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THE FOUR-TOWNSHIP STUDY AREA NEAR CARLSBAD, NEW MEXICO:

VULNERABILITY TO FUTURE SUBROSION

By Arthur M. Piper



ORNL Subcontract 3745

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# THE FOUR-TOWNSHIP STUDY AREA NEAR CARLSBAD, NEW MEXICO: VULNERABILITY TO FUTURE SUBROSION

By Arthur M. Piper

## SCOPE AND ACKNOWLEDGMENTS

In an earlier paper (Piper, 1973-b) the writer summarized information then available as to the present extent and prospective future progress of subrosion in and about a four-township study area near Carlsbad, New Mexico--specifically, Ts. 21 and 22 S., Rs. 31 and 32 E. This paper extends that summary according to additional information now at hand from recent, and current investigations by others. Both papers concern one aspect of storing wastes from the nuclear-fired power industry in bedded salt of the Salado formation.

The one aspect of concern has been the vulnerability of the four-township study area and the candidate storage horizon to future subrosion. The writer's earlier paper was reasonably definitive in regard to natural vulnerability from the west; the present paper seeks chiefly to assess vulnerability from the north, east, and south.

The writer must acknowledge his great indebtedness to G. O. Bachman, W. L. Hiss, and C. L. Jones of the U. S. Geological Survey, sources of most of the new information at hand. All three of these investigators were quite open handed with their recent findings, even as their individual reports were in draft or pending publication.

## HYDROLOGIC SETTING

### Capitan aquifer and associated rocks of Permian (Guadalupe) age

#### General features

The so-called Capitan aquifer comprises the Capitan and Goat Seep limestones of Permian (Guadalupe) age. Throughout its history it has dominated deep movement of ground water in the region surrounding the study area, and so it has been a principal factor in the subrosive process. Its features that are germane to this report are summarized below, after Hiss (1973, 1974).

The aquifer matrix is the limestone of a reef which fringed the Delaware Basin (fig. 2) during virtually all the Castile-evaporite epoch and the earlier part of the Salado-evaporite epoch. in the later part of the Salado epoch, however, the reef was topped by evaporites which spread beyond the basin, especially northward onto the Northwestern Shelf. The basinward margin of the aquifer is generally rather abrupt; its shelfward margin is a complex of interfingering tongues. Width of the aquifer ranges from about 5 miles along the eastern side of the basin to about 12 miles at its northernmost reach, where it sweeps through the vicinity of the present study area (fig. 1).

Hydraulic conductivity of the Capitan aquifer is relatively large; it ranges about between 1 and 20 ft/day and averages about 5 ft/day along the northern and eastern limbs of the basin--that is, between the present Guadalupe Mountains near Carlsbad, New Mexico, and the Glass Mountains near Alpine, Texas (fig. 2). In contrast, conductivity of the contiguous San Andres limestone in the Hobbs Channel (which in Guadalupe time extended nearly eastward from the area treated in this report) is about 0.15 to 0.3 ft/day--that is, about one order of magnitude less than that of the Capitan. In further contrast, conductivity of contiguous shelf sediments in Eddy and Lea Counties, New Mexico, averages about 0.04 ft/day; that of contiguous basin sediments in adjacent Ward and Winkler Counties, Texas, averages about 0.02 ft/day. In other words, conductivities of these shelf and basin sediments are about two orders of magnitude less than conductivity of the Capitan.

Transmissivity of the Capitan aquifer ranges about from 10,000 to 500 ft/day in the vicinity of the present study area. Minimum transmissivity appears to be in easternmost Eddy County, where cross-sectional area of the aquifer diminishes sharply in a cluster of former surge channels or "submarine canyons" transverse to the reef. Evidently this cluster has, since the reef was formed, limited movement of water between western and eastern limbs of the aquifer. Other channels and "canyons" segment the transmissivity of the aquifer elsewhere but, seemingly, nowhere as sharply as just described.

Until late in the Cretaceous period, the Capitan aquifer remained virtually undeformed. Lying closely or immediately beneath the Salado formation, and generally abutting the Castile formation along its basinward margin, it could have served as a regional interceptor or drain for any subrosive circulation that may have developed. No specific pattern of such circulation can be projected from information at hand. As will be outlined, however, there is persuasive evidence that salt was dissolved extensively.

## Late Cretaceous to Middle(?) Pleistocene time

The crustal deformation of late Cretaceous time tilted the entire aquifer downward to the east; also, it raised the present Guadalupe Mountains area southwest of Carlsbad, New Mexico, and the Glass Mountains area to the south and east, in Texas. Rejuvenated erosion soon exposed the aquifer in the two mountainous terranes, which so became unconfined catchment areas. A regional artesian circulation in the Capitan aquifer then developed--eastward from the Guadalupe Mountains area in the northern limb and northward from the Glass Mountains area in the eastern limb.

Fairly definitive evidence indicates that the aquifer discharged eastward, principally by way of the Hobbs Channel from beneath the northeastern corner of the area represented by figure 1, and secondarily by way of the Sheffield Channel to the south, toward the present Brazos River basin, in Texas. Presumably the hydrostatic head stood above the Salado and Rustler formations throughout the vicinity of the present study area, much as it does today. Thus, a hydraulic drive competent to have sustained subrosion would have required a greater head in formations overlying the Rustler formation, also much as is true today.

Post-Middle(?) Pleistocene time

By Pleistocene (probably Middle Pleistocene) time, erosion of the present Pecos River valley had cut through the Capitan aquifer near Carlsbad, with two effects here of concern: (1) Water moving eastward in the aquifer from the Guadalupe Mountains has subsequently been intercepted and discharged to the land surface from the so-called Carlsbad Springs. (2) Hydraulic drive from the Guadalupe Mountains having been so cut off, a virtual ground-water divide developed in the Capitan aquifer at the cluster of transverse "canyons" and channels about beneath the western boundary of the present study area.

Natural hydrologic conditions.-- Half a century ago, under native conditions of the current hydrologic epoch, the piezometric surface (corrected to fresh-water density) for the Capitan aquifer and shelf sediments in relatively good hydraulic communication with that aquifer, was about 3,200 feet above sea level immediately north of the present study area. In other terms, it was about 2,600 feet above the top of the aquifer, 700 feet above the top of the top of the Salado formation, and at or slightly above the top of the Dewey Lake redbeds. Thence, the piezometric surface declined generally eastward in a gentle trough, at rates diminishing about from 25 to 5 ft/mile. Such configuration would indicate circulation generally eastward to the head of the Hobbs Channel, which has been described.

