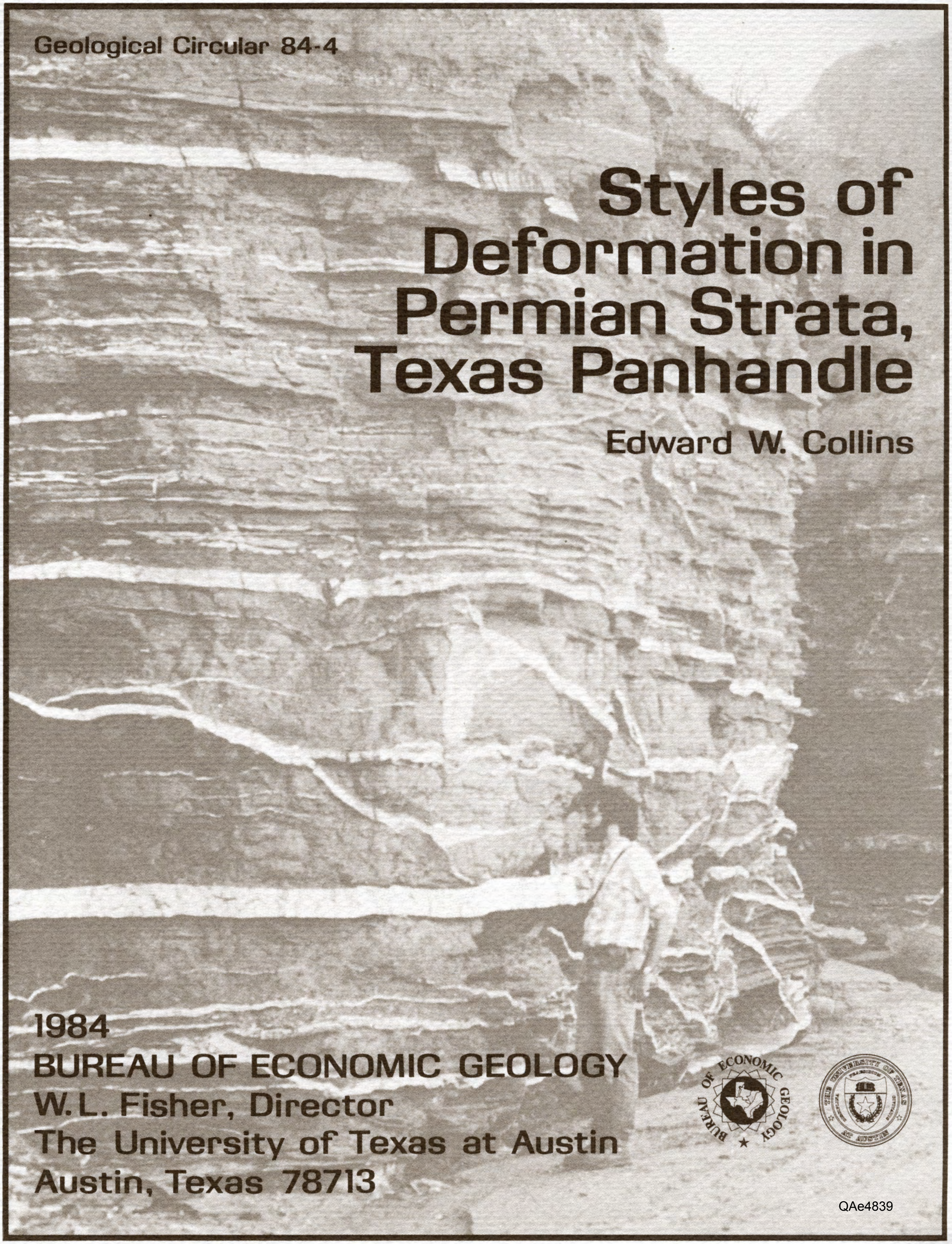
Geological Circular 84-4

Styles of Deformation in Permian Strata, Texas Panhandle

Edward W. Collins



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BUREAU OF ECONOMIC GEOLOGY
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ABSTRACT

Permian strata in the Texas Panhandle exhibit a variety of deformation styles that are attributed to tectonic stresses as well as to collapse caused by evaporite dissolution. At Caprock Canyons State Park, deformation structures above salt dissolution zones include veins, faults, and folds. The geometry and distribution of the structures indicate that systematic regional joints older than the dissolution collapse have influenced salt dissolution. At Palo Duro Canyon State Park, subparallel cylindrical folds and minor reverse faults indicate east-northeast and west-northwest (075° to 255°) compression related to regional folding. Evaporite dissolution and subsequent collapse of strata have also deformed Permian strata and developed closed synclinal depressions, faults, and veins. Along the Canadian River valley in Potter County, Permian and Triassic strata are folded over fault-bounded basement highs as the result of either differential compaction or recurrent motion on basement faults. Synclinal depressions, clastic plugs, and clastic dikes caused by dissolution-induced collapse processes also occur throughout this area.

Keywords: Texas Panhandle, Permian, structure, fractures, folding, salt dissolution

INTRODUCTION

Permian strata cropping out in the Texas Panhandle display a variety of structural styles that have resulted from both tectonic and nontectonic deformation. Recognition of the different deformational styles is of particular interest because Permian evaporite strata within the Palo Duro Basin, Texas Panhandle, are currently being investigated as a potential storage site for high-level nuclear wastes. Even though tectonic folding of Permian strata is well developed in some areas, recent nontectonic folding caused by evaporite dissolution and collapse of overlying strata has been superimposed on preexisting folds. Thus, tectonic folds are difficult to distinguish from nontectonic structures.

Dissolution of evaporite strata is an active process in the Texas Panhandle. Recognition of salt dissolution has been based on the stratigraphic evidence, the identification of surface collapse features, and the presence of saline springs (Gustavson and others, 1980; Gustavson and others, 1982; Gustavson and Finley, in press). Locally, structures such as low-amplitude, long-wavelength folds, sinkholes, breccia pipes, and synclinal depressions have been attributed to dissolution and vertical subsidence or collapse of as much as 70 m (Gustavson and others, 1982; Goldstein and Collins, 1984). Even though deformation caused by dissolution-induced collapse is common in the Texas Panhandle, subparallel cylindrical folds of tectonic origin have been traced for several kilometers in outcrop. Drape folds bounding regional basement uplifts have also been observed at the surface.

This outcrop study addresses deformation of Permian strata in three areas within the Texas Panhandle: (1) Caprock Canyons State Park, Briscoe County, (2) Palo Duro Canyon State Park, Randall County, and (3) Canadian River valley, Potter, Moore, Carson, and Hutchinson Counties. Permian strata in each of these areas display a distinct style of deformation. This investigation shows that many deformational features in the Texas Panhandle result from evaporite dissolution collapse and that preexisting joints and folds have influenced dissolution processes. Furthermore, an angular unconformity between Permian and Triassic strata provides evidence of the structural history of Randall County, as do regionally folded Permian and Triassic strata along the Canadian River valley.

STRUCTURAL SETTING

Areas investigated in this study are within the Palo Duro Basin and on the Amarillo Uplift (fig. 1). The Palo Duro Basin, an element of the late Paleozoic Ancestral Rocky Mountains structural system, is bordered on the north by the Amarillo Uplift, on the south by the Matador Arch, and on the west by the Sierra Grande Uplift and the Tucumcari Basin. These basement uplifts are fault controlled. Various types of fault motions proposed to explain the development of the Amarillo-Wichita Uplift include transcurrent motions along the easternmost segment (Wickham, 1978), low-angle thrusting along the central segment (Brewer and others, 1983), and high-angle reverse faulting along the western segment (Goldstein, 1981).

The Palo Duro Basin encompasses an area of approximately 50,000 km^2. The basin may have formed late in the Mississippian Period, and its development continued into the Permian Period (Totten, 1956). During basin development, uplifts bounding the basin were subaerially exposed, and coarse arkosic debris was transported into the basin (Dutton, 1980). After the Wolfcampian Epoch, the basin comprised marginal subtidal and supratidal marine evaporite environments, which existed throughout the rest of the Permian Period (Presley, 1981). Middle and Upper Permian evaporite deposits comprise red mudstone, anhydrite, and bedded halite. Some faults are known to displace Upper Permian strata at the margins of the basin and the basement uplifts. The absence of verifiable fault displacements of Upper Permian strata within the central Palo Duro Basin suggests that the basin was structurally quiescent during evaporite deposition. Evidence of various styles of nontectonic deformation caused by evaporite dissolution and collapse of strata also exists throughout the Texas Panhandle in the form of various structures that are superimposed on existing tectonic structures. In some areas, tectonic and nontectonic deformation may have been contemporaneous.

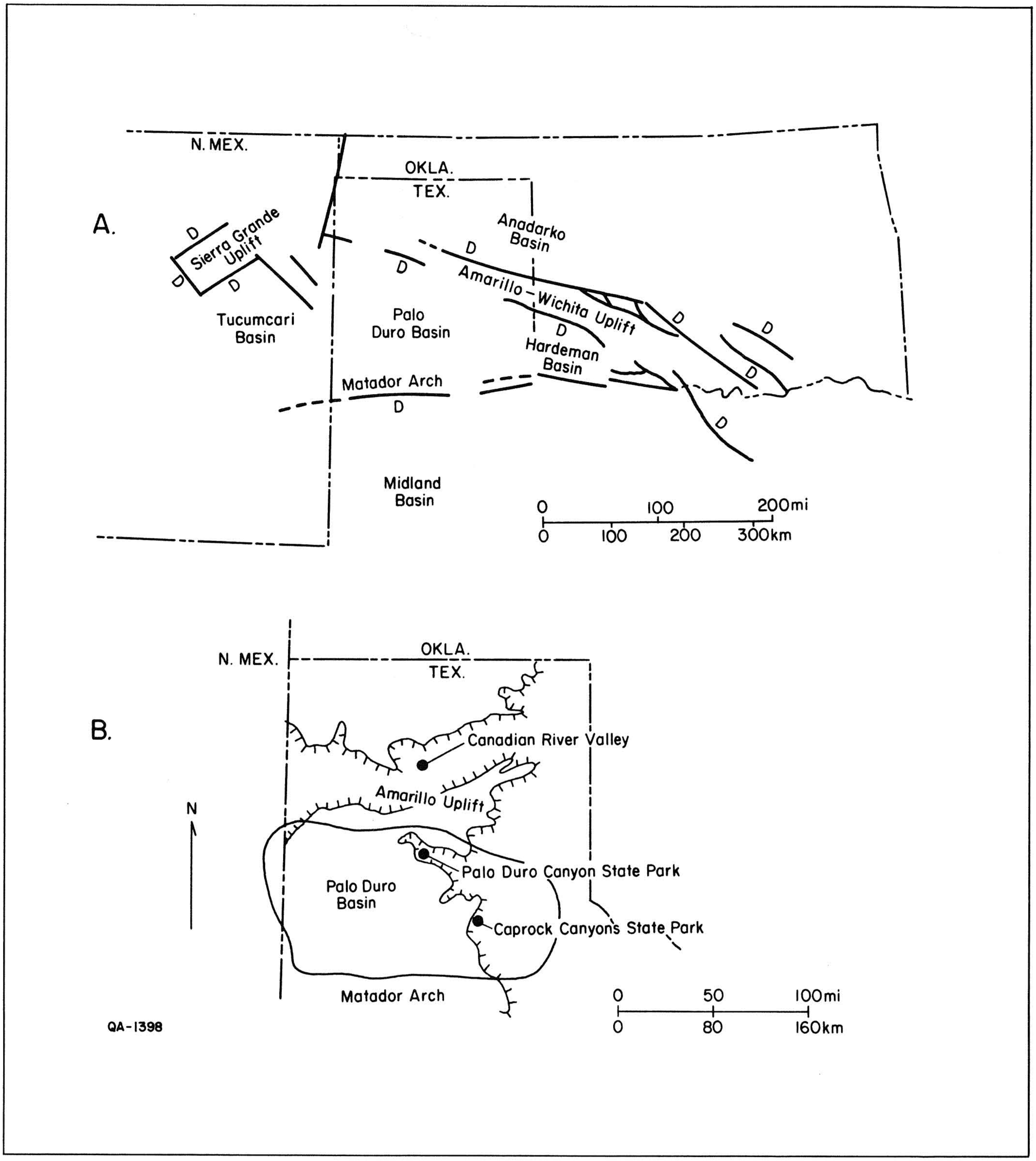

Figure 1. Structural setting and study areas, Texas Panhandle. (A) Regional structure map. (B) Locations of study areas.

CAPROCK CANYONS STATE PARK

Caprock Canyons State Park straddles the eastern High Plains Escarpment, which has relief of up to 200 m in the park area (fig. 1). There are excellent exposures of Upper Permian strata along the escarpment and in incised streams that drain eastward into the Rolling Plains. East of the park, exposures are rare. Exposed in the park (fig. 2) are the Upper Permian Whitehorse Sandstone and the Cloud Chief Gypsum of the Whitehorse Group. These units consist of interbedded shale, siltstone, sandstone, and gypsum beds. In this area, gypsum beds near the top of the Whitehorse Group are as thick as 4 m. Massive, thickly bedded sandstones and shales of the Permian Quartermaster Formation overlie the Whitehorse Group. Sandstones, shales, and conglomerates of the Triassic Dockum Group overlie Permian strata. The Triassic rocks are capped by Tertiary Ogallala sediments and caliche. A zone of regional salt dissolution exists beneath the park (Gustavson and others, 1982).

