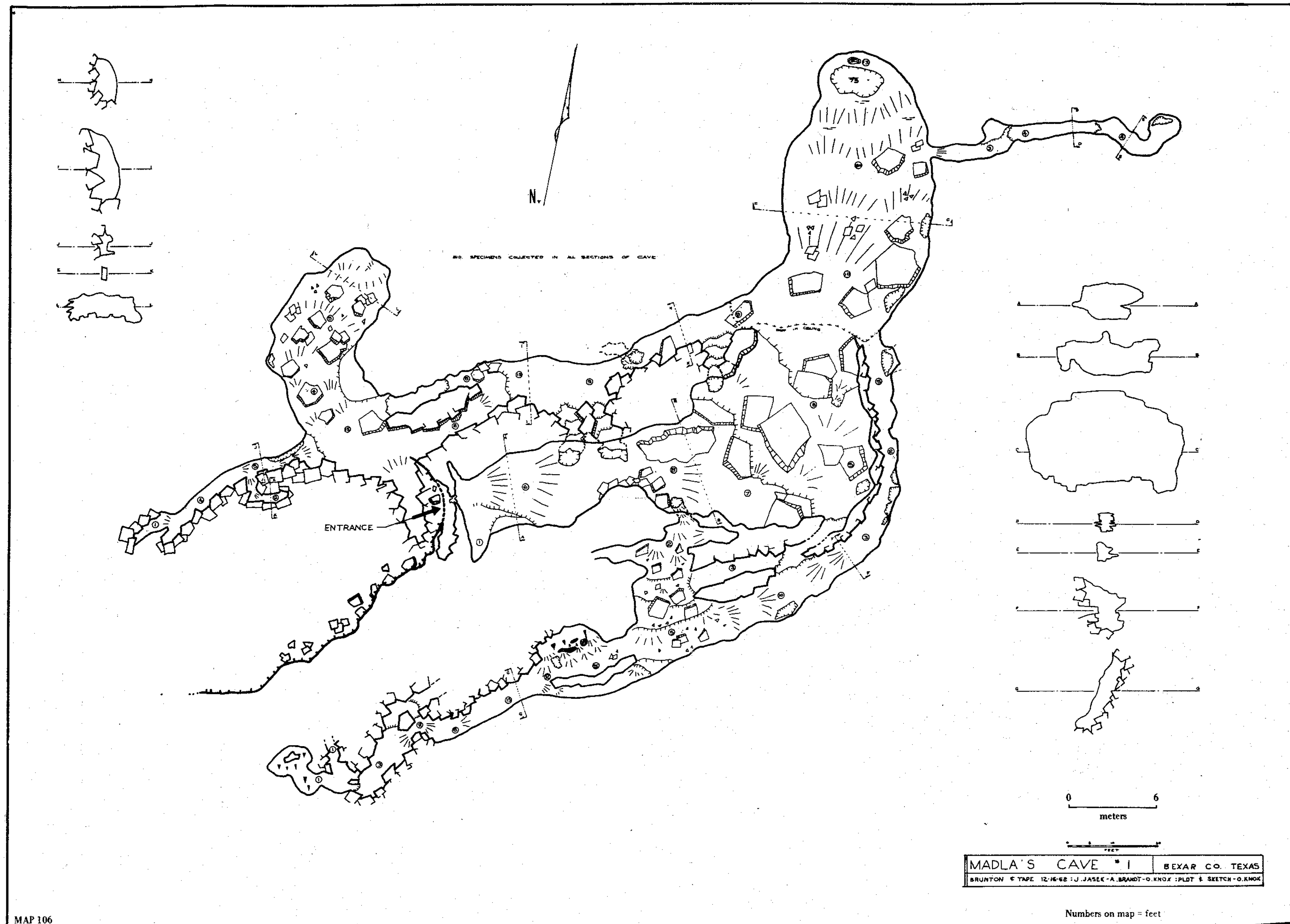


Figure 12 (from Veni, 1988)

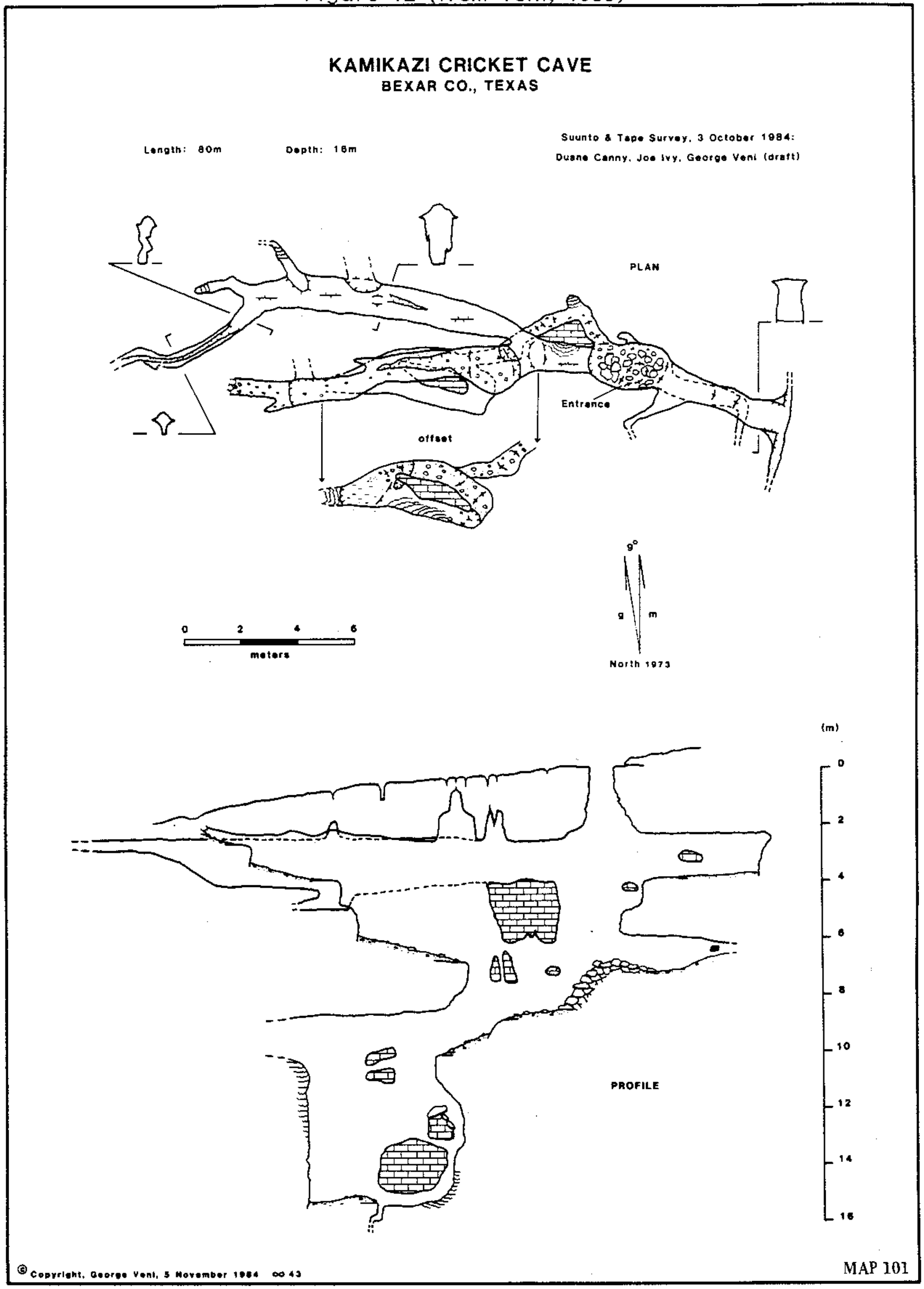


Figure 13 (from Veni, 1988)

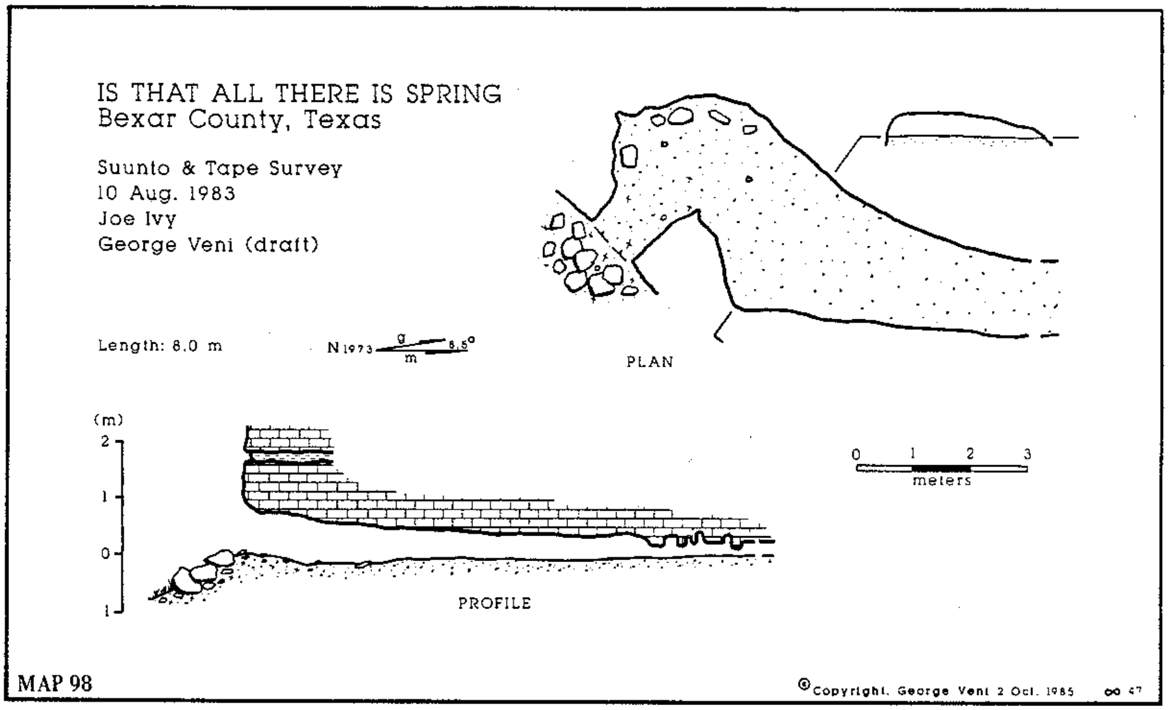
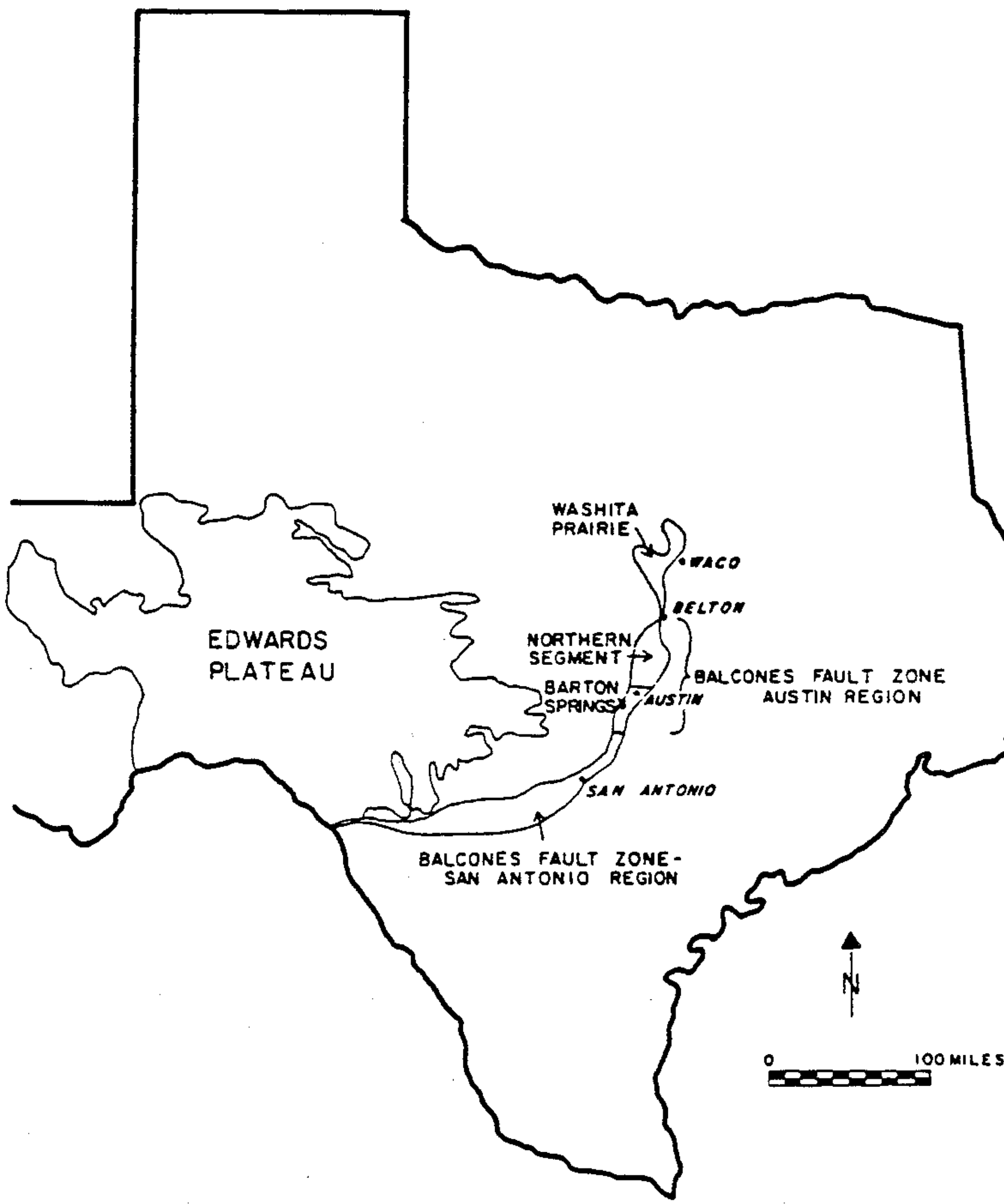


Figure 14: Location of the Edwards Aquifer
and its subdivisions (from Yelderman et al., 1987)



within the fault zone. The Helotes and Stone Oak karst areas are formed within the San Antonio segment.

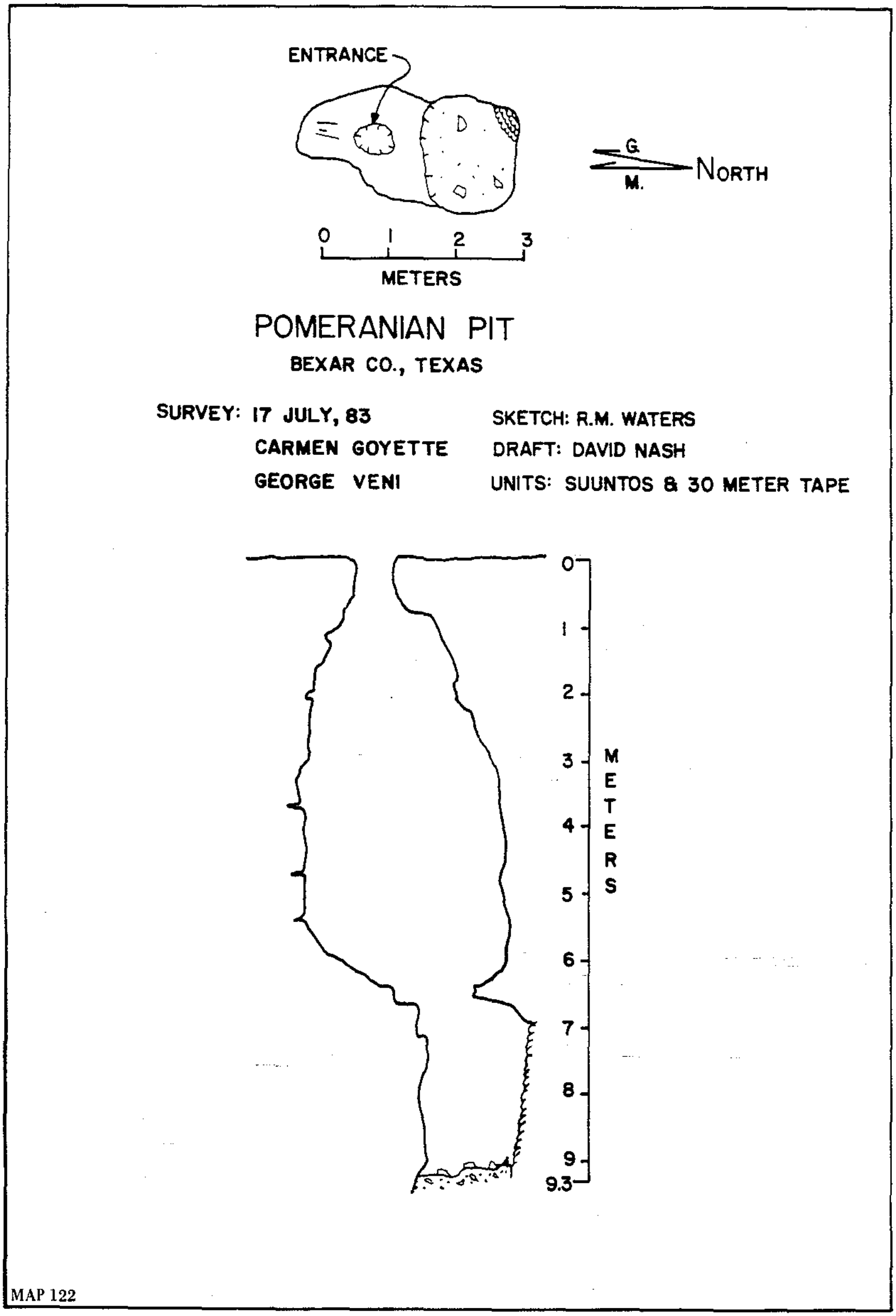
Maclay and Small (1984) examine the hydrogeology of the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer, which can each be divided into four zones: drainage or contributing zone, recharge zone, artesian or *confined* zone, and saline zone. The drainage zone is the upgradient non-Edwards 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 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 Bexar County is generally down-dip southeastward, then northeastward along strike.

The width of the recharge zone in the San Antonio Segment is irregular and ranges from 2 km along Helotes Creek up to 13 km across the Stone Oak area. The artesian zone steadily narrows from 33 km near the Medina County line to 11 km along Cibolo Creek as faults increase in number and in average displacement. The hydraulic gradient in the recharge zone is much steeper than the artesian zone. Current regional aquifer maps do not well reflect detailed features of the potentiometric surface, although some detailed studies have recently been made in some areas (Burgess, 1991; Wattereus, 1992). Depth to water in the recharge zone increases to the south as a result of both downgradient position and fault-thickening of the Edwards Limestone. The mean depth ranges from 50-70 m, but there are considerable local variations.

All five hydrologic cave types known in Bexar County occur in the Edwards recharge zone. Vadose caves are the most common and recently formed. Generally single shafts (e.g. Pomeranian Pit, Figure 15) or a series of shafts connected by short sections of horizontal passages (e.g. Genesis Cave, Figure 16), they form the deepest caves in the county. The preponderance and depth of these caves results from the vertical hydraulic gradient and greater vadose thickness in the recharge zone. The true horizontal extent of these caves is seldom seen. Coarse sediments are commonly deposited in passages atop the water table or less permeable strata where hydraulic gradients suddenly decrease, thus limiting exploration and study. Severe flooding is rare in recharge zone caves, limited to caves within streambeds. Groups of recharge caves may drain sizeable interstream areas, but individual caves rarely drain large enough tracts to be inundated. As a group, vadose caves extend through the entire thickness of the Edwards Limestone and much of the upper Glen Rose, breaching impermeable strata via permeable vertical fractures.

