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JOINTING HISTORY OF THE PALO DURO BASIN

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Joints are fractures or partings in a rock that exhibit no displacement (Bates and Jackson, 1980, p. 334). Two styles of joints are systematic joints and nonsystematic joints (Hodgson, 1961). Systematic joints occur in sets. Joints composing each set are subparallel and are commonly orthogonal to the upper and lower surfaces of the rock units in which they are present. Nonsystematic joints display no preferred orientation and truncate against systematic joints.

Origin of Joints

Previous work on the origin of joints has determined different mechanisms to explain fracturing. Some researchers have explained joints in terms of their relationship to tectonic deformation and major structural elements (Harris and others, 1960; Price, 1966; Stearns and Friedman, 1972). Others have shown that joints may develop independently from tectonic deformation and that joints may form in sedimentary rocks early in their history (Parker, 1942; Hodgson, 1961; Price, 1966; Cook and Johnson, 1970). Price (1974) investigated the development of joints and stress systems in undeformed sediments during the accumulation of a sedimentary series, its downwarping and subsequent uplift, and accompanying dewatering of the sediments. Joints can also result from unloading due to erosion (Chapman, 1958). The formation of joints in sedimentary rocks is dependent on three factors (Hobbs, 1967): (1) physical properties of both the fractured rock bed and the surrounding rock beds;

(2) thickness of the rock bed; and (3) degree of tectonic deformation of the beds.

Joints in Pennsylvanian and Permian strata of the Palo Duro Basin area were probably formed by stress systems associated with the development of the basin and the surrounding areas of uplift. Joint orientations in Triassic and Permian rocks are similar in some areas, suggesting the same stress systems affected these sediments (see section on Fracture Orientations in Swisher and Deaf Smith Counties, page 5). Joints in Tertiary rocks are not common. Some joints and fractures are related to folds and faults that occur along the margins of the Palo Duro Basin (see section on Faults, Folds and Joints, page 3). Fractures have also developed from processes associated with collapse or downwarping of strata related to evaporite dissolution (see section on Fractures and Veins in Core, page 6).

Regional Fracture Trends

Ongoing studies to determine the regional fracture trends of the Texas Panhandle consist of measuring joint strikes in outcrop and fracture orientations from fracture identification logs. Most data have been collected along the High Plains Escarpment and the Canadian River Valley (fig. 1). Outcrops are sparse in the Texas Panhandle; thus, there is a wide range (10 to >100) in the number of measurements that were made at the various study locations. Stations with the greater number of measurements are given more emphasis for interpretations. Dominant fracture trends were determined using the X^2 test of significance at a 95 percent confidence interval. Methods for using this statistical test have been described in detail by Dix and Jackson (1981).

Figure 2 shows the dominant fracture orientations in the Texas Panhandle and Eastern New Mexico. A group of east-west oriented fractures with an azimuth range of 070°-120° occur throughout the study area. Several sets occur within this fracture group. One set striking 100°-120° (280°-300°) is important, because it trends across Swisher County and possibly through Deaf Smith County (fig. 3). Two sets of northwest-oriented fractures strike at 300°-320° and 330°-350° (figs. 4 and 5). These fractures appear to be most common northeast of Swisher and Deaf Smith Counties; however, data are sparse southwestward. A group of fractures striking northeast at 030°-060° probably occur in two sets (fig. 6). This group of fractures prevails in the northwestern part of the study area and are not common southeast of Deaf Smith County. A fracture set oriented at 000°-020° is less common than the other fracture trends (fig. 7).

Faults, Folds, and Joints

Fracture orientations at various locations in the Texas Panhandle and Eastern New Mexico coincide with trends of faults and folds. At the western margin of the Palo Duro Basin, joint trends are similar to the strikes of faults mapped from surface exposures (fig. 8). The Bonita Fault and the Alamosa Creek Fault strike at 040°-050°. The Bonita Fault occurs in Quay County, New Mexico, and has been mapped and described by Lovelace (1972a, 1972b), Stearns (1972), Berkstresser and Mourant (1966), Dobrovolny and others (1946), and Winchester (1933). The Bonita Fault is a normal fault that trends 045°, dips 60° westward, and has a throw up to [illegible] feet. It is associated with an antithetic fault zone, so that the complete Bonita Fault System consists of a tilted graben block up to 1.5 miles wide. Cretaceous age strata are faulted against Triassic Dockum rocks. Shear and extension fractures are associated with the Bonita Fault Zone (Stearns, 1972).

In northern Roosevelt County the Alamosa Creek Fault has been mapped by Lovelace (1972b). The fault strikes at 055°; the dip and throw have not been determined. The total faulted system comprises a graben block with Cretaceous age strata faulted against Triassic Dockum strata, similar to the Bonita Fault System. Undisturbed Tertiary Ogallala sediments are mapped over both faults, suggesting pre-Ogallala fault movement. Ongoing field studies are investigating possible post-Ogallala fault movement at the Alamosa Creek Fault, because a post-Ogallala stream valley diverts the surface drainage and follows the fault. The Bonita and Alamosa Creek structures are also recognized in the subsurface in figure 9. The structure exhibited at the base of the Permian San Andres Formation is below any salt dissolution that might have occurred in this area. Boreholes drilled to basement are too sparse to determine if basement structure exists.

These faults strike similar to the regional fracture group shown in figure 6. Also aligned with these northeast trending structures is an unnamed fault located in Potter County, Texas, near latitude 35°30', longitude 101°45' (fig. 10). This small, normal fault strikes at 045° and dips 80°-90° to the southeast. The Permian Alibates Formation is offset 30 feet and faulted Permian Quartermaster strata are overlain by undisturbed Tertiary Ogallala sediments.

Data also indicate fractures are associated with broad, drape folds related to the Amarillo Uplift. East and west of the U.S. Highway 287 bridge crossing the Canadian River in Potter County, Texas, Permian and Triassic strata dip gently off the John Ray and Bush Domes (fig. 10). About 5 km east of the highway, Permian, Triassic, and Tertiary strata dip 0-15° south-southwestward off of John Ray Dome. Also flanking John Ray Dome is a surface fault that displaces Permian and Triassic rocks (Barnes, 1969). The strike of this fault is 310°-295°. Joints in the folded Permian and Triassic strata strike 310°, similar to the fault trend in this area (fig. 11). The joints are almost perpendicular to the sandstone beds; thus, joints in dipping strata dip only 80°-90° northeastward. The close spacing of fractures is apparent in the thick Triassic sandstone beds; 10-16 fractures per 2 m occur in beds 1 to 2 m thick.

The trends of joint sets and small-scale faults in basal, Tertiary Ogallala sandstones and conglomerates suggest stress directions changed after fracturing of the Triassic rocks. Joint sets in the Tertiary Ogallala rocks strike at 025° and 295° (fig. 11). Normal faults with displacements less than 0.5 m also occur in the Ogallala strata (fig. 12). Two categories are based on the dip of the faults. Faults dip (1) nearly vertical and (2) 50°-60° north-northeast and south-southwest. Most faults strike between 270° to 300°. Beds thicken on the downthrown blocks of several faults that dip 50°-60°. This indicates some syndepositional fault movement. Faults and fractures are usually not common in Tertiary Ogallala rocks in the Texas Panhandle.

The fractures are believed to be caused by extension related to the folding of the strata. The John Ray Dome is one of several regional anticlines associated with the Amarillo Uplift (Rogatz, 1939). Early studies by Powers (1922) identified only a few faults with small displacements associated with these domes. He explained these domes by differential compaction of strata over basement highs rather than by recurrent motion of fault-bound basement blocks. However, basement fault motion should not be dismissed as a possible cause of the doming (Budnik, 1984) (Budnik, see SCR sections 3.3.2.2 Faulting History and 3.3.2.3 Folding History). Extensive drilling throughout the region has identified more faults in the subsurface.

Fracture Orientations in Swisher and Deaf Smith Counties

Fracture orientations in Pennsylvanian, Permian, Triassic and Tertiary strata were measured from Schlumberger fracture identification logs in Swisher and Deaf Smith Counties (figs. 13 and 14). A fracture set striking at 280°-300° occurs within the Pennsylvanian, Permian, and Triassic strata in Swisher County (fig. 13). Within the Permian salt zone units fracture sets also strike at 000°-020° and 080°-090°; fractures striking at 030°-040° and 320°-330° are not as abundant. In the Tule Canyon area joints in Triassic rocks predominantly strike 280°-290° and 300°-320°. Less common joint sets strike 330°-350°, 000°-020°, and 030°-040°.

In northeast Deaf Smith County, fractures oriented eastward and northeastward prevail (fig. 14). Pennsylvanian strata have dominant fracture sets striking 290°-300° and 020°-030°. Other fractures trend at 080°-090° and 340°-350°. A strong east-west (080°-100°) fracture set occurs in the Wolfcamp strata. Fracture sets striking at 070°-100° and 030°-050° occur in Permian salt zone units, as well as Triassic and Tertiary rocks.

Fractures and Veins in Core

The abundance of fractures and veins in Permian strata has been analyzed in core from boreholes drilled in Oldham, Deaf Smith, and Swisher Counties (fig. 15). The cored strata range from Wolfcamp Group to the Alibates Formation. Units are grouped into three categories based on lithology and stratigraphic sequence (Hovorka, personal communication, 1983). The categories are (1) strata below salt units (Wolfcamp Group), (2) salt zones units, and (3) dissolution zone units. The boundary between the dissolution zone units and the salt zone units is not the same at each borehole.

The number of one-foot intervals that contain fractures are recorded for all of the cored intervals. The percentage of fractured core for each unit is determined by dividing the number of one-foot core intervals containing fractures by the total core footage, and then multiplying by one hundred (fig. 16).

Figure 16 compares the boreholes and the percentage of fractures in the core for the units (1) below the salt zone, (2) within the salt zone, and (3) within the dissolution zone. The dissolution zone units are more fractured than salt zone units. The salt zone unit category contains the lowest percentages of fractured core, probably because the fractures almost always occur in thin mudstone, siltstone, and anhydrite interbeds. Vein-filled fractures within the thicker salt sequences are rare. The Stone and Webster-Mansfield #1 borehole in Oldham County has the greatest percentage of fractured core for the three categories. This might be expected, because this borehole is located within the Bravo Dome-Amarillo Uplift area. The uplift area borders the Palo Duro Basin on the north and is believed to have been more tectonically active than the basin during and after Permian time. The frequency of fractures in Wolfcamp core decreases away from the Bravo Dome-Amarillo Uplift. The fracture percentages in core within the salt zone units are similar for all boreholes in the three counties.

The fractures are commonly filled with gypsum, halite, anhydrite, or calcite veins. Vein fillings within the salt dissolution zone strata are predominantly fibrous gypsum (fig. 17). Gypsum veins in Permian strata of Randall and Briscoe Counties have been described by Goldstein (1982) and Goldstein and Collins (1984). The gypsum veins are bisected by a medial scar and are believed to be an antitaxial type of "crack-seal" vein (Ramsey, 1980; Ramsey and Kligfield, 1983, section 14). Gypsum veins as wide as 5 cm are common.

Fractures within the salt zone units are characterized by fibrous, halite veins, commonly 0.5-1.0 cm wide. The veins usually occur within mudstone, siltstone, and anhydrite beds. Halite fills over 80 percent of the fractures in the salt zone strata (fig. 18).

In the strata beneath the salt zone units, the fractures are commonly filled with anhydrite and calcite or have no vein fillings (fig. 19). Halite and gypsum veins occur within upper Red Cave and Wichita strata, respectively, in the Oldham County, Stone and Webster-Mansfield #1 borehole. The fibrous veins in the units beneath the salt-bearing strata are usually less than 1.0 cm wide.

Veins and Fractures in Outcrop

Detailed field studies of joints and gypsum veins have been done at Caprock Canyons State Park in Briscoe County (Goldstein and Collins, 1984; Goldstein, 1982). This area was studied because few outcrops occur in the interior of the High Plains. Caprock Canyons State Park straddles the eastern high-plains escarpment, which has relief up to 200 m in the park area (fig. 20). There are excellent exposures of Upper Permian strata along the escarpment and in incised streams that drain eastward into the Rolling Plains. Other exposures are rare. Exposed in the park (fig. 21) are the Upper Permian Whitehorse Sandstone and Cloud Chief Gypsum of the Whitehorse Group. These units are composed of interbedded shale, siltstone, sandstone, and gypsum beds. In this area, gypsum beds near the top of the Whitehorse Group are up to 4 m thick. 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. The park is located above a zone of regional salt dissolution (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 deformation structures occur within the park (fig. 21). The upper, relatively undeformed strata zone occurs in the massive, thickly bedded sandstones in the upper portion 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. 21). In this zone thinly bedded siltstones and sandstones are interlayered with bedded gypsum. Within the more deformed rocks of this lower zone are normal faults, reverse faults, and gypsum veins along fault contacts, bedded planes, and joint surfaces. Folds and funnel-shaped depressions also occur.

Systematic and nonsystematic joints are characteristic of the undeformed zone (fig. 21). Systematic joints are vertical, evenly-spaced, regularly oriented fractures. The predominant systematic joint sets strike north, northeast, and east. A less significant set strikes northwest. One or more of these four sets of joints are predominant within different domains in the park area. Hackle fringes and plume structures on joint faces are evidence of horizontal propagation under the influence of horizontal extension. Nonsystematic joints are curved, irregularly spaced, show no preferred orientation and truncate against systematic joints. Many nonsystematic joints have surface markings that indicate vertical propagation directions (Goldstein, 1982).

Zones of closely-spaced systematic joints exist throughout the park (Collins, 1983). Joint zones as wide as 40 m extend vertically through Permian and Triassic beds and horizontally up to at least 1 km (fig. 22). Within joint zones, the density of joints averages 5 joints/m for sandstone beds 3 m thick. Away from joint zones, densities average 0 to 1.5 joints/m 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 (fig. 23). Joint densities are almost constant for beds greater than 1 m thick.

Three types of gypsum veins are present in the deformed zone of strata. They are either vertical, parallel to bedding, or cut the bedding at 30 to 60 degrees (fig. 24). The veins are composed of fibrous gypsum bisected by a medial scar. They are believed to be of the antitaxial type of crack-seal veins (Ramsay, 1980; Ramsay and Kligfield, 1983, section 3.14), in which the medial scar probably marks the site of earliest mineralization with new material added at the vein-wall rock contact. The mineral fibers denote the direction of maximum principal extension at the time they were added to the vein.

The gypsum fibers in the vertical veins are horizontal, indicating that these veins formed by horizontal extension. These veins probably formed under high fluid pressure in the 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. 25a), 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. 25b) display similar orientations to the normal faults. Most of the reverse faults exhibit northward, eastward, and southward dips. Reverse faults are less common than normal faults. Inclined veins (fig. 25c) have orientations similar to faults, suggesting that they are filled faults. Nearly all veins along fault planes display undeformed crystals adjacent to the vein wall rock contact, indicating that fault movement predated mineralization.

The geometry of vein intersections also reveals that faulting predated mineralization (Goldstein, 1982). The 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. For the most part, however, vein fibers are straight and do not deviate from vertical by more than about 10 degrees in the horizontal and inclined veins, evidence that these veins were formed by vertical extension. Where the veins intersect, vertical veins are everywhere cut by inclined veins and nearly everywhere cut by the horizontal veins.

Chaotic folds in the upper zone of deformed strata cause the Quartermaster and Whitehorse beds to dip commonly 10 to 20 degrees. Detailed structural mapping has defined synclines that vary from elongate to circular (fig. 26). These synclinal depressions are up to 1.5 km long and are composed of conical synclines and anticlines that plunge gently up to 10 degrees toward the center of the depression (fig. 27). The amplitude of these folds is normally less than 10-15 m. Rim anticlines or domes may also occur along the periphery of the principal synclinal depressions, commonly separating them. Smaller-scale folds with amplitudes less than 2 m also exist. Although they may be associated with the formation of the larger synclinal depressions, some of the smaller folds were probably formed by expansion associated with the conversion of anhydrite to gypsum (Fandrich, 1966).

A close association exists between the systematic joints, veins, and principal synclinal depressions. The major trends of the depression axes are 005°, 025°, 055°, 080°, and 275°, similar to the vertical veins and systematic joint sets (fig. 28). 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. 29). Strikes of the small-scale faults exhibit a similar relationship, although the faults are less common than the other structures.

Dissolution of salt and collapse or gentle subsidence under the influence of gravity is believed to be the process that caused the folds, faults, and veins observed in this area. A simplified model for the development of the deformation structures is shown in figure 30 (Goldstein, 1982). Stage 1 is a normal burial process and is recorded in nearly every sedimentary rock. Stage 2 is a result of horizontal extension and occurred when dissolution was initiated. This 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 proceeded, maximum extension changed from near horizontal to near vertical. Gentle folding and nonsystematic fracturing continued due to the removal of support from below; veins are mineralized with vertical extension of 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 enhanced fluid flow and dissolution was, and presumably is, at least partially controlled by predissolution joints.

The position of the boundary between the deformed zone and overlying undeformed zone is a function of bed thickness and vertical distance from dissolution (fig. 21) (Goldstein and Collins, in press). Beds in the zone of deformed strata are almost everywhere 1 m to 0.1 m thick. Overlying undeformed beds are rarely less than 2 m thick and more commonly are as thick as 10 m. Thicker beds have a higher flexural rigidity and would not flex to allow local development of extension parallel to the layers.

Clastic Dikes

Clastic dikes are among the deformational features observed in outcrop in Randall, Potter, Moore, Oldham, Briscoe, Hartley, and Hall Counties of the Texas Panhandle, as well as at localities in the Oklahoma Panhandle and eastern and northeastern New Mexico. These clastic dikes usually range in thickness from about 15 cm to 3 mm, although dikes in northeastern New Mexico and western Oklahoma are as thick as 1.5 m. In the Texas Panhandle, poor exposures prevent tracing the vertical and lateral extent of most of the dikes. Almost all of the dikes cut upper Triassic or Permian strata, although clastic dikes have also been observed in the Pliocene Rita Blanca Formation in Hartley County and in Pleistocene deposits in Hall County.