Deformation of the Permian strata at Caprock Canyons State Park has been described in detail by Goldstein and Collins (1984). Two zones defined on the basis of type of deformation structures exist within the park (fig. 2). The upper, relatively undeformed zone occurs in the

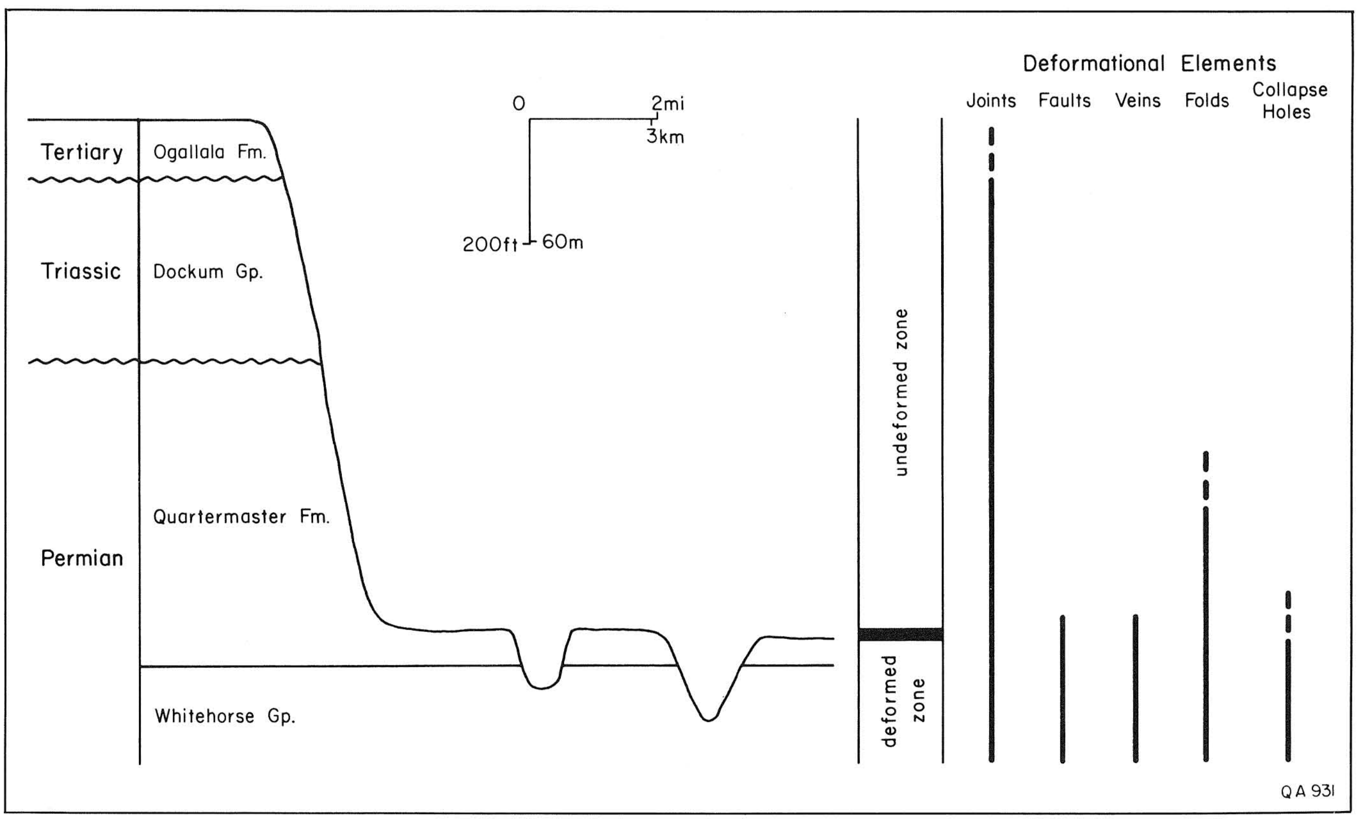

Figure 2. Stratigraphy and deformational elements at Caprock Canyons State Park.

massive, thickly bedded sandstones in the upper part of the Permian Quartermaster Formation and is characterized primarily by joints. The lower, deformed zone of strata encompasses the Whitehorse Group and lower Quartermaster Formation (fig. 2). In this zone, thinly bedded siltstones and sandstones are interlayered with gypsum beds. Within the more deformed rocks of this lower zone are normal faults, reverse faults, and gypsum veins along fault contacts, bedding planes, and joint surfaces. Folds and funnel-shaped depressions also occur in the lower zone.

Joints

Systematic and nonsystematic joints characterize the undeformed zone (fig. 2). Systematic joints are vertical, evenly spaced, regularly oriented fractures. The predominant strike of the systematic joint sets is north, northeast, and east. A less significant set strikes northwest. One or more of these four sets of joints predominate within different domains in the park area. Hackle fringes and plume structures on joint faces are evidence of horizontal propagation prompted by horizontal extension. Nonsystematic joints are curved and irregularly spaced, show no preferred orientation, and truncate against systematic joints. Many nonsystematic joints have surface markings that indicate vertical propagation (Goldstein, 1982).

Zones of closely spaced systematic joints exist throughout the park (Collins, 1983a). Joint zones as wide as 40 m extend vertically through Permian and Triassic beds and horizontally for at least 1 km. Within joint zones, joint density averages 5 joints per meter for sandstone beds 3 m thick; away from joint zones, densities average from 0 to 1.5 joints per meter for 3-m-thick sandstone beds. Bed thickness affects the spacing of the joints within and beyond zones of closely spaced joints. In general, joint densities in sandstone and siltstone beds less than 1 m thick increase as the bed thickness decreases. Joint densities are almost constant for beds thicker than 1 m.

Veins and Faults

Three types of gypsum veins exist in the deformed zone of strata: they are either vertical, parallel to bedding, or cut the bedding at 30° to 60° (fig. 3). The veins are composed of fibrous gypsum bisected by a medial scar. They seem to be similar to a type described by Ramsay (1980) as crack-seal veins, in which the medial scar probably marks the site of earliest mineralization, and new material is added at the vein-wall rock contact. Mineral fibers denote the direction of maximum principal extension when they were added to the vein.

The gypsum fibers in the vertical veins are horizontal, indicating that these veins formed during horizontal extension and probably fill preexisting joints. Mineral fibers of the inclined and horizontal veins are vertical, indicating that mineralization occurred during vertical extension.

Small-scale normal and reverse faults are common within the deformed zone of Quartermaster and Whitehorse strata and are also gypsum filled. Fault displacements are typically less than 0.5 m. Normal faults are oriented in all directions (fig. 4A) but dominantly dip north, south, east, and west. No relative age data are available for these fault sets. The orientations reveal either a north-south horizontal maximum principal extension followed by an east-west extension or vice versa. Reverse faults (fig. 4B) display orientations similar to those of the normal faults. Most of the reverse faults exhibit northward, southward, and eastward dips. Reverse faults are less common than normal faults. Inclined veins (fig. 4C) have orientations similar to those of faults, which suggests that they are filled faults. Nearly all veins along fault planes display undeformed crystals adjacent to the contact between the vein and wall rock, indicating that fault movement predated mineralization.

Figure 3. Gypsum veins in Permian strata at Caprock Canyons State Park.

The geometry of vein intersections also reveals that faulting predated mineralization (Goldstein, 1982). Mineral fibers of adjacent horizontal and inclined veins merge without a break. Some veins are composed of sigmoidal fibers, documenting that simple shear occurred during vein growth. Most vein fibers, however, are straight and do not deviate from vertical by

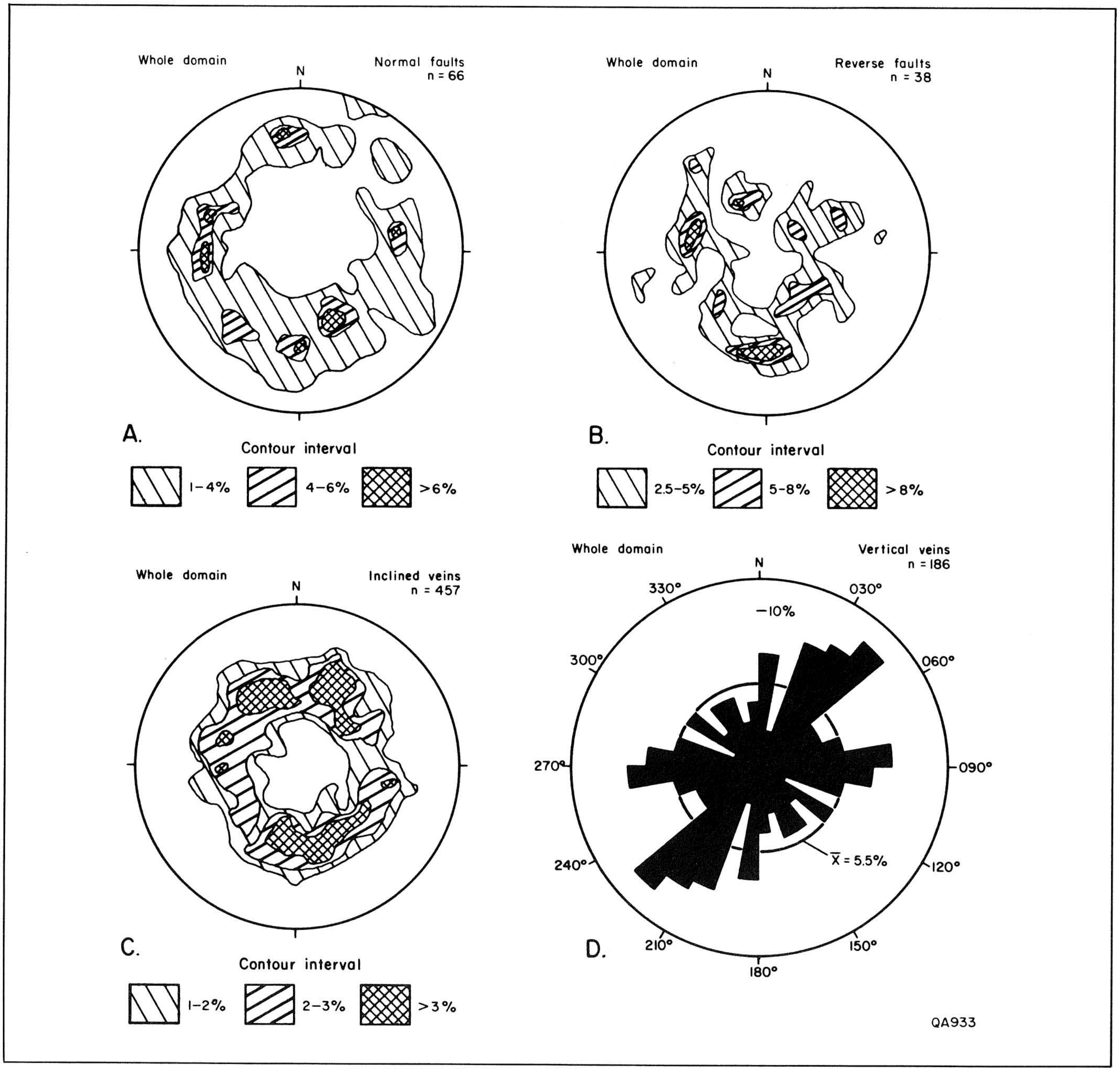

Figure 4. Lower-hemisphere, equal-area net plots of faults and veins mapped at Caprock Canyons State Park (fig. 5). (A) Poles to normal faults with average dip to 50°. (B) Poles to reverse faults with average dip of 40°. (C) Poles to inclined veins with average dip of 40°. (D) Azimuths of vertical veins are plotted as a rose diagram (from Goldstein and Collins, 1984).

more than about 10° in the horizontal and inclined veins--evidence that these veins were formed by vertical extension. Where veins intersect, vertical veins are everywhere cut by inclined veins and nearly everywhere cut by the horizontal veins.

Folds

Chaotic folds in the upper zone of deformed strata cause the Quartermaster and Whitehorse beds to dip 10° to 20°. Detailed structural mapping defined synclines that vary from elongate to circular (fig. 5). These synclinal depressions are as much as 1.5 km long and are composed of conical synclines and anticlines that plunge gently as much as 10° toward the center of the depression (fig. 6). The amplitude of these folds is normally less than 10 to 15 m. Rim anticlines may also occur along the periphery of the principal synclinal depressions, commonly separating the depressions. Small-scale folds having amplitudes of less than 2 m also exist. Although possibly related to the formation of the larger synclinal depressions, some of the smaller folds probably formed by expansion associated with the conversion of anhydrite to gypsum (Fandrich, 1966).

The systematic joints, veins, and principal synclinal depressions are closely associated. Major trends of the depression axes are 005°, 025°, 055°, 080°, and 275°, which are similar to those of the vertical veins and systematic joint sets (fig. 7). These structural elements also exhibit a weak northwest (310°) trend. Within a specific depression, the most significant trend of the vertical veins parallels the axis of the depression. Even though the inclined veins strike in many directions, the dominant strike parallels the orientation of the depression (fig. 8). Strikes of the small-scale faults exhibit a similar relation, although these faults are less common than the other structures.

