GW - 6

GENERAL CORRESPONDENCE

YEAR(S):

1979 - 1955

STATE OF NEW MEXICO
ENERGY AND MINERALS DEPARTMENT
OIL CONSERVATION DIVISION
State Land Office Building
Santa Fe, New Mexico
17 October, 1979

EXAMINER HEARING

IN THE MATTER OF:

Application of El Paso Natural Gas Company for underground gas storage, Eddy County, New Mexico.

CASE 6703

BEFORE: Daniel S. Nutter

TRANSCRIPT OF HEARING

A P P E A R A N C E S

For El Paso Natural Gas Company:

David Burleson, Esq.
EL PASO NATURAL GAS COMPANY
El Paso, Texas 79978

For the Oil Conservation Division:

Ernest L. Padilla, Esq.
Legal Counsel for the Division
State Land Office Building
Santa Fe, New Mexico 87503

For El Paso Natural Gas Company:

Owen Lopez, Esq.
MONTGOMERY LAW FIRM
Paseo de Peralta
Santa Fe, New Mexico 87501

within the Morrow producing interval as illustrated by this borehole compensated sonic gamma ray caliper log.

The top of the Morrow Clastics interval is indicated to be at 6628, 2887 feet subsea, and it extends downward to 6864 feet, 3123 feet subsea, to the base of the Morrow Clastics interval.

MR. NUTTER: What were those intervals again?

A The top, Mr. Nutter, was --

MR. NUTTER: No, I got the top but those two figures for the bottom.

A The bottom was 6864, which is a -3123.

MR. NUTTER: Thank you.

A Yes, sir.

And El Paso requests that this vertical interval be expanded to include 100 feet of section above and 100 feet of section below the Morrow Clastics interval, as described by this log.

Q For what reason to you propose to include this 100 foot interval above and below the Morrow Clastics interval?

A We would like to include this 100 feet above and below to protect the gas within the unit area in the case the interval is not as well defined in other wells as it is in this base type well.

Q Would you expect that the top and the bottom of this zone would be such as to prevent the loss of gas which may be injected into the storage area?

A Yes, I would.

Q Please, would you explain what you mean by that?

A Well, the Morrow Clastics zone consists of a series of sand benches that are separated by shale lenses, or beds.

The top of the Morrow Clastics zone is a shale bed which seals off the top of this first Morrow Sand bench from an overlying dense limestone formation.

The bottom of the Morrow Clastic zone is delineated by the underlying shale zone, which is dense and impervious.

The shale zones above and below the Morrow Sand benches prevent any vertical migration of gas, and our requesting an additional 100 feet of section above the top and the bottom of this Morrow Clastics interval, as described in the discovery well, is simply a precautionary measure in the unlikely event that the overlying or underlying shale beds thin within the unit area outline.

Q Do you have an exhibit which indicates the horizontal limits of the pool as you have mapped it?

A Yes, I do. If you would refer to Exhibit is the main gas producing benches, or bench, on this field.

Q But we propose that 100 feet below the top of the Morrow and 100 feet below the bottom of the Morrow, all that interval intervening would be the storage area.

A That's right, we would request that the entire top and -- the entire Morrow interval be included in our storage project, and that would include, Mr. Examiner, 100 feet above the top, as we show it there on this cross section, and 100 feet below, or downward, from the base of this thing.

Q With respect to the operation of the storage project, what's the proposed maximum storage capacity of the project?

A Well, the maximum capacity, like when we fill it back up, would be 68.6 billion and 47.6 billion cubic feet of this would be working gas, and 21 billion cubic feet would be cushion gas.

Q Based on proposed injection-withdrawal wells and taking into account the facilities which we propose to install, what would be the maximum capacity injection and maximum capacity withdrawal rate?

A Initially a maximum injection capacity will be approximately 505 million cubic feet per day into these 23 injection wells, injection-withdrawal wells. And the maximum withdrawal rate at initial conditions there, would be approximately 400 million cubic feet per day; however, dehydration and facilities would limit this withdrawal rate to about 400 MMCF per day.

Q Let's see, you said the maximum withdrawal rate, did you mean to say that it would be 491 million cubic feet per day?

A Yes, sir, I thought that's what I said.

MR. NUTTER: No, you said 400 million withdrawal.

A Well, it's 491, I beg your pardon.

MR. NUTTER: 491 withdrawal --

A Yes, sir.

MR. NUTTER: And after dehydration and shrinkage, it would be down to 400 million.

A 400, yes, sir, I'm sorry I made that --

Q What is the date by which El Paso hopes to have the project in service?

A Well, given timely regulatory approvals, it is planned that the field will be available for withdrawals during the '81-'82 winter heating season, 1981-1982.

Q Does El Paso propose to meter gas injected and withdrawn?

A Yes. We would meter this gas, and this is done on an individual well -- by an individual well injection wells. In addition, we propose using 6 of the existing 10 wells as withdrawal-injection wells, and the other 4 as observation wells.

Q Have you prepared, or caused to be prepared, a diagram depicting the proposed casing and drilling plan for the proposed withdrawal-injection wells?

A Yes, I have.

Q What have you used in the preparation of this exhibit?

A This is my own well design based on the geology of the area and applicable rules and regulations of the New Mexico Oil Conservation Division.

Q Now this exhibit is labeled Exhibit Number Eight, is that correct?

A Yes.

Q Would you please explain this exhibit for the Examiner?

A As the exhibit shows, the withdrawal-injection wells will be fluid drilled to the surface shoe depth; 9-5/8ths surface pipe would be set at approximately 800 feet through all fresh water bearing formations, and 300 feet into the Upper Delaware Mountain Group and cemented to surface.

This surface casing shoe is approximately 300 feet below the lowest fresh water sand.

The production casing hole will be fluid drilled to total depth and 7-inch casing will be run and set at total depth of approximately 7050 feet, and cemented with a cement top approximately 1500 feet above the shoe.

The Morrow zone will then be jet perforated and tubing landed in mid-perforations.

Q Now, Exhibit Number Eight shows the average withdrawal-injection well, that's correct, is it not?

A Yes, sir.

Q I notice that it's labeled proposed new 1-W Well, which I assume means 1 withdrawal well, but you're saying it also represents an injection well that would be used for both purposes?

A Withdrawal-injection or injection-withdrawal.

Q I notice that your proposed well does not include a packer, is this correct?

A In my opinion, a packer can serve no useful purpose. We do not expect any corrosion. The gas is pipeline quality gas. All fresh water zones are well protected by casing and cement. Using annular flow along with tubing flow, we can operate the well more efficiently. Also there is cost to consider. Larger tubing and a packer to handle our gas volumes would increase the cost per well as much as $18,000.

Q Mr. Disch, you indicated that you plan to the annular withdrawal-injection operation. Would you please explain that?

A The annular withdrawal and injection will utilize the annulus between the 7-inch casing and the tubing. Flow through the tubing will also be used at the same time.

Q Will you have an annulus between the production casing and the surface casing, which can be used to monitor for leaks?

A Yes, this annulus would be an excellent way to monitor for leaks.

Q In your opinion would annular injection-withdrawal endanger fresh water sources?

A No, sir. Because of the casing designs and cementing program, the ground waters are more than adequately protected.

Q Is the production casing you propose sufficient to withstand any pressures which you would expect to encounter?

A Yes. The production casing is 7-inch K-55 23 pound, with a burst pressure of 4360 pounds per square inch. With a maximum injection pressure of approximately 3000 pounds per square inch, this gives us a safety factor of 1.45.

Q In your opinion would operations in this pressure range preclude the possibility of fracturing the any or all of your withdrawal-injection wells which will be drilled?

A We will run a cement bond log on all the new wells and on any well that will be reworked.

Q Has your casing program been designed to comply with the proposed EPA rules that were published in the Federal Register on -- in March of 1979?

A Yes.

Q In your opinion do your proposed casing designs fully protect any ground water which may exist in the Washington Ranch area?

A Yes. As I previously testified, the surface casing will be set well below any fresh water bearing formation and cemented to surface.

In my opinion, this will adequately protect any fresh water formations.

Q As to any observation wells that may be drilled, would they have the same program as that indicated in your Exhibit Eight?

A Any new observation wells to be drilled, -- would be the same as in this Exhibit Eight.

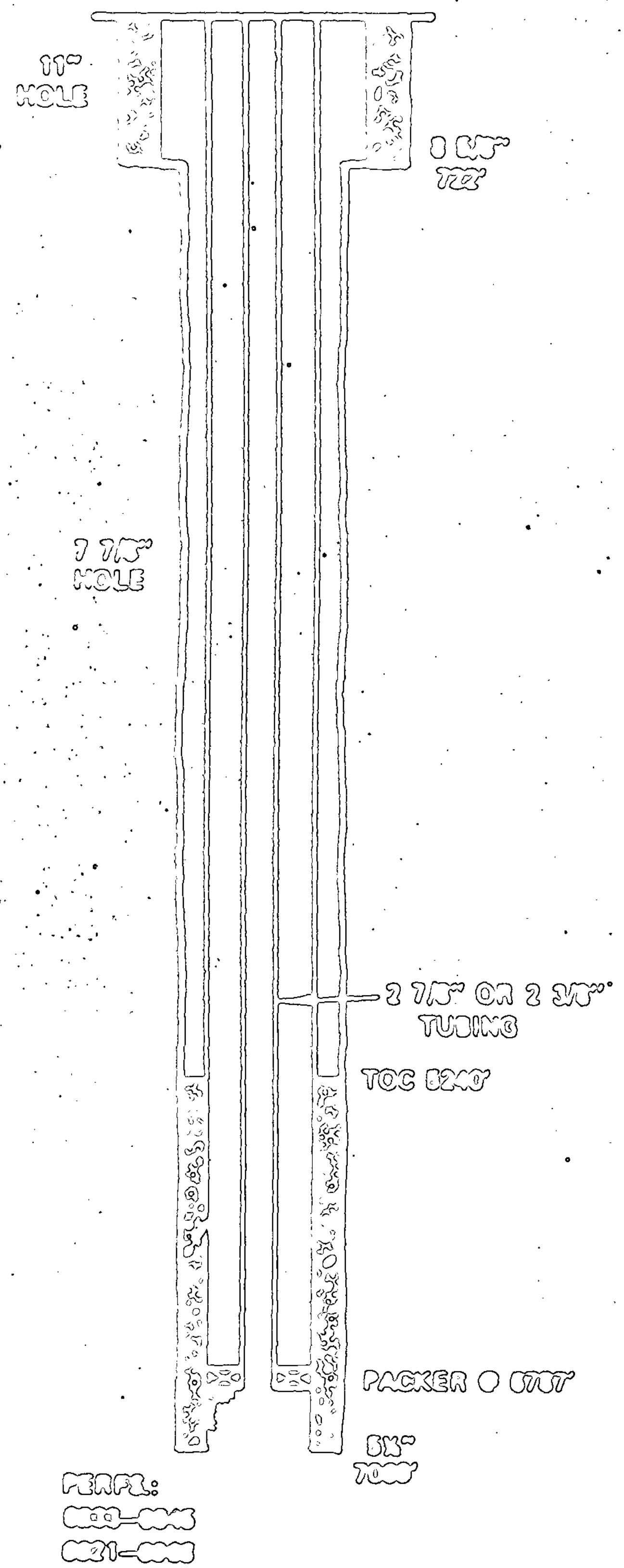
Q But you don't currently propose to drill any observation wells?

A Not at this time.

Q You have prepared another exhibit, have

WASHINGTON RANCH
TYPICAL EXISTING
PRODUCING WELL

BEFORE EXAMINER NUTTER
OIL CONSERVATION DIVISION
El Paso EXHIBIT NO. 9
CASE NO. 6703



SIZE	GRADE	WT	BURST	COLLAPSE	DRIFT ID
8 5/8"	—	24	—	—	—
5 1/2"	—	14	—	—	—
5 1/2"	—	15.5	—	—	—
2 3/8"	J-55	—	—	—	—
or	or				
2 7/8"	N-80	—	—	—	—

Introduction:

On March 19, 1979, an application was made to the Federal Energy Regulatory Commission (FERC) for authority to construct and operate the Washington Ranch Gas Storage field. In the application, El Paso proposed to covert 6 of the 10 existing producible wells and drill and complete 17 additional wells in the field for injection and withdrawal purposes. The 4 remaining producible wells were to be utilized for observation purposes. The project was approved by FERC on March 26, 1981 which resulted in the drilling of the 17 new injection/withdrawal wells, in converting 6 producing wells to injection/withdrawal operations, in converting 4 producing wells to observation wells, and the drilling of an additional observation well. The location of the injection/withdrawal and observation wells are delineated on the map behind Tab B.

The Washington Ranch field was discovered in June, 1971 by the completion of the Black River Corporation - Cities Federal #1 well which had an open flow potential of 42,596 Mcf/D through perforation in the Morrow Formation from 6,795 to 6,844 feet. Cumulative production from the field as of May 1, 1981 was 58.0 Bcf. This production was obtained from 13 wells that were completed and produced in the field. During the production phase, the field exhibited a depletion drive mechanism with the original gas-in-place estimated at 68.6 Bcf. Gas storage rights were obtained from the various land owners in the area and the aerial extent, together with the depths of rights are also shown on the map behind Tab B.

Geology:

The structure on which the Washington Ranch field is located is a north-south trending anticline nosing somewhat to the west and south. The subsurface closure is approximately 300 feet with the feature abutting on the north into the high angle Huapache fault. This fault is a regional tectonic feature and in the subsurface, exhibits up to 4,000 feet of displacement. A structure map - Top of Lower Morrow Sand is located behind Tab C, Isopachous Maps are behind Tab D and Morrow Reservoir cross-sections are behind Tab E.

The storage portion of the Morrow Formation in the Washington Ranch field is composed of 3 sands separated by shales and silts in the lower clastic zone of the formation. The thickness of this clastic portion ranges from 200 to 250 feet. The lower sand is much better developed and exhibits superior porosity and permeability characteristics. During the depletion phase of the field, production was obtained from all 3 sand members; however, the upper 2 sands are not as consistent in aerial extent as the lower sand and the productive characterstics are of a lesser magnitude. Due to the type of deposition, either in fluvial channels or at the marine - non-marine interface as a series of deltaic lobes, the upper sand bodies capable of gas production are of limited areal extent and have widely varying porosities and permeabilities. This is borne out by comparing the porosities and permeabilities of the sands determined from core analyses.

Development:

After receiving approval to develop the Washington Ranch Gas Storage field, a 17 well development program commenced on September 5, 1981 with the last well being drilled and completed on May 1, 1982. A schematic diagram of a typical new injection/withdrawal well is behind Tab F. Upon completion of each individual well, a 4 point back pressure test was conducted to determine that well's production capabilities. During the development phase, five of the new wells were cored and the reservoir rock was analyzed. From this information, various well locations were redetermined in order to maximize the completion of wells in the most permeable and productive section of the Morrow storage zone. After all of the new injection/withdrawal wells were drilled and completed, production tests were run and productivity estimates were made.

Testing:

Upon completion of the wells, 17.4 Bcf of gas that was then stored in the Clay Basin area was transferred to Washington Ranch. Injection commenced in Washington Ranch on March 6, 1982 and completed on February 28, 1983. After transfer of the gas from Clay Basin, a productivity test was conducted on the reservoir on January 13-15, 1983, at which time all wells were opened up into a gathering system of approximating 850 pounds. The combined deliverability from the Washington

Ranch Gas Storage Project was 290 MMcf/D; the gas-in-place at this time was 27.9 Bcf. This was a 24 hour productivity test of all the wells conducted in two stages over a 3 day period. The withdrawal volume during this test was approximately 0.4 Bcf and was reinjected into the reservoir after completion of the test.

As further confirmation of the production characteristics of the Washington Ranch Storage Project, an extended flow test was conducted during the period August 10-17, 1985. The initial rate of 235 MMcf/D from 23 withdrawal wells was limited by the dehydration capacity in the field. Final deliverability out of the field amounted to 160 MMcf/D with all the wells producing at maximum capability against a gathering system of approximately 862 psia. The results of the test information available to date are shown behind Tab 6 which is a composite back pressure curve test for the Washington Ranch Gas field as presently considered. It can be noted from this curve that when the original wellhead pressure of 2,593 psia is reached, the productivity of the wells would be 720 MMcf/D against zero back pressure and would produce 600 MMcf/D against a gathering system pressure of 850 psia. The productivity of the wells in Washington Ranch is substantially greater than the expectations that were perceived at the time of the FERC application. The expected maximum withdrawal rate for the FERC application was 491 MMcf/D against a gathering system pressure of 850 psia.

During the development of the new 17 injection/withdrawal wells, all Morrow sands exhibiting porosity characteristics of 5% or greater were perforated in all 3 sand members. As mentioned earlier under the Geology section, the upper sand members have lesser sand quality characteristics, are tighter and have less porosity and, therefore, their contribution to the storage project is not substantial. Based upon the analysis of core and log data, confirmed by the productivity tests that have been conducted to date, the effective gas storage reservoir volume has been estimated for immediate injection and withdrawal volumes and pressures. It has been determined that the effective gas-in-place is 44.1 Bcf as shown in the graph behind Tab H of Effective Pressure and Withdrawal Rates versus Gas Inventory. This means that maximum withdrawal pressures will be reached before the 63.6 Bcf of gas-in-place materializes and that initial reservoir pressures will be reached in the effective area when total gas-in-place volumes reach 44.1 Bcf, at which time a maximum withdrawal of 600 MMcf/D, against a 800 psia gathering system can be obtained at this gas inventory level immediately after this level is reached. Behind Tab I is a table showing the project availability at various gas inventory levels.

P. O. BOX [illegible]
EL PASO, TEXAS [illegible]

PHONE: [illegible]

March 6, 1984

RECEIVED
MAR 0 9 1984
OIL CONSERVATION DIVISION
SANTA FE

New Mexico Oil Conservation Commission
P. O. Box 2088
Santa Fe, New Mexico 87501

Gentlemen:

Re: El Paso Natural Gas Company's
Washington Ranch Morrow Gas
Storage Field

In accordance with the Commission Order R-6175 ¶6, please be advised that the El Paso Natural Gas #1 Susco 32 State Com. well was completed on January 18, 1982 as a "dry hole". By "dry hole", we mean that it was incapable of producing gas in commercial quantities, however, the Morrow sands were present and saturated with water. This well then was completed with perforations from 7,191 - 7,394 feet in the Morrow Gas Storage reservoir on said date and is being utilized by El Paso as an observation well for its Washington Ranch Morrow Gas Storage Field.

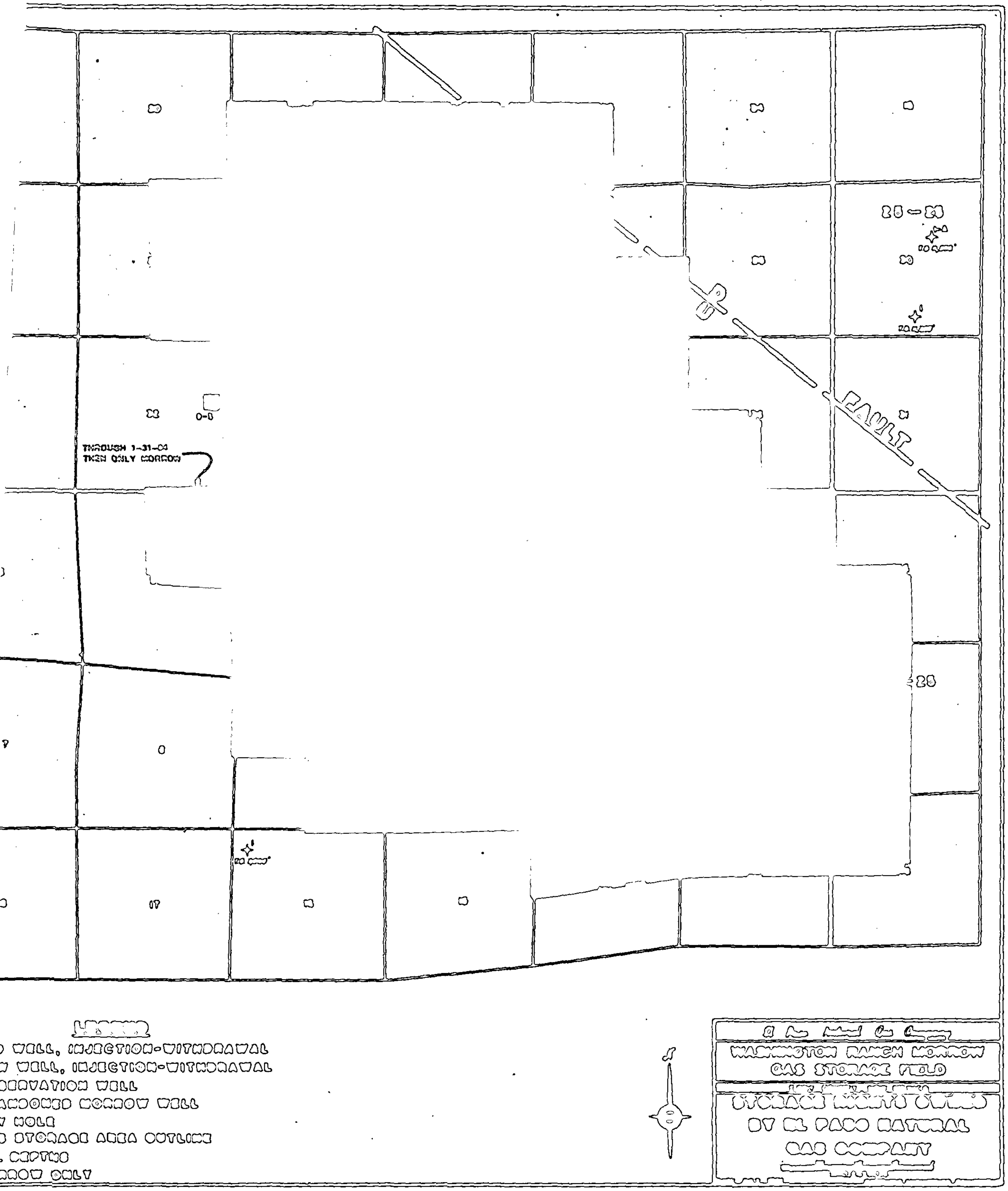
Attached herewith is a map showing the location and status of each well in El Paso's Washington Ranch Morrow Gas Storage field.

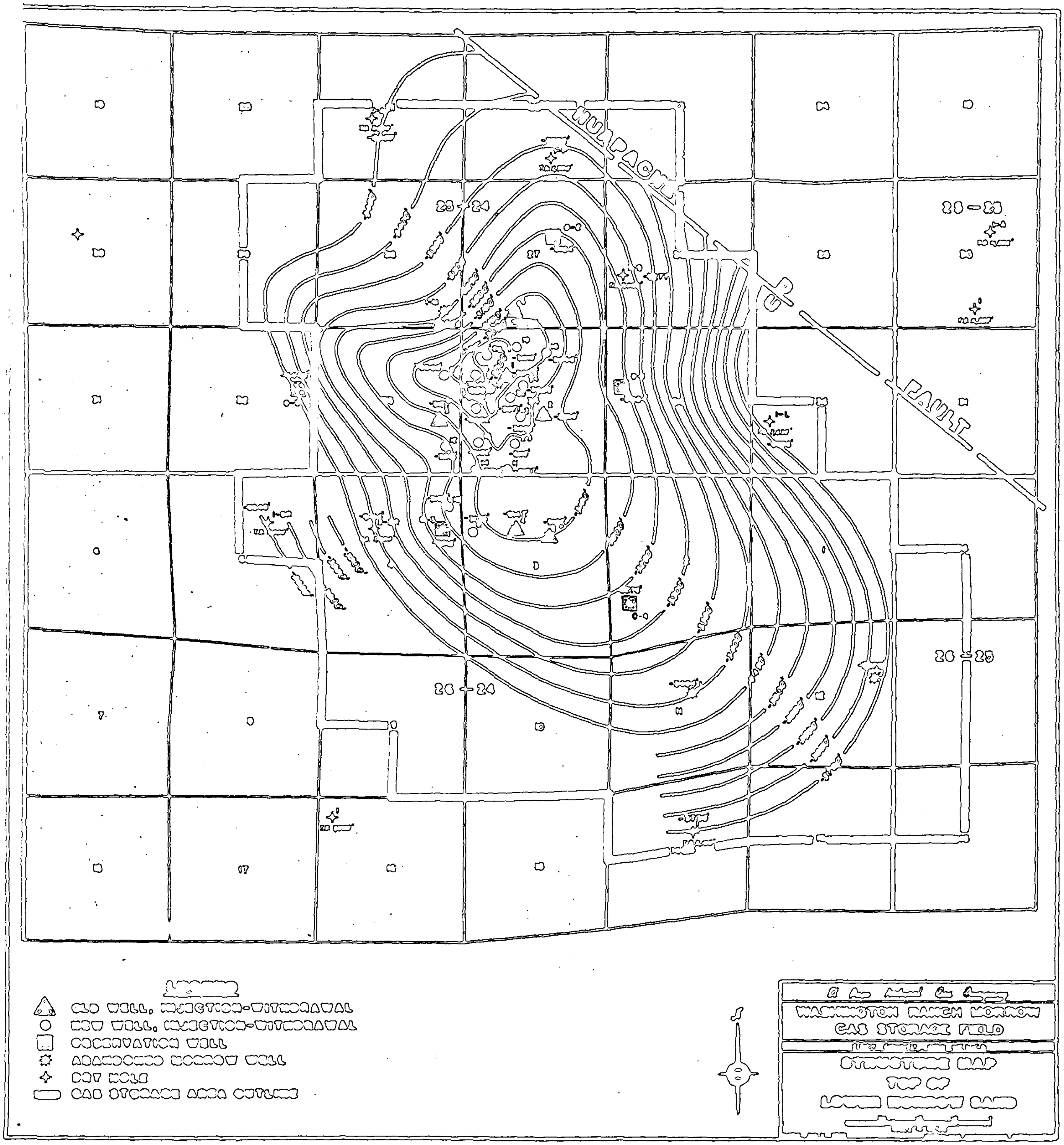
Respectfully submitted,

D. E. Adams, Director
Reservoir Engineering Dept.

DEA:cc

Attachment


THROUGH 1-31-04
THEN ONLY MORROW
FAULT
WASHINGTON RANCH MORROW
GAS STORAGE FIELD
BY EL PASO NATURAL
GAS COMPANY



HUAPACHE FAULT
LEGEND
OLD WELL, INJECTION-WITHDRAWAL
NEW WELL, INJECTION-WITHDRAWAL
OBSERVATION WELL
ABANDONED MORROW WELL
DRY HOLE
GAS STORAGE AREA OUTLINE
WASHINGTON RANCH MORROW
GAS STORAGE FIELD
STRUCTURE MAP
TOP OF
LOWER MORROW SAND

STATE OF NEW MEXICO
ENERGY AND MINERALS DEPARTMENT
OIL CONSERVATION DIVISION

IN THE MATTER OF THE HEARING
CALLED BY THE OIL CONSERVATION
DIVISION FOR THE PURPOSE OF
CONSIDERING:

CASE NO. 6703
Order No. R-6175

APPLICATION OF EL PASO NATURAL
GAS COMPANY FOR UNDERGROUND GAS
STORAGE, EDDY COUNTY, NEW MEXICO.

