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SUBROSION IN AND ABOUT THE FOUR-TOWNSHIP STUDY AREA NEAR CARLSBAD, NEW MEXICO

By Arthur M. Piper

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SUBROSION IN AND ABOUT THE FOUR-TOWNSHIP STUDY AREA NEAR CARLSBAD, NEW MEXICO

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SCOPE AND ACKNOWLEDGMENTS

This paper concerns one aspect of the feasibility of storing wastes from the nuclear-fired power industry in bedded salt of the Salado formation near Carlsbad, New Mexico. The center of concern is a four-township study area--Ts. 21 and 22 S., Rs. 31 and 32 E.--which has been selected by the Oak Ridge National Laboratory as a candidate locality for a pilot repository. The paper is based wholly on prior investigations by others, and so is no more than an appraisal of information at hand. Figures 1 and 2 (in pocket) illustrate selected features in the vicinity of the study area.

The one aspect here considered is the vulnerability of the candidate area and storage horizon to future subrosion--specifically, to dissolution and removal of common salt and other evaporites by circulating ground water, also to other agents by which thickness, composition, texture, and structure of rock units may be modified in place. Principal among these other agents are: (1) subsidence or collapse of strata overlying a zone of dissolution; (2) volume expansion of anhydrite as it converts to gypsum in the presence of water, such expansion commonly shattering the texture of enclosing strata that are lightly loaded or merely inflating those strata if they are heavily loaded; (3) plastic flow of common salt under unequal load, tending to close voids created by dissolution; and (4) up-doming of strata as underlying anhydrite-bearing beds inflate or as salt flows.

Principles of dissolution are examined in another paper (Piper, 1973). Only the three general requirements are restated here, because they are misunderstood commonly. These are: (1) a continual source of unsaturated water, generally of land origin, either physically above or under a hydraulic head higher than strata of soluble evaporite; (2) an aquifer system passing from the water source to the soluble evaporite, and beyond to (3) a discharge area at the land surface, either local or remote, and either physically lower than, or under a hydraulic head below, the particular evaporite zone.

Published sources of information are identified under "references" and by citations in the text. Further, the writer acknowledges a considerable indebtedness to A. L. Brokaw and C. L. Jones of the U. S. Geological Survey, who have discussed freely their current investigation in the area, and who have furnished advance copies of illustrations from their pending report. Most comprehensive of the published sources is that by Brokaw, Jones, Cooley, and Hays (1972), which summarizes the topography, stratigraphy, structure, and hydrology of the western half of the area represented by figure 1. That summary affords a necessary background for this greatly condensed paper.

STRATIGRAPHIC, STRUCTURAL, GEOMORPHIC, AND HYDROLOGIC SETTING

The stratigraphic units relevant to the subject matter of this paper are shown in the following summary by Jones (written communication, 1973).

Summary of rock units of latest Permian (Ochoa) and younger age,

Los Medanos area, Eddy and Lea Counties, New Mexico

Age		Rock unit	Thickness (feet)	Description
Quaternary	Holocene	Mescalero sand	0-15	Sand, eolian, fine- to medium-grained, uniformly reddish brown.
		Caliche	0-5	Limestone, chalky, nodular, poorly indurated, grades into underlying rock.
		* * * * * *	* * * * *	* * * * ** * * * UNCONFORMITY * * * * * * * *
	Pleis-tocene	Gatuna formation	0-375	Sandstone and shale, poorly indurated, dominantly reddish orange.
* * *	* * *	* * * * * *	* * * * *	* * * * * * * * UNCONFORMITY * * * * * * * *
Tertiary	Pliocene	Ogallala formation	20-60	Sandtone, fine- to medium-grained, tan, pink and gray, locally conglomeratic, typically has resistant cap of well-indurated caliche.
* * *	* * *	* * * * * *	* * * * *	* * * * * * * * UNCONFORMITY * * * * * * * *
Triassic	Late Triassic	Chinle formation	300-800	Shale, reddish-brown, interbedded lenses of gray and reddish-brown sandstone and greenish-gray shale.
		Santa Rosa sandstone	205-245	Sandstone, fine- to medium-grained, commonly cross-stratified, gray, yellowish-brown and reddish-brown, contains pebble conglomerate and shale beds.
* * *	* * *	* * * * * *	* * * * *	* * * * * * * * UNCONFORMITY * * * * * * * *
Permian	Ochoa	Dewey Lake redbeds	470-560	Sandstone, very-fine- to fine-grained, reddish-orange to reddish-brown, contains inter-bedded reddish-brown shale, small scale lamination and cross stratification. common.
		Rustler formation	300-490	Anhydrite and rock salt with subordinate dolomite, sandstone, shale and polyhalite.
		Salado formation	1160-2310	Rock salt with subordinate anhydrite, polyhalite, potash ores, sandstone, and magnesite.
		Castile formation	30-1840	Anhydrite and rock salt with subordinate limestone.

