OF-WTWI-1984-3

SALT DISSOLUTION: EXAMPLES FROM BENEATH THE SOUTHERN HIGH PLAINS

by

Thomas C. Gustavson

Roy T. Budnik

Prepared for the
U. S. Department of Energy
Office of Nuclear Waste Isolation
under contract no. DE-AC-97-83WM46615

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
University Station, P. O. Box X
Austin, Texas 78712

1984

Salt Dissolution: Examples from Beneath the Southern High Plains

T. C. Gustavson and R. T. Budnik

INTRODUCTION

Regional salt dissolution and the subsequent collapse of overlying strata have affected substantial parts of the Texas and Oklahoma Panhandles (Gustavson and others, 1980; Johnson, 1981). There are seven salt-bearing units within the Permian System of the Texas Panhandle and eastern New Mexico. With the probable exception of the lower Clear Fork Formation, all the younger salt-bearing units are locally undergoing dissolution.

Several lines of evidence support the conclusion that zones of salt dissolution underlie parts of the Southern High Plains, the Rolling Plains, and the Canadian River Breaks (Gustavson and others, 1980, 1982): (1) The major streams draining the region surrounding the Southern High Plains carry high-solute loads, indicating that dissolution is active. For example, the Prairie Dog Town Fork of the Red River carries a mean annual solute load of 1,003.4 x 10^3 tons of dissolved solids per year, including 425.3 x 10^3 tons of chloride per year (U.S. Geological Survey, 1969-1977). Brine springs, salt springs, and salt pans appear along this and other stream valleys.

(2) The abrupt loss of salt sequences between relatively closely spaced oil and gas exploration wells indicates salt dissolution and not facies change. Structural collapse of overlying strata is evident in the wells where salt is missing (fig. 1).

(3) Brecciated zones, fractures with slickensides, extension fractures filled with gypsum, and insoluble residues composed of mud, anhydrite, or dolomite overlie the uppermost salts in cores from the DOE-Gruy Federal

No. 1 Rex H. White well in Randall County, the DOE-Gruy Federal No. 1 D. N. Grabbe well and the Stone and Webster Engineering Corp. No. 1 Zeeck and No. 1 Harmon wells in Swisher County, the Stone and Webster Engineering Corp. No. 1 Sawyer well in Donley County, the Stone and Webster Engineering Corp. No. 1 G. Friemel, No. 1 J. Friemel and No. 1 Detten wells in Deaf Smith County, and the Stone and Webster Engineering Corp. No. 1 Mansfield well in Oldham County.

(4) Numerous sinkholes and closed depressions (dolines) have formed recently in the Rolling Plains and are interpreted to be the result of dissolution and subsidence (Gustavson and others, 1982).

(5) Permian outcrops both east of the Caprock Escarpment and in the Canadian River valley display folds, systems of extension fractures, breccia beds, and remnants of caverns.

Structural, stratigraphic, core and geomorphic evidence suggest that salt dissolution was active beneath the Southern High Plains during the Pliocene and probably the Pleistocene. Two case studies are presented, one describing evidence for dissolution in eastern Deaf Smith County and one describing evidence for dissolution in eastern Swisher County. Using core and stratigraphic data interpretations of the geology on the two case study areas can be extrapolated to the preferred sites in Deaf Smith and Swisher Counties. In each case it is both reasonable and conservative to infer that dissolution and subsidence of overlying strata occurred during the Pliocene and probably during the Pleistocene.

DEAF SMITH

Basement Structure

Precambrian basement in the Palo Duro Basin of the Texas Panhandle consists mainly of volcanic and igneous rocks (Flawn, 1956). Basement faults within the Palo Duro Basin strike primarily northwest (Budnik and Smith, 1982), with a secondary system striking northeast (fig. 2). The structural axis of the basin strikes northwest through Castro and Deaf Smith Counties. In eastern Deaf Smith County, secondary structural lows are bounded by northeast-trending faults. These structural lows are paralleled by a basement high to the southeast. Basement structural relief in the area is approximately 300 m (1,000 ft).

Basement structure on the Precambrian erosional surface in eastern Deaf Smith County has been interpreted from both well logs and approximately 136 km (85 mi) of seismic-reflection data. Faults, interpreted on seismic profiles, offset basement rocks, but appear to die out below the repository horizon, the San Andres Formation. Stratigraphic relationships, however, suggest that structural adjustments persist higher in the section to at least the Upper Permian Alibates Formation.

Structural Influence on Deposition

Isopach maps of Paleozoic units within the Palo Duro Basin suggest that thickness was influenced by differential subsidence during deposition (Budnik and Smith, 1982; Budnik, 1983). Upper Paleozoic units thicken over a basement structural low in eastern Deaf Smith County and thin over basement structural highs. This thickening along a northeast-southwest trend in eastern Deaf Smith County exists in Lower Pennsylvanian limestones (Dutton, 1980), as well as

Permian carbonates, clastics, and evaporites (Handford, 1979; Presley, 1981; McGillis and Presley, 1981; Presley and McGillis, 1982) (figs. 3 and 4). The northeast-trending axes of thickening of the upper Permian San Andres and Alibates Formations nearly coincide and document approximately 40 m (130 ft) of subsidence in this subbasin during deposition of these units. Subsidence in Pennsylvanian and Permian strata could be due to differential compaction of underlying rocks or to tectonic influences. Less than 80 m (250 ft) of Mississippian carbonates lie between Pennsylvanian strata and crystalline Precambrian basement; this thickness cannot provide the differential compaction necessary to account for subsidence in the overlying section. Although there is no evidence of fault displacement as high as either the San Andres Formation or the Alibates Formation, the vertical juxtaposition and northeast orientation of axes of thickening above a structural low in the Precambrian basement clearly suggest basement structural influence in the form of a broad downwarp during deposition of these upper Paleozoic strata.

Regional Jointing

Fractures in Paleozoic and Mesozoic rocks, interpreted from Schlumberger, Inc. Fracture Identification Logs run in DOE test wells, have preferred northeasterly and northwesterly orientations in eastern Deaf Smith County (fig. 4). Fractures in cores from the same intervals are nearly vertical, and some are mineralized with gypsum or halite. Both the northeast and northwest fracture orientations are parallel to basement structural trends. In addition, the northeast-southwest fracture trends are parallel to the axes of thickening of San Andres evaporites and the Alibates Formation (figs. 3 and 4).

In situ stress measurements following hydraulic fracturing of Permian strata in the Stone and Webster Engineering Corp. No. 1 Holtzclaw well in Randall County (fig. 5) indicate that regional northeast-southwest principal compressive stresses occur between N40E and N60E. This is consistent with the observed pattern of northeast-trending fractures.

Salt Dissolution

Contrary to thickening trends in both underlying and overlying units, salt in the Seven Rivers Formation thins above northeast-trending basement structural elements (fig. 5). The axis of thin salt, however, is offset approximately 16 km (10 mi) to the southeast of the axes of thickening of the San Andres and Alibates Formations. Gustavson and others (in press) and Gustavson and Finley (in press) have shown that the Seven Rivers salts have undergone extensive dissolution in the study region. Strata immediately above salt of the Seven Rivers Formation contain microbreccias, insoluble residues, and complexly fractured units that are thought to result from dissolution and subsidence. Analyses of insoluble residues suggest that at least 30 m (100 ft) of salt has been lost from the top of the Seven Rivers Formation. Prior to dissolution of Seven Rivers salt, approximately 30 m (100 ft) of salt was removed from the overlying Salado Formation (Gustavson and others, 1980; McGillis and Presley, 1981).

Preferential dissolution that occurred along the northeast structural trend may be related to in situ regional stress conditions. Northeast-southwest principal compressive stresses would tend to keep northwest-trending fractures closed, while northeast-trending fractures could remain relatively more open. In this case, enhanced ground-water movement along the northeast-trending fractures could account for accelerated salt dissolution along the same trend.

Structure on the Alibates Formation

Structure on top of the Alibates Formation, which overlies the Salado and Seven Rivers Formations, was interpreted from 136 km (85 mi) of 24-fold seismic-reflection profiles (fig. 6). Several structural basins lie within a structural trough that trends to the northeast. Although the northeast structural trend is apparent on structure maps of stratigraphic units below the Seven Rivers Formation, the smaller structural basins are not evident, and, thus, formation of these basins is probably not directly related to basement structural adjustments.

Evidence of salt dissolution has been observed in cores of the Seven Rivers and Salado Formations in this area, and, therefore, differential subsidence as a result of dissolution may have led to the development of the structural basins recognized on the top of the Alibates Formation.

Mid-Tertiary Erosional Surface

Figure 7 is a structure-contour map on the base of the High Plains Aquifer or the Miocene-Pliocene Ogallala Formation. It is, in effect, a paleotopographic map of the mid-Tertiary erosional surface that was developed on Triassic Dockum Group rocks. Relief on the mid-Tertiary erosional surface is approximately 80 m (250 ft).

The most conspicuous paleotopographic features are a regional low trending to the northeast from Parmer County to eastern Deaf Smith County, a series of closed basins within the paleotopographic low, and a northeast-trending paleotopographic high to the east. In addition, the paleotopography in eastern Deaf Smith County shows a strong northeasterly grain.

The paleotopographic low and the northeast-trending series of closed basins overlie the area of thin salt in the Seven Rivers Formation. The northeasterly grain of the paleotopography parallels the dominant northeasterly orientation of fractures recognized in the subsurface in Dockum Group and older strata. Some of the individual closed basins also tend to overlie structural basins mapped on the Alibates Formation (figs. 6 and 7). The difference in the shapes of basins on the two maps is probably because they are based on different data sets and methodologies.

Topography

The Southern High Plains surface slopes regionally to the southeast. All major streams except Tierra Blanca Creek, Frio Draw, and Palo Duro Creek drain to the southeast (fig. 8). Tierra Blanca Creek and Frio Draw are the only major streams that flow to the northeast. These streams flow in a broad topographic trough that overlies the dissolution thin in Seven Rivers salt. Tierra Blanca Creek flows parallel to the string of paleotopographic lows on the mid-Tertiary erosional surface in eastern Deaf Smith County and vicinity (compare figs. 8 and 7).