The mechanics of dike emplacement are difficult to determine unless the dikes can be traced in outcrop to source beds. The composition of a dike usually cannot indicate a definite source bed, because Triassic, Tertiary, and Quaternary sediments have similar lithologies.

The dikes appear to have been formed from the filling of fractures of fissures from above. At Buffalo Lake in western Randall County, dikes from overlying Ogallala source beds cut Triassic Dockum sediments. Where a dike termination can be observed with depth, the dike thins and pinches out. The trends of these dikes are very similar to fracture orientations measured at this location (fig. 31). Dikes in Hartley, Randall, and Oldham Counties, Texas, and dikes in southeastern Quay County, New Mexico, also appear to be due to fracture filling (fig. 31). Subsidence is the likely mechanism by which horizontal strain and extension have opened the fractures or fissures. In the Texas Panhandle geomorphic features such as recent fissures, sinkholes, collapse basins, and breccia-filled chimneys have been attributed to subsidence processes caused by evaporite dissolution (Gustavson and others, 1980; Gustavson and others, 1982). Subsidence created by differential compaction is another mechanism that can develop fissures (Jachens and Holzer, 1982), although in the Texas Panhandle evaporite dissolution is the most likely cause for subsidence.

Although most of the clastic dikes in the Texas Panhandle appear to be emplaced during the Cenozoic, dikes cutting Triassic sediments at one locality in Palo Duro Canyon State Park appear to have originated from a sand unit within the Triassic. The predominant dike trend at this locality is the same as one of the joint trends, although dikes strike in other directions (fig. 31).

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Figure Captions

Figure 1. Station locations for fracture measurements in the Palo Duro Basin Area, Texas Panhandle.

Figure 2. Strikes of predominant fracture sets in the Palo Duro Basin area, Texas Panhandle.

Figure 3. Locations where a predominant fracture set strikes at 280°-300°.

Figure 4. Locations where a predominant fracture set strikes at 300°-320°.

Figure 5. Locations where a predominant fracture set strikes at 330°-350°.

Figure 6. Locations where a predominant fracture group strikes at 030°-060°.

Figure 7. Locations where a predominant fracture set strikes at 000°-020°.

Figure 8. Strikes of faults and joints at the western margin of the Palo Duro Basin in eastern New Mexico.

Figure 9. Structure contour map on base of the Permian San Andres Formation in Quay, Curry, and Roosevelt Counties, eastern New Mexico.

Figure 10. Locations of the John Ray and Bush Domes, Potter County, Texas.

Figure 11. Joint strikes in overlying Permian, Triassic, and Tertiary rocks exposed at a northwest trending drape fold on the southwest flank of John Ray Dome, Potter County, Texas (fig. 10).

Figure 12. Poles to normal faults cutting Tertiary Ogallala strata at a northwest trending drape fold on the southwest flank of John Ray Dome, Potter County, Texas (fig. 10). Fault displacements are less than 0.5 m.

Figure 13. Strikes of fractures in Pennsylvanian, Permian, and Triassic strata in Swisher County, Texas. Fracture orientations in Pennsylvanian and Permian strata were determined with fracture identification logs from the Stone and Webster-Harman #1 and Stone and Webster-Zeeck #1 boreholes. Joints in Triassic strata were measured from outcrop.

Figure 14. Strikes of fractures in Pennsylvanian, Permian, Triassic, and Tertiary strata in Deaf Smith County, Texas. Fracture orientations were determined with fracture identification logs from the Stone and Webster-G. Friemel #1, Stone and Webster-Detten #1, and Stone and Webster-J. Friemel #1 boreholes.

Figure 15. Locations of boreholes used for fracture studies in the Palo Duro Basin area.

Figure 16. Percentage of fractured Permian core from boreholes in Oldham, Deaf Smith, and Randall Counties, Texas. Abbreviations of Permian formations are as follows: A - Alibates; S/T - Salado-Tansill; Y - Yates; SR - Seven Rivers; QG - Queen Grayburg; SA -San Andres; G - Glorieta; uCF - upper Clear Fork; T - Tubb; lCF - lower Clear Fork.

Figure 17. Composition of veins in core of the Red Cave Formation and Wichita and Wolfcamp Groups. These units are stratigraphically below the Permian salt-bearing units.

Figure 18. Composition of veins in core of Permian salt-bearing strata.

Figure 19. Composition of veins in core of Permian strata that has been affected by salt dissolution.

Figure 20. Structural setting of the Palo Duro Basin (A) and location of Caprock Canyons State Park (B).

Figure 21. Stratigraphy and deformational elements at Caprock Canyons State Park.

Figure 22. Cross-section view of a joint zone extending through Permian and Triassic rocks at Caprock Canyons State Park in Briscoe County. Overlying Tertiary Ogallala sediments are also fractured, although it is uncertain if the Ogallala fractures are actually systematic joints that are part of the joint zone.

Figure 23. Graph showing weighted joint density vs. log of bed thickness for data from Caprock Canyons State Park, Palo Duro Canyon State Park, and joint zones at both parks. Joint densities were weighted using the following expression (Jackson, personal communication, 1983):

$$\text{double weighted mean joint density} = \bar{X}_m + \sum_{i=1}^{n} (s_i - x_m) \cdot \frac{y_i}{y_m} \cdot \frac{N_i}{N_m}$$

n = 5 in 5 point weighting

n = 3 in 3 point weighting

subscript $_m$ refers to value for midpoint

Figure 24. Gypsum veins in Permian strata at Caprock Canyons State Park.

Figure 25. Lower hemisphere, equal-area net plots of faults and veins mapped at Caprock Canyons State Park (from Goldstein and Collins, in press): (A) poles to normal faults, (B) poles to reverse faults; (C) poles to inclined veins; and (D) azimuths of vertical veins plotted as a rose diagram.

Figure 26. Map of structural elements of an area within Caprock Canyons State Park (from Collins, 1983).

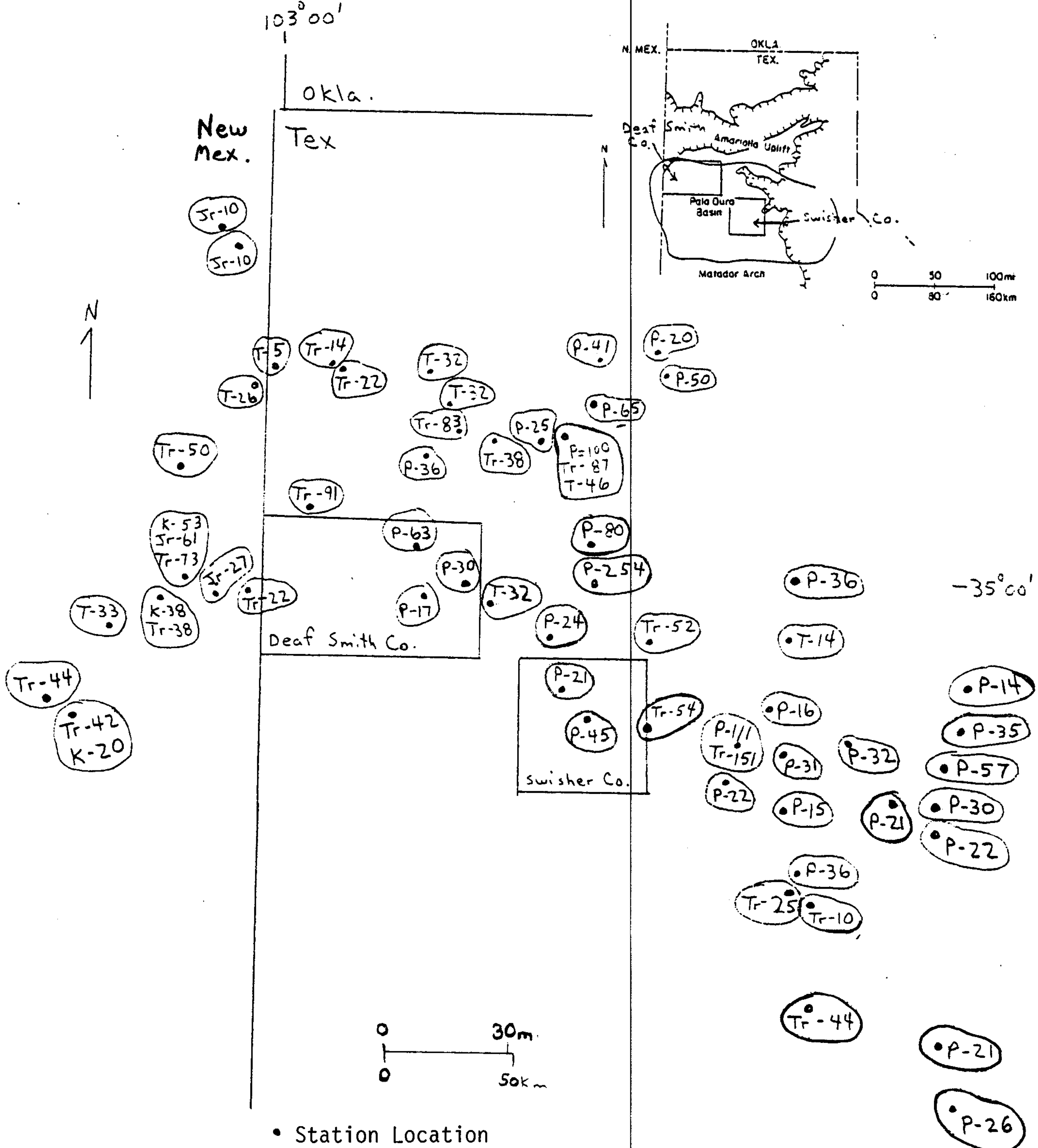
Figure 27. Detailed map of structural elements of individual synclinal depressions located 2 km (1.25 mi) north of Lake Theo. The major axes of the two depressions trend NE-SE (045^{o}-225^{o}).

Figure 28. Histograms of (A) systematic joints and (B) axes to synclinal depressions in Caprock Canyons State Park (from Goldstein and Collins, in press). The data have been smoothed by a 10-degree running average every 2 degrees of azimuth. Vertical axis is a concentration factor (Wise and McCrory, 1982).

Figure 29. Orientations of veins in synclinal depressions mapped in figure 27, 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 30. Conceptual model of brittle deformation above dissolution zones. Stage 1 represents normal burial; Stage 2 represents horizontal extension as a precursor to dissolution collapse; and Stage 3 represents collapse (from Goldstein, 1982).

Figure 31. Comparison of clastic dikes and joint orientations in the Texas Panhandle and eastern New Mexico. Data were collected from the following localities: (a) near Buffalo Lake dam, western Randall County, Texas; (b) U.S. Highway 385 at the southern edge of the Canadian River Valley, eastern Oldham County, Texas; (c) New Mexico State Highway 93 at the western caprock escarpment, Quay County, eastern New Mexico; and (d) 1.8 km north of Lighthouse Peak at Palo Duro Canyon State Park, eastern Randall County, Texas. The clastic dikes cut Triassic Dockum sediments and the joints were measured in Triassic Dockum (Trd) and Tertiary Ogallala (To) rocks. The joint data from the Buffalo Lake locality (a) are from Finley and Gustavson (1981, p. 25).



• Station Location

T-50 Number of Measurements in Tertiary Strata
K-50 Number of Measurements in Cretaceous Strata
Jr-50 Number of Measurements in Jurassic Strata
Tr-50 Number of measurements in Triassic Strata
P-50 Number of measurements in Permian Strata

Figure 1. Station Locations for fracture measurements in the Palo Duro Basin area, Texas Panhandle.

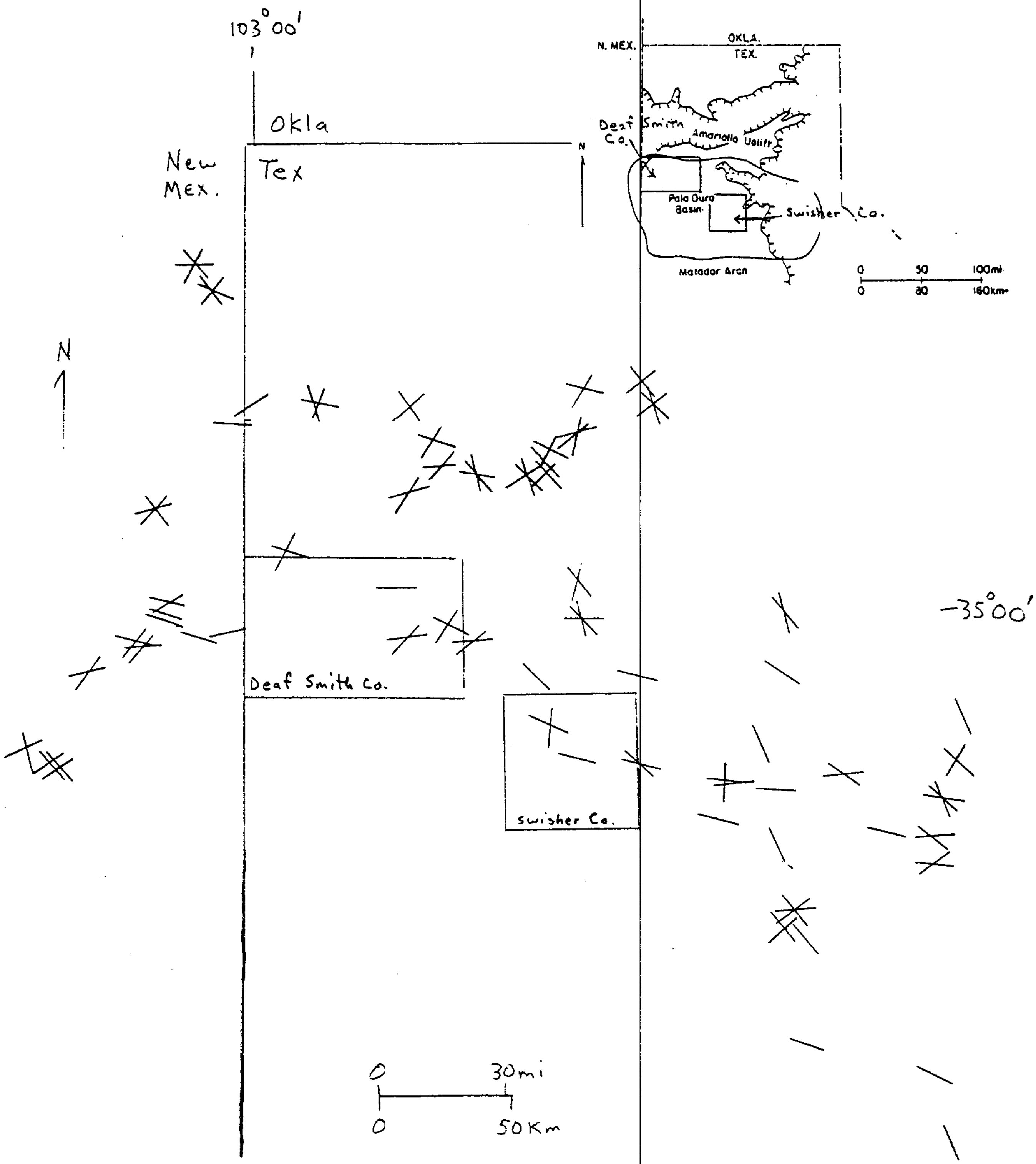


Figure 2. Strikes of predominant fracture sets in the Palo Duro Basin area, Texas Panhandle.

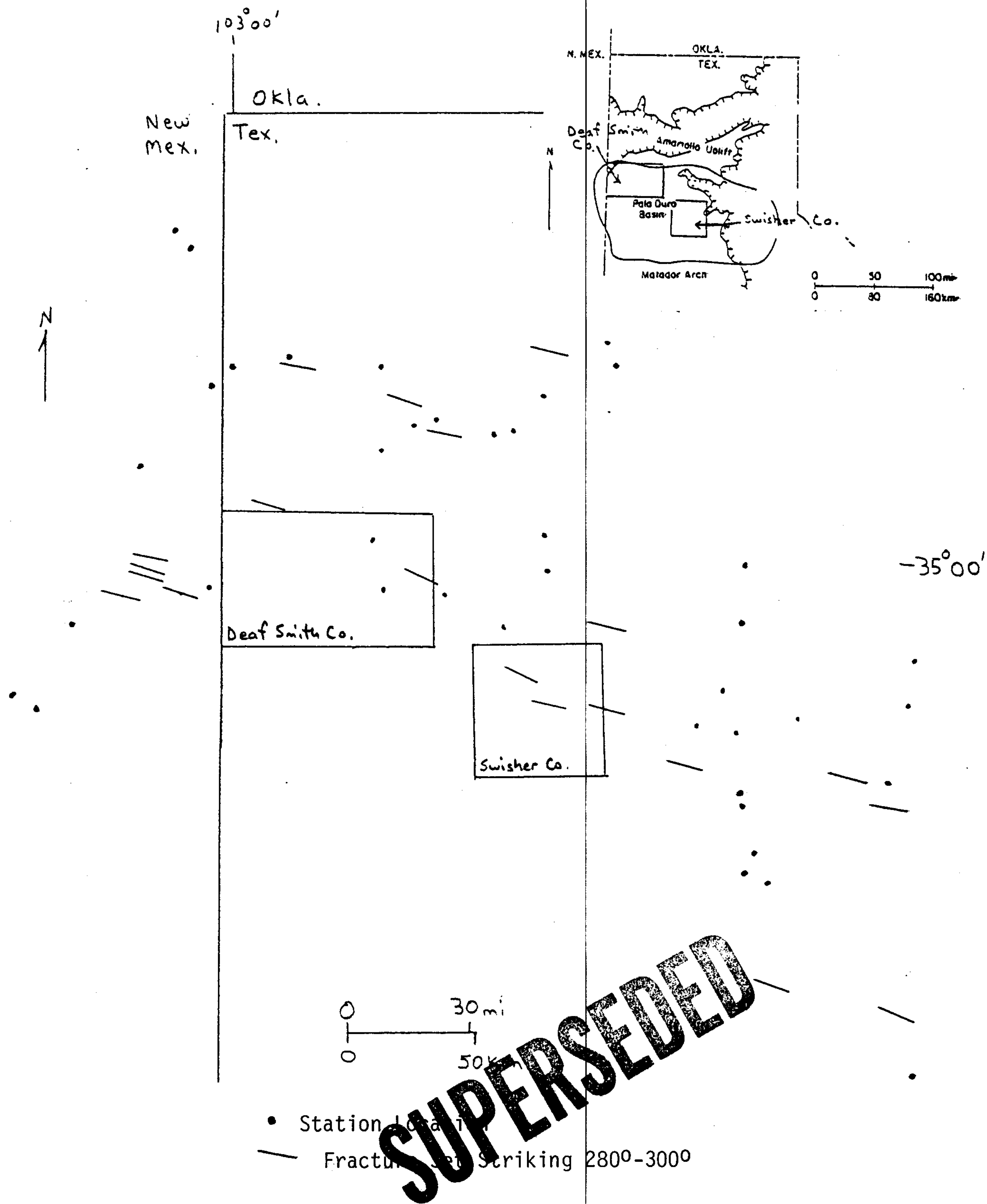


Figure 3. Locations where a predominant fracture set strikes at 280°-300°.