Phreatic chambers are the second most common recharge zone cave. Developed prior to the modern hydrologic regime of the Edwards (Balcones Fault Zone) Aquifer, they likely formed within the Edwards-Trinity (Plateau) Aquifer. Like the previously described phreatic chambers of the plateau outlier aquifer, the recharge zone chambers were drained of water and separated from the plateau aquifer by stream dissection along the Balcones Escarpment. Prior to

Figure 15 (from Veni, 1988)



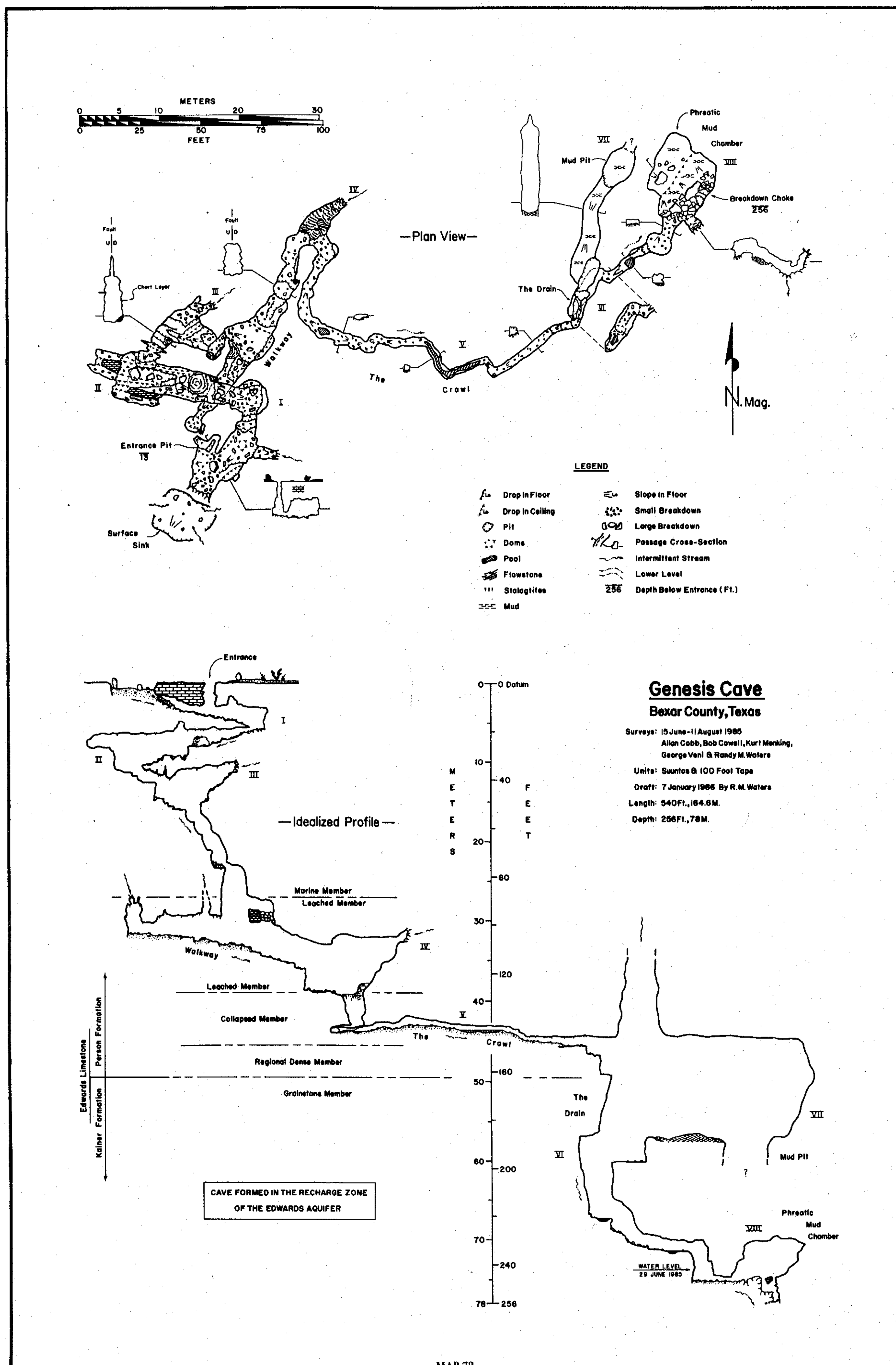


Figure 16 (from Veni, 1988)

separation these caves were probably within a hydrologic subsystem of the plateau aquifer whose low-velocity water flowed through the fault zone.

The origin of these phreatic caves deserves closer study. They appear as isolated chambers with no significant off-going passages (e.g Voight's Bat Cave, Figure 17). Many of these caves are modified by extensive collapse which restricts access to any associated phreatic conduits, the third and most rarely found cave type in the region (e.g. No Exit Cave, Figure 18). Collapse from chambers may hide phreatic conduits, and the conduits' more stable structural configuration makes them less prone to collapse that would open them to the surface. However, sufficient phreatic chambers have been examined to tentatively propose that most of their infeeding phreatic conduits are disproportionately small, and possibly impassable for human entry. The location and size of the chambers would probably result from groundwater mixing at hydrostratigraphically favorable locations; the rarity of major fractures in the chambers suggests minor structural control.

Transitional caves are the last major cave type in the Edwards recharge zone. Thirteen caves of this origin are currently known in Bexar County. Like phreatic chambers and conduits, these caves occur in all topographic settings but are usually found in areas of greater aquifer recharge. Hills and Dales Pit (Figure 19) is an example of a phreatic chamber located under a more recently formed streambed which loses all its flow into the cave. While the cave efficiently drains all recharge (estimated up to 114 l/s) and never floods more than 1.2 m deep, its draining passage (not shown on the map) is newly developed and thus humanly impassable. Transitional caves in interstream areas form more slowly by gradually developing sinkholes where they first breach the surface. Black Cat Cave (Figure 20) is a phreatic conduit that now drains an area of about 100 m^2. The hydrologic behavior of both streambed- and sinkhole-formed transitional caves is identical to their vadose-type counterparts.

Spring caves are the last and least common cave type in the Edwards recharge zone. These caves form under high hydraulic gradients by draining upland areas to nearby incised creeks, and are generally small due to rapid abandonment of flow as groundwater seeks new and lower discharge points along the downcutting valleys (e.g. Shot-and-a-Prayer Cave, Figure 21). The larger and more extensive spring caves tend to be pre-existing groundwater conduits that were intersected by valleys (e.g. 2 For 1 Cave and 2 For 1 Spring, Figure 22).

Austin Chalk Aquifer

Little research has been done on the Austin Chalk Aquifer. Livingstone, Sayre, and White (1936) found that in some places in Bexar County, Edwards (Balcones Fault Zone) Aquifer water leaked upward along fractures to become Austin groundwater. Arnow (1959), George (1952), and Holt (1956) respectively describe typical Austin groundwater in Bexar, Comal, and Medina counties as yielding only small volumes to water wells, and to commonly be high in hydrogen sulfide from the oxidation of pyrite nodules contained within the chalk.

Veni (1988) conducted a preliminary hydrologic assessment of Austin Chalk caves and found the majority, and all significant caves, vadosely developed as either network mazes or discrete recharge sites. Closer analysis reveals that the

Figure 17 (from Veni, 1988)

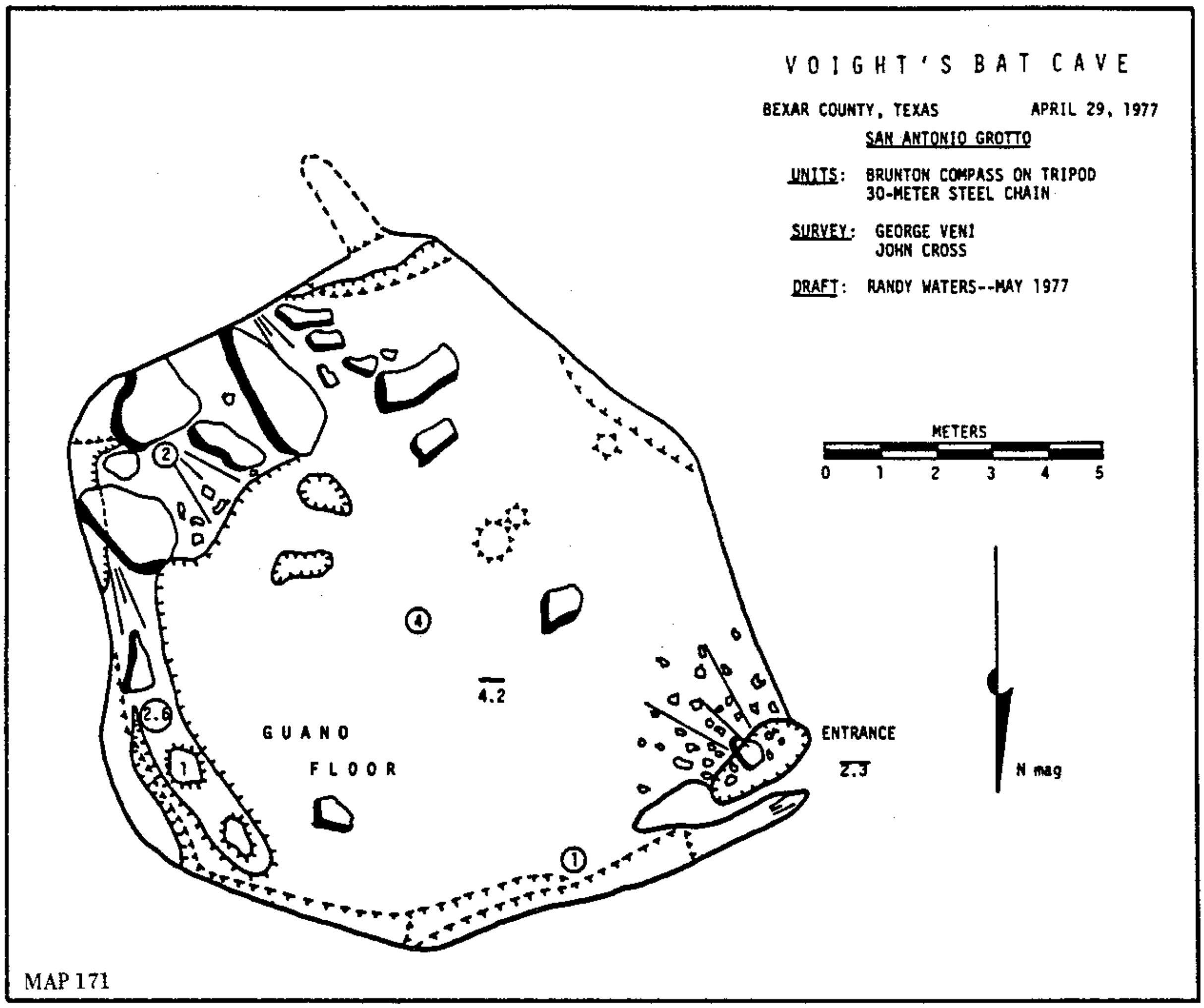


Figure 18 (from Veni, 1988)

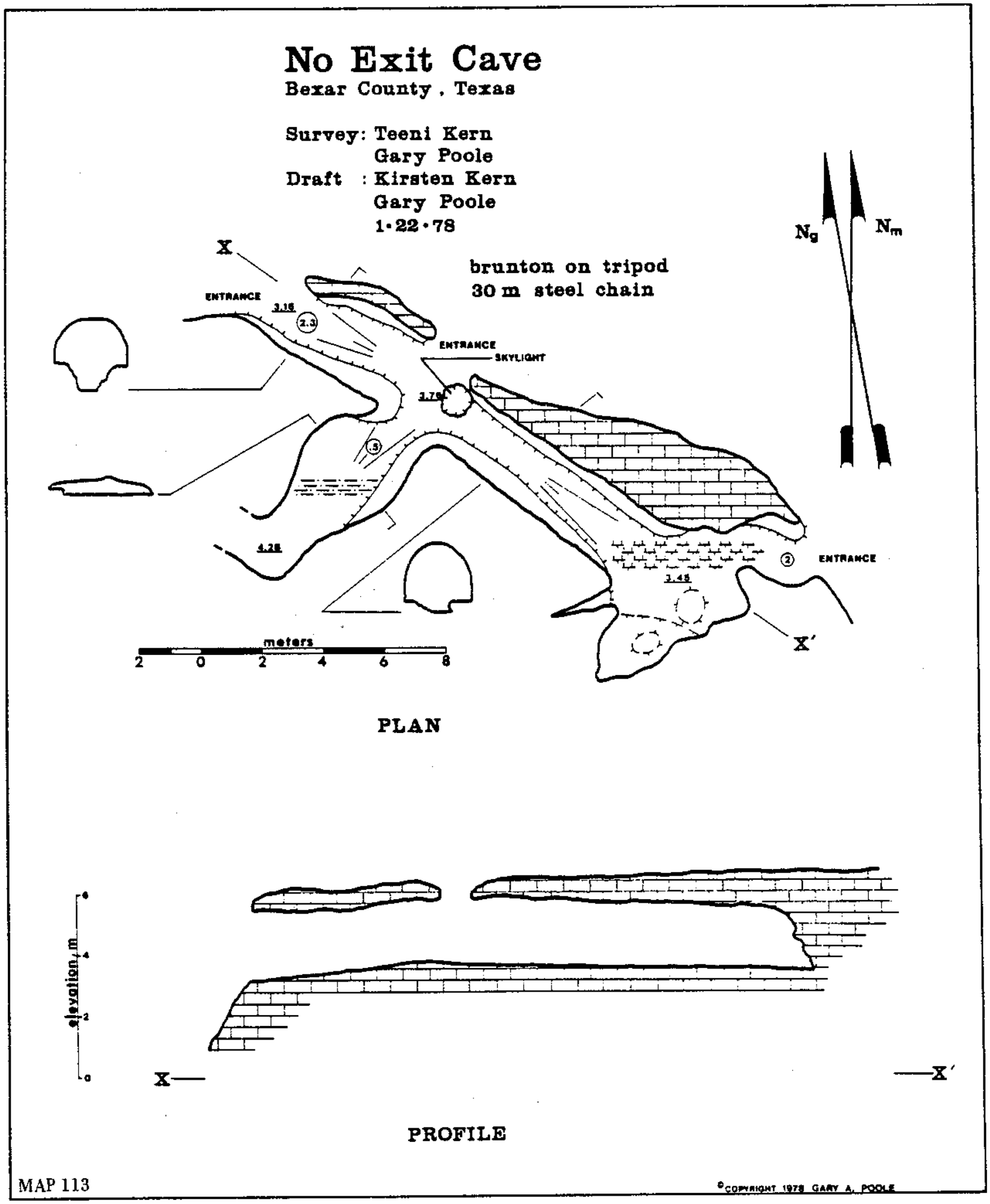
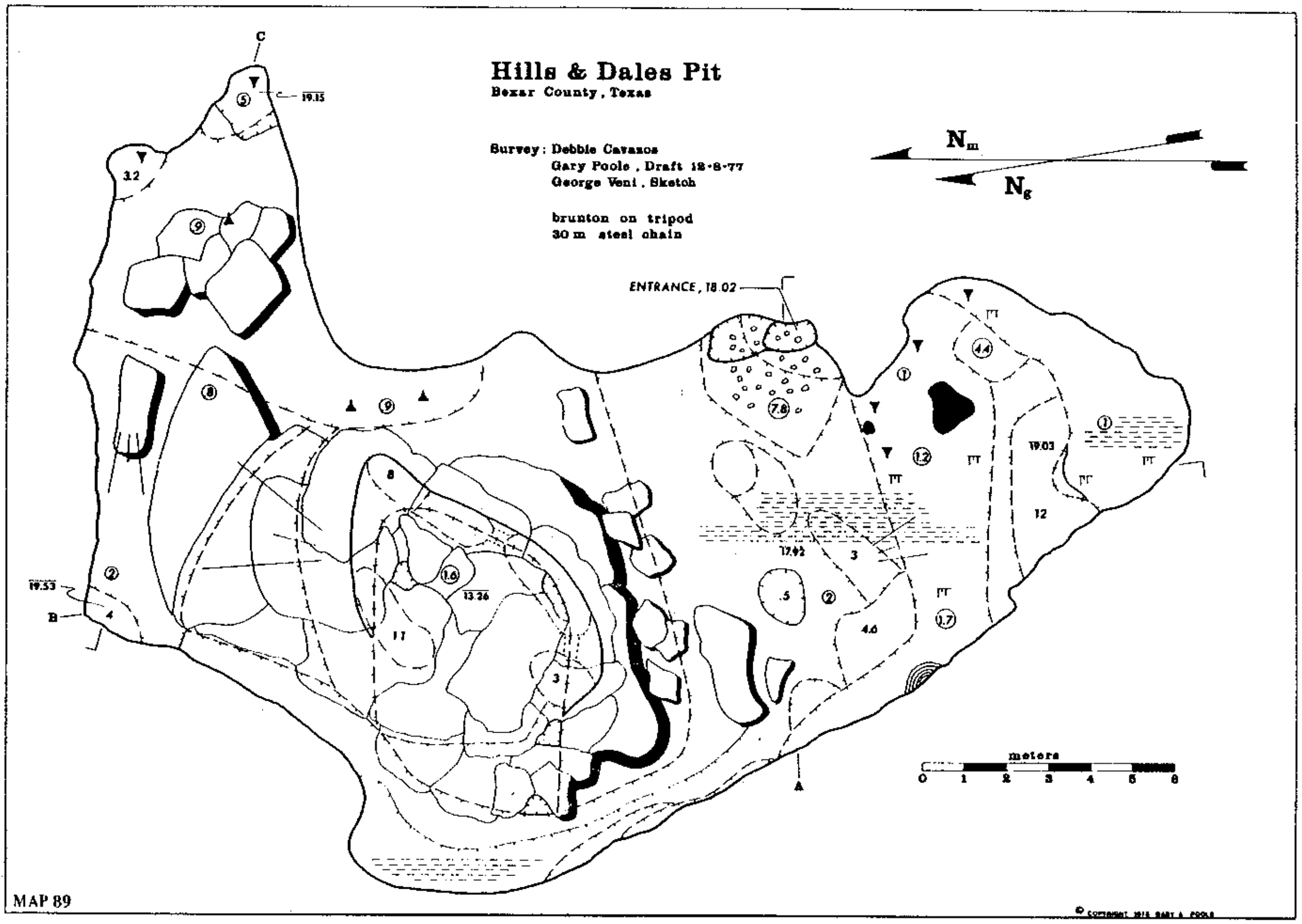
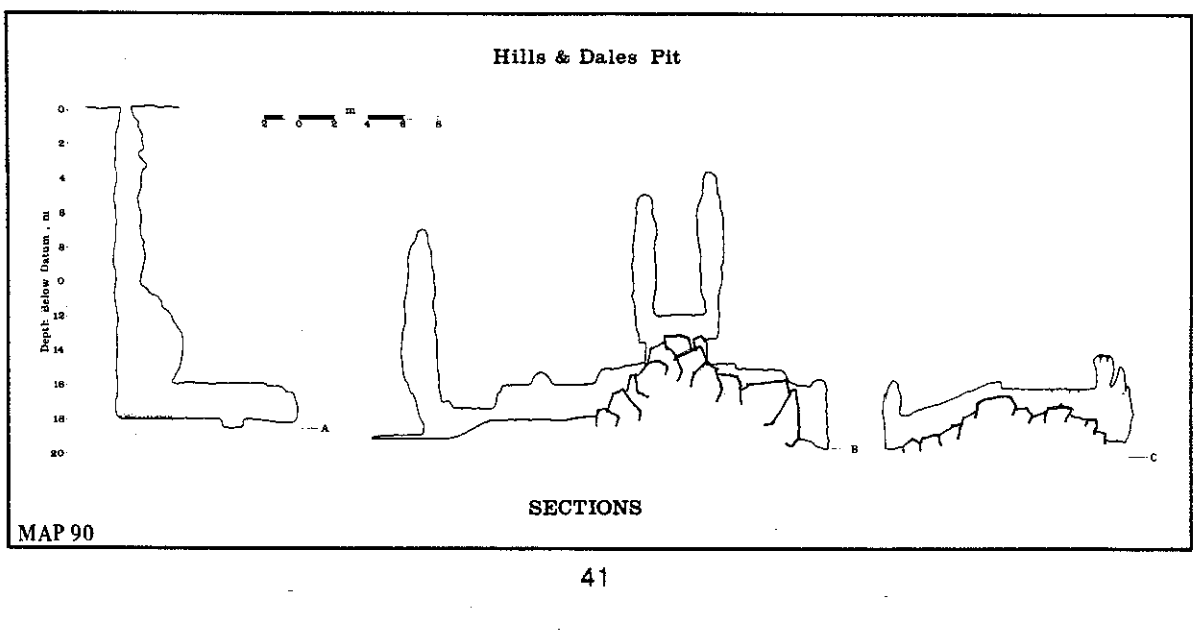