Plio-Pleistocene Lacustrine Deposits

In the Late Pliocene fine-grained sediments, interpreted to be lacustrine deposits, accumulated in a basin east of Hereford, Texas (Norton, 1954) (fig. 8). A larger lacustrine basin approximately 40 km (25 mi) to the northeast at Canyon, Texas, (fig. 8) contains a mid-Pleistocene molluscan fauna (Frye and Leonard, 1963; G. E. Schultz, personal communication, 1981) and presumably formed during the Pleistocene. These basins occur above the paleotopographic trough shown in figure 8 and along the trend of thin Seven Rivers salt.

INTERPRETATIONS

Structural Controls on Dissolution

Basement structural trends and overlying Paleozoic thickness trends are oriented to the northeast beneath eastern Deaf Smith County, suggesting that differential movement on basement fault blocks has affected the depositional thickness of Paleozoic formations. Fracture systems in this area also trend to the northeast and northwest, but based on in situ stress measurements, northeast-trending fractures are relatively more likely to be open. Collapse breccias and insoluble residues in cores indicate that thinning of salt in the Seven Rivers Formation in this area is the result of dissolution. The zone of thinnest Seven Rivers salt also trends to the northeast in eastern Deaf Smith County. The northeast alignment of faults, fractures and thickness trends suggests that structural adjustments and controls have propagated upwards, perhaps through fracture systems, to influence the pattern of dissolution. The zone of thin salt in eastern Deaf Smith County may have resulted from accelerated dissolution caused by the enhanced movement of ground water along northeast-trending fractures.

Timing of Dissolution

Structural basins seen on the Alibates Formation and on the mid-Tertiary erosional surface are thought to result from differential subsidence following dissolution. The basins on the mid-Tertiary erosional surface are filled with Ogallala Formation sediments, and the northeast-trending structural trough on this surface cuts across the regional paleotopographic slope to the southeast. This suggests that the episode of dissolution that resulted in the northeast-trending salt thin was not initiated until after regional Tertiary uplift and deposition of the Miocene-Pliocene Ogallala Formation. A regional southeasterly slope as indicated by sand distribution patterns was present in eastern Deaf Smith County during deposition of the Ogallala Formation (Seni, 1980). Subsequent to the end of Ogallala deposition in the late Pliocene, regional southeasterly drainage was diverted to the current northeasterly drainage. The modern drainage of Tierra Blanca Creek and the valley in which it flows overlies and parallels the zone of thin Seven Rivers salt. Plio-Pleistocene and Pleistocene sediments fill lacustrine basins along Tierra Blanca Creek. Continued dissolution and surface subsidence following the end of Ogallala deposition led to the formation of lacustrine basins and to the diversion of drainage to the northeast.

No single structural or geomorphic feature in this area provides conclusive evidence of salt dissolution during the Quaternary. However, there is a persistent pattern of structural and geomorphic features that can be explained by dissolution of Seven Rivers salt during the Tertiary and perhaps as late as the Quaternary.

SWISHER COUNTY

The Tule Formation (Pleistocene) is exposed around the margin of Lake Mackenzie at the boundary of Swisher and Briscoe Counties and lies within a basin that partly resulted from subsidence due to salt dissolution (figs. 9 and 10).

Stratigraphy of the Tule Formation has been discussed by Evans and Meade (1945), Frye and Leonard (1957), Reeves (1970), Kumanchan (1972) and Schultz (in press). These sediments have generally been interpreted as lacustrine deposits, although Frye and Leonard (1957) thought them to be fluvial. The presence of thin limestone and dolomite beds and laminated mudstones is strong evidence that the Tule Formation is lacustrine.

Most recently Schultz (1977 and in press) has reviewed evidence for the age of these beds. Based on vertebrate remains and on the presence of Lava Creek B Ash (Pearlette type "O") and the Cerro Toledo-X Ash (Izett, 1977) Schultz has suggested that the Tule Beds span most of the Irvingtonian Mammal Age. Earlier Evans and Meade (1945) referred to these beds as middle Pleistocene and Frye and Leonard (1957) considered them as Kansan in age. The presence of an Irvingtonian fauna within the Tule Formation indicates that the basin that it fills must have been in existence by the early Pleistocene.

Several possible origins have been proposed for this basin. Baker (1915) and Patton (1935) attributed the origin of the larger partly filled basins on the High Plains to subsidence due to dissolution of Upper Permian bedded salts. Evans and Meade (1945) suggested that solution and deflation were both important processes in the development of lacustrine basins on the High Plains, with deflation being the primary process. Frye and Leonard (1957) suggested that the Tule Basin was a stream valley and not a deflation basin as suggested by Evans and Meade (1945). Later, Reeves (1970) suggested that the position of the Tule Basin, along with other large basins on the High Plains, was controlled by intersecting sets of regmatic shear fractures. Gustavson and Finley (in press) have suggested that the location of the Tule Basin resulted from subsidence due to dissolution of Permian salts, but that this subsidence probably accounts for only a small part of the depth of the basin.

Dissolution of Permian bedded salts beneath the Tule Lake Basin is suggested in figure 1 which shows that the Salado Formation salts thin by approximately 30 m (100 ft) between the Humble Oil Co. #1 Howard Ranch in central Briscoe County and the Gulf Oil Co. #1 Rodgers "D" well near Tule

Creek. Overlying and underlying non-salt beds do not change in thickness or lithology which suggests that neither Permian structural nor facies changes can account for the changes in salt thickness. Differences in regional dip between beds overlying and underlying the Salado Formation salts west of the Humble well suggest that subsidence has occurred.

Core through the Salado Formation in the Stone and Webster Engineering Corp. #1 Zeeck and the DOE/Gruy Federal #1 Grabbe wells, which lie several kilometers west and northwest, respectively, of the Tule Basin, both contain insoluble residues and gypsum-filled extension fractures resulting from dissolution of Salado Formation salts. The net-salt map of the Salado Formation salts in the vicinity of the Tule Lake Basin shows that Salado salts thin from 150 ft in central Briscoe County to less than 50 ft beneath the Tule Lake Basin (fig. 11).

If dissolution of salt has in fact occurred, then the structure of overlying units should reflect subsidence. Elevation of the Alibates Formation decreases from approximately 2,625 ft above sea level in central Briscoe County to about 2,500 ft beneath the Tule Basin, nearly paralleling the changes in Salado salt thickness (fig. 12). A structure contour map on the middle Tertiary erosion surface at the base of the Ogallala Formation shows a paleotopographic trough similar to and overlying the structural trough on the Alibates Formation (fig. 13). The vertical juxtaposition of thin salt in the Salado Formation, attributed to dissolution, a structural low on the Alibates Formation, and a paleotopographic low on the middle Tertiary erosion surface, all of which underlie the Tule Basin, suggests that dissolution and subsidence have played a role in the development of the Tule Basin.

If strata underlying the Tule Basin have undergone subsidence, some evidence of deformation should be apparent in outcrop. Evans and Meade (1944) described subtle flexures in Triassic strata exposed in the "narrows" of Tule

Canyon east of Lake Mackenzie and attributed this structure to subsidence resulting from dissolution (fig. 10).

Dockum strata exposed along the access road on the north side of the Tule Basin are highly fractured and fractures are filled with gypsum (var. selenite). Closely spaced, less than 15 cm (6 inches), subhorizontal, gypsum-filled, bedding-plane fractures are common. Inclined (30^{o} to 60^{o}) and near vertical gypsum-filled fractures are present but less common than bedding-plane fractures. Gypsum fillings in bedding-plane fractures are mostly less than 1.8 cm (0.75 inch) thick, and appear to have a medial scar. The geometry of these fractures is similar to that of extension fractures in Permian rocks east of this area (Goldstein, 1982). A preliminary interpretation of the formation of these features is that gypsum was deposited as vertical extension took place. Extension could have resulted from subsidence of underlying strata as a result of dissolution.

Both the Triassic Dockum Group and the Quaternary Tule Formation strata show the effects of minor structural warping in the Lake Mackenzie area. In the area where Dockum Group strata contain gypsum-filled fractures, strikes vary from N5^{o}E to N80^{o}W and dips vary from 5^{o} to 15^{o}N. In this same area strike and dip on the Tule Formation are difficult to measure, but Tule strata appear to dip south between 5^{o} and 10^{o}. On the south side of Lake Mackenzie Tule beds appear to dip to the north from 5 to 15 degrees. On Texas Highway 207, the south flank of Tule Canyon, Tule beds underlying a syndepositionally disturbed horizon dip to the north at approximately 5 degrees.

Fine-grained lacustrine strata would probably not be stable on depositional slopes of 5 to 10 degrees. It seems more likely that the Tule sediments have been slightly tilted towards the center of the basin. Tilting could result from either subsidence or differential compaction of a thicker fine-grained section of lacustrine sediments towards the center of the Tule Basin. If tilting is due to subsidence, then dissolution of underlying salts is the most likely cause.

The Tule Formation contains an Irvingtonian fauna indicating that these units were deposited in a lacustrine basin that was formed by middle Pleistocene time. Tule beds rest unconformably on both Triassic and Ogallala sediments indicating that substantial erosion had occurred prior to deposition of the Tule Formation. Tule sediments are at least 30 m (100 ft) thick and, therefore, the original basin must have been at least that depth. In addition, the Tule Basin lies within a larger topographic basin suggesting that at the onset of Tule deposition the floor of the Tule Basin was at least 53 m (175 ft) below the topographic basin edge. Salt dissolution alone could not have accounted for a basin of this depth. Structure on the Alibates Formation suggests that a maximum of 30 m (100 ft) of subsidence occurred. Furthermore, vertical extension fracturing with mineralization of the fractures such as seen in Dockum strata beneath the Tule Basin and in Permian strata in the Rolling Plains suggests that the effects of subsidence diminishes upwards (Goldstein and Collins, in press). Therefore, it is likely that surface erosion accounted for at least 30 m (100 ft) and probably more of the early Pleistocene Tule Basin.