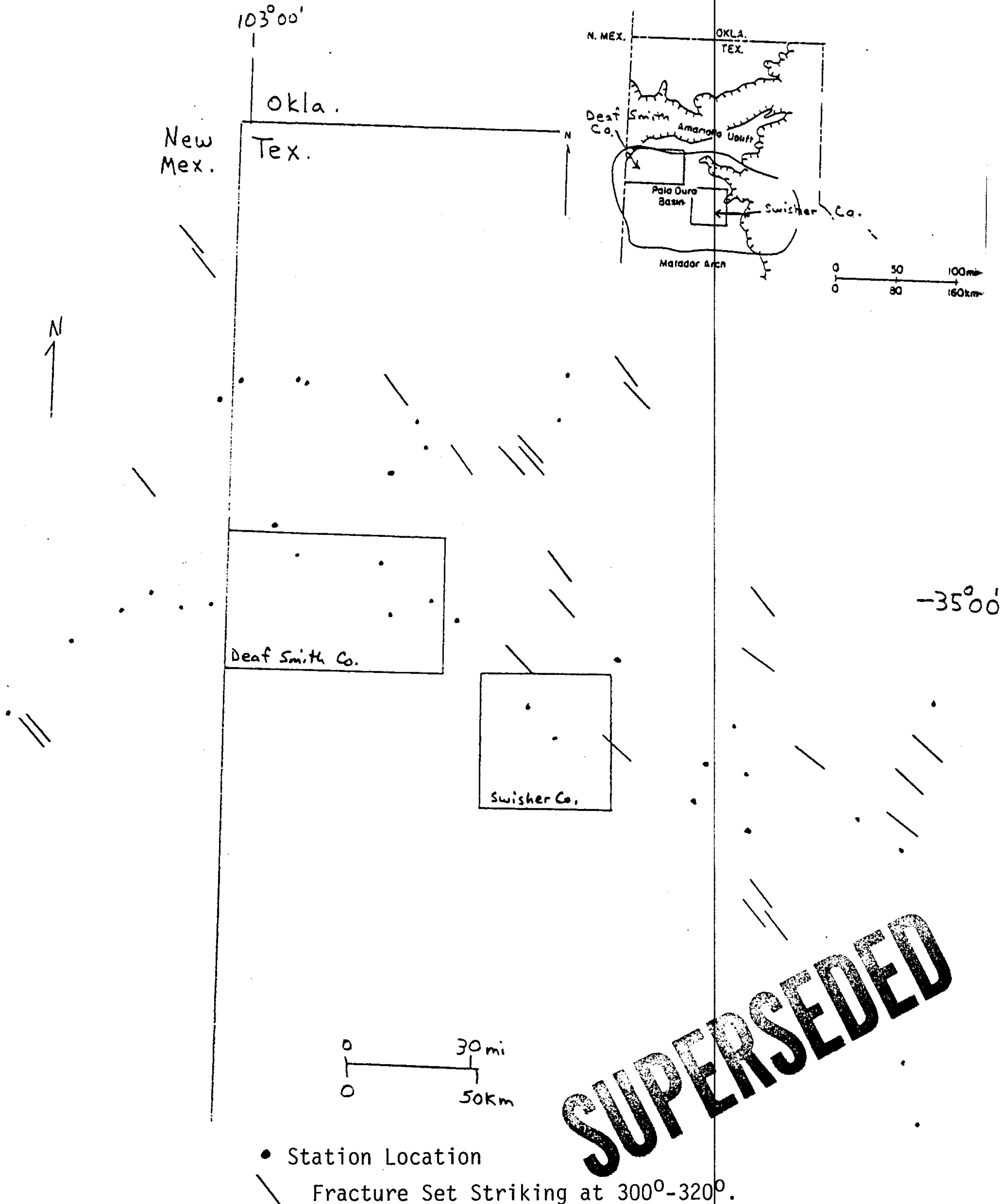


Figure 4. Locations where a predominant fracture set strikes at 300°-320°.

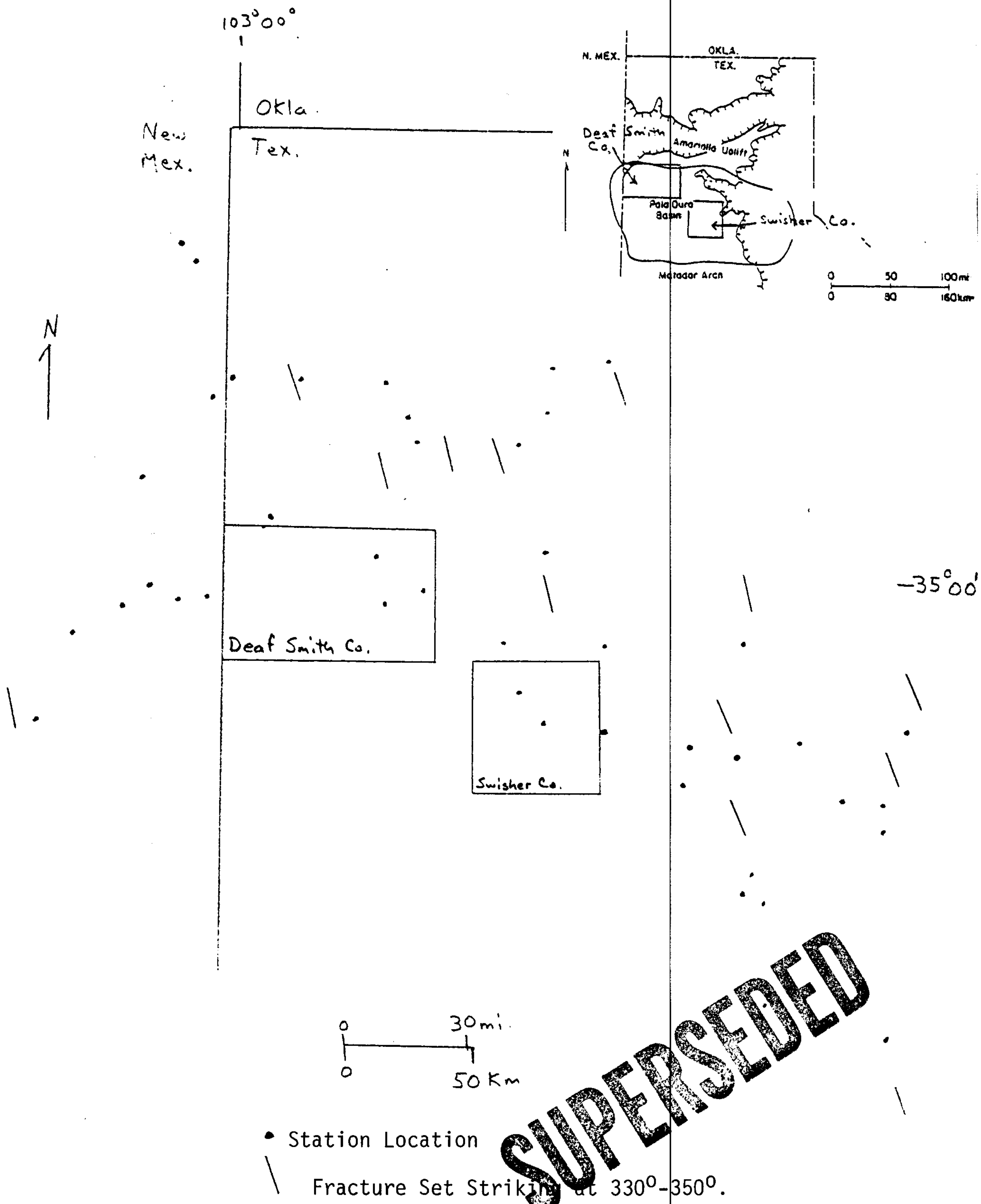
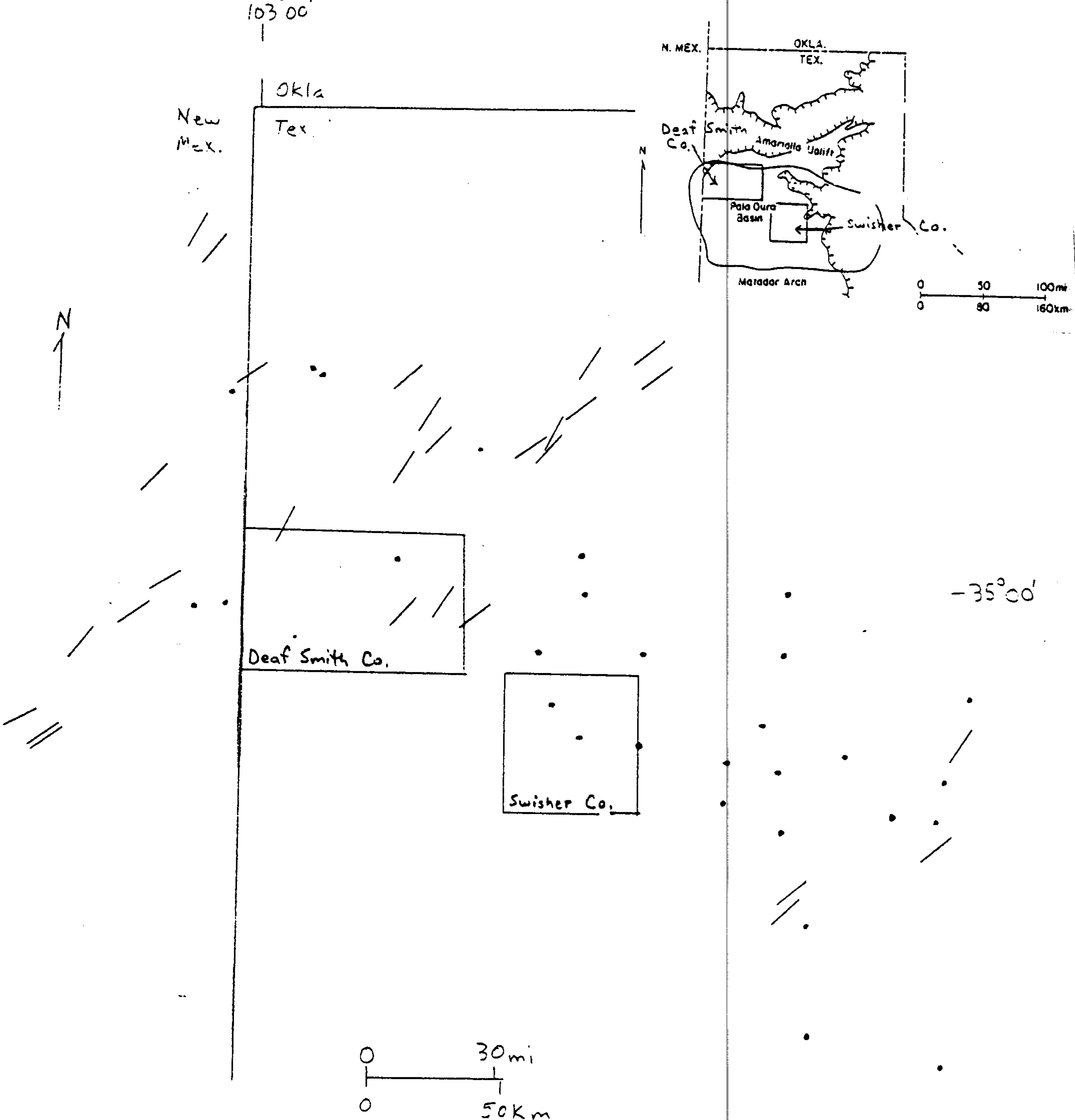


Figure 5. Locations where a predominant fracture set strikes at 330°-350°.



• Station Location

/ Fracture Group Striking at 030°-060°.

Figure 6. Locations where a predominant fracture group strikes at 030°-060°.

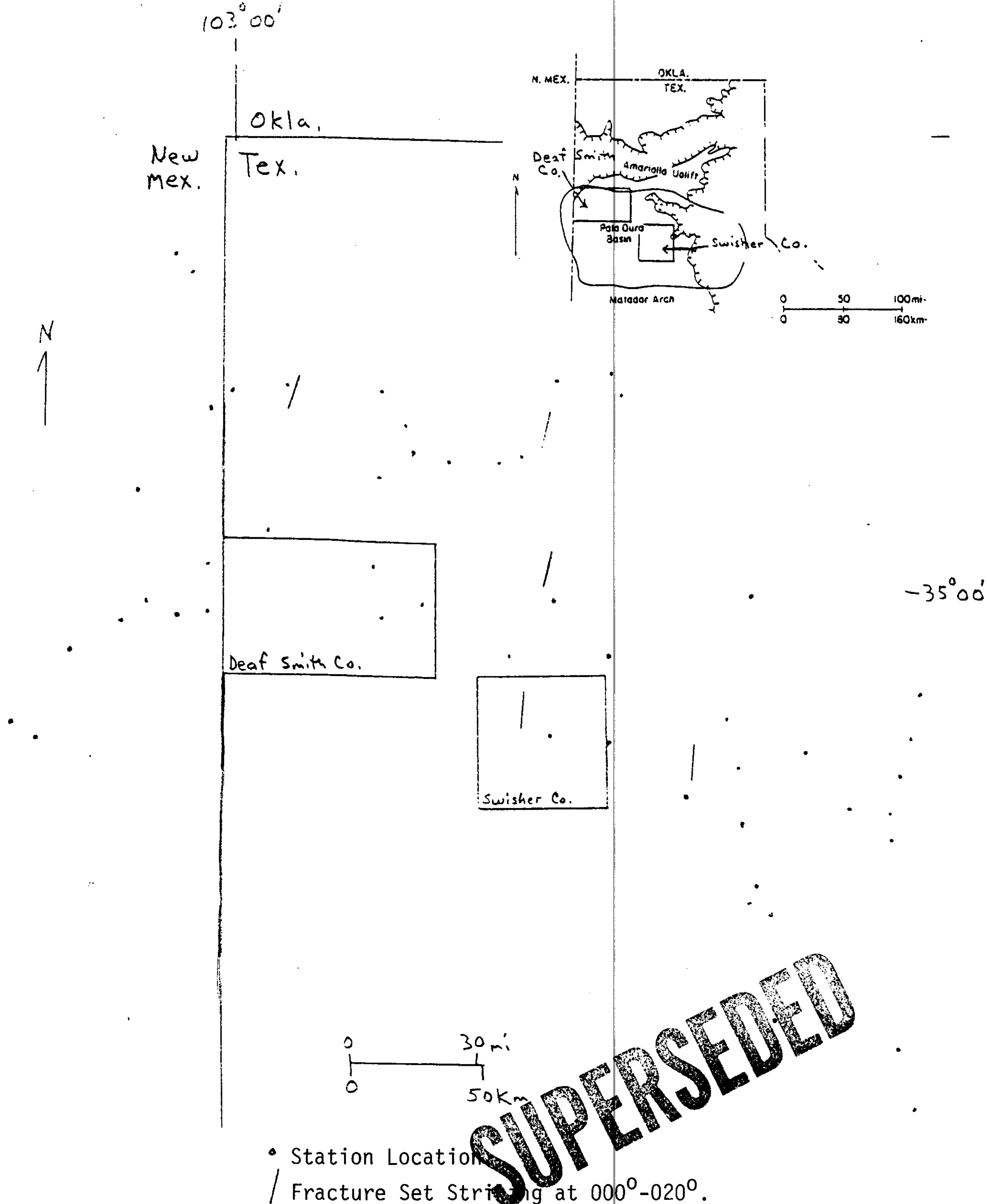


Figure 7. Locations where a predominant fracture set strikes at 000°-020°.