Beneath the study area, basin sediments of the same general age as the Capitan aquifer are generally in poor hydraulic communication with that aquifer. For those sediments, at the center of the study area, the native piezometric surface was about 3,300 feet above sea level. Thence, the surface declined northeastward about 15 ft/mile. This piezometric configuration would signify water movement generally toward the Capitan aquifer. Rate of such movement would have been about two orders of magnitude less than capability of the Capitan to intercept.

Present conditions of hydraulic stress.-- During the last 50 years, natural piezometric configuration has been modified greatly for the Capitan aquifer, and modified somewhat for associated rocks, by very large extractions of water. Specifically, from the discovery of oil in 1923 (in Eddy County) through 1969, water withdrawn with oil from rocks of Permian (Guadalupe) age, in Eddy and Lea Counties, New Mexico, and five adjacent counties in Texas totaled about 1.4 million acre-feet. Much of this was from fields in poor hydraulic communication with the Capitan aquifer, but about 0.82 million acre-feet was from one large Capitan-water-drive field in Winkler County, Texas, about 50 miles southeast of the study area. During about the first three decades of oil production, waste water from the oil fields was discharged at the land surface into pits or natural undrained depressions. In large part this dissipated by percolation (Nicholson and Clebsch, 1961, p. 103-106). Since the mid-fifties, however, waste water generally has been re-injected; currently the trend is to "recycle" into the very zone from which it had been extracted (Garza and Wesselman, 1962, p. 30).

Beginning in the forties, Capitan water has been extracted from eight fields for secondary recovery of oil, in an aggregate volume of 0.32 million acre-feet through 1969. Additionally, about 0.41 million acre-feet has been extracted from the Capitan for municipal use, irrigation, and other purposes excluding the petroleum industry. As the net result of these large and continuing extractions and the re-injection, the piezometric surface has been depressed notably in the eastern and northern limbs of the Capitan aquifer--specifically, as much as 200 feet in the recharge area of the Glass Mountains, and a maximum of about 700 feet (fresh-water equivalent) about the regional center of pumping near Kermit, Texas, 15 miles southeast of the area shown on figure 1. Northward into Lea County, New Mexico, depression of the piezometric surface extends into shelf rocks which are in relatively good hydraulic communication with the Capitan aquifer. It is about 500 feet in T. 22 S., 400 feet at the head of the Hobbs Channel, and 200 feet immediately north of the study area in Rs. 31 to 33 E. Still farther west, toward Carlsbad, the amount of depression diminishes rather rapidly and then feathers out. This major piezometric depression is deepening currently; in Lea County, about 20 feet per year in 1970 and 1971 (Hiss, 1973, fig. 6). Presumably the depression dies out eastward along the Hobbs Channel (and the Sheffield Channel to the south). As a consequence it is inferred that, the antecedent natural hydraulic gradient having been reversed, the Capitan aquifer no longer discharges toward the Brazos River basin in Texas.

Presently there is a virtual piezometric discontinuity at the basinward edge of the Capitan aquifer along the northern and eastern limbs of that aquifer. Eastward across the four-township study area, the discontinuity increases about from 250 to 450 feet. Toward the southeast it increases progressively to about 750 feet at the New Mexico-Texas boundary. As will be shown more specifically, its effect would be to increase several-fold the potential hydraulic drive for subrosive circulation in and near the study area. This is a man-caused effect of a few decades only; it post-dates the latest and historic subsidence in San Simon Sink and so can not have caused that subsidence.

### Chemical character of the waters

Chemical character of water in the Capitan aquifer and associated rocks varies greatly, most conspicuously in chloride content. Within the Capitan itself, in one zone or another, chloride-ion concentration is extensively less than 1,000 mg/l from the Glass Mountains recharge area northward in the eastern limb of the aquifer about to the Texas-New Mexico boundary; less than 5,000 mg/l northward into T. 20 S. in Lea County, New Mexico, and thence northeastward in a 12-mile-wide tongue to and beyond Hobbs; and, in the northern limb of the aquifer, about from 10,000 to 20,000 mg/l westward to the vicinity of the Pecos River. In local zones of the Capitan, and in interfingered tongues of associated rocks along the shelfward edge, higher concentrations are common.

In rocks associated with the Capitan within the Delaware Basin, chloride-ion concentration of native waters generally increases northeastward from about 50,000 mg/l beneath the Pecos River to 150,000 mg/l near the basinward edge of the Capitan reef. In associated rocks on the Northwestern Shelf, chloride-ion concentration generally exceeds 80,000 mg/l except adjacent to the Hobbs Channel. Local extreme concentrations in Lea County, New Mexico, reach at least 186,000 mg/l in basin rocks and 199,000 mg/l in shelf rocks. Chloride-ion concentrations so large signify waters virtually saturated in sodium chloride.

From these variations in the chemical character of the waters, also from the piezometric configurations that have been outlined, it is inferred that: (1) Before uplift and tilting late in Cretaceous time, rocks of the Guadalupe series in the Delaware Basin, and their counterparts on the Northwestern Shelf, contained virtually saturated brine derived from extensive, but slow and probably intermittent, subrosive circulation. (2) Subsequently, the very-slightly-permeable basin and shelf rocks have been flushed incompletely by fresh water from the west, beyond the present Pecos River. At the latitude of the present study area, the Pecos River and its antecedents presumably have been perennial much of, if not all, the time. However, having the lower head, the river has not been (and is not) a competent source for flushing rocks of the Guadalupe series. (3) Also in post-uplift time, the core of the permeable Capitan aquifer has been almost completely flushed by land-derived fresh water, principally from the Glass Mountain in Texas and, until Middle (?) Pleistocene time, from the Guadalupe Mountains in New Mexico. These inferences attest to the very slow rates of regional subrosive and flushing circulations. Certain specific rates will be derived.

## Aquifers above the Rustler formation

In the vicinity of the study area, principal fresh-water aquifers above the Rustler formation are (1) the Santa Rosa sandstone of Late Triassic age and (2) coarse zones in alluvium of Quaternary age, especially in thick tongues of alluvium filling former stream channels. In general the Santa Rosa sandstone is the more consistent producer; wells tapping it commonly yield 100 gpm (gallons per minute) or more and as much as 1,875 gpm is reported from one well in which the sandstone was "fractured." The Chinle formation which overlies the Santa Rosa sandstone, and the Dewey Lake redbeds which immediately underlie it, are of small average permeability and do not sustain water-supply wells. The Rustler formation, which intervenes between the Dewey Lake redbeds above and the Salado formation below, yields only saline water containing as much as 90,000 mg/l of chloride ion (Nicholson and Clebsch, 1961; Garza and Wesselman, 1962).

