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Mr. Jeff Pohle
Division of Waste Management
Mail Stop 623-SS
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

WM-RES
WM Record File D1020 W+A
WM Project 10, 11, 16
Docket No.
PDR ✓
LPDR B, N, S
Distribution: Pohle
(Return to WM, 623-SS)

RE: SALT

Dear Jeff:

A copy of the review of each of the following documents is enclosed.

2. Conti, R.D., Senger, R.K., Wiroganagud, P., and Herron, M.J., 1984, Wolfcampiam Series Porosity Distribution: Implications for Deep-Basin Ground-Water Flow in the Palo Duro Basin, Texas Panhandle. Texas Bureau of Economic Geology, Austin, TX (Revision 1), OF-WTWI-1984-33.

1. Bair, E.S., June 1985, Hydrodynamic Investigations in the Texas Panhandle Area. Report prepared by Stone and Webster Engineering Corp. for Battelle Memorial Institute, Topical Report, ONWI/SUB/85/E512-05000-T42, 68 p.

3. Senger, R.K., Fogg, G.E., and Kreitler, C.W., 1985, Effects of Hydrostratigraphy and Basin Development on Hydrodynamics of the Palo Duro Basin, Texas. Texas Bureau of Economic Geology, Austin, TX, OF-WTWI-1985-37.

Please contact me if you have any questions concerning these reviews.

Sincerely,

Gerry Winter/sl

Gerry Winter

GW:sl
enclosures

2830

WMGT DOCUMENT REVIEW SHEET

FILE #:

TEXAS BUREAU OF ECONOMIC GEOLOGY #: OF-WTWI-1984-33

DOCUMENT: Conti, R.D., Senger, R.K., Wiroganagud, P., and Herron, M.J., 1984, Wolfcampiam Series Porosity Distribution: Implications for Deep-Basin Ground-Water Flow in the Palo Duro Basin, Texas Panhandle. Texas Bureau of Economic Geology, Austin, TX (Revision 1).

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: August 28, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The document under review uses borehole geophysical logs to estimate the porosity of the Wolfcampian Series rock in the Palo Duro Basin. The report compares standard cross-plotting techniques using neutron density logs and neutron sonic logs for quantitative determinations of porosity and lithology. Planimetry based analyses of porosity distributions derived from borehole geophysical logs are used to estimate the "total effective pore volume." The supposedly improved definition of the distribution of porosity of the Wolfcampian rocks is used to help define "porosity-fairways" and their relationship to Wolfcampian shelf margin positions, major lithofacies, and zones of diagenesis. The refined porosity distributions are used in fluid modeling simulations; they provide a foundation for estimating the total effective pore volume. The report states that the porosity distributions ultimately may be used to yield maps of permeability trends which incorporate lithology dependent porosity and permeability relationships. The report estimates that the average time (middle of the basin) required to exchange the groundwater (flush) in the Wolfcamp Series is once per two million years for the typical porosity flow model. The report states that the exchange of groundwater in the basin would be once per 1.2 million years based on the borehole log derived porosity flow model.

Two major problems exist with the report under review. The first problem concerns the continued use of the phrase effective porosity. Effective porosity cannot be derived from neutron-density logs or from neutron-sonic logs. These logs can be evaluated for the determination of a value that approximates the total porosity of the medium being investigated. Effective porosity can be measured only in the field by tracer type tests. The report assumes that the porosity values derived from the borehole geophysical log evaluations can be used to estimate the rate of groundwater exchange or frequency of the deep basin brine aquifer system which includes the Wolfcampian Series rocks. The use of this total porosity value is not correct for this purpose.

The second problem occurs because of the necessity for extrapolating and interpolating data between widely scattered data points. The interpretation and interpolation of geophysical and geologic logs requires that large distances be covered on the basis of a relatively small data base. This limitation is a consequence of the very limited existing data base.

BRIEF SUMMARY OF DOCUMENT:

The report states that the Wolfcampian Series contains part of the deep basin aquifer system within the Palo Duro Basin. The Wolfcampian Series underlies about 2,100 to 3,100 feet (640-945 m) of low permeability strata which separate the porous Wolfcamp Series from the bedded San Andres salt. Previous studies of Wolfcamp stratigraphy are based on correlations of resistivity, self-potential, and gamma log responses and lithologic descriptions and sample logs. The document under review states that the term "Wolfcamp" is used as an informal stratigraphic designation for subsurface rock units that overlie the uppermost Pennsylvanian rocks and underlie the Wichita Group (p. 10).

The report attempts to quantify the geographic distribution of Wolfcampian rock porosity in the Palo Duro Basin. The porosity trends are related to shelf margin positions and depositional systems. Lithology and diagenesis also are considered in this procedure.

High quality porosity logs were used as a basis for accurate lithology and porosity determinations. Verification of cross-plot results was attempted by comparing the results to lithologic core descriptions and lab measurements of porosity. The cross-plot porosities were mapped. The net thickness of the sediments was determined for 5% porosity ranges on the maps.

The porosity maps were used to calculate residence time for groundwater flow through Wolfcamp strata in the Palo Duro Basin.

The report states that the porosity values derived from borehole logs are shown to reflect accurately the porosity assessments made by laboratory analyses. The report states further that no distinction is made between fracture induced porosity and primary porosity in the assessment of the porosity distribution of the basin. The detection limits of secondary porosity exceed the resolution capabilities of the radiation log analysis.

The Wolfcamp strata were deposited in four marine environments. These environments produced deposition of fan delta systems, highly constructive delta systems, carbonate shelf margin systems, and slope and basin systems (p. 4). The report states that the uppermost porous and permeable unit is comprised primarily of open ring platform carbonates and fluvial-deltic arkosic sandstones interbedded with mudstones (p. 5). The report states that present hydraulic conditions were initiated during the Laramide Orogeny. The Orogeny resulted in the regional tilting of the sedimentary strata toward the east. A potential discharge location is the Hardeman Basin (p. 6). Groundwater flow in the Wolfcamp carbonates generally is believed to be east-northeast. The flow direction is based on the evaluation of computed freshwater hydraulic heads.