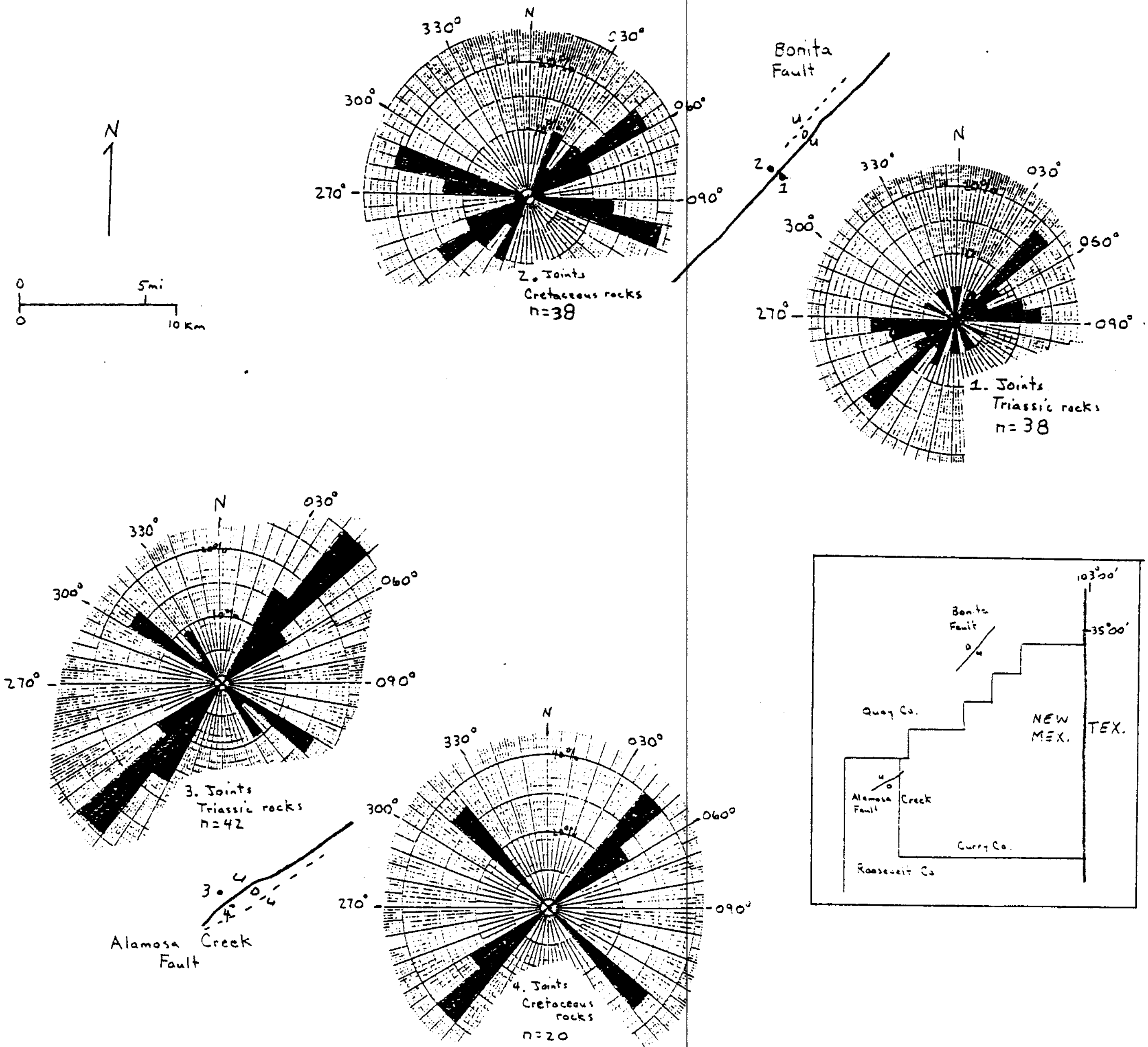


Figure 8. Strikes of faults and joints at the western margin of the Palo Duro Basin in eastern New Mexico.

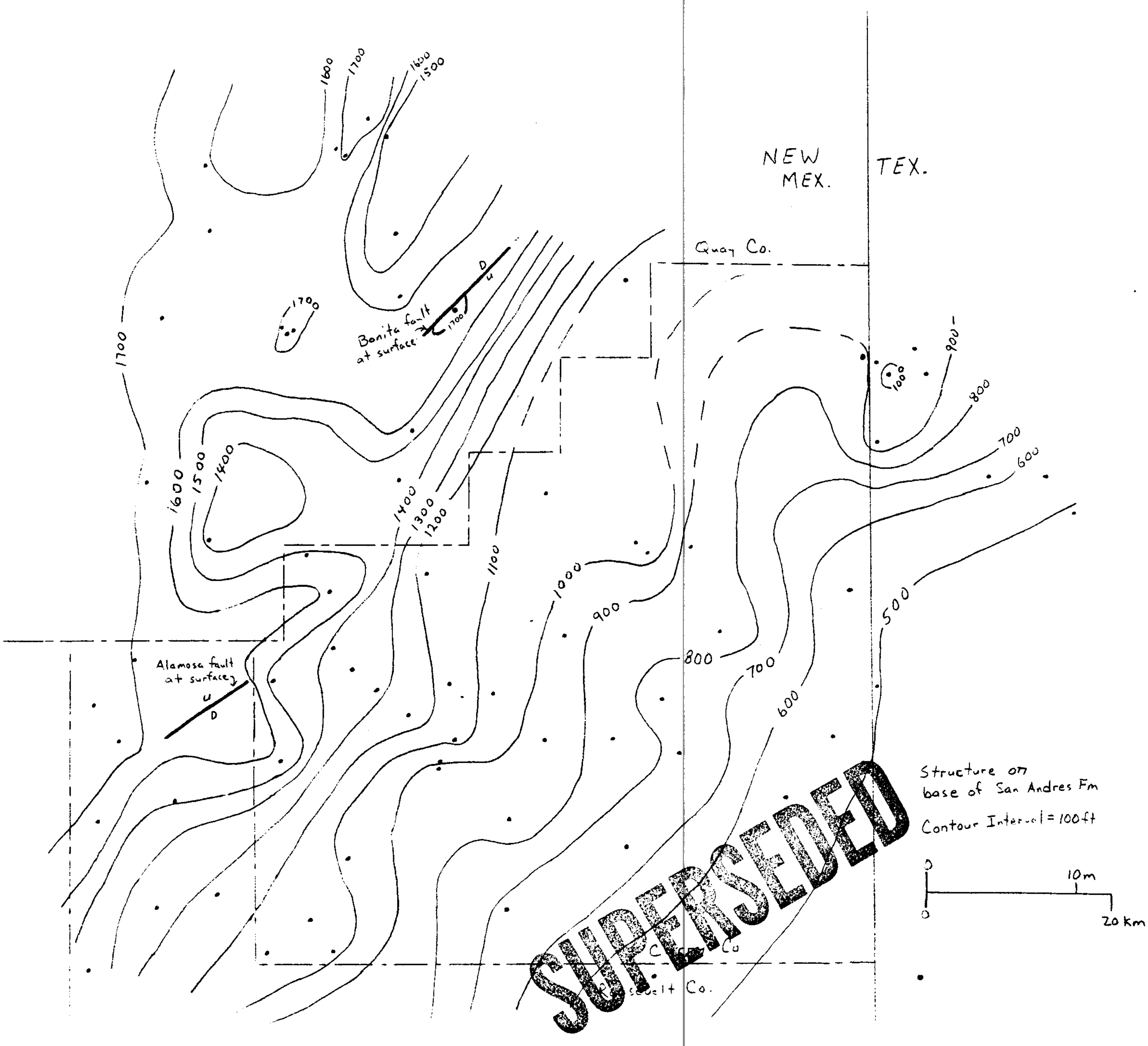


Figure 9. Structure contour map on base of the Permian San Andres Formation in Quay, Curry, and Roosevelt Counties, eastern New Mexico.

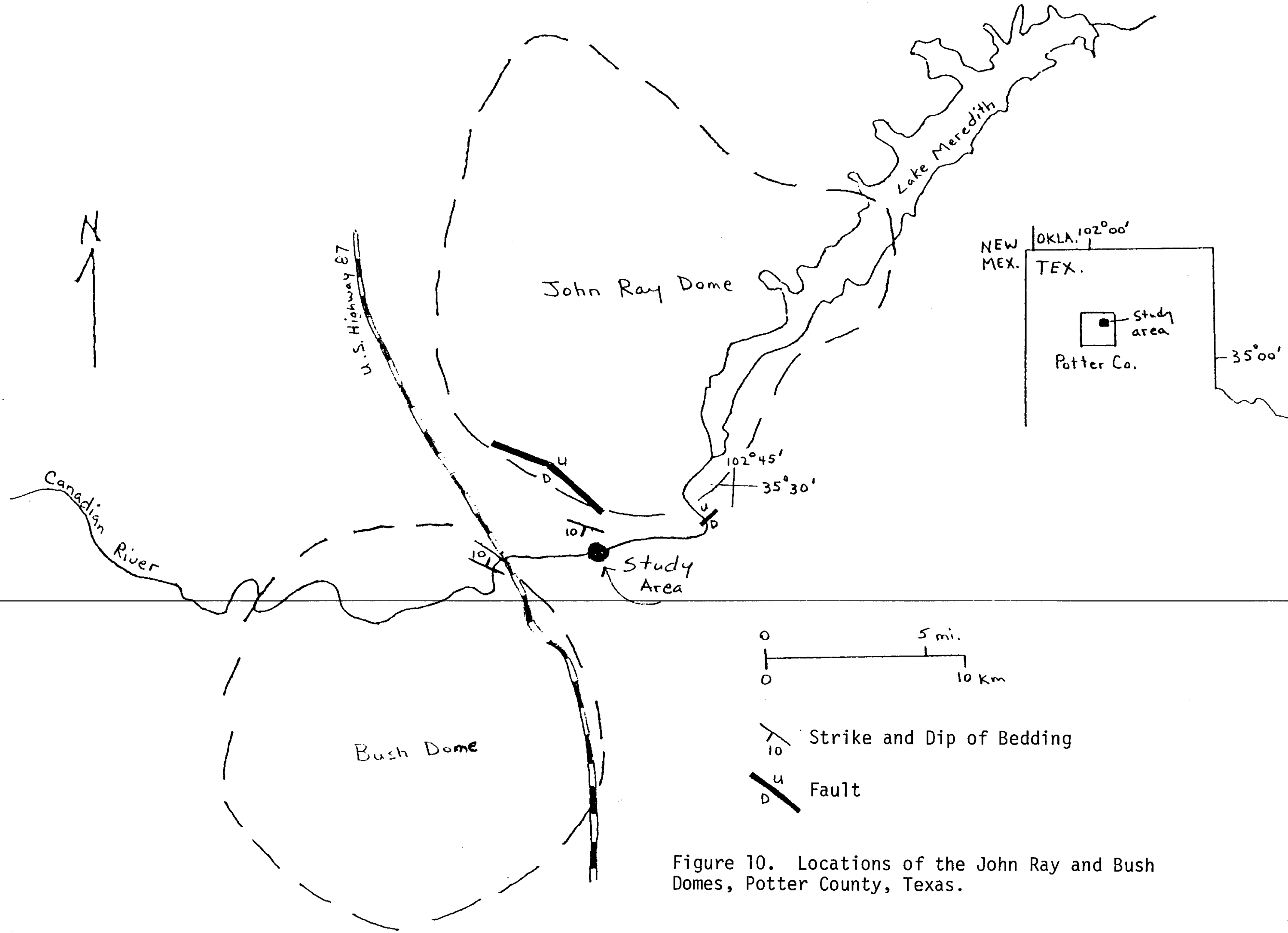


Figure 10. Locations of the John Ray and Bush Domes, Potter County, Texas.

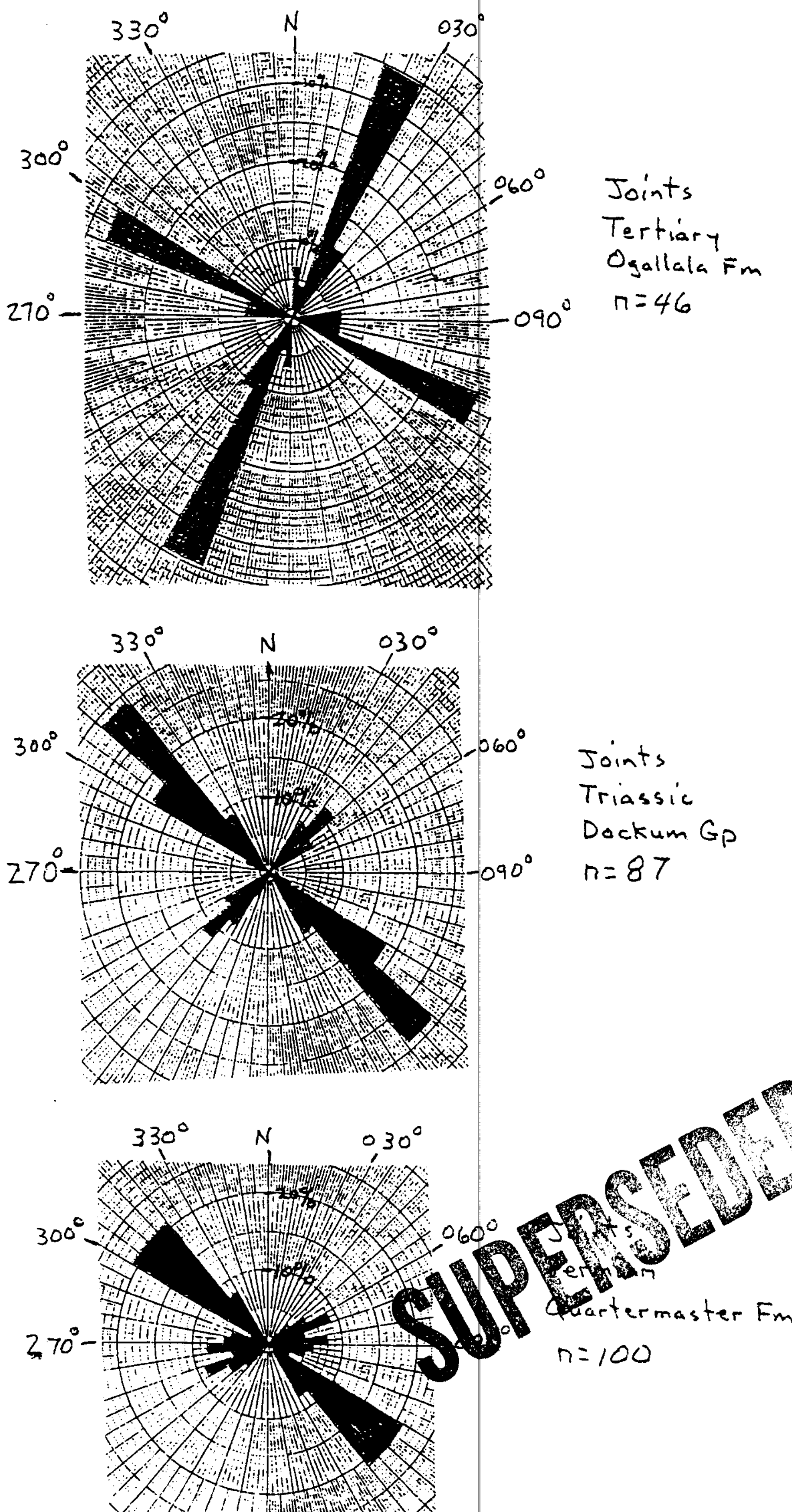


Figure 11. Joint strikes in overlying Permian, Triassic, and Tertiary Rocks exposed at a northwest trending drape fold on the southwest flank of John Ray Dome, Potter County, Texas. (fig. 10)

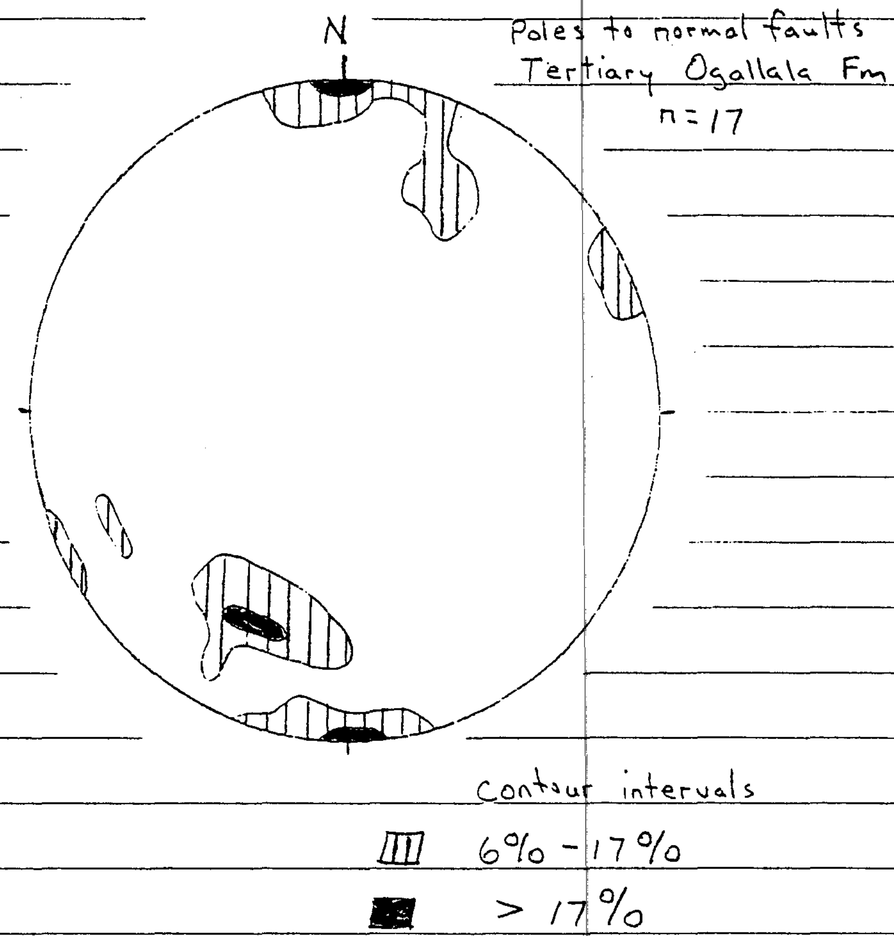
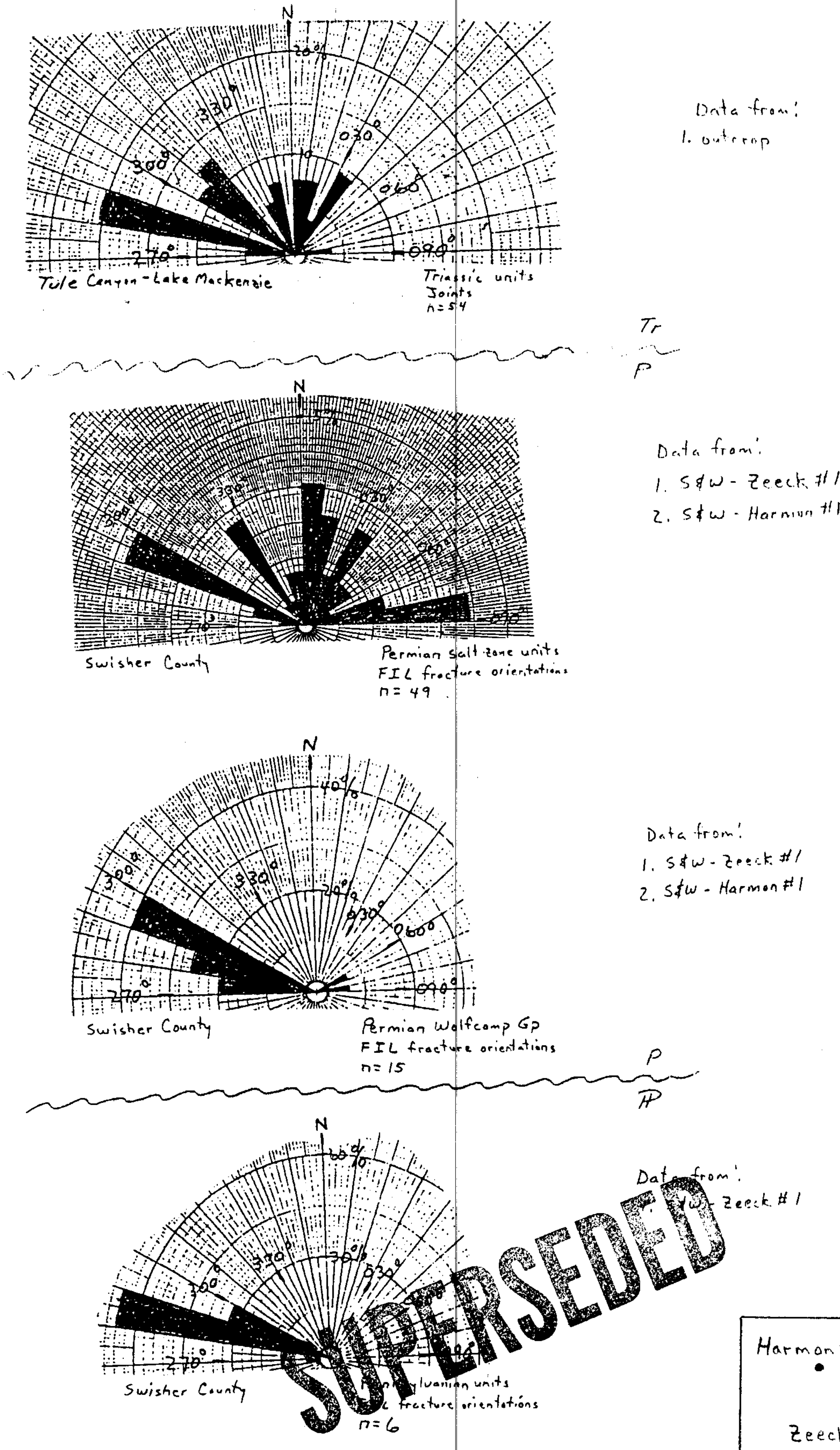