Was the surface erosion that helped to excavate the Tule Basin primarily eolian deflation as suggested by Evans and Meade (1945) or was stream erosion as suggested by Frye and Leonard (1957) the more important process? There appears to be no direct evidence to answer this question. However, Recent intermittent lakes on the Southern High Plains in most cases have large lee dunes on the eastern sides indicating that deflation was a significant process in their formation. Salt Lake, Illusion Lake, Yellow Lake, and Coyote Lake all lie in basins that are more than 100 ft deep and similar in size to the Tule Basin. Stream erosion could also have eroded the Tule Basin. However, if the basin was the result of stream erosion, some mechanism to create a dam over 30 m (100 ft) high to contain the Tule Lake must be invoked. This would be difficult to do given the low relief that must have existed on the early Pleistocene High Plains. Furthermore, the dam must have remained stable for a geologically significant period of time. Therefore, it seems that deflation is a more likely process than stream erosion in the development of the Tule Basin.

It appears that salt dissolution and deflation were the most important processes contributing to the development of the Tule lacustrine basin. The age of the Tule Formation suggests that formation of the basin and salt dissolution occurred during the Plio-Pleistocene. Minor deformation of Tule Formation strata suggests that dissolution and subsidence were active during or following deposition of Tule Formation sediments.

REFERENCES

Baker, C. L., 1915, Geology and underground waters of the northern Llano Estacado: Austin, University of Texas Bulletin No. 57, 93 p.

Budnik, R. T., 1983, Recurrent motion on Pre-Cambrian-age basement faults, Palo Duro Basin, Texas Panhandle (abs.): American Association of Petroleum Geologists Bulletin, v. 677, p. 433.

Budnik, R. T., and Smith, D., 1982, Regional stratigraphic framework of the Texas Panhandle, in Gustavson, T. C., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: A report on the progress of nuclear waste isolation feasibility studies (1981): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 82-7, p. 38-86.

Dutton, S. P., 1980, Depositional systems and hydrocarbon resource potential of the Pennsylvanian System, Palo Duro and Dalhart Basins, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-8, 49 p.

Evans, G. L., and Meade, G. E., 1945, Quaternary of the Texas High Plains: University of Texas, Austin, Bureau of Economic Geology Publication 4401, p. 485-507.

Flawn, P. T., 1956, Basement rocks of Texas and southeast New Mexico: University of Texas, Austin, Bureau of Economic Geology Publication 5605, 261 p.

Frye, J. C., and Leonard, A. B., 1957, Studies of Cenozoic geology along eastern margin of Texas High Plains, Armstrong to Howard Counties: University of Texas, Austin, Bureau of Economic Geology Report of Investigations No. 32, 62 p.

Frye, J. C., and Leonard, A. B., 1963, Pleistocene geology of the Red River Basin in Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 49, 37 p.

Frye, J. C., Swineford, A., and Leonard, A. B., 1948, Correlation of Pleistocene deposits of the central Great Plains with the glacial section: Journal of Geology, v. 56, no. 6, p. 501-525.

Goldstein, A. G., 1982, Brittle deformation associated with salt dissolution, Palo Duro Basin, Texas Panhandle, a report on the progress of nuclear waste isolation feasibility studies (1981): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 82-7, p. 18-27.

Goldstein, A. G., and Collins, E. W., in press, Deformation of Permian strata overlying a zone of salt dissolution and collapse in the Texas Panhandle: Geology.

Gould, Charles N., 1906, The geology and water resources of the eastern portion of the Panhandle of Texas: U.S. Geological Survey Water-Supply and Irrigation Paper No. 154, Washington, D.C. (reprint).

Gustavson, T. C., and Finley, R. J., in press, Late Cenozoic geomorphic evolution of the Texas Panhandle and northeast New Mexico--case studies of structural controls of drainage development: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations.

Gustavson, T. C., Finley, R. J., and McGillis, K. A., 1980, Salt dissolution in the Anadarko, Dalhart and Palo Duro Basins, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 106, 39 p.

Gustavson, T. C., Hovorka, S. D., and McGookey, D. A., in press, Petrographic, stratigraphic, and structural evidence for dissolution of Upper Permian bedded salt, Texas Panhandle: American Association of Petroleum Geologists, Special Publication.

Gustavson, T. C., Simpkins, W. W., Alhades, Alan, and Hoadley, Ann, 1982, Evaporite dissolution and development of karst features on the Rolling Plains of the Texas Panhandle: Journal of Earth Surface Processes and Landforms, v. 7, p. 545-563.

Handford, C. R., 1979, Lower Permian depositional systems, in Dutton, S. P., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: a report on the progress of nuclear waste isolation feasibility studies (1978): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 79-1, p. 26-38.

Izett, G. A., 1977, Volcanic ash beds in continental deposits of the southern High Plains: their bearing on the time of the Blancan-Irvingtonian faunal transition: Geological Society of America Annual Meeting Abstracts with Programs, v. 9, no. 7, p. 1034.

Johnson, K. S., 1981, Dissolution of salt on the east flank of the Permian Basin in the southwestern U.S.A.: Journal of Hydrology, v. 54, p. 75-93.

Knowles, T., Nordstrom, P., and Klemt, W. B., 1982, Evaluating the ground-water resources of the High Plains of Texas--final report: Texas Department of Water Resources LP-173, 3 volumes.

Kumanchan, Prasert, 1972, Mineralogy, petrology and field studies of the deposits of the Pleistocene Tule basin, Briscoe and Swisher Counties, Texas: Northeastern Louisiana University, Monroe, Louisiana, unpublished thesis, 74 p.

McGillis, K. A., and Presley, M. W., 1981, Tansill, Salado, and Alibates Formations: Upper Permian evaporite/carbonate strata of the Texas

Panhandle: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-8, 31 p.

Norton, P., 1954, A new Blancan vertebrate locality: Journal of Paleontology, v. 28, p. 487.

Patton, L. T., 1935, Some observations on the so-called "lakes" of the Llano Estacado of Texas (abst.): Geological Society of America Proceedings (1934), p. 451.

Presley, M. W., 1981, San Andres salt stratigraphy and salt purity, in Gustavson, T. C., and others, Geology and geohydrology of the Palo Duro Basin, Texas Panhandle: A report on the progress of nuclear waste isolation feasibility studies (1980): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 81-3, p. 33-40.

Presley, M. W., and McGillis, K. A., 1982, Coastal evaporite and tidal-flat sediments of the Upper Clear Fork and Glorieta Formations, Texas Panhandle: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 115, 50 p.

Reeves, C. C., 1970, Drainage basin analysis, Southern High Plains, West Texas and eastern New Mexico, in Mattox, R. B., and Miller, W. D., eds., The Ogallala aquifer symposium: Texas Tech University, ICASALS Special Report No. 39, p. 58-71.

Schultz, G. E., 1977, Field conference on late Cenozoic biostratigraphy of the Texas Panhandle and adjacent Oklahoma: West Texas University, Kilgore Research Center, Department of Geology and Anthropology Special Publication No. 1, 160 p.

Seni, S. J., 1980, Sand-body geometry and depositional systems, Ogallala Formation: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 105, 36 p.

U.S. Geological Survey, 1969-1977, Water resources for Texas, part II: surface water quality.

FIGURE CAPTIONS

Figure 1. Stratigraphic cross section showing Upper Permian, Triassic, Tertiary and Quaternary strata. Salt dissolution is illustrated between wells where some or all of the salt section is missing and where structural collapse of strata has occurred.

Figure 2. Basement structure for the northern part of the Palo Duro Basin, Texas Panhandle. Faults in the Texas Panhandle strike northwest with a secondary system striking northeast. Basement structure in eastern Deaf Smith County is interpreted from both well logs and seismic-reflection data.

Figure 3. Net salt map of the middle Permian upper San Andres Formation. Salts tend to thicken over basement structural lows (Presley, 1981). Compare to figures 2 and 4.

Figure 4. Isopach map of the Upper Permian Alibates Formation. The Alibates Formation thickens over basement structural lows and thins over basement structural highs (McGillis and Presley, 1981). Compare to figures 2 and 3. In eastern Deaf Smith County preferred fracture orientations are northwest and northeast. Fractures are interpreted from Schlumberger, Inc. Fracture Identification Logs.

Figure 5. Net-salt map of the Upper Permian Seven Rivers Formation. The northeast trend of thinning of the uppermost salt in this part of the Palo Duro Basin parallels local northeast fracture trends and northeast-trending basement faults. Thinning in this case is attributed to salt dissolution. Collapse breccias and other evidence of dissolution were observed in cores from Stone and Webster Engineering Corp. J. Friemel No. 1 (A), G. Friemel No. 1 (B), and Detten No. 1 (C). In situ stress measurements were made in the Stone and Webster Engineering Corp. No. 1 Holtzclaw well (D).

Figure 6. Structure-contour map on top of the Upper Permian Alibates Formation. Structure on the Alibates Formation probably resulted partly from collapse following dissolution of salt in the underlying Salado and Seven Rivers Formations. Two-way travel times have been corrected for velocity differences in overlying units and converted to elevation above sea level.

Figure 7. Structure-contour map on the base of the Ogallala Formation. A series of paleotopographic lows and closed depressions on the mid-Tertiary erosional surface overlies the northeast structural and dissolution-collapse trends. Paleotopographic lows probably result from both stream erosion and collapse following dissolution (after Knowles and others, 1982).

Figure 8. Topographic map of a part of the Southern High Plains of the Texas Panhandle. Contours are in feet below sea level. Deaf Smith County, Texas, is a potential location for a high-level nuclear waste repository. Regional topographic slope on the Southern High Plains is to the southeast at approximately 2.0 m/km (10.6 ft/mi). Streams drain to the southeast with the exception of Tierra Blanca Creek, Palo Duro Creek, and their tributaries.

Figure 9. Topographic map derived from U.S. Geological Survey Cope Creek and Rock Creek 7.5-minute (1965) Quadrangles showing locations of stops and archeological sites.