Figure 1 generalizes the configuration of the piezometric surface for the fresh-water aquifer; principal features include: (1) In the northern part of the area, a bifurcated terrace in T. 20 S., Rs. 31 and 34-35 E. (2) In the south-central part, a prominent ridge or divide cresting in two "highs," one in the southern half of the four-township study area. (3) In the western third of the area, a broad trough or drain spanning the Pecos River valley, of which trough a conspicuous branch heads immediately north of the study area in Ts. #19 and #20 S., Rs. #32 and #33 E., trends across the northwest quadrant of the study area, and then passes beneath Nash Draw. (4) Southeast of the study area, a second broad trough heading in a closed depression or "sink" beneath San Simon Swale. These principal features are inferred to be natural in general form. The piezometric terrace and ridge would signify areas of ground-water recharge, whereas the piezometric troughs would signify drains toward which the ground water tends to concentrate and along which water may move downward as well as horizontally. The piezometric sink would signify water movement only downward, at some interior focal area.

The fresh-water aquifers and the fresh-water circulation just outlined constitute the potential source sustaining any present subrosion of the Rustler and Salado formations beneath the study area and its vicinity. The potential hydraulic driving force for subrosive circulation can be assessed in terms of differential head (corrected to fresh-water density) between the fresh-water aquifer system above the Rustler formation, here described, and the deeper Capitan aquifer and associated rocks of Guadalupe age, previously described. Two fairly distinct hydrologic subprovinces are involved; these are (1) the area of the Capitan aquifer and associated shelf rocks to the north and east, and (2) the area of the Delaware Basin.

Under natural conditions and with regard to the Capitan and shelf aquifers alone, this differential appears to have been: (1) virtually zero at mid-point of the north boundary of the study area--that is, along the axis of the piezometric trough shown on figure 1: (2) 300 to 400 feet positive (that is, greater head in the aquifer system above the Rustler) in T. 20 S., R. 34 E., and eastward toward the head of the Hobbs Channel; (3) 250 to 300 feet positive in T. 21 S., Rs. 33 to 35 E.; (4) 100 feet positive in T. 23 S., R. 36 E.; and (5) farther south, 100 feet or more negative.

Under the present condition of hydraulic stress, the positive differential head in the aquifer system above the Rustler is greater and more extensive--specifically, (1) about 350 feet at mid-point of the northern boundary of the study area; (2) to the east, as much as 1,000 feet at the head of the Hobbs Channel; (3) 700 feet at mid-point of the eastern boundary of the study area, also eastward in T. 21 S. and southward in R. 36 E. to the latitude of San Simon Sink; (4) 500 feet along the eastern flank of San Simon Swale and southward about through T. 24 S.; and (5) about 250 feet at the New Mexico-Texas Boundary.

As just outlined, the positive differential heads translate into vertically-downward hydraulic gradients sufficient that, under natural conditions and over geologic time, subrosive circulation presumably would have penetrated from the land surface to the Capitan aquifer in the northernmost and northeasternmost parts of the study area and thence eastward and southeastward to, and 5 to 10 miles beyond, the latitude of San Simon Sink. Subrosion would have resulted wherever a permeable path was open to the Rustler or Salado formation. Inferentially, regional discharge could have been eastward through the Hobbs Channel to the Brazos River basin in Texas.

Under the present conditions of hydraulic stress, vertically-downward hydraulic gradients adjacent to the study area on the north and east appear to be two- or three-fold greater that natural. The greater gradients would tend to accelerate subrosive circulation commensurately. As has been noted however, the horizontal gradient in or near the Hobbs Channel presumably has been flattened or reversed. Thus, under the stressed condition, accelerated downward circulation from above the Rustler formation would be compensated in the extraction by pumping from the Capitan.

In the part of the area that overlies the Delaware Basin head of the aquifer system above the Rustler formation is naturally about equal to, or lower than, that of water ln the underlying rocks of Gradalupe age (fresh-water equivalent). At the latitude of the study area and along the axis of the Pecos River valley, the above-Rustler head is about at land surface and 400 to 500 feet lower than the head for rocks of the Guadalupe series. Accordingly, the potential for vertical movement of water generally is the reverse of that in the Capitan subprovince, and upward from the Guadalupe; subrosion would be very largely by relatively shallow circulation of local rather than regional reach.

## Relation to past and prospective climates

Rate of bedded-evaporite dissolution would tend to increase with volume rate of subrosive circulation, and rate of circulation to increase with wetness of climate. The first relationship approaches simple cause and effect and the two rates well might be in arithmetic proportion, one to the other because, in general, velocity of circulation would be sufficiently slow that any water making contact with evaporite could become saturated. The second relationship is indirect, however, and the controlling factors are transmissivity of the relevant aquifer system and hydraulic gradient or driving force. As will be shown, variability of these two factors is limited.

Over a moderate interval of geologic time, say up to a million years or so, physical geometry of a particular aquifer system ordinarily would change little, and that largely by modification of intake zone, discharge zone, or both. Thus, as a first approximation, transmissivity of the aquifer system may be assumed to be nearly a constant (under a particular hydraulic gradient). Hydraulic gradient would have two limits--specifically, (1) zero recharge under an extremely dry climate, with gradient and circulation diminishing ultimately to zero; and (2) recharge area saturated to land surface under a wet climate, with gradient a maximum whatever the "wetness."

A reasonable basis for projecting future rates of subrosive circulation would be to assume that the climatic and hydrologic environments of Pleistocene time will recur. In other words, there would be expected an alternation between relatively cool, wet pluvial (glacial) epochs and warm, dry interpluvial (interglacial) epochs. The past few centuries have been virtually interpluvial, probably somewhat cooler and wetter than the interpluvial extreme of Pleistocene time but considerably warmer and drier than the pluvial extreme.

As will be noted, during certain interpluvial epochs of the Pleistocene, caliche developed extensively over stable land surfaces in and near the study area of this report. Caliche, essentially a carbonate-cemented soil, forms only in a relatively warm and dry climate--so dry that all the little rainfall is dissipated by evaporation and none percolates to and below the water table. Once formed, an unbreached layer of caliche several feet thick is all but impermeable. Accordingly, it can be concluded that, locally in and near the study area, subrosive circulation probably has lapsed intermittently in the past and will lapse intermittently in the future.

There is evidence that during pluvial epochs of the Pleistocene, precipitation in the region about the study area was several-fold greater than in historic time. Rocks of the area being of relatively low average permeability, conceivably the infiltration from such precipitation was sufficient that principal recharge areas were saturated up to the land surface. Even so, hydraulic potential to drive subrosive circulation down to the Capitan aquifer and associated shelf rocks could not have been more than two- or three-fold greater than natural potential in the historic past. This natural potential has been outlined. Further, this maximum conceivable potential of the past would be about equal to present potential under the hydraulic stress caused by large extraction of water in the past three decades. Over the northeastern part of the Delaware Basin, a part which includes the greater part of the study area (fig. 1), it seems likely that even the maximum precipitation of the past could have sustained only a nominal deep circulation, much weaker than circulation in the contiguous Capitan subprovince.