ORDER OF THE DIVISION

BY THE DIVISION:

This cause came on for hearing at 9 a.m. on October 17, 1979, at Santa Fe, New Mexico, before Examiner Daniel S. Nutter.

NOW, on this 2nd day of November, 1979, the Division Director, having considered the testimony, the record, and the recommendations of the Examiner, and being fully advised in the premises,

FINDS:

(1) That due public notice having been given as required by law, the Division has jurisdiction of this cause and the subject matter thereof.

(2) That the applicant, El Paso Natural Gas Company, proposes the establishment of an underground gas storage project in Eddy County, New Mexico, to be known as the Washington Ranch Gas Storage Project.

(3) That the applicant has conducted geological and engineering studies to confirm the existence and areal extent of a geological structure underlying all or portions of Sections 21, 22, 23, 26, 27, 28, 29, 32, 33, 34, 35 and 36, Township 25 South, Range 24 East, NMPM, and all or portions of Sections 1, 2, 3, 4, 5, 9, 10, 11, 12, 13, and 14, Township 26 South, Range 24 East, NMPM, and all or portions of Sections 6, 7, and 18, Township 26 South, Range 25 East, NMPM, Eddy County, New Mexico, and to determine the suitability of said structure for the underground storage of natural gas.

(4) That gas storage within said structure would be in the Pennsylvanian Morrow formation and contained within the

Morrow Clastics interval.

(5) That the aforesaid vertical interval of the Morrow formation beneath the following described lands:

EDDY COUNTY, NEW MEXICO
<u>TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM</u>
Section 27: All
Section 28: S/2
Section 33: E/2
Section 34: All
Section 35: W/2

<u>TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM</u>
Section 2: W/2
Section 3: All
Section 4: E/2
Section 11: All
Section 12: W/2

is a gas reservoir in New Mexico, having been created and defined by the Division as the Washington Ranch-Morrow Gas Pool by Division Order No. R-4279, effective April 1, 1972, and subsequently extended by Orders Nos. R-4377, R-4437, R-4734, and R-4782, the last dated June 1, 1974.

(6) That said Washington Ranch-Morrow Gas Pool is essentially depleted of native natural gas.

(7) That the applicant proposes to convert some 4 presently producing wells into observation wells on the outer flanks of the gas storage structure to permit the detection of any migration away from the project of gas placed in storage.

(8) That the applicant proposes to convert 6 presently producing wells into injection/withdrawal wells.

(9) That the applicant proposes to drill and complete some 17 injection/withdrawal wells in the proposed gas storage project.

(10) That the location of the injection/withdrawal wells to be drilled is proposed as follows:

TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM

Unit N	Section 27
Unit O	Section 27
Unit A	Section 33
Unit P	Section 33
Unit B	Section 34
Unit D	Section 34
Unit E	Section 34
Unit G	Section 34
Unit L	Section 34
Unit M	Section 34
Unit N	Section 34

TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM

Unit A	Section 4
Unit C	Section 3
Unit D	Section 3
Unit E	Section 3
Unit K	Section 3
Unit L	Section 3

(11) That the applicant proposes to drill and complete the aforesaid injection/withdrawal wells as follows:

(A) Set 9 5/8-inch surface casing approximately 300 feet into the Upper Mountain Delaware Group at a depth of approximately 800 feet and circulate cement to the surface;

(B) Drill to total depth of approximately 7,050 feet and set 7-inch casing and cement to approximately 1,500 feet above the casing shoe.

(C) Perforate the casing opposite the Morrow zone.

(D) Land 2 7/8-inch tubing at approximately 6,970 feet.

(12) That the above casing and cementing programs are adequate and should afford ample protection against loss of gas while being injected, withdrawn, or held in storage, and will provide good and sufficient protection against contamination of ground waters.

(13) That the proposed El Paso Natural Gas Company Washington Ranch Gas Storage Project is in the interest of conservation, will not cause waste, and will not impair correlative rights and should be approved, provided:

(A) The following described area would be known as the Washington Ranch Gas Storage Project Area:

<u>TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM</u>
Section 21: S/2
Section 22: S/2
Section 23: SW/4
Section 26: W/2 and SE/4
Sections 27 and 28: All
Section 29: E/2
Section 32: E/2
Sections 33, 34, and 35: All
Section 36: SW/4

<u>TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM</u>
Sections 1 through 4: All
Section 5: NE/4
Section 9: N/2 and SE/4
Sections 10, 11, and 12: All
Section 13: N/2
Section 14: N/2

<u>TOWNSHIP 26 SOUTH, RANGE 25 EAST, NMPM</u>
Section 6: SW/4
Section 7: W/2
Section 18: NW/4

(B) The following described area would be known as the Active Area of the Washington Ranch Gas Storage Project:

<u>TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM</u>
Section 21: S/2
Section 22: S/2
Section 23: SW/4
Section 26: W/2 and SE/4
Sections 27 and 28: All
Sections 33, 34, and 35: All

<u>TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM</u>
Sections 1 through 4: All
Section 9: N/2 and SE/4
Sections 10, 11, and 12: All

(C) That the Division's rules and regulations governing well locations, acreage dedication, and the production of natural gas from gas reservoirs should not be applicable to wells located within the Active Area of the Washington Ranch Gas Storage Project as described in (12) (B) above;

(D) That an administrative procedure for approval of amended locations for injection/withdrawal wells and observation wells or for the drilling of additional wells at locations within the Active Area of the Washington Ranch Gas Storage Project as described in (12) (B) above should be established;

(E) That any well drilled within the Washington Ranch Gas Storage Project Area as described in (12) (A) above but outside the Active Area of the Washington Ranch Gas Storage Project as described in (12) (B) above

((1)) Would be located according to the General Rules of the Division, and

((2)) Would be cased and cemented in such a manner as to protect the Morrow gas storage zone.

(F) That the applicant should file injection/withdrawal reports monthly with the Division.

IT IS THEREFORE ORDERED:

(1) That the applicant herein, El Paso Natural Gas Company, is hereby authorized to establish its Washington Ranch Gas Storage Project by the injection into and withdrawal from the Morrow formation of natural gas in the following described area in Eddy County, New Mexico:

TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM
Section 21: S/2
Section 22: S/2
Section 23: SW/4
Section 26: W/2 and SE/4
Sections 27 and 28: All
Section 29: E/2
Section 32: E/2
Sections 33, 34, and 35: All
Section 36: SW/4

TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM
Sections [illegible]: All
Section 8: SE/4
Section 9: N/2 and SE/4
Sections 10, 11, and 12: All
Section 13: N/2
Section 14: N/2

TOWNSHIP 26 SOUTH, RANGE 25 EAST, NMPM
Section 6: SW/4
Section 7: W/2
Section 18: NW/4

(2) That said area shall be known as the El Paso Natural Gas Company Washington Ranch Gas Storage Project.

(3) That the applicant is hereby authorized to drill, complete, and operate gas storage injection/withdrawal wells at the following locations:

TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM

Unit M	Section 27
Unit O	Section 27
Unit A	Section 33
Unit P	Section 33
Unit B	Section 34
Unit D	Section 34
Unit E	Section 34
Unit G	Section 34
Unit L	Section 34
Unit [illegible]	Section 34
Unit J	Section 34

TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM

Unit A	Section 4
Unit C	Section 3
Unit D	Section 3
Unit E	Section 3
Unit K	Section 3
Unit L	Section 3

(4) That the applicant is hereby authorized to utilize the following presently existing Morrow gas wells as gas storage injection/withdrawal wells:

<u>TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM</u>

Cities Service Gov't. M #2, Unit H, Section 27
Black River Cities Fed. #3, Unit I, Section 33
Black River Cities Fed. #1, Unit P, Section 34
Black River Cities Fed. #2, Unit J, Section 34

<u>TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM</u>

Black River Cities 3 Fed. #1, Unit F, Section 3
Black River Cities 3 Fed. #2, Unit G, Section 3

(5) That the applicant is hereby authorized to utilize the following existing Morrow gas wells as gas storage observation wells:

<u>TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM</u>

Cities Service Gov't. M #3, Unit O, Section 27
Black River Cities E Fed. #1, Unit E, Section 35

<u>TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM</u>

Black River Miller Com #1, Unit L, Section 2
Black River MM4 Fed. #1, Unit H, Section 4

(6) That should topographic or geologic conditions render any well location described in Orders Nos. (3), (4), and (5) above less advisable than an alternative location, or if any additional injection/withdrawal well or observation well is deemed necessary, the applicant shall notify the Division Director of such fact by letter, and shall by copies thereof also notify the Artesia District Office of the Division and the Roswell, New Mexico, Office of the United States Geological Survey.

(7) That the applicant shall file monthly Division Form C-131, Monthly Gas Storage Report, covering operations of the subject gas storage project.

(8) That the applicant shall notify the Division immediately of any evidence of leakage of gas from the gas storage project, or of any evidence of contamination of ground waters as the result of operations in the gas storage project.

(9) That should any operator drill a well to a formation deeper than the Morrow storage zone within the boundary of the Washington Ranch Gas Storage Project as described in Order

No. (1) above, the following special drilling and casing requirements shall be observed:

(A) Either water or drilling mud shall be utilized as the circulating medium while drilling through the Morrow formation;

(B) A separate, or extra, casing string shall be set at a point one hundred (100) feet below the base of the Morrow Clastics as found at a log depth of 6364 feet on the Schlumberger Gamma Ray-Sonic log of the Black River Cities Federal Well No. 1 located in Unit F of Section 34, Township 25 South, Range 24 East, NMPM, Eddy County, New Mexico;

(C) The casing shall be cemented with enough cement to cause cement to be placed behind the pipe from the casing shoe to a point 1,500 feet above the casing shoe.

(10) That the following described area shall be known as the Active Area of the Washington Ranch Storage Project:

TOWNSHIP 25 SOUTH, RANGE 24 EAST, NMPM
Section 21: S/2
Section 22: S/2
Section 23: SW/4
Section 26: W/2 and SE/4
Sections 27 and 28: All
Sections 33, 34, and 35: All

TOWNSHIP 26 SOUTH, RANGE 24 EAST, NMPM
Sections 1 through 4: All
Section 9: W/2 and SE/4
Sections 10, 11, and 12: All

(11) That the Rules and Regulations of the Division pertaining to gas well locations, acreage dedication, and normal gas production practices shall not apply to the subject active gas storage project as described in Order No. (10) above so long as waste does not result from such inapplication.

(12) Any well to be drilled within the Washington Ranch Gas Storage Project Area as described in Order No. (1) above but at a location not included in the Active Area of the Washington Ranch Gas Storage Project as described in Order No. (10) shall be located according to the General Rules and Regulations of the Division.

Case No. 6703
Order No. R-6173

(11) That jurisdiction of this cause is retained for the entry of such further orders as the Division may deem necessary.

DONE at Santa Fe, New Mexico, on the day and year hereinabove designated.

STATE OF NEW MEXICO
OIL CONSERVATION DIVISION

JOE D. RAMEY
Director

Technical Report — Number 3

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Santa Fe, New Mexico

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STATE OF NEW MEXICO
State Engineer Office

John R. Erickson
State Engineer

GROUND-WATER CONDITIONS IN THE VICINITY OF RATTLESNAKE SPRINGS, EDDY COUNTY, NEW MEXICO

Prepared in cooperation with the
Geological Survey and National Park Service,
United States Department of the Interior

January 1955

STATE OF NEW MEXICO

STATE ENGINEER OFFICE
TECHNICAL DIVISION

GROUND-WATER CONDITIONS IN THE VICINITY OF RATTLESNAKE SPRINGS, EDDY COUNTY, NEW MEXICO

by

W. E. Hale, Engineer
U. S. Geological Survey

January 1955

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GROUND-WATER CONDITIONS IN THE VICINITY OF RATTLESNAKE SPRINGS, EDDY COUNTY, NEW MEXICO

by
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U. S. Geological Survey

ABSTRACT

The flows of Rattlesnake Springs, Blue Spring, and the Black River in the upper Black River valley in southwestern Eddy County, N. Mex., are utilized mostly for irrigation. Part of the water from Rattlesnake Springs also is pumped by the National Park Service for use at the Carlsbad Caverns about 5.5 miles distant. Concern over the possible effects of pumping of recently developed irrigation wells in the area on the surface-water supply prompted an investigation by the U. S. Geological Survey, in cooperation with the State Engineer of New Mexico and the National Park Service.

The upper Black River valley is bounded on the northwest by the Guadalupe Mountains and along the southeast by hills of low relief which near the State line are called the Yeso Hills. The valley is 4 to 9 miles wide. The Black River, the principal stream, heads in the Guadalupe Mountains. Its course is normally dry in the mountains and across the alluvial fan at the mouth of Black Canyon. A perennial stretch of about 4 miles starts about 4 miles north of the State line. Below this stretch and in a northeastward direction the channel is normally dry for a distance of about 10 miles. From the lower end of the normally dry channel to the Pecos River, a distance of roughly 20 miles, the river has a perennial flow. The chief source of water in the lower perennial stretch of the Black River is Blue Spring.

Alluvium, ranging in thickness up to 200 feet, is the principal source for important ground-water supplies in the upper Black River valley. Recharge to the alluvium probably occurs mostly from flood waters originating in the canyons of the bordering Guadalupe Mountains. These flood waters percolate into the alluvium in the canyons and the alluvial fans at the mouths of the canyons. Occasionally, flood waters reach the lower courses of the various draws. Water moves through the alluvium in a general northeastward direction down the valley of Black River. Accretions to the water in the alluvium occur, in part, by movement of water from adjacent shallow water-bearing beds in gypsum of the Castile formation. Recharge to the shallow aquifer in the Castile formation occurs mostly from precipitation in the area of outcrop of the formation. Water in the gypsum has a high calcium sulfate content, and where this water moves into the alluvium it mixes with water of better quality in the alluvium. Thus a progressive increase in mineral content occurs as the water moves through the alluvium down the valley.

Irrigation from wells in upper Black River valley reportedly began in 1946 with the irrigation of 18 acres in sec. 3, T. 26 S., R. 24 E., about 3.5 miles south of Rattlesnake Springs. Further development was slow until 1951. During 1952 approximately 670 acres were being irrigated from wells in the upper valley and a substantial part of the acreage was within 2 miles of Rattlesnake Springs. Wells having yields of as much as 1,300 gallons a minute are developed in the conglomeratic beds in the alluvium.

The upper perennial stretch of the Black River extends from sec. 3, T. 26 S., R. 24 E., northward about 4 miles. The river begins to lose water to the underlying alluvium in the lower half mile of this stretch, and the dry-weather flow disappears in the NE¼ sec. 24, T. 25 S., R. 24 E. The maximum dry-weather flow is about 2 to 3 cfs. The average annual discharge of wells in the area immediately upstream from this perennial stretch is about 0.7 cfs; estimating about a 30-percent return from irrigation, the net withdrawal of water is about 0.5 cfs. The effect of this pumping has probably reached the springs at the head of the upper perennial stretch, about 3.5 miles above Rattlesnake Springs, but it probably will reduce their flow by less than 0.3 cfs in the next few years, if the pumping in the locality is not increased. An observed decline in the flow of these headward springs from 1.0 cfs in October to 0.7 cfs in December 1953 probably was caused largely by the continued below-normal recharge resulting from a 50-percent deficiency in normal precipitation during 1951-53.

Rattlesnake Springs issues from the alluvium in a developed pool on the flats of Nuevo Canyon Draw in the SW¼ sec. 23, T. 25 S., R. 24 E. The discharge of the springs, as observed from periodic measurements, has ranged between 1.7 and 4.2 cfs, the smaller flow coinciding with pumping from nearby irrigation wells. The aquifer discharging water at Rattlesnake Springs also is tapped by four irrigation wells. The seasonal discharge from these wells in 1953 was approximately equivalent to the decrease in discharge of Rattlesnake Springs, allowing for some decrease in the spring discharge caused by drought conditions. An increase in the pumpage from these wells or the development of additional wells in the locality southwest from Rattlesnake Springs would result in further decline in the flow of the springs, and the springs might cease to flow near the end of the irrigation season.

Blue Spring, in the NW¼ sec. 33, T. 24 S., R. 26 E., with a discharge of approximately 12 cfs, probably is the principal discharge point for the water in the alluvium in the Black River valley westward from Blue Spring. The present average net diversion of ground water caused by pumping of irrigation wells in upper Black River valley is of the order of 1 cfs. This should result in a decline in the flow of Blue Spring of approximately this amount within a few months or several years, depending upon whether the water occurs under water-table conditions in fairly open channels or under artesian conditions.

INTRODUCTION

Investigation of the ground-water conditions in the vicinity of Rattlesnake Springs in southern Eddy County, N. Mex., was begun in April 1952 by the United States Geological Survey and the State Engineer of New Mexico, with the cooperation of the National Park Service (fig. 1).

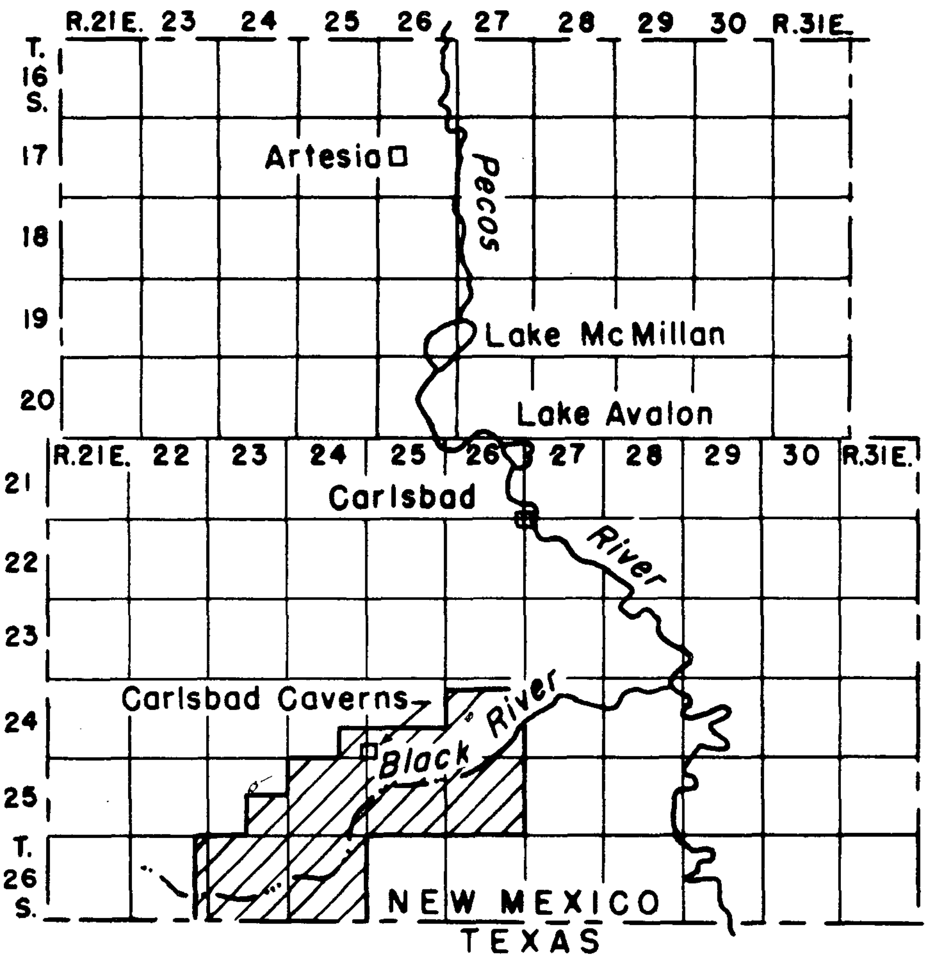

Figure 1.--Area (hachured) covered by this investigation.

The waters of the Black River and Rattlesnake Springs have been used for the irrigation of lands in the vicinity of Rattlesnake Springs for many years. In addition, a part of the flow of Rattlesnake Springs is pumped through a pipeline by the National Park Service for use at the Carlsbad Caverns, approximately 5.5 miles distant. A part of the flow of the springs also is used by the State Department of Game and Fish to maintain a few pools for fish and wildlife along the Rattlesnake Springs drainageway, and part of the flow from both the springs and the Black River maintains pools along the Black River in the lower part of its upper perennial stretch, that in the vicinity of Rattlesnake Springs.

Below these pools the Black River is normally dry for a distance of 10 miles, below which the river has a perennial flow to its junction with the Pecos River. Blue Spring is the principal source of the water in Black River in its lower stretch, and water from this spring and the Black River is utilized by the Carlsbad Irrigation District and other parties for irrigation.

Water reportedly was first pumped from wells in 1946 near Rattlesnake Springs in the upper Black River valley for the irrigation of lands, when water was applied to about 18 acres of land along the Black River about 3.5 miles upstream from Rattlesnake Springs. Development of additional lands by means of irrigation from wells was not appreciable until 1951. During 1952, approximately 670 acres were irrigated from wells, and a large part of this acreage was within 2 miles of Rattlesnake Springs.

Purpose and Scope of the Investigation

With the construction of wells for irrigation use within 2 miles of Rattlesnake Springs, the National Park Service became concerned as to what effect this and possible further development of irrigation wells in the locality might have on the flow of the springs. The State Department of Game and Fish also was concerned about the effects of nearby pumping on the flow of the Black River as well as Rattlesnake Springs. Further, there was the question as to what effect pumping from these wells might have upon the flow of Blue Spring and the Black River farther down the valley. The State Engineer, because of his responsibilities in the administration of water rights of both ground water and surface water in the State, was concerned as to the relation of ground water to surface water in the area.

This investigation was made to determine the ground-water conditions in the upper Black River valley, the relation of ground water to surface water in the area, and the effect of the pumping of wells, if any, on the flow of Rattlesnake Springs and other surface waters. This report discusses principally the relation of ground water to Rattlesnake Springs, and the effects of pumping from wells in the area on the flow of these springs.

Previous Investigations

Considerable study has been made of the geology of the general area, mostly by oil geologists and members of the Geological Survey, particularly in the past 20 years, because of the relation of the rocks exposed in this general area to those from which oil is obtained in the subsurface farther east in southeastern New Mexico and west Texas. The work by the several investigators has been published largely in bulletins of the American Association of Petroleum Geologists and by the Geological Survey, and the several endeavors have resulted in a general clarification of the complex geology of the region. One of the most important recent works on the region is that by King (1948). Reference to studies in the area prior to 1940 is given by King, and the reader is referred to King's report for more detail on the geology of the area covered by this investigation. During 1952 and 1953 the 15-minute quadrangle, identified as Carlsbad Caverns East, N. Mex., was mapped geologically by P. T. Hayes of the Fuels Branch of the Geologic Division of the Geological Survey. His work covered a large part of the area included in this investigation, and although the report on the quadrangle is still in preparation, the results of the work were kindly made available for use in this report. Thus the work of King, Hayes, and several others is drawn on in the discussion of the general geology of the area in this report, without particular reference to the various works.

The general ground-water conditions in the area of this investigation are described in a report by Hendrickson and Jones (1952) which was a result of an investigation made by the Geological Survey in cooperation with the State Bureau of Mines and Mineral Resources and the State Engineer of New Mexico. Information in that report also has been drawn on freely in the preparation of the present report.

Present Investigation

Intensive field work in the area was done by E. H. Herrick, geologist, Geological Survey, and the writer from April through June 1952. It involved the collection of well data, measurement of water levels, determination of elevations at wells, and collection of water samples for mineral analyses. A network of observation wells was established, and arrangements were made for the measurement at monthly intervals of the flow of Rattlesnake Springs, Blue Spring, and the Black River at several places. The investigation is being continued as part of an investigation of the Carlsbad, N. Mex., area through the measurement of depths to water level in observation wells and of the flow of surface water, together with additional studies of the relation of ground water to surface water in the vicinity of Blue Spring.

Personnel and Acknowledgments

This investigation was made under the general direction of A. N. Sayre, Chief of the Ground Water Branch of the Geological Survey, and Clyde S. Conover, District Engineer of the Branch for New Mexico, and under the direct supervision of the writer. Measurements of surface-water flows were made under the direction of S. O. Decker of the Surface Water Branch. The general geologic map is a modification of the map prepared by P. T. Hayes, of the Geologic Division. Personnel of the State Engineer Office assisted with the work, and special acknowledgment is due J. C. Yates and S. E. Galloway of that office for their work in collecting well data, running spirit levels, and determining the irrigated acreage. Lester Stroup of the State Department of Game and Fish, personnel of the National Park Service, and the well owners in the area were helpful in giving pertinent information on the area.

Well-Numbering System

The system of numbering wells in this report is the same as that used in other parts of New Mexico by the Ground Water Branch of the U. S. Geological Survey. This system is based on the common subdivisions in sectionized land, and by means of it the well number, in addition to designating the well, locates its position to the nearest 10-acre tract in the land net. The number is divided into four segments by periods. The first segment denotes the township, the second denotes the range, and the third denotes the section. In Eddy County all the townships are south of the base line and east of the principal meridian.

The fourth segment of the number consists of three digits and denotes the particular 10-acre tract in which the well is situated. For this purpose, the section is divided into four quarters, numbered 1,2,3, and 4, and in the normal reading order, for the northwest, northeast, southwest, and southeast quarters, respectively. The first digit of the fourth segment gives the quarter section, which is normally a 160-acre tract. Similarly, the quarter section is divided into 40-acre tracts numbered in the same manner, and the second digit denotes the 40-acre tract. Finally, the 40-acre tract is divided into four 10-acre tracts, and the third digit denotes the 10-acre tract. Thus, well 25.24.27.124 is in the SE$\frac{1}{4}$NE$\frac{1}{4}$NW$\frac{1}{4}$ sec. 27, T. 25 S., R. 24 E. If the well is not located accurately to a 10-acre tract, a zero is used as the third digit, and if it is not located accurately to a 40-acre tract, zeros are used for both the second and third digit. If the well is not located more accurately than the section, the fourth segment of the well number is omitted. Letters a, b, c,-----are added to the fourth segment to designate the second, third, fourth, and succeeding wells situated in the same 10-acre tract. The following diagram shows the method of numbering the tracts within a section.