Figure 10. Geologic map of portions of Cope Creek and Rock Creek Quadrangles (after Kumanchan, 1972).

Figure 11. Net-salt map for the Upper Permian Salado Formation, Swisher and Briscoe Counties.

Figure 12. Structure-contour map on the top of the Upper Permian Alibates Formation, Swisher and Briscoe Counties.

Figure 13. Paleotopography on the middle Tertiary erosion surface (base of the High Plains Aquifer), Swisher and Briscoe Counties (after Knowles and others, 1982).

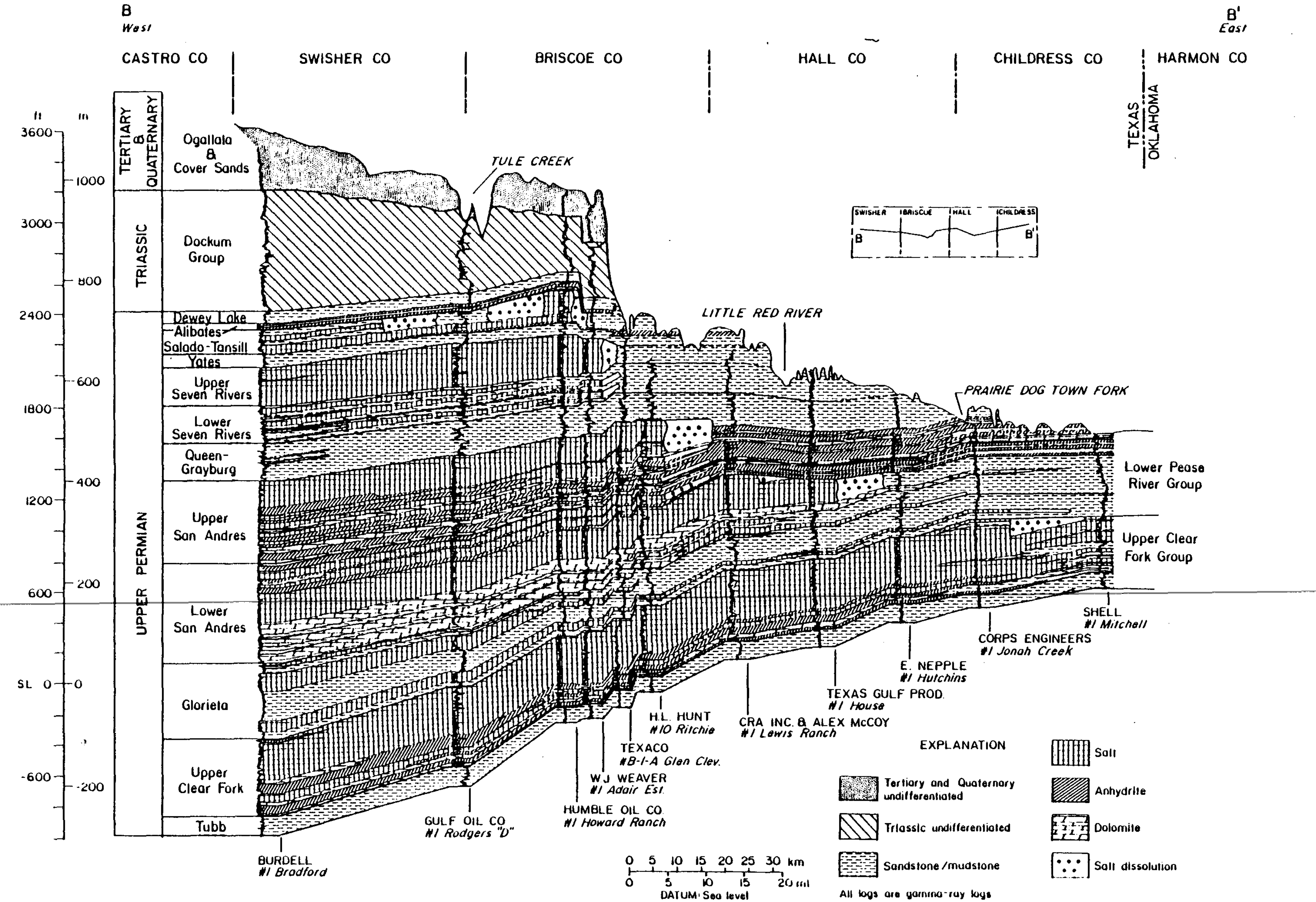


Figure [illegible]. Stratigraphic cross section showing Upper Permian, Triassic, Tertiary and Quaternary strata. Salt dissolution is illustrated between wells where some or all of the salt section is missing and where structural collapse of strata has occurred.