Late Permian (Ochoa) to mid-Cretaceous time

In late Permian (Ochoa) time, sedimentation in the area of concern changed progressively from the great accumulation of evaporites during the Castile, Salado, and Rustler epochs to the fluvial sandstone and shale of the Dewey Lake epoch. Dissolution in the Salado formation occurred locally, as evidenced by thinning of that formation and compensatory thickening of the Rustler formation in at least one small basin (Maley and Huffington, 1953, p. 541). Fluvial deposition resumed in late Triassic time, during the Santa Rosa and Chinle epochs. However, in early Triassic time, also through all the Jurassic period and thereafter, the area was land and was subject to erosion and fluvial deposition. Also, the area being tectonically stable, presumably (1) the Permian and Triassic rocks could have deformed only locally, by differential compaction or by plastic flow, and (2) the evaporites of the Rustler, Salado, and Castile formations remained under a progressively thickening cover of insoluble rocks. In these circumstances it seems unlikely that the three requirements for in-situ dissolution could have been satisfied widely; they might have been satisfied locally and transiently. No definitive evidence of dissolution in the Rustler or the Salado during this time interval (post-Triassic, pre-middle-Cretaceous) has been reported.

Ogallala formation and High Plains

About in the later half of the Cretaceous period, the rocks were deformed by extensive upwarping centered locally in the vicinity of the Guadalupe Mountains west of Carlsbad (fig. 1) and of the Sacramento Mountains farther north. In and near the study area, the resultant present dip of Permian and Triassic rock units is generally no more than 2°, toward the east or southeast. Owing to this upwarping, erosion was rejuvenated widely and culminated locally in a rock-cut surface of little relief; subsequently, the fluvial Ogallala formation was deposited widely. The upper surface of that formation was a featureless plain flanking the present Guadalupe and Sacramento Mountains; virtually unmodified remnants constitute the present High Plains.

One extensive remnant of the High Plains extends into the northeastern corner of the area represented by figure 1, and there terminates in Mescalero Ridge, a southwestward-facing escarpment about 60 feet high (fig. 2, section B-B'). Hat Mesa, near the northeast corner of the four-township study area, is definitely an outlier, as are certain of the highest summits of Grama Ridge to the east. Here the reconstructed High-Plains surface descends 18 to 22 feet to the mile, S. 60° to 70° E.; its altitude is about 3,950 feet above sea level at the northeast corner of the study area. Projected westward, the reconstructed surface would be about 4,300 feet above sea level at the head of present Nash Draw and 4,425 feet at present Clayton Basin.

About 4 miles south-southwest of Hat Mesa, another isolated topographic high, The Divide, is capped by the Ogallala formation and in form suggests another High-Plains outlier; however, its summit altitude is about 120 feet lower than the original High-Plains surface as reconstructed by the writer. This low position of the Divide is inferred tentatively to be an effect of subrosion in the underlying Rustler formation.

The altitude and slope of the High-Plains surface, also the thickness of the very permeable Ogallala formation are definitive factors in retracing the early subrosion history of the study area and its surroundings. Thus, let it be assumed that, within the area represented on figure 1: (1) the High-Plains surface can be projected southward and westward at the altitude and slope of its present remnants, as summarized above; (2) the Ogallala formation ranges in thickness from 0 to 300 feet; and (3) the Rustler and Salado formations can be projected westward from the study area in constant thicknesses of 400 feet and 1,900 feet, respectively. Then, the projected base of the Ogallala would, in principle, have truncated the projected Rustler formation within a belt some 5 to 10 miles wide, trending somewhat west of south, and about spanning present Clayton Basin. Westward, the sub-Ogallala surface would likewise have truncated the Salado formation, beginning some 6 to 10 miles beyond the axis of present Clayton Basin--that is, about 5 miles east of the present western edge of salt in the Salado (see fig. 1 and fig. 2, section A-A'). The belt of implied Salado truncation would have been tens of miles wide.