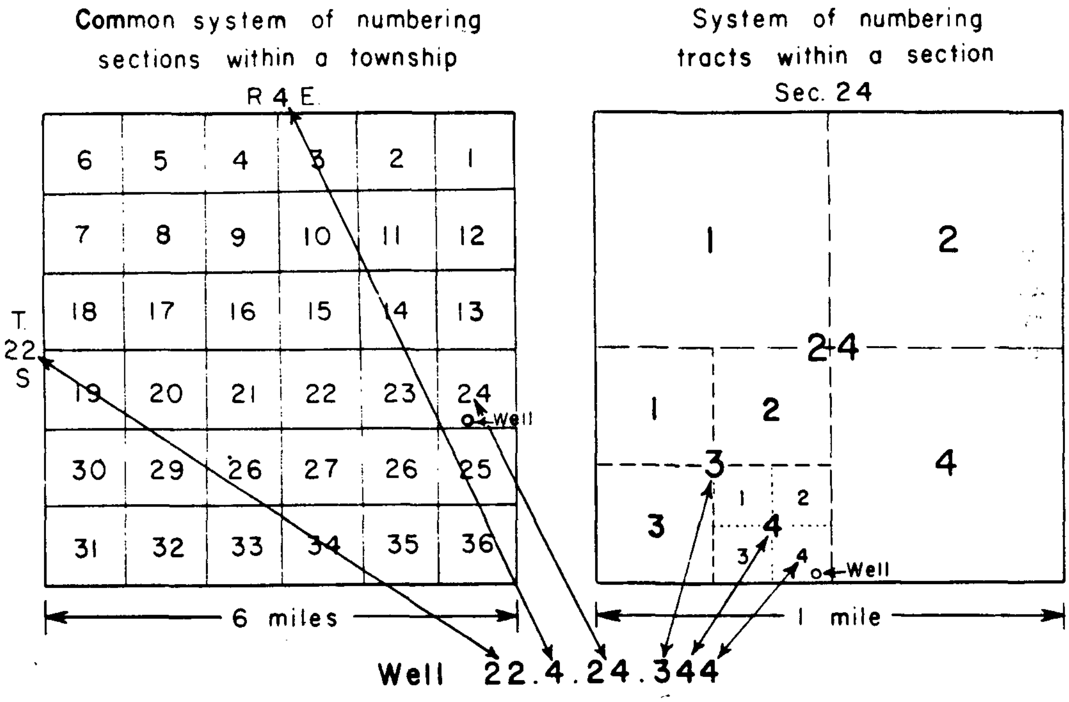

Figure 2. --System of numbering wells in New Mexico.

GEOGRAPHY

Location and Extent of the Area

The area included in this investigation is in the upper Black River valley in the southwestern part of Eddy County and extends upstream from the vicinity of Black River Village to the New Mexico-Texas State line (pl. 1). This area of about 200 square miles in southeastern New Mexico coincides approximately with the extension of the Carlsbad ground-water basin declared by the State Engineer on October 21, 1952, after the investigation was started (pl. 1). The main emphasis of the study is centered around Rattlesnake Springs.

Topography and Drainage

The Black River valley headward from Black River Village is bounded on the north and west by the Guadalupe Mountains and along the south and east by hills and bluffs of low relief which near the State line are called the Yeso Hills. The valley bottom slopes northeastward at approximately 25 feet per mile. The actual flood plain of the Black River is, in general, only a few hundred feet wide, but coalescing alluvial fans border the flood plain to the north and west and make the entire valley 3 to 4 miles wide in the stretch between Black River Village and Rattlesnake Springs. From Rattlesnake Springs headward, the valley widens to about 9 miles at the State line.

The general relief of the alluvial fans from Black River to the foot of the Guadalupe Mountains, as determined from topographic maps, ranges from 250 feet near Black River Village to more than 700 feet in the southwestern part of the area.

Guadalupe Ridge, the eastern limb of the Guadalupe Mountains in this locality, terminates along its southeast side in an even scarp referred to as the "reef escarpment." The height of the ridge above the adjacent alluvial fans ranges from 300 feet in the northeast part of the area to about 2,000 feet in the southwestern part. Guadalupe Ridge is dissected by many canyons in the area, some of the most prominent being Walnut, Rattlesnake, Slaughter, and Black canyons.

The principal drainageway is the Black River, whose channel in general borders the low hills along the southeast side of the Black River valley. The river is normally dry along its course in the mountains and across the alluvial fan extending eastward from the mouth of Black Canyon. Perennial flow occurs in a 4-mile stretch of the river starting from a series of springs (called the headward springs in this report) in the south part of sec. 3,

T. 26 S., R. 24 E., about 3.5 miles south of Rattlesnake Springs. The flow of the Black River, at the station below Mayes Ranch in the NE¼SE¼ sec. 3, T. 26 S., R. 24 E., just below the headward springs, was about 1 cfs during most of 1953.

Downstream about 1.5 miles from the headward springs, a dam has been constructed and maintained on the river for several years for use in diverting water for irrigation of lands in parts of secs. 23, 24, 25, and 26, T. 25 S., R. 24 E. (fig. 4). Some water can be stored behind the dam, known as the upper diversion dam, permitting the diversion of water at much greater rates than the natural flow in the river. Water is run through the diversion canal only during periods of actual irrigation of lands. Periodic measurements of the flow of the Black River made just below the upper diversion dam in the SE¼NW¼ sec. 35, T. 25 S., R. 24 E., at times when water was not being diverted, indicate flows ranging between 1 and 3 cfs. The lower flows, about 1 cfs, measured during the irrigation season presumably in part result from the incomplete recovery of the storage behind the diversion dam from a previous diversion period. During periods of diversion of water from the river the water level in the storage pool behind the dam is lowered below the spillway of the diversion dam. Some leakage occurs through the dam to maintain a small flow down the river channel while water is being diverted through the main canal. After the gate to the canal is closed, the storage behind the dam increases until the discharge over the spillway and through the dam equals the inflow. The lower flows during the irrigation season, about 1 cfs, presumably were measured shortly after diversion of water had ceased, during the period of adjustment to stable nondiversion conditions. A gain of 1 to 1.5 cfs occurs between the headward springs and this station.

Another dam located farther downstream in the SE¼ sec. 24, T. 25 S., R. 24 E., known as the lower diversion dam, is used to divert water to a small acreage in section 24. Very little water can be stored, and as a result the rate of diversion is about that of the natural flow in the stream. Periodic measurements made on the flow of the Black River just above the lower diversion dam indicate a dry-weather flow ranging between 0.3 and 3.2 cfs. The extremely low flows were observed during the irrigation season when water was being diverted at the upper diversion dam. Generally, under natural conditions, the stream gains a fraction of a cfs between the station below the upper diversion dam and this point (see table 4).

Below the lower diversion dam in the southwest part of sec. 24, T. 25 S., R. 24 E., loss of water in the channel occurs and the dry-weather flow ceases in the northeast part of the section. From this point downstream about 10 miles to the south part of sec. 4, T. 25 S., R. 26 E., the Black River is normally dry. Just above the junction with Blue Spring Creek in sec. 35, T. 24 S.,

R. 26 E., the normal flow of the Black River in 1953 was about 0.3 cfs. Blue Spring Creek contributes a substantial part of the flow of the Black River, and the river has a perennial flow from this confluence to its junction with the Pecos River.

Several springs occur in the valley of Black River, the largest of which is Blue Spring. This spring, with a flow of more than 11 cfs, is in the north part of sec. 33, T. 24 S., R. 26 E. The water from this spring forms Blue Spring Creek which joins Black River about 2 miles to the east. The next largest spring in the area is Rattlesnake Springs in the southwest part of sec. 23, T. 25 S., R. 24 E. From April 1952 through June 1954, the observed flow from this spring area ranged between 1.7 and 4.2 cfs. Other named springs include XT Spring and Geyser Spring in the southern part of the area. The results of spot discharge measurements made at Castle Springs, Blue Spring, Rattlesnake Springs, and various places on the Black River are given in table 4, and hydrographs for most of these stations are presented in figure 3.

Precipitation

Stations for recording precipitation have been maintained by the Weather Bureau for a number of years at Carlsbad Caverns on the north side of the area and at Carlsbad, Eddy County, about 20 miles northeast of the area. The upper valley of the Black River is somewhat higher than the Carlsbad station and, in general, about 800 feet below the Carlsbad Caverns station. The average precipitation in the area of investigation is probably about an average of that at the two stations. About 75 percent of the precipitation occurs from May through October, but even in normal years it is not sufficient for dry farming. During 1951, 1952, and 1953 precipitation in the area was approximately 50 percent of normal, as shown in the following tabulation of the precipitation at Carlsbad and the Carlsbad Caverns. Storms in this area generally are quite local, and hence runoff and recharge in parts of the area may not correlate in detail with the precipitation recorded at the Carlsbad and Carlsbad Caverns stations.

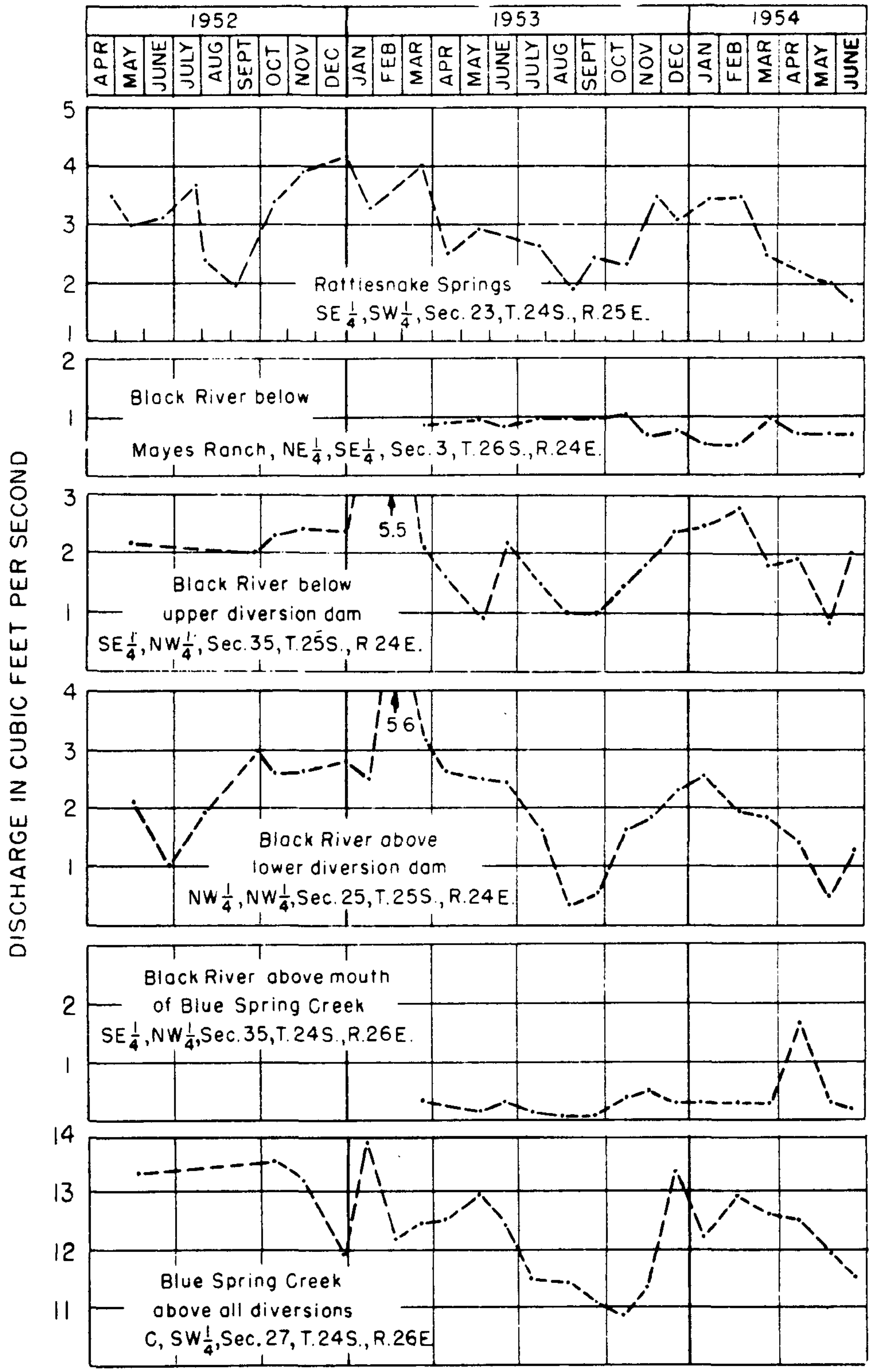

Figure 3.--Hydrographs of spring and stream flow in the upper Black River valley, Eddy County, N. Mex., 1952-54 (Periodic measurements represented by dots.)

Precipitation in inches for 1951-53 and average for period of record
(from records of the U. S. Weather Bureau)

Carlsbad

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1951	0.14	0.34	1.05	0.67	1.17	0.05	0.96	1.78	0.05	0.22	0.00	0.00	6.43
1952	.15	.17	.10	.42	.51	2.21	E2.03	.16	.61	.00	.73	T	E7.09
1953	.02	.01	.44	.35	1.05	.43	1.69	.47	.16	.93	.00	.42	5.97
Average for station (59 years)	.39	.37	.52	.76	1.16	1.72	2.12	1.78	1.91	1.44	.53	.55	13.25

E. Estimated.

T. Trace, less than .01 inch.

Carlsbad Caverns

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1951	0.08	0.30	1.48	0.09	0.55	0.24	0.51	0.61	0.30	0.21	0.07	0.03	4.47
1952	.09	.10	.13	1.14	.68	1.78	3.38	.18	.81	.00	.66	.13	9.08
1953	.03	.06	.02	.68	1.19	2.07	1.16	.61	.01	.98	.11	.94	7.86
Average for station (24 years)	.59	.43	.41	.63	1.73	1.68	2.03	1.98	3.27	1.55	.45	.60	15.35

Agriculture

In most of the area the land is used for grazing cattle. Small tracts along the Black River and Grapevine Draw have been irrigated for a number of years by water diverted from the Black River, Rattlesnake Springs, and Geyser Spring. About 60 acres are reported to be irrigated from Geyser Spring. In the vicinity of Rattlesnake Springs, the area irrigated from the springs and the Black River varies somewhat from year to year, but it is estimated that 250 acres were irrigated in this locality from surface waters (including spring water) in 1953 (fig.4).

Development of irrigation from wells in the vicinity of Rattlesnake Springs began in 1946 with the farming of about 18 acres in sec. 3, T. 26 S., R. 24 E. There was little increase in acreage irrigated from wells until 1951. The following table shows the development of irrigated lands in the upper Black River area. Irrigated acreage prior to 1951 is reported by the different owners; that for 1952 is from a plane-table survey by the New Mexico State Engineer; and that for 1953 is from a reconnaissance based upon the 1952 data. The estimated pumpage was calculated on the basis of a duty of 2.5

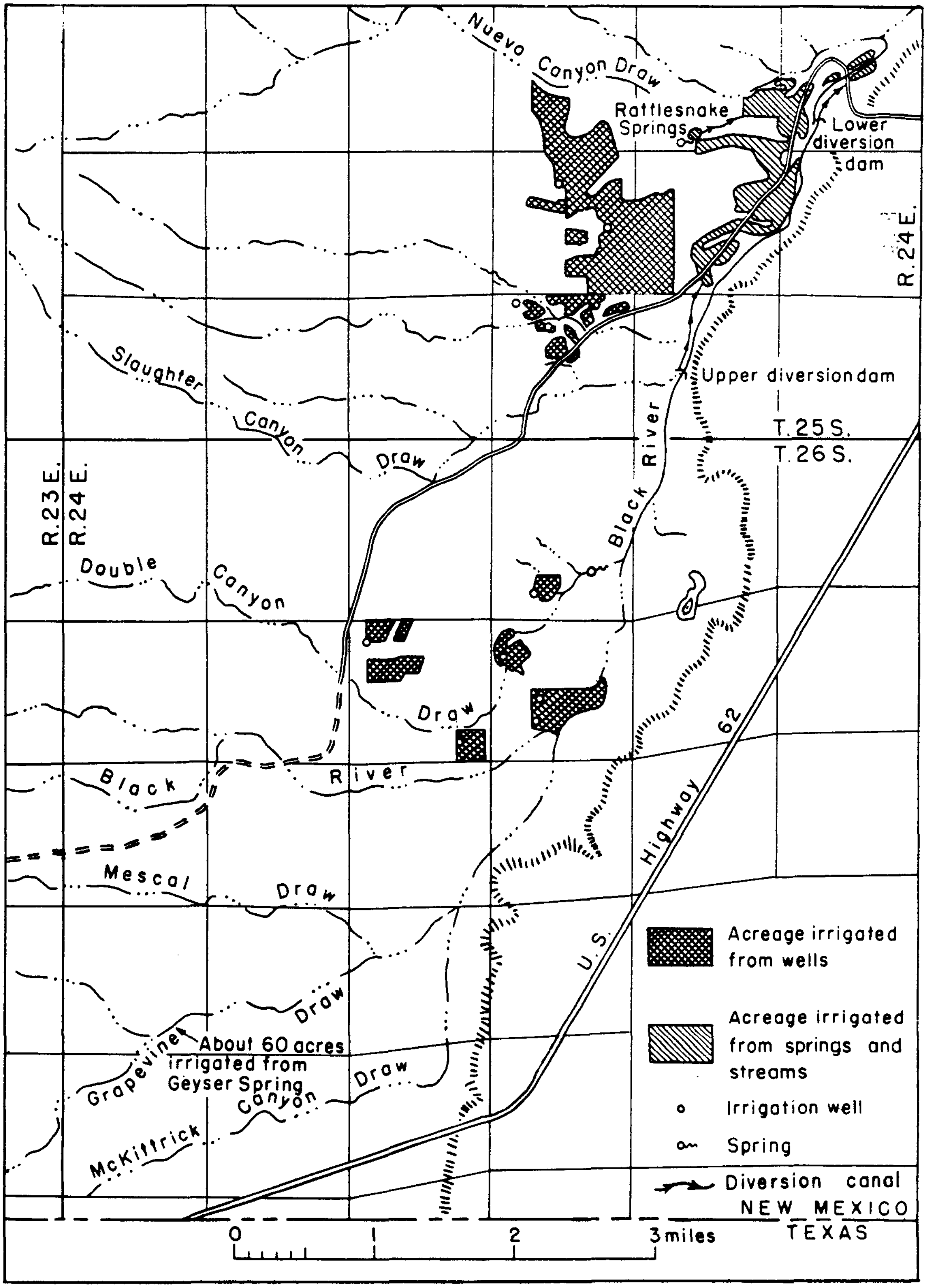

Figure 4.--Irrigated lands in upper Black River valley, Eddy County, N. Mex., 1953.

feet of water for cropland and about 0.5 foot of water for pasture land per season.

Acreage irrigated from wells and estimated pumpage in the upper Black River Valley, by years

Year	Irrigated land: Crop (acres)	Irrigated land: Pasture (acres)	Total (acres)	Estimated pumpage (acre-feet)
1946	18	0	18	45
1947	18	0	18	45
1948	23	0	23	55
1949	23	0	23	55
1950	50	10	60	130
1951	230	20	250	600
1952	395	275	670	1,100
1953	460	260	720	1,250

Additional lands probably could be irrigated on the relatively wide valley bottom in T. 26 S., R. 24 E., without much leveling of land, if sufficient ground water could be obtained. Additional lands on the alluvial fans near the valley floor in this same township and farther north in the vicinity of Rattlesnake Springs also could be developed without much leveling of land. In all, 2,000 to 3,000 acres probably are susceptible to irrigation in the area upstream from the Highway 62 crossing over the Black River.

GENERAL GEOLOGY

The oldest rocks exposed in the area are those belonging to the limestone facies of the Guadalupe series of Permian age. These rocks crop out in the Guadalupe Mountains along the northwest boundary of the area. Along the reef escarpment the reef talus beds dip steeply to the southeast and terminate in the subsurface where they interfinger with sandstone beds. The limestone and sandstone beds of equivalent age southeast of the escarpment are covered by anhydrite and gypsum beds of the lower part of the Ochoa series, also of Permian age. Above the gypsum beds, the much younger alluvial sediments mantle most of the bedrock in the Black River valley and are confined mostly to that valley and the canyons in the Guadalupe Mountains.

Guadalupe Series

Capitan and Carlsbad Limestones

The massive beds of limestone and partly dolomitic limestone that crop out principally in the walls of canyons cut through the reef escarpment of the Guadalupe Mountains are a part of the Capitan limestone. Along the crest of the mountains near the reef escarpment, the Capitan limestone is overlain by more thinly bedded limestone, dolomitic limestone, and siltstone which is part of the Carlsbad limestone. The Carlsbad limestone thickens to the northwest and at depth it interfingers with the Capitan limestone. These formations, together with deeper lying limestone units not considered in this report, constitute the limestone facies of the Guadalupe series.

The reef talus beds of the Capitan limestone have a steep dip to the southeast and within a very short distance from the reef escarpment dip beneath the surface. These reef talus beds underlie the northwestern part of the Black River valley but probably terminate within a few miles to the southeast of the reef escarpment, where the talus beds interfinger with dominantly sandstone beds of the Bell Canyon formation of equivalent age. The Bell Canyon formation has a general southeastward dip in the Black River valley and in the area to the southeast. The top of the Bell Canyon formation was encountered at a depth of about 400 feet in three oil-test wells in secs. 9 and 10, T. 25 S., R. 24 E., and is encountered at a lower altitude to the south and east of these wells. The Bell Canyon formation and, to the northwest, the Capitan limestone southeast of the reef escarpment are overlain by gypsum and anhydrite of the Castile formation.

Solution of the limestone by ground water in the Capitan and Carlsbad limestones along fractures has resulted in the development of many large caverns, the most famous of which are the Carlsbad Caverns, but the limestone adjacent to the caverns is commonly very dense and the over-all porosity of the Capitan and Carlsbad limestones may be small. The porosity of the Capitan limestone probably decreases markedly southeast of the reef escarpment where the talus beds are overlain by the anhydrite and gypsum of the Castile formation. Newell and others (1953, p. 208, 209) state:

"The Permian rocks which are now most permeable in the Guadalupe Mountains are marked by a narrow belt of caverns and vesicular dolomite along the posterior margin of the Capitan reef, where calcitic rocks of the Capitan reef are abruptly replaced by dolomites of the Carlsbad facies. The celebrated Carlsbad Caverns and innumerable smaller caverns of the area represent extensive ground-water solution in the belt of highly permeable rocks in the transition zone immediately behind the reef. The localization of high permeability in the zone of horizontal replacement of calcitic reef limestones by backreef dolomites may have resulted from leaching of calcium carbonate inclusions (e.g., shell detritus) in a dolomitic matrix. The reef limestone and reef talus, originally highly permeable, have been sites of extensive enrichment by calcium carbonate, so that the permeability now appears to be quite low."

Ochoa Series

Castile Formation

The Castile formation overlies the Bell Canyon formation and Capitan limestone southeastward from the Guadalupe Mountains and thickens to the southeast. In the eastern part of the area under investigation the Castile formation is overlain by residual materials of the Salado formation and by the Rustler formation. The bulk of the Castile formation is anhydrite. The formation does contain some limestone and sandstone beds and, farther east, salt beds.

Gypsum beds of the Castile formation crop out in the valley of the Black River, particularly in the area between Rattlesnake Springs and Black River village. An almost continuous outcrop of gypsum beds forms the south and east valley walls of the Black River from south of the State line northeastward to Black River village, and gypsum beds are exposed or are very near the surface farther southeast. Those gypsum beds also are mostly a part of the Castile formation.

Solution and other erosion probably have removed much of the Castile formation in this area. The depth to which the anhydrite has been altered to gypsum in the area seems to be between 100 and 200 feet. Many sinkholes and small solution passages exist, the presence of which is revealed by a hollow ring given out as one walks across many of the gypsum beds. Below the alluvial cover, alteration of the anhydrite to gypsum and solution of gypsum probably also have occurred, but here the channels in gypsum may be filled largely with clay, silt, and sand from the overlying alluvium, materially reducing permeability of the gypsum beds.

Cracks which develop in anhydrite may allow circulation of water. When this occurs, the anhydrite is altered by the addition of water to form gypsum. As the volume of the resulting gypsum is larger than the initial anhydrite, this results in further disruption of the beds which in turn allows more circulation of water. By these means, much of the anhydrite may eventually be converted to gypsum. Inasmuch as the lower part of the Castile formation in this area, even where the formation is thin, is reported to contain anhydrite, it appears that very little circulation of ground water occurs between the alluvium of the Black River valley and the Capitan limestone and Bell Canyon formation underlying the Castile formation.

In places north of Rattlesnake Springs there are exposures of gypsum blocks which have been recemented with gypsum to form a gypsum conglomerate which immediately overlies regularly bedded gypsum. This may represent a gypsum residuum of the Salado formation from which the common salt and some gypsum beds have been leached, as the Salado formation farther east contains much common salt and anhydrite. Blocks of limestone cemented with gypsum also are exposed north of Rattlesnake Springs. These conglomerates are probably remnants of the Rustler formation. These patches are thin and probably of minor extent and for this reason have been included in the Castile formation. Farther east there are more extensive exposures of the Rustler formation, but even there the exposures are small and the formation has not been distinguished from the Castile formation on the geologic map of the area (pl. 1).

Alluvium

The alluvium consists of sand, gravel, conglomerate, clay, and reworked gypsum which extend over most of the valley of Black River. The alluvium ranges in thickness from a featheredge to at least 200 feet. Locally the alluvium fills sinkholes developed in the underlying gypsum beds of the Castile formation.

North of Rattlesnake Canyon and eastward to Highway 62 south of White City, the alluvium occurs primarily as relatively isolated hills less than 50 feet high resting on a rather even bedrock floor of gypsum. To the south, along the Black River, the alluvium is much thicker. Water wells drilled in secs. 26, 27, and 34, T. 25 S., R. 24 E., indicate that the alluvium ranges in thickness from at least 100 feet to more than 165 feet. Farther south in secs. 9 and 10, T. 26 S., R. 24 E., logs of oil-test wells report the top of the gypsum at depths ranging between 165 and 200 feet. To the west of the oil-test wells and the wells near Rattlesnake Springs, the alluvium in the fans along the mountain front may be somewhat thicker than 200 feet in places. The thickness of the alluvium in the canyons is not known but probably is no greater than 200 feet in some of the larger canyons and more likely about 100 feet.

The sand and gravel in the canyons are commonly very coarse and, though they are poorly sorted, the permeability probably is fairly high. The material near the apexes of the alluvial fans also is poorly sorted; that in the fans probably is best sorted near their toes. The fans, however, contain much more clay than the alluvium in the canyons, and for that reason the sediments in the fans probably are much less permeable than the sediments in the canyons. The conglomerates constitute only a small part of the alluvium, but it is from the conglomerates that the largest yields of water have been obtained in the upper Black River valley. Commonly, the conglomerates are composed of limestone pebbles and boulders cemented by calcium carbonate to form a dense rock. Exposures of conglomerate occur along the Black River downstream from the vicinity of Rattlesnake Springs. Every exposure of the conglomerate is highly fractured, and slump blocks are common. It is reasonable to suppose that these structures exist in parts of the alluvium that are deeply buried. The fracturing and slumping of the conglomerate may be caused by the uneven removal by solution of the underlying gypsum beds, or by the settling of the fill. The conglomerates seem to occur, in part, as fill in buried channels that were cut in the gypsum or older alluvium. In places, after the channels had been filled, the gravels were deposited on the adjacent slopes. Thus some of the conglomerates seem to occur in stringers. This is suggested by the logs of three wells in sec. 27, T. 25 S., R. 24 E., and illustrated in figure 5. Here two cemented gravel beds are separated by clay and hydraulically act as two independent aquifers in this locality. The trend in water levels observed during production tests on some of the wells finished in the conglomerates indicate boundary effects which further suggest stringer deposits.