Two methods were used in the report for quantitatively describing the lithology and the porosity of the formations that were logged. Both methods use bivariate graphs of two different porosity log responses for an interval at a given depth. One method uses the acoustic responses (interval travel time) plotted against responses from the neutron-porosity log. The second method uses a density-porosity value plotted against neutron-porosity log responses. The appropriate cross-plotting chart appears in Schlumberger (1979). Laboratory determined porosity values from core plugs provide control data. The control data were compared with porosities derived from cross-plots. Neutron-porosity and density-porosity values were recorded from a simultaneous compensated neutron formation density log (Schlumberger trade-mark) in the Stone and Webster Engineering Corporation Sawyer #1 well and Mansfield #1 well for the cored pure carbonate intervals. A simultaneous compensated neutron-lithodensity log (Schlumberger trade-mark) was recorded for the Zeeck #1 well for the cored pure carbonate intervals. The borehole compensated sonic log (Schlumberger trade-mark) was used to record depth equivalent interval transit time values. Neutron-porosity was plotted against density-porosity for the neutron-density cross-plotting analysis. Neutron-porosity was plotted against acoustic interval travel time for the neutron sonic cross-plotting analysis.

The neutron-density cross-plotting method was compared to the neutron sonic method for pure dolomite intervals. The report states that neutron-density data cluster more closely to the dolomite line than do the neutron sonic data. This observation indicates that the neutron density plotting produces a more accurate identification of dolomite. The neutron density method and the neutron sonic cross-plotting method for pure limestone also indicate that the limestone data cluster more closely to the appropriate limestone line with the neutron-density method. The neutron density cross-plotting analysis constitutes a more accurate assessment of carbonate lithology.

The report states that porosity determinations made by laboratory analyses of core agree well with porosity values determined by the geophysical log response analyses. The report states also that the porosity determinations agree more closely in the cross-plot derived approach if porosity values are taken from within 5 feet of the recorded core plug depth. This differential depth procedure accounts for probable footage slips during the recording of the core interval depths. A linear regression analysis of the depth adjusted data increases the correlation coefficient from 0.68 to 0.93.

The investigators also attempted to evaluate the relationship of permeability and porosity. The report evaluated this relationship using permeability of core samples using air as the fluid medium. The investigators found that the common logrithm of permeability to air increases linearly with increasing porosity. Predictable relationships exist between porosity and permeability for sandstone, limestone, and dolomite. Investigators found correlation coefficients of 0.81 for sandstone, 0.84 for limestone, and 0.87 for dolomite (p. 14). The log of permeability increases with respect to porosity at a faster rate for dolomite (slope equals 0.25) than it does for sandstone and limestone sediments (slope equals 0.12). The permeability is higher in sandstone than it is for equivalent porosities in limestone. The report states that the large variance of permeabilities derived from core plugs suggests extreme heterogeneity within the intervals analyzed by pumping and drill stem tests. Generally higher permeabilities were obtained from pumping tests and drill stem tests in the Mansfield #1 well which may be due to fracture permeability. These in-situ values of permeability are higher than the permeabilities derived from core plugs for the same interval. The report states that abundant fractures are present in the cored intervals of the Mansfield #1 well (p. 15).

The report refers to "Total Effective Porosity" on page 16. The total volume and the total pore volume of Wolfcampian Series rocks were calculated. The "average effective porosity" was calculated for the Wolfcampian Series by dividing the total core volume by total sediment volume. The report refers to an "average effective porosity of 6.4% for the predominantly carbonate unit" (p. 16). The report includes an average porosity distribution map. The highest average porosities are in the northern part of the basin in northern Randall and Armstrong Counties and in northeastern Deaf Smith County. The lowest average porosities are found in the western part of the basin (Palmer, Lamb, and southwestern Deaf Smith Counties). The report attributes the highest average porosity zones to alternating, high porosity clastic and carbonate sediments. An "interpreted effective porosity of 0%" has been assigned to the southwestern shelf margin sediments that basically are shaly sediments (p. 16).

The report discusses the thickness and porosity trends of the brown dolomite. The report describes the porosity distribution for the Wolfcampian Series. Maps are included in the report for the porosity distributions.

The report cites the basinwide travel times produced by other investigators (Wirojangud et al., 1984). The report states that using "typical porosity values" of 8% for carbonates, 14% for granite wash, and 5% for shale results in longer travel times than the travel times derived based on geophysical log porosities. The report states that travel times using typical porosity values are 3.8 million years along the southeasternmost flow line, 2.0 million years for the northeastern traverse, and 0.25 to 1.0 million years for a northwesternmost basinwide traverse. Travel times using the interpretations derived from geophysical logs are lower. The southeasternmost flow line crosses the basin in about 2.1 million years. Flow lines across the central part of the basin, northeastward traverse, indicate a travel time of about one million years. A travel time of about 0.25 to 0.8 million years is indicated for the northwesternmost part of the basin. The travel times are used to estimate the time required for flushing of the deep basin flow system. The report states (p. 23) that the basin would be flushed once every 2.0 million years based on the typical porosity model (Wirojangud et al., 1984). A porosity model derived from geophysical logs yields a flushing time of 1.2 million years.

<u>SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM</u>:

This report is important to the Waste Management Program because it outlines a new approach toward determining porosity values within the deep basin ground water flow system. Borehole geophysics has not been used to any great extent at any of the sites for any similar purpose. This report constitutes an advancement in this direction. The porosity values derived from interpreting the geophysical logs are used to estimate ground water travel times based on concurrent modeling studies. The porosity values derived from these geophysical logs are not conservative but the porosity values do represent an improvement over past values derived from the literature.