Figure 12. Poles to normal faults cutting Tertiary Ogallala strata at a northwest trending drape fold on the southwest flank of John Ray Dome, Potter County, Texas (fig. 10). Fault displacements are less than 0.5m.



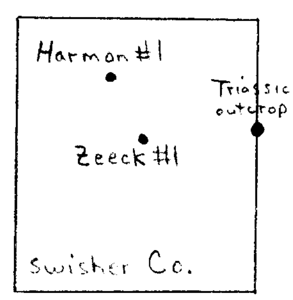


Figure 13. Strikes of fractures in Pennsylvanian, Permian, and Triassic strata in Swisher County, Texas. Fracture orientations in Pennsylvanian and Permian strata were determined with fracture identification logs from the Stone and Webster-Harman #1 and Stone and Webster-Zeeck #1 boreholes. Joints in Triassic strata were measured from outcrop.

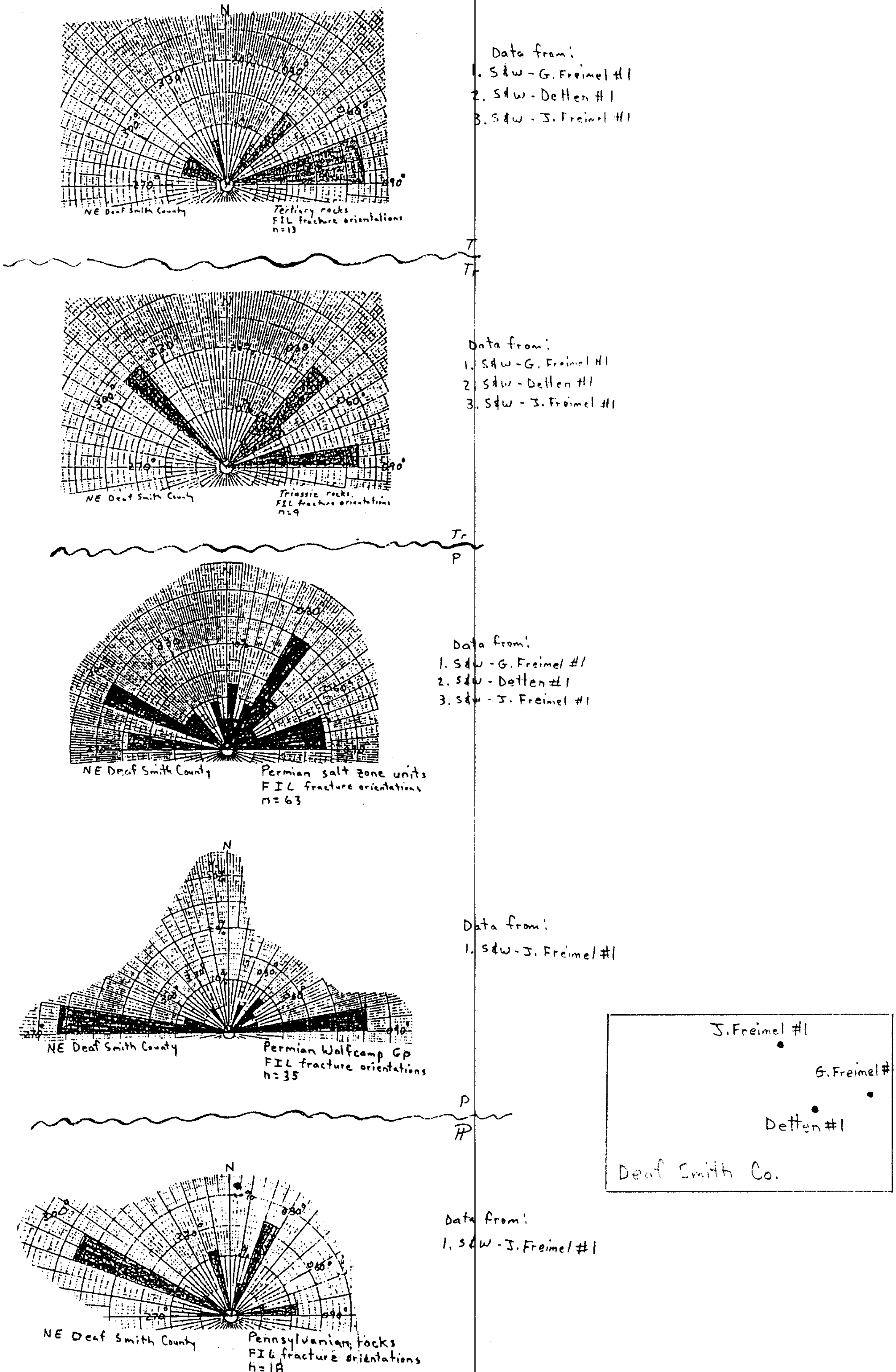

NE Deaf Smith County
Tertiary rocks
FIL fracture orientations
n=13
Data from:
1. S&W - G. Freimel #1
2. S&W - Detten #1
3. S&W - J. Freimel #1
T
Tr
NE Deaf Smith County
Triassic rocks
FIL fracture orientations
n=9
Data from:
1. S&W - G. Freimel #1
2. S&W - Detten #1
3. S&W - J. Freimel #1
Tr
P
NE Deaf Smith County
Permian salt zone units
FIL fracture orientations
n=63
Data from:
1. S&W - G. Freimel #1
2. S&W - Detten #1
3. S&W - J. Freimel #1
NE Deaf Smith County
Permian Wolfcamp Gp
FIL fracture orientations
n=35
Data from:
1. S&W - J. Freimel #1
J. Freimel #1
G. Freimel #1
Detten #1
Deaf Smith Co.
P
NE Deaf Smith County
Pennsylvanian rocks
FIL fracture orientations
n=18
Data from:
1. S&W - J. Freimel #1

Figure 14.

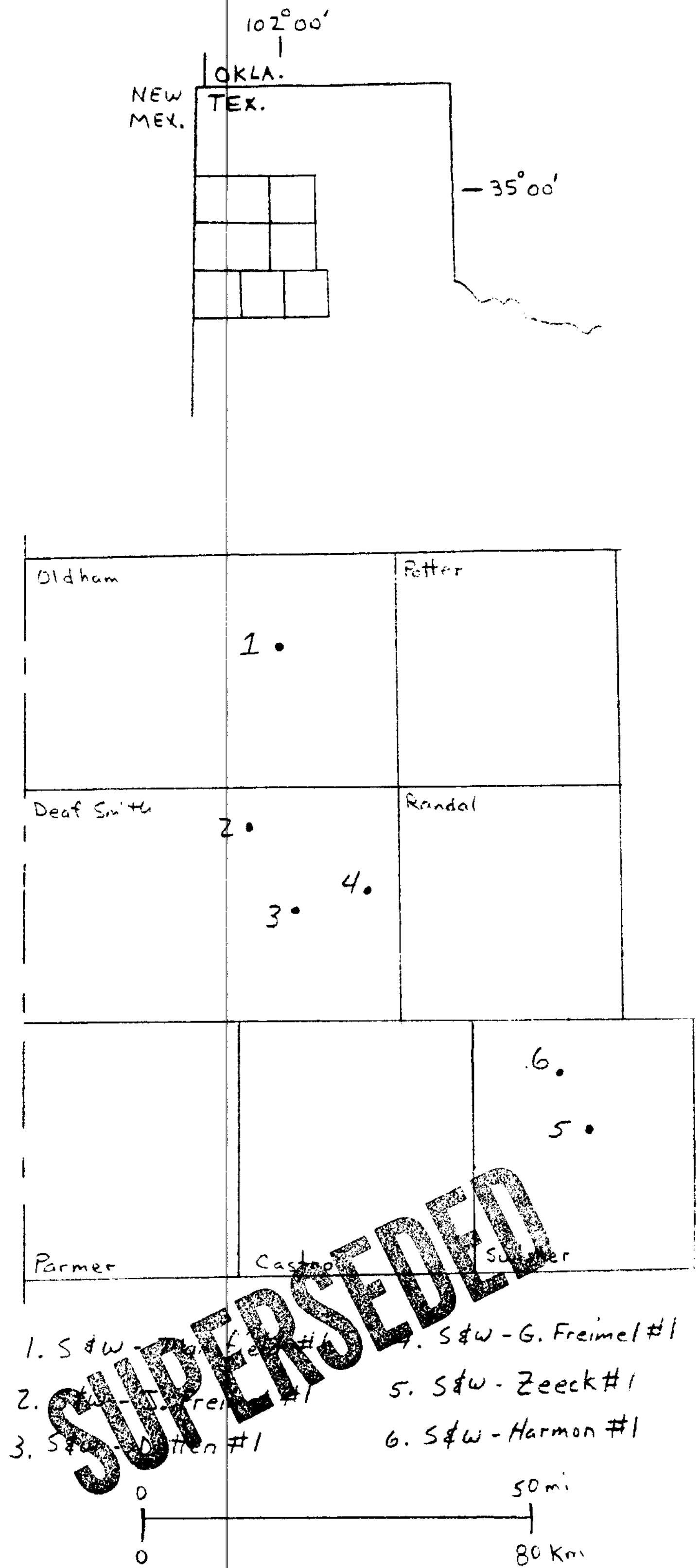
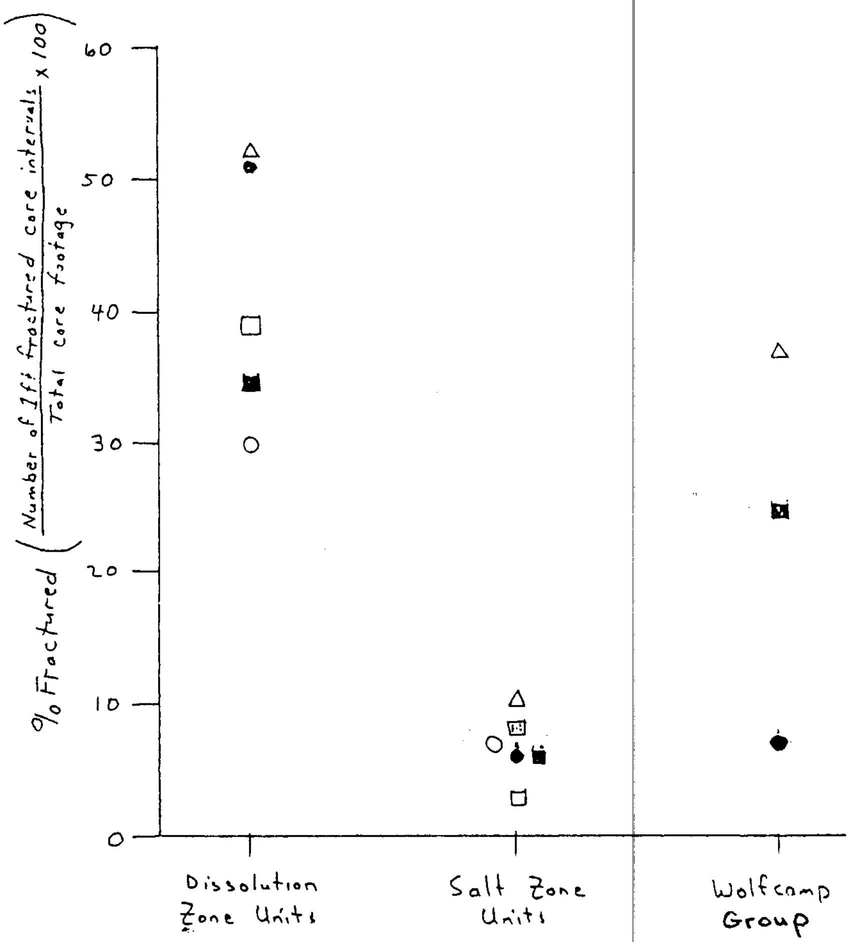


Figure 15. Locations of boreholes used for fracture studies in the Palo Duro Basin area.



EXPLANATION

Well	Dissolution Zone Units	Salt Zone Units
△ S&W - Mansfield #1	A, S/T, Y, SR	QG, SA, G, uCF, T, lCF
▩ S&W - J. Freimel #1	A, S/T, Y, SR	SR, SA
□ S&W - Detten #1	A, S/T, Y	SA
⊡ S&W - G. Freimel #1		SR, QG, SA
● S&W - Zeeck #1	S/T	SA
○ S&W - Harmon #1	A, S/T, Y	QG, SA

Figure 16. Percentage of fractured Permian core from boreholes in Oldham, Deaf Smith, and Randall Counties, Texas. Abbreviations of Permian formations are as follows: A - Alibates; S/T - Salado-Transill; Y - Yates; SR - Seven Rivers; QG - Queen Grayburg; SA - San Andres; G - Glorieta; uCF - upper Clear Fork; T - Tubb; lCF - lower Clear Frok.

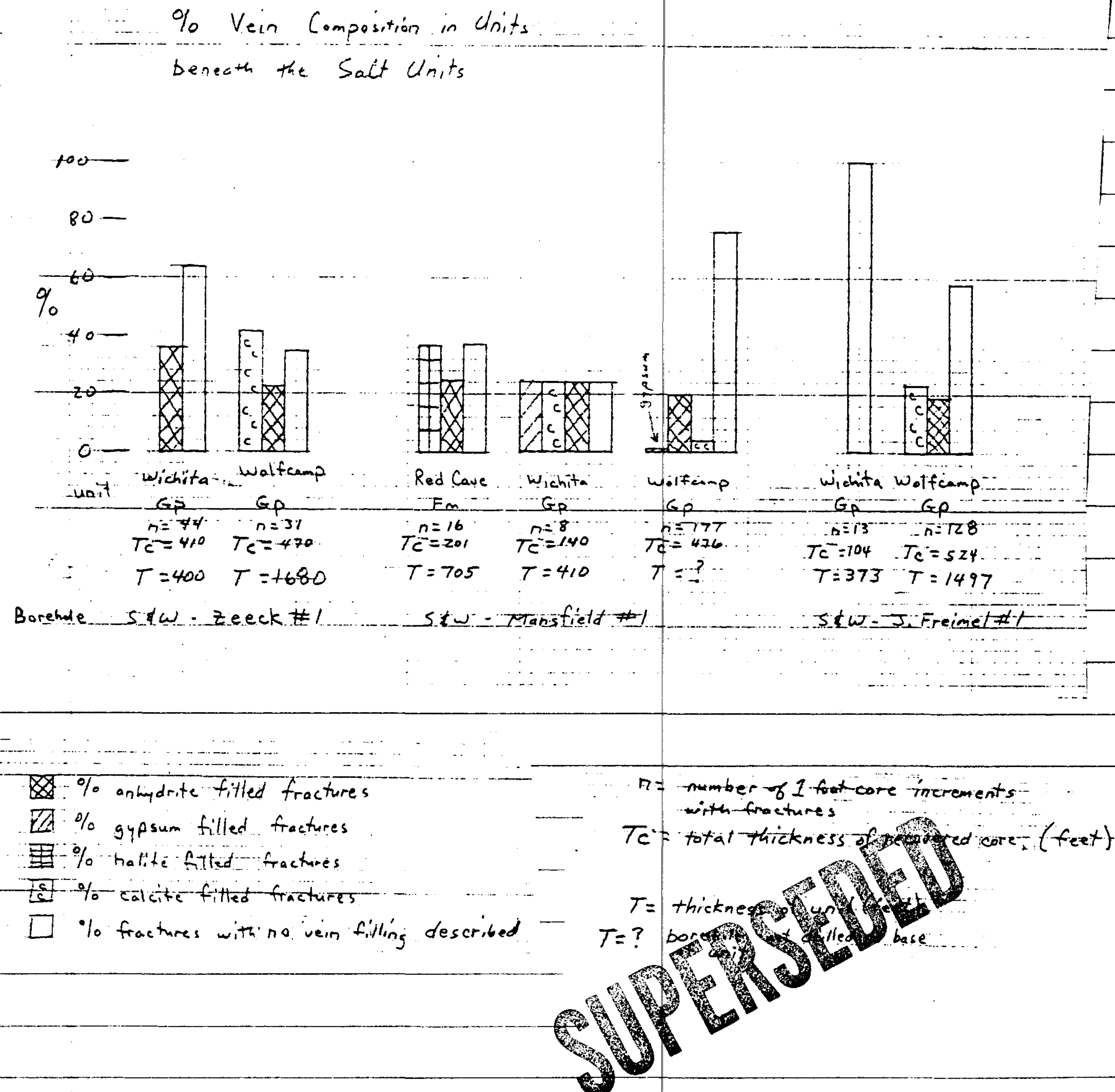


Figure 17. Composition of veins in core of the Red Cave Formation and Wichita and Wolfcamp Groups. These units are stratigraphically below the Permian salt-bearing units.