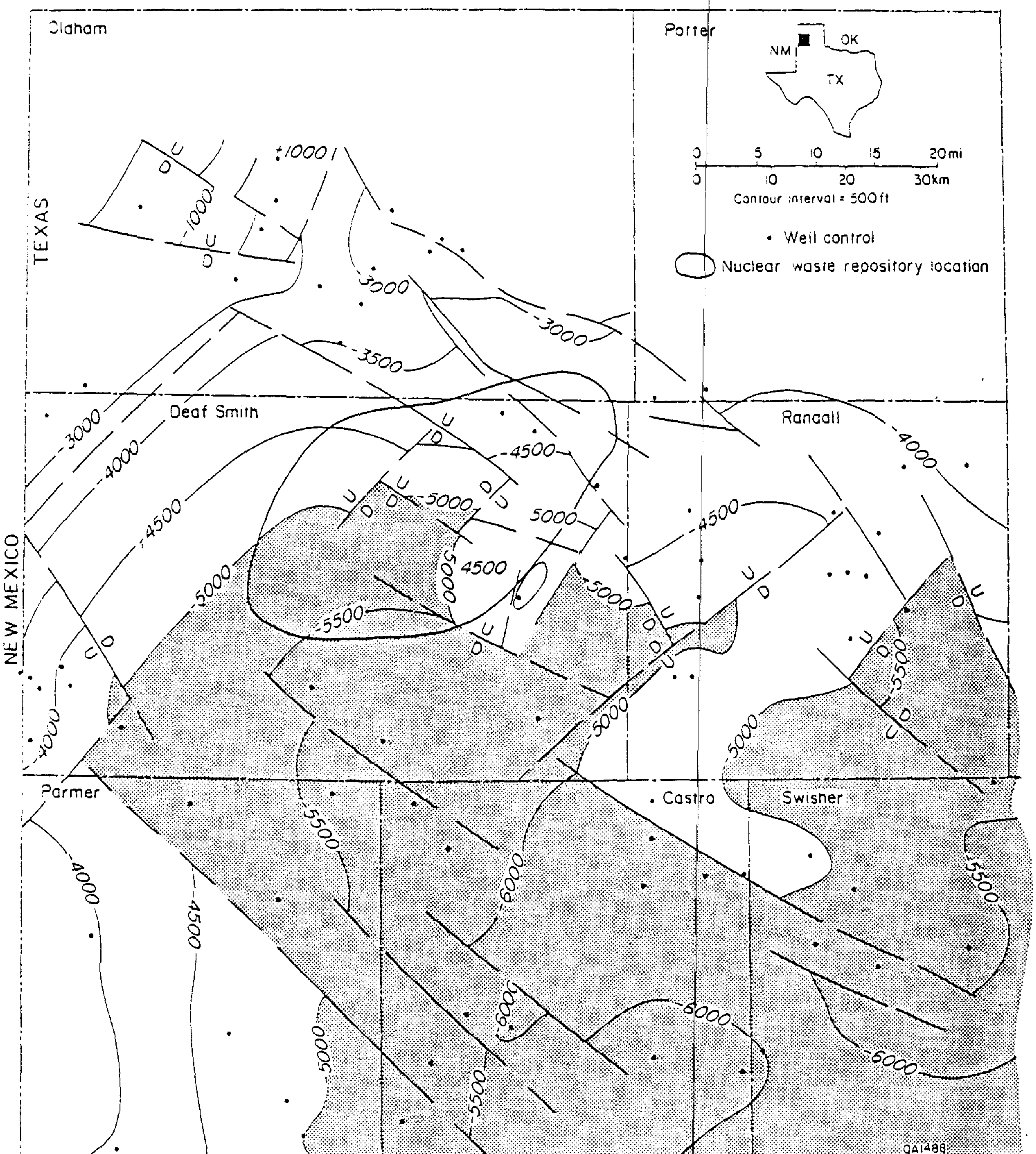


Figure 2. ~~Gustavson and Budnik~~

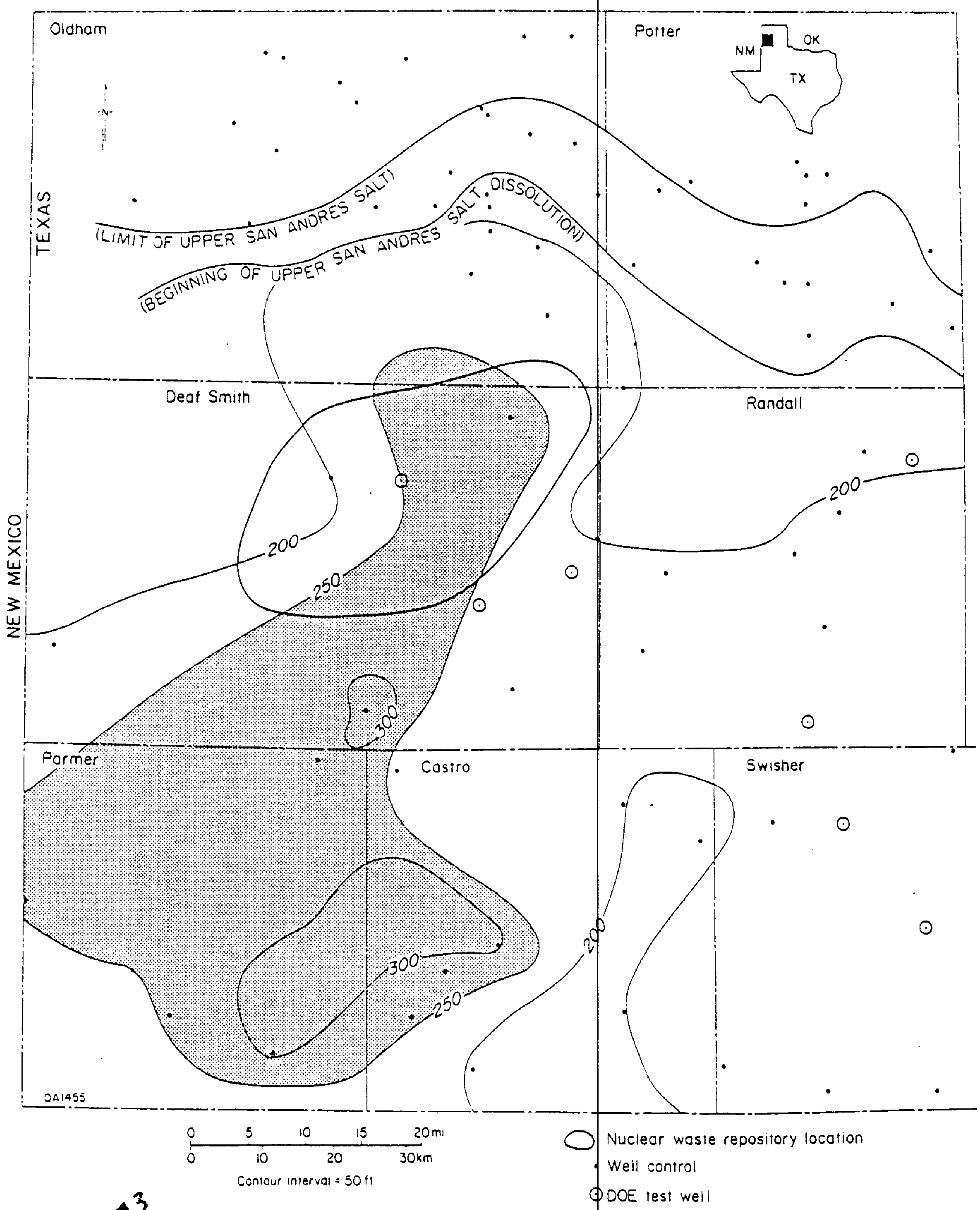


Figure 13. ~~Gustavson and Budnik~~

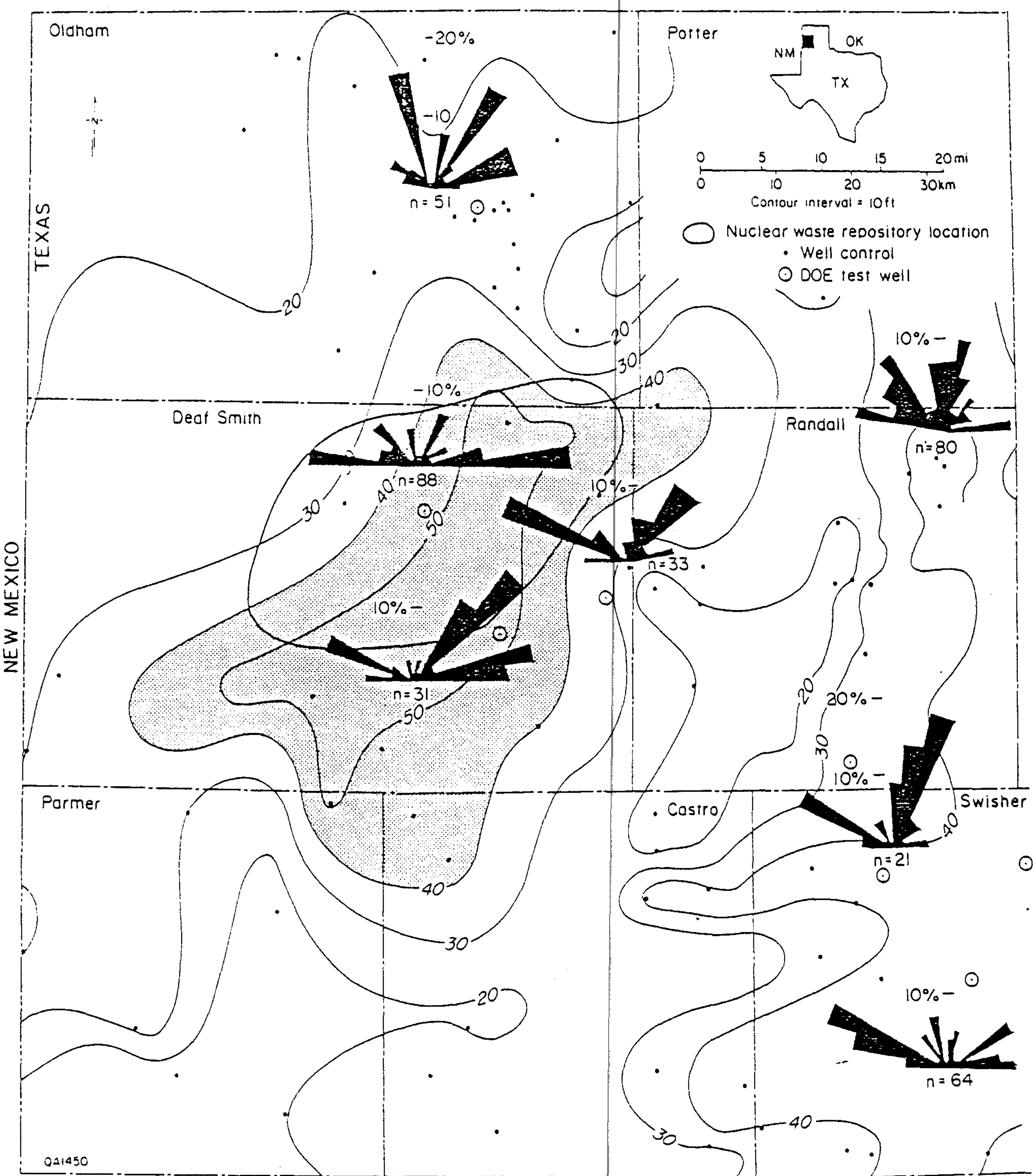


Figure ~~7~~ 34. ~~Gustavson and Budnik~~

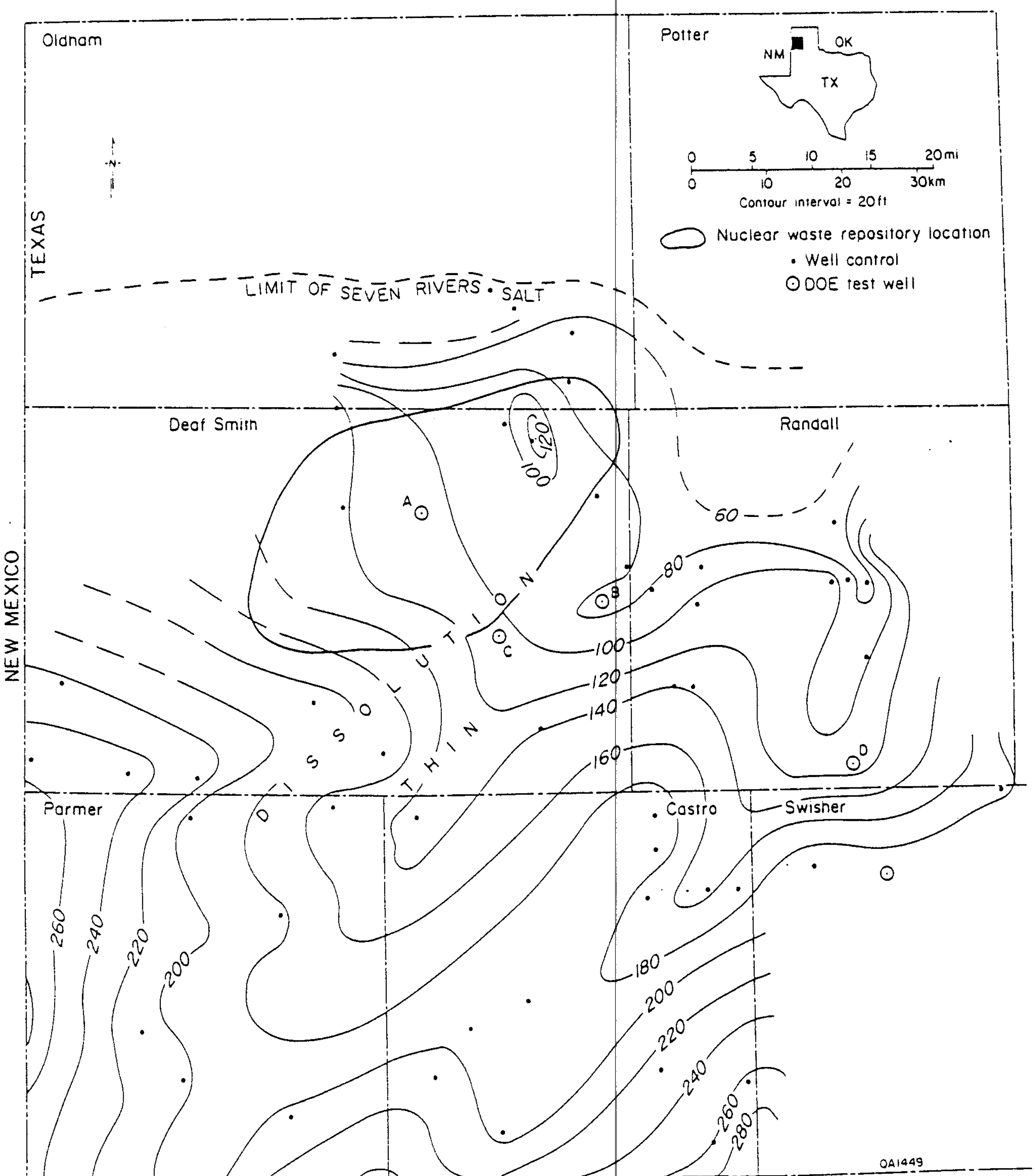


Figure ~~6~~ 5. ~~Gustavson and Budnik~~