PROBLEMS, DEFICIENCIES, OR LIMITATIONS OF REPORT:

The report under review preceded a similar report by Conti and Senger (1985). The report by Conti and Senger was reviewed by Williams and Associates as Communication No. 32. The Conti and Senger report did not cite the report under review here. The approaches and the purposes of the reports are very similar. It is not clear why this report was not referenced by the earlier report by Conti and Senger (1985). The same problems we noted in our review of Conti and Senger are relevant to this document.

The report should point out the limitations of the uses of the geophysical logs. The limitation of the logs is due to the small volume of material affected by the radiation logs. As a consequence, geophysical logs are not particularly valuable for determining the porosity of a fractured medium. This point is discussed very briefly in the report.

In-situ tests constitute the only valid method for measuring effective porosity. The methodology discussed in the report uses interpretations of indirect measurements of porosity which are correlated with laboratory core analyses. The interpretive nature of the geophysical log analyses of effective porosity and the small scale of laboratory test volumes compromises the validity of the results and their application to large scale problems. The report does not state adequately that laboratory tests of core are subject to stress conditions that differ from in-situ stress conditions.

The report discusses the limitations of the core and geophysical analyses with respect to permeability. The report states briefly that fracture induced permeability may exist and that it probably accounts for the apparent heterogeneity apparent when the core plug test values of permeability are compared with the in-situ calculated permeability values. This problem cannot be addressed or resolved by means of small scale tests and geophysical logs. Again, large scale in situ tests are the state of the art means for determining effective porosity and in situ permeability at our scale of interest.

The report specifically refers to "total effective porosity" on pages 11 and 16. The phrases "effective porosity" and "total effective porosity" are used erroneously in the report. The values of porosity derived from neutron density logs and neutron sonic logs reflect total porosity. Methodologies used to interpret resistivity logs are more apt to yield porosity values that reflect effective porosity. Multiple well tracer tests constitute the only accurate means of determining effective porosities that approach the scale of interest herein. The porosity values derived in this report are not conservative for purposes of calculating groundwater travel times. The report should state more accurately the limitations of the analyses and the test techniques. Interpretations of the data should reflect more accurately the nonconservative nature of the values derived therein.

REFERENCES CITED:

Conti, R.D., and Senger, R.K., 1985, Hydrostratigraphy of the Wolfcamp Aquifer, Palo Duro Basin, Texas Panhandle. Texas Bureau of Economic Geology, Austin, TX, OF-WTWI-1985-38.

Schlumberger, 1979, Log Interpretation Charts. New York, Schlumberger Limited, 97 p.

Wiroganagud, P., Kreitler, C.W., and Smith, D.A., 1984, Numerical Modeling of Regional Ground-Water Flow in the Deep-Brine Aquifers of the Palo Duro Basin, Texas Panhandle. University of Texas, Bureau of Economic Geology, Report of Investigations.

WMGT DOCUMENT REVIEW SHEET

FILE #:

ONWI #: ONWI/SUB/85/E512-05000-T42

DOCUMENT: Bair, E.S., June 1985, Hydrodynamic Investigations in the Texas Panhandle Area. Report prepared by Stone and Webster Engineering Corp. for Battelle Memorial Institute, Topical Report, 68 p.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: August 28, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E Williams

The purpose of the report under review is to describe the hydrodynamic relationships between major aquifers and the evaporite and shale aquitard that have been described in other reports. A primary interest is determining the direction of flow as indicated by hydraulic gradients in the host rock and in the shale and evaporite aquitard.

Water level, shut-in pressure, specific gravity data from inventoried wells, drill-stem tests and long-term pumping tests were used to construct various potentiometric surfaces and pressure depth diagrams. The water level and pressure data were evaluated for hydrostratigraphic units (HSU) A, B, and C. HSU A consists of the Ogallala Formation and the Dockum Group. HSU B consists of the shale and evaporite aquitard that extends from the Dewey Lake Formation through the San Andres/Blaine Formations and includes the Clearfork and Wichita Groups. HSU C is the deep basin flow system; HSU C consists of Pennsylvanian, Mississippian, Ordovician, and Cambrian rocks.

Equipotential patterns indicate that some groundwater may be moving downward across the shale and evaporite aquitard and into the deep basin aquifer system. Equipotential patterns indicate that the salt evaporite strata and the upper part of the Clearfork Group constitute a major confining zone. The equipotential patterns indicate that some groundwater may be moving upward across the host rock in a shallow localized flow system in the vicinity of and parallel to the eastern caprock escarpment. The report also concludes that the equipotential pattern in the deep basin aquifer system is influenced by permeability variations. The permeability variations are related to facies changes. Hydraulic gradients are flatter in the more permeable shelf, shelf-margin, and fan-delta facies. Hydraulic gradients are steeper in the less permeable deep basin facies.

The report identifies at least two permeable zones within the Dockum Group. Therefore, HSU A consists of the permeable Ogallala Formation and the two permeable zones within the Dockum Group. The existence of two permeable zones in the Dockum Group was noted in an earlier report. The report under review acknowledges that HSU C probably consists of more than one aquifer. This report continues to refer to HSU C as a single aquifer system but it does couch the discussion in terms of the probability that it is more than one aquifer. Williams and Associates, Inc. has focused attention previously on the probability that HSU C consists of more than one aquifer.

A major problem occurs in the report based on a statement (p. 45) that pressure data can be used to eliminate problems associated with the evaluation of fluids of variable density in flow systems. This statement is incorrect. Problems associated with evaluating variable density fluids in flow systems still exist regardless of whether pressure data or head data are used for the evaluation.

BRIEF SUMMARY OF DOCUMENT:

The purpose of the report under review is to describe the hydrodynamic relationships between major aquifers and the aquitard which is proposed as the repository host rock. Primary importance is placed on the determination of the direction of flow in the host rock (shale and evaporite aquitard) and in the immediately surrounding hydrogeologic units.