Figure 19 (from Veni, 1988)





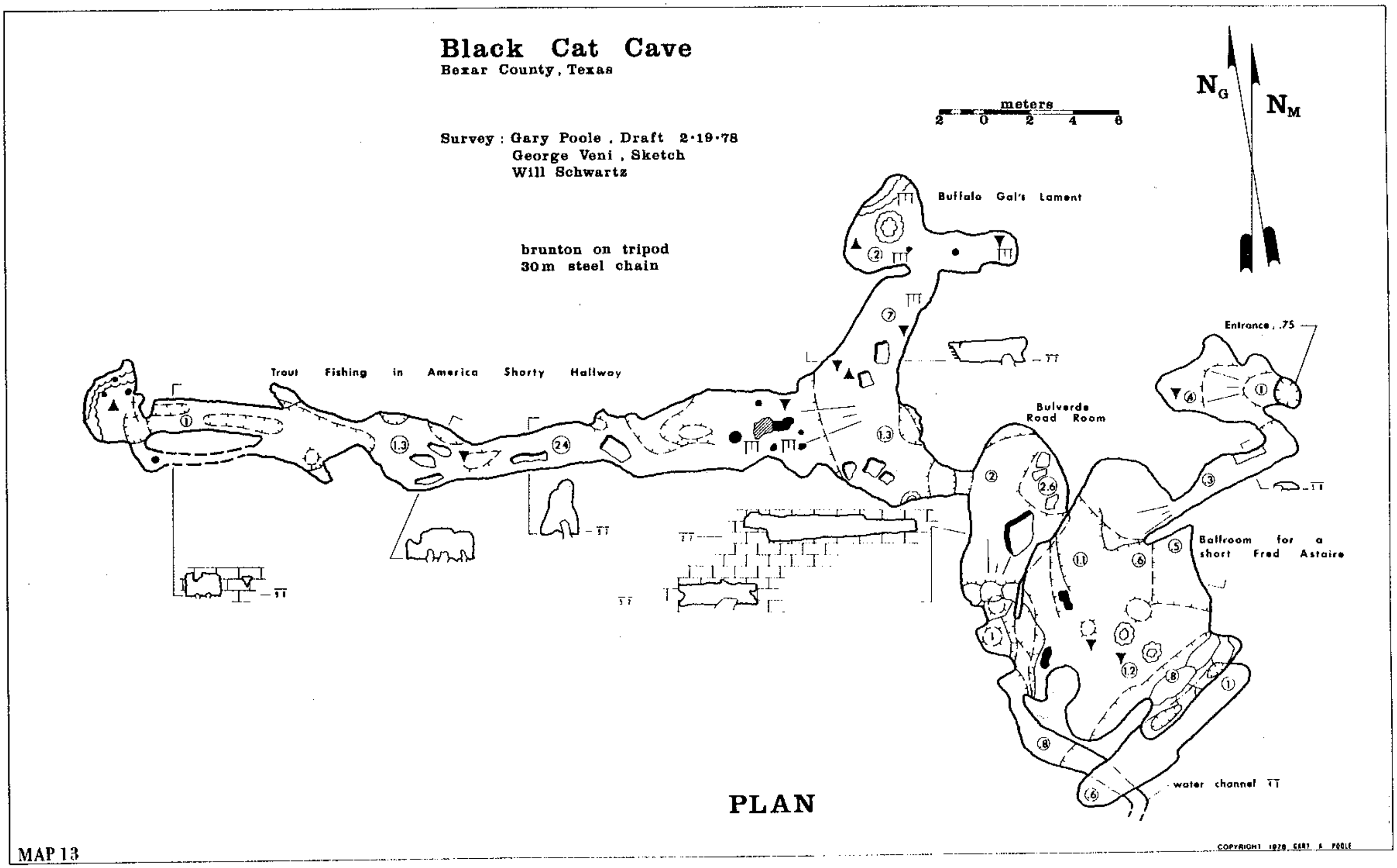


Figure 20 (from Veni, 1988)

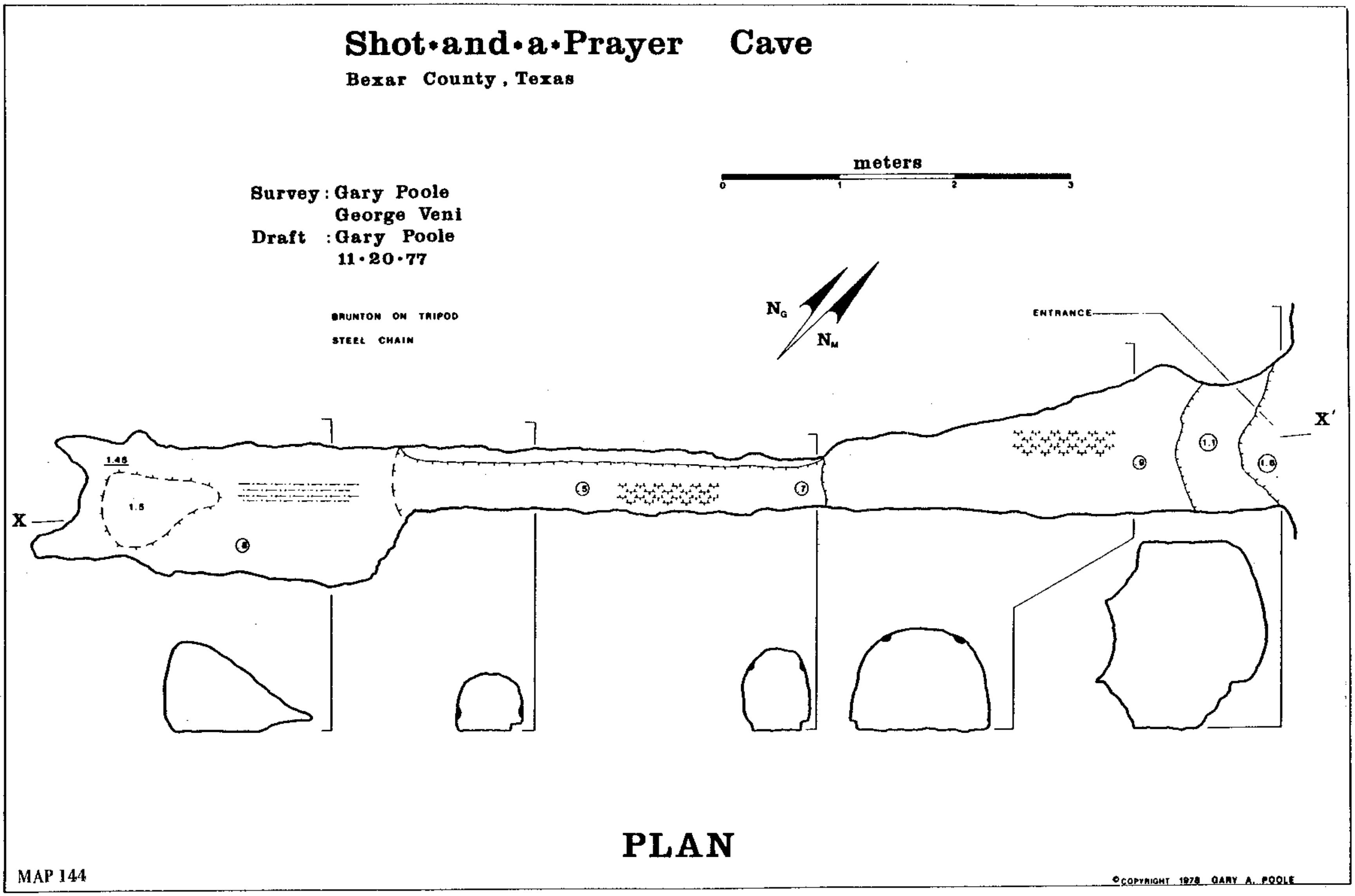


Figure 21 (from Veni, 1988)

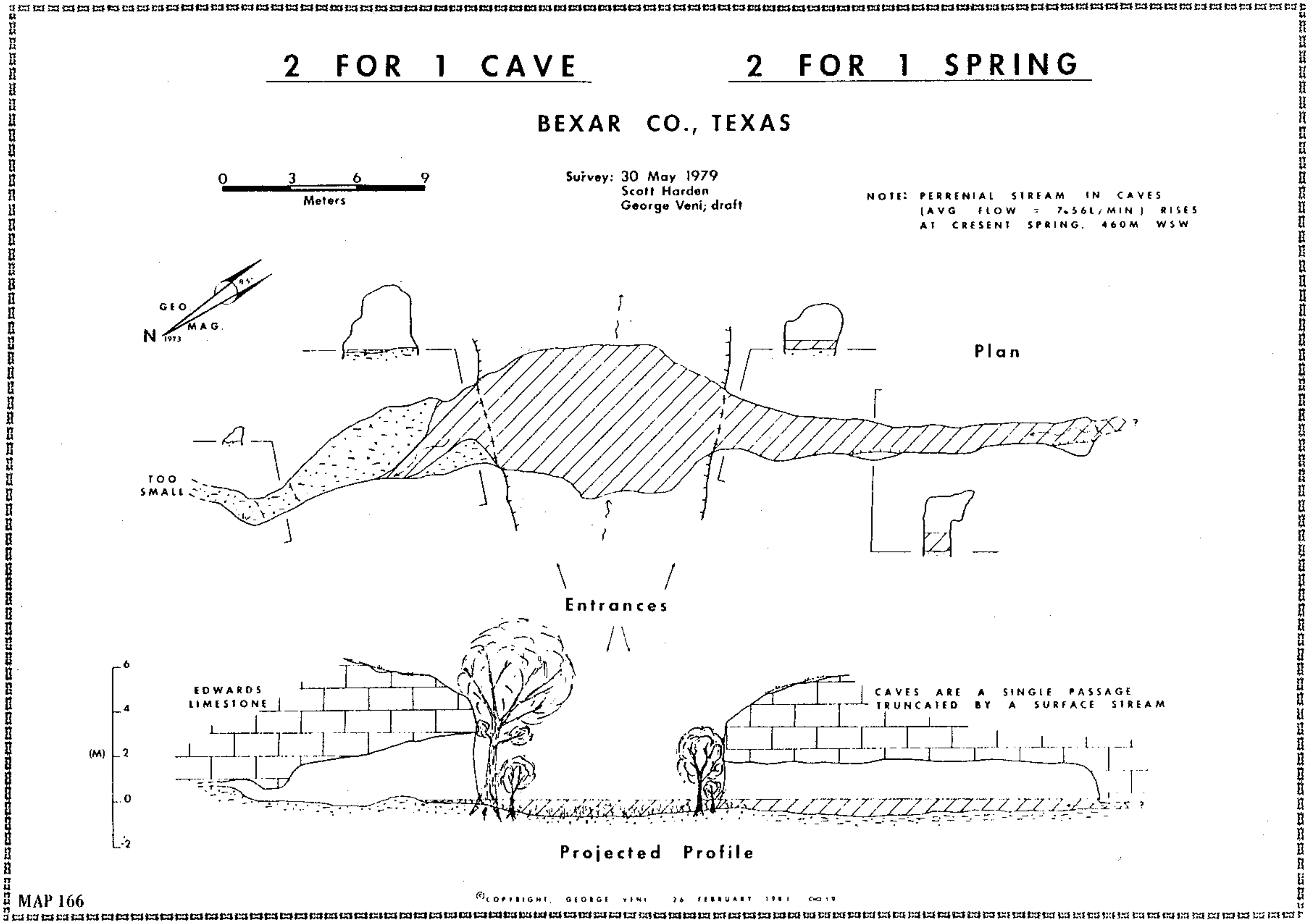


Figure 22 (from Veni, 1988)

mazes are restricted to the Alamo Heights horst and the recharge caves are exclusive to the Culebra Anticline.

Robber Baron Cave (Figure 23) is the best studied Alamo Heights area cave. This network maze formed by vadose groundwater seeping down joints through a clayey upper horizon of the Austin to uniformly dissolve passages in the underlying more soluble strata. The passages enlarged linearly along the joints until they interconnected to form the over 1.45 km long maze (this length includes sections not shown on the map). Urbanization and commercial development blocked off most of the cave, estimated at up to 20 km long.

Despite Robber Baron's impressive entrance sinkhole, little water flows into the entrance. No significant water flows into the much smaller entrances of the area's other maze caves; most water in these caves is diffuse vadose flow from joints. Due to the minimal surface inflow, sediment in Robber Baron is predominantly the insoluble residual of the chalk that dissolved to form the passages. Small pools occasionally develop in Robber Baron, but streams have never been found in its mapped section. Flowing streams reported beyond the collapse may be areas where Edwards water upwells into the chalk; however, there is no evidence that this water influenced the genesis of the known passages in this or any other Alamo Heights maze cave.

Isopit (Figure 24) is the model Culebra Anticline vadose cave. Most caves on the anticline are simple shafts where exploration abruptly ends in sediment fill, while vadose water readily moves through the material down to the water table. Isopit permits access down to and along nearly 300 m of a perennial cave stream. Recharge to the stream is from the numerous solution sinkholes in the area. Unlike the more permeable Edwards outcrop, the less permeable Austin produces greater runoff which in turn develops larger and more frequent sinkholes than on the Edwards. These sinkholes channel the recharge to the water table down conduits solutionally enlarged along fractures. Throughout the length of Isopit are domes which transmit water from sinkholes with no cave entrances to the cave stream. The stream passage increases in size downstream, probably because of increased distance from sediments washed down the entrance.

There is little information on the response of Culebra Anticline cave streams to recharge. Wurzbach Bat Cave and Stevens Ranch Cave No. 2 both recharge large volumes of water estimated to exceed 100 l/s, but floodwater levels in both are minimal, indicating effective transmission. Cobbles in the perennial stream in Isopit suggest significant increases in discharge, but its base flow is generally low and slowly moves through and around sediment bars which cross the passage.

Flow routes of the Austin Chalk cave streams are poorly defined, and their downgradient springs have not yet been located. Isopit is closely oriented along the N65°E strike of the anticline, while the Death Crawl which drains nearby Wurzbach Bat Cave (Figure 25) runs N40.5°E. No potentiometric maps exist of the Austin Chalk aquifer, so their trend relative to the water table is unknown. While none have been reported, the likely springs for Isopit and Wurzbach Bat Cave probably occur along Medio Creek about 1 km to the northeast. Some geologists speculate that the lack of known springs may indicate that some

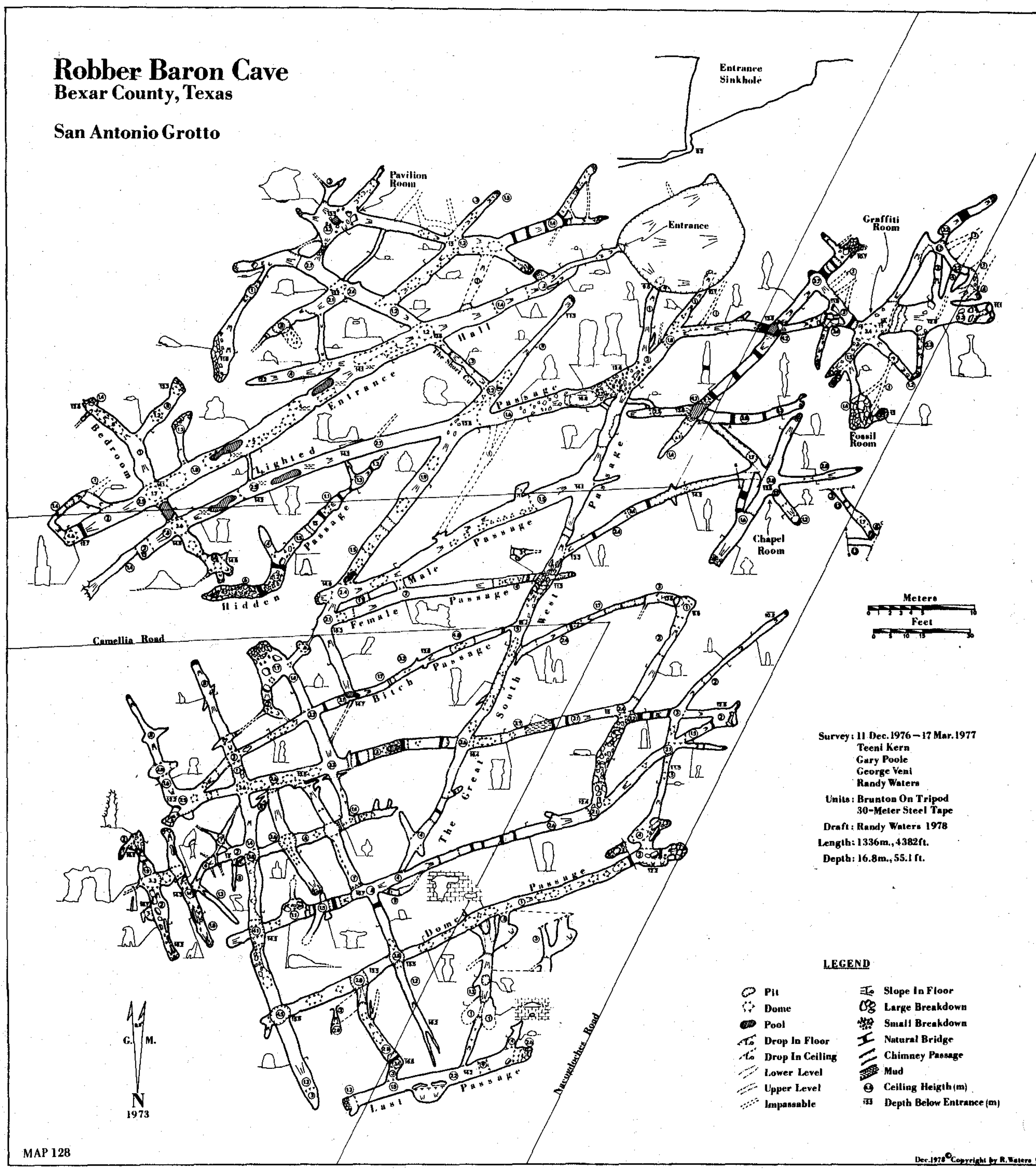


Figure 23 (from Veni, 1988)