Model of Deformation

Dissolution of salt followed by collapse of strata or gentle subsidence influenced by gravity is thought to be the process that caused the folds, faults, and veins observed in this area. Figure 9 depicts a simplified model of the development of the deformation structures (Goldstein, 1982). Stage 1 is a normal burial process and is recorded in nearly every sedimentary rock. Stage 2 results from horizontal extension and occurs when dissolution is initiated. This horizontal extension could have produced the normal faults. Rarer reverse and thrust faults indicate local horizontal compression. Stage 3 is a different stress regime characterized by vertical extension. As collapse proceeds, maximum extension changes from

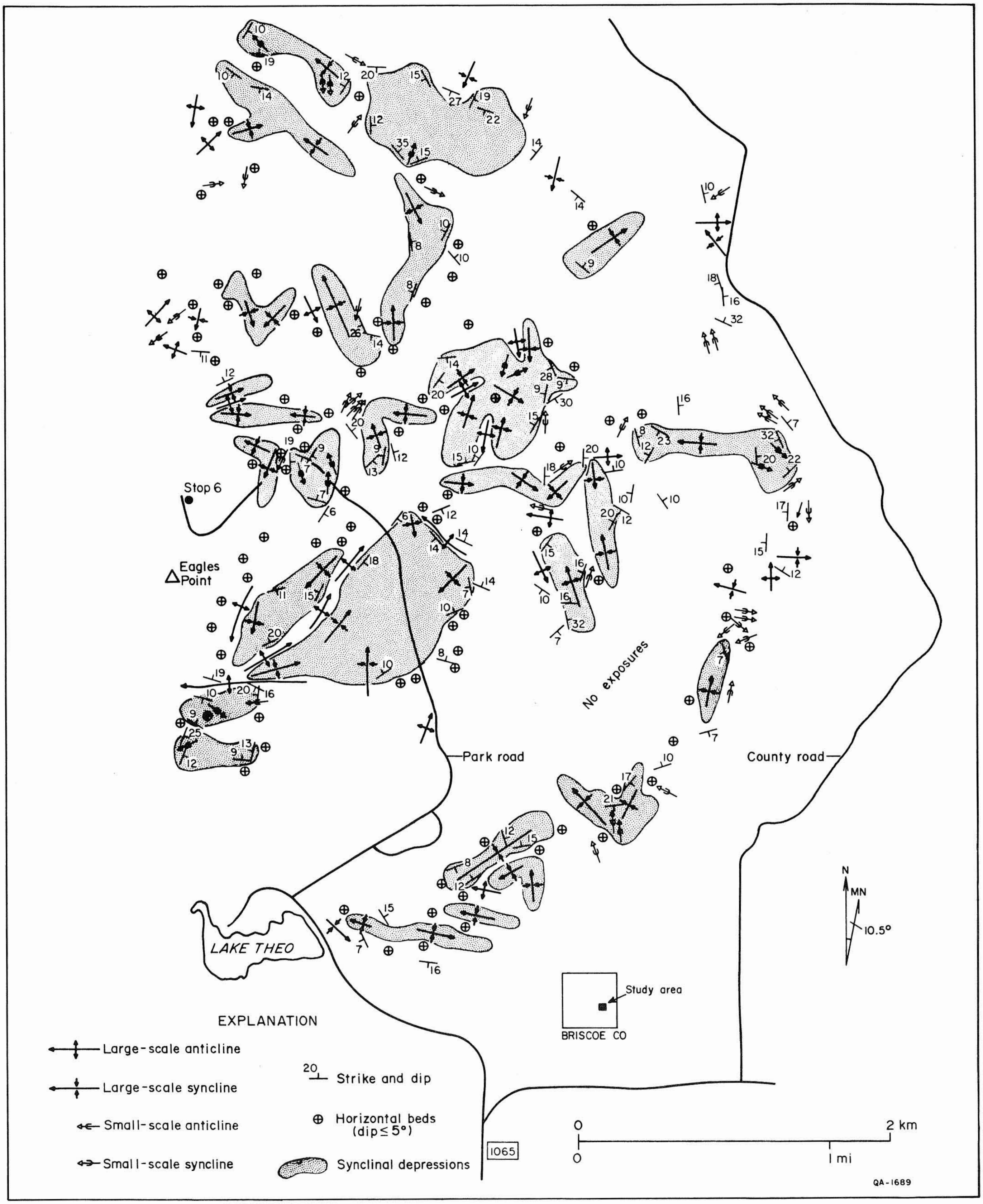

Figure 5. Structural elements in the lower Quartermaster Formation and upper Whitehorse Group within part of Caprock Canyons State Park. Folds are characterized by synclinal depressions of various shapes (from Collins, 1983b).

nearly horizontal to nearly vertical. Gentle folding and nonsystematic fracturing continue as support is removed from below; veins are mineralized with vertical extension fibers.

Dissolution in the Caprock Canyons State Park area appears to have occurred in a mosaic of localized areas displaying varying rates of enhanced dissolution. The similarity between the orientations of joints that predate dissolution and the synclinal depressions suggests that

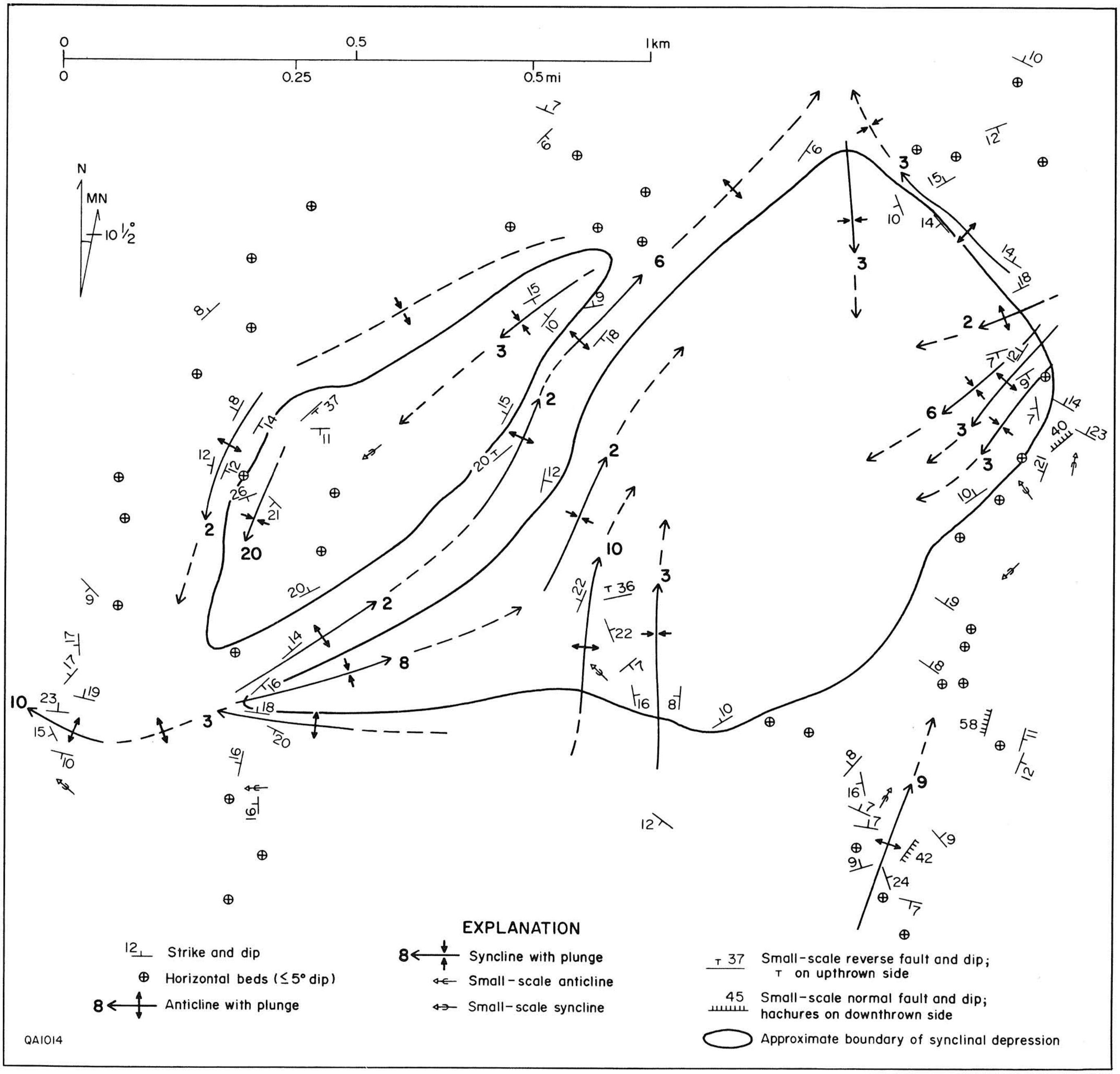

Figure 6. Detailed map of synclinal depressions located 1.5 km north of Lake Theo, Caprock Canyons State Park. Major axes of the two depressions trend northeast-southwest (045° to 225°).

enhanced fluid flow and dissolution were, and presumably are, at least partly controlled by predissolution joints.

The position of the boundary between the deformed zone and the overlying undeformed zone is a function of bed thickness and vertical distance from dissolution (fig. 2) (Goldstein and Collins, 1984). Beds in the zone of deformed strata are almost everywhere 0.1 m to 1 m thick. Overlying undeformed beds are rarely less than 2 m thick and more commonly are as much as 10 m thick. Thicker beds have a higher flexural rigidity and thus would not flex to allow local development of extension parallel to the layers.

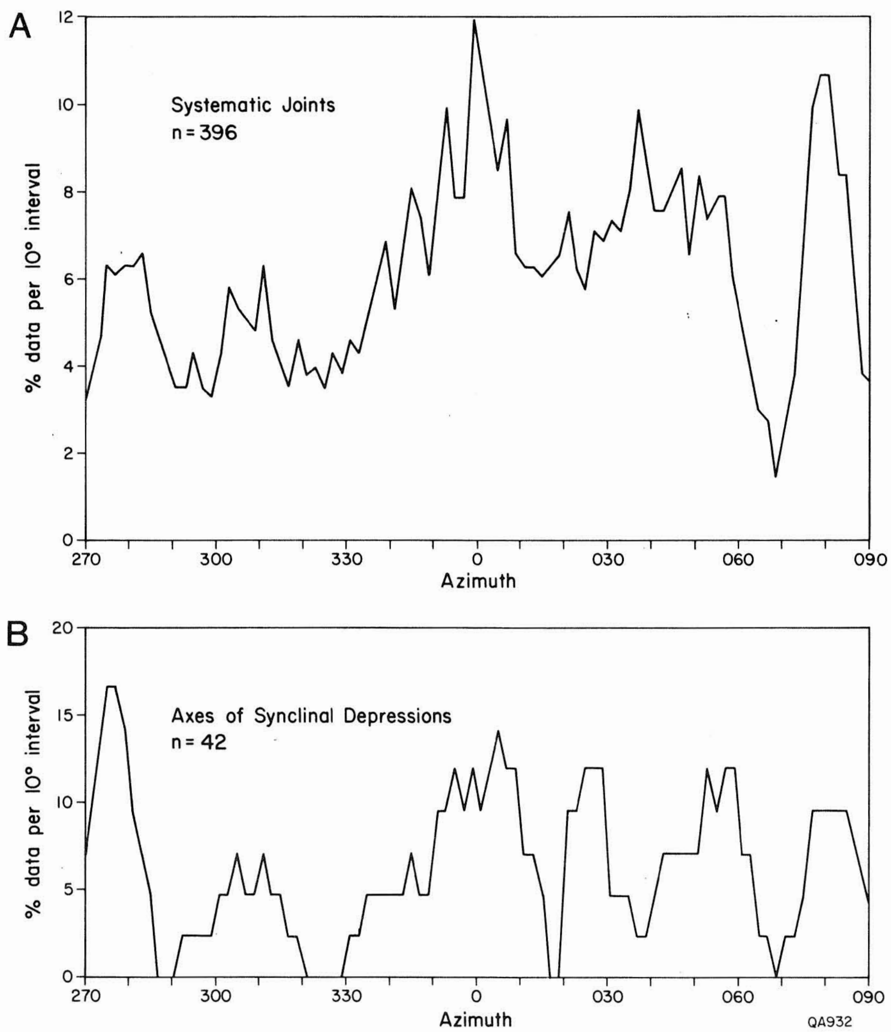

Figure 7. Histograms of (A) systematic joints and (B) axes of synclinal depressions at Caprock Canyons State Park. The percent data per 10° intervals have been smoothed by a 10° running average every 2° of azimuth (Wise and McCrory, 1982).

Palo Duro Canyon State Park is located in the northern part of Palo Duro Canyon, primarily in eastern Randall County. The canyon has about 200 m of relief. The park is in the northern part of the Palo Duro Basin near the Amarillo Uplift (fig. 1). Stratigraphy in the area is similar to that exposed in Caprock Canyons State Park. Isolated exposures of the Permian Cloud Chief Gypsum are overlain by sandstones and shales of the Permian Quartermaster Formation. The Triassic Dockum Group is divided into two formations in this area: the basal Tecovas Formation, characterized by shales, mudstones, and fine-grained sandstones; and the Trujillo Formation, a thickly bedded sandstone unit. Tertiary Ogallala sediments and caliche are also exposed in the park, as are Pliocene-Pleistocene lacustrine deposits (Hood, 1977).

Permian strata at Palo Duro Canyon State Park have been deformed into gentle folds and cut by small-scale faults, veins, and joints. Even though these structures also exist at Caprock Canyons State Park, the geometry of the structures in the Palo Duro Canyon study area indicates a different deformational history.

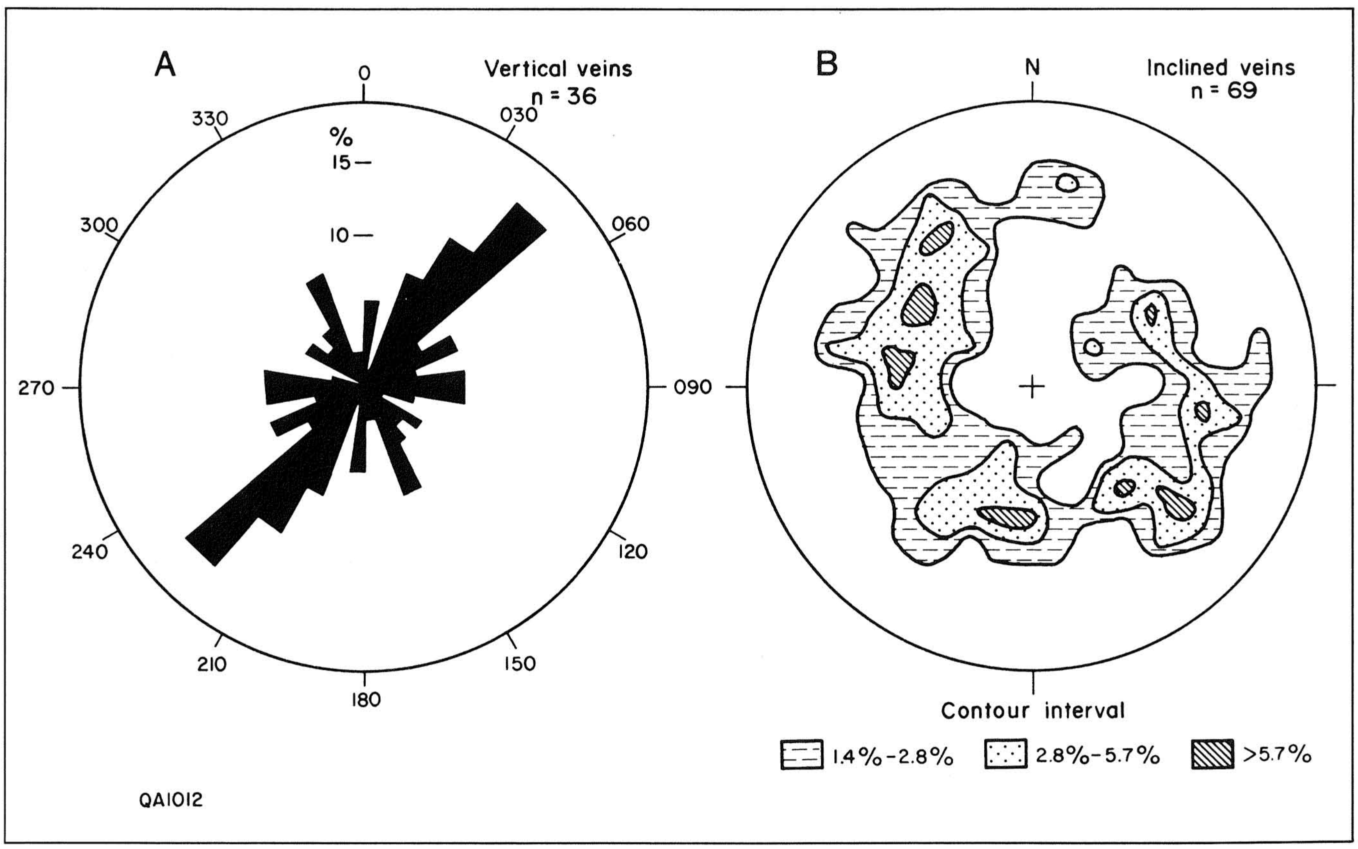

Figure 8. Orientations of veins in synclinal depressions (fig. 6), Caprock Canyons State Park. (A) Rose diagram of orientations of vertical veins. (B) Lower-hemisphere equal-area net plots for poles to inclined veins.