Hydrostratigraphic unit (HSU) A consists of alluvial, pluvial, and lacustrine deposits of the Neogene Ogallala Formation and the Triassic Dockum Group. The Ogallala Formation consists of highly permeable sand and gravel; the water has a low total dissolved solids content that is generally less than 500 mg/L. Two permeable zones commonly exist within the Dockum Group in the area of the candidate sites. The report states that the lower permeable zone generally contains water with 500 to 1,500 mg/L TDS content. Water in the Dockum Group dramatically increases in TDS content (greater than 50,000 mg/L) south of the candidate sites.

HSU B consists of the upper Permian Dewey Lake, Alibates, Salado, Yates, Seven Rivers, Queen/Grayburg, and San Andres Formations, and the Clearfork and Wichita Groups. These strata consist of shales, siltstones, evaporites, along with some carbonates and sandstones. Brines in HSU B commonly contain over 200,000 mg/L TDS.

HSU C consists predominantly of the Wolfcamp Series and the Pennsylvanian system and locally can include Mississippian, Devonian, Silurian, Ordovician, and Cambrian strata. The Wolfcamp Series can consist of three units. These units are the upper dolomitic unit, middle carbonate unit, and shale unit, and a lower arkosic sandstone unit that may be present near the uplifts. The report describes HSU C as a deep, confined brine aquifer system. The report notes that the term aquifer is used in this report in a manner which is not coincident with the traditional definition in hydrogeologic nomenclature. The report states that "Herein, aquifer is used to define one or more geologic units capable of laterally transmitting fluids, regardless of the geochemical composition of the fluid or the relative permeability of the geologic units" (p. 10).

Data used in the report consist of water level measurements made in inventoried wells in HSU A and records of drill stem tests (DSTs) and long-term pumping tests performed in HSUs B and C. The potentiometric data base for HSU A consists of over 3,000 wells completed solely in the Ogallala Formation and over 120 wells completed solely in the Dockum Group. The potentiometric data base in HSUs B and C contains over 600 hydraulic head values calculated from pressure measurements recorded during DSTs. The initial DST data base consisted of over 5,500 sets of incomplete pressure records which had been purchased from Petroleum Information Corporation. These pressure records represent DSTs performed in over 2,000 wildcat wells and 11 sets of complete pressure records that were obtained from DSTs performed in 4 DOE wells. These data were classified and screened according to a screening criteria described by Bair et al. (1985a and 1985b).

The report states that water level data from the Ogallala Formation and the Dockum Group accurately represent hydraulic heads in these aquifers. Equivalent freshwater heads and equivalent brine heads do not accurately represent hydraulic heads in HSU B and C. The inaccuracy in the heads in HSU B and C occurs because the pressure data from the DSTs performed in these units is an inexact representation because of the variable density of the fluids in HSU B and C. In addition, formation pressure data from DSTs do not necessarily represent true formation pressures. The report uses ISIP (initial shut in pressures) values to approximate true formation pressures. This procedure is used because less than 0.5% of the total number of DSTs could be used to construct Horner plots. The report considers this procedure to be consistent and to yield approximate formation pressures.

The report cites Lusczynski (1961) as showing that equivalent freshwater heads properly define horizontal hydraulic head relationships. Lusczynski also showed that environmental heads must be determined to evaluate vertical hydraulic gradients more precisely. The report states that although Lusczynski's method has been accepted for application to variable density fluid environments, questions have been raised regarding its applicability for hydrodynamic head losses across confining beds (Bond, 1972). The report under review does use equivalent freshwater heads to determine regional flow directions in the Wolfcamp, Pennsylvanian, and lower San Andres rocks. Equivalent freshwater heads from HSU B and C were combined with water level data from HSU A to construct potentiometric profiles of the regional groundwater flow system. The hydrodynamic relationships between major aquifers and aquitard are evaluated based on these potentiometric profiles in conjunction with potentiometric surfaces based on equivalent freshwater heads and equivalent brine heads, head difference maps, and pressure depth data. The vertical direction of flow is based on a method that uses formation pressure data and which incorporates the effects of variable fluid density (p. 14). Potentiometric surface maps and head difference maps were contoured using a computer program.

Potentiometric surface maps are included in the report for the Ogallala aquifer, the Dockum aquifer, the lower San Andres Formation, the Wolfcamp Series, and the Pennsylvanian system. The potentiometric map for the lower San Andres and Pennsylvanian system are dependent upon poor data distributions.

The potentiometric surface map of the Ogallala Formation indicates that regionally groundwater flows toward the southeast. Regional flow is directed to natural discharge areas along the Canadian River Valley, Palo Duro Canyon, and the eastern caprock escarpment. The Dockum Group has a regional direction of groundwater flow from west to east in the northern part of the potentiometric surface map. Groundwater flows from the northwest to the southeast in the southeastern part of the potentiometric surface map. Groundwater flows toward discharge areas along outcrops in the Canadian River Valley, Palo Duro Canyon, and the eastern caprock escarpment. The Ogallala Formation and the Dockum Group constitute HSU A.

HSU B has a regional flow direction that is vertically downward from the Dockum across HSU B and into the Wolfcamp Series. The report states that the difference between the equivalent freshwater heads in the Wolfcamp Series and the heads in the Dockum Group is approximately 1,100 to 1,400 feet at the Deaf Smith County site. The report states that the use of equivalent freshwater heads for the Wolfcamp Series is a conservative approach because environmental heads would increase the head difference between the Dockum Group and the Wolfcamp Series by lowering the elevation of the Wolfcamp potentiometric surface. The report states further that the interpretation of downward flow is consistent with the plot of pressure depth data from HSU B. A pressure depth data plot results in a slope, as determined by linear regression, that is less than the slopes of both the freshwater hydrostatic pressure gradient (0.433 psi/ft) and a brine hydrostatic pressure gradient (0.484 psi/ft). The pressure depth data plot resulted in a correlation coefficient of 0.977; a linear regression technique was used to assess the pressure depth relationship. The specific gravity of the brines in HSU B is based on 368 formation fluid samples which correspond to an average specific gravity of 1.12 and an average TDS content of 170,000 mg/L (p. 38).