However, truncation in the sense of Rustler or Salado evaporites exposed on a land surface seems highly unlikely. Rather, as erosive downcutting approached truncation in principle, the requirements for dissolution probably would have been satisfied and evaporites would have been removed from the Rustler formation, and possibly from the Salado formation, to a depth sufficient that, across the hypothetical belts of truncation, land surface would have remained continuously on subrosional residue until the onset of Ogallala deposition.

Having been deposited, presumably in an environment considerably wetter than the recent and present, the coarse textured Ogallala formation would have been both a prolific source of unsaturated water and an aquifer system contacting the soluble evaporites across the two belts of hypothetical truncation. Numerous cells of unconfined ground-water circulation, returning brine to the land surface, seem self evident. Thus, dissolution of the evaporites must have been rather rapid. Eastward from the belts of hypothetical truncation, confined ground-water circulation presumably would have supported dissolution for some moderate distance down dip. On the other hand, increasing down-dip distance would have increased the likelihood of hydraulic traps beneath rock units of small permeability (Dewey Lake and Chinle), thus restricting brine discharge and so finally inhibiting further dissolution.

It seems evident that, within about the western third of the area represented by figure 1, regional dissolution of evaporites from the Rustler, and possibly from the Salado, probably began about with deposition of the Ogallala. Frye (1970) and others describe the Ogallala as of late Miocene and Pliocene age; granting such an age, the dissolution here postulated would have begun some 12 million years ago. It would have been the earliest dissolution to bear on the purposes of this paper.

This retracement of early dissolution history assumes that the Ogallala formation is wholly a pediment mantle, and that the area here of concern was of low relief prior to Ogallala deposition. Such has been the position taken or accepted by most prior investigators.

Deeply filled dissolution basins to the south

Maley and Huffington (1953) describe "silts, sands, and gravels" as much as 1,700 feet thick, which fill very extensive dissolution basins south of the area represented by figure 1. They conclude that "although most of the fill is probably Quaternary [Pleistocene] in age, it is likely that some of the older deposits are Tertiary." According to this age assignment, the older basin fill may be about contemporaneous with the Ogallala formation as described previously.

A northeastern lobe of the basin fill is mapped as extending into T. 25 S., R. 36 E., about 15 miles south-southeast of San Simon Sink and there underlying San Simon Swale. This lobe may have acted, or now may act, as one component of an aquifer system sustaining dissolution beneath the Swale. However, no specific evidence to that effect is at hand. To the west another lobe of the basin fill is shown extending into T. 25 S., R. 30 E., about 8 miles southeast of Malaga Bend of the Pecos River. Mapping by Brokaw and others (1972, fig. 8) indicates that this particular lobe of the deep basin extends even farther north, into T. 24 S. (see fig. 1); however, neither presence nor absence of fill is reported for that northward extension.

No counterpart thick and extensive bodies of basin fill have been reported in the area of figure 1 of this paper. Conceivably, however, the Gatuna formation in the head of Nash Draw (the Draw will be described) is a stratigraphic equivalent of the younger part of the basin fill to the south. In Nash Draw, the Gatuna may serve as a conduit by which ground water can reach the Rustler formation (fig. 2, section A-A').

The deep-basin fill to the south may have another counterpart in certain small scattered deposits of quartz gravel or conglomerate low in present Pecos River valley, deposits which Bretz and Horberg (1949) and Thomas (1972) both ascribe to basal Ogallala. One such deposit is along Black River, about in sec. 9, T. 24 S., R. 28 E. (see fig. 1). Thomas "suggests 1,300 feet of Ogallala valley fill" in an ancestral Pecos River valley, now exhumed in the vicinity of Carlsbad and Roswell. On the other hand, Frye (in Thomas, 1972, p. 2, footnote 2) challenges the evident presumption by Thomas that the quartz gravel in question is "Ogallala in situ." Further, Maley and Huffington (op. cit.) cite persuasive evidence that the basin fill occupies neither an ancestral Pecos River valley nor any other prehistoric valley or valleys.

Evidence at hand is not competent to correlate any part of the deep-basin fill with particular glacial or interglacial stages. Some of the younger fill may have post-dated the High-Plains epoch and may be a time equivalent of features next to be described.

Querecho Plains and related land forms

Locally, dissection of the High Plains began late in the Pliocene epoch, probably about 4 million years ago (Bachman and Johnson, 1973, p. 8) and possibly due to further slight upwarping (Smith, 1940, p. 94). The region has been tectonically stable since.