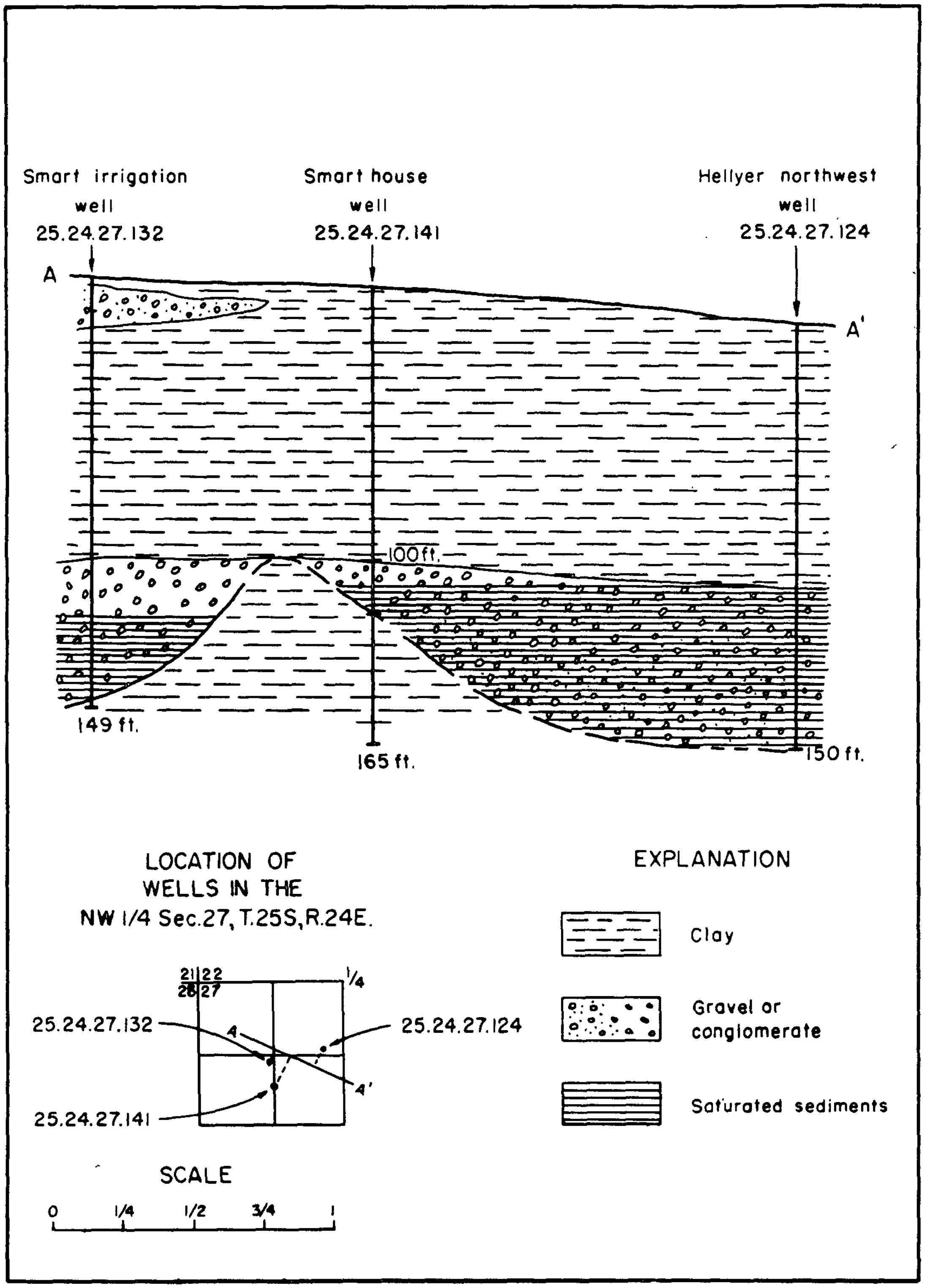

Figure 5.--Inferred relation between aquifers tapped by wells in sec. 27, T. 25 S., R. 24 E., Eddy County, N. Mex. (Based on driller's logs of three wells and results of production tests.)

GROUND WATER

The principal water-bearing formation in the upper Black River valley is the alluvium. Most of the irrigation wells are finished entirely in the alluvium, and even wells drilled below the alluvium obtain most of their water from the alluvium. Further, the large springs in the area issue from the conglomerate and gravel of the alluvium. However, in the valley north of Rattlesnake Springs and downstream to the east where the alluvium is thin, some wells finished in the gypsum beds in the upper part of the Castile formation furnish water for stock. The Capitan and Carlsbad limestones yield water to wells in the Guadalupe Mountains along the northwest border of the area. The relation of the water in the Capitan and Carlsbad limestones and the Castile formation to the water in the alluvium is discussed briefly in the following sections. The discussion deals principally with water in the alluvium and more particularly with the occurrence of water in the alluvium in the vicinity of Rattlesnake Springs.

Capitan and Carlsbad Limestones

Several seeps and small springs occur high on the slopes along Guadalupe Ridge near the reef escarpment. Many of these seeps and springs issue from limestone beds that overlie silt and fine sandstone beds in the Carlsbad limestone. The water from each spring either is lost by evaporation and transpiration or sinks into the next lower limestone bed within a short distance of the spring from which it issues. The springs represent only part of the discharge from perched water-bearing beds. A large part of the perched water probably moves slowly through the partially confining silt and sandstone beds to the next lower perched aquifer, and finally into the massive beds of the Capitan limestone. The general direction of movement of the water in these perched aquifers is northeast, in the general direction of the dip of beds, and downward to the main zone of saturation. Locally, along the reef escarpment, some of the perched water may move to the southeast along the dip of the beds in the Capitan limestone or move laterally into the adjacent fill in the deeper canyons, but there is no evidence of such movement.

The zone of saturation in the limestone near the escarpment is not well defined by the available data. In the Carlsbad Caverns the zone of saturation is no higher than the surface of the unsounded pool in the bottom of the caverns, 1,025 feet below the mouth of the cave and at an altitude of approximately 3,325 feet (Bretz, 1949, p. 449). In that pool the water level is approximately 300 feet below that in the gypsum beds and alluvium in the Black River valley 1.5 miles south of the caverns. A short distance east of the Carlsbad Caverns, the water level in one of the deep wells at White City in sec. 34, T. 24 S., R. 25 E., is reported to be 800 feet below the land surface and at an altitude of approximately 3,100 feet. In this particular stretch along the reef escarpment, water in the zone of saturation in the Capitan limestone is not moving southeastward through the Castile formation into the alluvium of Black River valley. Farther southwest from the Carlsbad Caverns, the zone of saturation in the Capitan limestone undoubtedly is higher than it is at the caverns, but it probably is still well below the base of the alluvium in the canyons. It thus appears that the water in the zone of saturation in the Capitan limestone does not move southeastward into the upper gypsum beds of the Castile formation or the alluvium of the canyons or fans in the valley of Black River. On the contrary, if there is any hydraulic connection between the limestone and alluvium in Black River valley, water must move downward into the limestone. However, some water from perched aquifers in the limestone may contribute some of the recharge to the aquifers in the gypsum beds and alluvium.

Some of the water in the zone of saturation in the Capitan limestone near the Carlsbad Caverns might move southeastward into the sandstones of the Guadalupe series; but any movement in this direction is probably slow, because salt water is encountered in these sandstone beds generally within a few miles of the reef escarpment, whereas the water in the Capitan limestone is very low in chloride. Farther southwest from the Carlsbad Caverns water in the Capitan limestone may be moving more freely to the east into the sandstones of the Guadalupe series. An oil-test well located in the NW¼ sec. 9, T. 26 S., R. 24 E., that later was converted into an irrigation well, reportedly develops water from the Bell Canyon formation. The well is cased to a reported depth of 450 feet and finished at a depth of 595 feet. The well is pumped at the rate of 1,000 gallons a minute and yields water having a chloride content of 7 parts per million, a sulfate content of 818 parts per million, and a hardness of 1,030 parts per million. Although most of the water may be coming from the Bell Canyon formation in this well, the low chloride content suggests that the water is coming from the alluvium. Further, the temperature of the water pumped, 68½° F., is about the temperature of that pumped by other wells finished in the alluvium. The water level in the finished well in June 1952 agrees within a few feet of the water level measured in the well in April 1952 when the well was being drilled in the alluvium. It is unlikely that the water in the alluvium and that in the underlying Bell Canyon formation would have about the same head unless there was a general connection between the two aquifers, and this does not seem to be the case in the general area.

Castile Formation

In the valley of the Black River where the alluvium is thin or above the zone of saturation, some water is developed for stock use from wells finished in the gypsum beds of the Castile formation at depths of less than 100 feet. Below this depth the Castile formation is mostly anhydrite, which indicates that no appreciable circulation of ground water has occurred in this part of the section (see p. 17). The water in the gypsum to the north of the Black River moves from near the reef escarpment into the alluvium in the vicinity of the Black River at a gradient of as much as 75 feet per mile in places. South of the Black River also some water moves through the gypsum beds into the alluvium from within a short distance of Black River. Some water probably moves also in a downstream direction through the gypsum beds underlying the alluvium. The water occurs under water-table conditions and is continuous with the water in the alluvium. Water moving through these gypsum beds is very hard and contains 1,200 to 1,500 parts per million of sulfate. The relatively high mineral content distinguishes these waters from those which have moved mostly through the alluvium. Because these waters move into the alluvium, the sulfate content of the water in the alluvium becomes increasingly higher downgradient. Water that enters the Castile formation is derived largely from rainfall in the area, and it is inferred from the small recharge area that the amount of water moving through the Castile formation and into the alluvium is small compared to that which moves almost entirely through aquifers in the alluvium.

Alluvium

The water in the alluvium of the upper Black River valley probably is derived primarily from floodwaters in the larger canyons heading in the Guadalupe Mountains, although, as stated previously, smaller amounts of water move out of the gypsum beds into the alluvium. Some water is derived also from direct precipitation on the alluvium, and probably some water finds its way into the alluvium in the canyons as discharge from perched water-bearing beds in the Capitan and Carlsbad limestones. The water in the alluvium in the mountains moves into the alluvial fans and through them toward the alluvium of the Black River valley where, together with the water in the gypsum beds, it moves in a general northeastward direction down the Black River valley in this area. Plate 1 shows the inferred slope and configuration of the water table in the alluvium and adjacent gypsum beds in the vicinity of the present irrigation wells in upper Black River valley. Water-level information is too meager to reveal the precise direction of movement of water in the alluvium between the crossing of Highway 62 over the Black River in sec. 16, T. 25 S., R. 25 E., and Black River Village.

Large yields of water have been obtained from some of the wells finished in or drilled through various conglomerate beds. Well 25.24.27.124 was pumped at the rate of 1,240 gallons a minute for 9 hours on September 8, 1952, with a resulting drawdown of

10.1 feet. Well 25.24.27.421 had a drawdown of 17.3 feet after being pumped 9 hours at the rate of 1,320 gallons a minute on September 8, 1952. Another well (25.24.34.112a) yielded 450 gallons a minute and had a drawdown of approximately 3 feet. However, in places where the conglomerate is absent, thin, or does not contain fractures, the yields from wells have not been adequate for irrigation purposes.

The chemical quality of the water in the alluvium depends to a large extent on the source of the water. The water moving into the alluvium from adjacent gypsum beds is high in sulfate, whereas water that has moved mostly through alluvium from its source in the canyons is comparatively low in sulfate, as shown in red on plate 1. The wells in the Black River valley in sec. 10, T. 26 S., R. 24 E., yield water high in sulfate, and the water that issues from the headward springs on the Black River in sec. 3, T. 26 S., R. 24 E. is high in sulfate also. Water that moves eastward through the alluvial fans between Rattlesnake Springs and the State line to the south is generally low in sulfate. Irrigation wells 25.24.27.421 and 25.24.34.112a yield water in which the sulfate concentration is about 600 parts per million, which is considerably higher than might be expected if the water moving through the aquifer in this locality had been restricted entirely to the alluvium. It suggests that upgradient the alluvium is thin in places and that water may move for some distance through underlying gypsum beds. Between Rattlesnake Canyon and Walnut Canyon north of Black River, the water is moving toward the Black River largely through gypsum beds and has a concentration of about 1,500 ppm of sulfate. In the alluvium adjacent to the Black River as far east as the crossing of Highway 62 in sec. 16, T. 25 S., R. 25 E., water containing only 530 parts per million of sulfate has been encountered but is probably flanked by more gypsiferous water that moves in from either side through aquifers in gypsum beds.

The dry-weather flow of the Black River and the flow of the various springs in the valley are dependent on the water in the alluvium. Changes in storage of water in the alluvium result in change in flow of the various springs and Black River. In addition to natural changes in storage caused, in part, by variations in recharge, the storage is now decreased by pumping of the water from wells in the area.

Relation of the Flow in the Upper Perennial Stretch of Black River to Water in the Alluvium

The upper perennial stretch of the Black River between the headward springs in the SE¼ sec. 3, T. 26 S., R. 24 E., and the point of observed maximum flow near the NW¼ sec. 25, T. 25 S., R. 24 E., coincides roughly with a line of gypsum exposures along the right bank of the river. In the SE¼ sec. 26, T. 25 S., R. 24 E., exposures of gypsum occur immediately west of the Black River. These conditions suggest that the water moving through the thicker alluvium to the south and west is forced to the surface in the stretch where the apparently less permeable gypsum beds are at or very near the surface. Farther downstream, where exposures of conglomerates and other alluvial material occur in the valley, the alluvium is evidently thicker and more extensive, and the stream begins to lose water, the flow disappearing into sand, gravel, travertine, and conglomerate in the NE¼ sec. 24, T. 25 S., R. 24 E. Some water may move as underflow in the shallow fill below the river, but a larger part of the water probably moves through the thicker alluvium a short distance west of the river in this upper perennial stretch.

The flow of the headward springs of the upper perennial stretch of the Black River appears to have declined from about 1.0 cfs in the latter part of 1953 to about 0.7 cfs in the early part of 1954 (see fig. 3). The decline in flow caused by natural changes in storage probably has not been appreciable during the past year. In wet years, however, the discharge may be far greater than the 1.0 cfs measured in 1953. If the drought conditions persist, the flow of the springs will continue to diminish but at a slow rate. Pumping in the locality probably has had a greater effect on the flow of the headward springs than the drought conditions.

Pumpage from wells that appear to draw their water primarily from the alluvium in secs. 9 and 10, T. 26 S., R. 24 E., south and southwest of the upper perennial stretch of the Black River, amounted to approximately 530 acre-feet in 1953, or a yearly average of about 0.7 cfs. Of this amount an estimated 30 percent of the water might be returned to the ground-water body and the net withdrawal then would be about 0.5 cfs.

The coefficient of transmissibility of the aquifer in the alluvium in this area, based on the yield of the headward springs of about 1 cfs, the gradient of the water table south of the springs of about 25 feet per mile, and a contributing cross-section about 1 mile wide, would appear to be about 25,000 gallons a day per foot. (The coefficient of transmissibility is expressed here as the gallons a day that would be transmitted through a vertical section of the aquifer 1 foot wide under a unit hydraulic gradient or the quantity that would move through a section of the aquifer 1 mile wide under a gradient of 1 foot per mile). The coefficient of storage is assumed to be about 0.2, which is the order of magnitude of the storage coefficient for unconsolidated alluvium under water-table conditions. (The coefficient of storage may be expressed as the volume of water in cubic feet released from storage in a column of the aquifer with a cross-section of 1 square foot when the water level is lowered 1 foot). The effective center of pumping is in the SE¼NE¼ sec. 9, T. 26 S., R. 24 E., about 2,600 feet north of well 26.24.9.441 and about 6,600 feet from the headward springs.

On the basis of the estimated coefficient of transmissibility of 25,000 gallons a day per foot and a coefficient of storage of 0.2, the drawdown at the headward springs would be about 0.26 foot at the end of 2 years of pumping and in well 26.24.9.441 about 1.6 feet at the end of 1953, the second year of pumping from the wells in this area. The water level in well 26.24.9.441 declined about 2.8 feet during the past 2 years (fig. 6). The difference in the observed decline and that estimated to be caused by pumping in the area represents the natural decline in water levels at this well and apparently amounts to 1.2 feet for the two-year period. A natural decline in water levels also has occurred in the water table in the vicinity of the headward springs but the magnitude of the decline is not known. Thus the diminution in the flow of the headward springs is a combination of the natural decline in head and the decline caused by pumping in the area.

Probably more than half of the water pumped in the area in the next few years will be taken from storage in the aquifer, and water levels will continue to decline in this area during this period, but at a decreasing rate. The diminution of the spring flow due to pumping will probably be less than 0.3 cfs during the next few years, but eventually the diminution should approach 0.5 cfs if the pumping rate were to remain about the same as at present.

Diversion of water from the Black River in the upper perennial stretch for use in the irrigation of lands in the vicinity of Rattlesnake Springs is accomplished by means of two diversion dams. The upstream diversion dam, the larger of the two, is in the NW¼ NE¼SW¼ sec. 35, T. 25 S., R. 24 E. Considerable water can be held behind the dam as surface storage, and as ground-water or bank storage. Diversion is by gravity flow through a canal and hence the rate of diversion varies with the level of the pool behind the dam. During the irrigation periods, water is diverted at a rate appreciably greater than the normal flow of the stream. The rate of flow of diverted water near the end of the irrigation season often is considerably less than the rate at the beginning of the season because the level of the pool has declined and not necessarily because of diminution in the natural stream-flow. The other diversion dam, in the NE¼NW¼SW¼ sec. 24, T. 25 S., R. 24 E., can hold very little water in storage. The water diverted at this point is essentially the natural flow of the stream and generally ranges between 1 and 3 cfs.

Rattlesnake Springs

Rattlesnake Springs issue as a series of faint boils through the sandy bottom of a small developed pool situated on the flats of Nuevo Canyon Draw in the SW¼ sec. 23, T. 25 S., R. 24 E. (fig. 2). A covered concrete sump has been constructed in the pool from which water is drawn and pumped to the Carlsbad Caverns for domes-

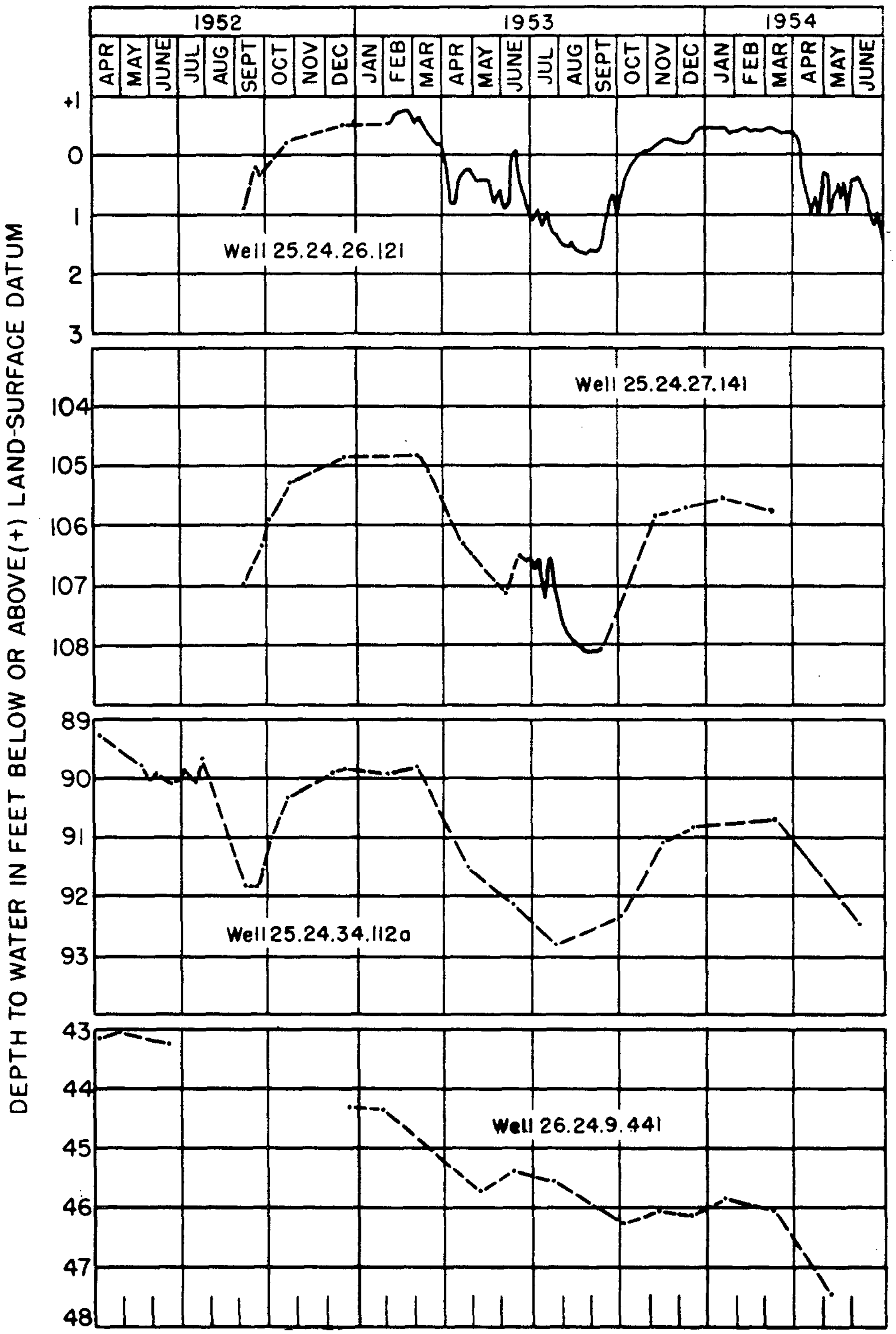

Figure 6.--Hydrographs of selected observation wells in upper Black River valley, Eddy County, N. Mex., 1952-54. (Periodic measurements represented by dots.)

tic use. The National Park Service estimates that 35,000 gallons a day is pumped to the caverns during the summer by the high-pressure pump which operates intermittently at 60 gallons a minute.

The flow of Rattlesnake Springs can be diverted through two ditches known as the north and south ditch for the irrigation of nearby lands, or the water can be discharged out the east or main outlet down the natural channel where it can be ponded behind small dams constructed across the channel or allowed to flow on eastward to the Black River (fig. 7). The flow can be controlled temporarily by adjusting the size of the openings of the submerged slide head-gates at the various outlets, but the long-period flow is the natural flow of the springs. The pool surface usually fluctuates a foot or more in response to the control by the gate openings, but the average altitude of the pool surface is about 3,635 feet, about 0.5 foot below that of the encircling stone wall. Periodic measurement of the discharge from Rattlesnake Springs at monthly intervals was begun in April 1952. The discharge is measured under conditions as they exist at the time of the regular visit; that is, the discharge may be measured in any one or both of the ditches and main outlet within 50 feet of the pool. The stage and flow of the springs are allowed to stabilize for several hours prior to measurement of the discharge, but the stage of the pool at time of measurement of the spring flow has differed somewhat from month to month. If complete stabilization is reached, the flow at any stage would be the actual flow from the springs. Thus, although the discharge measurements of the springs were not made from month to month with the same pool stage and the discharges therefore are not strictly comparable, the error caused by the difference in stage probably is not very large. From April 1952 to June 1954, the observed flow of the springs has varied between 1.7 and 4.2 cfs. The flow is at a minimum during the irrigation season and largest during the late winter and early spring (see table 4 and fig. 3). In general, the stage of the pool is somewhat higher in the winter and spring than at other times of the year.

The mineral content of the water issuing from the springs is about the lowest existing in the area (see table 3 and pl. 1). The water has a bicarbonate content of about 290 parts per million, a sulfate content of 120 parts per million, and a chloride content of 6 parts per million. Several partial analyses made of the spring waters at different times indicate no significant change in the quality of the water in the past few years.

<u>Source of the Springs</u>.--The water that issues from Rattlesnake Springs discharges from a conglomerate through overlying sand and gravel and into the spring pool. In the area around the springs in Nuevo Canyon Draw the conglomerate is overlain by silt and clay and the water in the conglomerate is under slight artesian pressure. This particular conglomerate may be

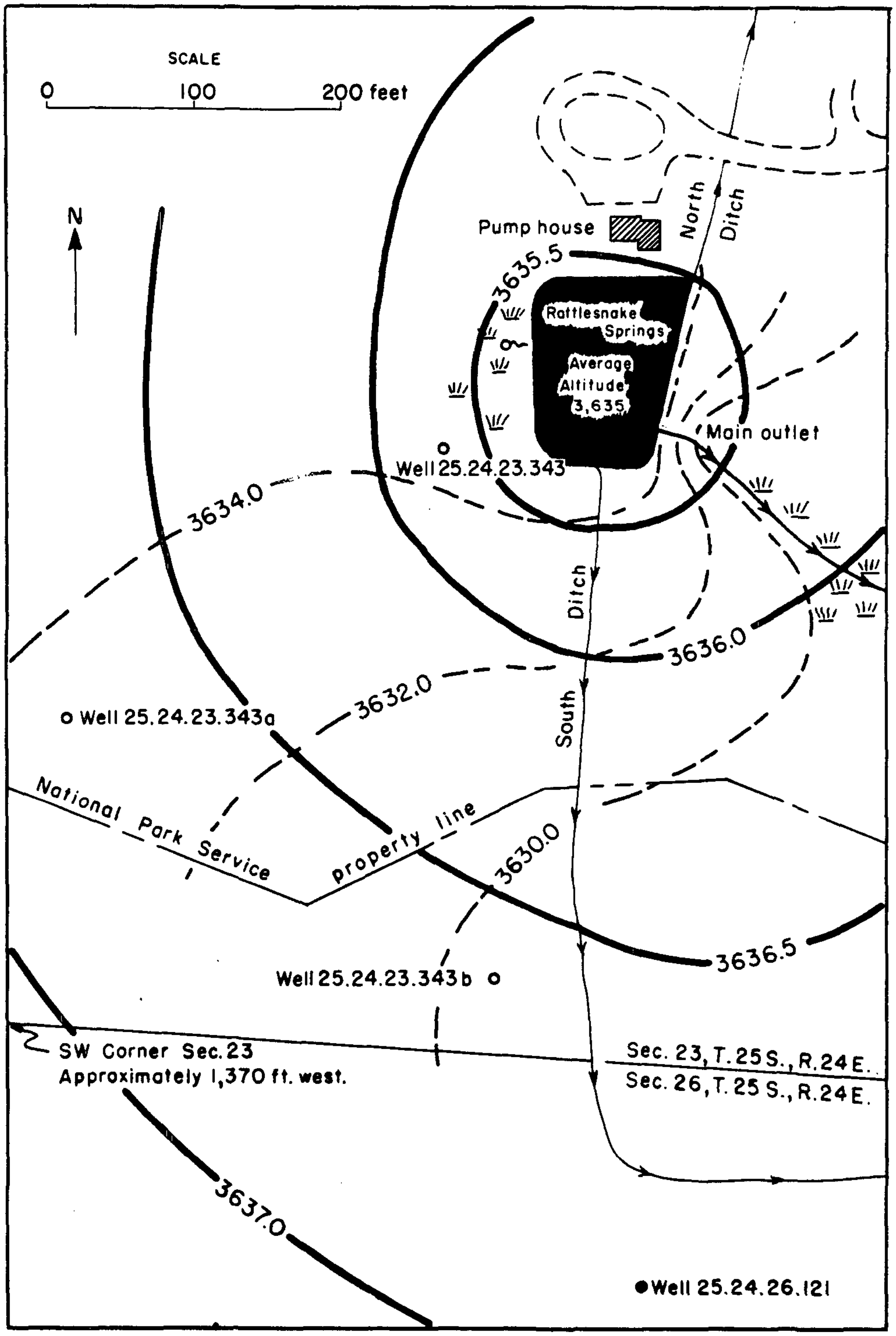

Figure 7.--Altitude and configuration of the piezometric surface (solid line contours) of the conglomerate aquifer and the water table (dashed contours) in the silts in the vicinity of Rattlesnake Springs, Eddy County, N. Mex. (Wells in silt, open circles; well in conglomerate, solid circle.)

cut off to the northeast and abut against clays; at least, the movement of water is so restricted by some means that most of the water in the aquifer to the west discharges at Rattlesnake Springs. A small volume of the water from the springs moves from the pool into the adjacent silts, as shown by the altitude of the water level in a few shallow observation wells finished in the silts. The inferred altitude and configuration of the piezometric surface of the water in the conglomerate and the water table in the silts in the vicinity of Rattlesnake Springs are illustrated in figure 7.