The report states that two figures (figs. 2-9 and 2-12) indicate a shallow localized flow system in the vicinity of and parallel to the eastern caprock escarpment within the upper part of HSU B. The upward flow component in this localized flow system is stated to be a result of the overly conservative representation of the flow system because of the use equivalent freshwater head values. The report states that the magnitude and direction of this "seemingly upward flow component" cannot be evaluated properly by using equivalent freshwater heads.

The report states that the dolomitic limestone units in the lower San Andres Formation yielded small quantities of brine (92 to 520 gal/day) during drill stem testing and long term pumping in the four DOE wells. The 80 ft thick dolomitic limestone unit directly underlies the repository host rock. The report notes that there is insufficient well control in some areas for the lower San Andres Formation. However, the report states that the four data points near the candidate sites used in conjunction with available data indicate a regional flow direction, in the lower San Andres Formation, toward the southeast. The report states that the equivalent freshwater heads in the lower San Andres Formation are greater than the heads in the Dockum Group at the candidate sites (p. 43). The report states that the use of equivalent freshwater heads for the determination of the vertical direction of flow across the host rock is misleading and overly conservative. The TDS content of the water in the lower San Andres Formation is approximately 300,000 mg/L based on formation fluid samples obtained from the DOE wells. The head difference at the candidate sites is 150 to 400 ft at the Deaf Smith site and 0 to 300 ft at the Swisher site based on equivalent brine heads with a specific gravity of 1.20. The difference between equivalent freshwater heads and equivalent brine heads in the lower San Andres Formation ranges from 350 to 400 ft at the Deaf Smith site. The report states that "Sole use of pressure data to determine vertical hydraulic gradients eliminates the problems associated with calculating heads in variable density flow systems, as variations in fluid density can be incorporated into the analysis" (p. 45). The direction and magnitude of the vertical hydraulic gradient across the host rock was determined by using a derivation of an equation presented by Lusczynski (1961) and as modified by Wilton and Picking (1985). The equation states:

$$i = \frac{1}{\delta_f}\left[\frac{P_2 P_1}{\Delta_z} - \delta_a\right]$$

where:

- i = vertical hydraulic gradient (positive equals upward flow),
- δ_f = unit weight of freshwater,
- P_2 = formation pressure of deeper test zone,
- P_1 = formation pressure of shallower test zone,
- Δ_z = vertical distance between tested zones, and
- δ_a = average unit weight of formation water between freshwater zone and deeper tested zone (p. 49).

The potentiometric surface map for the Wolfcamp rock indicates a regional direction of groundwater flow that is from the southwest to the northeast across the central and northern parts of the study area. The regional direction of flow is from the west to east across the southern part of the study area.

The potentiometric surface map for the Pennsylvanian system indicates a regional direction of groundwater flow from the north-northeast in the central part of the study area. The regional direction of flow is more easterly in the eastern part of the study area; the flow in the north central part of the study area is northerly toward the Dalhart Basin (p. 52).

The report states that regional flow in HSU C is predominantly horizontal; local upward or downward flow may occur within HSU C. The pressure depth data indicate that regional horizontal flow occurs within HSU C. A comparison of regional Wolfcamp Series and Pennsylvania system equipotential patterns indicates that the regional flow pattern may be significantly modified on a local scale by facies changes. The hydraulic gradient in HSU C is flatter in the shelf and shelf margin facies; the hydraulic gradient is steeper in the deep basin facies.

The report makes a significant recommendation. The report recommends that several sets of formation pressure and fluid density data should be obtained in the same well from one or more units in the shale and evaporite aquitard, both overlying and underlying the host rock. This procedure will facilitate a more accurate determination of the pressure versus depth diagrams and to assess more accurately the vertical hydraulic gradients.

SIGNIFICANCE TO NRC WASTE MANAGEMENT PROGRAM:

This report is significant to the Waste Management Program because it continues the series of reports that discuss the potentiometric surfaces within HSU A, HSU B, and HSU C. The potentiometric surfaces are important because they are used to determine the direction of groundwater flow in a lateral and vertical sense. Also, these data are used to calculate hydraulic gradients and to predict groundwater travel times.

PROBLEMS, DEFICIENCIES, OR LIMITATIONS OF REPORT:

It is significant that this report states that the term aquifer is used in a different context than is used normally in hydrogeologic nomenclature. As noted in the summary of this document, the author has noted that a non traditional definition of aquifer is used in the report. It can be concluded, although it is not stated, that the definition of aquifer used in this report is applicable to other reports that have been prepared on the Palo Duro Basin for the Department of Energy. This report defines aquifer as consisting of one or more geologic units capable of transmitting fluids laterally regardless of the chemical composition of the fluid or the relative permeability of the geologic units. The report also indicates that more than one aquifer exists in the deep basin strata. Distinctions that indicate the number of additional aquifers in the deep basin system are not stated.

The report has used environmental heads, equivalent freshwater heads, and equivalent brine heads in various contexts. The report has used equivalent freshwater heads to determine the characteristics of vertical flow between units. Such usage normally would not be appropriate; the report does couch its assessment of the use of equivalent freshwater heads by indicating that this is a conservative approach to indicate whether there a potential for upward flow. We consider the approach used in the report to be conservative for assessing upward flow. We acknowledge also that the author is aware that this use of equivalent freshwater heads is inappropriate for assessing vertical flow.

The report states that the potentiometric surface map for the Dockum aquifer does not represent the potentiometric surface at a specific time. This limitation occurs because the water level data were collected over a period of time within the Dockum Group. This clarification is not applied to the deeper "aquifers" discussed in the report. The report should point out that all of the data used in the report are subject to the same condition. We acknowledge that potentiometric conditions within the deeper aquifers should be relatively constant (steady state flow conditions).