The most conspicuous land-form element next below the High Plains is a 5-to-15-mile-wide apron, the Querecho Plains (Mescalero Pediment), which slopes southward to southwestward from the base of Mescalero Ridge escarpment into the northern third of the area here described (figs. 1 and 2). A counterpart, northward-sloping surface descends locally from Hat Mesa in the northeasternmost part of the study area (fig. 2, profile C-C').

Eastward from Hat Mesa and The Divide, the Querecho Plains merge into a series of shallow, vague drainage ways, principally the heads of San Simon Swale and of Monument Draw (fig. 1). Locally these drains trend east-southeast, normal to the constructional slope of the High Plains. They are interpreted by the writer as basically infant erosion forms consequent on the original High-Plains surface. Regionally, San Simon Swale and Monument Draw extend far to the south, as ephemeral tributaries of the Pecos River in Texas.

Westward from The Divide, the Querecho Plains merge locally into a broad, gentle sag with nominal westward drainage toward the Pecos River. At Nimenim Ridge the sag is interrupted by Clayton Basin (to be described), but resumes beyond that basin and extends nearly to the western edge of the area represented by figure 1.

In regard to the subrosion of evaporites, the significance of the Querecho Plains is that they cut some 350 to 800 feet below the reconstructed High-Plains surface within the area here of concern. Thus, they would have intersected the projected initial top of the Rustler formation about along the axis of present Nash Draw, and the northward projection of that axis. Further, they would have intersected the projected initial top of the Salado formation (base of the Rustler) somewhat east of Nimenim Ridge and in principle would have truncated the Salado across present Clayton Basin and beyond, toward the west.

The Querecho Plains appear to be the counterpart of a land-form element which Frye and Leonard (1959, 1964) correlate with the Kansan glacial stage; the overlying Mescalero sands then may be the counterpart of extensive "Kansan deposits that contain a strong caliche soil profile--Yarmouth [interglacial] Soil--in the top" (op. cit.). Granting these correlations, the shaping of the Querecho Plains and counterparts spanned at least the Nebraskan glacial stage, the Aftonian interglacial stage, and the Kansan glacial stage--an aggregate time lapse of about 1 million years.

It seems evident that, during dissection of the High Plains to the Querecho Plains stage, subrosion immediately west of the four-township study area must have continued without interruption because: (1) The time interval includes two glacial stages during which rainfall--and so a source of unsaturated water for dissolution--may be presumed to have been several fold greater than during historic time. (2) The hypothetical belts of truncation across the Rustler and Salado would have shifted progressively eastward as the dissection deepened. (3) The presumptive hydrologic setting doubtless would have continued to favor dissolution both by local unconfined circulation and by wider-reaching confined circulation.

Clayton Basin and Nash Draw

Clayton Basin, the most extensive and deepest undrained depression in the area here described, centers about 10 miles northwest from the northwest corner of the four-township study area and has a "closure" about 11 miles long, 5 miles across, and 130 feet deep. Its long dimension trends about N. 35° E.--that is, about parallel to the hypothetical belt of truncation across the Rustler formation (described previously). It interrupts a Querecho Plains counterpart which is extensive both to the east and to the west, and so is inferred to be largely a product of post-Yarmouth time--that is, of about the past 350,000 years; if so, its formation has spanned the Illinoian and Wisconsin glacial stages, during which rainfall presumably was several times greater than in the intervening Sangamon interglacial stage and the subsequent post-Wisoncsin "recent" stage. Clayton Basin is clearly a feature of land-surface subsidence, probably intermittent subsidence and presumably an effect of subrosion in the underlying Rustler and Salado formations. Its floor is about 325 feet above the local base of such subrosion (fig. 2, section A-A').

Nash Draw heads abruptly below the Maroon Cliffs to the west of, and within the northwesternmost part of, the four-township study area. Thence it trends about S. 35° W. about 16 miles to Salt Lake and there opens onto the Pecos River valley. Being about 300 feet deep below Livingston Ridge to the east and having pseudo-terraced walls, the Draw is anomalous among local land forms. In major features it suggests an erosion form; doubtless, however, its origin was in considerable part by subsidence owing to subrosion in the Rustler and Salado. Its floor, undrained in detail, is 250 to 400 feet above the local base of subrosion (fig. 2, section B-B').

Nash Draw presumably was formed about simultaneously with Clayton Basin to the north and west--that is, largely after the Yarmouth interglacial stage. With Clayton Basin it has afforded, during the post-Yarmouth interval of about 350,000 years, a moderately extensive catchment for unsaturated water (from rainfall) and so has constituted a principal local source for sustaining subrosion. During the two glacial stages of post-Yarmouth time its competence as a water source doubtless has been several-fold greater than in historic time.