About 550 feet south of Rattlesnake Springs, well 25.24.26.121, which was dug and blasted into the conglomerate, taps the same aquifer as the springs. Detailed fluctuations of water level were obtained from a recording gage installed on this well. The water level is, in general, about 1 foot above the level of the pool at Rattlesnake Springs, and fluctuates in phase with the pool level. However, the water level in this well also fluctuates in phase with the discharge from the springs at constant pool level; that is, the elevation of the water level in the well lowers with respect to the pool level as the discharge from the springs decreases. This relation is illustrated as a graph in figure 8. The altitude of land-surface datum at this well is 3,636.4 feet.

The departure of individual control points from the straight line in figure 8 is caused mostly by the difference in the stage of the pool of Rattlesnake Springs from measurement to measurement and hence in the water level in the well. A straight line relation between the change in water level in the well and the discharge of the pool should hold for all discharge rates. Using the graph, the inferred water level in well 25.24.26.121 at a time when no flow would occur from Rattlesnake Springs at a pool stage of 3,635 feet above sea level would be more than 1 foot below the pool level. If the water level in well 25.24.26.121 under conditions of no flow from Rattlesnake Springs were below the pool level, it would imply that water may be leaking from the conglomerate aquifer through well 25.24.26.121 into the overlying silts, resulting in a lower head, or that some of the water in the conglomerate is bypassing Rattlesnake Springs. If the pool of Rattlesnake Springs were maintained at a constant elevation, apparently a fairly accurate rating curve based on the elevation of the water level in well 25.24.26.121 could be developed for the flow of the springs and could be used to determine this flow at times when discharge measurements were not made.

The source of the water in the conglomerate discharging water at Rattlesnake Springs must be from the direction of higher head and the principal source must furnish water of good chemical quality. The source is inferred from three types of data - namely, the quality of the water, the altitude of water levels in nearby wells with respect to the springs, and the fluctuations in the discharge of Rattlesnake Springs in relation to the pumping of nearby wells.

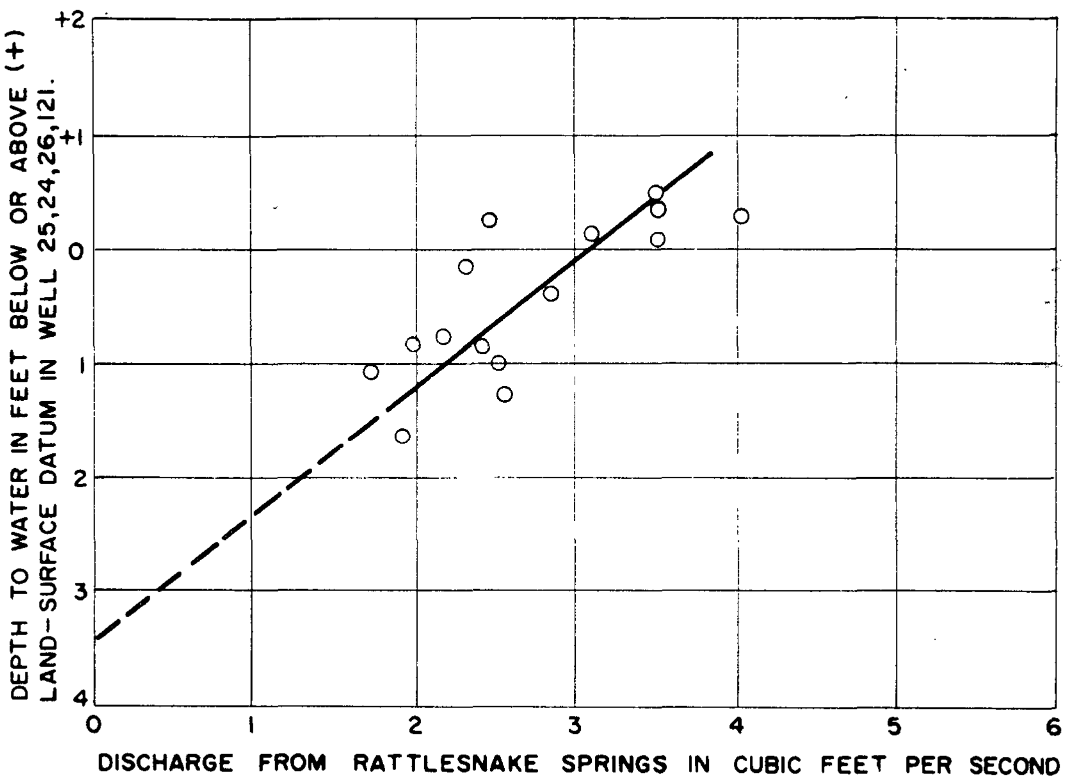

Figure 8.--Relation between stage of well 25.24.26.121 and the flow of Rattlesnake Springs, Eddy County, N. Mex.

In general, altitudes of water levels in wells in the alluvium and gypsum beds to the south, west, and north of the springs are higher than the pool of Rattlesnake Springs, and to the east and northeast are lower; consequently, the water could be derived from the north, west, or south of Rattlesnake Springs. To the north and northwest of the springs, beyond Rattlesnake Canyon, the fill is thin and shallow water occurs only in the gypsum beds which contain water having a sulfate concentration of more than 1,000 parts per million. To the south along Black River, the alluvial fill also contains water high in sulfate. The concentration of sulfate in the water pumped from wells 25.24.27.421 and 25.24.34.112, to the southwest of Rattlesnake Springs, was 621 and 565 parts per million, respectively, which is considerably more than the concentration of sulfate in the spring water. Northwest of these wells and west southwest from the springs, well 25.24.27.124 yields water in which the concentration of sulfate is 39 parts per million, which is considerably lower than that in the spring water. A water sample bailed from the unused well 25.24.27.132 contained 144 parts per million of sulfate. Only to the west and southwest of the springs, therefore, has water of moderate to low concentration of sulfate been found. Thus, on the basis of quality-of-water data, the water emerging from the springs would appear to be derived from the area west to southwest of Rattlesnake Springs.

Well 25.24.26.121, 550 feet south of the springs, fluctuates in phase with the stage of the spring pool, and the spring flow also correlates with the general trend in water levels in this well as observed from a continuous record of water-level stage obtained by a recording gage. About 1 mile west-southwest from this well, detailed fluctuations of water level were obtained by means of a recording gage on unused well 25.24.27.141. Large fluctuations of water level in this latter well are caused by pumping of irrigation well 25.24.27.124 about 1,150 feet to the northeast. Pumping of irrigation well 25.24.27.421, about 3,000 feet east and somewhat south of well 25.24.27.141, also causes minor fluctuations in the two observation wells (25.24.26.121 and 25.24.27.141), but the effect is masked when well 25.24.27.124 is being pumped. The trend in water level in well 25.24.27.141 parallels the trend of the water level in the well near the springs. Figure 9 shows a plot of the daily fluctuation of water level in wells 25.24.26.121 and 25.24.27.141 for July, August, and a part of September 1953. During the period from July 16 to July 20, when irrigation well 25.24.27.124 was idle, the water levels rose in the two observation wells. It thus seems that irrigation well 25.24.27.124 taps the same aquifer as that discharging water to Rattlesnake Springs, and that the water-bearing bed in which well 25.24.27.421 is finished is also a part of the same aquifer system. Parts of this aquifer system probably have only a limited connection with other parts because of the stringer-like occurrence of the conglomerates, as mentioned in the section describing the geology of the area.

About 0.7 mile southwest of well 25.24.27.421, irrigation wells 25.24.34.112a and 25.24.34.124 pump water of about the same quality as that from well 25.24.27.421. Further, the pattern and magnitude of the water-level fluctuations in these wells and the observation well 25.24.27.141 are similar. It is inferred that pumping of these two irrigation wells, 25.24.34.112a and 25.24.34.124, also will have some effect on the flow of Rattlesnake Springs, even though in a 12-hour test the pumping of nearby wells 25.24.27.124 and 25.24.27.421, produced no observable effect on the water level in these two wells.

Well 25.24.27.132, drilled for irrigation purposes but presently not in use, is about 1,100 feet west of the large producing well 25.24.27.124. Well 25.24.27.132 is reported, when tested in 1952, to have been pumped at 1,200 gallons a minute with no detectable drawdown as measured by an airgage. However, in a test made in 1954, it is reported that the well was pumped dry in a very short time, suggesting that the well has become almost completely sealed off from the aquifer in which it was finished. Although the water level in the well probably does not reflect detailed fluctuations of water level in the aquifer, and so is not an ideal observation well, the general trend of water levels in it are instructive.

The water level in well 25.24.27.132 declined very slowly during the period of observation from an altitude of 3,635.1 feet

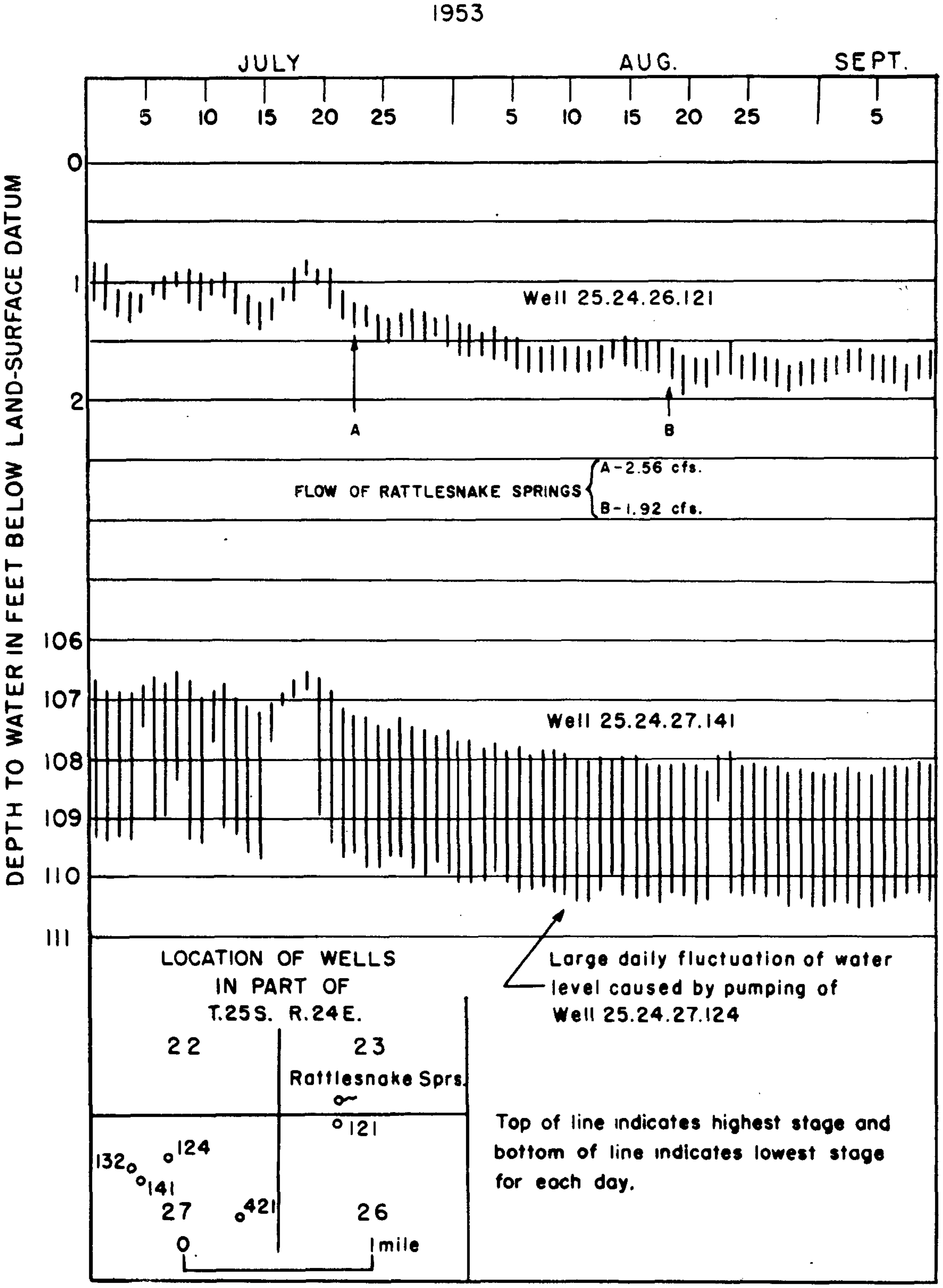

Figure 9.--Relation of daily fluctuation of water level in wells 25.24.26.121 and 25.24.27.141 during July, August, and part of September 1953, Eddy County, N. Mex.

in April 1952 to an altitude of 3,634.6 feet in January 1954. The altitude of the water level on February 1, 1953, was 3,634.9 feet. On the same date, the altitude of the water level in well 25.24.27.124 to the east was 3,642.0 feet, more than 7 feet higher. In well 25.24.26.121 south of Rattlesnake Springs, the water level on February 1, 1953, was at an altitude of 3,636.9, about 2 feet above that of well 25.24.27.132, and the water level in the pool of Rattlesnake Springs was at an altitude of 3,635.2 feet. Pumping of the nearby well to the east (25.24.27.124) has caused no detectable fluctuation of water level in well 25.24.27.132. This suggests that the aquifer tapped by well 25.24.27.132 is independent of, or poorly connected with, the aquifer that discharges water to Rattlesnake Springs. Water in this aquifer probably moves to the northeast, between Rattlesnake Canyon and Rattlesnake Springs.

Effect of Pumping of Nearby Wells on the Flow of Rattlesnake Springs.-- During the 1953 irrigation season from April through part of September, three irrigation wells were in use which draw their water from the aquifer discharging water at Rattlesnake Springs. These wells, 25.24.27.124, 25.24.27.421, and 25.24.34.112a, were pumped, respectively, at 1,240, 1,320, and 450 gallons a minute for an average of about 10.5 hours a day and for an estimated 110 days during the irrigation season. The daily pumping rate of these three wells is about 3.2 cfs, not much less than the winter flow of Rattlesnake Springs. Based on the measured pumping rate and the estimated time pumped, production from these wells was about 700 acre-feet of water between April and September 1953. Assuming a return of 30 percent of the water, the net depletion of the water supply would be about 500 acre-feet during the irrigation season. However, the returned water probably moves toward the river at a shallow depth and does not reach the underlying conglomerate from which the water was pumped, as the conglomerate is overlain by clays having appreciable thickness in this locality.

The discharge from Rattlesnake Springs in March 1953 was 4.0 cfs. By the end of the irrigation season the flow was 1.9 cfs, a difference of 2.1 cfs. Referring to figure 3, if it is assumed that the flow of the springs recovers from pumping effects from year to year, the average flow during the irrigation season might have been approximately 3.8 cfs if no wells had been pumped. However, during the period from April through the middle of November 1953, the average flow appears to have been about 2.5 cfs. This difference of 1.3 cfs for this period amounts to 600 acre-feet and compares reasonably well with the estimated amount of water pumped from wells in the locality. After the close of the irrigation season each year, water levels rise in the area and the discharge of the springs increases and approaches the discharge of the previous winter period. Thus, pumping of the nearby irrigation wells seems to have a definite effect on the flow of the springs. As the discharge from the wells seems to be offset largely by a comparable decrease in the flow of the springs, there should be no appreciable net lowering of water levels in this aquifer from season to season caused by pumping of wells if the volume of water pumped annually remains approximately constant and less than the spring discharge.

Under present conditions of withdrawal, therefore, any persistent change from year to year in the flow of Rattlesnake Springs and water levels in the aquifer tapped by the wells probably would be related more closely to the recharge of the aquifer rather than to withdrawals for irrigation. As precipitation and probably intensity of rainfall have been less than normal in the past few years, the decrease in the flow of the springs of about 0.5 cfs and the decline in water level of about 0.7 foot from March 1953 to March 1954 (figs. 3 and 6) in the vicinity of Rattlesnake Springs probably were caused by deficient recharge.

If the present irrigation wells in the locality were pumped continuously at their present capacities for most of the irrigation season, the spring flow would be reduced appreciably within a few days of the start of pumping and Rattlesnake Springs might be expected to cease flowing in the latter part of the irrigation season. If the pumpage exceeded the spring flow (plus any water that might be salvaged from evaportranspiration in the spring area as a result of lowered water levels), the water levels in nearby wells probably would show net annual declines.

Should the springs cease flowing, shallow wells might be drilled in the spring area to tap the conglomerate. Ample water probably could be obtained for use at the caverns and possibly for irrigation use to take the place of the spring flow. The pumping of any wells drilled in the immediate vicinity of the springs before the spring flow ceased, however, could be expected to decrease the spring flow by the amount of water pumped.

The water issuing from the springs is more highly mineralized than that pumped from well 25.24.27.124 but of better quality than that pumped from wells 25.24.27.421 and 25.24.34.112a. Assuming that the water discharged from the springs represents a mixture of water of these two types, the bulk of the spring discharge is made up of the water having the better quality. Because approximately half the water pumped in the locality is obtained from the aquifer at the point where it yields the more highly mineralized water, the proportion of the water of better quality issuing at the springs might be expected to increase, and the over-all quality to improve, in time. Further, the small amount of the more highly mineralized water required to give the springs the observed sulfate content suggests that some of the more highly mineralized water in the aquifer is bypassing the springs and, if so, it must move northeastward to the east of the springs.

Blue Spring

Blue Spring issues as a series of large boils between broken and slumped blocks of conglomerate. From the point of issue of the spring water in the NE¼NW¼ sec. 33, T. 24 S., R. 26 E., to its junction with a more pronounced drainageway a few hundred yards downstream, the stream channel apparently has been developed in an older channel once filled with a conglomerate. The discharge of Blue Spring has been measured at monthly intervals since October 1952 at a point about 1 mile east of the spring area and above any diversions from Blue Spring Creek. During the period from October 1952 to June 1954, the observed flow has ranged from 10.8 to 13.8 cfs (see fig. 3). The fluctuation of the flow has shown no definite cyclic pattern during the short period of observation. The quality of water issuing from the spring is fair compared with the quality of that obtained in some of the stock wells to the west. The water has a bicarbonate content of 240 parts per million, a sulfate content of 580 parts per million, and a chloride content of 10 parts per million. The temperature of the water at the spring is 66° F.

The source of the water issuing from Blue Spring is not definitely known from the data available, but these data suggest possible sources and eliminate others from further consideration.

The temperature of the spring water is essentially the same as that of water pumped from shallow wells in the locality and thus eliminates any deep-seated source for the spring in the immediate locality. The quality of the water also is better than that which might be expected from deep sources at this site. It therefore appears that the water issuing at the spring is moving through the alluvium and possibly to some extent in the gypsum in the upper part of the adjacent Castile formation. However, the quality of the water suggests that the water has moved mostly through the alluvium.

The magnitude of the discharge from the spring rules out local recharge to the aquifer and suggests recharge over a much larger area such as the upper Black River valley and the canyons in the Guadalupe Mountains. Further, the dry-weather flow in the Black River above the junction with Blue Spring Creek is less than 0.5 cfs, far less than the flow in the perennial stretch of the Black River near Rattlesnake Springs and that of Rattlesnake Springs farther upstream. Blue Spring could be the discharge point for those waters, but additional water is required to make up the observed flow at Blue Spring.

Although there are areas of alluvium of unknown thickness to the north and northwest of Blue Spring, the many exposures of gypsum in that locality suggest that the alluvium is thin, and although a large volume of water could move a short distance through a large solution channel in the gypsum without acquiring a high sulfate concentration, it seems more likely that the source of the water of Blue Spring is the alluvium to the southwest, up the valley of the Black River. Assuming that the average discharge from Blue Spring of approximately 12 cfs represents the entire discharge of ground water from the upper Black River valley, some inferences as to the amount of water moving through various parts of the alluvium upstream from Blue Spring can be made.

Between Blue Spring and the highway crossing over Black River, about 7 miles southwest of the spring, the few stock wells in that area yield water having a sulfate content of about 1,500 parts per million. It is apparent that these wells are not situated in that part of the alluvium having the water of better quality, but this high-sulfate water probably is contributing a small part of the flow of Blue Spring. Well 25.25.16.141 near the highway crossing over Black River yields water containing 530 parts per million of sulfate from the alluvium. Inasmuch as the contour map (pl. 1) suggests that water in the alluvium and gypsum beds in the Black River valley above the highway crossing seems to converge and flow through the alluvium at the highway crossing, the water from well 25.25.16.141 may represent the average quality of water moving through the alluvium in the valley at the highway crossing. On the basis of the quality of the water in that well, and that of the water of Blue Spring, it is estimated that less than 1 cfs of the high-sulfate water in the intervening area could be added to the water moving through the alluvium at the highway crossing to yield the quality of water issuing at Blue Spring. This would mean that about 11 cfs moves through the alluvium at the Highway 62 crossing over the Black River. At the highway crossing, the saturated part of the alluvium is about 0.25 mile wide and probably less than 50 feet thick. With a water-table gradient of 45 feet to the mile (determined from the contours in pl. 1), the alluvium would need to have a coefficient of transmissibility of the order of 600,000 gallons a day per foot. This is a very high value and suggests the occurrence of water in channels in a conglomerate rather than in uniformly permeable gravel or sand. A network of passageways in a conglomerate would not need to have a very large cross section to transmit 11 cfs under the prevailing hydraulic gradient.

Of the 11 cfs possibly moving through the alluvium at the highway crossing over the Black River, about 4.5 cfs can be accounted for in the loss of visible flow in the upper perennial stretch of the Black River and Rattlesnake Springs. Rattlesnake Springs has an average flow of about 3 cfs which, together with the small amount of unmeasured discharge that enters the silts around the pool and allowing for some loss by evapotranspiration, might amount to a net recharge to the alluvium downstream of approximately 2.5 cfs. The discharge of the Black River in the upper perennial stretch, at the point where the maximum dry weather flow occurs, is approximately 2.0 cfs. The underflow in this reach of the Black River and in the thicker alluvium immediately west of the stream might amount to an additional 0.5 cfs. The total volume of water of the quality similar to that in the upper stretch of the Black River thus may be as much as 2.5 cfs. During the period from September 1953 through July 1954, eight water samples were collected at 1- to 3-month intervals from the Black River above the lower diversion dam. The sulfate content of the water ranged between 1,170 and 1,320 ppm and averaged approximately 1,250 ppm. Commingling of 2.5 cfs of water from Rattlesnake Springs, which has a sulfate concentration of 120 parts per million, and 2.5 cfs of Black River water, which has a sulfate concentration of 1,250 ppm, would give an estimated sulfate concentration of about 700 parts per million, which is higher than that occurring in the alluvium at the highway crossing. The difference between the estimated flow in the alluvium at the highway crossing of 11 cfs, and the contribution from Rattlesnake Springs and the upper perennial stretch of the Black River and adjacent alluvium of about 5 cfs, is about 6 cfs. Thus about 6 cfs of ground water from sources other than that supplying water to Rattlesnake Springs and the alluvium adjacent to the upper perennial stretch of the Black River is inferred to be moving down the valley of the Black River. The sulfate content of the mixture of water of 6 cfs from these other sources would be about 380 parts per million.

A part of this unaccounted-for flow of 6 cfs must move toward the Black River through the gypsum beds in the area north of Rattlesnake Canyon and west of Highway 62. The water in this area has a sulfate content of approximately 1,500 parts per million, but the amount of water is small, possibly 0.5 cfs. Also, water with a sulfate concentration of 140 parts per million would move between Rattlesnake Canyon and Rattlesnake Springs through the alluvium independently of that issuing at Rattlesnake Springs (see p.33). To the south of Rattlesnake Springs, part of the water in the aquifer tapped by wells 25.24.27.421 and 25.24.34.112a and which has a sulfate content of 650 parts per million may be bypassing Rattlesnake Springs. If water from the three different sources is assumed to contribute a total of 6 cfs of the water moving through the alluvium at the highway crossing over the Black River, then approximately 4.0 cfs must be contributed by the aquifer between Rattlesnake Canyon and Rattlesnake Springs and about 1.5 cfs must move through the alluvium south of Rattlesnake Springs, bypassing those springs.

In summary, on the basis of the above assumptions, data, and calculations, it is concluded that about 4.5 cfs of the water issuing at Blue Spring could be contributed by the surface flow lost to the alluvium in the upper perennial stretch of the Black River and Rattlesnake Springs, about 0.5 cfs from the underflow of the Black River in this stretch and the alluvium immediately west of the river, about 1.5 cfs from water moving through the alluvium immediately south of Rattlesnake Springs and bypassing the springs, about 4 cfs from the alluvium between Rattlesnake Springs and Rattlesnake Canyon to the north, and about 1.5 cfs in the gypsum beds between Rattlesnake Canyon and Blue Spring.

The calculated quantities of water moving through the alluvium at various places in the upper Black River valley, based on the quality of the water and the observed surface flow, cannot be relied upon at present with much assurance. They merely serve as a general indication of the sources of water in the alluvium. As additional data are acquired, the interpretation of the source of the water issuing at Blue Spring may be altered somewhat, but it seems likely that at least the visible flow in the upper Black River valley that seeps into the alluvium is being discharged at Blue Spring. A decrease in the amount of surface water seeping into the alluvium in upper Black River valley caused by increased diversion for irrigation or by a decrease of the spring flow in the Black River or Rattlesnake Springs may be expected to decrease the flow of Blue Spring in time. The net diminution in the ground-water supply caused by pumping of irrigation wells in the upper Black River valley in 1953 was on the order of 1 cfs. The change in the supply of ground water caused by changes, if any, in the diversion of surface water in the area in the past few years is not known. If the water in the alluvium between Blue Spring and the highway crossing over the Black River occurs under water-table conditions and is moving in rather open channels in a conglomerate, a decrease in the volume of water moving through the alluvium in the upper Black River valley might be reflected by a smaller discharge at Blue Spring within a few months' time. If, however, the water is under artesian conditions in this stretch (which is not likely) or the water moves through a much wider cross section of lower permeability, the effect of a decrease in movement of water in the upper Black River valley may not cause a measurable change in the flow of Blue Spring for several years.