## EPOCHS AND RATES OF SUBROSION

Subrosion, the subsurface dissolution of salt with attendant collapse of the land surface and other related processes, proceeds only under a continuing circulation of unsaturated water and so, generally, requires an environment of terrestrial erosion (Piper, 1973-a). This being so, each principal interruption in marine sedimentation potentially has been an epoch of subrosion, either youthful or rejuvenant. For the general vicinity of the four-township study area, six such epochs are inferred or are discriminated tentatively; these will be described.

Salt also can be dissolved during or between epochs of evaporite accumulation, as the sea re-occupies an area previously desiccated. Thus, in the vicinity of the present study area, inter-formational dissolution occurred during the interval between the Castile and Salado epochs of accumulation and, even more notably, between the Salado and Rustler epochs (Adams, 1944, p. 1608). Having no direct bearing on the questions here at issue, the effects of such dissolution will not be described.

### Early and Middle Triassic time

In and near the study area, the earliest recognizable epoch of salt dissolution, presumably in a terrestrial environment, was during Early and Middle Triassic time. Then, the Salado formation and the overlying Rustler formation would have been un-deformed and overlain only by the Dewey Lake redbeds, about 470 to 560 feet thick, and of moderate to small permeability. The water circulation required for dissolution of salt from the Rustler and the Salado presumably could readily have been tributary to the Capitan aquifer.

Dissolution of salt in Triassic time was recognized by Adams (1944, p. 1622-1624) in a "small" basin adjacent to the Capitan (reef) limestone along the eastern margin of the Delaware Basin. There, according to Adams, dissolution of salt from the Salado formation created a trough 800 to 900 feet deep, which subsequently was filled by rocks of Triassic age, in an over-thick section. The location of the basin is described vaguely; Jones (1974) infers it to be one that is transected by the Pecos River some 100 miles southeast of the study area. The particular basin is one segment of an eastern lobe of very extensive and deeply filled dissolution basins which lie south of the study area and largely in Texas (Maley and Huffington, 1953). Among those extensive basins the greatest thickness of "fill" is about 1,800 feet, or approximately twice the excess thickness of rocks of Triassic age as discriminated by Adams. More will be said concerning this.

If the over-thick section of Triassic rocks noted above is wholly correlative with the Santa Rosa sandstone and Chinle formation it is of late Triassic age. Accordingly, the solution trough it occupies would have developed in some part of Early and Middle Triassic time. Assuming trough development to have spanned half this available time, or about a third of all Triassic time, the mean rate of basin deepening--that is, vertical rate of subrosive removal of salt--would have been in the order of 85 feet per million years.

Gorman and Roebeck (1946) have recognized Triassic subrosion near Santa Rosa, 175 miles north of Carlsba . Recently, Bachman and Jones (1974) have found additional evidence that subrosion at the time was extensive in eastern New Mexico--specifically, (1) in the vicinity of Crow Flat, about 35 miles north-northwest of the study area, "chaos" structure involves tilted blocks of rocks as old as Triassic; (2) about 25 miles west of the study area, rocks of Triassic age were deposited in an antecedent sinkhole; and (3) cores from wells some 20 miles south-southwest of the study area disclose, in salt as much as 400 feet below the top of the Salado formation, enclosed blocks of dolomite, chert pebbles, materials reminiscent of the Dewey Lake redbeds, and other features interpreted as debris filling a former karst topography. At the latter locality the contact between the Rustler formation and the Dewey Lake redbeds seemingly had been depressed about 300 feet by collapse. None of this evidence affords an estimate of the vertical rate of subrosion.

Jones (1974) interprets all the evidence at hand to indicate that, by Late Triassic time erosion and subrosion probably had removed all salt of the Salado formation west of the general longitude of Carlsbad. If so, presumably the feather edge of erosion and subrosion would have reached even farther eastward toward the study area. However, because thickness of the Santa Rosa sandstone (Late Triassic age) varies little within the study area (generally about 200 to 250 feet), the writer feels that the eastward reach of subrosion in this earliest epoch (Early and Middle Triassic time) probably was somewhat less than implied by Jones.

## Jurassic (?) time

By the start of Jurassic time the evaporites of the Salado and Rustler formations in and near the four-township study area would have been mantled by some 1,000 to 1,500 feet or more of insoluble sedimentary rocks of moderate to low permeability--specifically, by the Dewey Lake redbeds of of Permian (Ochoa) age, 470 to 560 feet thick as already noted; and additionally by the Santa Rosa sandstone, 205 to 245 feet thick, and the Chinle formation, 300 to 800 or more feet thick, both of Late Triassic age. During Jurassic time, several lines of evidence imply strongly that the area was land: (1) No rocks of that age are known presently to exist closer than about 80 miles to the south in trans-Pecos Texas, or 160 miles to the north near Tucumcari, New Mexico. (2) Extensively west of Carlsbad, New Mexico, rocks of Triassic age are absent and rocks of Cretaceous age rest on those of Permian age or older (Bachman, 1974). In general the presumed terrestrial environment would have favored subrosion, either new or rejuvenant, despite the thickened mantle described above. In fact, Jones (1974) concludes that subrosion and land-surface subsidence were extensive in the area of the present Gypsum Plains and the Rustler Hills.

Reference has been made to an eastern lobe of deeply-filled subrosive basins heading some 40 miles southeast of the study area. A more extensive western lobe heads in T. 25 S., R. 30 E., about 20 miles south-southwest of the study area (Maley and Huffington, op. cit.). Adams (1944, p. 1609, 1612) conculdes that the subrosion of that lobe was localized and facilitated by beds of coarse sand there interfingered into the upper part of the Salado formation, those beds serving as conduits for ready circulation of unsaturated water. Maximum thickness of fill in the western lobe is some 1,700 feet, near Pecos, Texas; in the eastern lobe, some 1,800 feet.