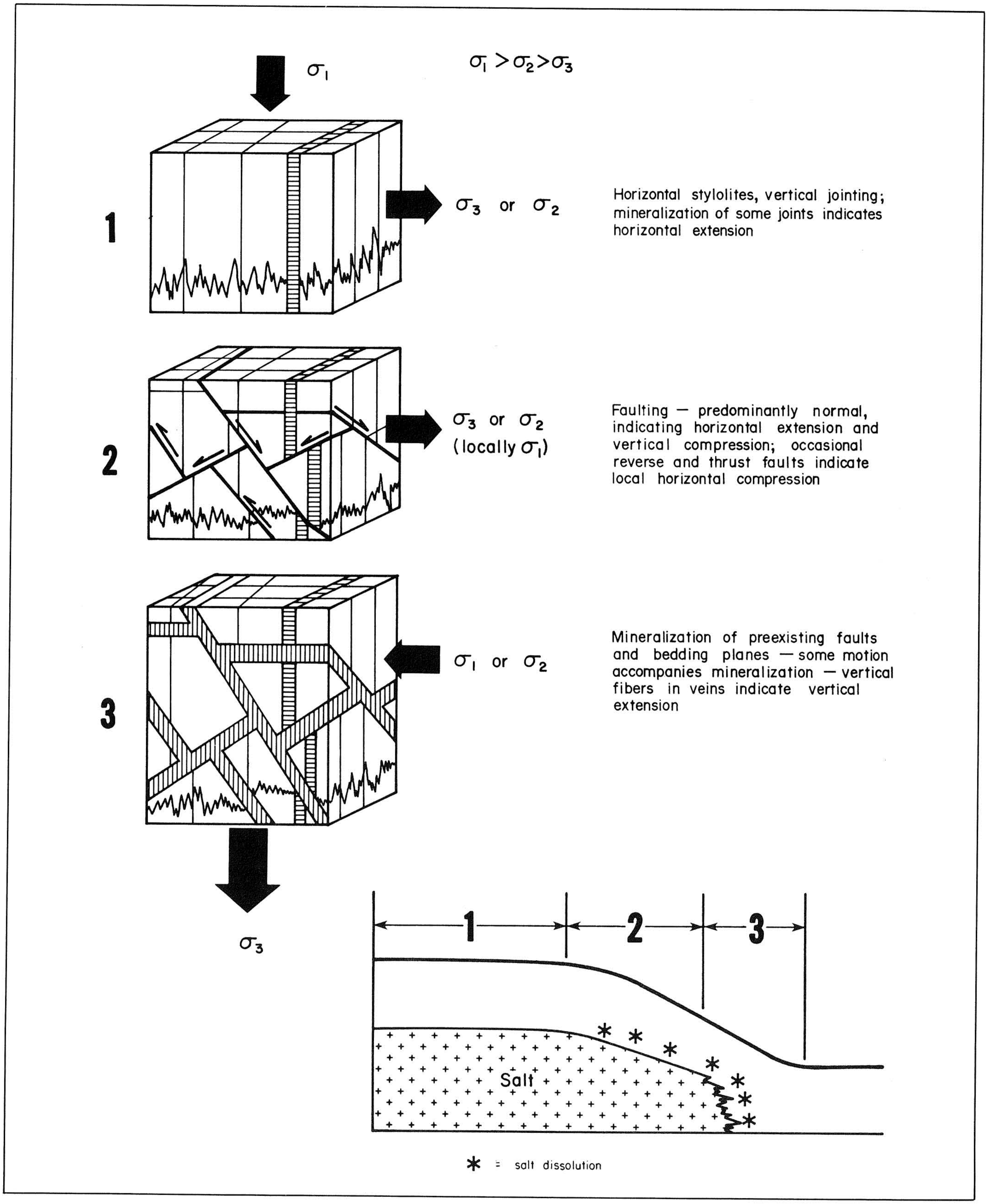

Figure 9. Conceptual model of brittle deformation above dissolution zones. Stage 1 represents normal burial; Stage 2 represents horizontal extension as a precursor to dissolution collapse; Stage 3 represents collapse (from Goldstein, 1982).

Basement Structure and Joint Trends

Several basement faults strike northwest and northeast in Randall County (fig. 10) (R. T. Budnik, personal communication, 1983). Regionally, recurrent fault motion has influenced the distribution of Paleozoic and Mesozoic sediments (Budnik, 1983). In Randall County, basement faults identified on seismic lines show reverse displacements. Fracture orientations measured from a fracture-identification log of the Gruy Federal - Rex White No. 1 borehole show dominant northwest and northeast trends and a less significant easterly trend (A. G. Goldstein, personal communication, 1982; fig. 10A). Joint measurements from Permian and Triassic rocks in Palo Duro Canyon State Park show a dominant trend to the northwest and weaker northeast and west trends (fig. 10B). The park area overlies a north-northwest-trending basement fault. Surface lineaments also trend northwest and northeast in this area (Finley and Gustavson, 1981, p. 16).

Orientations of gypsum-filled systematic joints in Permian rocks cropping out along the northwest-trending Palo Duro Canyon indicate that the joints have at least partly controlled the location and pattern of stream incision and canyon erosion (fig. 11). The gypsum that fills the joints was derived from evaporite dissolution; thus, these joints predate slump features associated with more recent unloading processes. The satin spar gypsum needles in these vertical veins are horizontal, which demonstrates that maximum principal extension was horizontal during mineralization.

Veins and Faults

The fibrous satin spar veins cutting Permian strata in Palo Duro Canyon State Park are similar to the veins in Caprock Canyons State Park, although in Palo Duro Canyon the veins are less abundant. Some vertical celestite veins were also observed (Hood, 1977). Small-scale faults in Palo Duro Canyon are also less common than in Caprock Canyons State Park. Normal faults exhibit displacements of less than 0.3 m and dip at an average of 55° in all directions (fig. 12A). No preferred strike and dip directions were observed for the normal faults. Some of the normal fault contacts are filled with gypsum veins.

Reverse faults were observed throughout the study area, although they are less abundant than normal faults. Fault displacement is mostly of two magnitudes: displacements that are less than 0.2 m and displacements from 1.0 m to 2.5 m. Reverse faults mostly strike between 340° and 350° and faults with the greatest displacement dip east-northeast (fig. 12B). The average dip of the reverse faults is 60°; dip of one thrust fault is 15°. Two other faults trending approximately 345° were recognized in the area; although poor exposure prevented detailed measurement, estimated displacements are 2.5 m and 7 m.

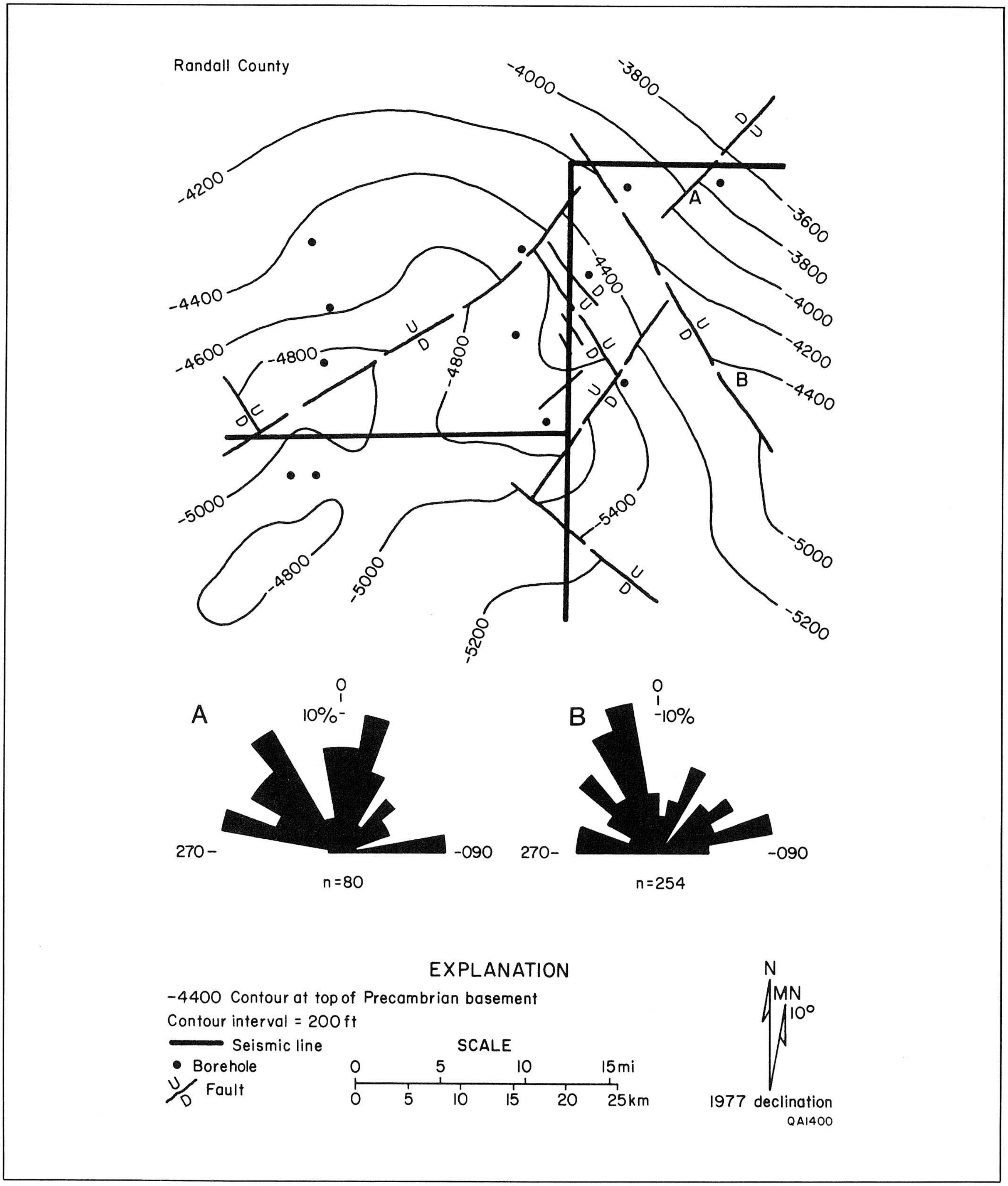

Figure 10. Map and rose diagrams showing basement faults and joint and fracture orientations in eastern Randall County (basement structure from R. T. Budnik, personal communication, 1983). (A) Fracture orientations from fracture-identification log for Gruy Federal - Rex White No. 1 (A. G. Goldstein, personal communication, 1982). (B) Systematic joints in Permian and Triassic rocks in Palo Duro Canyon State Park.

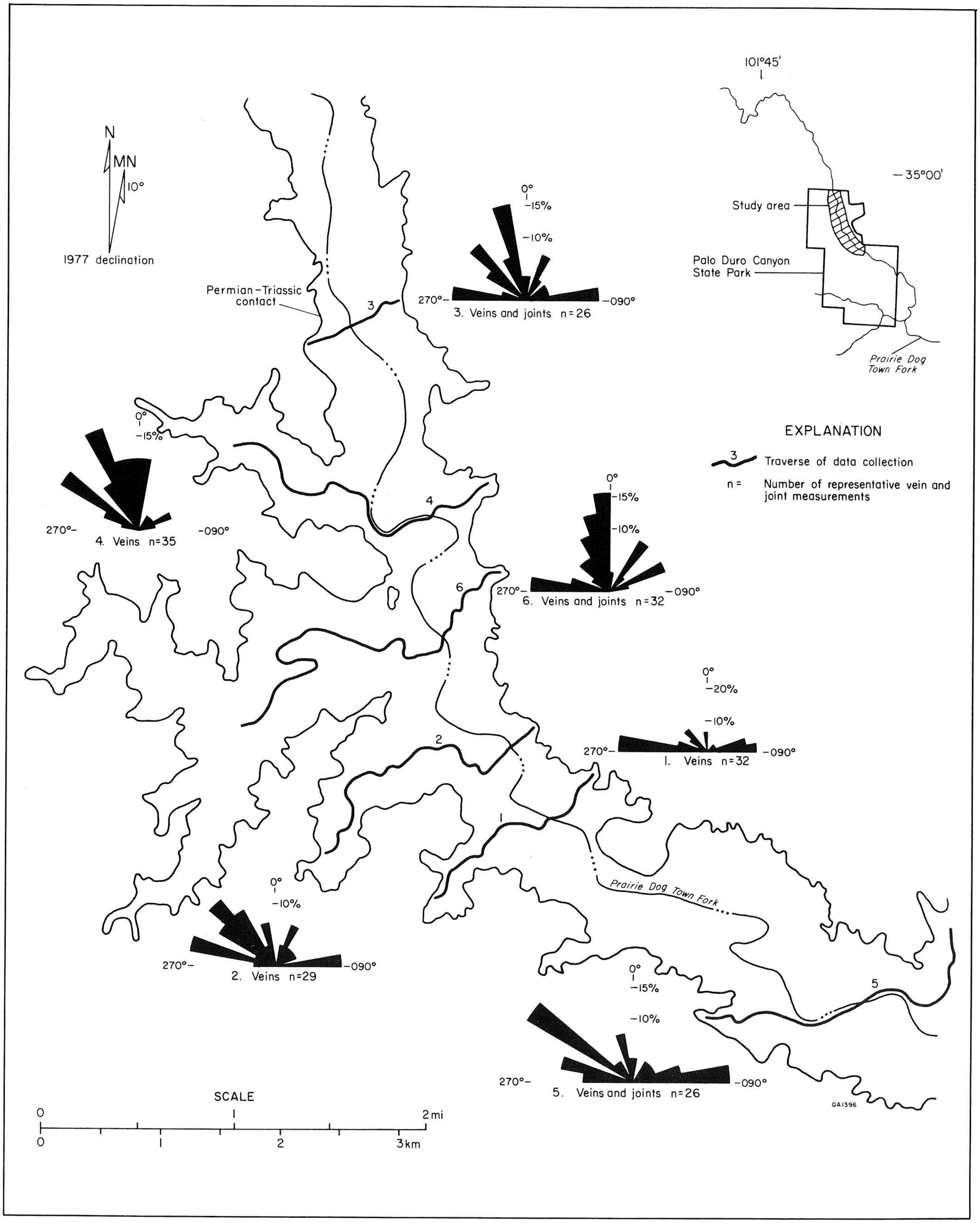

Figure 11. Systematic joint and vein orientations along the Prairie Dog Town Fork of the Red River, Palo Duro Canyon State Park.