CONCLUSIONS

1. Rattlesnake Springs represent the discharge from an aquifer in the alluvium whose source is considered to be southwest of the springs. Three presently used irrigation wells tap this aquifer and the pumping of these wells has a definite effect on the spring flow. Increased use of these irrigation wells and withdrawals from any new wells in the same locality as these existing wells will result in a further decline in the flow of Rattlesnake Springs.

Although there was a net decline in the spring flow between March 1953 and March 1954, that decline probably was caused mostly by decreased recharge to the aquifer resulting from below-normal precipitation rather than incomplete recovery from the effects of the pumping of wells in the irrigation season.

If Rattlesnake Springs should cease to flow as a result of large diversions from the aquifer, a shallow well probably could be drilled to the conglomerate that could supply the needs of the Carlsbad Caverns. An additional well or two also might take the place of the flow of the springs now used to irrigate lands in the locality. Any such wells drilled in the spring area before the springs ceased flowing would certainly decrease the flow or completely dry up the springs. If the springs dry up, water levels in the area probably would begin to show a net decline from year to year, as water would be drawn from storage within the aquifer.

2. Blue Spring probably is the principal discharge point for the water in the alluvium and upper gypsum beds of the Castile formation in the part of the Black River valley west of Blue Spring. If water moving down the Black River valley between the highway crossing over the river and Blue Spring occurs mainly under water-table conditions and in a few channels in conglomerate, then a change in the flow of water in the alluvium in the vicinity of the highway crossing might be reflected in a change in the flow of Blue Spring within a few months.

If present withdrawal of water by wells from the alluvium in the upper Black River valley is maintained at about 1 cfs annually, the average discharge from Blue Spring may be expected eventually to decline by about 1 cfs owing to this pumping. The seasonal variation in the flow may be greater and, owing to the lag in the effects from the upper valley, the discharge from Blue Spring may reach a minimum after the close of the irrigation season. A change in the use of surface water from the upper perennial stretch of the Black River and from Rattlesnake Springs also eventually would result in a change in the flow of Blue Spring. Inasmuch as the amount of surface water diverted for irrigation from these two sources is not known, the fluctuation in the flow of Blue Spring caused by this diversion of water is not known and a detailed interpretation of variations in the flow of Blue Spring is not possible at this time.

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TABLES

Table 1

Records of wells in upper Black River valley, Eddy County, N. Mex.

1. Location number designates well and its location. (See page 6 for explanation of well-numbering system.
2. Reported depths are given to the nearest foot, measured depths are given to nearest 0.1 foot.
3. Symbols for use: D, domestic; I, irrigation; U, unused; O, observation; S, stock.
4. R, reported yields. Yield given is that normally pumped.
5. Symbols for method of lift: ET, electric motor driven turbine; GT, gas motor-driven turbine; J, jet; N, none; W, windmill.
6. Altitudes determined by instrumental leveling are given to nearest 0.1 foot. Other altitudes determined by aneroid or estimated from topographic map are given to nearest foot above sea level.

Location number (1)	Name or owner	Depth of well (ft.) (2)	Diameter (in.)	Principal aquifer	Use (3)	Yield (gpm) (4)	Method of lift (5)	Year completed	Altitude of land surface (ft.) (6)	Water Level: Below land surface (ft.)	Water Level: Date of measurement	Measuring point: Description	Measuring point: Distance above land-surface datum (ft.)
24.26.32.123	Wm. Foley	200	8	Alluvium	D,S	-	W	-	3,435	109.4	Dec. 1, 1948	Top of wood block	0.5
25.23.34.444	Anna Colwell	130	6	do.	S	-	W	-	4,160	129.3	Jan. 19,1948	Top of casing	2.35
25.24.11.211	-	46.0	6	Castile (?) formation	S	2	W	-	3,763	29.9	June 8, 1952	Top of casing	.3
25.24.16.410	-	-	6	Alluvium	S	-	W	-	3,800	55.5	May 16, 1952	do.	1.0
25.24.19.421	-	-	10	do.	S	-	W	-	3,950	127.8	May 16, 1952	do.	1.2
25.24.23.343	National Park Service	3.5	4	Alluvium (sand & gravel)	O	-	N	1952	3,635.5	1.1	Mar. 5, 1953	do.	.4
25.24.23.343a	Do.	18.0	4	Alluvium (silt)	O	-	N	1952	3,638.3	4.9	Mar. 5, 1953	do.	1.6
25.24.23.343b	Do.	7.5	4	do.	O	-	N	1952	3,634.8	5.2	Mar. 5, 1953	do.	1.9
25.24.26.121	State Dept. of Game and Fish	15.4	24	Alluvium (conglomerate)	U	-	N	-	3,636.4	+.5	Mar. 5, 1953	do.	3.0
25.24.26.334	McClure and Hellyer	-	-	Alluvium (?)	S	2	W	-	3,674	36.5	Mar. 5, 1953	Top of concrete base	1.1
25.24.27.124	Do.	150	-	Alluvium (conglomerate)	I	1,240	ET	-	3,738.5	94.6	Mar. 5, 1953	Base of timber pump base	.4
25.24.27.132	George Smart	137.0	10	do.	U	1,200R	N	1952	3,753.2	118.3	Mar. 5, 1953	Top of casing	.9
25.24.27.141	Do.	165	22	do.	U	120R	N	1952	3,749.3	104.8	Mar. 5, 1953	Top of wooden platform	1.3
25.24.27.421	McClure and Hellyer	101	16	do.	I	1,320	ET	1951	3,701	56.8	Feb. 1, 1953	Top of casing	.5
25.24.27.423	Do.	100	-	Alluvium	U	-	N	-	3,685	39.1	Apr. 25,1952	-	-
25.24.27.434	Do.	300	-	do.	U	-	N	-	3,696	45.3	Apr. 25,1952	-	-
25.24.31.331	Anna Colwell	230	-	Alluvium	D,S	-	W	-	3,970	168.2	Jan. 19,1948	Top of casing	0.85
25.24.34.112	H. F. Ballard	97	-	do.	D,S	-	W	-	3,727	73.7	Jan. 19,1948	-	.9
25.24.34.112a	Do.	165	12	Alluvium (conglomerate)	I	450	ET	1951	3,739	89.8	Mar. 5, 1953	Top of casing	.9
25.24.34.124	Do.	165	12	do.	I	-	GT	-	3,714	64.5	Mar. 5, 1953	do.	1.5
25.25.4.144	G. R. Pipkin	-	-	Alluvium or Castile formation	S	-	W	-	3,570	53.1	Jan. 19,1948	Top of casing	.4
25.25.4.424	Paul Beedle	48	7	do.	D	-	W	-	3,550	36.5	Jan. 19,1948	Top of 4x4 timber	2.0

Table 1

Records of wells in upper Black River valley, Eddy County, New Mexico.--Continued

Location number (1)	Name or owner	Depth of well (ft.) (2)	Diameter (in.)	Principal aquifer	Use (3)	Yield (gpm) (4)	Method of lift (5)	Year completed	Altitude of land surface (ft.) (6)	Water level: Below land surface (ft.)	Water level: Date of measurement	Measuring point: Description	Measuring point: Distance above land-surface datum (ft.)
25.25.6.343	Old Stone place	10	-	Alluvium	S	-	W	-	3,625	9.0	Jan. 19,1948	Top of 3x3 timber: SE side	1.0
25.25.12.342	R. G. Ozley	65	4	do.	D,S	-	W	-	3,410	33.1	Dec. 1, 1948	Top of casing	.5
25.25.16.141	C. R. Jones	85	8	do.	D	-	J	-	3,470	64.3	Nov. 6, 1953	Top of casing	1.0
25.25.16.144	Do.	-	8	Castile (?) formation	S	-	W	-	3,500	74.5	Apr. 29,1952	do.	1.0
25.26.7.444	R. G. Ozley	70	6	Alluvium (?)	U	-	W	-	3,340	47.1	Dec. 1, 1948	Top of wood block	.5
25.26.19.111	-	-	8	Castile (?) formation	S	-	W	-	3,410	69.9	Nov. 19,1949	Top of casing	1.5
26.24.3.341	A. J. Mayes	121	8	Alluvium	I	-	GT	1946?	3,713	30.1	Apr. 4, 1952	Top of casing	.9
26.24.4.113	-	-	-	do.	S	-	W	-	3,812	115.3	Apr. 27,1952	do.	.5
26.24.9.111	Bradley	595	10	Bell Canyon (?) formation	I	1,250R	GT	1952	3,805	101.9	June 18,1952	do.	3.3
26.24.9.331	Thurman	-	-	Alluvium	U	-	N	-	3,780	65.3	Jan. 26,1948	Top of casing	.7
26.24.9.421	Old School house	-	6	do.	D,S	-	W	-	3,746	49.1	Apr. 2, 1952	Top of casing	.6
26.24.9.441	John Mayes	100	12	Alluvium	I	-	GT	1951	3,749	44.4	Jan. 31,1953	Top of concrete pump base	0.6
26.24.10.131	A. J. Mayes	129	12	do.	I	800R	GT	1950	3,726	33.4	Feb. 1, 1953	Top of casing	1.0
26.24.10.243	A. M. Leeman	100	6	Alluvium (?)	S	-	W	-	3,716	19.2	Apr. 6, 1952	do.	2.2
26.24.10.321	Do.	400±	10	Alluvium and Castile formation		800R	GT	1950(?)	3,724	20R	Apr. 2, 1952	-	-
26.24.10.341	Do.	350±	16	do.	I	-	GT	1951	3,727	25.1	Jan. 31,1953	Top of casing	1.7
26.24.11.314	Do.	60	-	Castile formation	S	-	W	-	3,730	21.9	Jan. 22,1948	Notch in casing	.1
26.24.19.431	Do.	196	-	Alluvium	D,S	-	W	-	3,880	57.7	Jan. 22,1948	Top of 4x4 timber	1.0
26.24.28.413	Do.	90	-	do.	S	-	W	-	3,790	68.6	Jan. 22,1948	Top of casing	1.1

Table 2

Records of springs in upper Black River valley, Eddy County, N. Mex.

1. Location number described in text p. 6. S denotes spring.
2. Altitudes estimated from topographic map given to nearest foot; those determined by instrumental leveling given to nearest 0.1 foot.
3. Estimated yields denoted by E; other yields listed are measured and given in Table 4.
4. Use of water: D, domestic; I, irrigation; U, unused; PS, Public supply; S, stock.

Location number (1)	Name	Altitude (ft.) (2)	Source aquifer	Yield (gpm) (3)	Use of water (4)	Remarks
S24.26.23.441	Castle Springs		Conglomerate	180-270	I	Tributary to Black River. Part of flow is return from irrigated lands.
S24.26.33.122	Blue Spring	3,320	Conglomerate	5,000 - 6,300	I	Issues as large boils.
S25.24.12.324	-	3,640	Gypsum	3E	S	Seeps maintain pool about 500 feet in length.
S25.24.23.343	Rattlesnake Springs	3,636.1	Conglomerate	860 - 1,900	I,PS	Developed springs. Supplies water for use at Carlsbad Caverns.
S25.25.7.244	-	3,560	Gypsum	.5E	S	Seeps maintain small pool.
S26.23.29.332	XT Spring	4,350	Alluvium	50E	D,S	
S26.23.35.121	Geyser Spring	4,120	Alluvium	2,000E	D,S,I	
S26.24.3.423	-	3,675	Alluvium	250E	U	Issues as boil in pool tributary to Black River.

Table 3

Chemical analyses of water from wells, springs, and Black River in Tps. 24-26S., Rgs. 24 to 26 E., Eddy County, New Mexico

(Analyses by U. S. Geological Survey)

Location number described in text on page 6; S denotes spring; R denotes river station. Undesignated number denotes well.

Location number (1)	Name or owner	Date of collection	Parts per million				Specific conductance (micromhos at 25°C)
			Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Hardness as $CaCO_3$	
S24.26.23.441	Castle Springs	10/20/53	231	797	12	-	1,620
S24.26.33.122	Blue Spring	10/27/47	238	580	10	796	1,300
R24.26.35.141	Black River above Blue Spring	9/21/53	248	1,200	11	-	2,140
25.24.11.211	-	9/4/52	200	1,560	16	-	2,520
S25.24.12.324	-	9/4/52	123	1,550	11	-	2,400
25.24.16.410	-	5/16/52	189	1,480	9	1,680	2,420
25.24.19.421	-	5/16/52	274	36	4.5	257	480
S25.24.23.343	Rattlesnake Springs	1/26/48	287	120	6	362	651
Do.	do.	4/6/52	283	-	6	362	673
R25.24.24.332	Black River	4/25/52	224	672	7	848	1,410
R25.24.25.111	Above lower diversion	11/16/53	221	1,230	7	-	2,110
25.24.26.121	State Department of Game and Fish	10/1/52	286	105	6	333	619
25.24.26.334	McClure and Hellyer	5/15/52	220	1,410	7	1,580	2,320
25.24.27.124	do.	6/18/52	296	39	5	283	523
25.24.27.132	George Smart	5/15/52	259	144	16	351	694
25.24.27.421	McClure and Hellyer	4/6/52	252	621	8	840	1,380
25.24.31.331	Colwell Ranch	5/15/52	287	72	10	306	578
25.24.34.112a	H. F. Ballard	4/4/52	243	565	10	774	1,310
R25.24.35.143	Below upper diversion	9/21/53	231	1,280	7	-	2,190
25.24.35.321	Black River	4/25/52	200	1,080	7	1,250	1,920
25.25.12.342	R. G. Ozley	11/20/53	-	1,520	1	-	2,050
25.25.16.141	C. R. Jones	11/6/53	259	527	5	750	1,040
R26.24.3.244	Near Mayes ranch	9/21/53	222	1,290	7	-	2,200
26.24.3.341	Arthur Mayes	6/18/52	230	1,110	9	1,350	2,010
S26.24.3.423	-	5/14/52	200	1,260	8.5	1,440	2,160
26.24.3.424	-	5/14/52	229	1,450	8	1,660	3,370
R26.24.3.440	Black River	4/6/52	136	1,690	7	1,860	2,590
26.24.4.110	-	5/15/52	275	29	7	253	482
26.24.9.331	Thurman ranch	1/26/48	296	647	14	920	1,520
26.24.10.131	Arthur Mayes	4/6/52	228	1,270	8	1,480	2,170
26.24.10.243	A. M. Leeman	4/24/52	223	1,610	28	1,770	2,640
26.24.10.321	do.	4/6/52	238	1,480	8	1,740	2,460
S26.24.11.122	Bottomless lakes 1/	1/22/48	238	1,560	10	1,830	2,540
Do.	2/	4/6/52	132	-	42	3,260	4,270
26.24.11.314	A. M. Leeman	1/22/48	215	1,560	11	1,810	2,540
26.24.28.413	do.	1/28/48	252	134	8	358	653

1/ Collected from spring (dry in April 1952).
2/ Collected from pond.

Table 4

Periodic measurement of flow of Blue Spring, Castle Springs, Rattlesnake Springs, and Black River, Eddy County, New Mexico.

Measurements made by Geological Survey, unless otherwise noted.

(Discharge, cubic feet per second)

Name and location	Blue Spring Creek, above all diversions C, SW¼, sec. 27, T. 24 S., R. 26 E.	Castle Springs, above Black River village. SE¼SE¼, sec. 23, T. 24 S., R. 26 E.	Rattlesnake Springs. SE¼SW¼, sec. 23, T. 25 S., R. 24 E.	Black River, above mouth of Blue Spring Creek. SE¼NW¼ sec. 35, T. 24 S., R. 26 E.	Black River, below lower diversion dam, at road. SE¼NW¼, sec. 24, T. 25 S., R. 24 E.	Black River, above lower diversion dam. NW¼NW¼, sec. 25, T. 25 S., R. 24 E.	Black River, below upper diversion dam. SE¼NW¼, sec. 35, T. 25 S., R. 24 E.	Black River, below Mayes Ranch. NE¼SE¼, sec. 3, T. 26 S., R. 24 E.
1952								
Mar. 11	12.6	-	-	-	-	-	-	-
Apr. 25	13.3	-	a3.5	-	-	-	-	-
May 15	-	-	3.0	-	-	2.1	2.2	-
June 18	-	-	a3.1	-	-	-	-	-
25	-	-	-	-	0	a1.0	(b)	-
July 21	-	-	3.7	-	-	-	-	-
Aug. 1	-	-	2.4	-	.5	1.9	(b)	-
Sept. 5	-	-	a2.0	-	0	-	-	-
24	-	-	-	-	0	3.0	2.0	-
Oct. 15	13.5	-	3.4	-	.1	2.6	2.3	-
Nov. 14	13.2	-	3.9	-	.2	2.7	2.4	-
Dec. 31	11.9	-	4.2	-	.1	2.8	2.3	-
1953								
Jan. 23	13.8	-	3.3	-	.1	2.5	(b)	-
Feb. 20	12.2	-	-	-	1.3	5.6	5.5	-
Mar. 19	12.4	-	4.0	.3	.7	3.2	2.1	.9
Apr. 14	12.5	-	2.5	-	.8	2.6	1.6	-
May 19	12.9	.6	2.9	.2	0	2.5	c.9	1.0
June 16	12.4	.5	-	.3	0	2.4	2.2	.8
July 15	11.5	.4	-	.2	-	-	-	-
July 23	-	-	2.6	-	0	1.6	1.5	1.0
Aug. 24	11.4	.5	1.9	.1	0	.3	d1.0	1.0
Sept. 21	11.1	.3	2.4	.1	0	.6	1.0	1.0
Oct. 20	10.8	.6	2.3	.4	0	1.7	1.5	1.1
Nov. 16	11.3	1.3	-	.5	0	1.8	1.8	.7
27	-	-	3.5	-	-	-	-	-
Dec. 15	13.3	1.6	3.1	.3	0	2.3	2.4	.8
1954								
Jan. 14	12.2	2.3	3.4	.3	0	2.6	2.5	.6
Feb. 18	12.9	1.8	3.4	.3	0	1.9	2.8	.6
Mar. 22	12.6	1.2	2.5	.3	0	1.8	1.8	1.0
Apr. 26	12.5	.6	2.2	1.7	0	1.4	1.9	.7
May 29	11.9	.6	2.0	.3	0	.5	.8	.7
June 17	11.5	.6	1.7	.2	0	1.3	2.0	.7

a. Measurement made by Geological Survey, Ground Water Branch.
b. Diverting water through canal.
c. Recent diversion of water through canal.
d. Pool below level of spillway. No diversion for 3 days.

Table 5

Records of water-level measurements in observation wells in upper Black River valley, Eddy County, New Mexico.

25.24.23.343. National Park Service. Dug, observation well in alluvial sand and gravel, diameter 4 inches, depth 3.5 feet. Water level affected by change in stage of Rattlesnake Springs pool 50 feet to east. Measuring point is top of casing, altitude 3,635.87 feet, 0.4 foot above land-surface datum.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Sept. 6, 1952	2.16	Dec. 17, 1952	.75	July 22, 1953	2.33	Mar. 8, 1954	.41
7	2.25	Feb. 1, 1953	0.28	Aug. 27	2.47	May 6	1.91
12	.49	Mar. 5	1.12	Nov. 10	0.76		
20	2.24	Apr. 23	1.09	Dec. 14	1.02		
Oct. 23	.52	June 5	1.93	Jan. 19, 1954	.45		

25.24.23.343a. National Park Service. Dug, observation well in alluvial silt, diameter 4 inches, depth 18.0 feet. Measuring point is top of casing, altitude 3,639.87 feet,1.6. feet above land-surface datum.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Sept. 5, 1952	6.92	Oct. 23, 1952	5.84	June 5, 1953	6.38	Jan. 19, 1954	5.00
6	6.86	Dec. 17	4.91	July 22	6.76	Mar. 8	4.94
7	6.83	Feb. 1, 1953	4.78	Aug. 27	7.56	May 6	5.66
12	6.52	Mar. 5	4.91	Nov. 10	5.70		
20	6.84	Apr. 23	5.76	Dec. 14	5.37		

25.24.23.343b. National Park Service. Dug, observation well in alluvial silt, diameter 4 inches, depth 7.5 feet. Measuring point is top of casing, altitude 3,636.74 feet, 1.9 feet above land-surface datum.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Sept. 12, 1952	6.55	Feb. 1, 1953	4.78	July 22, 1953	6.72	Mar. 8, 1954	5.04
20	6.45	Mar. 5,	5.21	Nov. 11	5.70	May 6	5.26
Oct. 23	6.24	Apr. 23	5.76	Dec. 14	5.41		
Dec. 17	4.81	June 5	6.44	Jan. 19, 1954	4.22		

25.24.26.121. -/ State Department of Game and Fish. Dug, unused well in alluvial conglomerate, diameter 24 inches, depth 15.4 feet. Measuring point is top of casing, altitude 3,639.39 feet, 3.0 feet above land-surface datum. Recording gage installed Feb. 6, 1953.

Depth to water in feet above (+) or below (-) land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
1952		1952--Con.		1952--Con.		1952--Con.	
Sept. 10	-0.93	Sept. 20	-.19	Sept. 25	-.38	Dec. 17	+0.50
12	-.72	Sept. 24	-0.31	Oct. 23	+.25	1953	
						Mar. 5	+.52

-/ Additional water-level data given in Table 6.

25.24.26.334. McClure and Hellyer. Drilled, stock well in alluvium (?), diameter 6 inches. Measuring point is top of concrete base, altitude 3,675 feet, 1.1 feet above land-surface datum.

Water level in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
June 18, 1952	36.76	Mar. 5, 1952	36.47	Aug. 27, 1953	36.82	Jan. 19, 1954	43.35
Oct. 23	36.50	Apr. 23, 1953	37.38	Sept. 30	37.73	Mar. 8	36.22
Dec. 17	36.24	June 11	37.42	Nov. 12	36.95	May 6	37.85
Feb. 1, 1953	36.69	July 22	36.14	Dec. 14	34.93		

Table 5

Records of water-level measurements in observation wells in upper Black River valley, Eddy County, New Mexico.--Continued

25.24.27.124. McClure and Hellyer. Drilled, irrigation well in alluvial conglomerate, reported depth 150 feet. Measuring point is base of timber pump base, altitude 3,738.9 feet, 0.4 foot above land-surface datum.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 4, 1952	93.56	Sept. 8, 1952	96.60	Feb. 1, 1953	94.46	Jan. 20, 1954	95.19
May 21	94.55	Sept.24	95.99	Mar. 5	94.55	Mar. 8.	95.27
July 2	94.61	Oct. 23	94.94	Apr. 23	95.99	May 6	117.6
15	95.05	Dec. 17	94.53	June 11	96.80		

25.24.27.132. George Smart. Drilled, unused well in alluvial conglomerate, diameter 10 inches, depth 137.0 feet. Measuring point is top of casing and concrete base, altitude 3,754.1 feet, 0.9 foot above land-surface datum.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 4, 1952	118.06	July 22, 1952	117.97	Oct. 23, 1952	118.18	July 22, 1953	118.43
26	118.10	28	118.08	Dec. 5	118.21	Aug. 27	118.47
May 29	118.03	Aug. 10	118.09	17	118.20	Sept. 30	118.57
June 5	118.02	Aug. 27	118.07	Feb. 1, 1953	118.27	Nov. 12	118.55
11	118.03	Sept. 4	118.11	Mar. 5	118.28	Dec. 14	118.62
27	118.05	17	118.10	11	118.28	Jan. 20, 1954	118.56
July 2	118.03	24	118.17	Apr. 23, 1953	118.35	May 6	129.60
15	118.09	Oct. 1	118.13	June 5	118.38		

25.24.27.141. George Smart. Unused drilled well in alluvium, reported depth 165 feet. Measuring point is top of wood platform, altitude 3,750.6 feet, 1.3 feet above land-surface datum.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Sept. 8, 1952	106.98	Mar. 18, 1953	105.11	June 22, 1953	106.52	Nov. 20, 1953	105.81
17	c109.58	Apr. 23	106.33	29	c109.32	Dec. 14	105.73
24	106.34	Apr. 28	c108.30	July 9	c109.36	Jan. 20, 1954	105.59
Oct. 1	105.92	24	106.48	15	c110.14	Mar. 8	105.76
23	105.28	May 1	c108.37	July 22	c110.03	May 6	110.42
Dec. 17	104.89	5	c108.63	Aug. 27	c110.78		
Mar. 5, 1953	104.84	June 5	c109.69	Sept. 30	107.44		
11	104.84	11	107.19	Nov. 12	105.86		

c Nearby well being pumped.

25.24.27.421. McClure and Hellyer. Drilled, irrigation well in alluvium, diameter 16 inches, reported depth 101 feet. Measuring point is top of casing, altitude 3,701 feet, 0.5 foot above land-surface datum. Land-surface datum is 3,701 feet above mean sea level.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 4, 1952	55.68	Sept. 24, 1952	57.61	Feb. 1, 1953	56.07	Jan. 19, 1954	56.66
May 21	55.86	Oct. 23	56.50	Nov. 10	57.05	Mar. 8	57.63
Sept. 8	58.41	Dec. 17	56.10	Dec. 14, 1953	57.12		

25.24.34.112a. H. F. Ballard. Drilled, irrigation well in alluvium, diameter 12 inches, reported depth 165 feet. Measuring point is top of casing, altitude 3,740 feet, 0.9 foot above land-surface datum.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 4, 1952	89.27	July 15, 1952	90.05	Dec. 5, 1952	89.90	Sept. 30, 1953	92.38
May 21	89.76	22	89.65	17	89.80	Nov. 12	91.06
29	90.00	Aug. 27	a94.80	Feb. 1, 1953	89.88	Dec. 15	90.86
June 5	89.94	Sept. 8	91.79	Mar. 5	89.78	Mar. 8, 1954	90.68
11	a93.10	17	91.86	Apr. 24	91.49	May 6	92.45
18	90.11	24	91.51	June 11	92.11		
27	90.02	Oct. 1	91.00	July 22	92.77		
July 2	89.88	23	90.31	Aug. 27	a96.69		

a Pumping.

Table 5

Records of water-level measurements in observation wells in upper Black River valley, Eddy County, New Mexico.--Continued

25.24.34.124. H. F. Ballard. Drilled, irrigation well in alluvium, diameter 12 inches, reported depth 165 feet. Measuring point is top of casing, altitude 3,715 feet, 1.5 feet above land-surface datum.

Depth to water in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 4, 1952	63.84	July 15, 1952	64.59	Oct. 23, 1952	64.12	Aug. 27, 1953	c68.19
May 21	64.39	22	64.16	Dec. 5	64.54	Sept. 30	70.50
29	64.68	Aug. 27	c66.24	17	64.48	Nov. 12	64.60
June 5	64.57	Sept. 4	66.44	Mar. 5, 1953	64.47	Dec. 14	63.60
11	c65.06	24	66.11	Apr. 24	66.20	Jan. 20, 1954	65.24
27	64.64	Oct. 1	65.58	June 11	66.74	Mar. 8	65.33
July 2	64.45	14	65.12	July 22	66.97	May 7	67.06

c Nearby well being pumped.

26.24.9.421. "Old School House"well. Drilled, domestic and stock well in alluvium, diameter 6 inches. Measuring point is top of casing, altitude 3,747 feet, 0.6 foot above land-surface datum.