One major problem occurs in the report. The report states that "Sole use of pressure data to determine vertical hydraulic gradients eliminates the problems associated with calculating heads and variable density flow systems, as variations in fluid density can be incorporated into the analysis" (p. 45). This statement is incorrect. The problems associated with variable density flow systems still exist whether pressure data or hydraulic head data are used for the analyses. The equation used (p. 49) to determine the direction and magnitude of the vertical hydraulic gradient across the host rock is derived from Lusczynski's paper. The derivation of the equation on page 49 was presented in Wilton and Picking (1985). The initial equation used by Wilton and Picking is couched in terms of hydraulic head. The subsequent derivation of the equations for determining vertical hydraulic gradient is based on the conversion of these heads to pressures which take into account the fluid densities. The calculation of an average unit weight of formation water between the two zones of interest does not eliminate the problems associated with calculating vertical head. In fact, the same averaging procedure could be used to calculate heads along a vertical as opposed to the approach used in the report. The statement in the report in inaccurate and misleading.

REFERENCES CITED:

Bair, E.S., O'Donnell, T.P., and Picking, L.W., 1985a, Hydrogeologic Investigations Based on Drill-Stem Test Data, Palo Duro Basin Area, Texas and New Mexico. Office of Nuclear Waste Isolation, BMI/ONWI-566.

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WMGT DOCUMENT REVIEW SHEET

FILE #:

TEXAS BUREAU OF ECONOMIC GEOLOGY #: OF-WTWI-1985-37

DOCUMENT: Senger, R.K., Fogg, G.E., and Kreitler, C.W., 1985, Effects of Hydrostratigraphy and Basin Development on Hydrodynamics of the Palo Duro Basin, Texas. Texas Bureau of Economic Geology, Austin, TX.

REVIEWER: Williams & Associates, Inc.

DATE REVIEW COMPLETED: August 28, 1986

ABSTRACT OF REVIEW: APPROVED BY: Roy E. Williams

The report describes the results of a two-dimensional groundwater flow model study of the Palo Duro Basin. The two-dimensional cross-sectional model was constructed to characterize regional groundwater flow paths and to investigate the causes of underpressuring and flow through the evaporite aquitard. The model also was used to study the mechanisms of recharge and discharge to and from the deep basin brine aquifer. Steady state flow simulations were used to study the effects of lithostratigraphy and topography on groundwater flow. Tectonic and geomorphic processes were investigated using transient flow simulations.

The Palo Duro Basin is characterized as containing a shallow groundwater flow system that is governed primarily by topography. The basin is characterized as having a deeper flow system that is recharged in New Mexico; the deep groundwater passes beneath the Pecos River into the deep section of the Palo Duro Basin. These two flow systems are hypothesized as being separated by the evaporite aquitard. The evaporite aquitard permits leakage to the deep basin aquifer system and could contribute up to 27% of the water passing through the deep basin aquifer system.

The permeable Granite Wash strata and the low recharge rates to the deep basin brine aquifer system cause the potentiometric surface of the deep basin brine aquifer to be subhydrostatic. The low permeability evaporite aquitard effectively segregates the deep aquifer system from the shallow aquifer system. The

aquitard maintains the large head differential across the aquitard. Some of the groundwater from the west that otherwise would have moved downdip into the deep aquifers discharges into the Pecos River.

Cenozoic uplift and tilting of the basin caused a significant increase in the magnitude of the groundwater velocities. The modeling effort also indicates that erosional unloading in connection with the retreat of the caprock escarpment is ineffective in creating large scale underpressuring. Significant subhydrostatic conditions within the shallow aquitard section could occur but only in the vicinity of the escarpment. The modeling study indicates that hydrocarbon production and the consequent reduction in reservoir pressure affects hydraulic heads locally but does not influence the regional groundwater flow system.

Williams and Associates do not have any major concerns regarding the report under review. The concern that has been expressed in our previous reviews of similar documents is that these modeling studies must incorporate data which were obtained from textbooks as opposed to in-situ testing programs. We recognize that this limitation is imposed because of the lack of quality test data from the basin and surrounding areas. The danger lies in the acceptance of the modeling results without the recognition that these results were obtained by using test data that were not obtained on site.

<u>BRIEF SUMMARY OF DOCUMENT</u>:

The objective of the report is to investigate various factors that affect overall groundwater flow patterns in the Palo Duro Basin. The objective was approached in two phases. The first phase used a model to simulate steady state groundwater flow conditions using data on hydraulic conductivity from various hydrogeologic units in the section and hydraulic head and recharge rates along the boundaries of the model. The second phase involved the simulation of long-term transient flow conditions caused by different tectonic and geomorphic processes. These tectonic and geomorphic processes were investigated by varying the boundary conditions.

The report describes the geology of the Palo Duro Basin. Geologic discussion includes both historical geology and the stratigraphy of the basin. The report describes the basic hydrogeologic framework for the Palo Duro Basin. The data base for the Palo Duro Basin varies in quantity and quality. An extensive water level data base exists for the Ogallala aquifer. These data indicate that groundwater generally moves toward the east and southeast. Hydraulic head data for the deep basin brine aquifer are generally the result of drill stem tests and a limited number of pumping tests. Pressure and hydraulic head data have been evaluated by other investigators. The head difference between the Ogallala aquifer and the deep basin brine aquifer can reach 1,805 feet. The hydraulic head difference between the shallow and the deep groundwater flow systems is about 1,150 feet along the cross-sectional traverse used for the two-dimensional simulation in this report.