Another type of small-scale faulting, caused by expansion during the hydration of anhydrite to gypsum, cuts thick gypsum beds. Fandrich (1966) reported reverse faults at an outcrop near the mouth of Sunday Creek that were related to the folding within thick gypsum beds. These faults cut only the gypsum strata in which they occur and are not associated with the reverse faults discussed previously. Displacement on these faults is less than 0.3 m.

Folds

Gentle folds displayed by Permian strata in the area are often attributed to (1) expansion associated with the hydration of anhydrite to gypsum or (2) collapse of strata caused by dissolution of evaporites (Matthews, 1969). Fandrich (1966) explained that expansion during the hydration of anhydrite created a 0.4-km^2 domal structure near the mouth of Sunday Creek. Small-scale folds in a thick section of interbedded gypsum and mudstone indicate that this section expanded laterally and vertically. The small folds plunge less than 10° in many directions. Folds caused by collapse of strata during dissolution include synclinal depressions up to 0.5 km in diameter and smaller funnel-shaped depressions.

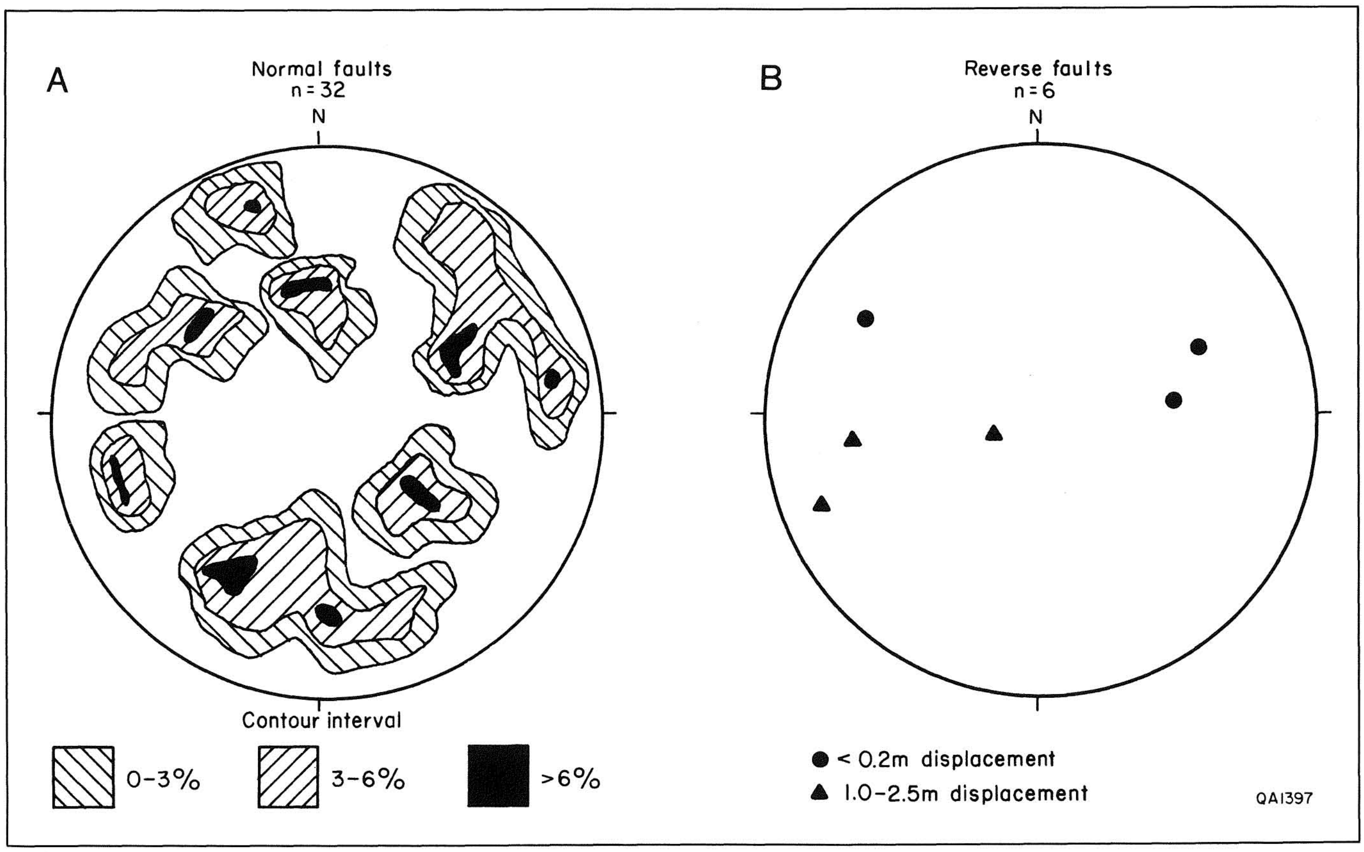

Figure 12. Lower-hemisphere, equal-area net plots of faults mapped at Palo Duro Canyon State Park. (A) Poles to normal faults. (B) Poles to reverse faults.

Dissolution-induced collapse and expansion caused by hydration of anhydrite have folded the Permian strata. Detailed structure maps of the area (figs. 13 and 14), however, exhibit a third folding style consisting of cylindrical folds having wavelengths of about 0.4 to 0.5 km and amplitudes of 10 to 15 m. Individual folds occur throughout the area and have been traced for more than 3 km. Three domains are indicated by different trends of these subparallel folds at 025°, 340°, and 305°. It has not been determined if one set of folds rotates into another set or if the folds terminate as they approach another domain. An angular unconformity between Permian and Triassic strata commonly occurs at the flanks of the anticlines (fig. 15). The unconformity indicates that the cylindrical folds were erosionally truncated before Triassic deposition. This folding is probably related to tectonic movement. Superimposed on the cylindrical tectonic folds are folds caused by dissolution-induced collapse.

History of Deformation

Permian strata exposed in Palo Duro Canyon State Park display several styles of deformation. A north-northwest-striking basement fault was mapped beneath the park area on the basis of seismic and borehole data. The reverse offset displayed by the fault is probably at a high angle. Systematic joints in the area may be related to the basement structure. Westward across the study area, sets of joints shift in strike from northwest (305°) to north-northwest (345°) (fig. 11). Minor reverse faults occur throughout the area, evidence of local east-northeast and west-southwest compression (075° to 255°) (fig. 12b). In the area, cylindrical folds are probably secondary features associated with a broader, more regional flexure and also suggest east-northeast and west-southwest compression (075° to 255°). An angular unconformity at the Permian-Triassic contact indicates that the folding had ended before Triassic deposition began.

Deformation caused by evaporite dissolution and collapse of strata was superimposed on preexisting structures. This style of deformation produced veins, small-scale normal faults, and synclinal depressions. Collapse of the Permian strata may have been partly controlled by the existing folds. Inclined veins for each fold domain (fig. 16) strike in many directions, but preferred strikes parallel fold axes. The strikes of systematic joints are thought to be related to the regional structure rather than to the secondary folds. Nonsystematic joints and inclined veins caused by dissolution and collapse may strike in any direction, although in each domain the predominant strike of the inclined veins parallels the axial trends of folds (fig. 16). The preexisting cylindrical folds apparently influenced the collapse of strata and the development of the inclined veins.

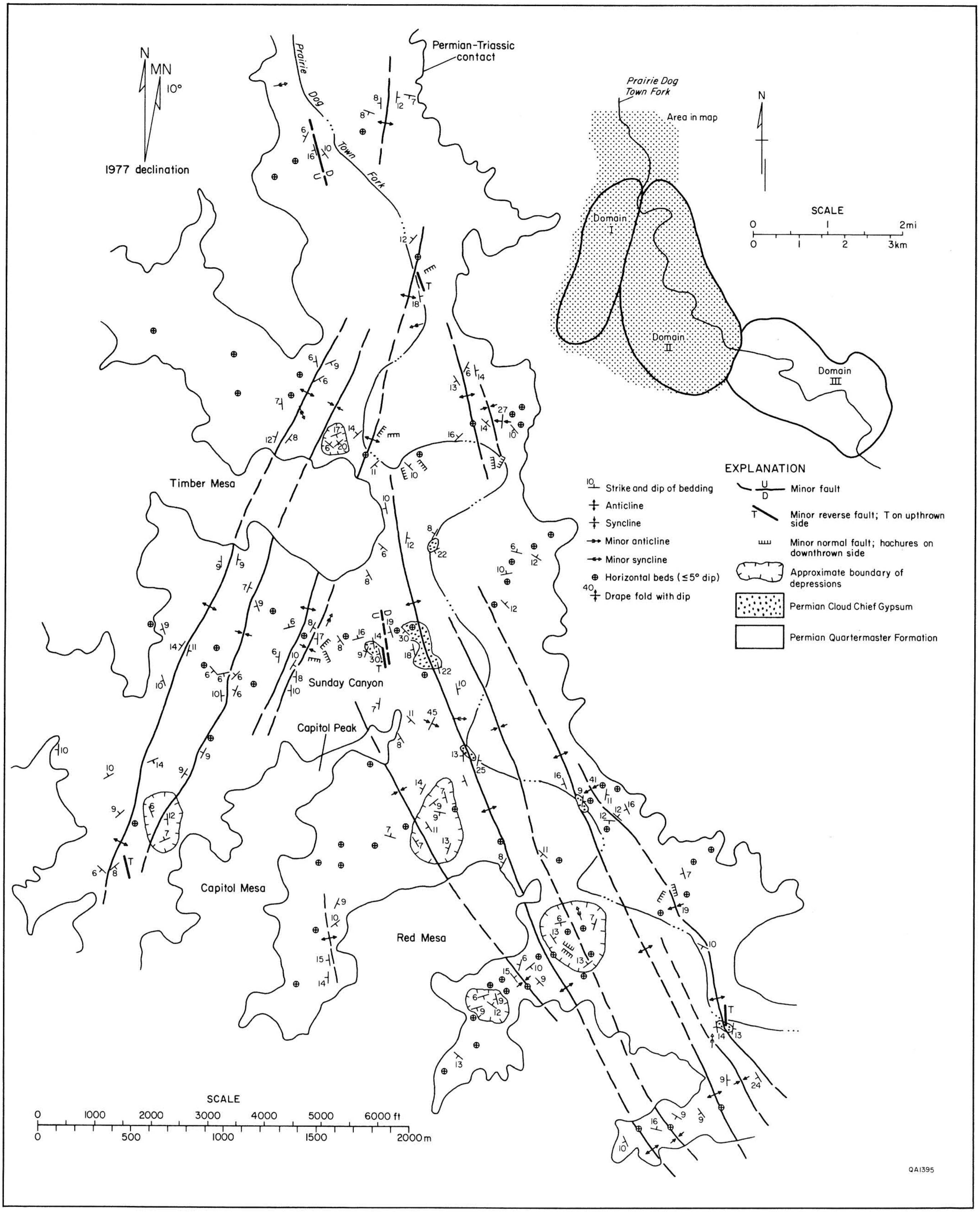

Figure 13. Structural elements of northwestern part of Palo Duro Canyon State Park.

The Canadian River valley crosses the central part of the Texas Panhandle above the Amarillo Uplift. The valley averages 180 m in depth and varies from 32 km to 60 km in width. Permian and Triassic strata are well exposed along the Canadian River and many of its tributaries. Here Permian red beds of the Whitehorse Group are overlain by the Alibates Dolomite, composed of dolomite beds intercalated with shale. The Alibates is about 4 to 5 m thick and is the stratigraphic equivalent of the Cloud Chief Gypsum exposed in Palo Duro Canyon State Park. Interbedded sandstones, siltstones, and claystones of the Permian Quartermaster Formation overlie the Alibates Dolomite. Triassic mudstones, siltstones, and sandstones of the Tecovas Formation and interbedded sandstones and conglomerates in the Trujillo Formation unconformably overlie Permian rocks. Tertiary Ogallala sediments and caliche overlie the Triassic deposits.