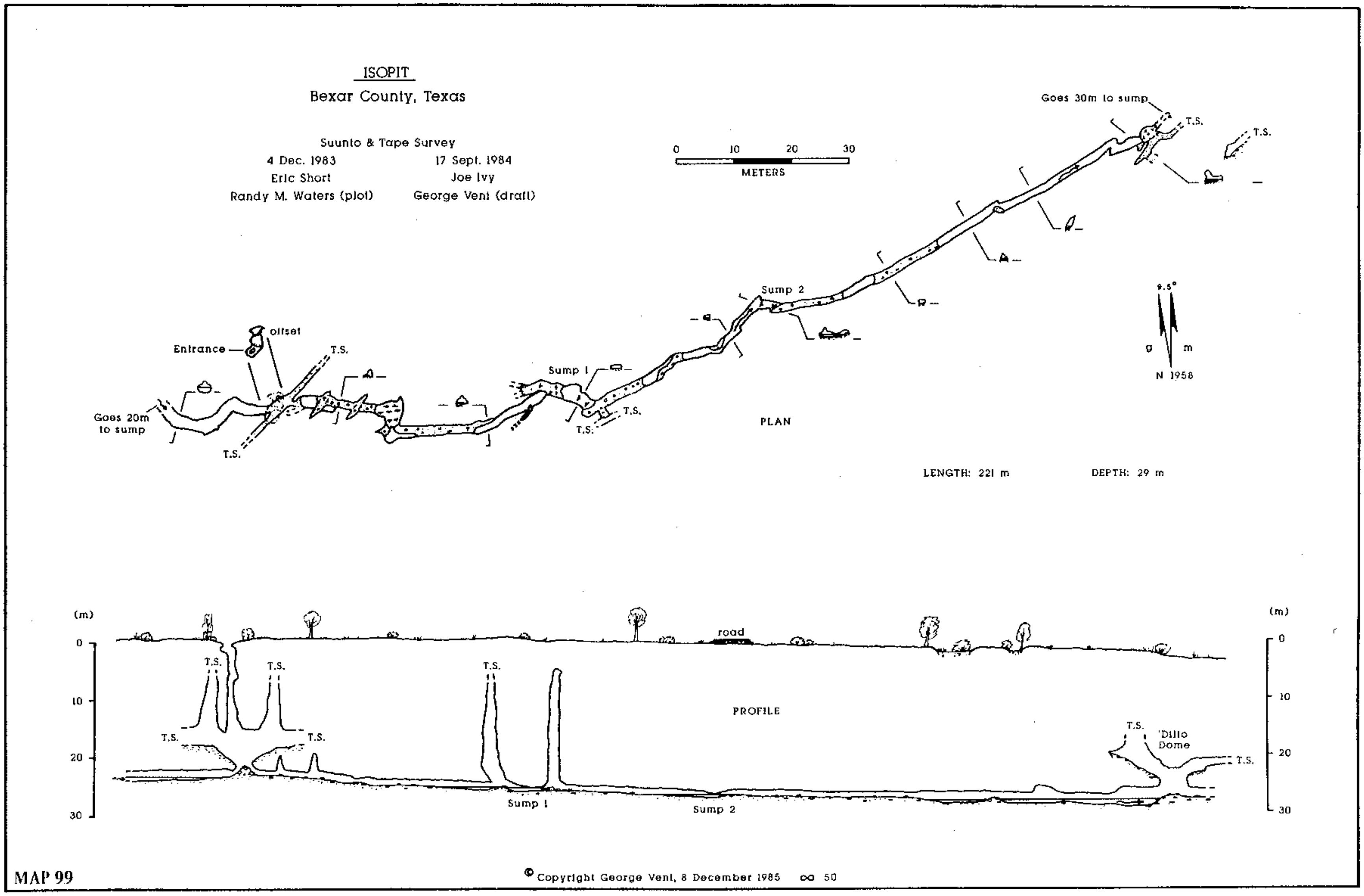
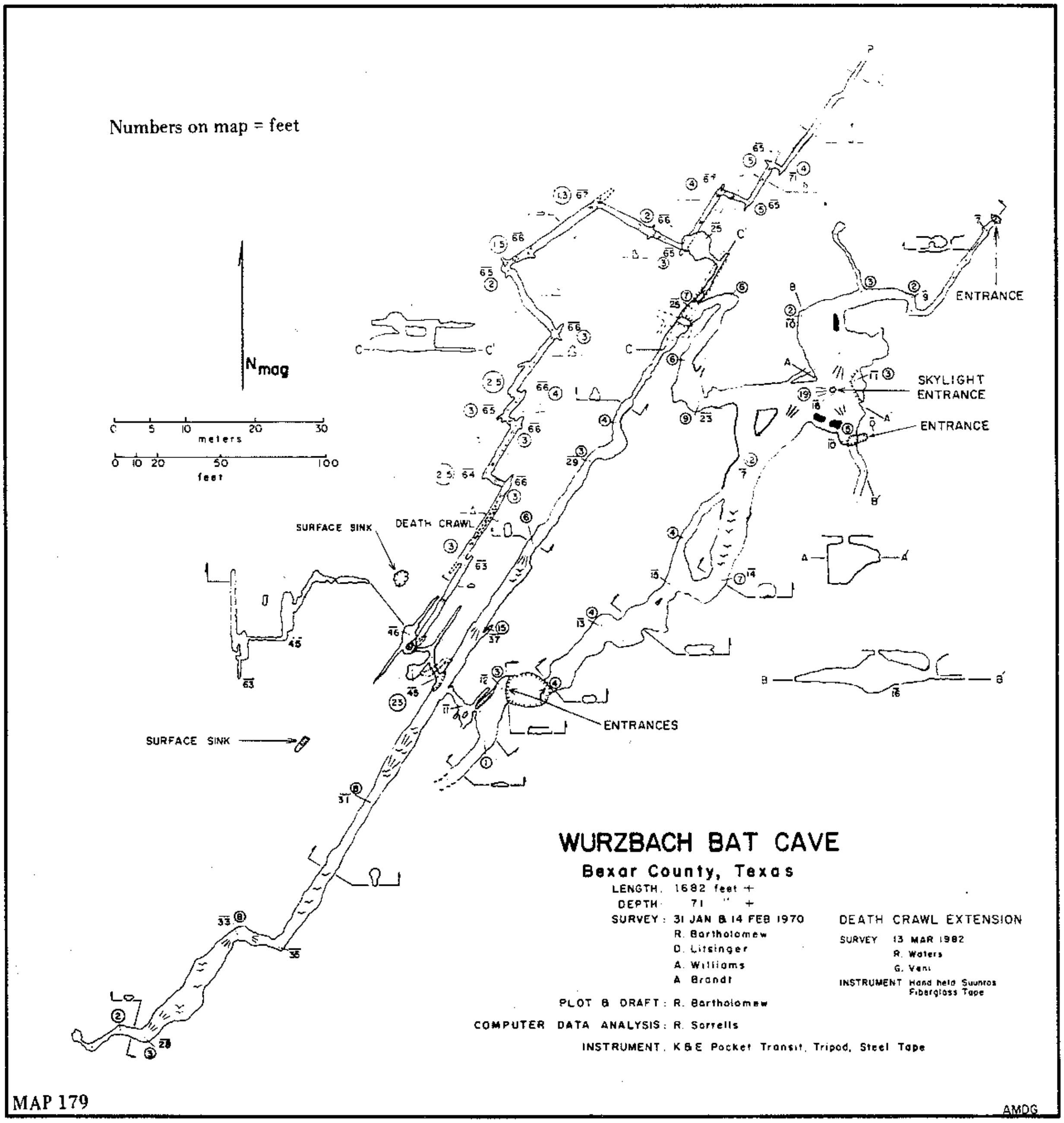


Figure 24 (from Veni, 1988)

Figure 25 (from Veni, 1988)



groundwater in the Culebra Anticline recharges the underlying Edwards (Balcones Fault Zone) Aquifer. Kipp, Farrington, and Albach (1993) report on contamination of Edwards water from landfills and other activities on the Austin in north-central Bexar County. So Austin groundwater certainly contributes to the Edwards, but there is insufficient data to determine its rate of inflow, and how that rate changes seasonally and geographically.

Epikarst

Mangin (1975) introduced the term ***epikarst*** to describe the highly solutioned zone in karst areas between the land surface and the predominantly unweathered bedrock. The epikarst has two zones, the first of which correlates to the A and B soil horizons, and the second which is equivalent to the C soil horizon. Veni (in review) found that in the lower Glen Rose outcrop, including portions of northern Bexar County, the epikarst and non-cavernous portions of the vadose zone are hydrologically and chemically indistinguishable in areas with little or no soil cover. Much water storage and CO_2 production that traditionally was thought to occur in the epikarst was found within the vadose zone.

Epikarst hydrology is a relatively new field of study and is often overlooked in hydrologic assessments of karst regions. Currently, most published data relating to epikarst are soil studies, and the only known relevant works for the San Antonio region are the soil survey for Bexar County (Taylor, Hailey, and Richmond, 1966) and a report on terra rossa soils by Young (1986). The predominant soil types in the Bexar County karst are Tarrant, Brackett-Tarrant, and Crawford and Bexar. Tarrant soils dominate much of the Edwards Limestone and Austin Chalk outcrops; they are dark brown to black, poorly permeable, stony soils, usually <25 cm deep. Brackett-Tarrant soils generally occur on upper Glen Rose slopes that range from 8-30%; these soils are thin to patchy, light brown to yellow in color, stony, and moderately permeable. The exposure of Crawford and Bexar soils correlates to the distribution of terra rossa described by Young (1986). These soils extend across the roughly level upland of the Edwards outcrop, following Loop 1604 most of the way from Helotes to Cibolo Creek. Crawford and Bexar soils are stony clays, often chert-rich, dark brown at the surface but brownish-red below; on average they range in thickness from 43-114 cm, and are permeable when dry and poorly permeable when wet. Although direct studies of epikarst hydrology have not been made in Bexar County, some characteristics can be ascertained by observations of the soils, and surface, cave, and spring hydrology.

In the Stone Oak and Helotes areas, caves within the Person Formation are generally overlain by Crawford and Bexar soils. These soil occurrences are erosional remnants. Toomey, Blum, and Valastro (1993) demonstrate that a thick terra rossa was wide-spread in the Edwards Plateau region and had mostly eroded away by about 5000 years ago as the climate became drier. Some of this soil washed underground, where it is often observed as red clays deposited in Person caves, and where Young (1986) noted how it completely fills numerous sinkholes, shafts, and conduits exposed in Loop 1604 roadcuts. Cave entrances and sinkholes commonly breach this relict surface soil and its underground deposits to effectively recharge the aquifer. However, the intact terra rossa and subsurface deposits have diminished the permeability of some upland areas between the open sinkholes and caves. The terra rossa-enhanced epikarst in these areas apparently stores more water than other local soil types, but the permeability is so low that little appears to be released into the bedrock.

Away from the Crawford and Bexar soils are Tarrant and Brackett soils which mainly overlay the Kainer Formation, Austin chalk, and the upper member of the Glen Rose. While these soils are poorly permeable, they lack sufficient thickness and lateral extent to retard groundwater recharge. Substantial surface water readily enters the limestone formations to recharge their local aquifers, even supporting perennial springflows in very steep and less permeable terrain such as that of the upper Glen Rose. Recharge along the highly permeable fractures of the Kainer Formation is especially impressive when water is observed streaming and even thundering into caves within 30 minutes of rainfall from fractures that show little or no evidence of solutional enlargement at the surface.

This rapid and nearly unimpeded recharge along fractures illustrates the region's largely underdeveloped epikarst. Further evidence is that active dripstone ***speleothems*** seldom occur near the surface, although they were probably active within the past 100 years when there was sufficient epikarstic storage. Since that time, settlement and overgrazing removed the remaining vestiges of soil left from or developed since the erosion of the terra rossa. Currently, most vadose groundwater is stored well below the epikarst within and along fractures, bedding plane partings, and other minor voids within 5-15 m from the top of the water table or major groundwater perching horizon (such as the Regional Dense Member in the Edwards Limestone). This water usually appears in caves as seeps, drips, or moisture on cave walls, and provides the baseflows of some cave streams (e.g. Isopit, Figure 24). There are presently insufficient data to calculate this vadose storage or assess its fluctuations with recharge in any of the karstified rocks in Bexar County.

<u>Synthesis of Factors Affecting Cave Development</u>

Based on the previous sections, several conclusions can be drawn about the factors controlling cave development in the San Antonio region.

Lithologic Factors:

1) The Kainer Formation and the upper member of the Glen Rose are hydrologically interconnected down to at least 38 m below the contact. Marly, dolomitic, and nodular beds retard downward groundwater flow and promote lateral flow along more soluble units in the Kainer's Basal Nodular member and in the upper Glen Rose. Conduits formed along these units serve to integrate groundwater flowpaths until breached by surface erosion to create springs. 2 For 1 Spring and 2 For 1 Cave (Figure 22) are an excellent example of an aquifer conduit that was recently truncated by an incising valley. The Kainer-Glen Rose contact becomes less permeable westward, but a high degree of fracturing maintains good interformational permeability throughout the study area. While permeability decreases with depth into the Glen Rose, cave and spring development within the upper member suggest potential for interformational flow as deep as 55 m below the contact. The abandoned cave springs and the lack of other springflow along Helotes Creek near the Haby Crossing Fault suggests groundwater in the upper Glen Rose is migrating deeper into the formation and is probably crossing the fault into the Edward Limestone.

2) Caves or portions of caves in the Dolomitic, Grainstone, and Regional Dense members of the Kainer and Person formations develop as shafts (e.g.

Genesis Cave, Figure 16). These units are largely ***homogeneous*** and thick-bedded with few significant insoluble beds to perch groundwater.

3) There are no preferential horizons of cave development in the Leached, Collapsed, Marine, and Cyclic members of the Person Formation. These members are thin- to thickly-bedded with scattered chert beds, clay seams, and other lithologic features which perch groundwater and develop passages at many levels. These same features promote the development of solution sinkholes on the Person Formation as discovered by Veni (1985). No significant sinkholes are known from the Kainer Formation due to its greater fracture permeability which limits overland runoff that would create sinkholes (Veni, 1987).

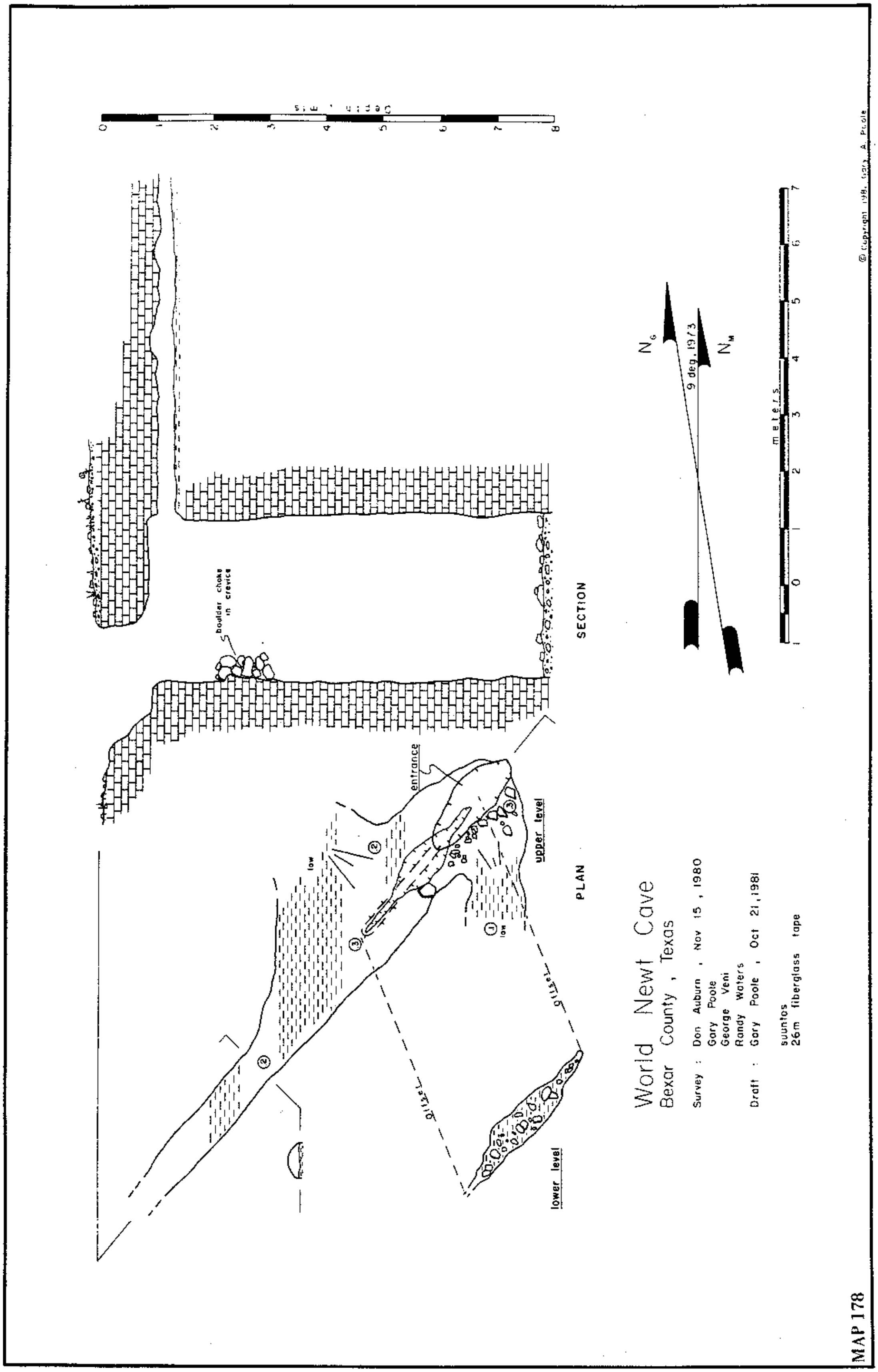
4) There are insufficient data to fully assess cave development within the Kainer's Kirschberg member. Few caves are known from the unit, mostly because of its limited exposure in the study area. A preferential zone of passage development may exist within the upper third of the unit, but additional data may prove it cavernous throughout and thus similar to the Person members.

5) The Regional Dense member promotes local perching of groundwater and associated cave development within the basal portion of the Collapsed member. Groundwater and passages are seldom perched for more than 100 m before intersecting a fracture that drops the cave and water down into the Kainer Formation (e.g. Genesis Cave, Figure 16).

6) The formations of the Austin Chalk Group are not mapped in Bexar County, but the gross stratigraphic position of its caves indicates extensive development in the Dessau and Vinson, and little development within the Atco. The non-cavernous zone located 24-29 m below the top of the Austin probably marks the Dessau-Vinson contact.

7) The Austin Group thickens and changes in lithology westward, affecting cave morphology. The caves on the Culebra Anticline are relatively simple recharge caves (e.g. World Newt Cave, Figure 26); some contain stream passages (e.g. Isopit, Figure 24) and minor floodwater maze development (e.g. Wurzbach Bat Cave, Figure 25). In contrast, caves of the Alamo Heights horst are network mazes formed by vadose seepage down joints in overlying non-cavernous strata. Veni (1988) described the seepage as coming through the Pecan Gap Chalk at Robber Baron Cave (Figure 23), but subsequent closer study has shown that the Pecan Gap does not occur in the entrance sinkhole and over the cave as previously believed. Since the Pecan Gap has also been recently eroded off cavernous areas on the Culebra Anticline where such mazes have not been found, it is not the likely cause of the network development. The clayey, non-cavernous upper 10 m of the Austin in the Alamo Heights horst, which is not present on the Culebra Anticline, is the probable cause of the extensive maze formation. The lateral extent of these mazes is not well understood since most Alamo Heights area caves have been sealed by urbanization. Of the significant open caves, The Labyrinth is poorly explored, and passages in Robber Baron were intentionally collapsed by commercial development in the late 1920's. Historical data and other reports indicate Robber Baron Cave stretched as a complex maze at least 1.4 km southwest and over 300 m east of its current 100 m diameter boundaries.

Figure 26 (from Veni, 1988)



Structural Factors:

1) Caves in the San Antonio region are rarely formed along faults. Most caves and passage segments form along joints due to their greater abundance and permeability.

2) Large caves or segments of caves within the Edwards Limestone and the upper member of the Glen Rose Formation preferentially form along joints parallel to Balcones faults. Small caves or segments may develop along less permeable non-Balcones joints. Small caves in steeply dissected terrain will form along fractures oriented down the local potentiometric surface or hydraulic gradient.

3) Caves in the Austin Chalk are strongly joint controlled due to greater permeability and solution along the fractures relative to lateral solution of non-fractured strata. Austin caves appear to form along joints parallel to nearby major Balcones faults and associated secondary joints, although further research on fractures in the Culebra Anticline area is needed to confirm this hypothesis.

4) Fractures in the region are continuous with depth through the various formations. Caves do not preferentially develop along formation- or member-specific fractures.

5) The effect of bedding attitude on cave development in the San Antonio region is not clear due to the low dip of the beds, the limited horizontal extent of most caves, and the overriding effect of fractures and hydraulic gradients.

Hydrologic Factors:

1) Caves within the upper member of the Glen Rose Formation and the Edwards Limestone Group formed during two distinct hydrologic periods. The first period was characterized by slow groundwater movement and a water table at least 60 m above the current floors of major valleys. Caves formed during this period were large, relatively isolated chambers with few significant interconnecting conduits. The second period is the modern Edwards (Balcones Fault Zone) Aquifer regime, characterized by vadose shaft development to recharge a water table located about 60 m below the mean land surface. Caves formed during this modern period have little horizontal extent in the vadose zone; lateral conduit development along the water table is probably extensive, but exploration is often restricted by sediment blockage and water-filled passages.