Presently, the potentiometric surface for aquifers in the Rustler and overlying formations has been trough-shaped beneath the Draw and, separately, beneath Clayton Basin (Cooley, M. E., in Brokaw and others, 1972, fig. 8); presumably it has been somewhat so shaped during a considerable part of post-Yarmouth time. Thus, ground-water circulation beneath the Draw is, and presumably for some time has been, generally toward the axis of the potentiometric trough then southward toward Salt Lake and Malaga Bend of the Pecos River. Circulation beneath Clayton Basin is toward and along the axis of its separate trough; farther south the direction is poorly defined. This circulation is confined, at least in part.

Underlying much of or all Nash Draw is a so-called brine aquifer, a solution-breccia zone at the contact between the Rustler and Salado formations, about 5 miles in average width and having a transmissivity of about 60,000 gpd/ft (gallons per day per foot of width) (Hale, Hughes, and Cox, 1954, p. 22-24). From it, a nearly saturated sodium-chloride brine (260,000 ppm) discharges naturally into the Pecos River at and near Malaga Bend (fig. 1). Theis and others (1942, p. 69) estimated the amount of this discharge to be about 200 gpm (gallons per minute); this would be equivalent to 420 tons of sodium chloride daily or 160,000 tons yearly.

From data by the U. S. Geological Survey, published under "Quality of surface waters of the United States," the writer has computed the mean yearly dissolved-solids load of the Pecos River to include 310,000 tons of NaCl (common salt) and 170,000 tons of $CaSO_4$ (gypsum) at the sampling station about 6 air-line miles downstream from the area represented by figure 1.* Much of this load enters the river within a few miles beginning at Malaga Bend. A considerable part of the $CaSO_4$ may originate as leachate from irrigated lands upstream, also, some of the NaCl load is diverted from the river onto irrigated land (Swenson, in Bachman and Johnson, 1973, p. 50) but in large part, after some time lag, probably reenters the river as irrigation tail water. Thus, the mean NaCl load may be taken as an approximate measure of current dissolution from the Salado and Rustler formations upstream.

*Mean of the 28 years ending September 30, 1938-1965, omitting 1941-1943 in which years peak flow was uncommonly large and the record of total solute load was weak. Station at Red Bluff, New Mexico, 5.5 miles upstream from the Delaware River. Data from annual volumes of the Water-Supply Paper series.

These hydrologic features suggest that Nash Draw and Clayton Basin overlie the principal area of current dissolution and subrosion in the Rustler and Salado formations, in the western part of the area represented on figure 1. That figure shows the traces of arteries of recent dissolution at the top of the Salado formation as inferred by the writer. Two sub-systems of these arteries are indicated: (1) A rather strongly defined "main stem" which heads near the center of the four-township study area, trends generally west-northwestward to the northeast lobe of Nash Draw at its head, thence generally somewhat west of south about along the axis of the Draw, to and beyond Salt Lake. (2) A second ramifying system, in part vaguely defined, appears to drain Clayton Basin and the area to the west, nearly to Oil City. However, current discharge from this second inferred sub-system has not been discriminated along the Pecos River near Carlsbad. As just outlined, this hydrologic setting for recent dissolution and subrosion probably has persisted in much the same form since the Querecho Plains stage, at least.

Smaller areas of subsidence

Undrained depressions and "sinks", from a few yards to a few miles across, and from a few feet to a few tens of feet deep, are commonplace in several parts of the area. Those more than about a mile in longest dimension are shown on figure 1. Among these two groups are noteworthy: (1) To the north of the four-township study area, a cluster of five including Williams Sink, Laguna Plata, Laguna Toston, Laguna Tonto, and Laguna Gatuna. (2) About 10 to 15 miles east of the study area, San Simon Sink in T. 23 S., R. 35 E., and five unnamed depressions to the north.

San Simon Sink is definitely a feature of subsidence, having a series of ring fractures denoting successive collapse events. One such event is reported to have occurred in 1922 (Bachman and Johnson, 1973, p. 29). Exploratory drilling is reported to have penetrated 400 feet into the sink without encountering Triassic rocks (op. cit., after Nicholson and Clebsch, 1961, p. 46). Evidently the material penetrated by the drill is "fill," largely subrosional residue, indicating dissolution of underlying evaporites in a thickness equivalent to that of the residue. This leads to two conclusions relevant to the purposes of this paper: (1) The deep-basin "fill" of Maley and Huffington (op. cit.) extends northward to and beyond San Simon Sink, and so invades the area represented by figure 1; (2) accepting the residue in the Sink to be at least 400 feet thick, dissolution there may have down-reached through the Rustler formation into the top of the Salado formation. Presumably, the particular zone of dissolution is relatively extensive--the named Sink lies within an undrained depression about 7 miles long (northwest to southeast) and 4 miles wide (fig. 1).