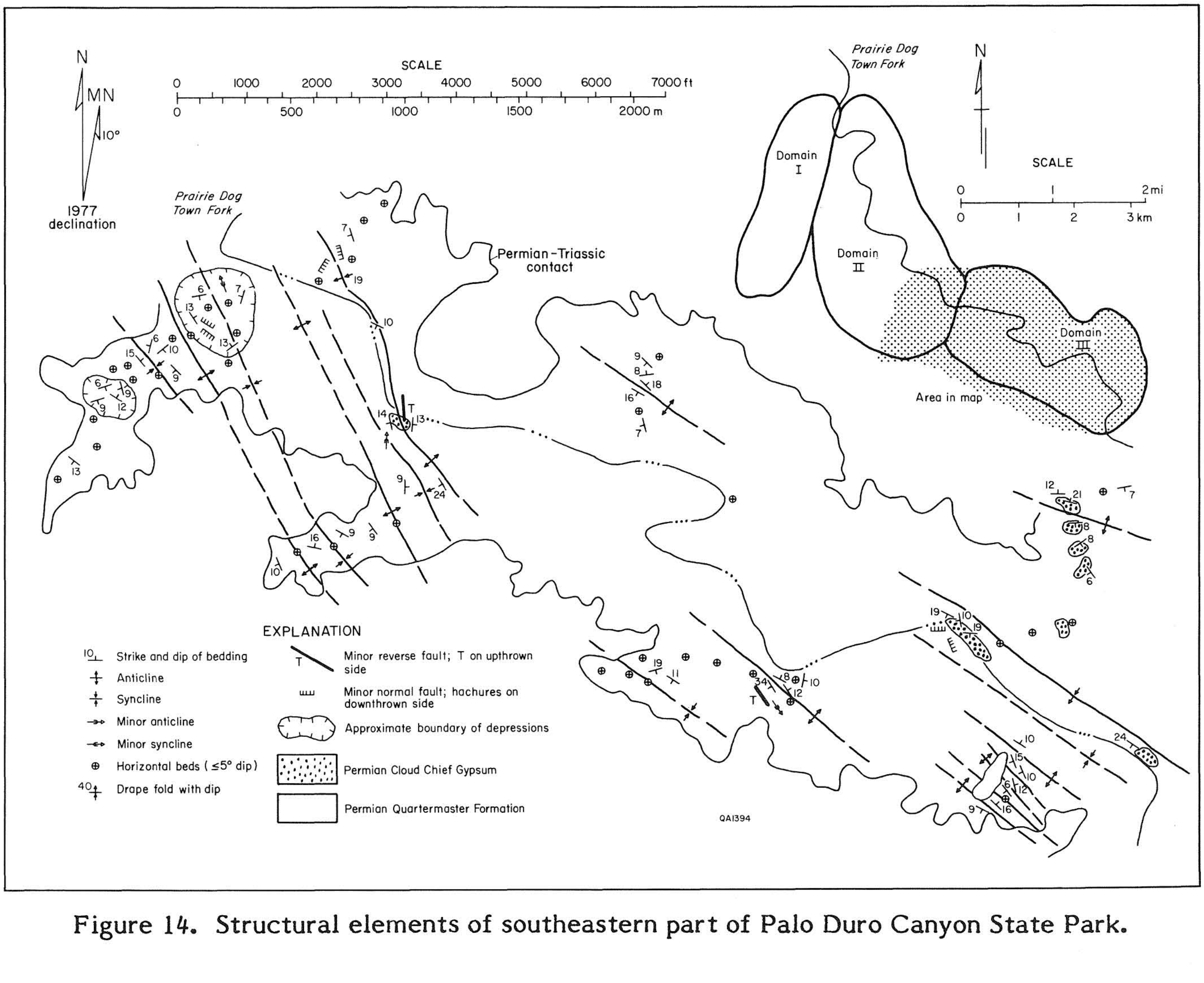

Figure 14. Structural elements of southeastern part of Palo Duro Canyon State Park.

The broad Bush Dome and the John Ray Dome (fig. 17) are associated with the Amarillo Uplift (Rogatz, 1939). To the east are Pantex Dome and 6666 Dome; Bravo Dome lies to the west. Early studies by Powers (1922) identify only a few faults that have small displacements associated with these domes. He explained that these domes formed by differential compaction of strata over basement highs rather than by recurrent motion of fault-bound basement blocks. Basement fault motion, however, should not be dismissed as a possible cause of the doming (McGookey and Budnik, 1983). Extensive drilling throughout the region revealed more faults in the subsurface. An exposed fault flanking the Bravo Dome was recognized by Pratt (1923, p. 248), who measured a throw of about 25 m. Deformed structures resulting from evaporite dissolution and collapse of strata were superimposed on the preexisting tectonic structures. Dissolution produced synclinal depressions, sinkholes, collapse chimneys, and clastic dikes.

Five locations within the Canadian River valley (fig. 17) are discussed in the following section. The first two localities are west and east of U.S. Highway 287 where it crosses the Canadian River. This area borders Bush and John Ray Domes; regional tectonic folds affect Permian and Triassic rocks here. The other three localities within the Lake Meredith National Recreation Area and the Alibates National Monument exhibit synclinal depressions, clastic plugs, and clastic dikes.

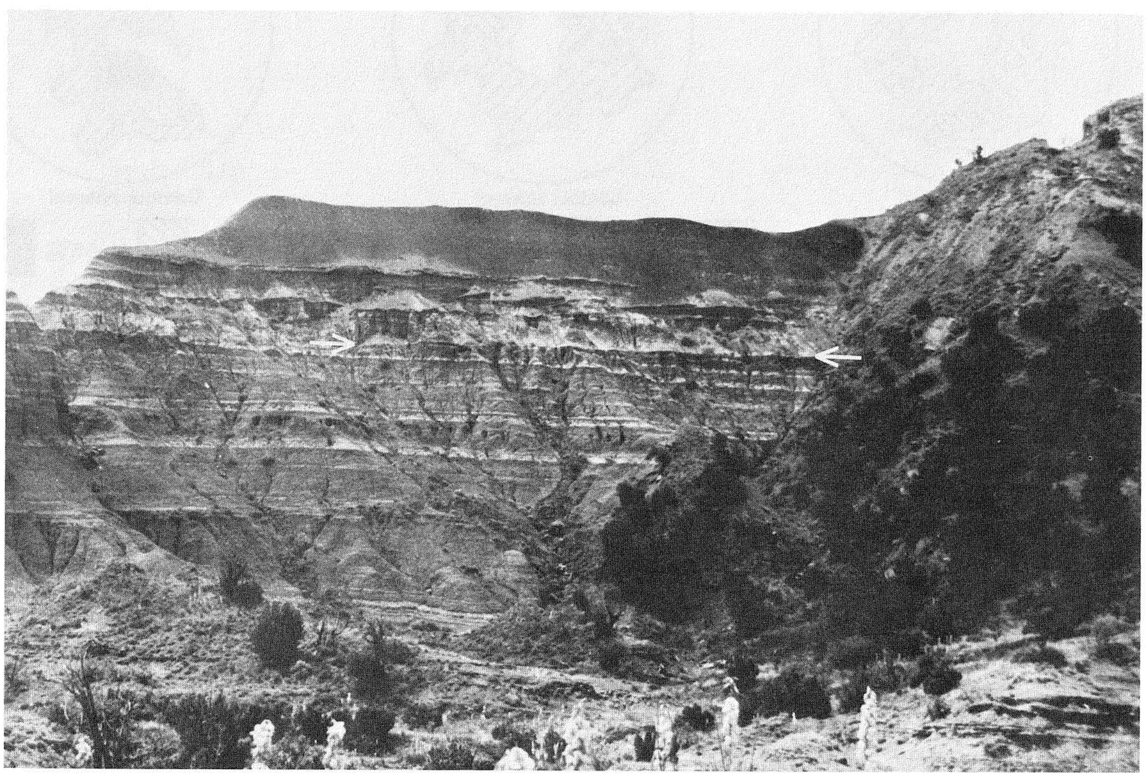

Figure 15. Angular unconformity between Upper Permian and Triassic strata. The exposure is approximately 0.1 km east of Capitol Peak; the view is southward. Arrow points to Permian-Triassic contact.

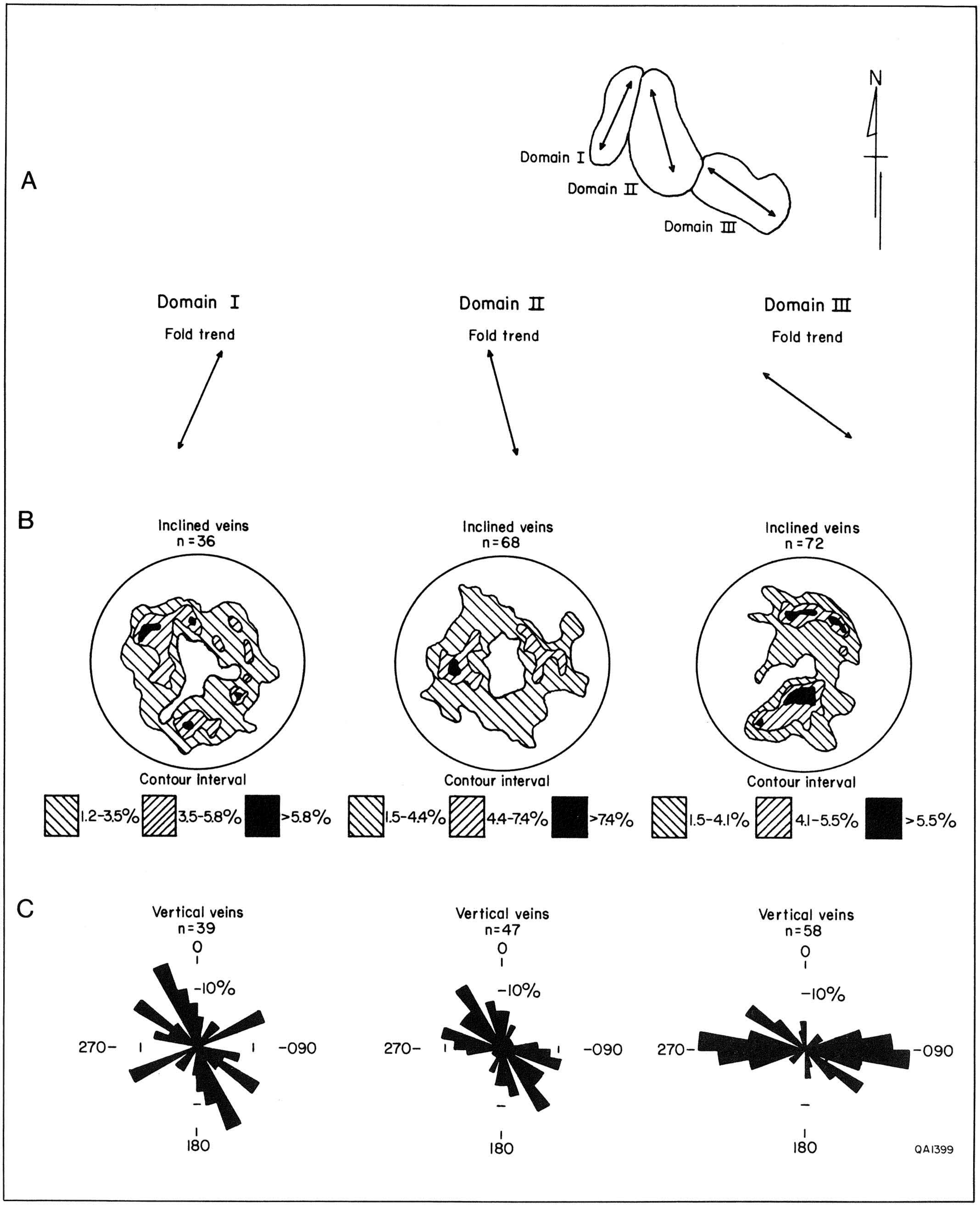

Figure 16. Structural characteristics in different domains within Palo Duro Canyon State Park. (A) Trends of folds. (B) Lower-hemisphere, equal-area net plots for inclined veins. (C) Rose diagram plots for vertical veins.

Regional Folds

East and west of the U.S. Highway 287 bridge over the Canadian River, Permian and Triassic strata dip gently away from John Ray and Bush Domes, respectively. About 5 km east of the highway, Permian and Triassic strata dip southwestward from the John Ray Dome (fig. 18): the Permian Alibates Dolomite and the Triassic Tecovas Formation dip 12° to 15° and 7° to 10°, and strike at 290° to 310°, respectively. At this flank of the dome, a zone of closely spaced joints in Triassic sandstones trends 310°.

About 1 km west of U.S. Highway 287, the Permian Alibates Dolomite dips away from Bush Dome at 7° to 15° to the northeast (fig. 19). Triassic Tecovas strata crop out east of

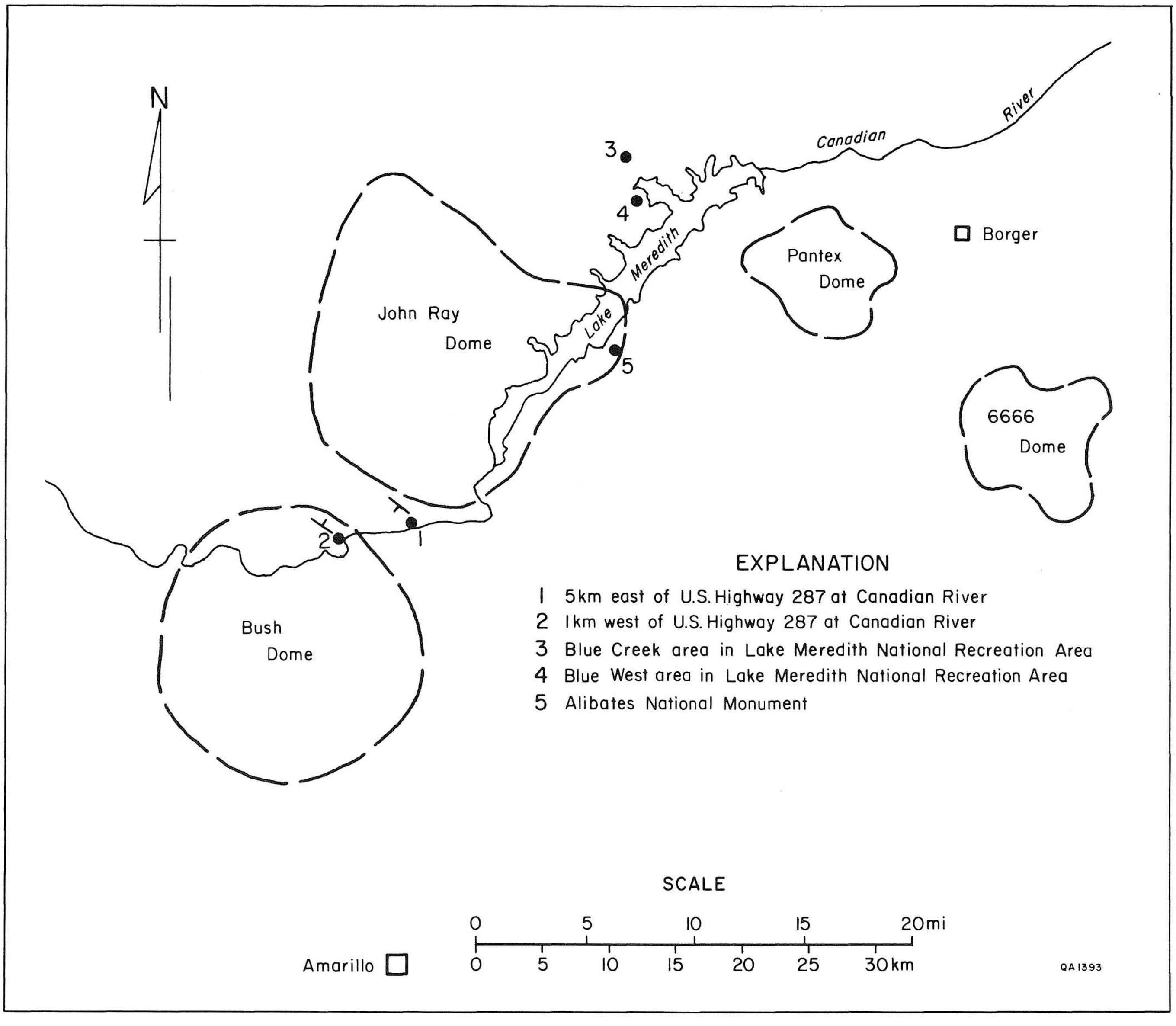

Figure 17. Structural setting and location of study areas within the Canadian River valley.