2) Recently formed Edwards and upper Glen Rose caves along deeply incised stream valleys develop along steep local gradients to discharge nearby upland recharge into those streams. Hydrologically, these caves are poorly connected to adjoining major aquifers.

3) Austin Chalk caves in the Alamo Heights horst predominantly form by diffuse vadose seepage uniformly moving down fractures to create maze networks. Some caves in this area also form by rising artesian water from the Edwards (Balcones Fault Zone) Aquifer, but physical access to study their morphology is rare and limited.

4) Interformational flow occurs between the Austin Chalk Aquifer and the Edwards (Balcones Fault Zone) Aquifer. The discharge of Edwards water into and from Austin springs, wells, and caves has been recognized for years. Recent

groundwater pollution incidents demonstrate that Austin groundwater also flows into the Edwards. More research is needed to quantify the volume, rate, and locations of Austin to Edwards flow.

5) Epikarst is poorly developed in Bexar County. Most soils have been long removed by erosion so surface water rapidly enters the cavernous formations along permeable fractures. Most vadose water is stored in minor fractures and voids from the water table upwards for 5-15 m.

6) Remnant terra rossa soils occur mainly on the Person Formation, and can locally restrict groundwater recharge by filling caves, sinkholes, and fractures with their poorly permeable clays. However, runoff from these soils often recharges the local aquifer by entering nearby caves and sinkholes, which breach the terra rossa in numerous locations.

<u>Cave Evolution and Faunal Speciation</u>

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 endangered or potentially endemic species requires an analysis of their cavernous habitat and its geologic evolution.

<u>Geologic Evolution of the San Antonio Region Karst</u>

The geologic history of the San Antonio region's karst begins with the deposition of the Edwards and associated formations during the Cretaceous Period (see Appendix E 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. Since Bexar County was on the fringe of the uplift, erosion was limited to the uppermost Person Formation and decreased westward in magnitude. By the Late Cretaceous, 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.

Weeks (1945) determined that major Balcones faulting occurred in the Early Miocene, by which time some streams had incised to near the top of the Edwards Limestone (Ely, 1957). 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 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 which were 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 changed into recharge areas after their flow had been captured; they could not erode their beds as deeply as neighboring streams and now fragments of some of these old waterways are preserved atop drainage divides (Woodruff, 1977 and 1984; Woodruff and Abbott, 1979).

Helotes Area Karst

The absolute ages of the San Antonio region caves cannot be precisely determined within the scope of this investigation, but many will probably correlate to the downcutting of Cibolo Creek and tributaries of the San Antonio River. The phreatic chambers of the Helotes area in the Kainer Formation and the upper member of the Glen Rose are certainly the oldest caves in the San Antonio region, and some may possibly date to the Early Miocene. The caves are relicts of an aquifer that lacked the velocity to develop a well-interconnected conduit system. This type of aquifer system existed in the northern Bexar County area during the time Cibolo Creek began cutting into the Edwards Plateau about 20 Ma (million years ago).

The lower age limit of the phreatic chamber type caves can be estimated by calculating the incision rate of Helotes Creek. Veni (in review) estimates the mean elevation of the Edwards Plateau in the Cibolo Creek and Guadalupe River watersheds was 685 m above modern sea level prior to Balcones faulting. Assuming this was also the mean elevation along the southern margin of the Cibolo drainage basin, Helotes Creek had to downcut 380 m to its current elevation near the phreatic chambers. Helotes Creek is a north-to-south stream oriented perpendicular to the Balcones Fault Zone, and since streams prior to faulting flowed west-to-east, the creek began to form 20 Ma with the onset of fault movement. An average stream incision rate of 19 mm/ky (thousand years) is thus calculated for the creek. For the phreatic chambers to form, the local ***base level*** (approximated by the base of the creek) had to be at least as high in elevation as the highest chamber. The ceiling in Madla's Drop Cave is the highest known phreatic feature relative to the creek, with an elevation difference of 68 m. Dividing the elevation difference with the incision rate gives an age of 3.58 Ma as the youngest possible age for the caves.

The broad age range of 3.58 to 20 Ma for the age of the phreatic chambers can be narrowed by observing that the larger and slightly oval to linear phreatic chambers in Bexar County occur in the Helotes area. This distribution suggests formation during the late Pliocene as local groundwater slowly converged on the deepening Helotes, San Geronimo, and Government Canyon valleys. Within the scope of this study an exact upper age limit cannot be determined, but as an approximation, the caves probably formed about 3.58 to 6 Ma.

As Cibolo, Helotes, and other creeks cut deeply into the plateau margins, groundwater drained out of the phreatic chambers. Substantial collapse occurred within most of these chambers as they lost the buoyant support of water; any vadose features developed during the water withdrawal were hidden by the ***breakdown***. However, vadose caves began to develop as favorable solution zones were eroded and exposed to recharge; within the upper Glen Rose, perched and modern phreatic conduits formed to channel that water to springs forming in the valleys. Erosion truncated and obliterated some phreatic chambers and vadose caves. Some modern phreatic conduits were also intersected by valley erosion, possibly because their water discharged upward into streambeds, indicating the water table may not have always been below the creekbeds as it is today. Of the vadose and spring caves that were not cut by erosion, few grew to an appreciable size since continued stream incision diverted water to deeper and/or different flow paths. Most vadose- and spring-formed caves in the Helotes area are probably middle to mostly late Pleistocene in age. The origin of Helotes area vadose caves which recharge the Edwards (Balcones Fault Zone) Aquifer is the same as recharge caves in the Stone Oak area discussed below.

Stone Oak Area Karst

Phreatic chambers in the Stone Oak area are probably contemporaneous with those in the Helotes area. However, less groundwater circulation kept these caves smaller and more circular in shape, suggesting a less prominent flow gradient. The lack of large phreatic chambers near Cibolo Creek is likely due to its greater incision rate of 39.4 mm/ka (Veni, in review) which would decrease the time available to develop chambers of any great size. The large phreatic passages of Natural Bridge Caverns and Bracken Bat Cave, located about 3 km east of Cibolo Creek and outside of the study area, probably formed by groundwater piracy along joints that cross a meander loop.

Vadose caves of the Stone Oak area are of recent origin and relate to development of the San Marcos and Comal Springs. Maclay and Land (1988) show that most recharge in the area flows to the San Marcos Springs and some to Comal. Prior to the springs' establishment or their capture of Stone Oak groundwater, circulation was slower and the potentiometric surface was substantially higher, minimizing the thickness of the vadose zone. When the springs formed and captured groundwater from the Stone Oak area, the water table dropped dramatically to create a thick vadose zone; the faster circulation also channelized water away from the recharge sites to develop passages along the water table. From the time vadose caves began to form, the water table has continually remained below the bed of Cibolo Creek, as indicated by the minimal horizontal cave development and absence of significant paleosprings along the Cibolo's reach through the Edwards outcrop.

The timing of this episode is probably middle-late Pleistocene, but as yet no one has well-dated the origin of the San Marcos and Comal Springs. Some estimates of minimum cave age can be made from records of vertebrate remains found in cave sediments. Most fossils from Balcones Escarpment caves date from about 30 ka (thousand years ago) to the present (Lundelius, 1986), and the oldest known in Bexar County were found in Friesenhahn Cave and date to about 20 ka

(Graham, 1976). Abbott (1984) places the earliest opening of the Balcones caves to the surface during the Sangamon interglacial (120-140 ka) based on microfossils from a cave in the city of Austin.

The small size (relative to human exploration) of many Bexar County recharge caves is due to their recent development, competition with numerous alternative high permeability flow routes, access limited by sediment occlusion, and basal locations along the water table. None of these factors significantly restricts vadose or phreatic groundwater movement.

Alamo Heights Area Karst

Determining the age of this area's Austin Chalk cave development is difficult due to the lack of supporting research and constraining factors. Minor caves in the area are formed by backflooding of Olmos and Salado creeks, and are certainly no older than late Pleistocene; other minor caves formed by artesian waters, possible as early as the mid-Pleistocene. In contrast, the large network maze caves have few and only recently deposited faunal remains, sediments that are largely unexamined, and no isotopic datings of speleothems.

The only available factor that will constrain the period of cave development is the downcutting of Olmos and Salado Creek, which respectively delimit the western and eastern boundaries of the Alamo Heights horst. The beds of the creeks are roughly 20 m below the uppermost solutionally developed ceiling in Robber Baron Cave. These streams are similar in origin to Helotes Creek and since there is insufficient information to determine their incision rates, the 19 mm/ky rate of Helotes Creek will be used as an approximation. Consequently, the water table in the Austin Chalk Aquifer would have been near the upper solution limit of Robber Baron Cave about 1.05 Ma. The cave's vadose maze development would have initiated at that time as water levels descended, and would have certainly been active when the water table was at the mapped base of the cave about 526 ka. Recent discoveries of passages below this level have not been geologically examined, but may include phreatically formed passages. The sinkhole entrance to the cave is probably terminal Pleistocene or Holocene in age.

Culebra Anticline Area Karst

Two similar phases of cave development occur in the Austin Chalk of the Culebra Anticline. Both phases involve recharge of the Austin Chalk Aquifer with the development of major insurgences at the contact of cavernous and non-cavernous strata, and of stream conduits along the water table. The first phase is seen at the Stevens Ranch caves near the Medina County line, and the second phase involves the caves clustered around Wurzbach Bat Cave and Isopit about 3 km to the east.

The Stevens Ranch Caves are among the youngest in Bexar County. They are recharge caves and underlay the area where the Pecan Gap Chalk has recently been stripped by erosion. Caves near the contact (Stevens Ranch caves nos. 1 and 2) capture significant recharge flowing off the Pecan Gap. Groundwater is perched along the probable Dessau-Vinson contact.

The Wurzbach-Isopit area caves are also recently developed recharge caves located below a low permeability horizon, in this case the probable Dessau-Vinson contact. Their water enters well defined stream conduits along the probable

Vinson-Atco contact, but there is insufficient information to determine if this is the true water table or if it is also lithologically perched. The size and morphology of Wurzbach Bat Cave suggest it initially formed in the Vinson Formation as a phreatic lower level to an upper level in the Dessau; the upper level probably formed when the Pecan Gap was first eroded from that location, and its morphology and hydrology were likely similar to Stevens Ranch Cave No. 2. Wurzbach's open lower conduits allowed it to develop another large drainage basin when its upper Dessau levels were lost to erosion.

So except for Wurzbach Bat Cave which overlaps both phases of cave development, both the Stevens Ranch and Wurzbach area cave groups are recently formed and probably date to the late Pleistocene. There is no information on Culebra Anticline erosion rates to estimate the time when Wurzbach first formed.

Interstitial Zones

Most of this report has focused on the caves of the San Antonio region, only touching on the existence and importance of the interstitial zone during the discussion of epikarst. 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 contribute 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 associated with epikarstic solution of 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 San Antonio 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 (e.g. Veni and Associates, 1988). Such an assessment requires a detailed survey of the cave, measurement of its interface with the interstitial zone, and consideration of the epikarst, 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 to be generally less than 1 mm in the Georgetown Limestone, which is not known to have a cavernicole fauna, 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, both relatively shallow and deep, have been encountered during San Antonio 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 a low permeability strata or a thick, intact deposit of terra rossa.

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 the foci of nutrient and water input into the subsurface and thus are the 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 San Antonio Region Karst

The distribution of cave fauna in the San Antonio region, including the species petitioned for endangered listing, is discussed by James R. Reddell (1993) in a companion report to this study. The following discussion considers the region's specific geologic barriers to the distribution of troglobites based on spatial analyses of 19 troglobite species. Although other troglobites are also known, these species are limited to Bexar and eastern Medina County and are better indicators of barriers or avenues to species migration. Table 10 lists the 19 species and their relative degrees of troglobitic development (i.e. physiologic adaptation to being obligate cave dwellers). The following analyses are based on all 19 species, not just the petitioned species, since reasons for petitioning and for endangered listing often include consideration of factors that have no bearing on their natural distributions (e.g., human activities which threaten species' survival).

The following discussion frequently uses the terms "migration," "barrier," and "restriction." Most troglobites in the region do not individually move far from where they were born, thus migration is used here to describe the gradual, long-term movement of troglobite populations beyond the area where they originally developed. 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 outcrop of cavernous rock connecting the UTSA and Government Canyon area, or temporal, when the intermittent drying of some streams allows the migration of terrestrial troglobites.

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.

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

Geologic barriers to the migration of troglobites are lithologic, structural, or hydrologic. The primary lithologic barrier is the simple lack of cavernous rock, but others include impermeable layers within an otherwise cavernous sequence. Structural barriers are usually coupled with lithologic 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 following analysis of Figures 27-33 examines only the distribution of terrestrial troglobites.

The areas where it is easiest to define zones of limited cavernicole distribution are isolated hills or "islands" of limestone, such as those north of the town of Helotes. Beyond this type of area the distribution of species becomes more subtle and complex.

Figure 27 is a schematic representation of the San Antonio region illustrating six 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 Helotes area. The karst areas are numbered 1-6 and are keyed to Table 11, which includes area descriptions. Figure 28 has the actual outlines of each area.

Figures 29-33 illustrate the distribution of the 38 troglobites in the San

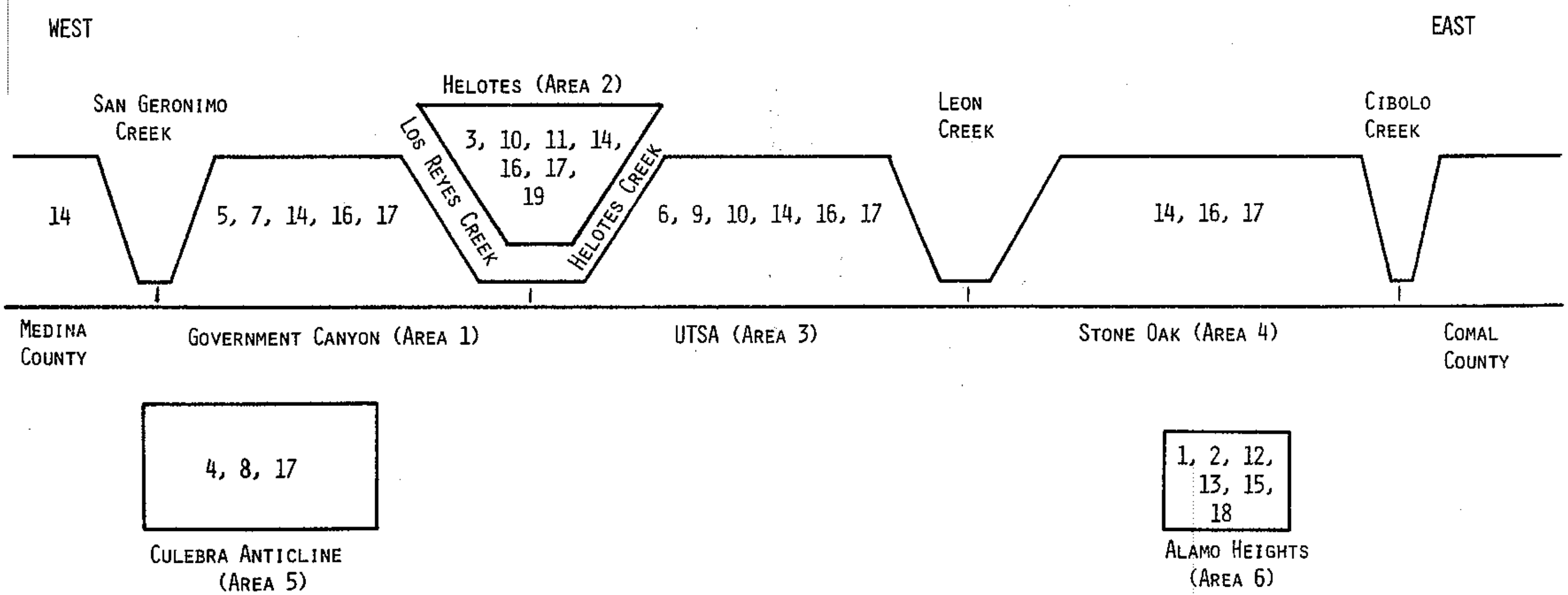


Figure 27: Schematic of San Antonio region karst areas and distribution of troglobites (species numbers keyed to Table 10).

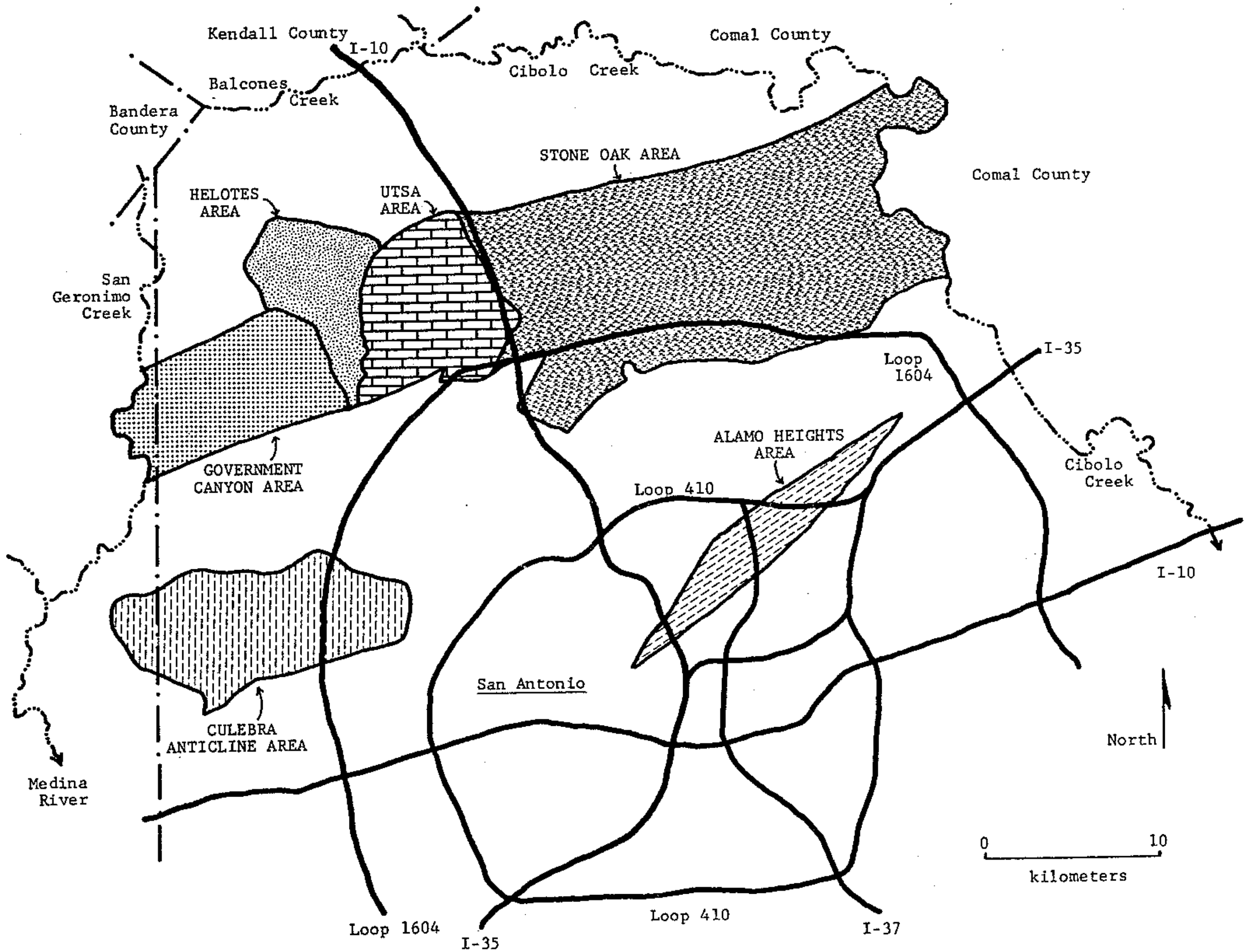


Figure 28: San Antonio karst areas.