Age of these subrosive basins and of their fill has been dated variously by different investigators. Adams (1944) concluded that dissolution of salt in the western lobe occurred mainly in Tertiary time, and seemingly was limited to areas from which Cretaceous cover had been stripped. As has been noted, however, he ascribed some subrosion in the eastern lobe to Triassic time; it seems most unlikely that the area of the western lobe could have gone unscathed by subrosion at the same time. On the other hand, it has been pointed out that the local over-thickness of (Late?) Triassic rocks in the eastern lobe is only about half the maximum thickness of fill (depth of subrosion) along that lobe. Thus, it seems also most unlikely that the area of the eastern lobe could have gone unscathed by subrosion through all post-Triassic time. Maley and Huffington (1956) presumed the fill in the basins probably to be largely Quaternary /Pleistocene/ in age, but in its older part to be of Tertiary age. Thus they imply the antecedent subrosion to have occurred in Tertiary time. From inspection of well cuttings, Jones (1974) tentatively assigns much of the fill in the northwesternmost of these extensive basins to the Cretaceous, owing to lithologic similarity between it and deposits of accepted Cretaceous age in the surrounding region. Thus, he ascribes the antecedent subrosion to Jurassic time.

More definitive information as to character distribution, and age of the deep-basin fill(s) seems necessary before the antecedent subrosion can be dated closely and conclusively. Lacking such close dating, a commensurately dependable estimate of rate of subrosion is precluded. However, a useful range of such estimates can be derived; these follow.

Assuming that the maximum thickness of basin fill--1,800 feet--indicates the same vertical reach of subrosion, mean vertical rate was about: (1) 80 feet per million years if all the subrosion occurred within Early and Middle Triassic time or within Jurassic time; (2) possibly as slow as 35 feet per million years if the subrosion was continual during much of Triassic and Jurassic time; and (3) 60 feet per million years if the subrosion occurred within the Paleogene (early) division of Tertiary time. The preceding mean rates derive from the central part of the filled-basin area, where subrosive downcutting was presumably most rapid or longest sustained.

With the close of Jurassic time, any antecedent subrosion in the filled-basin area presumably would have lapsed. Certainly return of a marine environment early in the ensuing Cretaceous period would have ended the fresh-water hydraulic drive necessary for subrosive circulation.

Cretaceous and early Tertiary (pre-Ogallala) time)

Early in Cretaceous time, erosive planation and local sedimentation presumably smoothed the landscape inherited from Jurassic time. Then in an encroaching sea, insoluble marine sediments were deposited extensively. Late in Cretaceous time, or possibly in earliest Tertiary time, the study area and its vicinity were tilted eastward, with two effects here of concern: (1) The strain from tilting induced flowage of salt in the Castile and Salado formations, resulting in some local thickening and updoming of the Salado (Jones, 1974). (2) The study area and its vicinity again became land; erosion stripped antecedent sediments of Cretaceous age and locally thinned the remaining mantle overlying the evaporites of the Rustler and Salado formations. (3) Probably subrosion was soon rejuvenated locally, although no particular locales can be identified with certainty. It is at this stage of geologic history that, under the chronology of Maley and Huffington (1956), subrosion would have started in the deep-basin area to the south.

Bachmen (1974) does not recognize an interruption of subrosive processes during Cretaceous time; rather, he covers into a single epoch all post-Triassic pre-Gatuna time. Jones (1974) concludes that, generally in and near the study area, subrosion had reached its maximum geographic extent by early Tertiary time and that "insofar as has been determined there has been no extension of the subrosional processes beyond the * * * areas of pre-Ogallala salt removal."

Late Tertiary (Ogallala) time

By latest Miocene or Pliocene time, erosive downcutting had reached a landscape-relief of a few hundred feet; subsequent fluvial deposition (Ogallala formation) built an extensive plain of extremely low relief, a plain which reached its climax about with the close of Pliocene time (Bachman, 1974). Present remnants of this climax land surface are the conspicuous High Plains of southeastern New Mexico and adjacent parts of Texas. Features of these remnants in the study area are summarized in the writer's earlier paper (Piper, 1973-b, p. 5-8).

To the west of the study area, subrosion of the Rustler and Salado formations must have been rejuvenated by the beginning of Ogallala deposition--that is, some 12 million years ago. Thus, as summarized in the writer's earlier paper (op. cit.), the base of the Ogallala would have intersectaed the tilted Rustler formation within a belt some 5 to 10 miles wide, trending somewhat west of south, and about spanning the present site of Clayton Basin. Likewise, the top of the tilted Salado formation would have been intersected in a parallel belt beginning some 6 to 10 miles west of the present axis of Clayton Basin. Also, the permeable Ogallala formation doubtless would have constituted a regional fresh-water aquifer, serving as a competent source for, and maintaining the hydraulic drive of, widespread subrosive water circulation.

The evaporites of the Rustler and Salado having been so truncated, the writer presumes that, in and near the local area of truncation, subrosion has been continual through essentially all subsequent time--that is, throughout the several stages in which the present Pecos River valley has been sculptured. There the rate of subrosive downcutting may have varied considerably during the two epochs yet to be described, but there is no clear evidence that the requirements for subrosive circulation lapsed completely at any time. Thus, the writer recognizes no basis for a separate estimate of a vertical rate of subrosion in the particular local area during the Ogallala epoch alone. Including post-Ogallala time, the mean vertical rate west of the four-township study area has been estimated (Piper, 1973-b, p. 22) as about 80 feet per million years. This estimate is a mean during the presumed time interval and over a moderately extensive geographic area. Assuming that actual depth of subrosion varied uniformly across the area, from some maximum to a feather edge, the mean maximum rate would have been twice that just stated, or 160 feet per million years. The estimate assumed that, at the onset of Ogallala deposition and at the longitude of present Carlsbad, truncation had removed all the Rustler formation and had thinned the Salado formation to one fourth of its thickness as deposited. On the other hand, Jones (1974) has concluded that, by early Late Triassic time, the "eroded edge of Salado salt /was at the/ general longitude of Carlsbad"--in other words, that all the Salado had been removed farther west.

Eastward from the inferred belts of truncation, evaporites of the Rustler and Salado formations dip beneath a progressively thickening mantle of strata of low average permeability--specifically, beneath the Dewey Lake redbeds of Permian (Ochoa) age and the Santa Rosa sandstone and the Chinle formation of Late Triassic age. In Ogallala time, this mantle was generally about 750 to 1,000 feet thick at the longitude of the study area, and probably as much as 2,000 feet thick 20 miles farther east at the general longitude of present San Simon Swale. Being so thick and lacking aquifers of large transmissivity, this mantle doubtless restricted subrosive circulation of unsaturated water to the Rustler and the Salado rather extensively over much of the Delaware Basin. However, above the Capitan limestone and associated shelf rocks to the northeast, it seems likely that, as is true today, fresh-water head in aquifers above the Rustler formation was sufficiently high in Ogallala time to drive a subrosive circulation discharging generally eastward by way of the Hobbs Channel. Configuration of the top of the Rustler formation in this area, as mapped by Hiss (1974), suggests that such may have occurred, although corroborative evidence is not at hand. Also, the evident subrosive collapse at San Simon Sink could have started in this epoch, presumably with circulation generally southward toward the eastern lobe of Jurassic (?) subrosion already noted. At whatever time it did occur (the ensuing Gatuna or post-Gatuna epoch seems the more likely), subsidence at the sink undoubtedly generated fractures transecting all strata above the Rustler (and Salado ?) and so imparting substantial transverse permeability to those strata locally.