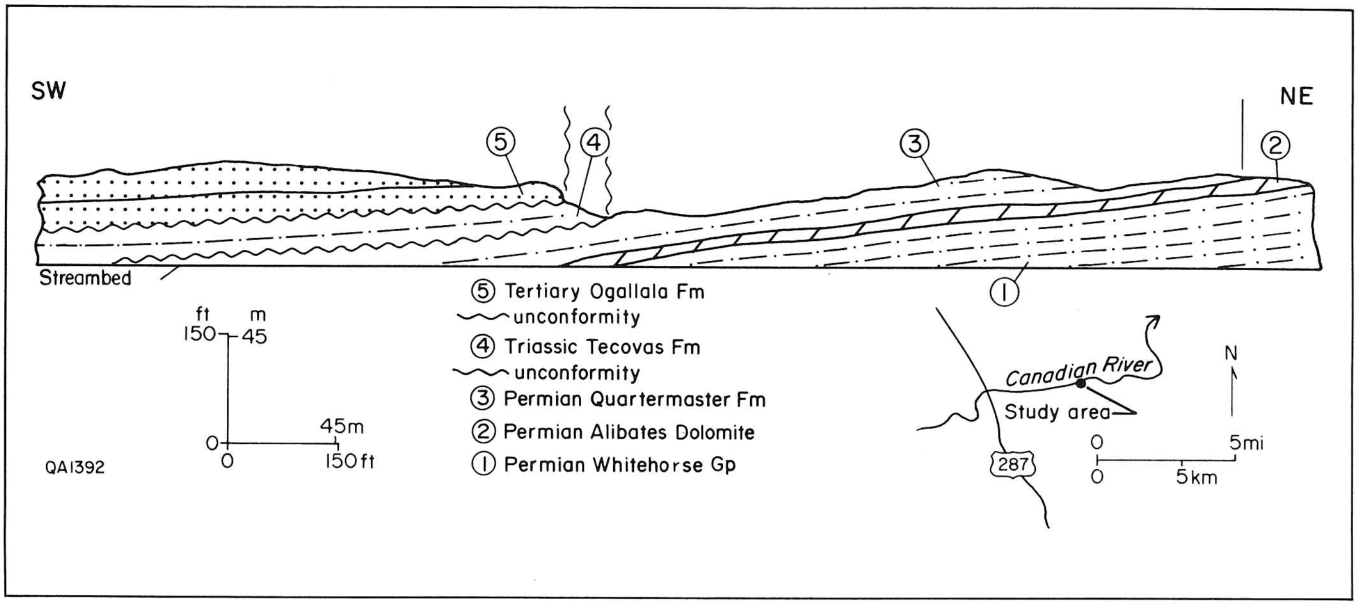

Figure 18. Cross section of Permian and Triassic strata exposed along the Canadian River, 5 km east of U.S. Highway 287. The cross section is drawn from a photograph.

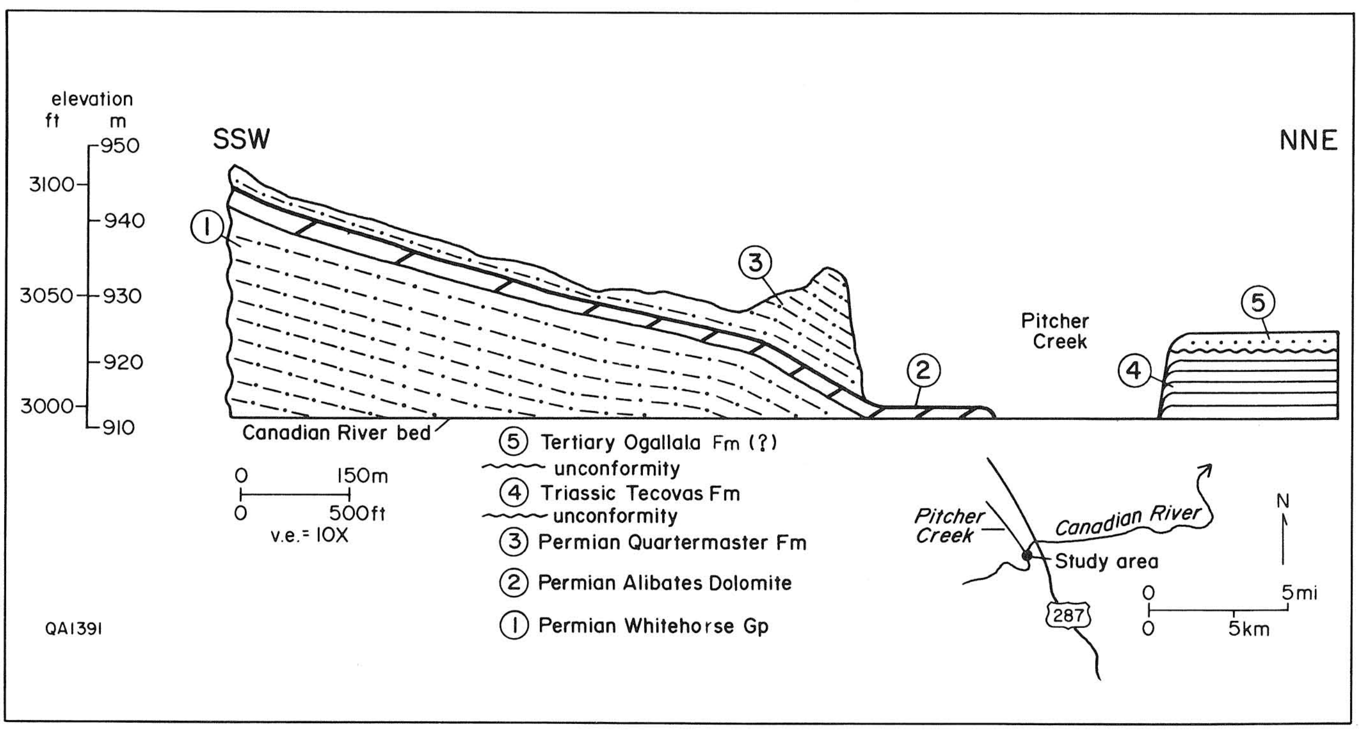

Figure 19. Cross section of Permian and Triassic strata exposed along the Canadian River, about 1 km east of U.S. Highway 287.

Pitcher Creek and dip to the southwest about 8° at the western limits of the outcrop; to the east, the Tecovas beds are horizontal. A fault may exist between the exposures of Permian and Triassic rocks at Pitcher Creek, although the folding of the strata can also account for the stratigraphic differences on either side of the creek. Joint sets in the Permian rocks strike at 310° to 340° and 050° to 070°.

The area between the Bush and John Ray Domes appears to be a broad syncline characterized by smaller scale folds. Faults were not noted in the area, although 1 km north of the locality (fig. 18) a surface fault flanking John Ray Dome displaces Permian and Triassic rocks (Barnes, 1969). A few funnel-shaped depressions in the area indicate that dissolution-induced collapse processes have been active.

Synclinal Depressions, Clastic Plugs, and Clastic Dikes

Chaotic folds related to evaporite dissolution-induced collapse are common in the Canadian River valley. Within the Blue Creek picnic site at Lake Meredith National Recreation Area, a synclinal depression having a major axis of about 0.7 km affects Permian strata (fig. 20). Bedding dips as much as 30° in this location, generally steeper than at Caprock Canyons and Palo Duro Canyon State Parks. Conical folds plunge into the depressions at about 15°. Nearby at the Blue West area, clastic plugs are associated with a synclinal depression (figs. 21 and 22); this elongate depression is about 0.3 km long, and clastic plugs of two distinct lithologies occur near the center of the depression. At the contact between bedrock and plugs, Permian strata typically dip toward the clastic plugs from 40° to nearly 90°. A clastic plug consisting of unconsolidated red clay and red, very fine to fine quartz sand is cut by two plugs composed of unconsolidated white, fine to very coarse quartz sand and gravel consisting of granule- to pebble-sized chert and metamorphic and sedimentary rock fragments. At the contact between the clastic plugs, calcite cements the unconsolidated white quartz sand and gravel of the younger plugs. This calcite-cemented zone is more resistant to erosion than are uncemented plug materials, and weathering has caused the cemented sands to be expressed as 0.2- to 0.5-m-wide dikes that dip toward and surround the younger plugs from 75° to 90°. Small vertical faults that displace Permian beds less than 0.5 m have developed during slippage of preexisting joints.

Evaporite dissolution and collapse of strata generated the synclinal depressions and clastic plugs. Collapse of overlying strata may have occurred concurrently with dissolution. Caverns also may have formed (Gustavson and others, 1982). Natural stoping in a cavern probably occurred when the cavern room could not support itself. A series of roof falls caused the collapse to propagate upward. Sinkholes at the surface and clastic plugs filled with collapse

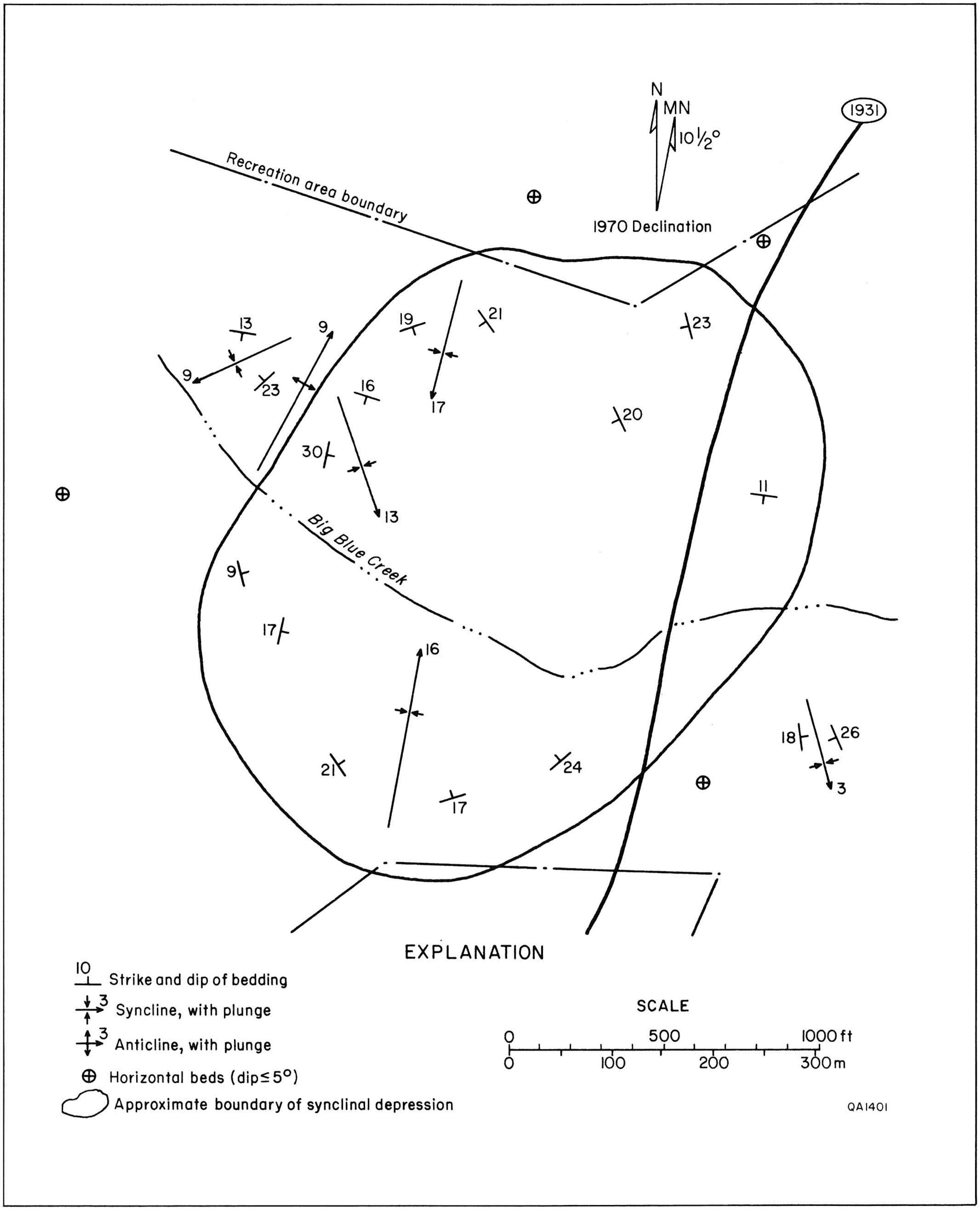

Figure 20. Map of synclinal depression at the Blue Creek area, Lake Meredith National Recreation Area.