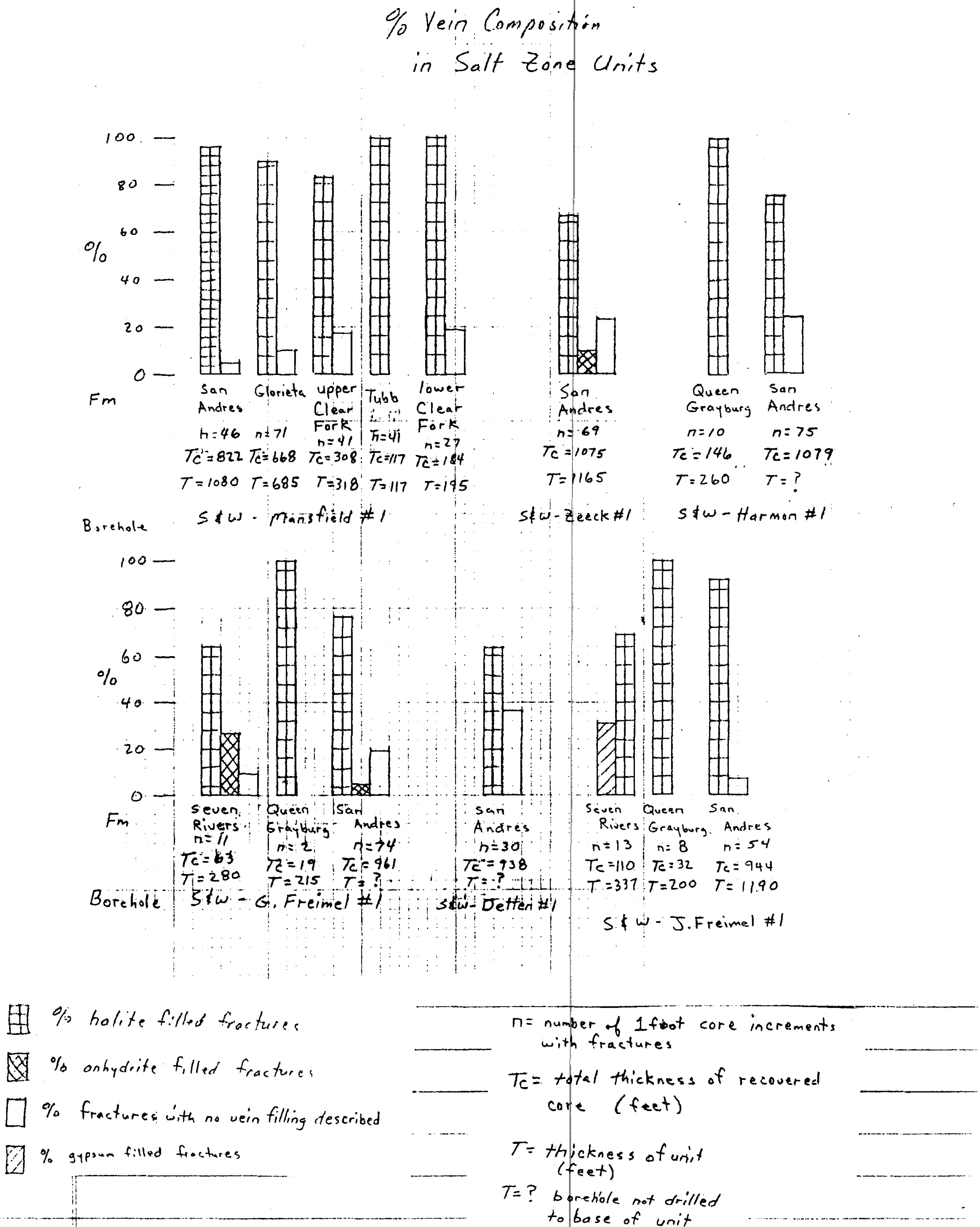


Figure 18. Composition of veins in core of Permian salt-bearing strata.

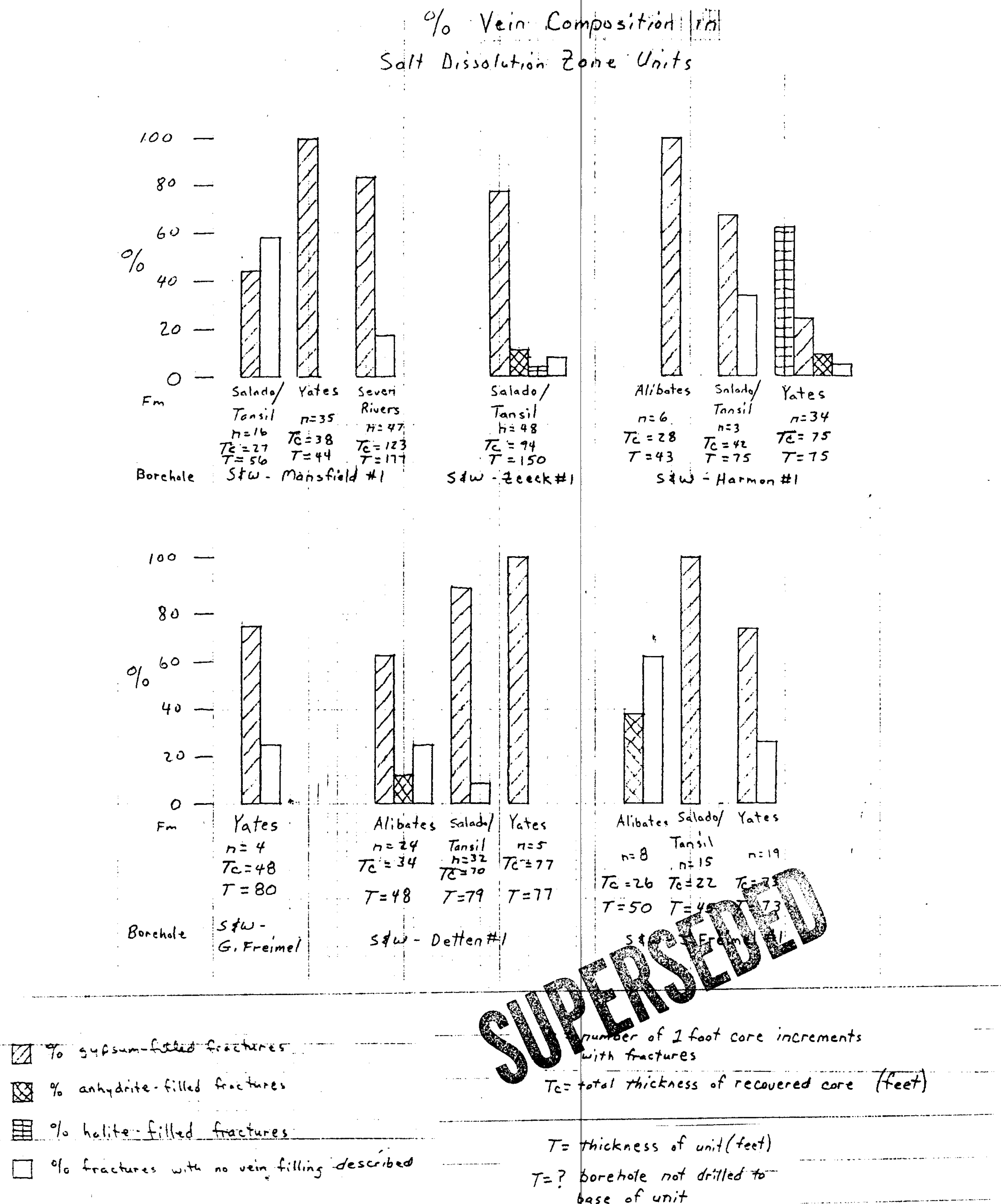


Figure 19. Composition of veins in core of Permian strata that has been affected by salt dissolution.

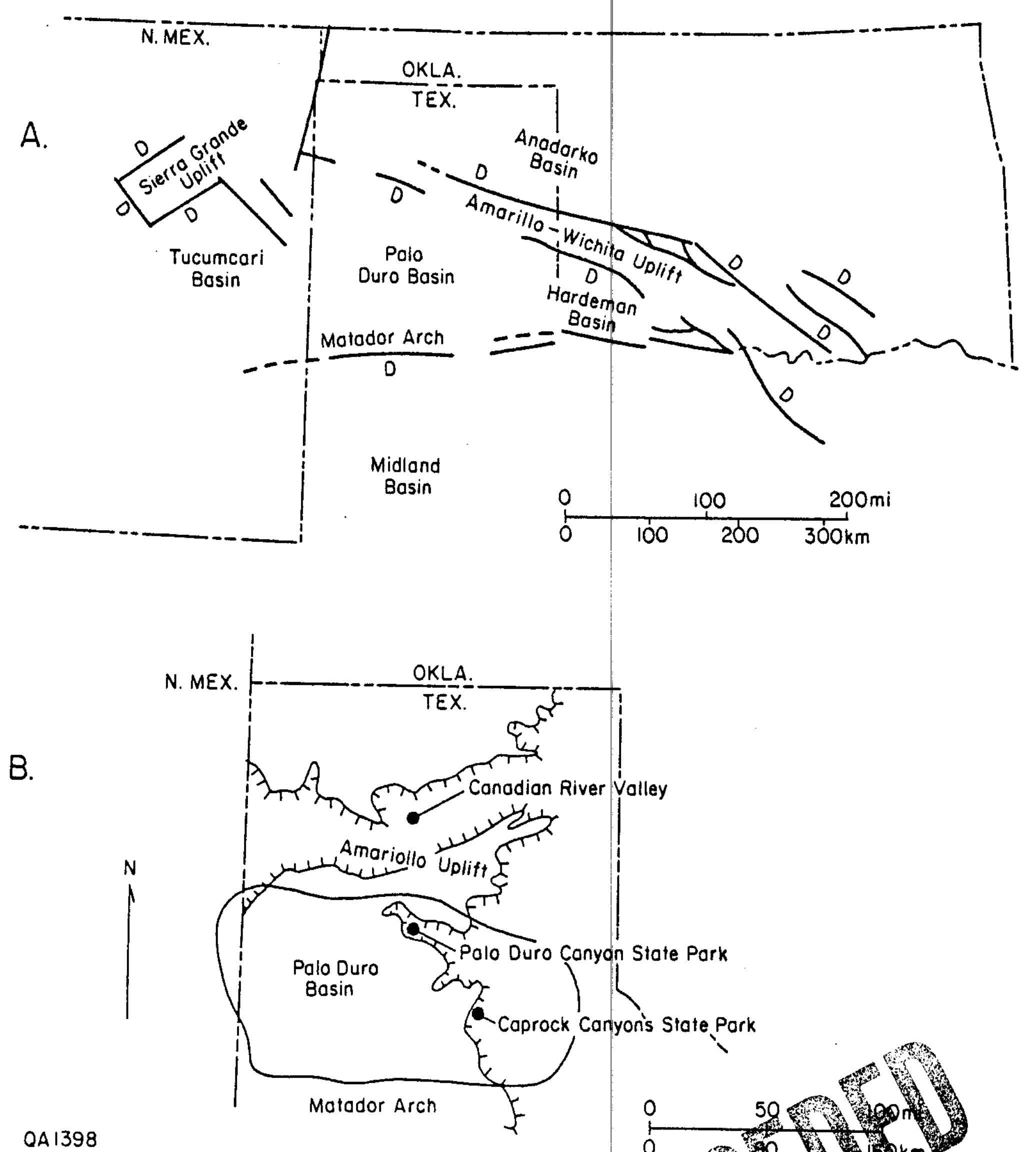


Figure 20. Structural setting of the Palo Duro Basin (A) and location of Caprock Canyons State Park (B).

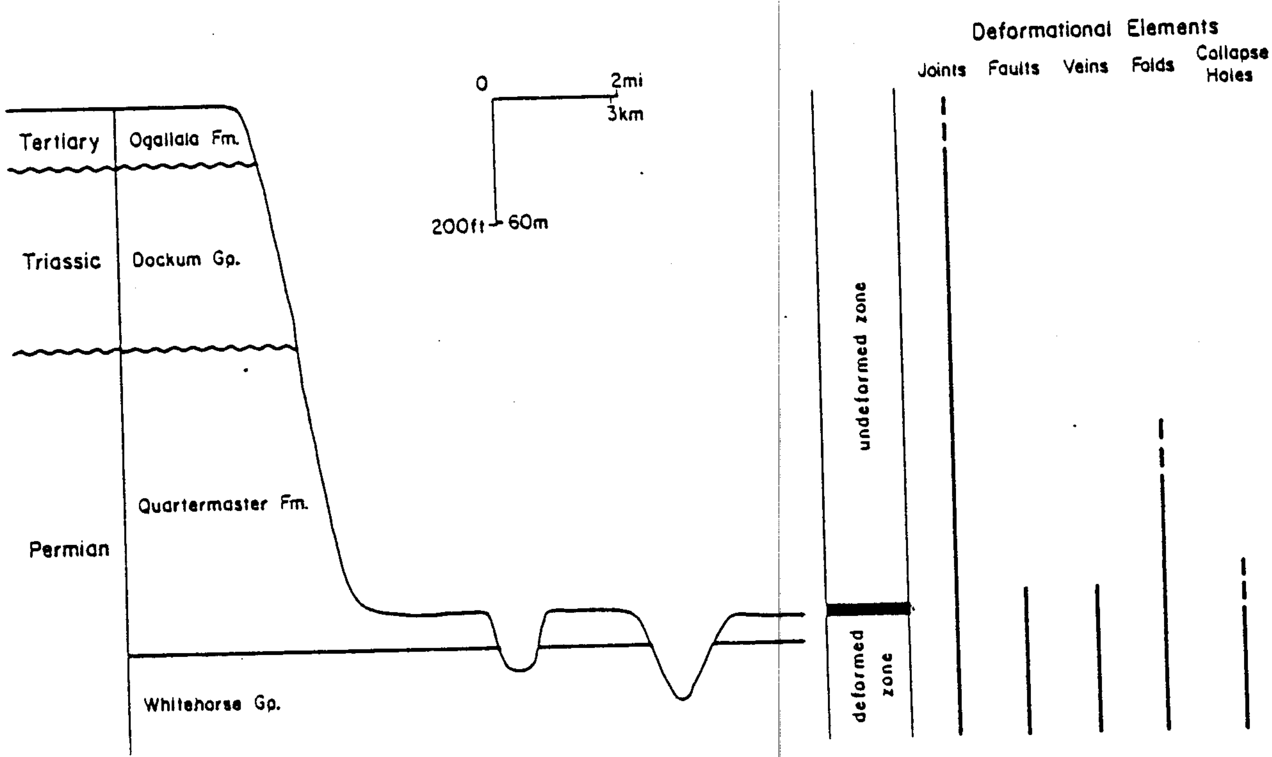


Figure 21. Stratigraphy and deformational elements at Caprock Canyons State Park.