Equally definitive information is not at hand in regard to the other depressions of the San Simon cluster. Their form, as disclosed by topographic map, suggests subsidence as the principal agent although cutting and deposition by the wind may have had a part.

To the north of the four-township study area, Williams Sink and the adjacent four "lagunas" are depressions in a counterpart of the Querecho Plains (fig. 2, section B-B'). Presumably, therefore, they are post-Yarmouth in age. The writer presumes that subsidence above zones of dissolution is one probable agent of their formation; Jones (oral communication, 1973) reports evidence of substantial eolian cutting and deposition in their vicinity. Definitive evidence measuring downward reach of dissolution, if any, is not at hand for this district.

It has been stated that the summit of The Divide, in the eastern half of the study area, appears to be about 120 feet too low to correlate with the reconstructed High-Plains surface. Local subsidence in about that amount is suggested by the log of a well--Culbertson & Irwin, 1 Murray--on the southern lobe of The Divide in sec. 9, T. 22 S., R. 32 E. That log (Jones, C. L., advance copy of stratigraphic section, 1973) shows the upper three fourths of the Rustler formation to be about 80 feet thinner than in a second well 8.6 miles to the north-northwest, and about 170 feet thinner than in a third well 9.0 miles to the south-southeast. However, a 60-foot bed of common salt with a parting of anhydrite near the botton of the Rustler appears not to be thinned. Thus it appears that subrosion here during all post-Pliocene time has not reached the top of the Salado formation.

Regional climatic and geomorphic history

The writer believes that, like the development of land forms, dissolution of evaporites proceeds by successive stages, each rejuvenated stage proceeding at a pace which slows progressively; further, that to a considerable degree the two processes respond concurrently to common agents. As has been shown, dissolution in the area here of concern probably began in late Miocene time, about simultaneously with Ogallala deposition, and has persisted through Pliocene time and the several glacial and interglacial stages of Pleistocene and Holocene time. There is strong evidence that rainfall during the several glacial epochs was several-fold greater than during historic time, and likewise greater than during interglacial intervals.

One major event of geomorphic history in southeastern New Mexico may have affected the rate of evaporite dissolution. Thus, Theis (1932, p. 113) has concluded that in early Pleistocene time the area north of Fort Sumner drained, not into an ancestral Pecos River but southeastward via the Portales Valley into an antecedent Brazos River. Frye and Leonard (1959, 1964) assign Kansan age to certain extensive stream deposits in the Portales Valley; thus, the capture of its present headwater area by the Pecos River occurred somewhat later than the Kansan glacial stage, and so somewhat later than the Querecho Plains stage in the area of this paper. By this capture, the Pecos River would have gained the drainage from the high and water-productive Sangre de Christo Mountains and the Pedernales Hills; it would have increased only slightly its area of exposed Permian rocks.

SOURCES OF WATER

Water to sustain dissolution of evaporites in the vicinity of the four-township study area comes presently from two active souces and potentially from a third source; in different relative amounts, presumably the same three have served also in the past. The three sources are:

1. The Pecos River, a minor and intermittent source in that, in the reach here discussed, most of the time it gains from, rather than loses to, the contiguous shallow ground water. The river becomes a losing stream, and so a local driving force in ground-water circulation, only during transient periods of high flow and only within a relatively narrow belt along either side of its channel. In the particular reach here considered, the intervals of high natural flow presently are diminished in frequency and duration by diversion and storage of water upstream for irrigation.

During pluvial (glacial) epochs of Pleistocene time, the antecedent Pecos River presumably would have had a greater mean flow and may have contributed more to ground-water circulation, but not sufficiently more to have ever been the major source of water dissolving evaporites. Also, during past pluvial epochs some presently ephemeral drainage ways of the area--especially San Simon Swale, Monument Draw, and others to the east as well as Nash Draw to the west--may have been occupied by perennial streams. Depending on local configuration of the water table at the time, such hypothetical streams could have furnished a component of the water dissolving evaporites, a component which presently is zero.