Water level in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 24, 1952	49.15	Dec. 17, 1952	50.6	Nov. 20, 1953	52.81	Mar. 8, 1954	52.99
June 16	49.64	Feb. 1, 1953	50.99	Dec. 15	53.12	May 7	53.82
Sept. 20	50.61	June 11	52.00	Jan. 20, 1954	52.85		

26.24.9.441. John Mayes. Drilled, irrigation well in alluvium, diameter 12 inches, reported depth 100 feet. Measuring point is top of concrete pump base, altitude 3,750 feet, 0.6 foot above land-surface datum.

Water level in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 4, 1952	43.13	Jan. 31, 1953	44.35	Oct. 2, 1953	46.28	Mar. 8, 1954	46.03
24	43.05	May 5	45.74	Nov. 12	46.01	May 7	47.50
June 16	43.25	June 11	45.38	Dec. 15	46.14		
Dec. 17	44.30	July 22	45.61	Jan. 20, 1954	45.81		

26.24.10.131. Arthur Mayes. Drilled, irrigation well in alluvium, diameter 12 inches, reported depth 129 feet. Measuring point is top of casing, altitude 3,727 feet, 1.0 foot above land-surface datum.

Water level in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 2, 1952	30.3	Feb. 1, 1953	33.37	Oct. 2, 1953	36.06	Mar. 8, 1954	35.68
24	31.48	June 11	34.24	Nov. 12	35.50	May 7	36.63
June 18	31.02	July 22	34.86	Dec. 15	35.51		
Dec. 17	33.7	Aug. 27	35.55	Jan. 20, 1954	35.53		

26.24.10.341. A. M. Leeman. Drilled, irrigation well in alluvium and Castile formation, diameter 16 inches, reported depth 350± feet. Measuring point is top of casing, altitude 3,729 feet, 1.7 feet above land-surface datum.

Water level in feet below land-surface datum

Date	Water level	Date	Water level	Date	Water level	Date	Water level
Apr. 2, 1952	23.75	Dec. 17, 1952	27.30	Dec. 15, 1953	26.38	Jan. 20, 1954	26.18
25	25.69	Jan. 31, 1953	25.10			May 7	26.86
June 18	24.18	June 11	25.76				
Sept. 20	24.67	Nov. 12	26.02				

Table 6

Daily highest and lowest water level in feet above (+) or below (-) land-surface datum in well 25.24.26.121, Eddy County, New Mexico, 1953-54 (from recorder charts). 25.24.26.121. N. Mex. Dept. of Game and Fish. Dug, unused well in alluvial conglomerate, diameter 24 inches, depth 15.4 feet. Measuring point is top of casing, altitude 3,639.39 feet, 3.0 feet above land-surface datum. Recording gage installed Feb. 6, 1953.

1953

Day		Jan.	Feb.	Mar.	Apr.	May	June
1	High			+0.75	+0.21	-0.45	-0.57
	Low			.72	.02	.76	.92
2	High			.74	.09	.64	.78
	Low			.72	- .36	.88	1.04
3	High			.74	.32	.56	.87
	Low			.57	.63	.8[illegible]	1.14
4	High			.57	.47	.45	.97
	Low			.53	.60	.56	1.15
5	High			.53	.37	.46	.93
	Low			.51	.63	.60	1.12
6	High			.56	.48	.47	.89
	Low			.50	.75	.57	1.14
7	High		+0.54	.61	.57	.39	.91
	Low		.42	.56	.85	.51	1.08
8	High		.61	.62	.71	.32	.70
	Low		.54	.58	.98	.46	.91
9	High		.62	.66	.83	.26	.60
	Low		.61	.62	1.08	.44	.94
10	High		.63	.66	.86	.40	.78
	Low		.62	.65	1.00	.53	.99
11	High		.64	.66	.67	.36	.43
	Low		.60	.65	1.01	.52	.79
12	High		.60	.64	.69	.32	.25
	Low		.58	.51	1.02	.50	.43
13	High		.66	.51	.90	.42	.14
	Low		.58	.45	1.12	.64	.25
14	High		.68	.45	.94	.48	.08
	Low		.66	.39	1.07	.64	.14
15	High		.70	.39	.87	.39	.06
	Low		.58	.37	1.01	.48	.14
16	High		.66	.37	.75	.37	.04
	Low		.65	.36	.87	.45	.13
17	High		.69	.37	.57	.30	.01
	Low		.66	.36	.78	.38	.04
18	High		.74	.39	.47	.31	+ .01
	Low		.69	.32	.57	.39	- .00
19	High		.76	.32	.46	.34	+ .03
	Low		.73	.29	.55	.46	- .02
20	High		.73	.32	.38	.40	+ .02
	Low		.71	.30	.53	.52	- .19
21	High		.71	.42	.38	.36	.19
	Low		.69	.32	.45	.51	.37
22	High		.70	.39	.35	.40	.21
	Low		.72	.32	.45	.86	.46
23	High		.75	.35	.26	.75	.30
	Low		.73	.32	.32	.99	.55
24	High		.75	+ .41	.31	.84	.35
	Low		.73	- .02	.44	.95	.59
25	High		.74	+ .22	.27	.84	.49
	Low		.72	- .28	.50	1.17	.62
26	High		.74	+ .30	.38	1.01	.40
	Low		.72	.20	.62	1.14	.59
27	High		.74	.34	.46	.86	.52
	Low		.73	.16	.69	1.16	.64
28	High		.75	.39	.54	.66	.46
	Low		.73	.29	.69	1.04	.80
29	High			.44	.32	.57	.68
	Low			.39	.56	.80	1.01
30	High			.39	.27	.62	.76
	Low			.22	.51	.88	1.10
31	High			.22		.66	
	Low			.19		.82	

Table 6

Daily highest and lowest water level in feet above (+) or below (-) land-surface datum in well 25.24.26.121, Eddy County, New Mexico. --Continued

1953

Day		July	Aug.	Sept.	Oct.	Nov.	Dec.
1	High	-0.84	-1.37	-1.66	-0.78	-0.02	+0.16
	Low	1.17	1.62	1.85	.89	.02	.12
2	High	.86	1.39	1.63	.68	+ .01	.18
	Low	1.24	1.63	1.79	.78	- .02	.16
3	High	1.07	1.43	1.58	.61	.01	.17
	Low	1.30	1.62	1.77	.68	.00	.14
4	High	1.10	1.38	1.57	.56	.04	.18
	Low	1.36	1.66	1.77	.61	+ .02	.14
5	High	1.11	1.47	1.61	.52	.07	.18
	Low	1.28	1.69	1.82	.56	.04	.15
6	High	1.02	1.49	1.61	.49	.08	.16
	Low	1.12	1.74	1.83	.54	.06	.12
7	High	.96	1.56	1.63	.53	.06	.13
	Low	1.16	1.78	1.85	.56	.04	.12
8	High	.92	1.56	1.70	.52	.05	.12
	Low	1.01	1.78	1.92	.55	.04	.07
9	High	.90	1.54	1.61	.50	.08	.16
	Low	1.19	1.76	1.80	.52	.05	.06
10	High	.91	1.56	1.59	.36	.07	.17
	Low	1.26	1.77	1.81	.50	.06	.13
11	High	.98	1.55	1.60	.32	.08	.17
	Low	1.11	1.77	1.80	.39	.07	.14
12	High	.91	1.57	1.60	.26	.08	.21
	Low	1.16	1.77	1.81	.36	.08	.16
13	High	1.00	1.54	1.55	.22	.09	.21
	Low	1.28	1.73	-	.26	.08	.17
14	High	1.11	1.51	-	.20	.10	.17
	Low	1.37	1.66	-	.26	.09	.15
15	High	1.19	1.46	-	.23	.12	.19
	Low	1.42	1.71	-	.26	.08	.18
16	High	1.14	1.48	-	.22	.18	.18
	Low	1.34	1.72	-	.24	.08	.15
17	High	1.06	1.52	1.54	.20	.17	.18
	Low	1.16	1.75	1.77	.22	.15	.18
18	High	.89	1.53	1.36	.17	.20	.20
	Low	1.12	1.77	1.70	.20	.17	.18
19	High	.82	1.55	1.21	.14	.22	.24
	Low	.95	1.81	1.36	.20	.05	.18
20	High	.89	1.62	1.11	.13	+ .05	.33
	Low	1.01	1.97	1.21	.14	- .29	.24
21	High	.89	1.65	1.02	.11	+ .05	.48
	Low	1.22	1.85	1.11	.12	- .38	.33
22	High	1.09	1.65	.94	.08	+ .17	.34
	Low	1.34	1.90	1.02	.11	.05	.32
23	High	1.18	1.60	.86	.04	.24	.35
	Low	1.39	1.80	.94	.08	.12	.33
24	High	1.20	1.51	.77	.05	.22	.38
	Low	1.47	1.79	.88	.06	.18	.35
25	High	1.28	1.62	.72	.04	.18	.40
	Low	1.52	1.82	.89	.06	.14	.38
26	High	1.31	1.62	.68	.06	.14	.45
	Low	1.52	1.85	.84	.08	.13	.40
27	High	1.28	1.63	.64	.08	.13	.45
	Low	1.48	1.84	.85	.08	.12	.38
28	High	1.25	1.65	.76	.07	.12	.41
	Low	1.50	1.89	.98	.08	.11	.38
29	High	1.28	1.71	.82	.04	.11	.43
	Low	1.52	1.91	.94	.07	.10	.38
30	High	1.31	1.67	.89	.03	.13	.38
	Low	1.51	1.87	1.06	.04	.10	.36
31	High	1.30	1.66		.02		.42
	Low	1.55	1.87		.03		.38

Table 6

Daily highest and lowest water level in feet above (+) or below (-) land-surface datum in well 25.24.26.121, Eddy County, New Mexico. -- Continued

1954

Day		Jan.	Feb.	Mar.	Apr.	May	June
1	High	+0.44	+0.40	-	+0.25	-0.40	-0.52
	Low	.42	.34	-	.23	.53	.57
2	High	.44	.34	-	.28	.46	.48
	Low	.38	.32	-	.15	.53	.62
3	High	.43	.34	-	.32	.42	.59
	Low	.38	.31	-	.29	.50	.65
4	High	.42	.32	-	.32	.44	.56
	Low	.40	.31	-	.12	.83	.69
5	High	.42	.42	-	.18	.74	.53
	Low	.41	.31	-	.12	1.03	.69
6	High	.43	.44	-	.19	.88	.46
	Low	.42	.42	-	.04	1.13	.53
7	High	.44	.44	-	+ .10	.92	.42
	Low	.43	.44	-	- .11	1.16	.66
8	High	.44	.45	-	.06	.94	.62
	Low	.44	.43	+0.32	.26	1.16	.71
9	High	.44	.44	.32	.10	.72	.56
	Low	.43	.42	.30	.40	1.04	.68
10	High	.43	.44	.30	.29	.64	.59
	Low	.40	.42	.28	.60	.89	.82
11	High	.43	.44	.31	.44	.76	.73
	Low	.40	.37	.28	.64	.89	.88
12	High	.43	.38	.32	.43	.73	.67
	Low	.42	.36	.28	.59	.85	.92
13	High	.44	.40	.28	.45	.65	.68
	Low	.43	.38	.25	.69	.80	.92
14	High	.44	.41	.31	.53	.68	.59
	Low	.44	.38	.28	.78	.81	.92
15	High	.45	.38	.31	.64	.68	.79
	Low	.42	.32	.28	.88	.80	.40
16	High	.44	.32	.29	.75	.54	.82
	Low	.42	.31	.28	.96	.76	1.00
17	High	.46	.40	.34	.80	.48	.84
	Low	.44	.32	.29	1.05	.85	1.15
18	High	.46	.44	.34	.68	.74	1.16
	Low	.39	.40	.31	1.00	.84	1.44
19	High	.41	.43	.31	.66	.69	1.43
	Low	.39	.41	.29	.90	.95	1.53
20	High	.42	.43	.33	.78	.80	1.20
	Low	.40	.41	.31	1.09	.90	1.53
21	High	.42	.43	.32	.94	.76	1.05
	Low	.40	.33	.29	1.19	.90	1.20
22	High	.47	.46	.29	1.03	.74	1.08
	Low	.42	.40	.27	1.25	.86	1.40
23	High	.48	-	.30	1.09	.58	1.43
	Low	.46	-	.26	1.27	.74	1.60
24	High	.46	-	.31	1.08	.51	1.43
	Low	.45	-	.28	1.30	.59	1.46
25	High	.46	-	.30	.84	.52	1.51
	Low	.30	-	.27	1.15	.59	1.62
26	High	.34	-	.32	.70	.52	1.44
	Low	.22	-	.30	.84	.70	1.61
27	High	.35	-	.32	.53	.65	1.25
	Low	.34	-	.30	.70	.75	1.61
28	High	.36	-	.33	.42	.67	1.25
	Low	.35	-	.32	.53	.88	1.42
29	High	.36	-	.33	.35	.74	1.30
	Low	.34		.29	.42	1.02	1.57
30	High	.36		.28	.34	.69	1.40
	Low	.34		.26	.43	1.00	1.56
31	High	.37		.27		.57	
	Low	.34		.26		.70	

View of stream below Rattlesnake Spring, looking north to Guadalupe Mountains, on skyline. Conglomerate exposed in middle ground. Photo by Edward D. Heath, 1945.

GROUND-WATER CONDITIONS IN THE VICINITY OF RATTLESNAKE SPRINGS, EDDY COUNTY, NEW MEXICO

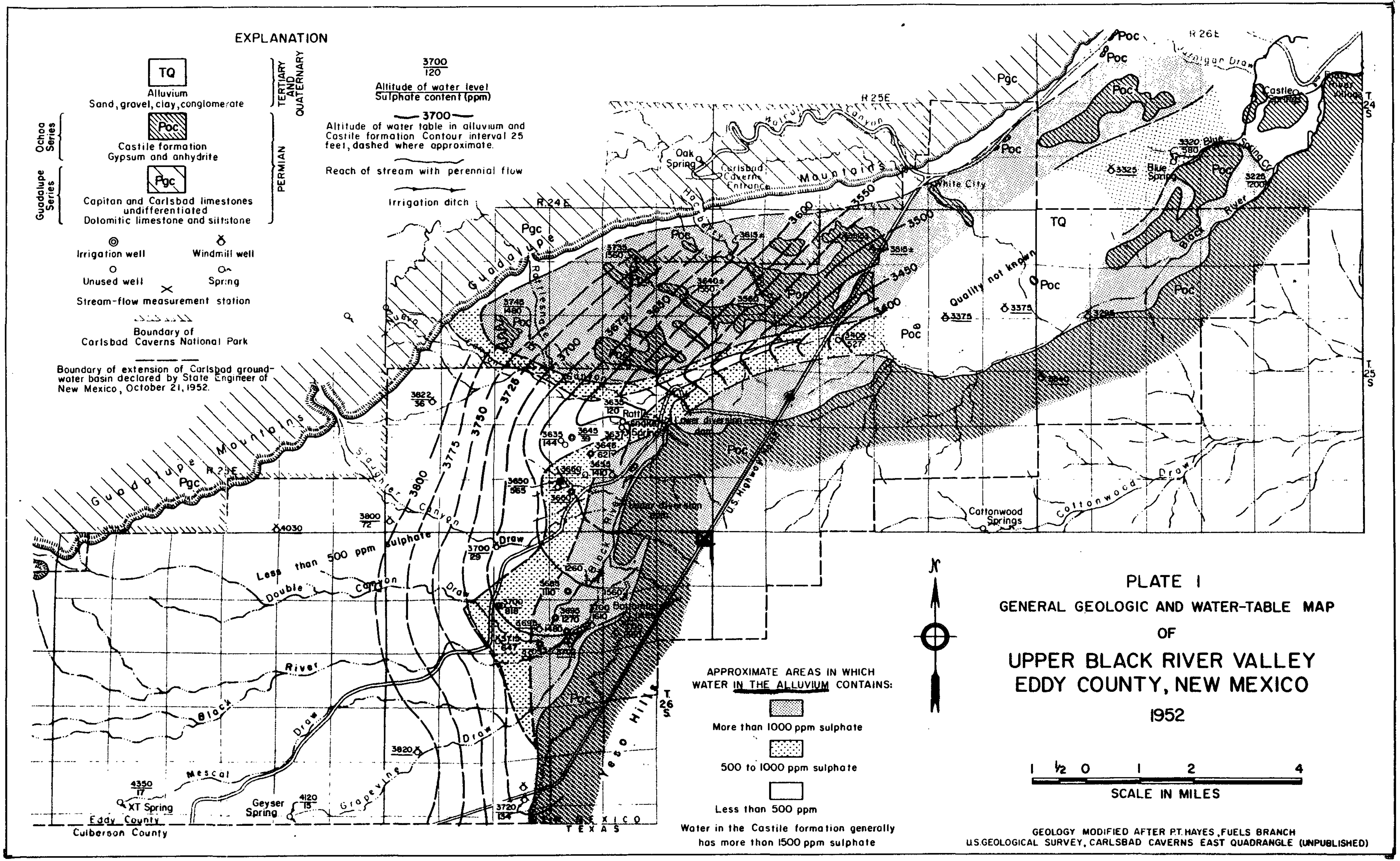

PLATE I

GENERAL GEOLOGIC AND WATER-TABLE MAP OF UPPER BLACK RIVER VALLEY EDDY COUNTY, NEW MEXICO

1952

The American Association of Petroleum Geologists Bulletin
No. 11 (November 1990), P. 1685-1694, 8 Figs.

Sulfuric Acid Speleogenesis of Carlsbad Cavern and Its Relationship to Hydrocarbons, Delaware Basin, New Mexico and Texas[1]

Carol A. Hill[2]

ABSTRACT

Sulfur-isotope data and pH-dependence of the mineral endellite support the hypothesis that Carlsbad Cavern and other caves in the Guadalupe Mountains were dissolved primarily by sulfuric acid rather than by carbonic acid. Floor gypsum deposits up to 10 m thick and native sulfur in the caves are significantly enriched in ^{32}S; $\delta^{34}S$ values as low as -25.8 ‰ (CDT) indicate that the cave sulfur and gypsum are the end products of microbial reactions associated with hydrocarbons.

A model for a genetic connection between hydrocarbons in the basin and caves in the Guadalupe Mountains is proposed. As the Guadalupe Mountains were uplifted during the late Pliocene-Pleistocene, oil and gas moved updip in the basin. The gas reacted with sulfate anions derived from dissolution of the Castile anhydrite to form H_2S, CO_2, and "castile" limestone. The hydrogen sulfide rose into the Capitan reef along joints, forereef carbonate beds, or Bell Canyon siliciclastic beds and there reacted with oxygenated groundwater to form sulfuric acid and Carlsbad Cavern.

A sulfuric-acid mode of dissolution may be responsible for large-scale porosity of some Delaware basin reservoirs and for oil-field karst reservoirs in other petroleum basins of the world.

INTRODUCTION

The origin of Carlsbad Cavern and other caves in the Guadalupe Mountains has long been a subject of controversy. The Guadalupe caves bear little resemblance to other great cave systems of the world. Rooms are huge, yet passages are not long and they terminate abruptly. The caves seem unrelated to surface topography or to groundwater-flow routes. Especially distinctive are the deposits of massive gypsum, native sulfur, and colorful waxy endellite clay in the caves.

For more than 40 years the prevailing theory has been that the Guadalupe caves formed similarly to other caves; that is, by carbonic-acid dissolution at the water table (Bretz, 1949). Within the past decade Bretz' model has been challenged by a new generation of speleologists. Queen et al. (1977) proposed a mixing model in which gypsum replaced limestone where gypsum-saturated basinal brines mixed with fresh water in the reef. Jagnow (1977) invoked sulfuric acid, with pyrite as its source, as being partly responsible for cave dissolution. Davis (1980) advocated a replacement-solution mechanism (first proposed by Egemeier, 1973, for the caves of the Big Horn basin, Wyoming) whereby hydrogen sulfide reacts with oxygen in the cave air to form sulfuric acid; the acid dissolves the limestone, which is replaced by a thin crust of gypsum. Davis (1980) was the first to suggest that the hydrogen sulfide originated "with oil and gas deposits," but he offered no explanation of where the hydrogen sulfide was generated or how the gas got into the reef. Hill (1987) supported a speleogenesis by sulfuric acid dissolution with sulfur isotopic and other data. She also proposed a specific source for the hydrogen sulfide (the "castile" masses and buttes in the basin) and discussed possible avenues by which the gas might have ascended from basin into reef.

The purpose of this paper is to describe a possible connection between hydrocarbons in the basin and speleogenesis by sulfuric acid in the reef, and to relate this model to such problems as the timing of oil and gas migration and the formation of large-scale porosity in Delaware basin reservoirs.

GEOLOGIC SETTING

The Guadalupe Mountains of southeastern New Mexico and west Texas are located along the northwest side of the Delaware basin, an area bordered by the Capitan reef of Permian (Guadalupian) age (Figure 1). The geology of the Guadalupe Mountains region has been described by King (1948) and many others. Upper Permian rocks in the region can be divided from southeast to northwest into three major depositional settings: basin, reef, and backreef or shelf (Figure 2). Light-colored, thin-bedded dolostone and sandstone, backreef equivalents of the Capitan reef, are the Seven Rivers, Yates, and Tansill formations. These beds grade into shelf evaporites and into the Capitan reef with dips of a few degrees.

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[2]Cave Research Foundation, 17 El Arco Drive, Albuquerque, New Mexico 87123.

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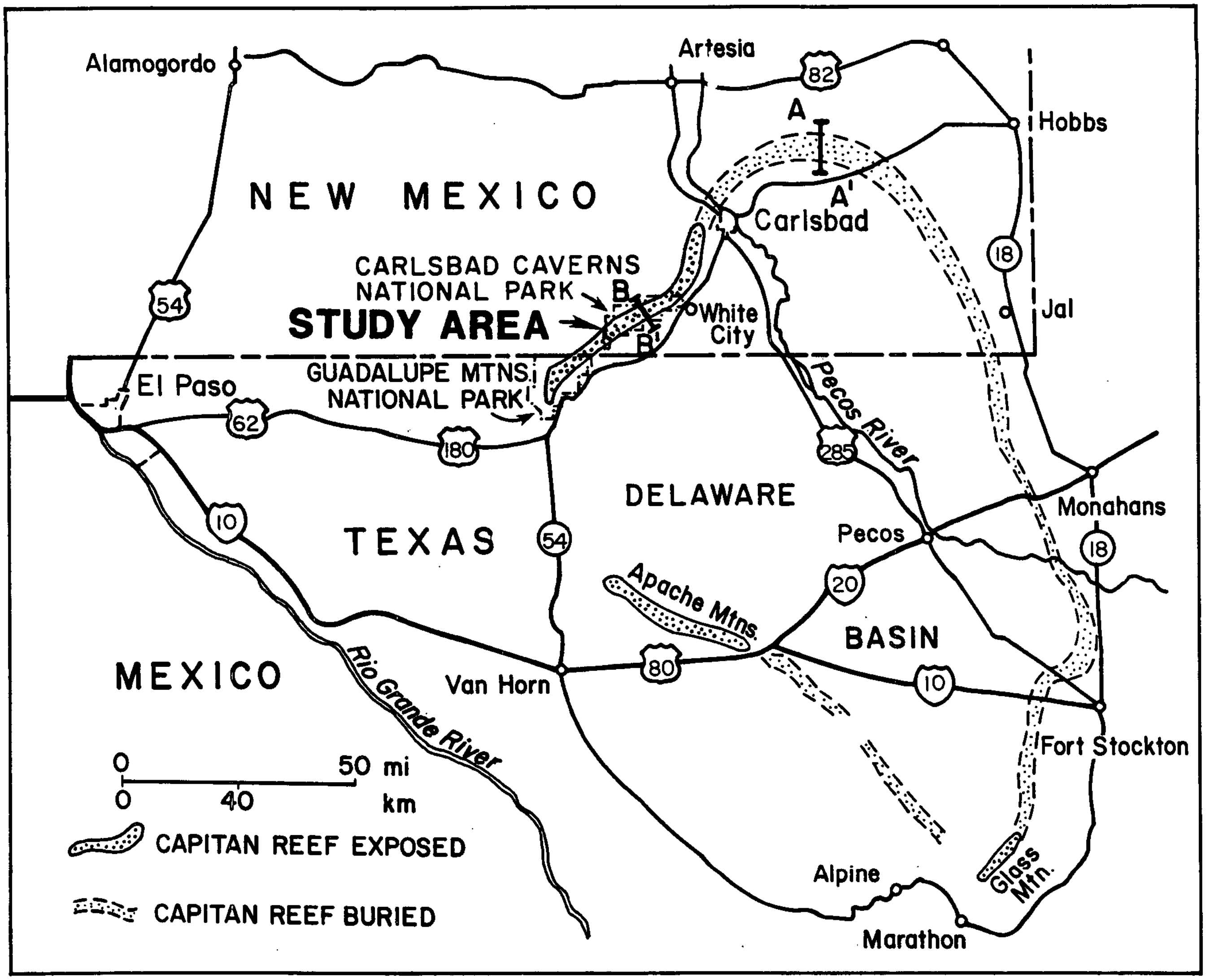

Figure 1—Regional map showing the study area and the Delaware basin bordered by the Capitan reef. From Hill (1987).

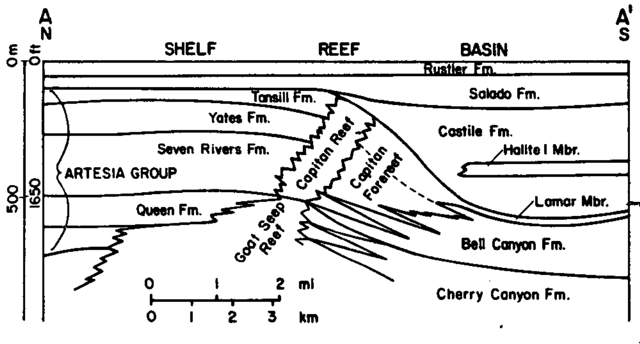

Figure 2—Upper Permian stratigraphic units of the backreef-shelf, reef, and basin. Location of cross section A–A′ is shown on Figure 1. After Bachman (1980).

The Capitan reef includes both the massive reef-core facies and the breccia (talus) forereef facies of the Capitan Limestone. The Capitan massive facies is the primary cavern-bearing unit in the Guadalupe Mountains and such caves as Carlsbad Cavern are developed in this unit. The Goat Seep reef directly underlies the Capitan reef (Figure 2). Lechuguilla Cave is developed primarily in the Goat Seep or along the contact of the Goat Seep and Capitan Limestones (Figure 8). Water moves down along dipping backreef facies and into the Capitan aquifer; it then moves northeast, parallel to the reef escarpment, to its discharge point at Carlsbad Springs, near Carlsbad, New Mexico.

Basinal equivalents of the Capitan and Goat Seep reefs include the shaly, bituminous limestone and clean, fine-grained, oil-bearing sandstone of the Bell Canyon Formation and the thin-bedded, fine-grained sandstones and persistent limestone beds of the Cherry Canyon Formation, both part of the Delaware Mountain Group. Thick anhydrite and halite evaporite sequences of the Castile, Salado, and Rustler formations overlie the Bell

Delaware
Mountain Group.