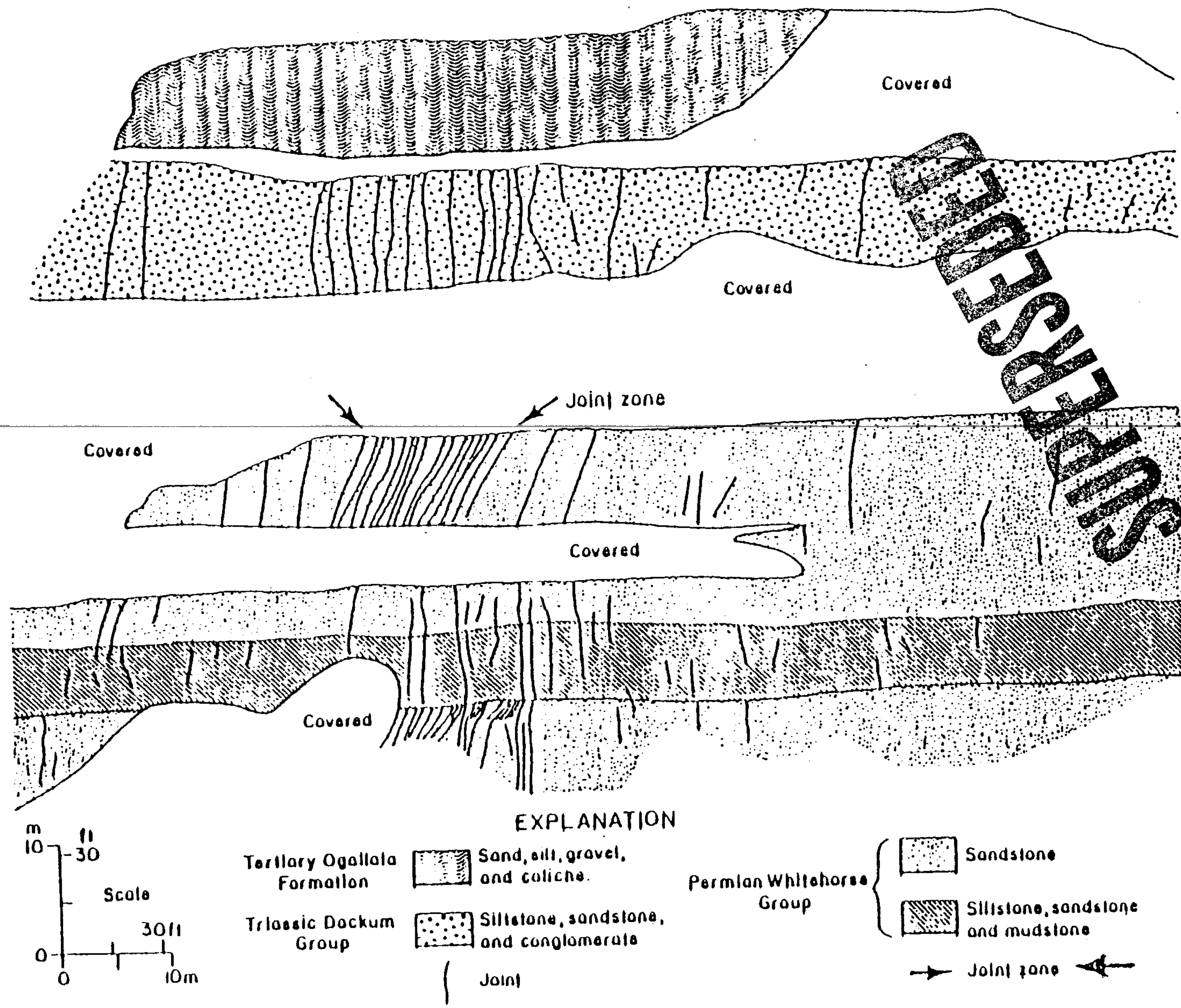
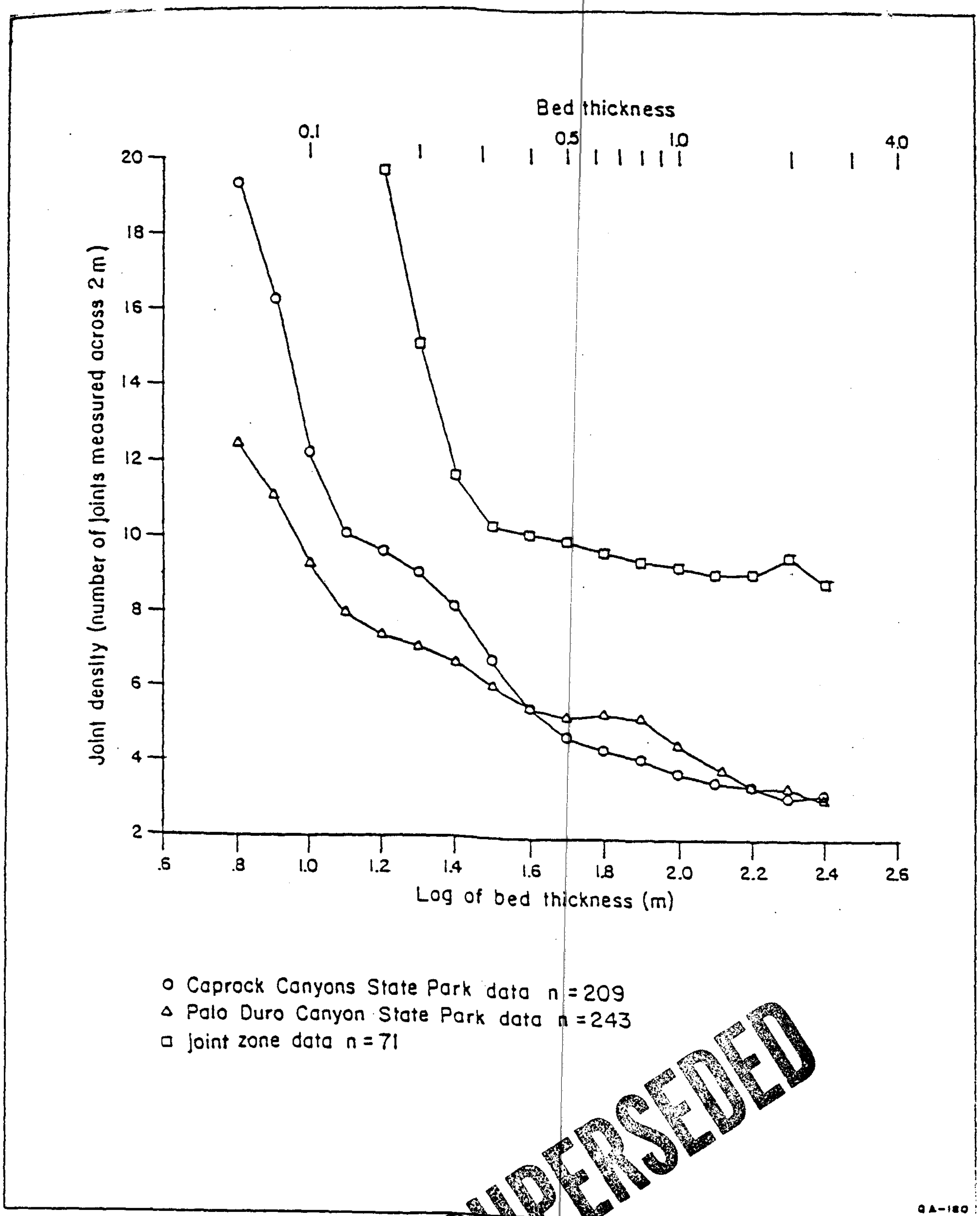


Figure 22. Cross-section veiw of a joint zone extending through Permian and Triassic rocks at Caprock Canyons State Park in Briscoe County.



SUPERSEDED

Figure 23. Graph showing weighted joint density vs. log of bed thickness for data from Caprock Canyons State Park, Palo Duro Canyon State Park, and joint zones at both parks.

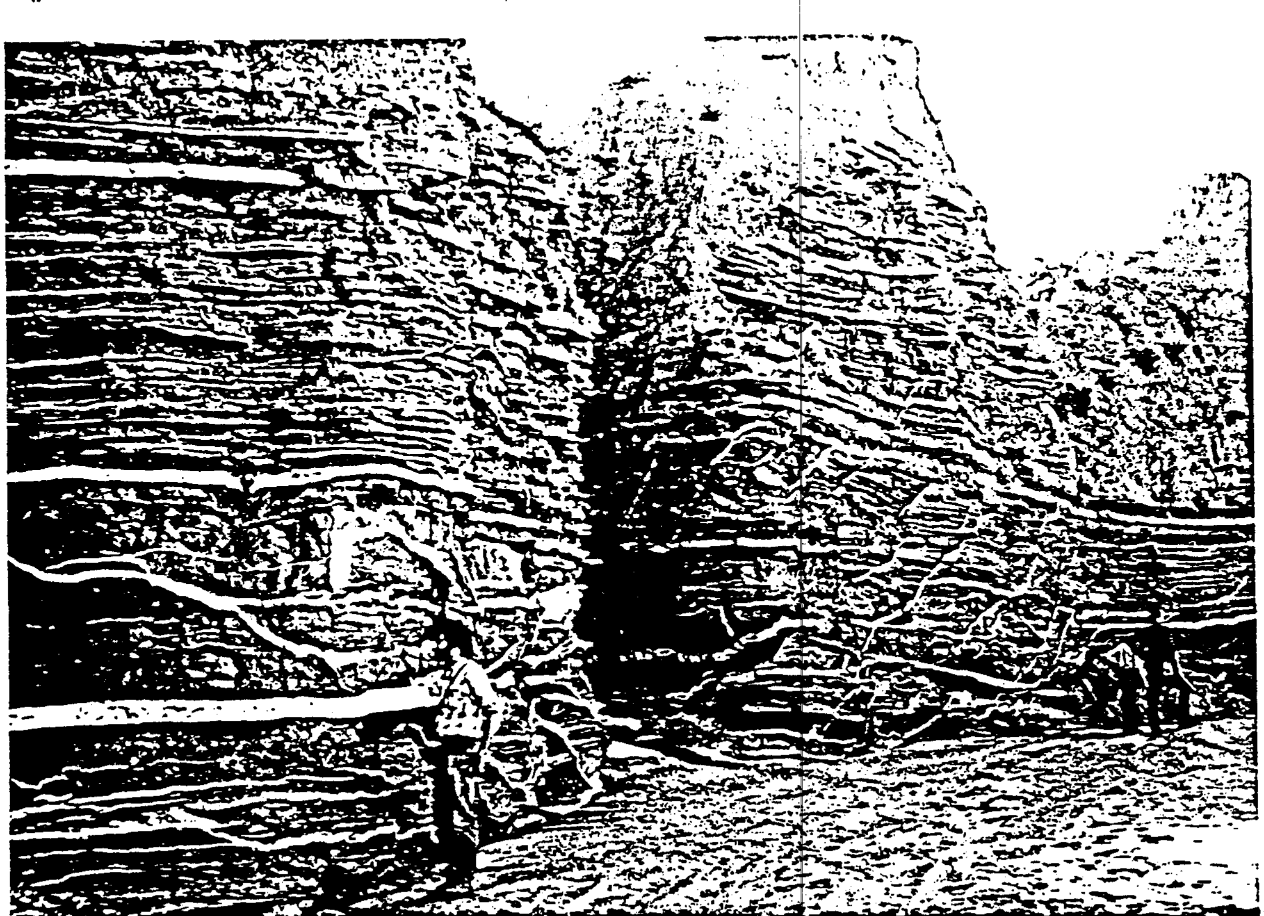


Figure 24. Gypsum veins in Permian strata at Caprock Canyons State Park.

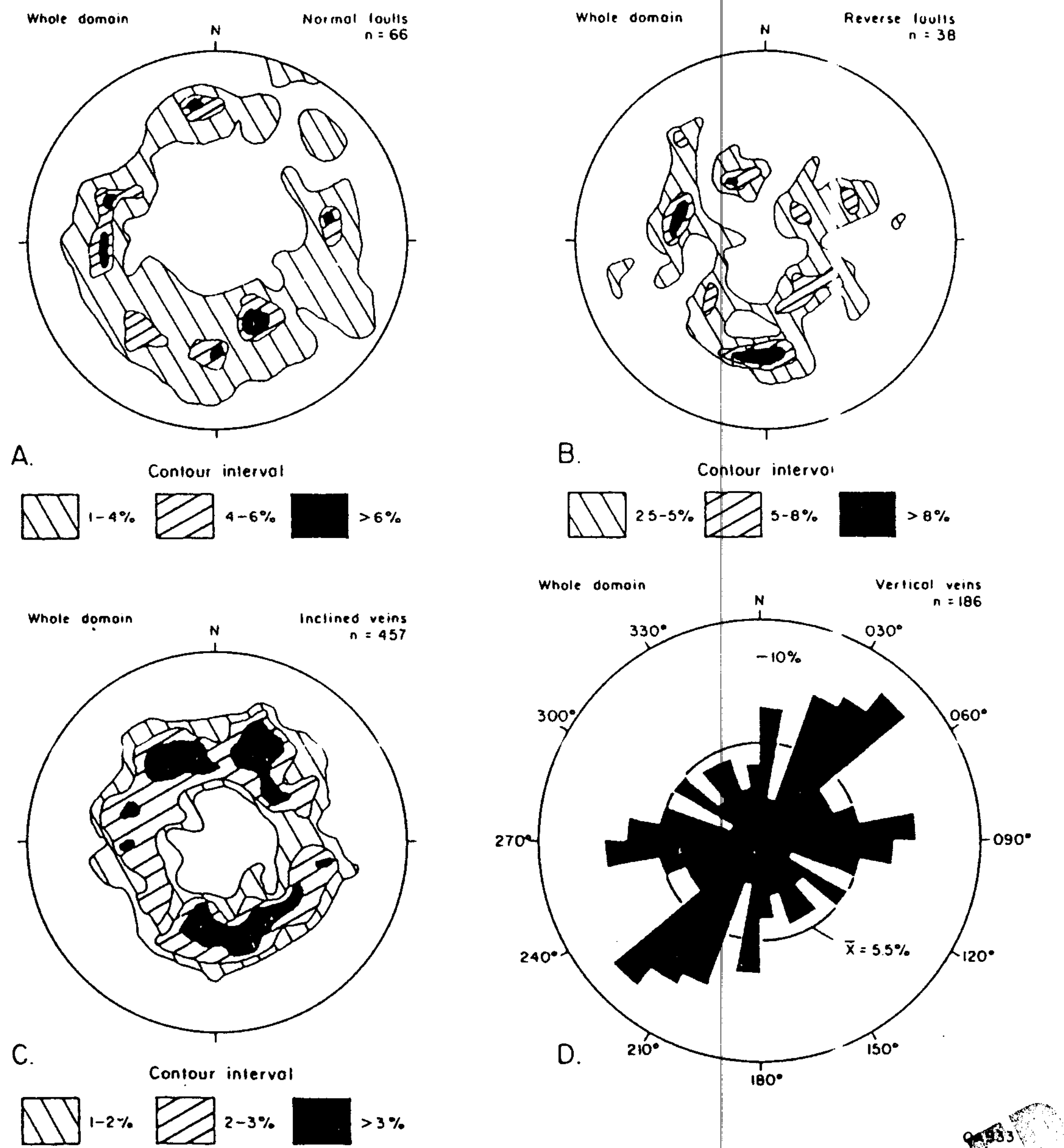


Figure 25. Lower Hemisphere, equal-area net plots of faults and veins mapped at Caprock Canyons State Park (from Goldstein and Collins, in press): (A) poles to normal faults; (B) poles to reverse faults; (C) poles to inclined veins; and (D) azimuths of vertical veins plotted as a rose diagram.

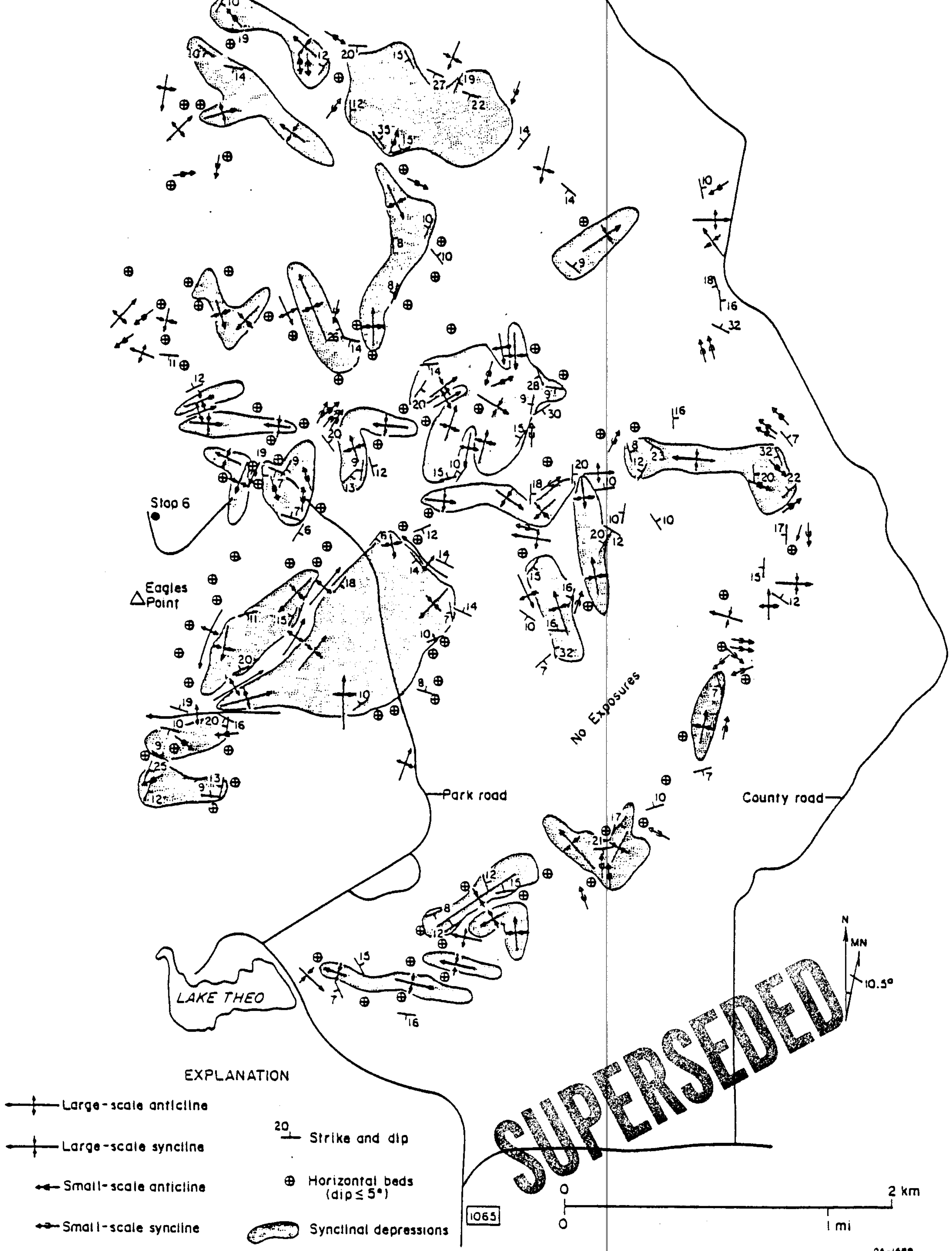


Figure 26. Map of structural elements of an area within Caprock Canyons State Park (from Collins, in press).