Distribution of Troglobites in the San Antonio Region

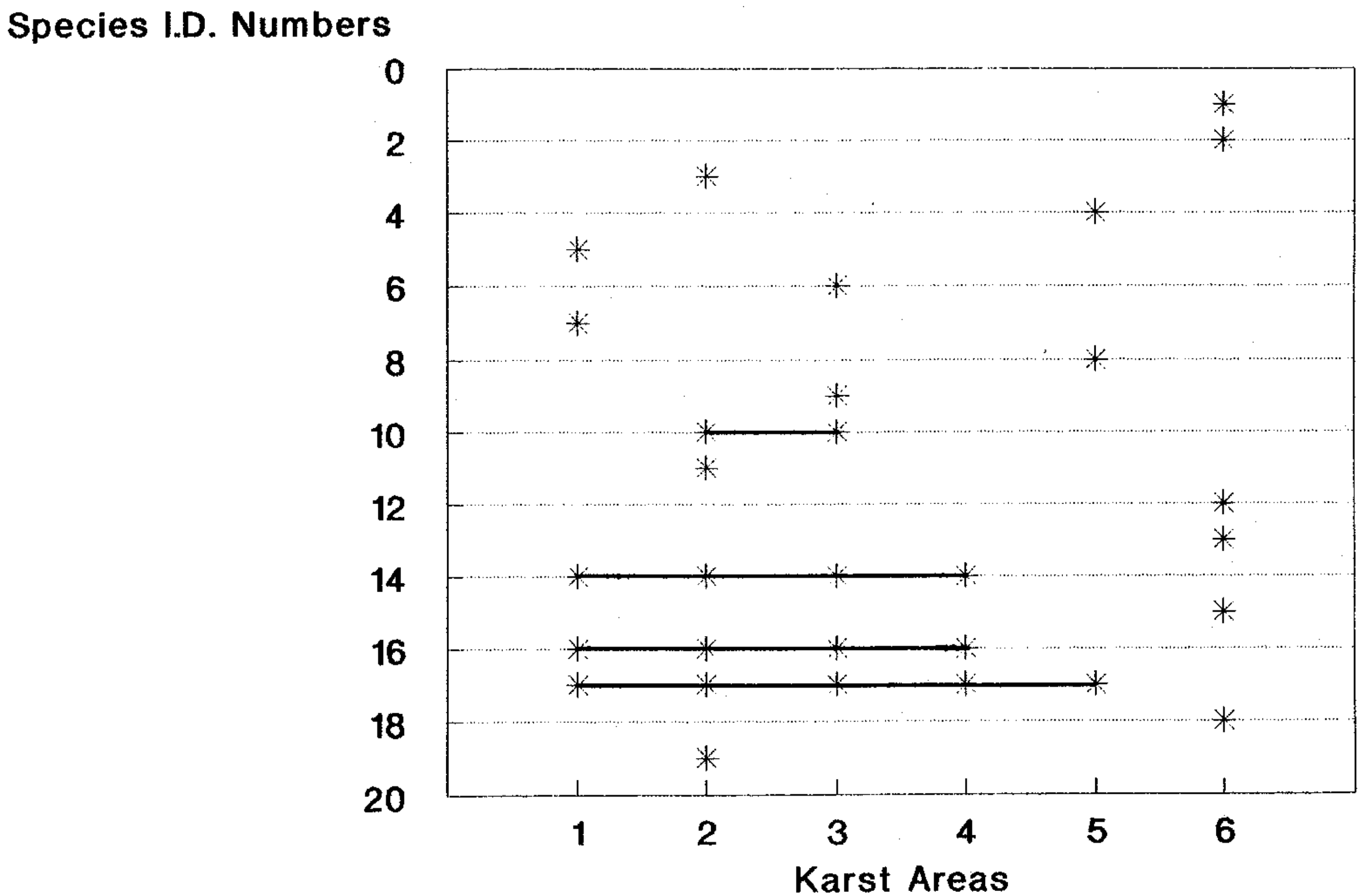


Figure 29

Troglobite Species Shared by Karst Areas of the San Antonio Region

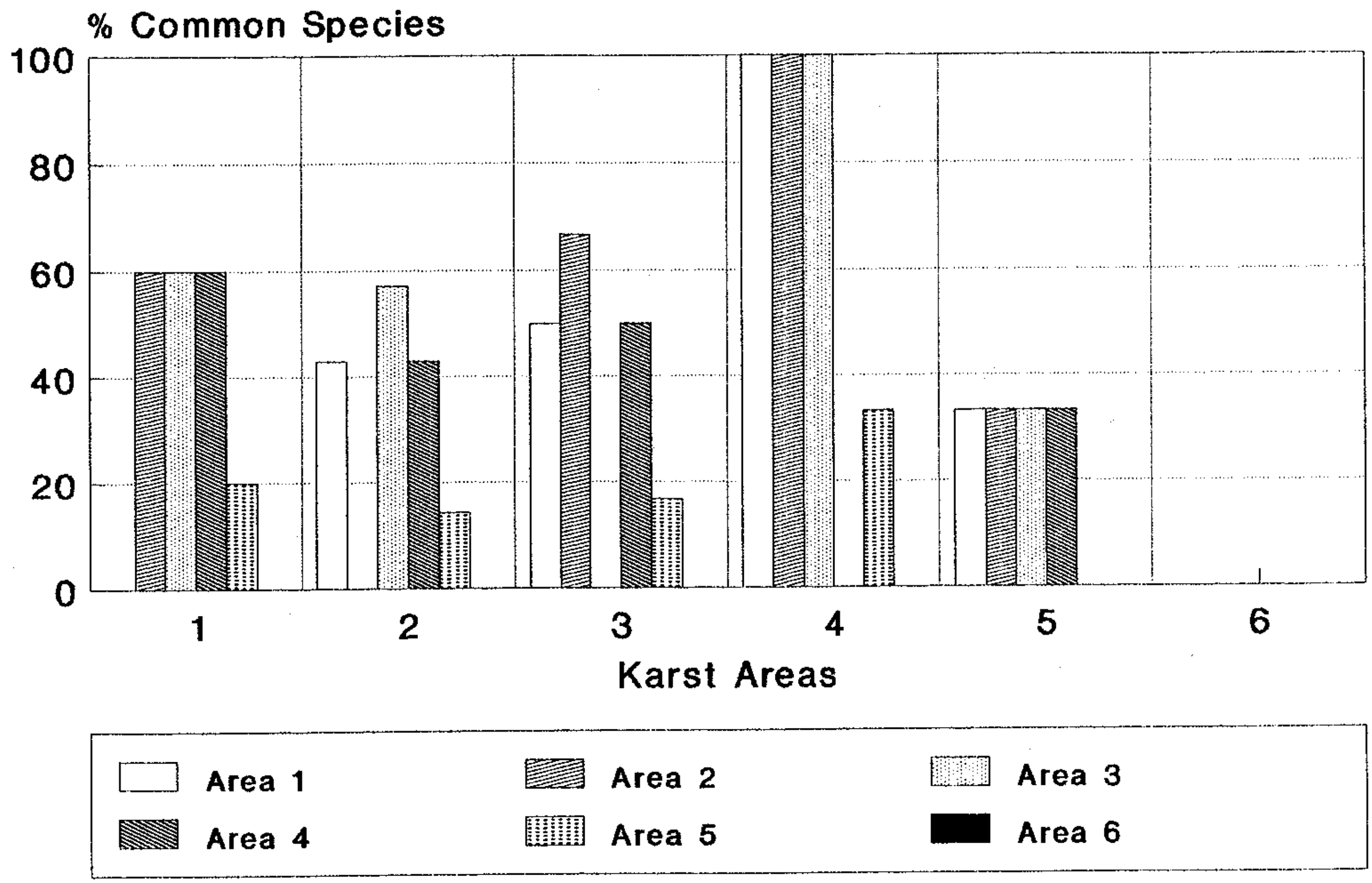


Figure 30

Average of Shared Troglobites in Karst Areas of the San Antonio Region

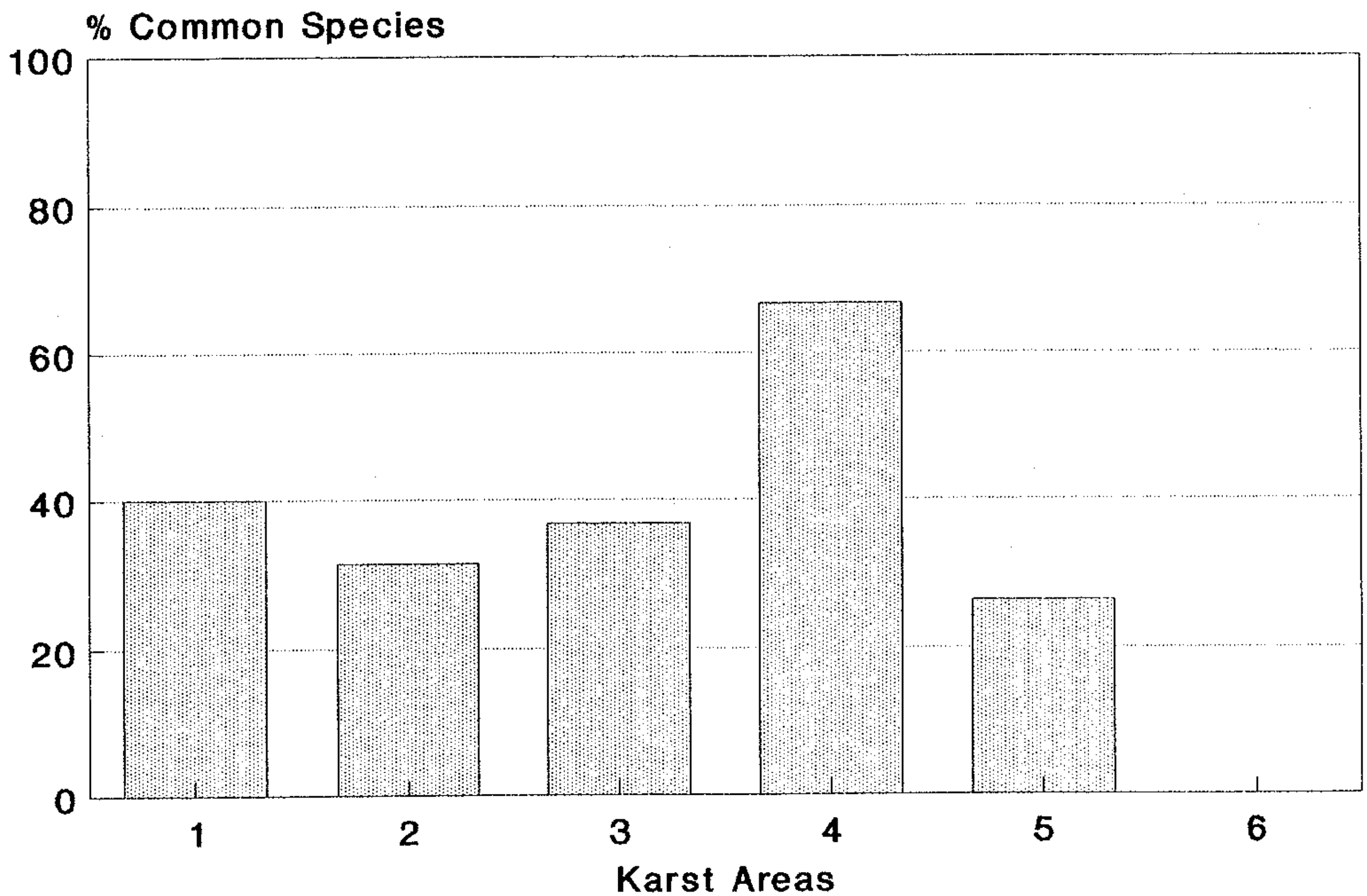


Figure 31

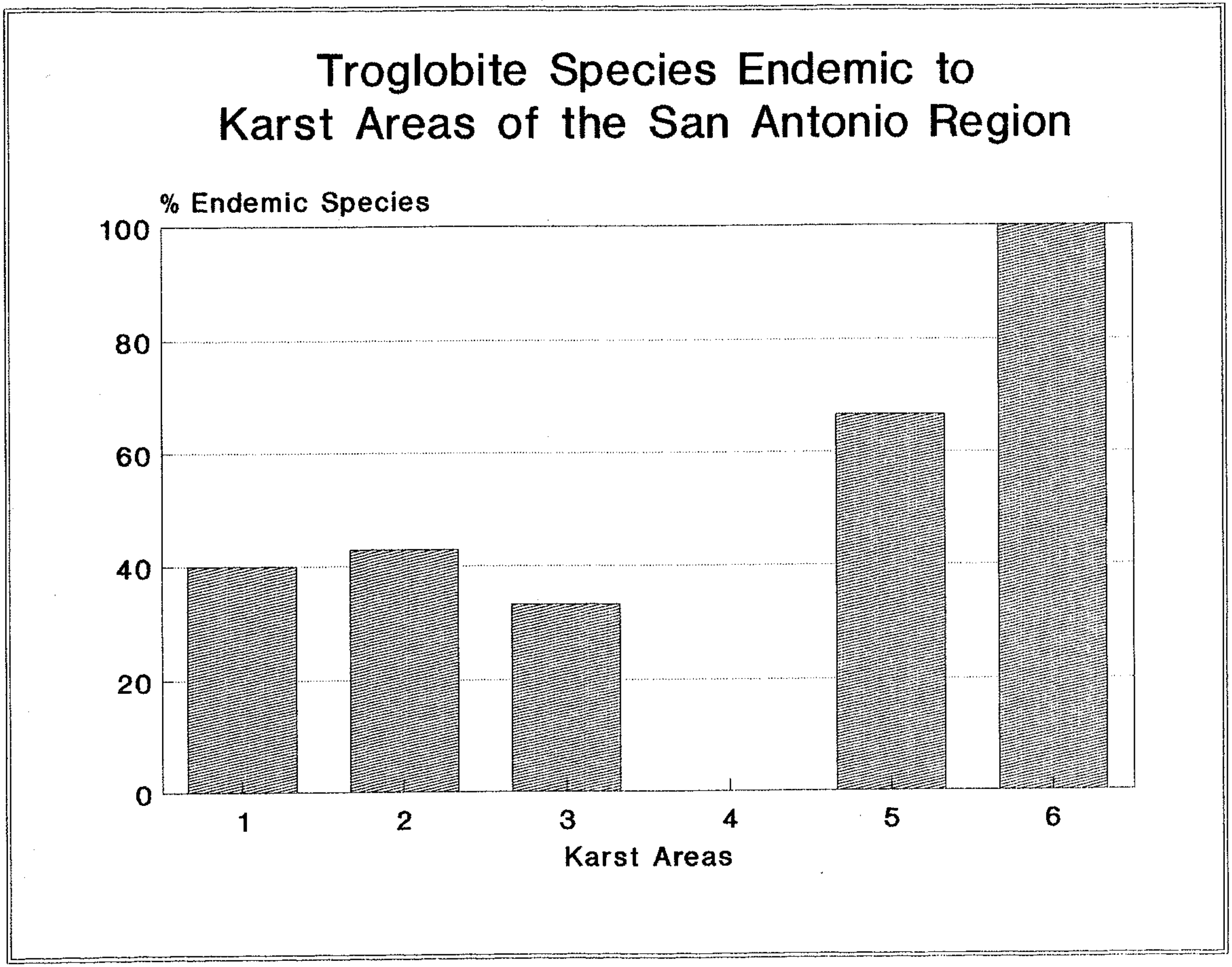

Troglobite Species Endemic to
Karst Areas of the San Antonio Region
% Endemic Species
100
80
60
40
20
0
1
2
3
4
5
6
Karst Areas

Figure 32

Antonio region. Figure 29 shows the specific species that occur in each karst area; connecting bold horizontal lines correlate their mutual presence among areas. The lack of connecting lines for a species indicates it restriction 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 migration. Areas that are crossed by some lines and not by others reflect developing or recently developed barriers where insufficient time has passed for speciation of all troglobites listed in Table 10.

Figures 30 and 31 illustrate the percentage of species each area has in common with other areas. Shown in Figure 30 are the specific comparisons of shared species that each area has with each of the other areas. Figure 31 is an average of all the comparisons obtained by summing the Figure 30 percentages and dividing by 5, the number of neighboring karst areas. Figure 32 provides a similar but somewhat "mirror image" view to faunal distribution by plotting each area's percent of endemic species. As will be discussed in further detail in the following pages, areas that have a relatively low percentage of species in

Table 10

TROGLOBITES OF THE SAN ANTONIO REGION ANALYZED IN FIGURES 27-33*

No.	Species name	Troglobitic development
1.	Trichoniscidae ?new genus and species	high
2.	*Cicurina (Cicurella) baronia* Gertsh	high+
3.	*Cicurina (Cicurella) madla* Gertsch	high+
4.	*Cicurina (Cicurella) venii* Gertsch	high+
5.	*Cicurina (Cicurella) vespera* Gertsch	high+
6.	*Neoleptoneta* new species	low
7.	*Neoleptoneta microps* Gertsch	low+
8.	*Tyrannochthonius* new species	low
9.	*Tartarocreagris* new species	low
10.	*Texella* species 1	high
11.	*Texella* species 2	low
12.	*Texella cokendolpheri* Ubick and Briggs	high+
13.	*Theatops* new species	high
14.	*Speodesmus* new species 1	high
15.	*Speodesmus* new species 2	high
16.	*Rhadine exilis* (Barr and Lawrence)	high+
17.	*Rhadine infernalis* (Barr and Lawrence)‡	medium+
18.	*Batrisodes* new species	medium
19.	*Batrisodes (Excavodes) venyivi* Chandler	medium+

* Data from Reddell (1993).
\+ Denotes petitioned for federal listing as an endangered species.
‡ The subspecies are not considered pending further study and clarification of the taxonomy (recommendation by James R. Reddell).

Table 11

SUMMARY DESCRIPTION OF SAN ANTONIO REGION KARST AREAS, DELINEATED IN FIGURES 27-28 AND ANALYZED IN FIGURES 29-33

No.	Karst area	Descriptions and boundaries
1.	Stone Oak	Includes the outcrops of the Edwards Limestone and the upper member of the Glen Rose Formation. Bounded to the north by Cibolo Creek and the contact with the lower member of the Glen Rose, to the east by Cibolo Creek, to the south by Balcones faults, and to the west by Leon Creek and intense faulting which narrow the Edwards outcrop. Faulting is moderate to intense.
2.	UTSA	Includes the outcrop of the Edwards Limestone, and the immediate down-slope outcrop of the upper member of the Glen Formation where the Edwards-Glen Rose contact is exposed. Bounded to the north by the interstream limit of the outcrops, to the east by Leon Creek and the intense faulting which narrows the Edwards outcrop, to the south by Balcones faults, and to the west by Helotes Creek and the Haby Crossing Fault which narrow the Edwards outcrop. Faulting is intense.
3.	Helotes	Bounded by the Haby Crossing Fault to the south, Helotes Creek to the east, Los Reyes Creek to the west, and the upper limits of the creeks' watersheds to the north. Includes isolated outcrops of Edwards Limestone on hilltops, and outcrops of the upper member of the Glen Rose. Faulting is moderate to intense.
4.	Government Canyon	Includes the outcrop of the Edwards Limestone and the immediate down-slope outcrop of the upper member of the Glen Rose Formation. Bounded to the north by a major fault, to the east by Los Reyes Creek, to the south by the Haby Crossing Fault, and to the west by San Geronimo Creek. Faulting is moderate.
5.	Alamo Heights	Includes the outcrop of Austin Chalk and Pecan Gap Chalk bounded within the horst beginning near San Pedro Park in San Antonio, and which heads northeast to where it pinches out near O'Conner Road roughly midway between Nacogdoches Road and Interstate Highway 35. Faulting is little to moderate.
6.	Culebra Anticline	Includes the outcrops of the Austin Chalk and Pecan Gap Chalk along the Culebra Anticline, extending west from Culebra Creek to the end of the outcrops about 3 km into Medina County. Faulting is little to moderate.

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 San Antonio region is needed and will modify the numbers of Figures 29-32, the level of detail among existing biospeleologic investigations suggest that most of the current figures will remain as adequate approximations.