(Incidentally, if a perennial stream occupied San Simon Swale during pluvial (glacial) stages, dissolution may well have been commensurate with the great accumulation of deep-basin fill to the south, previously described. That volume of fill seems incongruously large for the presumptive rate of dissolution under the present (and interglacial?) semiarid environment.

The influence on evaporite dissolution by the Pecos River and the hypothetical perennial streams is and has been indirect in large part. Thus, under erosive downcutting by rejuvenated streams, bodies of evaporite doubtless have been brought within reach of circulating ground water. Further, incision of stream channels has steepened ground-water gradients beneath interstream tracts, and so accelerated ground-water circulation. Conversely, as downcutting has slowed and stream gradients have flattened, so have ground-water gradients flattened and circulation slowed.

2. Ground-water recharge on interstream tracts, naturally by rainfall and artificially by irrigation, doubtless the major source of water for evaporite dissolution. Quantitatively, this source is the amount by which infiltration exceeds evapotranspiration at the land surface. In the present semiarid environment and over much of the area, such excess probably is zero in the driest years, nominal in most years, and plentiful only in the wettest years at intervals possibly as long as several decades. Locally, the numerous undrained depressions and their catchments may so concentrate infiltration that some recharge occurs in most years. In the more humid environment of pluvial epochs in the past, ground-water recharge presumably would have been several-fold greater in mean amount, and possibly perennial rather than intermittent.

In general, ground-water recharge probably is fully competent, over most of if not all the area, to sustain the small rate of circulation required for effective dissolution. For example current dissolution of common salt from the Salado and Rustler formations within and upstream from the area of figure 1 has been taken to be about 310,000 tons yearly. To remove this amount of salt as saturated brine would require a circulation of only 400 gpm or 800 acre feet yearly, dispersed over the entire area. This rate of dissolution would be equivalent to removing 0.16 mi^2ft (0.16 foot thick over 1 square mile) of pure common salt (halite) yearly, or a 160-foot-thick layer over 1,000 square miles in 1 million years. As will be shown, such a rate is of the same order of magnitude as the inferred mean rate at which common salt has been removed in post-Pliocene time, from all the area upstream from Malaga Bend.

3. Leakage from aquifers below the Castile formation, primarily from the Capitan limestone and its stratigraphic equivalents, the Yates and Tansill formations. These formations are moderately permeable; east of the Pecos River the head on their water is generally above the land surface, and at least locally their water is not saturated. Presently, therefore, a potential hydraulic gradient, vertically upward, exists across the Castile, Salado, and Rustler formations; the extent to which such a gradient may have existed in the geologic past is not known. In principle, extremely slow upward movement of water from the Capitan limestone and its equivalents is to be expected; if there are conduits having sensible transmissivity, the amount of upward movement may be sufficient that evaporites are dissolved on the way. Cooley (in Brokaw and others, 1972, p. 62) cites evidence consistent with such movement.

VULNERABILITY OF THE STUDY AREA TO FUTURE SUBROSION

Natural vulnerability on the west

Vulnerability of the study area to future subrosion can be assessed by projecting inferred past rates of dissolution--rates in terms of both horizontal advance of a subrosional "front" and of vertical downreaching of a subrosional base. Both rates probably have fluctuated by stages correlative with stages of geomorphic development, from a maximum following erosive rejuvenation to a minimum at erosive old age. In the area here of concern, the writer infers that present rates of subrosion presumably are substantially slower than their maximums of the past.

As has been stated, the writer infers that the dissolution and subrosion which can be retraced with some certainty began with the onset of Ogallala deposition about 12 million years ago. At that time, presumably, the southeastward dipping Salado formation (1) had been "truncated" along the western edge of the area represented by figure 1; and (2) together with a presumptive mantle of erosional and subrosional residue, there had been thinned to about one fourth of its thickness as deposited--specifically, to about 500 feet. Subsequently--during latest Pliocene time and all of Pleistocene and Holocene time--the "front" of subrosion has advanced eastward about from 10 to 20 miles, (measured at the projected top of the Salado formation), and the base of subrosion has lowered about from 500 to 1,500 feet (average in the order of 900 to 1,000 feet). Thus, the concurrent mean rate at which the "front" has moved eastward appears to have been in the order of 0.8 to 1.6 miles per million years; likewise, the mean rate at which the base of subrosion has lowered appears to have been in the order of 80 feet per million years.