Specifics of subrosive activity east of the study area in Ogallala time are obscure. Presumably any potential for subrosive circulation would have diminished or lapsed extensively at the end of the epoch, with development of the High Plains "caprock" or caliche.

Gatuna epoch (Querecho Plain)

Westward from the study area, major forms in the present landscape of the Pecos River valley developed by local subrosive collapse and by erosive dissection of the High Plains during the Nebraskan and Kansan pluvial stages of early and middle Pleistocene time. Presumably rainfall was substantially more than at present; temperature probably was lower. A juvenile Clayton Basin and Nash Draw, also other collapse features, presumably were early. The writer infers that there developed ultimately an integrated land-drainage system of whose valley-train deposits (Gatuna formation, 0 to 375 feet thick) discontinuous remnants extend generally southward from the head of the present Roswell Basin, along Long Arroyo east of Hagerman, pass 15 to 20 miles east of Artesia, and 20 to 30 miles east of Carlsbad to the New Mexico-Texas boundary. Contained pebbles are of rock types denoting origins as widely dispersed as the Capitan and Jicarilla mountains west and northwest of Roswell, and the High Plains caprock east of Roswell (Bachman and Jones, 1974). Southward this valley train alines closely with the western lobe of the subrosive basins of Jurassic (?) age (fill of Cretaceous (?) age) to which reference has been made.

At its climax level the upper surface of the valley train of Gatuna time appears to have merged into the extensive Querecho Plains (Mescalero Pediment) described briefly in the writer's earlier report (Piper, 1973-b, p. 9-11). Also, the Gatuna formation generally is capped and the Querecho Plain is widely underlain by the Mescalero caliche, whose existence denotes a stable land surface and a climate probably warmer and drier than the present. Bachman (1974) assigns the Mescalero caliche to Yarmouth-interpluvial age, about 600,000 years ago.

Altogether, the Gatuna epoch of land-surface sculpture in the Pecos River valley emerges as much more extensive and distinctive than had been demonstrated heretofore. Bachman (1974) recognizes a separate Gatuna epoch of subrosion during which "solution and collapse * * * was the most extensive that has occurred during the Pleistocene." It can be inferred that, prior to and during accumulation of the regional valley train and cutting of the bordering pediment, subrosive circulation was active and generally southward toward the western lobe of the filled basins of Jurassic (?) age. However, no clear evidence of subrosive rejuvenation at the head of that lobe in Gatuna time is known to the writer. Conversely, it can be inferred that subrosive circulation lapsed with formation of the caliche mantle over valley train and pediment. The writer recognizes no basis for a separate estimate of the vertical rate of subrosion during the Gatuna epoch alone.

Eastward from the general longitude of the study area, in the Gatuna epoch a succession of swales and ridges was eroded into the High Plains surface. Undoubtedly the High Plains caprock was breached locally. Local drainage ways integrated into San Simon Swale and Monument Draw, which discharged to the ancestral Pecos River in Texas. The Swale alined generally with the eastern lobe of the deep subrosive basins of Jurassic (?) age, which have been described. Now wholly ephemeral, at least the trunk reaches of the Gatuna drainage system well may have flowed perennially.

Locally along present San Simon Swale, the erosion cut entirely through the rocks of Triassic age (Chinle and Santa Rosa) and half through the Dewey Lake redbeds, leaving a bedrock mantle above the Rustler formation only about 300 feet thick at the latitude of San Simon Sink. The subsequent unconsolidated fill, now about 850 feet thick at the Sink (Jones, 1974), presumably was substantially more permeable than the antecedent mantle rocks. Thus, the potential for subrosive circulation was improved. However, information at hand to the writer is not specific as to actual extent of subrosion.

## Post-Gatuna time

Bachman (1974) considers all post-Gatuna time--about the last 600,000 years--to constitute a distinct epoch of "subsurface salt solution with related collapse of the land surface." Presumably the epoch began with subrosive rejuvenation after the onset of pluvial conditions following Yarmouth time; subsequently it has continued without known major interruption. In the epoch, most of the subrosive work occurred west of the study area, where Clayton Basin and Nash Draw were enlarged to their present bold form and considerable relief, very largely by collapse. In the same area, many smaller collapse features scarred the Mescalero Pediment (Querecho Plains) and counterparts. For two profiles across Nash Draw, Bachman (op. cit.) concludes that depth of subrosion in post-Gatuna time has been from 120 to 180 feet; in other terms, at rates equivalent to 200 to 300 feet per million years.

North of the study area, Williams Sink and the Lagunas Plata, Toston, Tonto, and Gatuna--all relatively shallow depressions in the Mescalero Pediment--were formed. Here, Jones (1974) reports that evidence from numerous wells, including wells on the Lagunas Plata and Gatuna, is clear that no salt has been removed from either the Rustler or the Salado in all post-Permian time. He and Bachman (1974) concur that Williams Sink and all four lagunas are products of deflation by the wind in post-Gatuna time. In other words, despite the conspicuous piezometric trough that encloses them (fig. 1), the sink and the lagunas are not products of subrosion.

East and southeast of the study area, with one exception, land forms afford no clear evidence of subrosion in post-Gatuna time. The exception is San Simon Sink, to which reference has been made and which is a conspicuous feature of collapse within ring fractures, along the axis of San Simon Swale and largely in sec. 18, T. 23 S., R. 35 E., 20 miles southeast of the study area. Here, one collapse event occurred as late as 1922 (Bachman and Johnson, 1973, p. 29). Bachman (1973, p. 21) ascribes the collapse to solution of salt in the underlying Rustler and Salado formations. Jones (1974) would ascribe the historic subsidence to delayed collapse into an antecedent cavern. To the writer, however, the hypothesis of delayed collapse fails owing to the large extent of the area enclosed by conspicuous ring fractures, about 1 by 1½ miles (Nicholson and Clebsch, 1961, fig. 8), and to strengths of the rocks involved. The writer concludes that, although historic subsidence signifies historic dissolution of salt at depth, as a depression on the present land surface the Sink is a product of the post-Gatuna epoch, but that dissolution of salt there may have started earlier. Hydrologic conditions which may have originated dissolution at the Sink have been outlined in the preceding discussion of late Tertiary (Ogallala) time.