The average permeability (arithmetic mean) of the Ogallala Formation is 8.0 m/day (26.3 feet/day). Vertical permeability is assumed to be one order of magnitude less than the horizontal permeability. The average permeability (arithmetic mean) for the Dockum Group is about 0.8 m/day (2.6 feet/day). The report states that vertical permeability of the Dockum Group must be at least four orders of magnitude lower than horizontal permeability based on Simulation D of this study (p. 13). The vertical permeability of the evaporite aquitard was estimated by taking the harmonic mean of permeabilities representing each substrata; the resultant permeability is 0.00028 md (p. 14). The San Andres Unit 4 carbonate thickness ranges from 15 to 25 m (50 to 80 feet). Unit 4 carbonate has permeabilities ranging from 0.1 md to 0.5 md based on data from tests in six DOE test wells. The geometric mean of the permeability for Wolfcampian and Pennsylvanian carbonates is 8.9 and 17.9 md, respectively. Granite Wash and Pre-Pennsylvanian strata have permeabilities of 8.6 md and 4.76 md, respectively (p. 15). The report states that the geometric mean was used rather than the arithmetic mean to account for the fact that the substrata tend to be discontinuous. The vertical permeability of the lower Permian and Pennsylvanian strata was assumed to be two orders of magnitude lower than the horizontal permeability. The values of permeability noted were converted to hydraulic conductivities by assuming an average fluid salinity and temperature of 127,000 mg/L and 46°C (115°F) respectively.

Data do not exist on the permeability of the mud flat and alluvial fan delta systems of Permian to Pennsylvania age. A generic value of about 70 md was assigned to the westernmost hydrogeologic unit based on typical values of comparable geologic materials (p. 16). The permeability of the salt dissolution zones located east and west of the High Plains was estimated conservatively to be 70 md. The report states that recent testing in the DOE salt dissolution wells gives a relatively high hydraulic conductivity of about 0.17 m/day. This value compares to a hydraulic conductivity of 0.082 m/day (70 md) as stated for the salt dissolution zone.

The specific storage for all of the hydrogeologic units is assumed to be 0.0001 m^{-1} (p. 17). The value of specific storage was derived from cited references.

The computer programs used in this report are FREESURF and FLUMPS (p. 17). FREESURF is a finite element model that uses a direct solution technique. FLUMPS is a modification of the original program FLUMP; FLUMPS was used to simulate transient groundwater flow conditions. FLUMPS is a finite element model that solves linear and non-linear groundwater flow problems in two-dimensional and quasi three-dimensional configurations. FLUMPS uses either a direct solution technique or an iterative solution technique (p. 18).

The groundwater flow model was constructed along a west to east cross section extending from New Mexico into Oklahoma across the Palo Duro Basin. An appendix is attached to the report indicating a large node spacing, relative to the horizontal and vertical directions, does not cause significant errors in the model results. The model incorporates three hydrogeologic units within the deep basin brine aquifer. These units are the carbonate shelf and shelf margin systems, mud filled basin and slope system, and the fan delta system (Granite Wash). The Permian evaporite sequence separates the deep basin brine aquifer from the overlying Ogallala and Dockum freshwater aquifer. The San Andres Unit 4 carbonate is located within the evaporite aquitard. The Unit 4 carbonate is considered as an individual hydrogeologic unit. The salt dissolution zones to the east and to the west of the High Plains are distinguished in the model as separate hydrogeologic units. The Permian mud flat system and Permian Pennsylvanian mud flat and alluvial fan delta systems are represented as additional hydrogeologic units.

Two types of boundary conditions are applied in this steady state groundwater flow model; both prescribed heads and prescribed flux are used in the model. The water table is simulated with prescribed head boundary conditions to the east and west of the High Plains. A recharge value of 0.145 cm/yr (0.058 inches/yr) was assigned over the High Plains in the Texas Panhandle. The recharge value was increased to 0.625 cm/yr (0.250 inches/yr) to account for the sandier soil type in the New Mexico area of the High Plains (p. 19). The lower boundary of the mesh was assumed to be impervious. Hydraulic head is assumed to be uniform with depth along the eastern boundary. Boundary conditions in the transient model are the same as in the steady state model except that prescribed heads are assigned along the entire upper surface of the mesh. Prescribed heads along the eastern boundary of the mesh are set equal to the water table at the surface node. Hydrocarbon production was simulated by reducing hydraulic heads with time at a particular node location representing a hydrocarbon reservoir (p. 20).

The report lists several limitations of the modeling study. The report states that hydraulic conductivities had to be reduced by an order of magnitude in both the Ogallala and Dockum aquifers in the western High Plains in New Mexico in order to produce the observed water levels in the Ogallala aquifer with reasonable accuracy. The discretization of the cross-sectional model required conceptualization and simplification of the lithostratigraphy of the basin. Major, potential sources of error in the model occur because of the necessity for estimating hydraulic conductivities and assumed anisotropies. Permeability values had to be assumed for some units where permeability data did not exist. The assumption that the fluid is homogeneous imposes another limitation upon the modeling results. Assigned values of specific storage are based on typical and measured values reported in the literature. Specific storage has not been measured in the Palo Duro Basin. The simulation of uplift, deposition, and erosion was performed in a simplistic manner.

The simulation strategy included several model runs in a steady state condition. Simulations A-1 and A-2 tested the spatial permeability variations of the Granite Wash deposits. Simulation A-2 is considered to be the most realistic model; this simulation is supported by permeability data available for the deep basin brine aquifer (p. 23).

Simulations B-1 to B-3 investigate the effect of leakage through the evaporite aquitard. Effective leakage was investigated by varying the vertical permeability of the aquitard. The assumed permeability of the aquitard was increased by one order of magnitude in Simulation B-1. Permeability was decreased by one and two orders of magnitude in Simulations B-2 and B-3.

The hydraulic interconnection of the Ogallala and Dockum aquifers was addressed in Simulation C. Simulation D investigated the effect of the Pecos River on the subhydrostatic conditions in the deep basin brine aquifer.