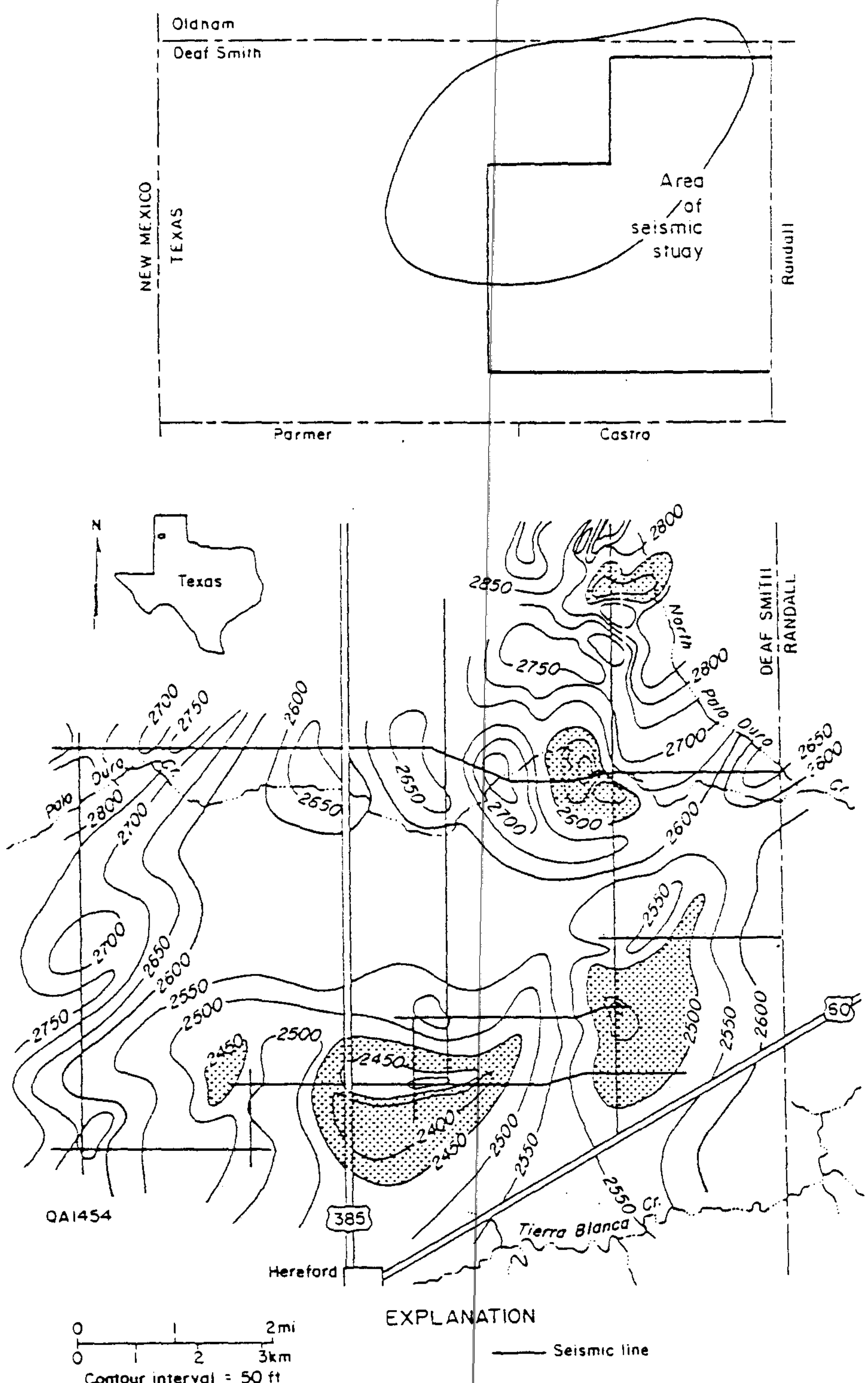


Figure 6. ~~Gustavson and Budnik~~

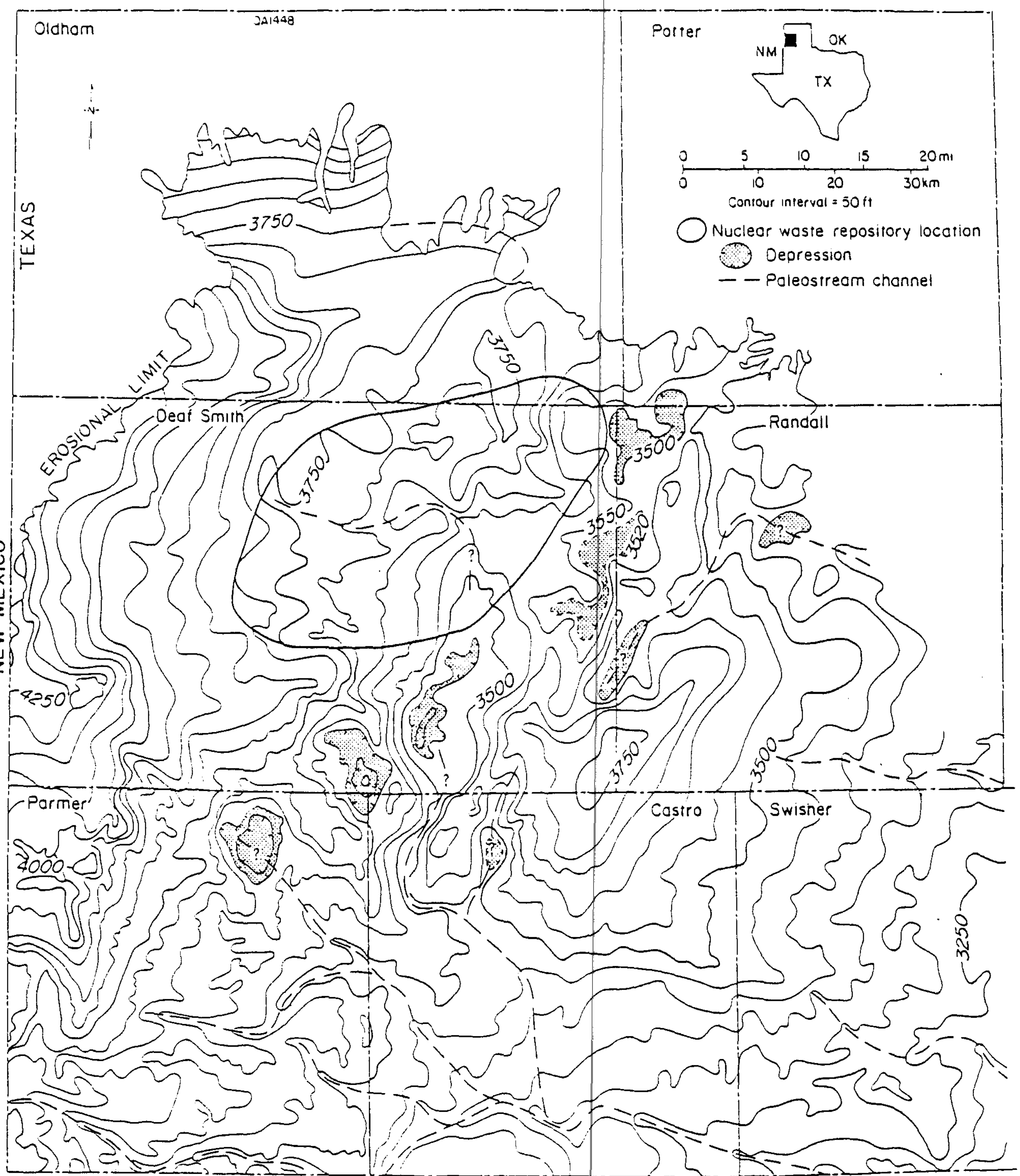


Figure 7. ~~Gustavson and Budnik~~

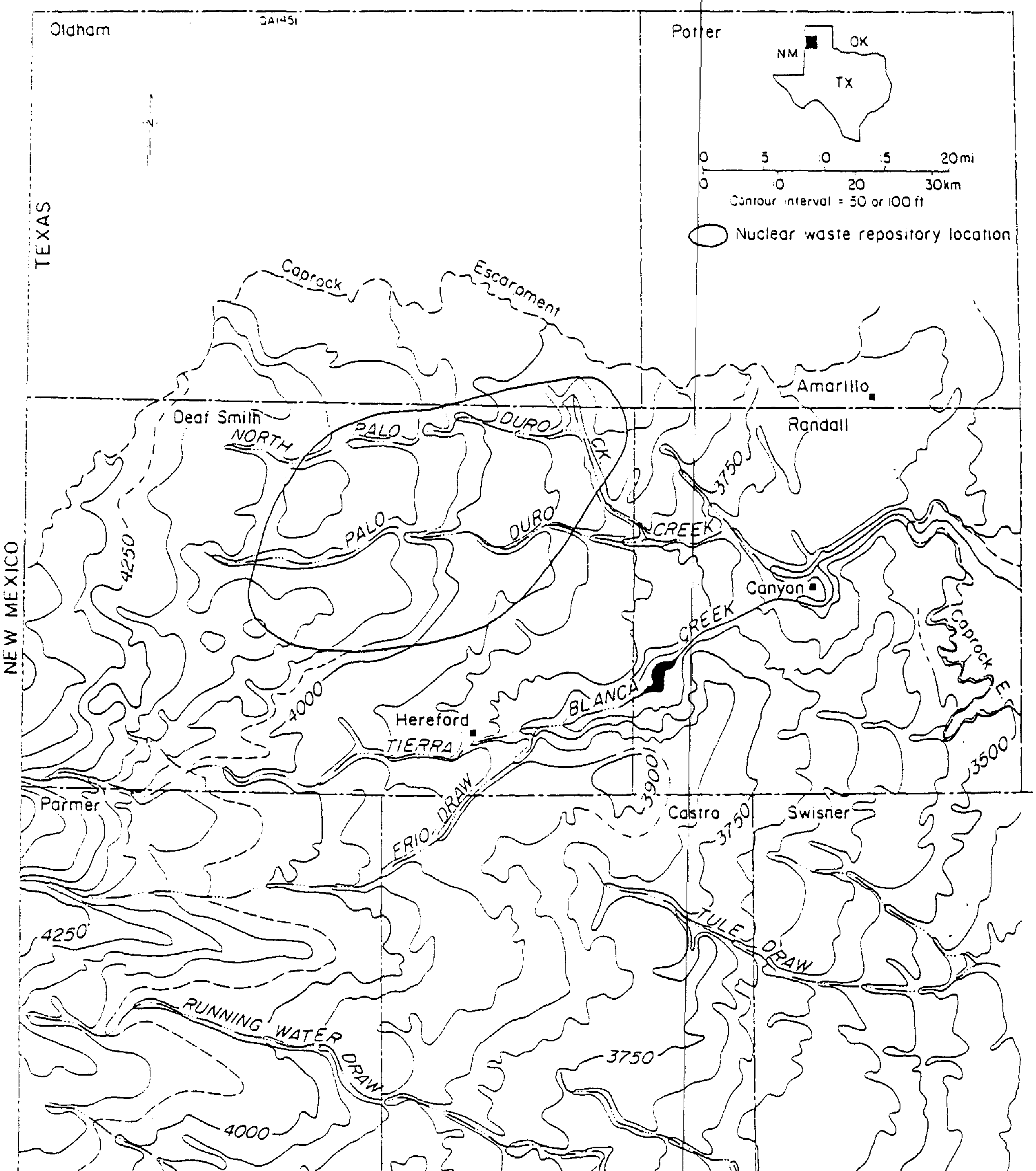
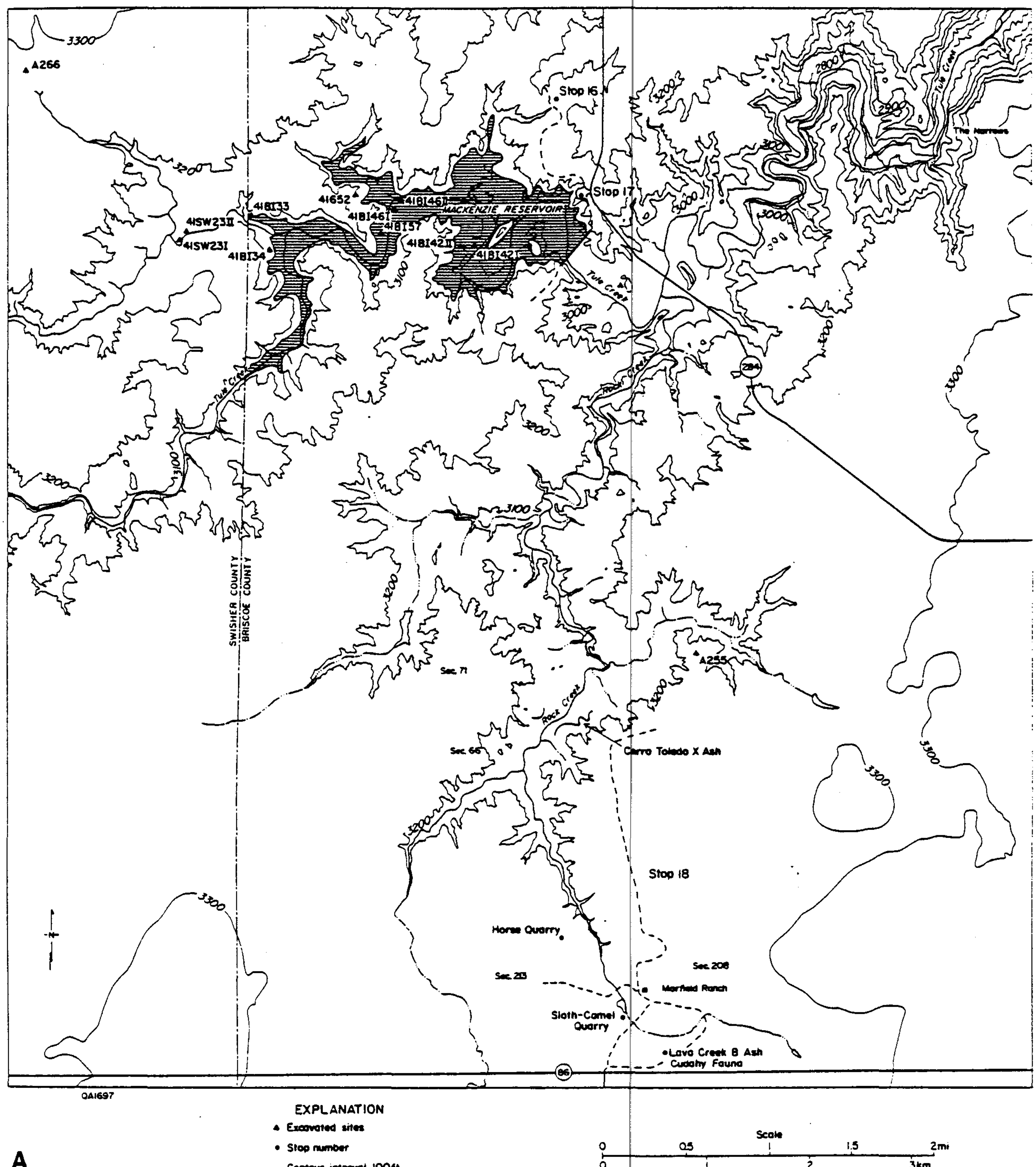


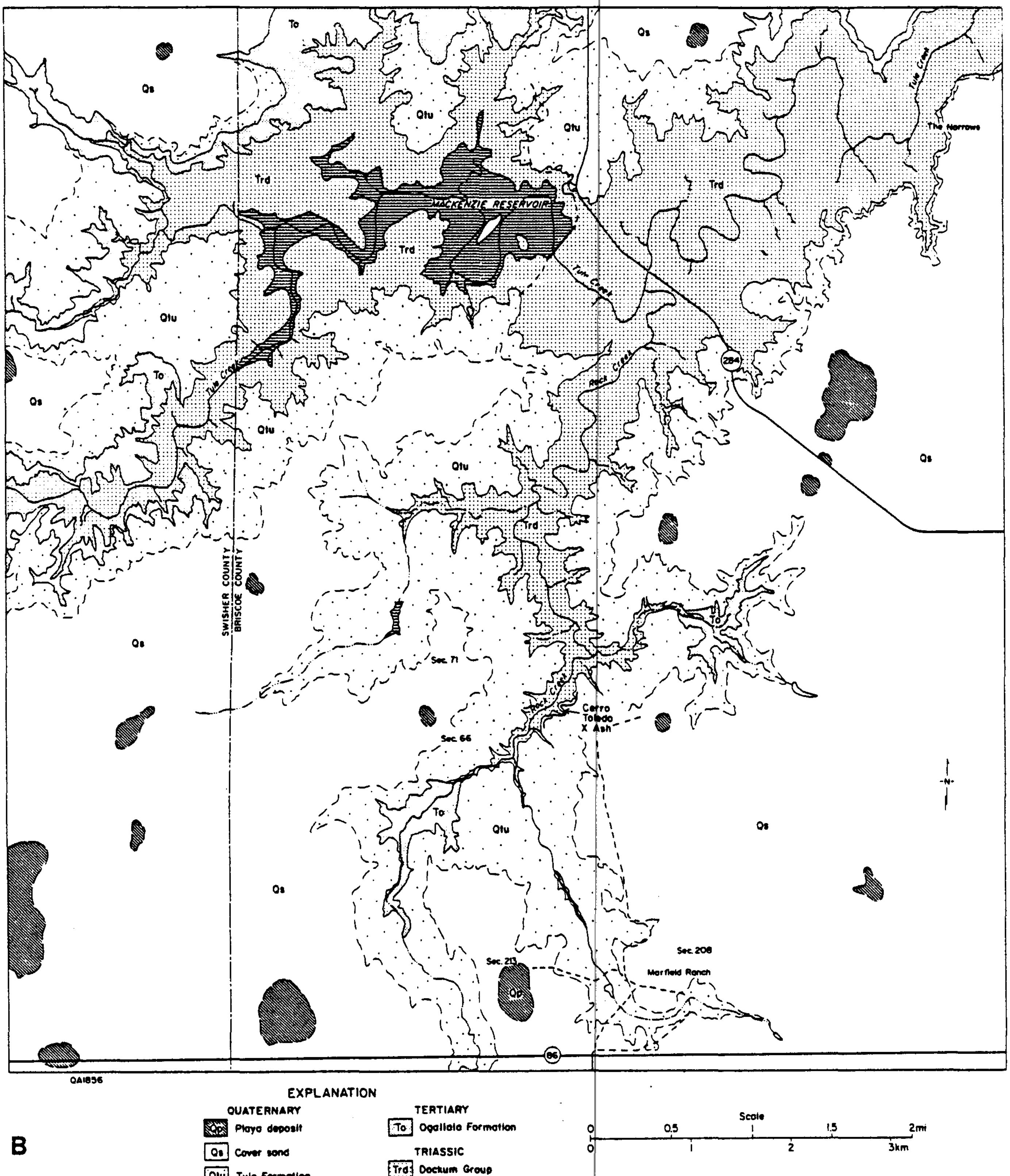
Figure 8. ~~Gustavson and Budnik~~



A

9

Figure [redacted]. Topographic map derived from U.S. Geological Survey Cope Creek and Rock Creek 7.5-minute (1965) Quadrangles showing locations of stops and archeological sites.



B

10

Figure [redacted]. Geologic map of portions of Cope Creek and Rock Creek Quadrangles (after Kumanchan, 1972).