## VULNERABILITY TO FUTURE SUBROSION

### Subrosion from natural causes

Figure 1 shows the accumulated extent of subrosion to date in and near the four-township study area, in the Rustler formation and separately in the underlying Salado formation. As has been noted, subrosion here of concern may have started early in Triassic time, as much as 185 million years ago; Clearly it has been active continually during and since late Tertiary (Ogallala) time--that is, during the last 12 million years. Throughout the latter interval the area has been land; crustal deformation has been virtually nil; erosion has progressed through regional planation, rejuvenation, and mature dissection; and climate has varied from cooler and considerably wetter to somewhat warmer and drier than in historic time. Subrosion presumably has varied in rate, but in major features has clung to one general geographic pattern. It may be presumed that this general pattern will persist into the future, for tens or a few hundreds of thousands of years.

Vulnerability of the study area to future natural subrosion appears clearly to be least on the north and northeast, also on the south. On the north and northeast, subrosion seemingly has yet to start; from that direction the hazard of immediate subrosive attack appears to be virtually zero. To the south and largely in Texas, in the deeply-filled basins described by Maley and Huffington (1953), subrosion appears to have been dormant for several million years at least. The nearest two lobes of that apparently dormant area are respectively about 20 miles south-southwest and 35 miles southeast from the center of the study area. Thus, immediate hazard to the study area through rejuvenant subrosive attack from the south and southeast is felt to be extremely small, if not also virtually zero.

Vulnerability om the east seems to be no more than moderate. Here, subrosion to date has attacked the Rustler formation within a belt 4 to 7 miles wide along or near the basinward edge of the Capitan aquifer. Attack reaching down to the underlying Salado formation is limited to a zone about 9 miles long by 3 miles wide, in part beneath San Simon Sink, and at its closest about 13 miles southeast from the center of the study area (fig. 1). The writer infers tentatively that this particular belt and zone of subrosion are products of water circulation to the underlying Capitan aquifer. As has been summarized, man-caused hydraulic stress presently has increased, two- or three-fold, the potential hydraulic drive for such circulation. Thus, for the early future and until the hydraulic stress may dissipate, vulnerability to subrosive attack here would be moderately greater than natural. On the other hand, potential hydraulic drive and vulnerability would be relatively insensitive to climatic variations. Incidentally, the area of past subrosive attack on the Salado in T. 26 S., R. 36 E. (fig. 1), represents the northeasternmost lobe of the deep-basin area of Maley and Huffington, where subrosive activity appears presently dormant.

Southwestward from the belt just described, and extending into the south-central part of the study area, is a second belt about 5 to 8 miles wide which, like the district north and northeast of the study area, appears thus far to have escaped subrosive attack. That second belt spans a local topographic and hydrologic divide and so is an area prospectively least likely to generate effective subrosional circulation.

Vulnerability to future natural subrosion appears definitely to be greatest from the west. There, past subrosion has reached down into the Salado formation extensively west of the study area, and locally within a tongue that penetrates nearly 5 miles into the northwest quadrant of the study area (fig. 1). Farther east, past subrosion has attacked only the Rustler formation in a belt some 3 to 6 miles wide, which spans most of the west half of the study area. Still farther east this latter belt merges into that which is alined about along the basinward edge of the Capitan aquifer, as described previously.

West of, and at the general latitude of the study area, subrosion in the Salado formation during and after late Tertiary (Ogallala) time appears to have been by relatively shallow circulation which presumably would have been sensitive to climatic fluctuation. As has been summarized, here has occurred the most aggressive dissolution of salt. Accordingly, vulnerability assessed for this part of the area should, in general, be conservative for other parts.

Several estimates for vertical rate of subrosion have been derived or cited earlier in this report. All these are of the same general order of magnitude; the maximum, 300 feet per million years, is a mean for all post-Gatuna time at one profile across Nash Draw, just west of the study area. Its time span includes two pluvial stages, the Illinoian and the Wisconsin; also, at least part of the Yarmouth interpluvial stage, all the Sangamon interpluvial stage, and all post-Pleistocene time which climate-wise is analogous to a third interpluvial interval. Accordingly, the cited mean rate would seem to represent a reasonable long-term average of climatic variations in the region surrounding the study area. Possibly this mean is biased somewhat toward the interpluvial.

The relation of variation in climate to variation in hydraulic drive for subrosion has been summarized. Generalizing from that summary, it seems unlikely that a true mean for all post-Gatuna time, which is about 600,000 years, would differ by a factor of more than three from the maximum rate for any part of the full term. Further, it seems inconceivable that mean and maximum could differ by a whole order of magnitude. Accordingly, applying a factor of three to the mean rate which has been cited, the writer suggests 1 foot per thousand years (1,000 feet per million years) as a probable maximum vertical rate of subrosion under natural conditions. On that basis a waste repository 1,000 feet below the top of salt in the Salado formation would be proof, with an assurance factor of five, against natural subrosion over a future term of 200,000 years.

Beyond this calculated depth below top of salt, suggested site criteria are: (1) present base of subrosion above the top of the Salado formation; (2) as close as practicable to the topographic and hydrologic divide which trends about southeastward from the south-central part of the study area; and (3) at least 5 miles southwestward from the basinward edge of the Capitan aquifer, hopefully to avoid unnaturally large hydraulic drive for subrosive circulation, as has been discussed. These suggested criteria would be satisfied within most of T. 22 S., R. 31 E., the southwest half of T. 22 S., R. 32 E., and most of T. 23 S., R. 32 E. They would disqualify all the northern half, and one-fourth of the southern half, of the present four-township study area.

## Subrosion potentially caused by man

Reiterating a statement from the writer's earlier report (1973-b, p. 26), the greatest threat to the integrity of a waste repository in the Salado formation, in or near the four-township study area, probably lies in inadequate or deteriorated casings in nearby oil or gas wells, or in inadequately plugged exploratory holes. Only fragmentary general information is at hand for assessing this threat. Specifically, (1) piezometric level (fresh-water equivalent) for aquifers of the Capitan-Yates-Tansill zone is in the order of 750 feet above the top of the Salado and (2) piezometric level is "extremely low" over oil fields of the Delaware Basin (Hiss, 1974). Thus, the potential threat to a repository is two-edged: flooding by the waters of high piezometric level, or subrosive circulation of injected oil-field waters downward to the zones of low piezometric level. Small producing oil fields or deep exploratory holes exist in three of the four townships that make up the present study area, also in all but one of the contiguous surrounding townships. Thus, the potential threat is not easily avoided. Integrity of each candidate location for a waste repository would need be assessed by meticulous inventory of all adjacent oil-field works and operating practices.