Area Analyses

AREA #1, GOVERNMENT CANYON:

This is one of the two least studied karst areas in Bexar County. Up until the August 1993 purchase of a large tract by the Texas Parks and Wildlife Department, nearly all of the land was closed to cave study and exploration. The species distribution assessment of this area is based solely on Government Canyon Bat Cave, and further biologic study should be conducted on other area caves to refine the following results. San Geronimo Creek may significantly restrict species migration westward into Medina County. One species (*Speodesmus* n. sp. 1) is known from a cave west of the creek, and none of the 19 San Antonio region species are known to occur west of the Medina River, which is certainly a major barrier to species migration. The effectiveness of San Geronimo Creek at restricting species migration requires study of more caves in the Government Canyon area, and of the area between the creek and the Medina River.

The Government Canyon area's northward limit of the Edwards Limestone outcrop and of the upper cavernous section of the upper member of the Glen Rose is an effective barrier to troglobite species. Figure 30 illustrates the Haby Crossing fault and intervening poorly-cavernous strata nearly isolate the area from the Culebra Anticline area to the south. Helotes and Los Reyes creeks restrict eastward migration of species from the Government Canyon area. Forty percent of the Government Canyon species are endemic to that area, while 43% and 33% of species are endemic to the adjacent Helotes and UTSA areas respectively (Figure 32). The presence of three species that are common to all three areas indicates the creeks and their associated faulting do not fully prevent troglobite migration.

AREA #2, HELOTES:

This area has the greatest number of species of the 19 listed for the San Antonio region. As discussed above, 43% are endemic to the area and the rest can be found in the karst areas to the east, west, and south (Figure 28). However, Los Reyes Creek apparently restricts troglobite migration more than Helotes Creek since 43% of the Helotes species occur in the Government Canyon area while 57% occur in the UTSA area (Figures 27, 29 and 30). On average, cavernous strata on opposite sides of the Los Reyes valley are about twice as far apart as in the Helotes valley, suggesting an earlier division of the ancestral cave species. Study of additional Government Canyon area caves is needed to confirm the percentages and this hypothesis.

An analysis of species distribution among individual Helotes area caves (based on data from Reddell, 1993) was conducted to determine if a lithologic barrier existed between caves in the Edwards Limestone and the upper Glen Rose. Except for animals known from single locations, the area's species occur throughout both units, and no evidence of a lithologic restriction is present.

Even Christmas Cave, situated between 27-35 m below the base of the Edwards Limestone (Figure 5, Table 4) has four species that are also found in Edwards caves in the Helotes area. These results support the conclusion stated earlier in this report, that in the San Antonio region there is hydrologic continuity between the Edwards Limestone and the upper 38 m of the upper member of the Glen Rose Formation.

AREA #3, UTSA:

Like the Government Canyon and Helotes areas, the UTSA area has a northward barrier to troglobite migration along the limit of cavernous strata in the Edwards Limestone and upper member of the Glen Rose. To the west, Helotes Creek restricts migration as described in the previous two sections. To the east Leon Creek poses another significant restriction as only 50% of the UTSA troglobites occur in the Stone Oak area (Figures 27, 29 and 30).

The presence of *R. infernalis* in caves of the Culebra Anticline area is probably due to the fault-juxtaposed position of the Edwards Limestone with the Austin Chalk in the southwestern portion of the UTSA area. Although the Edwards-Austin contact is more extensive along the southern boundary of the Government Canyon area, the Austin is too faulted, stream-dissected, and covered to provide as efficient a migratory path as from the UTSA area. Since the boundaries of the Culebra Anticline area are based on the presence of known caves, they do not include the entire portion of the Austin outcrop and exclude the section abutting the Edwards Limestone where sufficient conduits are apparently available for the migration of some troglobites.

AREA #4, STONE OAK:

All three troglobites identified in the Stone Oak area also occur in other areas. Figures 29 and 30 show that this area has all of its species in common with the Helotes, UTSA, and Government Canyon areas, and one-third with the Culebra Anticline area. However, the lack of endemic species in the area (Figure 32) may be the result of insufficient study. Only five caves could be visited during Reddell's (1993) biologic survey, two of which were overrun by fire ants; previous biologic collections described by Veni (1988) were generally not fully representative of the area's cave fauna.

Analysis of Reddell's (1993) species lists for individual caves in the Stone Oak area shows no restrictions to species migration between the Person and Kainer Formations of the Edwards Limestone Group. To the north and south, the area has troglobite boundaries defined by the limits of cavernous strata. In contrast, while cavernous units extend to the east and northeast into Comal County, Cibolo Creek is an apparent barrier to troglobite migration. None of the 19 San Antonio region species are known on the east side of the creek. *Rhadine speca*, known to live in several Comal County caves, does occur in Poison Ivy Pit, but Reddell (personal communication, 1993) believes it may be an undescribed subspecies that is isolated from other *R. speca* east of Cibolo Creek. The creek's major restriction to species migration supports the model proposed earlier in this report, that Edwards Limestone caves in Bexar County adjacent to the Cibolo formed primarily as vertical vadose conduits with minor horizontal development above the modern water table.

AREA #5, CULEBRA ANTICLINE:

Only three of the 19 troglobite species occur in the Culebra Anticline area and two are endemic (Figures 27, 29, 30, and 32). The area is largely isolated by faulting, the incision of Culebra, Helotes, Leon, and San Geronimo creeks, and the capping by the Pecan Gap Chalk which may limit cave development and/or nutrient input to underlying caves. The low number of troglobites may also partially reflect the ravaging of many cave populations by fire ants at the time of Reddell's (1993) biologic survey. Additionally, the caves are probably of relatively recent origin and few species may have had time to evolve into troglobites. Of the three known species, only one is an advanced troglobite, while the others are recent and moderately advanced troglobites.

There may be some lithologic restriction to species migration, since all three troglobites occur in the stratigraphically lower group around Wurzbach Bat Cave, while only one species occurs in the stratigraphically higher Stevens Ranch cave group. Since the Stevens Ranch caves are generally younger than the Wurzbach caves, the difference could also represent recent troglobite invasion or evolution in that area.

AREA #6, ALAMO HEIGHTS:

The Alamo Heights and Government Canyon areas are tied as the least biologically studied karst areas in the San Antonio region. All species information for both areas are derived from single caves. Unlike Government Canyon where the lack of study is due to the lack of permission to visit the caves, most caves in the Alamo Heights area have been sealed by urban development. Of the few which remain open, only Robber Baron Cave was available for study.

The trogolobite fauna in the Alamo Heights area is fully isolated from the other karst areas of the San Antonio region. All six species are endemic, and nearly all are highly advanced troglobites suggesting long-term separation from ancestral species held in common with the other areas (Table 10, Figures 27, 29-32). This isolation is primarily from major faulting that resulted in the separation of cavernous strata. Olmos Creek and Salado Creek deeply dissect the area so their effects on troglobite migration is probably significant but currently unproven. Robber Baron Cave is located between the two streams, but no open caves are known south of it and beyond Olmos Creek for comparison; The Labyrinth and Roy's Cave are open and located northeast of Robber Baron and beyond Salado Creek, but the owners would not allow access for study.

Distribution of Aquatic Troglobite Fauna

Little is known of the aquatic troglobite fauna of the San Antonio region, largely because few caves allow human access to the water table. Elm Springs Cave and Twin Pits within the Stone Oak area, and Isopit in the Culebra Anticline area are exceptions, but their relationships to neighboring caves and their local aquifers are not adequately known to make categorical conclusions on their species' distribution. Two species found among these caves (*Cirolanides texensis* and *Stygobromus russelli*) are widespread throughout Texas caves and would be poor indicators of local aquatic troglobite fauna migration. However, while *Eurycea tridentifera* is known from several stream caves in Comal County, in Bexar County it is only known from Elm Springs Cave, its only known occurrence in the Edwards Limestone. This salamander is currently listed by the State of

Texas as a threatened species (Resource Protection Division, 1991), and further study of its occurrence would likely be meaningful in assessing the distribution of troglobite aquatic communities.

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 Medina 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.

Synthesis

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

Geologic and Troglobite Evolution

The Helotes area has the oldest caves in the San Antonio region and is consequently the habitat for the region's most diverse group of troglobites (Table 10, Figures 27 and 29). The Helotes species, as ancestral ***troglophiles*** to the present troglobites, probably originated on the Edwards Plateau and were isolated by development of the Cibolo Creek valley. As more limestone was exposed by erosion and began to form caves in the Balcones Fault Zone, many species migrated east and west to the adjacent karst areas and then south to the Austin Chalk areas. Stream incision began to isolate the areas as gaps in cavernous strata developed.

Isolation of the entire San Antonio region probably began in the early to middle Pleistocene with the incision of the Medina and Guadalupe rivers. During the middle to late Pleistocene, stream valley incision was sufficient to begin restricting faunal migrations and promote speciation between the region's six karst areas. The wetter Pleistocene climates may have also restricted the migration of terrestrial troglobites by raising water levels in the aquifers and eliminating the vadose zones that currently exist under some stream valleys. The eastern boundary of the Stone Oak area along Cibolo Creek was probably the first migration barrier or restriction to develop. The Alamo Heights horst was the first karst area to be isolated, with the Government Canyon, Helotes, UTSA, Stone Oak, and Culebra Anticline areas respectively developing their restrictions at later times.

Summary of Barriers to Troglobite Migration in the San Antonio Region

Troglobite migration in the San Antonio 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 San Antonio karst areas to the south and southeast where the Edwards Limestone and Austin Chalk are buried under younger sediments and have not been exposed to the surface, and to the north where the Edwards and Austin have been removed by erosion. Broader study should confirm that the secondary barriers are the Medina River to the west, and probably Cibolo Creek (if not, then certainly the Guadalupe River) to the northeast. Of the 19 San Antonio region troglobite species, all occur between the Medina and Cibolo.

The most significant restriction to troglobite migration is stream incision into the Edwards and Austin outcrops. San Geronimo Creek may pose one of the greatest restrictions to troglobite migration in the San Antonio region, but there is insufficient sampling of caves from either side of the creek to fully assess its impact. Los Reyes and Leon Creeks are probably equally effective in restricting troglobites, and pending further investigation of fauna adjacent to San Geromino Creek, they must be considered the most important of the restrictions. Helotes Creek is also a major barrier, although not as significant as Los Reyes and Leon Creeks. The degree of troglobite restriction imposed by Culebra, Helotes, and Leon creeks on the Culebra Anticline area, and of Olmos and Salado creeks on the Alamo Heights area cannot be determined until more Austin Chalk caves on either side of each stream are biologically surveyed.

The second and third restrictions to troglobite migration are minor with only localized impact in the San Antonio region. Lithology can restrict migration in sites where poorly permeable and poorly soluble sections of the Edwards Limestone or Austin chalk are exposed at the surface, or where the Edwards is covered with terra rossa. These locales yield few caves and have poorly developed interstitial zones. Caves without entrances that underlie these areas usually have no significant access to nutrients for cavernicole fauna. Locales of this type in the San Antonio region are generally small and beyond the scope of this investigation to individually map and identify. There may be some restriction to migration between the top and middle portion of the Austin Chalk in the Culebra Anticline area, but further research is needed to be certain.

Faults pose the least significant restrictions to troglobite migration, except when they totally isolate sections of cavernous rock such as the Alamo Heights horst. Many faults cross the San Antonio region, and the distribution of troglobites in nearby caves shows no obvious affect. Minor fault restrictions probably occur in some locales and may be evident after the fauna of more caves has been studied.

Summary of Speciation and Endemism in Karst Areas of the San Antonio 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 31 and 32 illustrate the percentage of species distributed between and endemic to the San Antonio region's karst areas. Both figures are needed to assess endemism and are combined in Figure 33 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 contain isolated and speciated troglobite populations due to migration barriers and sufficient time for animal evolution. Negative index values imply that areas have few of the barriers or restrictions to migration which would promote endemism.

The Alamo Heights area (area 6) plots on the index as the area of greatest

Endemism Index: Karst Areas of the San Antonio Region

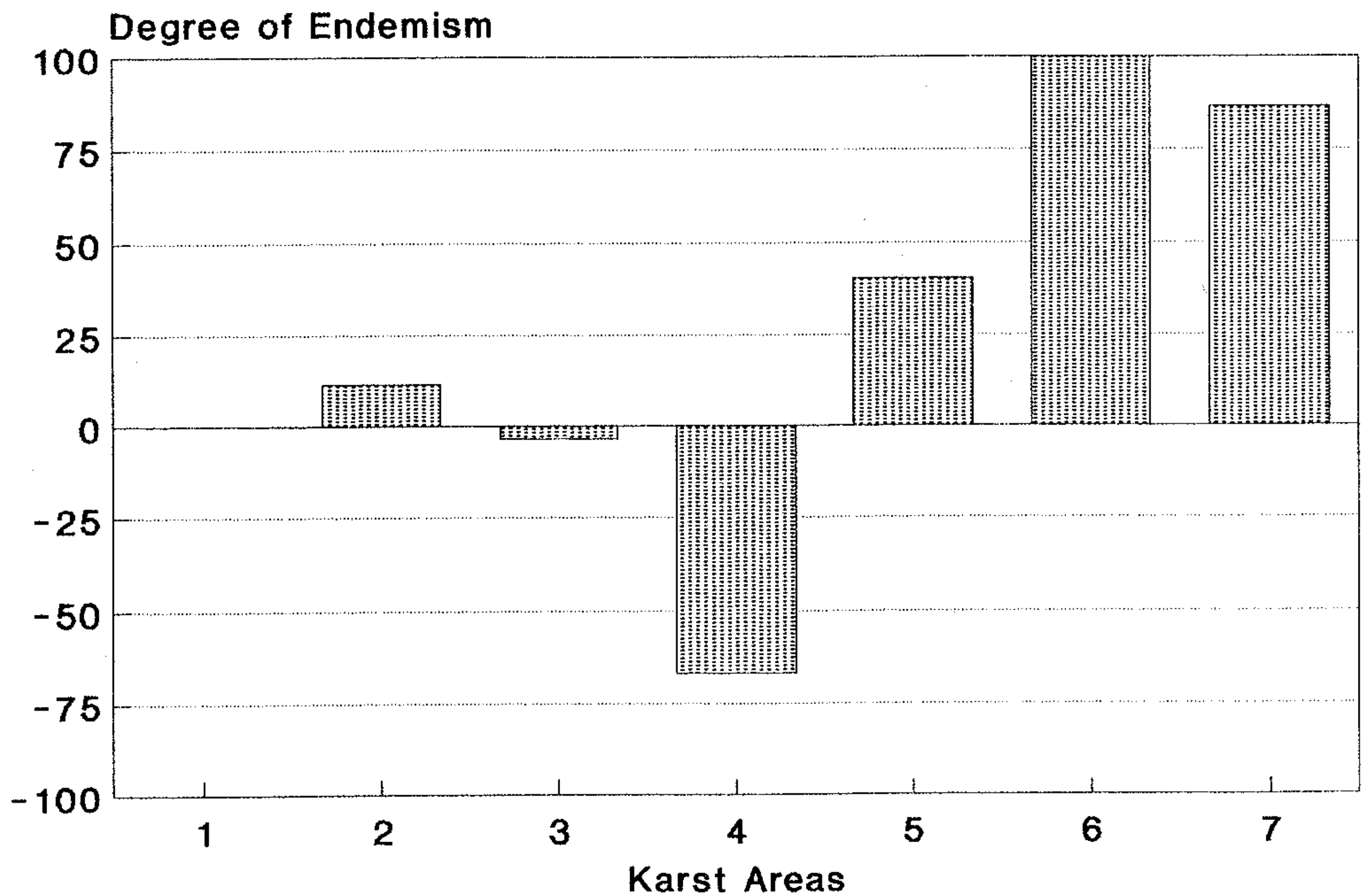


Figure 33

endemism; all of its troglobites listed in Table 10 are restricted to that area (Figure 32), and hence none are found in other karst areas (Figures 30 and 31). In contrast, the Stone Oak area's (area 4) value of -67 indicates no endemism; no troglobites are restricted to this area. The Government Canyon and UTSA areas plot near zero, having a small number of endemic species, while the rest can be found throughout four of the five other karst areas.

The Helotes and Culebra Anticline areas have low to moderate levels of endemism. Helotes is a site of early troglobite development, but restrictions with other areas are insufficient to produce a high endemism value. In contrast, the younger karst of the Culebra Anticline area ranks higher on the endemism index because of its more effective barriers to species migration.

Figure 33's endemism index includes an "area 7" which was not considered in the previous discussions. This area is the combined areas 1-4 which are defined by exposures of the Edwards Limestone and the upper member of the Glen Rose Formation. As demonstrated in the previous paragraphs, restrictions between areas 1-4 are only moderately effective and so the areas lend themselves for consideration as a single unit. As such a unit, area 7 has a high degree of endemism, with only one of its 11 species found in one of the two Austin Chalk areas.

Based on the endemism analysis of this study and similar research near Austin, Texas (Veni and Associates, 1992), 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.

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.

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.

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.

The endemism index provides a means of overall comparison of the barriers and biology of a region's karst areas. As shown with area 7, area boundaries can be redefined and the endemism index recalculated to better delineate the barriers to species migration. The results of this study support the first use of the endemism index by Veni and Associates (1992), and provide greater validity to the above index levels. Nonetheless, pending further application the index levels should only be considered generalities that may be useful in the assessment and management of karst areas and their troglobite 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 San Antonio region, plotted on Figure 33, indicates that all its Edwards Limestone, upper Glen Rose, and Austin Chalk karst areas are speciated zones where endemic troglobites may exist which could qualify for endangered or threatened listing due to their limited distributions.

Troglobites that inhabit non-speciated or less speciated areas (like Stone Oak) are not necessarily ineligible for endangered or threatened listing just because the species occur in neighboring areas to produce a negative index value. Extensive urbanization and other activities could have serious detrimental effects on the cave organisms and the habitats upon which they depend. Conversely, troglobites in areas with high endemism values but under no current threats are unlikely to gain endangered listing; however, no such areas presently exist in the San Antonio region.

<u>Development of Distribution Maps of Endangered Cavernicole Faunal</u>

Cavernicole faunal distribution maps are drawn on 7.5' USGS topographic quadrangles to indicate areas of greater or lesser probability of encountering petitioned or endemic troglobite cave species in the San Antonio 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 E 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.

Five zones are indicated on the maps:

Zone 1: areas known to contain petitioned endemic cave fauna;

Zone 2: areas having a high probability of suitable habitat for petitioned or other endemic cave fauna;

Zone 3: areas that probably do not contain petitioned or endemic cave fauna;

Zone 4: areas which require further research but are generally equivalent to Zone 3, although they may include sections which could be classified as Zone 2 or Zone 5; and

Zone 5: areas which do not contain petitioned or endemic 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 petitioned fauna may reside (except, of course, for Zone 1 where the animals have been observed or Zone 5 which is largely noncavernous rock). The general guidelines in delimiting the zones include the following conditions:

Zone 1: areas where petitioned species are present, and where speleogenetic, hydrologic or stratigraphic factors indicate continuity of the zone's karst and no restrictions to its fauna;

Zone 2: outcrops of the Edwards Limestone, the upper 20 m of the upper Glen Rose east of Leon Creek, the upper 25 m of the upper Glen Rose west of Leon Creek, and the known cavernous areas of the Austin Chalk;

Zone 3: outcrops the upper Glen Rose from 20-55 m below the Edwards Limestone east of Leon Creek, the upper Glen Rose from 25-55 m below the Edwards Limestone west of Leon Creek, the Buda Limestone, the Pecan Gap Chalk, areas of the Austin Chalk where caves are not known, and alluvium-covered outcrops of the upper Glen Rose, Edwards Limestone, Buda Limestone, Austin Chalk, and Pecan Gap Chalk;

Zone 4: outcrops of the upper Glen Rose stratigraphically more than 55 m below the Edwards Limestone; and

Zone 5: outcrops of non-karstic units, and areas where the Uvalde Gravel covers the karstic units.

Zone boundaries inside the Edwards Aquifer recharge zone are more precisely delimited because detailed geologic maps are available. Dashed lines mark approximate or uncertain boundaries and the limits of the study area along San Geronimo and Cibolo creeks where further research is needed to definitively classify those streams as boundaries.