Simulation A-2 resulted in a specific discharge of 8×10^{-6} to 10^{-4} m/day for the deep basin section (p. 34). This specific discharge equates to a fluid velocity of 1.1×10^{-4} m/day in the shelf carbonates and 4.4×10^{-4} m/day in the proximal Granite Wash. The velocities are based on average porosities of 8% and 23% respectively. The leakage rate through the evaporite section is about 6×10^{-8} m/day (p. 34). The report states that the contribution to the deep basin brine aquifer system through the evaporite aquitard may be 27% of the water passing through the deep basin brine aquifer based on Simulation A-2.

The geometry of the finite element mesh is the same in the transient model as used in the steady state flow model. Only prescribed heads along the surface of the model are varied in order to simulate changes in the water table. Simulation T-1 investigated the pre-uplift conditions. Simulation T-1 computes the hydraulic head distribution of the hypothetical groundwater flow regime prior to uplifting. Simulation T-2 investigates the effect of uplift and tilting of the basin on the hydraulic head distribution. Simulation T-2 uses the computed hydraulic head distribution from Simulation T-1. Simulation T-3 models the deposition of the Ogallala Formation. The report notes that uplift and deposition of the Ogallala probably were overlapping events; the events were modeled separately. Hydraulic heads were increased by 50 m (165 feet) in the east and up to 125 m (430 feet) in the west accounting for a general increase in the thickness of the Ogallala near the sediment source.

Simulation T-4 assigned prescribed heads along the surface nodes representing the Pecos River valley. These prescribed heads are lowered gradually for a time period of four million years. Simulation T-5 modeled the effect of the westward retreat of the caprock escarpment on the hydrogeologic conditions in the Palo Duro Basin. Prescribed hydraulic heads along the surface nodes located at the present day rolling plains surface were reduced to simulate the erosion in the High Plains. The reported maximum rate of caprock retreat of 18 cm/yr (7.1 inches/yr) was used. The report states that both the reduction in hydraulic head along the eastern boundary and the water table decline along the surface are equally important for creating significant underpressuring in the deep basin brine aquifer (p. 43).

Simulation P-1 investigates the possible impact of erosional unloading on hydraulic heads. The program FLUMPS was used to evaluate this possible condition. Simulation P-1 shows that the head distribution in the shallow aquitard section shows local underpressured conditions in the vicinity of the temporary location of the caprock. Hydraulic heads in the aquitard are largely equilibrated to approximate hydrostatic conditions further to the east.

Hydrocarbon production was simulated in Case H-1. Hydraulic heads at two reservoir nodes were gradually decreased from initial head values. The hydraulic heads were reduced by about 200 m which corresponds to a drop in reservoir pressure of about 400 psi. The pressure drop occurred over a 50 year period. Prescribed heads were kept constant for another 50 years before allowing reservoir pressures to recover. The report states that the reservoir pressure drop is restricted to the immediate vicinity of the reservoir. The reservoir simulation indicates that the overall groundwater flow pattern in the deep section is not altered.

SIGNIFICANCE TO THE NRC WASTE MANAGEMENT PROGRAM:

This report is important to the Waste Management Program because it constitutes an investigation into the distribution of hydraulic conductivities and hydraulic heads within the Palo Duro Basin. The report evaluates the hypotheses that variable geologic conditions could continue to create anomalous head (pressure) conditions in the basin. The report illustrates through the use of measured and assumed values for the hydrogeologic parameters that the conditions simulated have minimal impact on the current hydrogeologic conditions. The results of the report are used to predict groundwater flow velocities in the Palo Duro Basin. Flow velocities will be used to predict groundwater travel times to the accessible environment.

PROBLEMS, DEFICIENCIES, OR LIMITATIONS OF REPORT:

The report fails to cite a previous report by Senger and Fogg (1984) that conducted several of the same simulations included in this report. The results of the report are basically the same with the exception that different input values were used in some of the simulations. The current report also includes new simulations. The failure of the report to cite the Senger and Fogg reference should be corrected. Distinctions between the current report under review and the Senger and Fogg report should be stated and explained. Williams and Associates, Inc. reviewed the Senger and Fogg report as Communication No. 34.

Williams and Associates have commented on the use of the phrase "deep basin brine aquifer". We commented extensively on the use of this phrase in our Communication No. 33.

The hydraulic head data for the deep basin brine aquifer are based on the conversion of drill stem test data to equivalent freshwater heads. The use of equivalent freshwater heads must be used with caution. The use of freshwater heads supposedly is restricted to consideration of lateral flow within a hydrostratigraphic unit (Lusczynski, 1961). These data are used to compare vertical gradients in the report under review.

The report uses assumed values for permeability or hydraulic conductivity where test values are missing. Ratios of anisotropy are assumed in the report. In addition, this report assumes that the fluid is homogeneous with respect to salinity and temperature. Variable water quality affects the conversion of permeability to hydraulic conductivity. The effects of the variable water quality on the output of the model simulations is not known.

The report compares simulated hydraulic head values to those derived from a kriged hydraulic head map. Williams and Associates, Inc. commented on the kriged head maps produced by the Texas Bureau of Economic Geology and the Office of Nuclear Waste Isolation in Communication No. 56.

The report states that the computed heads become unrealistically high when using a value of vertical permeability for the evaporite aquitard that is greater than 2.8×10^{-4} md. The report fails to explain that increasing the horizontal permeability of the deep basin aquifer system would decrease the head build-up noted in this section of the report (p. 29). Sustaining the high head buildups in the deep basin brine aquifer system occurs because of the low horizontal permeabilities that are assumed to exist in the system. The approach used to simulate the required heads in the deep basin brine aquifer appears to be limited by an apparently preconceived notion that the horizontal permeability of the deep aquifer is represented accurately by the values used as input to the model.

Groundwater velocities calculated for the hydrogeologic units are based on assumed average porosities. These porosities are not based on in-situ testing. Lower values of effective porosity would increase the groundwater velocity and hence decrease the groundwater travel time. Obviously, in-situ tests must be conducted to obtain valid values of effective porosity.

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