REFERENCES


Adams, J. R., 1944, Upper Permian Ochoa Series of Delaware Basin, West Texas and southeastern New Mexico: Am. Assoc. Pet. Geol. Bull., v. 28 p. 1596-1625. Also in Origin of evaporites, 1971: Am. Assoc. Pet. Geol. Reprint Ser., no. 2, p. 60-89.

Bachman, G. O., 1973, Surficial features and late Cenozoic history in southeastern New Mexico: U. S. Geol. Survey open-file report (USGS-4339-8) 32 p.

__________ 1974, Oral and written communications.

Bachman, G. O., and Johnson, R. B., 1973, Stability of salt in the Permian salt basin of Kansas, Oklahoma, Texas, and New Mexico; with a section on Dissolved salts in surface water, by F. A. Swenson: U. S. Geol. Survey open-file report (USGS-4339-4), 62 p.

Garza, Sergio, and Wesselman, J. B., 1962, Geology and ground-water resources of Winkler County, Texas: U. S. Geol. Survey Water-Supply Paper 1582, 162 p.

Gorman, J. M., and Robeck, R. C., 1946, Geology and asphalt deposits of north-central Guadalupe County, New Mexico: U. S. Geol. Survey Oil and Gas Invs. Prelim. Map no. 44.

Hiss, W. L., 1970, Acquisition and machine processing of saline-water data from southeastern New Mexico and western Texas: Water Resources Research, v. 6, no. 5, p. 1471-1477.

__________ 1973, Capitan aquifer observation-well network, Carlsbad to Jal, New Mexico: N. Nex. State Engineer Tech. Rept. 38, 76 p.

__________ 1974, Oral communication.

Jones, C. L., 1973, Salt deposits of Los Medanos area, Eddy and Lea Counties, New Mexico: with sections on Ground-water hydrology y M. E. Cooley and on Surficial geology by G. O. Bachman: U. S. Geol. Survey open-file report (USGS-4339-7), 67 p.

__________ 1974, Oral and written communications.

Maley, V. C., and Huffington, R. M., 1953, Cenozoic fill and evaporate /evaporite/ solution in the Delaware Basin, Texas and New Mexico: Geol. Soc. Am. Bull, v. 64, p. 539-545.

Nicholson, Alexander, and Clebsch, Alfred, Jr., 1961, Geology and ground-water conditions in southern Lea County, New Mexico: N. Nex. Bur. Mines and Mineral Resources Ground Water Rept. 6, 123 p.

Piper, A. M., 1973-a, In situ dissolution of marine evaporites--Principles and concepts: Unpublished report to Union Carbide Corp., 18 p.

__________ 1973-b, Subrosion in and about the four-township study area near Carlsbad, New Mexico: Unpublished report to Union Carbide Corp., 28 p.

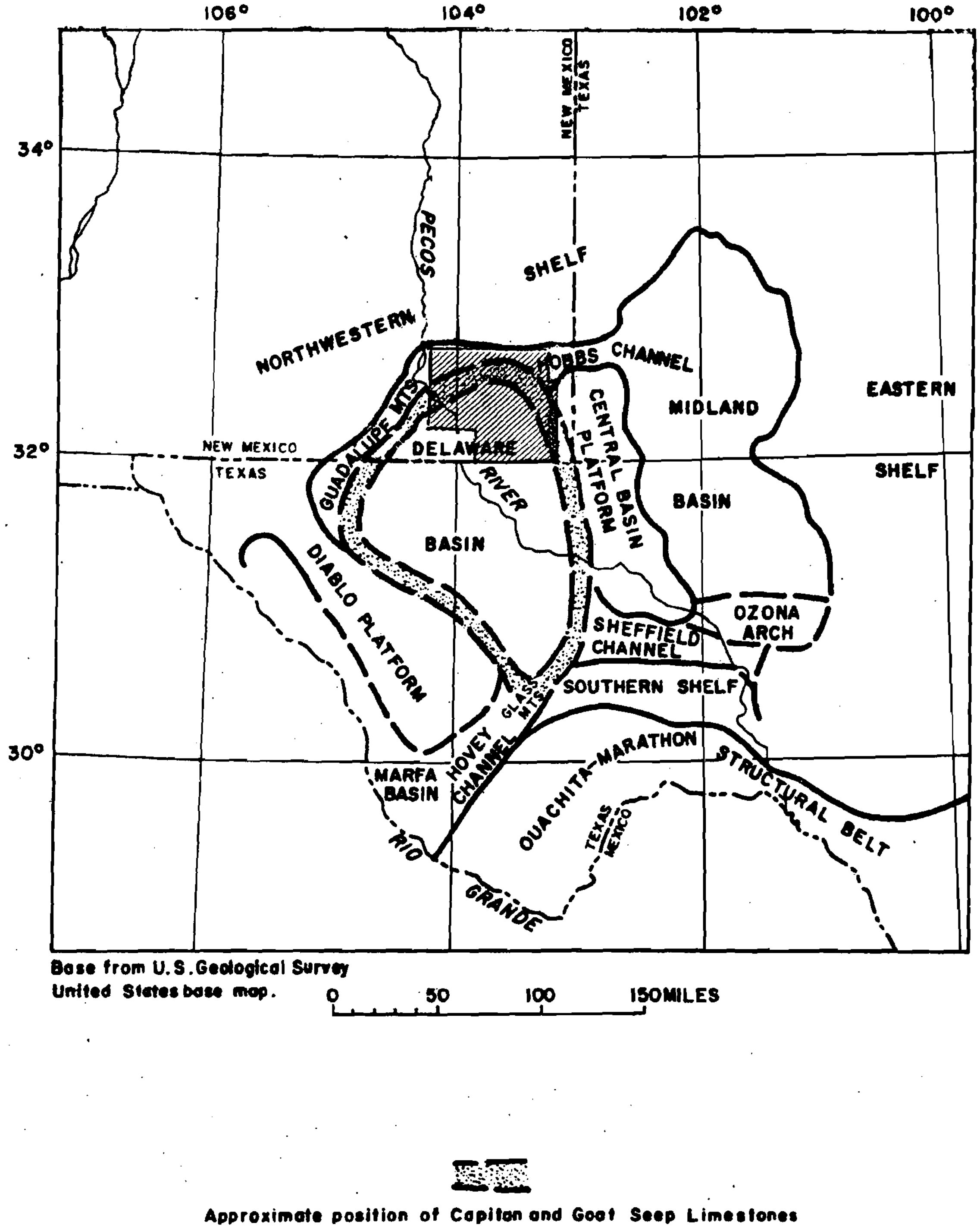


Figure 2.- Relation of area covered by Figure 1 (shaded) to tectonic elements in the Permian basin of southeastern New Mexico and western Texas (after Hiss, 1973).