Should the petitioned fauna be listed as endangered, the four map zones would serve to delineate areas of concern or potential concern in future planning. At such a time 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 ground-water 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: same as Zone 3;

Zone 5: no action.

Conclusions and Recommendations

Conclusions

The karst of the San Antonio region can be described as four distinct geologic zones, which can be subdivided into six 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 an endemism index. Conclusions from the index for the San Antonio region include that the Austin Chalk areas are highly speciated zones, as are the combined Edward Limestone and upper Glen Rose areas; however, these latter areas are individually less speciated and function together as a single habitat for some species. 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 research into areas that lack sufficient data to conduct adequate assessments.

1) Additional biologic and geologic research is needed in Edwards Limestone and upper Glen Rose caves between San Geronimo Creek and the Medina River to better determine the westward range of San Antonio region

troglobites, and to better assess San Geronimo Creek as a restriction to species migration.

2) More caves need to be biologically and geologically studied in the Government Canyon area. All troglobite evaluations for the area are based on a single cave and on limited geologic observations.
3) Edwards Limestone and upper Glen Rose caves along Cibolo Creek need further biogeologic study to confirm Cibolo Creek as a barrier to species migration.
4) The stratigraphy of the upper Glen Rose needs detailed mapping in the San Antonio region, especially the portion more than 25 m below the Edwards Limestone to better evaluate its lithologic controls on cave development.
5) The stratigraphy of the Austin Chalk needs detailed mapping in the San Antonio region. Caves in both the Alamo Heights and Culebra Anticline areas should then be evaluated for lithologic controls on cave development.
6) More Alamo Heights area caves need biologic and geologic evaluations. All geologic and troglobite observations are based on a single cave. Investigations of caves north of Salado Creek and south of Olmos Creek are especially needed to determine the impact of those streams on endemism.
7) The boundaries of this report's Culebra Anticline area should be expanded northwest of Culebra Creek to include all of the Austin Chalk up to the Edwards Limestone outcrop. Caves need to be found and studied in this added section to better evaluate troglobite isolation in the Culebra Anticline area.
8) A biogeologic study of the aquatic troglobite fauna of the San Antonio 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

Cave Locations

Figure 34 is map of the approximate locations of caves in Bexar County. The map is modified from Veni (1988) and is keyed to each cave's Bexar County Cave Survey identifier number. The numbers of caves discussed in this report are alphebetically listed below by cave name. Veni (1988) published data on 208 caves; caves with numbers higher than 208 were discovered since the book was published.

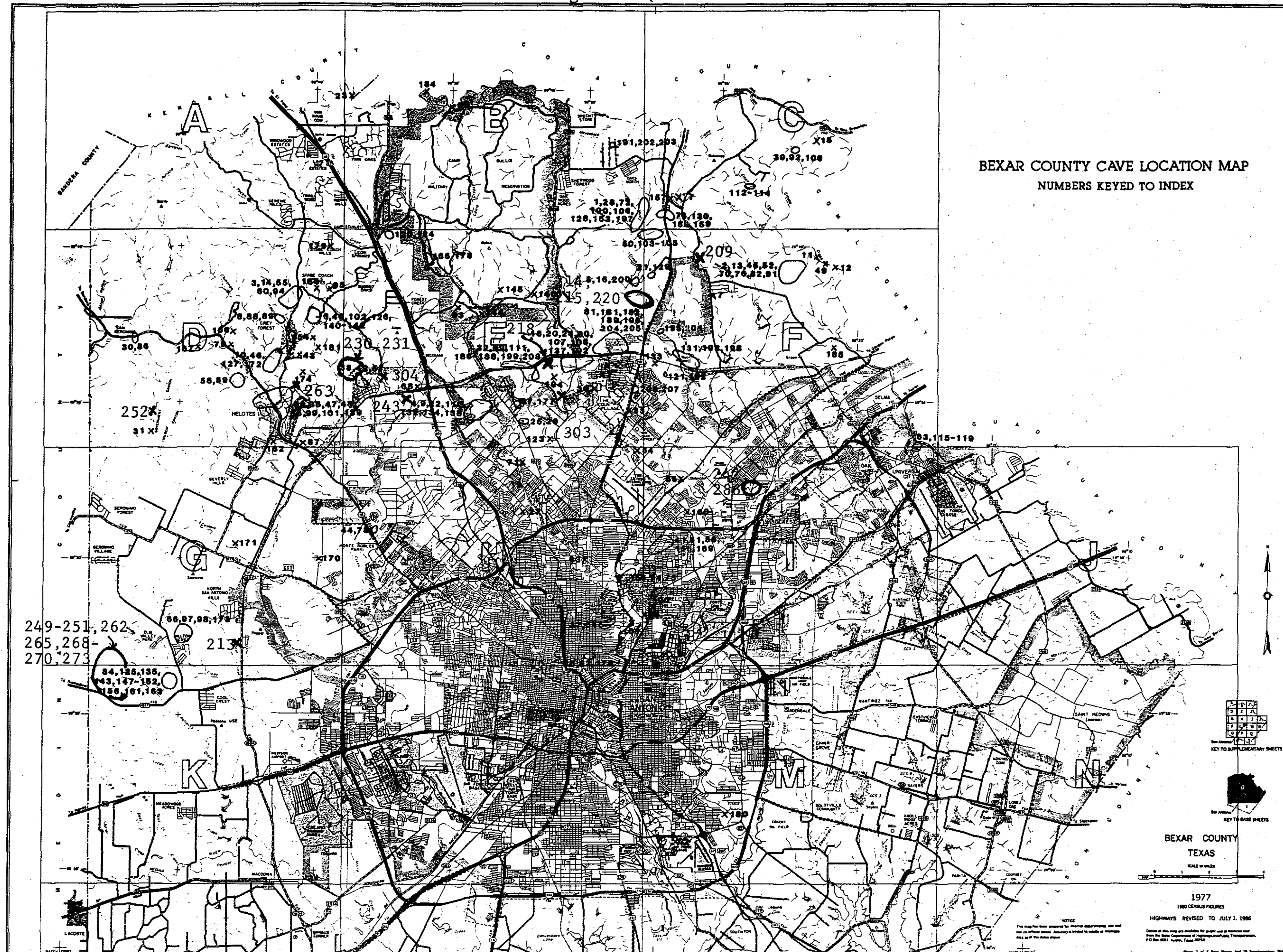
No.	Cave Name
1	Ackerman's Trash Hole
193	Assasin Cave
120	Aue Road Cave
230	B.J. Pit
2	Baling Wire Cave
86	Bandera Road Cave
3	Basement Cave
5	Bear Cave
4	Bet-Ya-Can't-Find-It Cave
6	Big Bexar Cave
7	Black Cat Cave
97	Black Widow Pit
303	Blanco Road Cave
8	Blue Hole No. 1
88	Blue Hole No. 2
89	Blue Hole No. 3
147	Braken Bat Cave
263	Brand X Pit
159	C-Section Cave
213	Caracol Creek Coon Cave
152	Carcass Cave
100	Cave File Cave
151	Cave of the Bearded Tree
138	Cave of the Bee Spirits
121	Cave of the Cliff
122	Cave of the Creek
150	Cave of the Half-Snake
156	Cave of the Mad Machete
273	Cave of the Skinny Snake
9	Cave of the Woods
201	Cave With Ladder In It
163	Chimney Cricket Cave
10	Christmas Cave
13	Corkscrew Cave
131	Council Cave
14	Crane Bat Cave
15	Creekbed Cave
105	Crescent Spring
109	Crystal Cave
16	Cub Cave

No.	Cave Name
114	Dam Crawl
18	Dead Deer Cave
157	Dick White Cave
137	Dirtwater Cave
268	Droll Cave
106	Drop and a Prayer Pit
20	Dynamite Cave
113	Elephant Spring
22	Elm Springs Cave
209	Elm Waterhole Cave
21	Elmore Cave
125	Fence Post Hole
25	Flint Bridge Cave
265	Forked Pit Cave
28	Friesenhahn Cave
249	Game Pasture Cave No. 1
29	Gandalf's Cave
196	Genesis Cave
30	Gladsam's Cave
195	Goonies Cave
31	Government Canyon Bat Cave
269	Grave Marker Cave
215	Hairy Tooth Cave
93	Headquarters Cave
33	Height's Cave No. 1
34	Helotes Blowhole
35	Helotes Hilltop Cave
36	Hidden View Cave
38	Hills and Dales Pit
39	Hitzfelder's Bone Hole
153	Hopeless Cave
200	Hornet's Last Laugh Pit
154	Huesta Cave
42	Hummingbird Cave
218	I Think Its A Cave
112	Is That All There Is Spring
143	Isopit
43	John Wagner Ranch Cave No. 3
44	KKYX Cave
99	Kamikazi Cricket Cave

No.	Cave Name
262	King Toad Cave
226	Logan's Cave
45	Looserock Cave
46	Madla's Cave
166	Madla's Drop Cave
243	Mastodon Pit
47	Mattke Cave
149	Molar Hole
94	Moonshine Cave
136	Niche Cave
49	No Exit Cave
128	Olive Pit
130	Pekingese Pit
50	Pick-Up Sticks Cave
52	Poison Ivy Pit
158	Pomeranian Pit
95	Post Hole
270	Pot-Bellied Stove Cave
220	Prayer to Oztotl Cave
214	Raging Cajun Cave
55	Roan's Cave
56	Robber Baron Cave
57	Robber's Cave
286	Roy's Cave
281	Salado Creek Water Cave
96	San Antonio Spring
62	San Pedro Park Spring (West)
65	Scorpion Cave
66	Screaming Meemies Pit
67	Shavano Park Cave
68	Shot and a Prayer Cave
70	Sink Hole

No.	Cave Name
164	Some Monk Chanted Evening Cave
101	Spider Hole
266	Stevens Ranch Cave No. 1
251	Stevens Ranch Cave No. 2
74	T.M.I. Cave
304	Tee 2 Cave
92	The Crawl
242	The Labyrinth
250	The Two Raccoon Cave
231	Three Fingers Cave
135	Thurman's Cave
72	Tick n' Delight Cave
132	Toad Cave
76	Tobacco Can Cave
104	2 For 1 Cave
103	2 For 1 Spring
78	Underwater Cave
79	Villa Rreal's Cave
80	Virgin Cave
81	Voight's Bat Cave
183	Wagner Ranch Pit
252	Washout Cave
82	Whistledrop Cave
161	Womly Pit
194	Wood's End Cave
48	World News Cave
148	World Newt Cave
84	Wurzbach Bat Cave
140	Young Cave No. 1
141	Young Cave No. 2

Figure 34 (modified from Veni, 1988)



APPENDIX B

Glossary of Geologic and Karst Terminology

This glossary is broad in scope to assist non-specialists reviewing this report, but is not meant to cover all possible terms. Additional karst definitions can be found in the karst glossary of Monroe (1970) or the karst texts of White (1988) and Ford and Williams (1989). For further geologic terms see the geologic dictionary of Bates and Jackson (1984); for biospeleologic terms see Culver (1982).

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

Anticline: A fold in rock which is generally upwardly convex.

Antithetic fault: A minor normal fault which dips in the opposite direction of the major fault with which it is associated.

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.

Attitude: The position of a bed of rock with respect to the horizontal plane; typically measured as strike and dip.

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.

Beds: See strata.

Bedding plane: A plane that divides 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 Texas Speleological Survey).

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

Chamber: See room.

Competence: With regard to a stream, the largest size of material that can be carried; increases with stream gradient.

Conduit: A subsurface bedrock channel formed by groundwater solution to transmit groundwater; often synonymous with cave and passage, but generally inclusive of 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.

Denudation: The sum processes that wear down the earth's surface, or which remove overlying soils or strata from atop underlying material.

Depth: In relation to the dimensions of a cave, it refers to the vertical distance from the elevation of the cave entrance to the elevation of its lowest point. See vertical extent for comparison.

Dip: The angle that joints, faults or beds of rock make with the horizontal; colloquially described as the "slope" of the fractures or beds. "Updip" and "downdip" refer to direction or movement relative to that slope.

Discharge: The water exiting an aquifer, usually through springs or wells; also the amount of water flowing in a stream.

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

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

Epikarst: The highly solutioned zone in karst areas between the land surface and the predominantly unweathered bedrock.

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

Fracture: A break in the bedrock; usually a fault or a joint.

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

Horst: An upthrown fault block, where rocks of the same elevation outside the faults have stratigraphically lower positions.

Hydraulic gradient: In the vadose zone, the rate of change with distance between the elevation of vadose water and base level; used where a water table or potentiometric surface does not exist. In the phreatic zone, the rate of change with distance in the elevation of a point on the water table (or potentiometric surface) and base level, usually a spring.

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.

Length: In relation to the dimensions of a cave, it refers to the summed true horizontal extent of the cave's passages.

Lithology: The description or physical characteristics of a rock.

Marl: Rock composed of a predominant mixture of clay and limestone.

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

Network maze: A maze cave whose plan view is characterized by narrow passages that intersect somewhat regularly at perpendicular or near-perpendicular angles.

Nodular: Composed of nodules (rounded mineral aggregates).

Normal fault: A fault where strata underlying the fault plane are higher in elevation than the same strata on the other side fault plane.

Paleospring: A once active spring that no longer discharges groundwater, usually because the water table has lowered, or because it has been truncated from its recharge zone.

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

Perched groundwater: Relatively small body of groundwater at a level above the water table; downward flow is impeded within the area, usually by impermeable strata.

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.

Piracy: The natural capture of water from a watershed, stream, aquifer, or cave stream, and its transmission to a different watershed, stream, aquifer, or cave stream.

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.

Reverse fault: A fault where strata underlying the fault plane are lower in elevation than the same strata on the other side fault plane.

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 (e.g., stalactites and stalagmites) in a cave; usually calcite but can include gypsum.

Spring: See resurgence.

Strata: Layers of sedimentary rocks; usually visually distinguishable. Often called beds. The plural of stratum.

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

Stratigraphy: Pertaining to or the study of rock and sediment strata, their composition and sequence of deposition.

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.

Structure: The study of and pertaining to the attitude and deformation of rock masses. Attitude is commonly measured by strike and dip; deformational features commonly include folds, joints, and faults.

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

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.

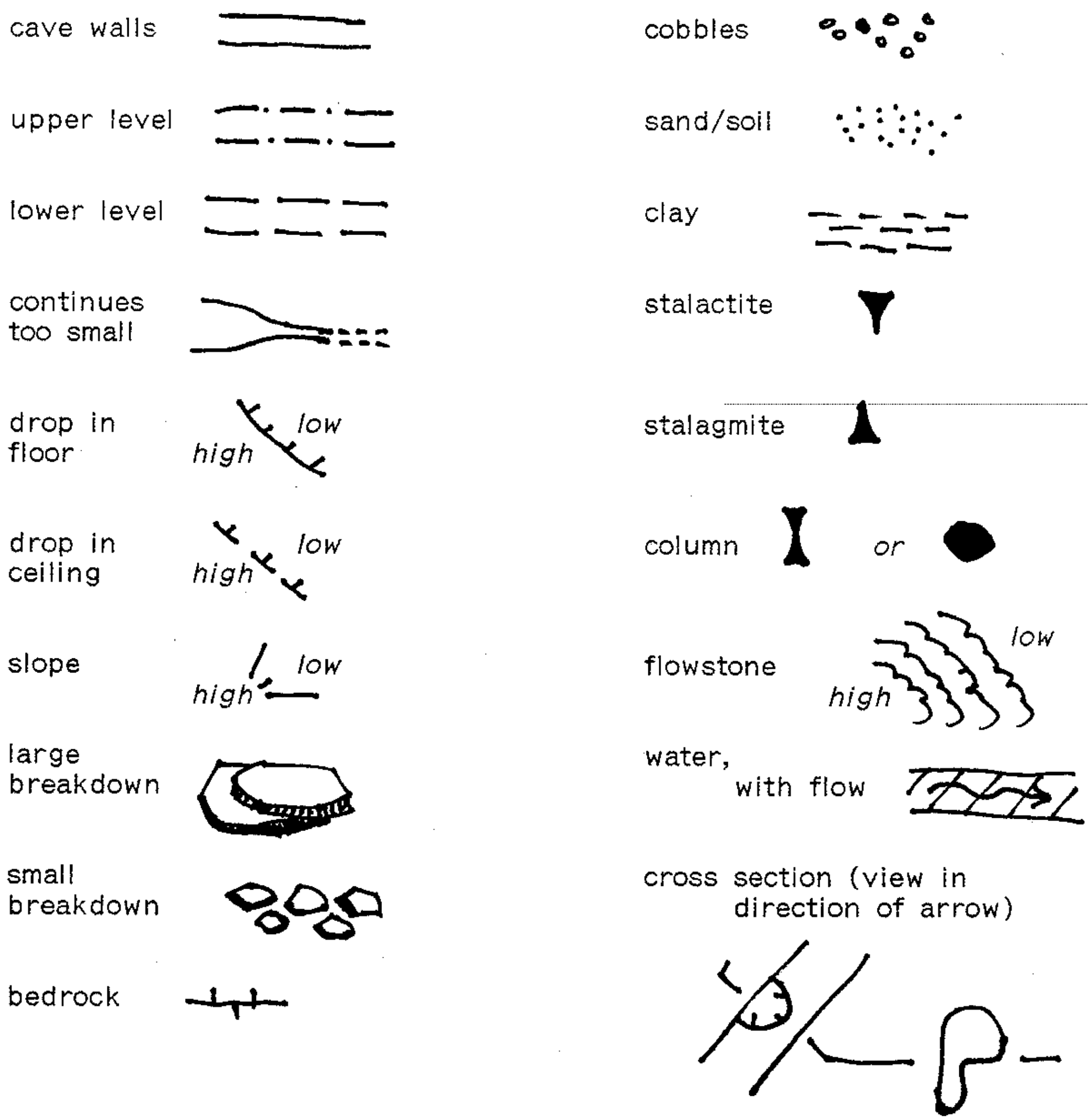
Vadose: Pertaining to the zone above the water table where all cavities are generally air-filled, except during temporary flooding.

Vertical extent: In relation to the dimensions of a cave, refers to the vertical distance from the highest elevation to the lowest elevation of the cave. Generally used when a portion of a cave extends above its entrance. See depth for comparison.

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

APPENDIX C

Standard Cave Map Symbols



APPENDIX D

Distribution Maps of Petitioned and Endemic Cavernicole Fauna in the San Antonio Region

The known and probable distribution of petitioned and endemic cave fauna in the San Antonio region is illustrated on 14 U.S. Geological Survey 7.5' topographic maps. The maps are listed below and their locations are keyed to Figure 35. Due to the size and total bulk of the maps, they accompany this report under a separate cover.

Bat Cave
Bulverde
Camp Bullis
Castle Hills
Culebra Hill
Helotes
Jack Mountain
LaCoste NE
Longhorn
San Antonio East
San Antonio West
San Geronimo
Schertz
Van Raub

Figure 35: Location of petitioned and endemic fauna distribution maps

Jack Mountain	Van Raub	Camp Bullis	Bulverde	Bat Cave
San Geronimo	Helotes	Castle Hills	Longhorn	Schertz
La Coste NE	Culebra Hill	San Antonio West	San Antonio East	

APPENDIX E

Geologic Time Scale
(from Press and Siever, 1978)

	Time term	Epoch	Period	Era	
	Rock term	Series	System		
		Recent	Quaternary	Cenozoic	
2		Pleistocene	Quaternary	Cenozoic	
12		Pliocene	Tertiary	Cenozoic	
26		Miocene	Tertiary	Cenozoic	
37		Oligocene	Tertiary	Cenozoic	
53		Eocene	Tertiary	Cenozoic	
		Paleocene	Tertiary	Cenozoic	65
136			Cretaceous	Mesozoic	
190			Jurassic	Mesozoic	
			Triassic	Mesozoic	225
280			Permian	Paleozoic	
320			Carboniferous: Pennsylvanian	Paleozoic	
345			Carboniferous: Mississippian	Paleozoic	
395			Devonian	Paleozoic	
430			Silurian	Paleozoic	
500			Ordovician	Paleozoic	
			Cambrian	Paleozoic	570
			Precambrian		

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