Actual rates presumably would have deviated substantially from the means just derived, conceivably by an order of magnitude more or less. Greatest rates would have been expected with the rejuvenation of erosion under which the High Plains were dissected, beginning about 4 million years ago; again with the onset of dissection of the Querecho Plains and counterpart surface in late (?) Yarmouth time, say 0.5 million years ago. Least rates would have been expected with full development of the Querecho Plains surface in Kansan time, about 0.7 million years ago.

Bachman (1973, p. 41) has concluded that "since the close of Ogallala time, about 4 million years ago, the salt front in Permian rocks has retreated eastward from 25 to 35 miles," and so that the average rate of movement has been about from 6 to 8 miles per million years. His derivation restricts all removal of salt to the Pleistocene and Holocene epochs and would exclude any such removal by erosion and subrosion antecedent to Ogallala deposition. However, Bachman's rate falls within the range that the writer has suggested to be conceivable.

Order-of-magnitude verification of the preceding estimates can be derived from generalizations and assumptions that (1) the area of subrosion upstream from and tributary to the brine-discharge area near Malaga Bend is 1,250 square miles (Brokaw and others, 1972, p. 56); (2) average thickness of salt in the Rustler formation, as deposited, was 125 feet over all the area of subrosion, and all this has been dissolved and removed; and (3) the Salado formation as deposited was 75 percent common salt, and all this has been removed from the zone of subrosion.

From these generalizations and from estimates stated previously, the volume of common salt removed would be about 3×10^{13} cubic feet or 2×10^{12} tons. Over the 12-million-year term of subrosion derived by the writer, this would average 1.7×10^{5} tons yearly and would be equivalent to a constant discharge of 220 gpm of saturated brine. Over the 4-million-year term of subrosion taken by Bachman (op. cit.) the above volume of salt would have sustained a 660-gpm discharge of saturated brine. These two inferred rates of brine discharge are comparable to actual rates, stated previously, of 200 gpm of brine as estimated by Theis and 390 gpm of brine equivalent as derived by the writer for mean NaCl load of the Pecos River at Red Bluff, New Mexico.

The "front" of subrosional advance being a near-horizontal feather edge rather than a vertical boundary, the writer feels that its position on the top of the Salado formation (unthinned) does not indicate vulnerability of a waste repository at depth in the Salado. Rather, that an assessment of vulnerability depends jointly on the present stratigraphic horizon of the subrosional base and on the prospective rate at which that base will lower. As has been outlined, the subrosional base appears to be presently above the top of the Salado formation in three quadrants of the four-township study area; in the remaining northwest quadrant the base appears to have been incised into the Salado locally, to a maximum depth of about 150 feet. Thus, anywhere within the study area and presuming that in the future the subrosional base might lower at the greatest credible rate previously derived, a waste repository 1,000 feet below the top of the Salado would seem to be proof against natural subrosion from the west for somewhat more than 1 million years. This estimate appears to offer an ample "factor of safety" against the contingency that a pluvial environment would resume during the effective life of a repository.

Natural vulnerability on the north, east, and south

Data are not at hand for a specific assessment, like the preceding, of vulnerability of the study area on the north, east, and south. General stratigraphic, geomorphic, and hydrologic features have been summarized; these suggest, but do not demonstrate conclusively, that the subrosional base is yet above the top of the Salado formation to the north and east. To the south, in the area of thick fill and its two lobes which invade the area of figure 1, the subrosional base could well be hundreds of feet below the top of the Salado.

If a waste repository in the Salado formation must remain functional for many thousands of years--that is, over a term sufficiently long that reversion to a pluvial environment would become credible--some specific information is desirable as to (1) stratigraphic horison of the subrosional base along and near all four sides of the study area, rather than the western side alone; and (2) hydrologic setting of the thick fill to the south. A little "spot" information might prove definitive.

Man-caused vulnerability

The greatest threat to the integrity of a waste repository in the Salado formation within the study area might be from works of man in the surroundings, especially from inadequate or deteriorated casings in oil or gas wells, or from inadequately plugged exploratory holes. Extensively if not universally, static fluid levels of deep aquifers in the Capitan-Yates-Tansill zone are considerably higher than the Salado formation; potentially, therefore, a repository could be flooded from those deep aquifers if it should cut an inadequately plugged deep well. Further, unnatural subrosion may have been, or may be, induced wherever unsaturated deep-aquifer water from an inadequately cased well might contact salt and then pass on to a discharge area. Information for assessing these hazards specifically is not at hand. As a first step toward assessment, the writer suggests a review of fluid levels in oil and gas fields and in other deep wells in the surroundings, to disclose any present anomalies of head indicating cross-stratigraphic fluid movement.

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