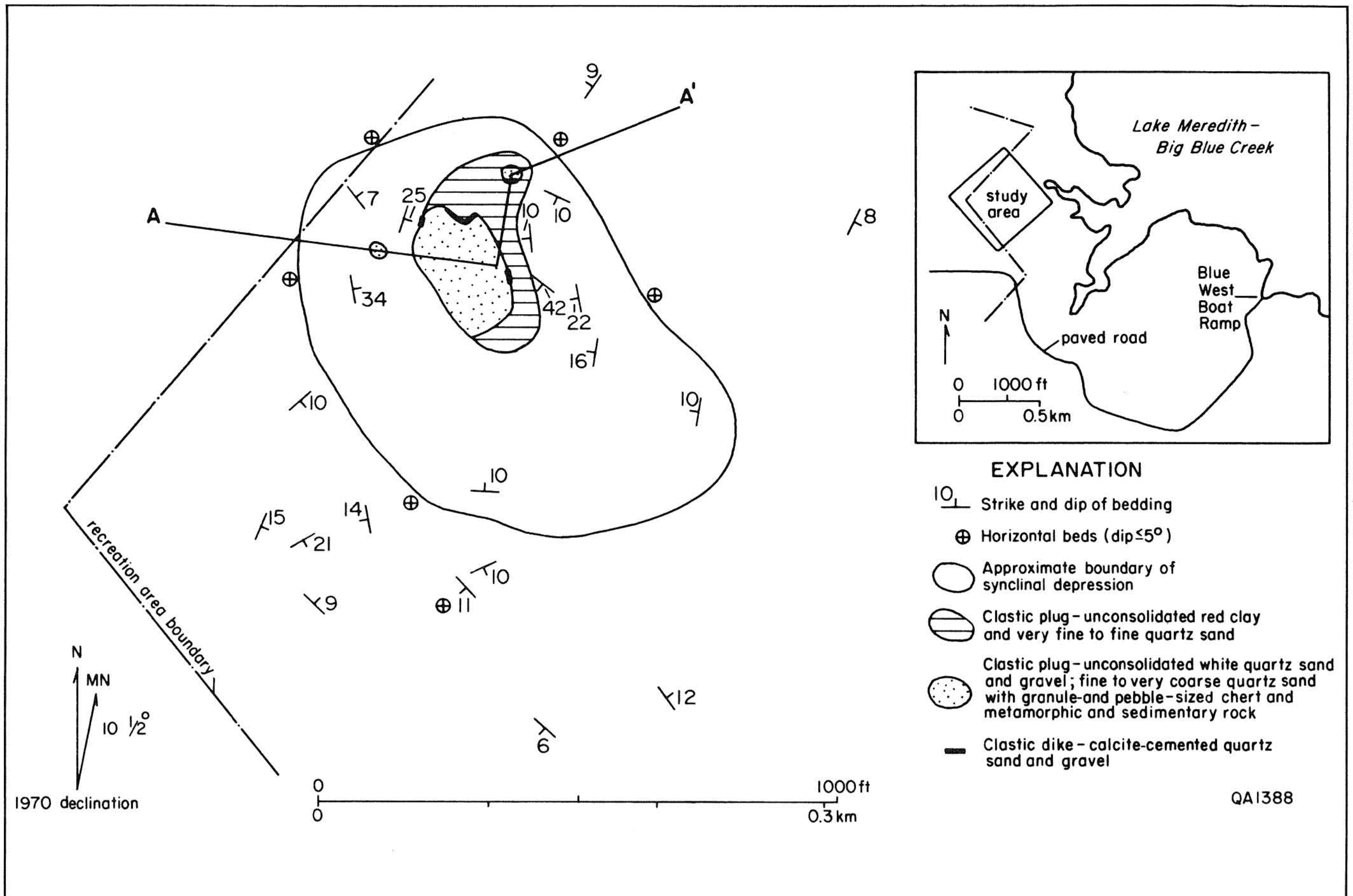

Figure 21. Map of synclinal depression and clastic plugs at the Blue West area, Lake Meredith National Recreation Area.

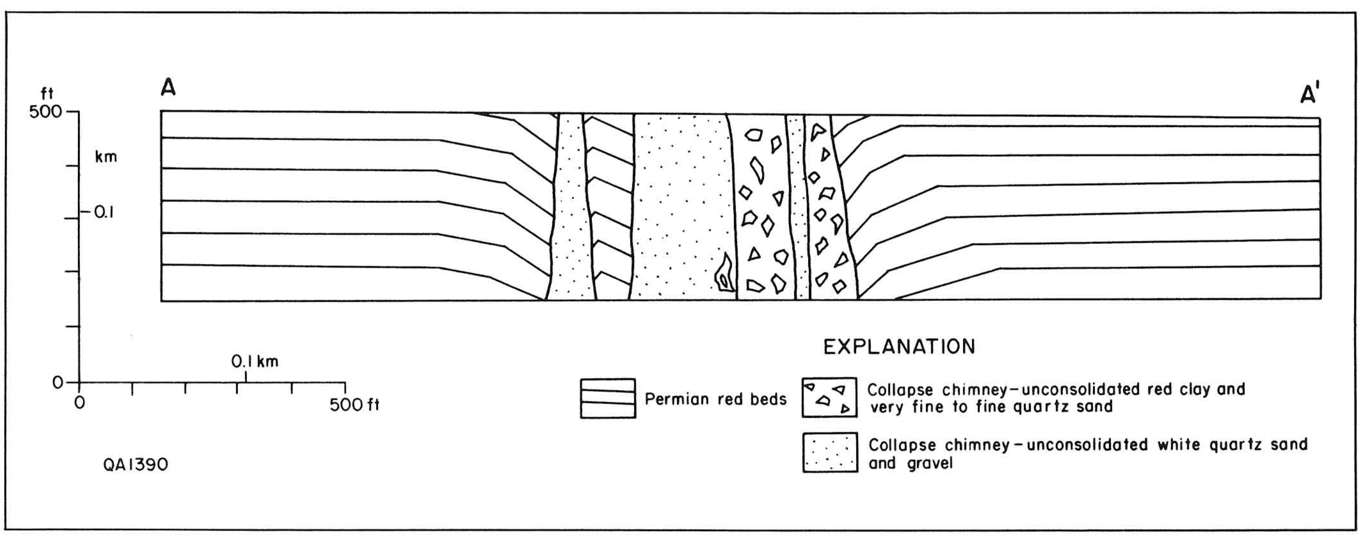

Figure 22. Cross section A-A' through clastic plugs (collapse chimneys). The older chimney composed of unconsolidated red clay and fine quartz sand is cut by a younger chimney composed of white quartz sand and gravel. Vertical scale is inferred. See figure 21 for line of section.

breccia were formed by this process (Gustavson and others, 1982). The crosscutting exhibited by clastic plugs at the Blue West area is evidence of different episodes of collapse. The age of the plugs is unknown, although recent sinkholes in the Panhandle indicate that collapse caused by dissolution is an ongoing process (Gustavson and others, 1982).

Clastic dikes appearing to be fractures or fissures that were filled from above cut strata throughout the Texas Panhandle (Collins, in press). At Alibates National Monument, numerous clastic dikes are adjacent to a funnel-shaped depression (fig. 23); Permian strata dip more than 35° toward the center of the depression. Composed of fine sand and clay clasts, the dikes at the edge of the sinkhole range in width from 1 to 20 cm and generally dip away from the depression at about 60° to 70° (fig. 23). The dikes thin, branch, and pinch out downward from the surface (fig. 24), denoting that they were filled from above. Subsidence caused by evaporite dissolution most likely produced the horizontal extension that opened the fractures.

CONCLUSIONS

Exposed Permian strata in the Texas Panhandle display a variety of deformational styles. At Caprock Canyons State Park in Briscoe County, a suite of structural features, thought to result from dissolution of evaporites and collapse of overlying strata, was observed. The structures include closed synclinal depressions, faults, and thick gypsum veins with vertical

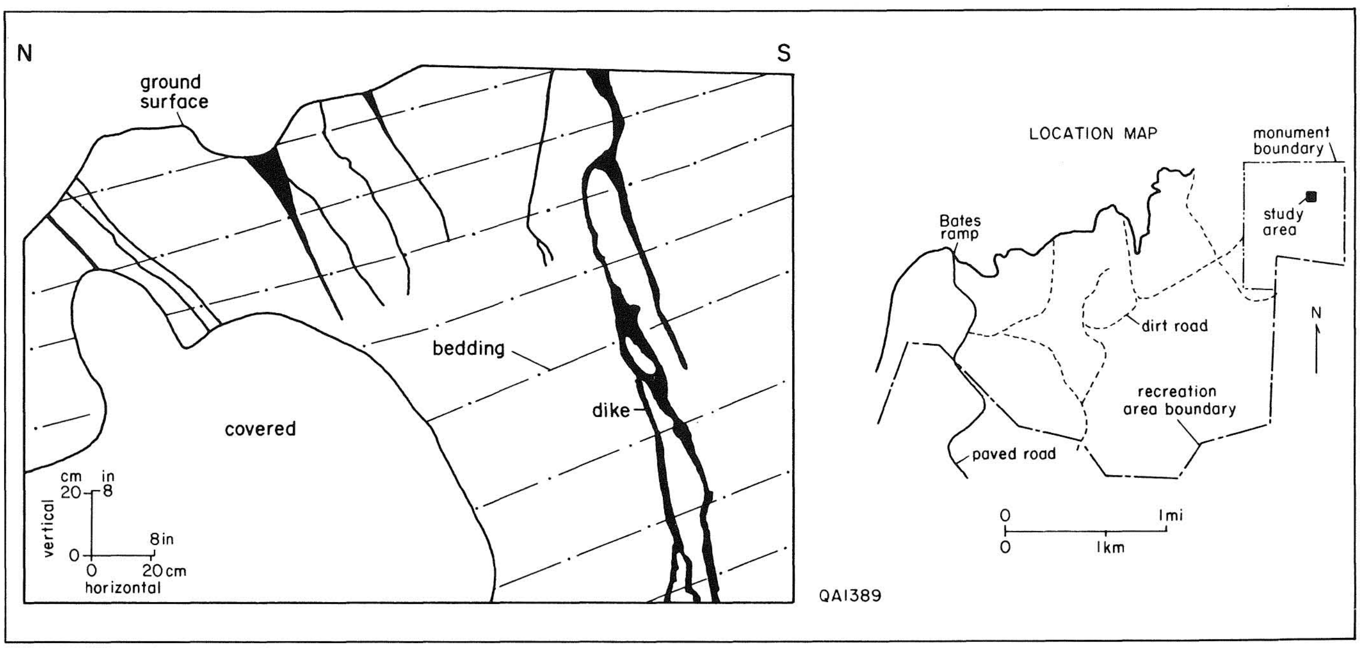

Figure 23. Clastic dikes adjacent to a funnel-shaped collapse depression at Alibates National Monument. Cross section is drawn from a photograph.

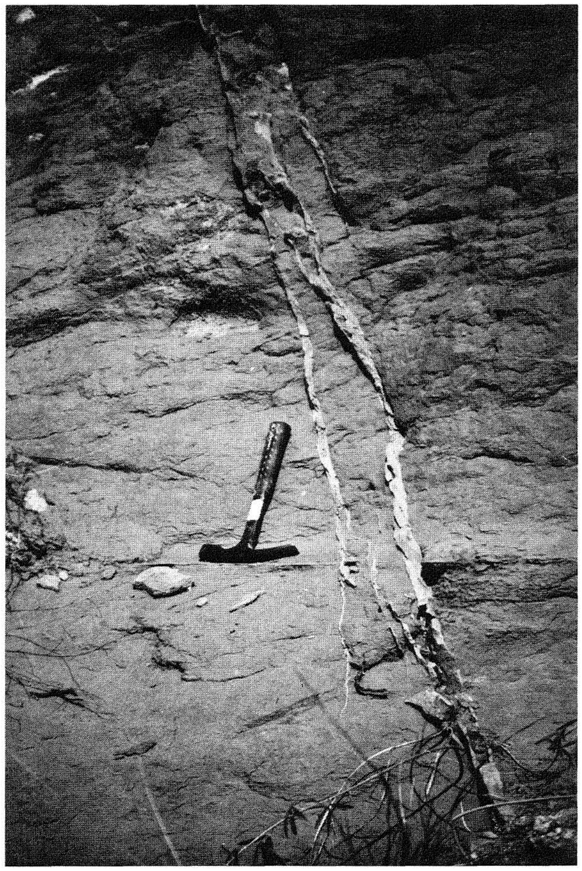

Figure 24. Clastic dikes that branch and pinch out with depth. Dikes are adjacent to a funnel-shaped depression at Alibates National Monument (fig. 23 study area).

extension fibers and are considered to have been strongly controlled by the presence of pre-dissolution zones of joints and by locally enhanced salt dissolution along these zones. These features suggest that ground-water movement and dissolution may be more pronounced along zones of systematic joints.

Deformation structures exposed at Palo Duro Canyon State Park in Randall County are probably associated with regional tectonic folding and evaporite dissolution and collapse. Subparallel cylindrical folds and minor reverse faults indicate east-northeast and west-southwest (075° to 255°) compression and are probably related to regional folding; the area overlies a northwest-southeast-trending basement fault. An angular unconformity between Upper Permian and Triassic strata along flanks of anticlines demonstrates that folding had ceased before Triassic deposition started. Evaporite dissolution and collapse of overburden have also deformed Permian strata in this area, resulting in closed synclinal depressions, faults, and gypsum veins.

Along the Canadian River valley in Potter, Moore, Carson, and Hutchinson Counties, both tectonic stress and salt dissolution have been documented. Regional drape folds overlying basement highs affect Permian and Triassic strata. These drape folds resulted from recurrent motion on fault-bounded basement uplifts or from differential compaction of strata over and adjacent to the uplifts. A suite of collapse structures comprising synclinal depressions, clastic plugs, and clastic dikes also exists in this area.

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