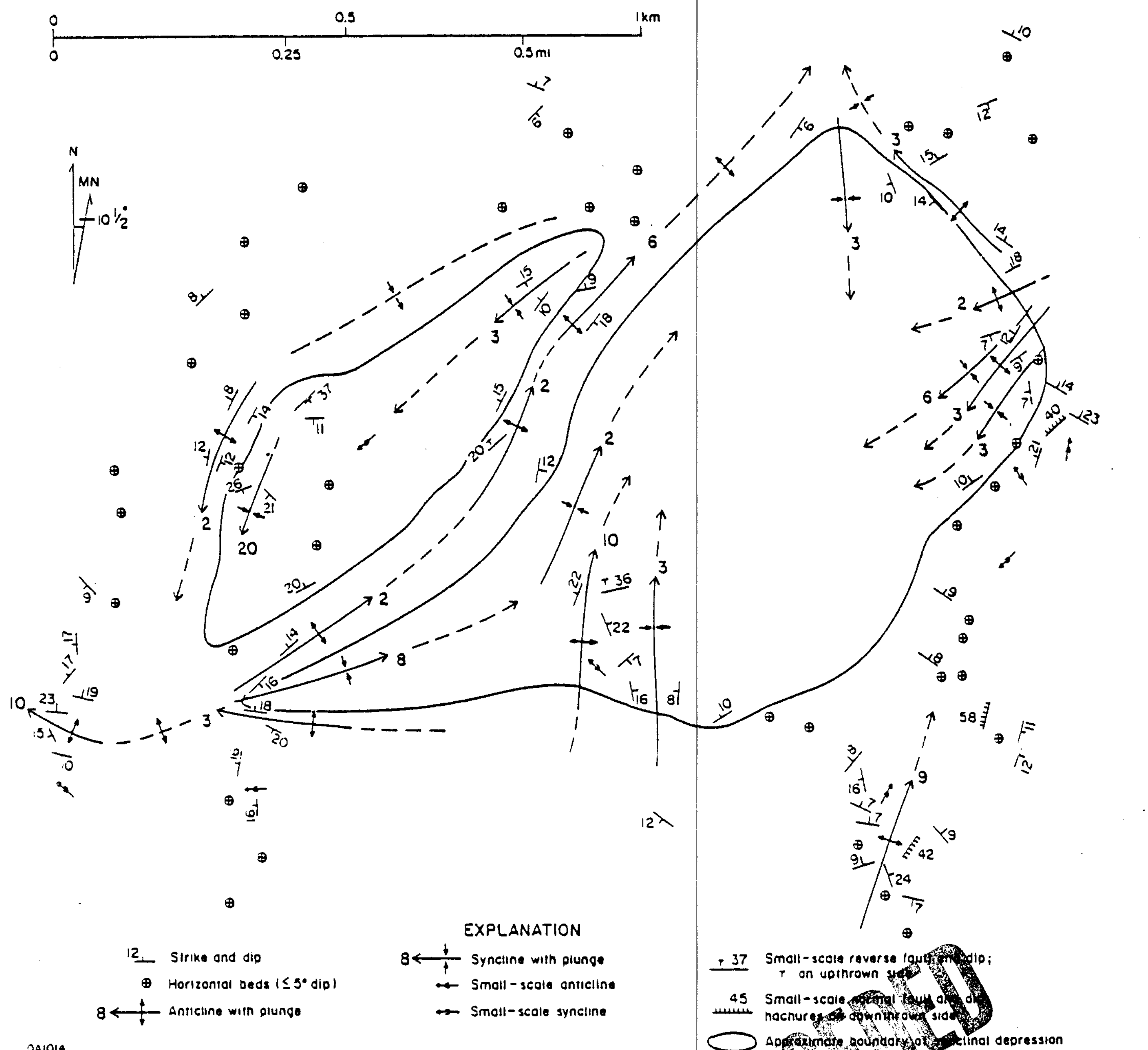


Figure 27. Detailed map of structural elements of individual synclinal depressions located 2 km (1.25 mi) north of Lake Theo. The major axes of the two depressions trend NE-SE (045-225).

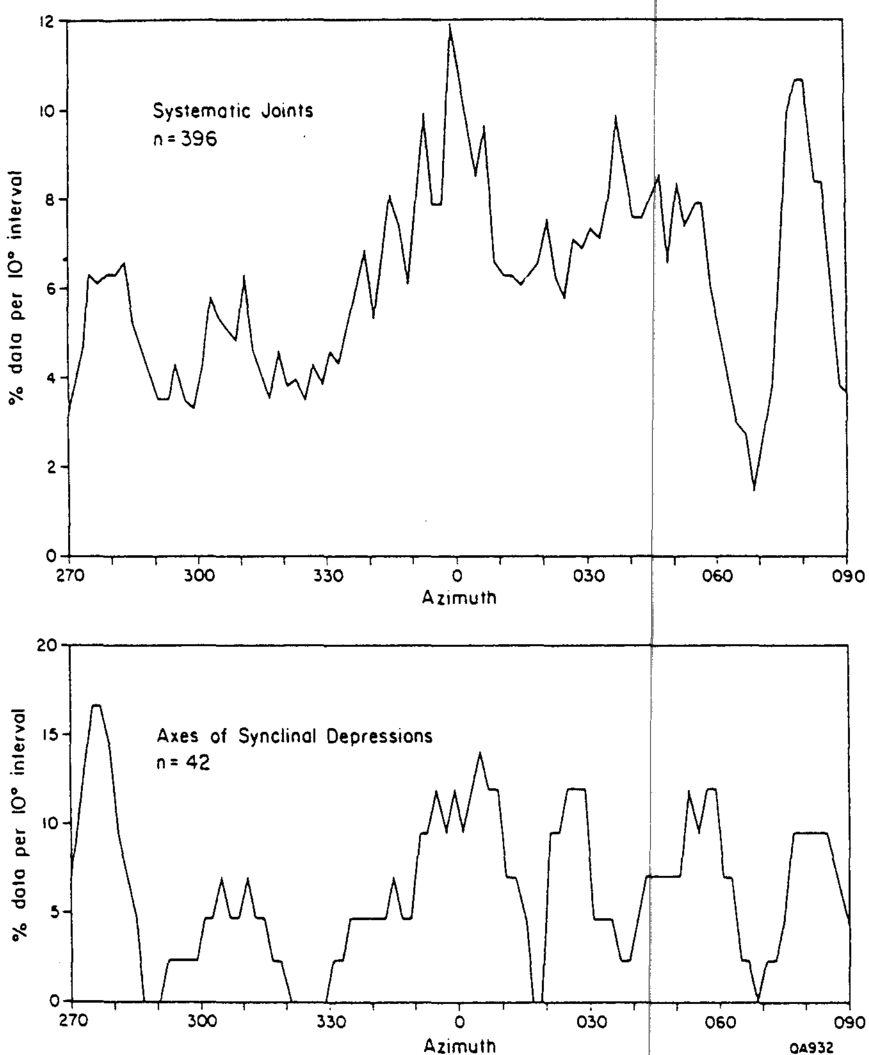


Figure 28. Histograms of (A) systematic joints and (B) axes to synclinal depressions in Caprock Canyons State Park (from Goldstein and Collins, in press).

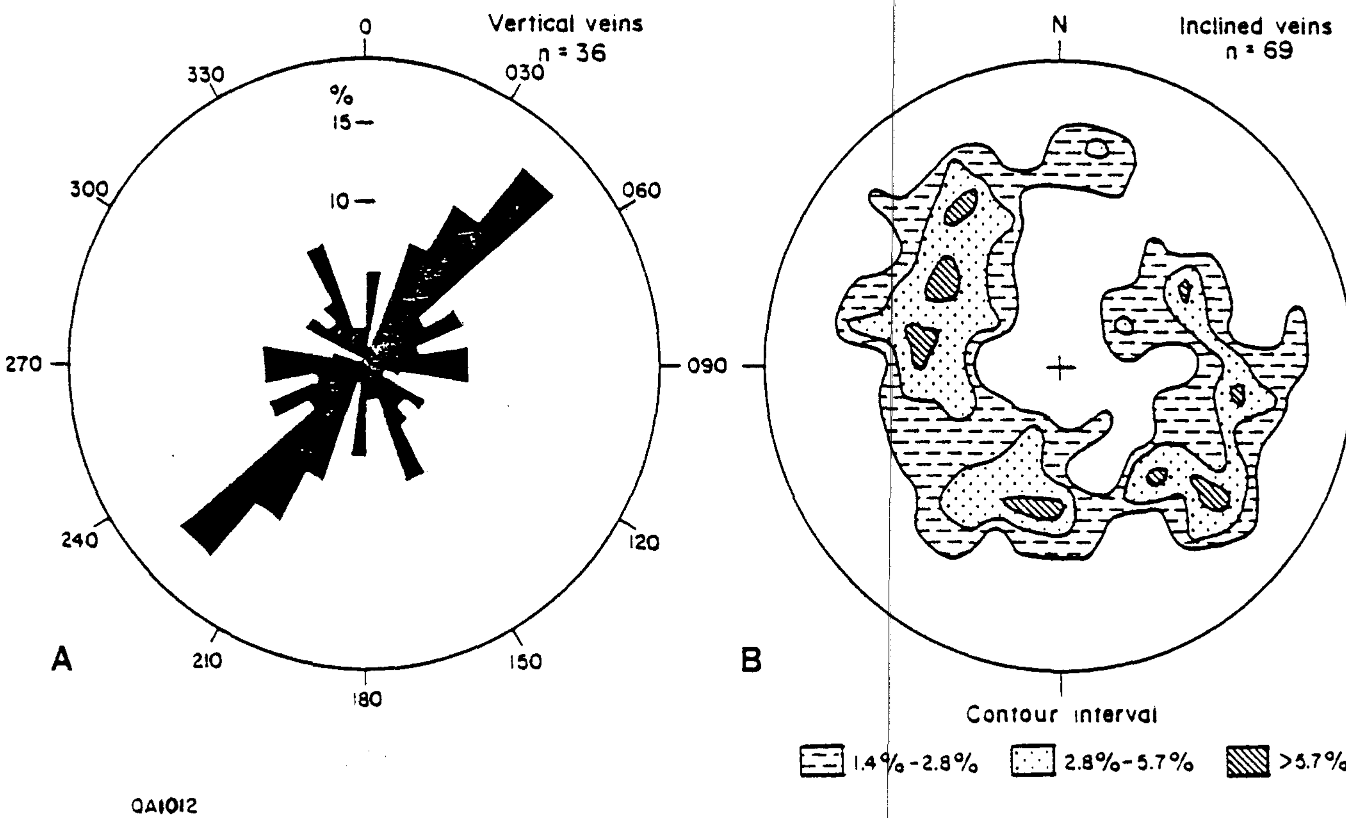


Figure 29. Orientations of veins in synclinal depressions mapped in figure 27, Caprock Canyons State Park. A. Rose diagram of orientations of vertical veins. B. Lower hemisphere equal-area net plots for poles to inclined veins.

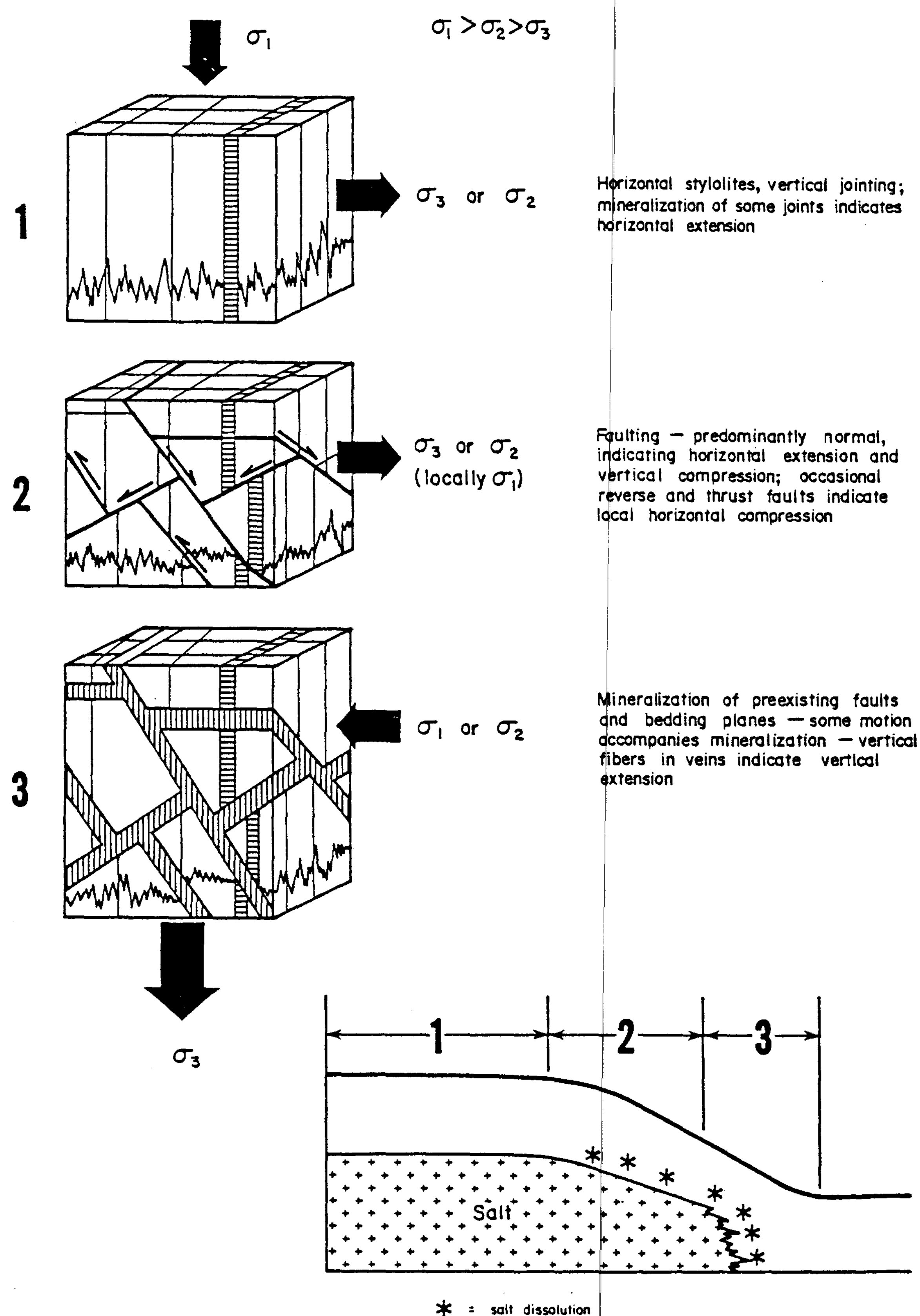


Figure 30. Conceptual model of brittle deformation above dissolution zones. Stage 1 represents normal burial; Stage 2 represents horizontal extension as a precursor to dissolution collapse; and Stage 3 represents collapse (from Goldstein, 1982).

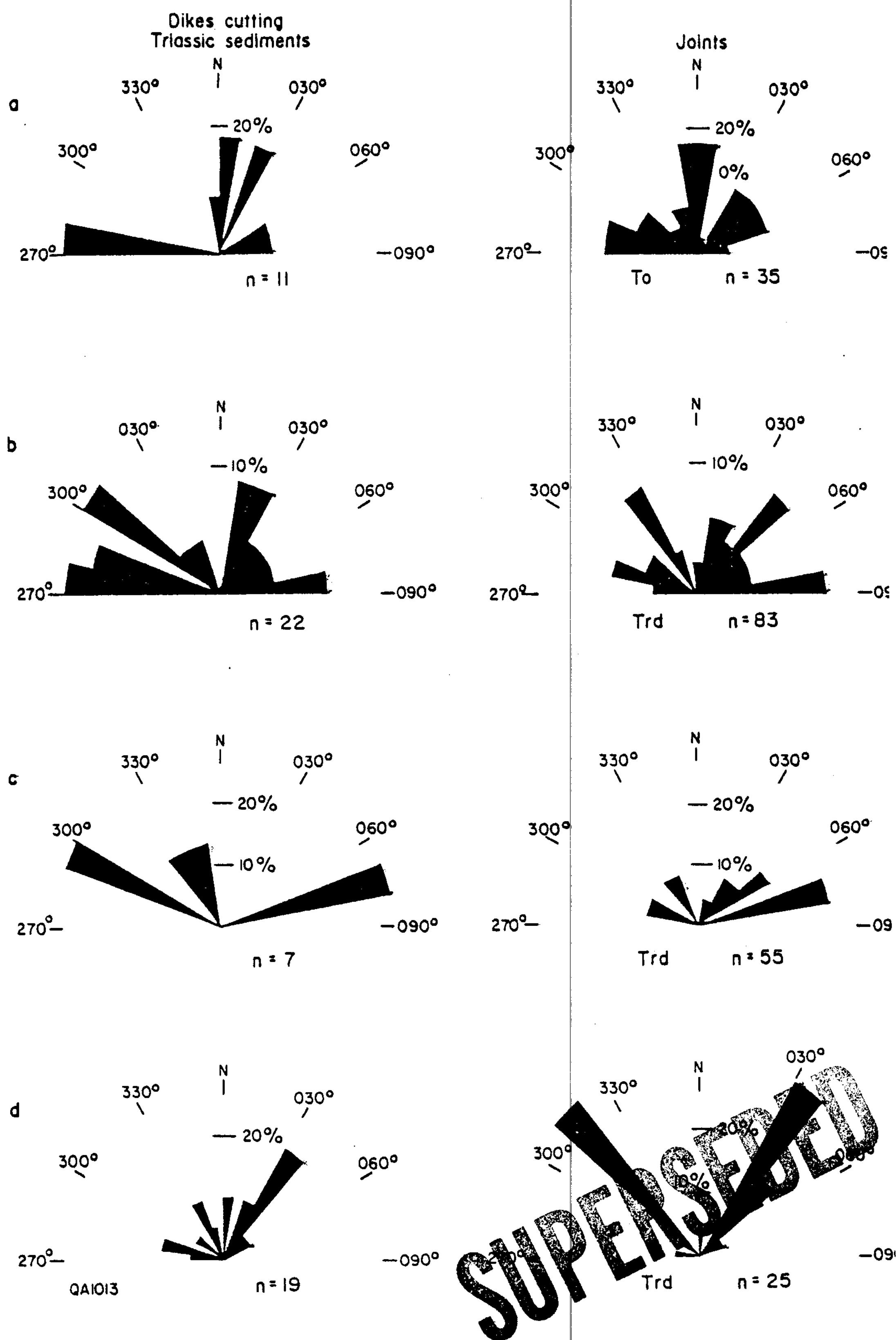


Figure 31. Comparison of clastic dikes and joint orientations in the Texas Panhandle and eastern New Mexico.