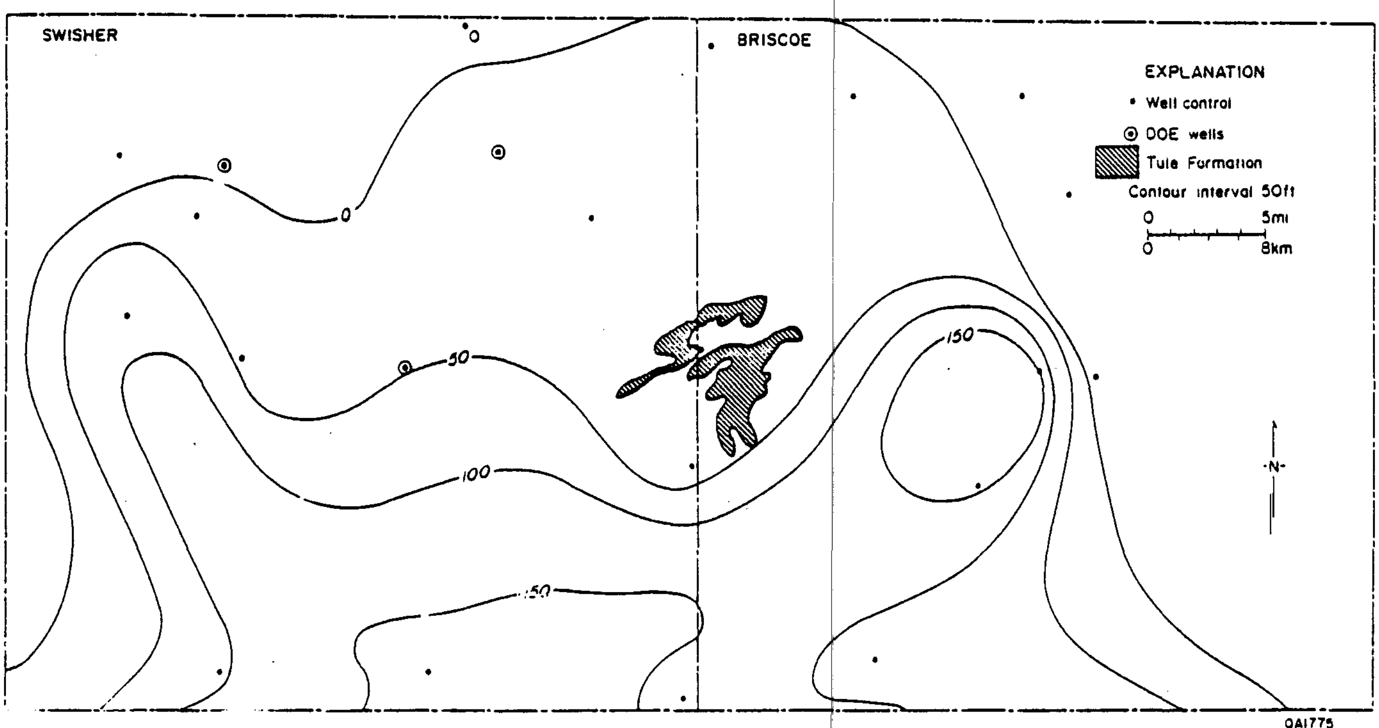


Figure 11. Net-salt map for the Upper Permian Salado Formation, Swisher and Briscoe Counties.

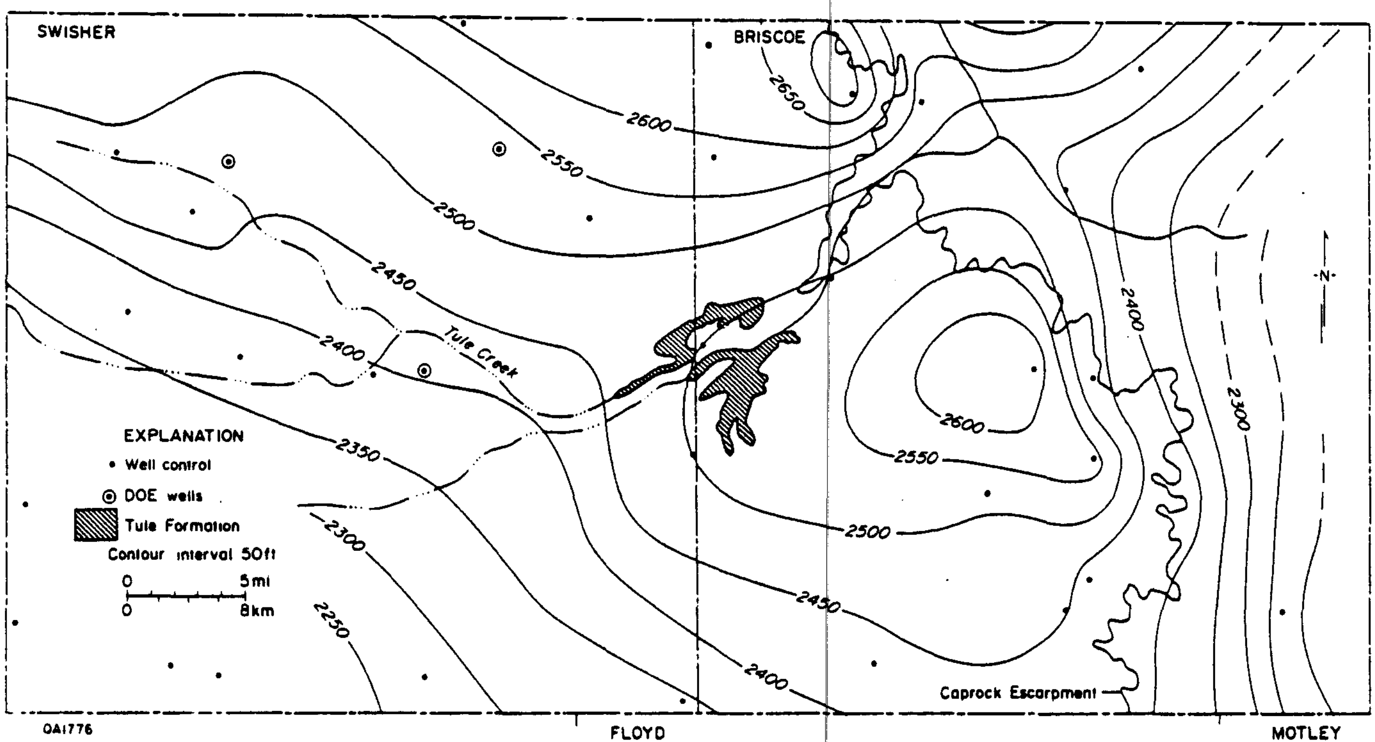


Figure 12. Structure-contour map on the top of the Upper Permian Alibates Formation, Swisher and Briscoe Counties.

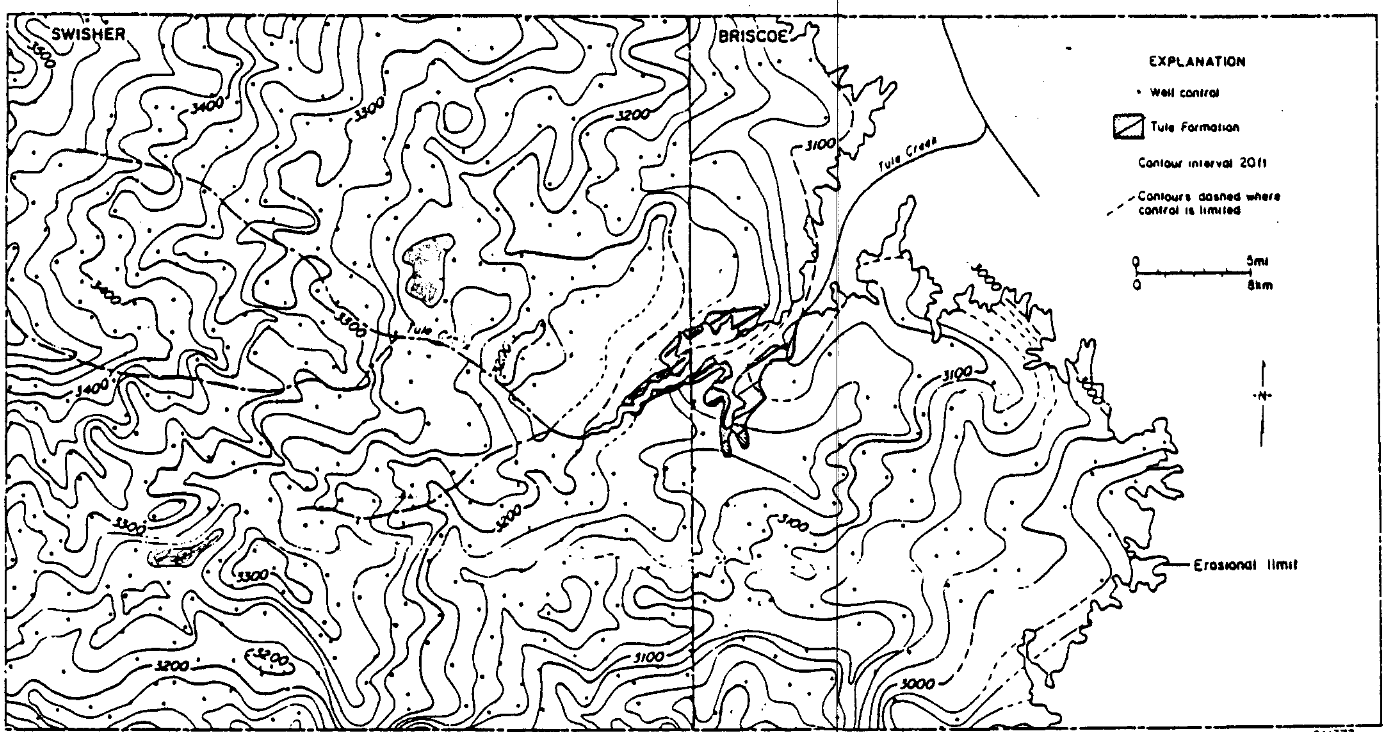


Figure 13. Paleotopography on the middle Tertiary erosion surface (base of the High Plains Aquifer), Swisher and Briscoe Counties (after Knowles and others, 1982).