Canyon Formation in the basin and postdate the Capitan reef and its shelf equivalents. At or near the contact of the Bell Canyon and Castile formations in the basin are the "castiles"—limestone buttes (those exposed on the surface) and masses (those underground) created by the replacement of anhydrite and gypsum, a process that preserved even the most minutely laminated and microfolded textures in the evaporite rock (Anderson and Kirkland, 1966).

Toward the end of the Permian the entire region was uplifted above sea level, a situation that continued (with the exception of the Early Cretaceous) throughout the Mesozoic and Cenozoic. During the middle Tertiary (30-40 Ma) the area was affected by an episode of tectonism and heating. The main period of uplift and tilting occurred in the Pliocene to Pleistocene (1-3 Ma). As a result of the tilting, the Guadalupe Mountains were uplifted along northwest-trending, high-angle, normal faults on their western flank; the evaporite surface in the basin was eroded by solution subsidence; and hydrocarbons in the Delaware Mountain Group were moved updip into stratigraphic traps.

SPELEOLOGIC SETTING

Hundreds of caves exist in the Guadalupe Mountains. These are located within 12 km of the reef escarpment (most are within 5 km), along the crests or flanks of anticlines or other positive structures, and at the contact of major facies changes (reef/forereef, reef/backreef, Yates/Seven Rivers; Jagnow, 1977). The caves were developed in the deep phreatic (bathyphreatic) zone and water-table zone. Water-table conditions were responsible for the horizontal development of caves along certain levels, and bathyphreatic conditions were responsible for the strong vertical development of these caves. The caves are late Pliocene–Pleistocene in age, as determined by dating of cave sediment and speleothems (Hill, 1987).

Carlsbad Cavern is renowned for the beauty and profusion of its carbonate speleothem deposits. However, these deposits, which have been described by Hill (1987), are unrelated to a speleogenesis by sulfuric acid and will not be addressed in this paper. Cave deposits related to a sulfuric acid speleogenesis are gypsum blocks and rinds, native sulfur, and endellite clay.

Gypsum in the Guadalupe caves occurs as (1) blocks and rinds, and (2) speleothems. Blocks and rinds are an alabaster-like, massive-granular gypsum deposit and are not speleothemic deposits such as gypsum cave flowers, selenite needles, and gypsum stalactites. Massive gypsum blocks on cave floors can be up to 10 m thick. Rinds occur as crust-like deposits coating bedrock. Many blocks and rinds display a laminated and microfolded fabric.

Native sulfur occurs in the Guadalupe caves admixed with massive gypsum of the gypsum blocks or as crystal coatings overlying bedrock and speleothems. In Carlsbad Cavern, canary-yellow sulfur crystals coat the undersides of dipping forereef beds and siliciclastic beds interpreted by Hill (1987) to be part of the Bell Canyon Formation. Sulfur also coats carbonate rafts and popcorn, gypsum flowers, and other types of late-stage speleothems.

Endellite ($Al_2Si_2O_5(OH)4{\cdot}2H_2O$) occurs in Carlsbad Cavern and other caves in the Guadalupe Mountains as a waxy, variably colored (blue, blue-green, white, and lavender) clay, associated with montmorillonite and filling spongework pockets in the limestone. Hill (1987) used endellite as one indicator of a sulfuric acid genesis for the Guadalupe caves. In non-cave localities, endellite forms in a low pH, sulfuric acid environment. Callaghan (1948) attributed the endellite in Gardner Mine Ridge, Indiana, to be the result of the action of sulfuric acid waters on aluminous material; Brindley and Comer (1956) did the same for the endellite at Les Eyzies, France. Keller et al. (1966) described an occurrence of endellite from Stanford, Kentucky, where, in the zone of endellite formation, pH measured 3.0-3.7. Keller et al. (1971) found endellite actively forming at a hydrogen sulfide-odorous spring in Michoacan, Mexico, where the pH measured 3.5-3.7; the authors concluded that endellite forms in acidic solutions in either hot or cold water.

SULFUR ISOTOPE DATA

Gypsum and native sulfur deposits in the Guadalupe caves are significantly enriched in ^{32}S (Figure 3). Hill (1981) reported $\delta^{34}S$ values as low as -21.1 ‰ (CDT) for cave gypsum and -20.0 ‰ for cave sulfur. Kirkland (1982) obtained similar isotopic values for the gypsum blocks of the Big Room, Carlsbad Cavern ($\delta^{34}S$ = -22.0 ‰ to -15.0 ‰). Hill (1989) compiled all of the $\delta^{34}S$ data on the Guadalupe cave gypsum and sulfur: depletions as great as -25.6 ‰ for gypsum and -25.8 ‰ for sulfur have been measured.

These sulfur isotope results are crucial to understanding the process of speleogenesis that produced the large cave passages in the Guadalupe Mountains. The evidence provided by the isotope data demonstrate that the cave gypsum could not have derived from Castile anhydrite beds by the local pooling model of Bretz (1949) or the mixing model of Queen et al. (1977). The average isotopic composition of the Castile Formation gypsum and anhydrite is +10.3 ‰ (Figure 3); if the cave gypsum precipitated amicrobially from Castile brines, as modeled by these authors, then the cave gypsum and Castile Formation gypsum and anhydrite should have virtually identical isotopic compositions.

The sulfur isotope data also discourage an origin from pyrite for the sulfuric acid as proposed by Jagnow (1977). Pyrite in the Guadalupe Mountains ranges from $\delta^{34}S$ = -9.3 ‰ to -0.3 ‰ (mean = -2.5 ‰ for nine samples; Figure 3). Since there is no significant isotopic fractionation involved in the leaching of sulfides (less than 1%; Goodwin et al., 1976), it is logical to conclude that the isotopically lighter gypsum and sulfur (mean = -16.8 ‰ for 19 samples) could not have derived from this source. A number of other arguments have been made against a pyrite source of sulfuric acid (Hill, 1987); perhaps the most important argument is that not enough pyrite exists in the overlying strata to explain the

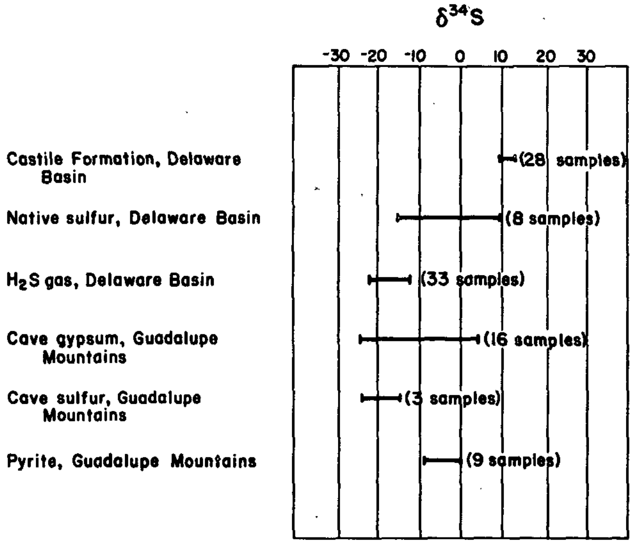

Figure 3—$\delta^{34}S$ values (CDT) of various deposits in the Delaware basin and Guadalupe Mountains. Values of gypsum and anhydrite from the Castile Formation, Delaware basin, Thode and Monster (1965), Holser and Kaplan (1966), and Popielak et al. (1983); values of sulfur from the Delaware basin, Davis and Kirkland (1970), Kirkland and Evans (1976), and Hill (1989); values of hydrogen sulfide from the Delaware basin, Popielak et al. (1983); values of the Guadalupe cave gypsum and sulfur, Hill (1981), Kirkland (1982), Hill (1987), and Hill (1989); and values of pyrite from the Guadalupe Mountains, Hill (1987) and Hill (1989).

immensity of the caves. Large caves like Carlsbad Cavern are not located near pyritic masses.

It is interesting to compare $\delta^{34}S$ values obtained for the cave deposits with those for native sulfur in the "castile" buttes, Delaware basin (Figure 3). The "castile" sulfur has $\delta^{34}S$ values of -15.1 ‰ to +9.2 ‰ (mean = 0.0 ‰, eight samples), whereas the cave gypsum and sulfur have values of -25.8‰ to +5.0 ‰ (mean = -16.8 ‰ for 19 samples). Kirkland and Evans (1976) attributed the origin of the "castile" buttes and the native sulfur therein to reactions between oil and natural gas (primarily methane) and sulfate derived from the Castile Formation; the isotopically light sulfur of the buttes relative to the Castile anhydrite was interpreted as being due to isotopic fractionation by sulfur bacteria. The Guadalupe cave sulfur and gypsum are even more enriched in ^{32}S than the sulfur in the "castile" buttes. This pronounced enrichment implies that hydrocarbons and sulfur bacteria were also involved in the genesis of the cave deposits. Only biologically aided reactions could have produced the large isotopic fractionations that characterize both the sulfur of the "castiles" and the gypsum and sulfur of the caves of the Guadalupe Mountains.

HYDROGEN SULFIDE GENERATION AT THE BELL CANYON-CASTILE

The Delaware basin of southeastern New Mexico is a major hydrocarbon province. Permian reservoirs occur primarily at the backreef-evaporite shelf contact and in stratigraphic traps in basinal sandstones of the Delaware Mountain Group (Ward et al., 1986). Characteristic of the natural gas of the region are high contents of hydrogen sulfide and carbon dioxide.

When the Guadalupe Mountains were uplifted during the Pliocene-Pleistocene, the oil-bearing Bell Canyon Formation in the basin was tilted a few degrees to the northeast. A primary consequence of this tilting was the remobilization of hydrocarbons. Joints and normal faults at or near the base of the Castile Formation allowed natural gas to ascend from the underlying Bell Canyon Formation into overlying Castile anhydrite beds, where it reacted with sulfate anions to form hydrogen sulfide, carbon dioxide, and the limestone of the "castile" masses and buttes (Kirkland and Evans, 1976; Smith, 1978). The following general reaction involving sulfate waters of the Castile Formation is believed responsible for the generation of hydrogen sulfide and carbon dioxide:

$$Ca^{2+} + 2SO_4^{2-} + 2CH_4 + 2H^+ = 2H_2S + CaCO_3 + 3H_2O + CO_2 \quad (1)$$

although other reactions involving gaseous and liquid hydrocarbons could also have taken place.

HYDROGEN SULFIDE MIGRATION FROM BASIN TO REEF

The hydrogen sulfide generated in reaction (1) rose to the surface in the basin where the host rock was not capped by impermeable halite, anhydrite, or clay beds. Where the hydrogen sulfide gas was confined by Castile Formation salt beds either it could have moved updip to the west limit of the salt to be oxidized by meteoric water to native sulfur (Figures 4 and 5), or it could have sought other avenues of escape out of the system. Other ways out of the system might have been permeability zones perpendicular to the margins of the basin. Northwest-trending joints might have been avenues for hydrogen sulfide gas ascent from basin to reef. Extrapolated into the basin, the N15°W trend of the Big Room, Carlsbad Cavern, passes near a dense concentration of exposed "castile" buttes (some with sulfuric acid-derived caves), oil, basinal sulfur deposits, and the west limit of Halite I beds (Figure 4). Other migration pathways along which hydrogen sulfide might have traveled from basin to reef was along interfingerings of the Capitan forereef facies or the permeable sands of the upper Bell Canyon Formation (Figure 6).

Episodes of tectonic movement may have triggered the migration of hydrogen sulfide gas from basin to reef. The gas might have ascended into the reef in response to a pressure differential between the two areas: the combined thickness of Castile-Salado beds in the basin could have determined the hydraulic head of the system and caused movement of gas into the reef to a level somewhat less than the hydraulic head. It is uncertain whether hydrogen sulfide dissolved in solution moved from basin to reef, or whether depressurized hydrogen

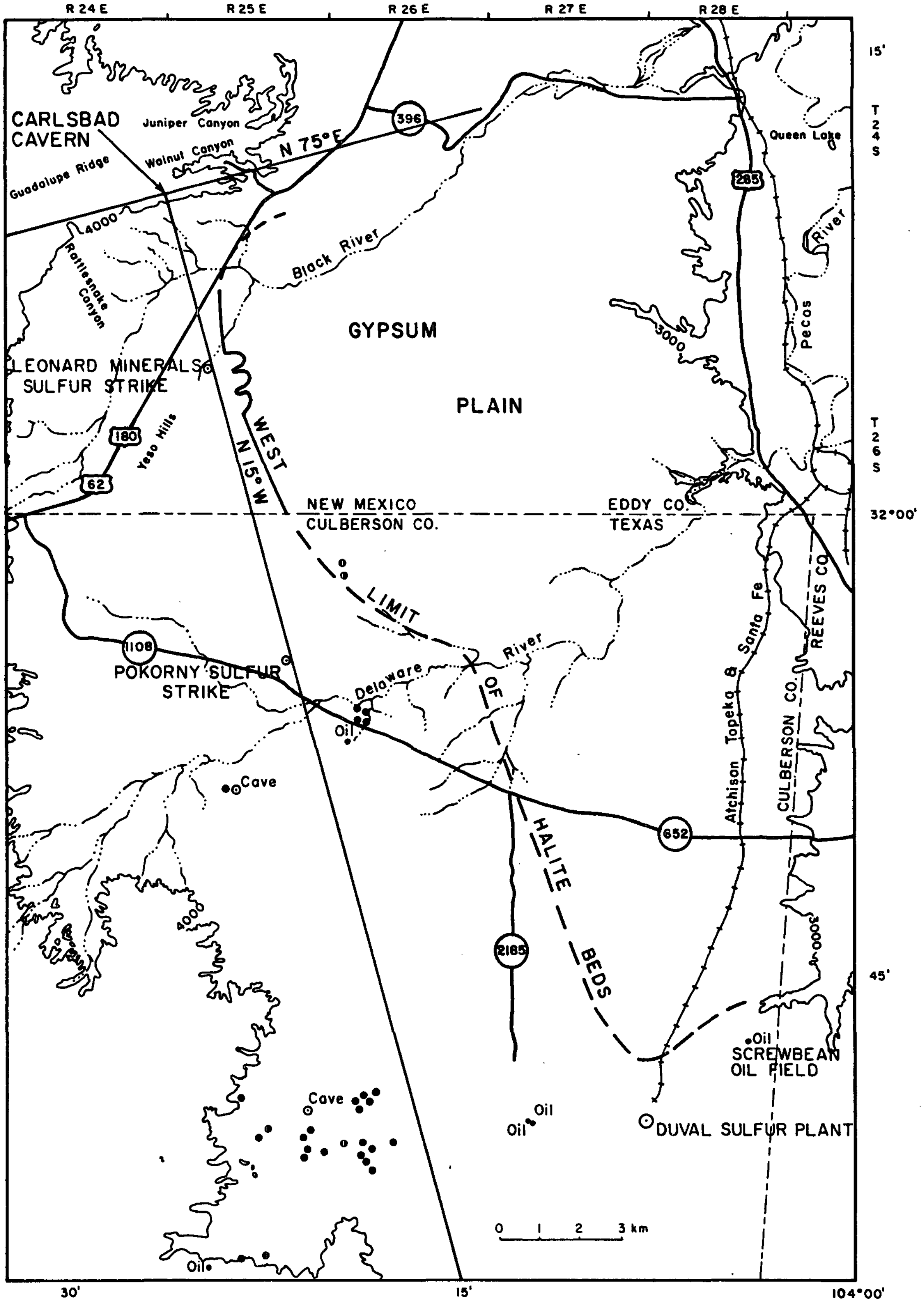

Figure 4—Location of Carlsbad Cavern in relation to oil (small black dots marked "oil"), sulfur, and the "castile" buttes (larger circular black dots) of the Gypsum Plain. The straight line is an extension of the N15°W trend of the Big Room, *Carlsbad Cavern*. Dashed and solid line is the west margin of Halite I beds in the Castile Formation; it is just west of this line that sulfur companies look for native sulfur deposits. Caves in the "castile" limestone buttes are coated with native sulfur and have hydrogen sulfide gas issuing from them. After Hill (1987).

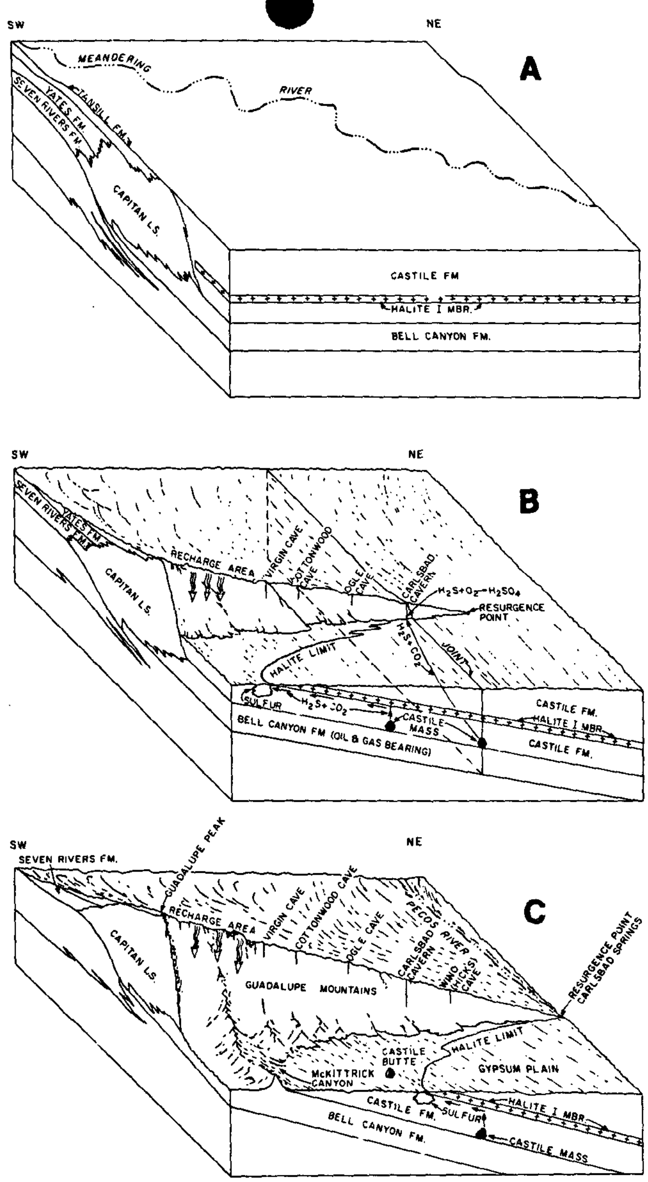

Figure 5—Model of Halite I unit in the Castile Formation of the Gypsum Plain in relation to the development of caves in the Guadalupe Mountains. (A) Rivers meandered across a low-lying erosion surface in the Miocene–Pliocene. (B) In the late Pliocene–Pleistocene the Guadalupe Mountains were uplifted and tilted. Oil and natural gas moved updip in the basin and reacted with Castile anhydrite solutions to form H_2S, CO_2, and the "castile" masses. Impermeable Castile salt beds trapped the hydrogen sulfide in the subsurface so that it either escaped at the west limit of the halite beds or ascended into the reef along joints, forereef beds, or interfingerings of the Bell Canyon Formation. As the Castile beds in the basin were eroded from west to east, and as spring positions in the Capitan reef continually shifted from southwest to northeast, caves in the Guadalupe Mountains also developed from west to east. As soon as the Castile margin moved east, past a particular cave location, development of that cave ceased because gas could no longer ascend into the reef at that point. (C) Native sulfur is found today just west of the erosion edge of Halite I beds. Hydrogen sulfide gas is found in the subsurface where halite beds are still intact. From Hill (1987).

sulfide might have diffused into the reef. Water flow may not have been required for the migration of gas as long as the rock was water-wet (McAuliffe, 1979). The hydrogen sulfide ascended into the reef and accumulated in structural traps (e.g., anticlines) and stratigraphic traps (e.g., beneath the Yates siltstone) where it eventually oxidized to sulfuric acid and formed the Guadalupe caves.

According to this model, cave development in the reef corresponded with the progressive west-to-east tilting, exposure, and erosion of Castile Formation beds in the basin. Where Castile salt beds still remained intact along a section of reef front, hydrogen sulfide could enter the reef edge along permeable zones and dissolve caves (Figure 5). But where the Castile salt beds in the basin had eroded past a forming cave in the reef, development of that cave ceased because gas could no longer ascend into the reef at that point. This might explain why caves in the Guadalupe Mountains "die with depth"—i.e., cave passages do not extend to the present-day water table. Carlsbad Cavern is an example of this principle: The western edge of Castile salt beds in the basin (denoted in Figure 4 as the "west limit of halite beds") has eroded east, past the position of Carlsbad Cavern in the reef. The Lake of Clouds (cover photo), the lowest passage in the cave, is about 30 m above the present water table in the Capitan reef aquifer and despite exhaustive exploration efforts appears to descend no further (Hill, 1987). Carlsbad Cavern has ceased forming because the Castile salt edge in the basin has moved past the position of the cave in the reef and hydrogen sulfide gas can no longer ascend into the reef at that point.

CAVE DISSOLUTION BY SULFURIC ACID

The hydrogen sulfide gas remained in a reduced state while ascending from basin to reef and did not become oxidized until it reached the water table in the Capitan reef aquifer. Oxygenated water descended to the water table along dipping backreef beds or joints in the overlying land surface (Figure 7), and upon oxidation the hydrogen sulfide converted to sulfuric acid:

$$H_2S + 2O_2 = HSO_4^- + H^+ \qquad (2)$$

The sulfuric acid produced by reaction (2) immediately attracted the limestone bedrock and dissolved out the cave voids:

$$HSO_4^- + H^+ + CaCO_3 + 2H_2O = Ca^{2+} + SO_4^{2-} + 3H_2O + CO_2 \qquad (3)$$

The greatest amount of sulfuric acid dissolution took place at the water table, which was a mixing zone for oxygen and hydrogen sulfide gas. Acidic water dissolved out the horizontal cave levels, transformed montmorillonite clay into endellite and, as a by-product of the acidic reaction, autochthonous silt released from the limestone settled to the floor (Figure 7). Later, massive gypsum, derived from the calcium and sulfate ions produced in reaction (3), precipitated out on top of the silt. After

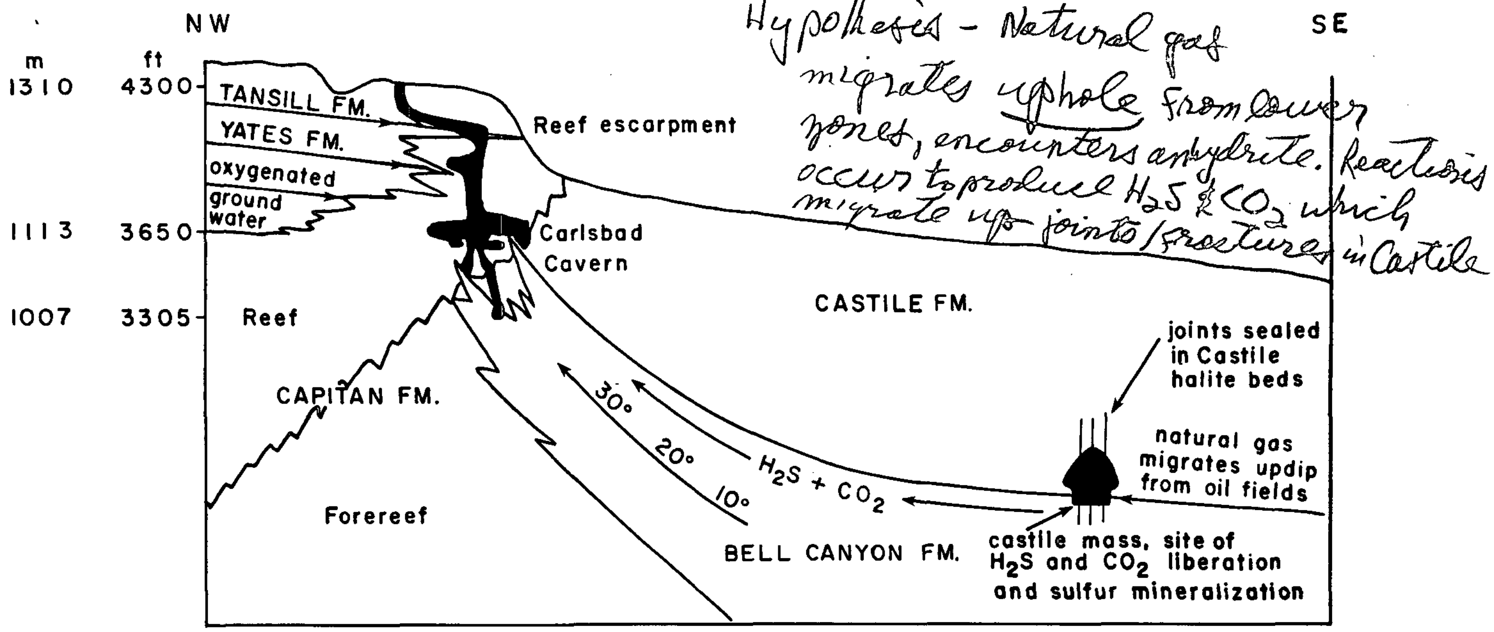

Figure 6—Model of gas ascension from basin to reef along the upper Bell Canyon Formation. Natural gas migrated updip from the oil fields to the east and encountered anhydrite at the base of the Castile Formation. Reactions between natural gas and sulfate anions produced hydrogen sulfide, carbon dioxide, and the "castile" limestone masses. The hydrogen sulfide and carbon dioxide continued updip along permeable Bell Canyon Formation beds into the Capitan reef where they mixed with oxygenated groundwater moving downdip along backreef beds. The hydrogen sulfide and oxygen combined to form sulfuric acid that dissolved the large cave passages in the Guadalupe Mountains. Water flow in the Capitan reef aquifer is northeast, or perpendicular to the cross section. From Hill (1987).

the water table lowered from cave passages, this wet massive gypsum solidified to form blocks and rinds—it is this same gypsum that is significantly enriched in ^{32}S.

According to this model, vertical tubes, fissures, and pits in the Guadalupe caves are interpreted as having formed along injection points for hydrogen sulfide gas, and horizontal levels are interpreted as forming at the water table where dissolved oxygen was the most concentrated. Cave walls of large rooms end abruptly in the horizontal plane because, away from gas-injection points, the acid was neutralized by bedrock (Figure 7). Since the amount of dissolved oxygen decreased with depth below the water table, fissure passages and pits terminate vertically and do not possess basal drains. Carbonic acid may have aided in the dissolution of the caves, but its dissolving capacity was minor compared to that of sulfuric acid. High carbon dioxide levels in the cave air [produced in reaction (3)] caused pronounced condensation-corrosion (gas weathering) in the vadose zone of the caves; geomorphic and speleothemic forms have been significantly modified by this process (Hill, 1987; Figure 7).

OTHER SOURCES OF HYDROGEN SULFIDE

The model just discussed proposes that the hydrogen sulfide responsible for sulfuric acid dissolution of *Carlsbad* Cavern was produced at or near the contact of the Bell Canyon–Castile formations, an idea based primarily on field observations in Carlsbad Cavern where sulfur occurs on the undersides of forereef and siliciclastic (Bell Canyon?) beds dipping toward the basin (Figure 8). Also, the Big Room, Carlsbad Cavern, occurs along the same trend as known sulfur deposits in the basin (i.e., Leonard Minerals sulfur deposit; Figure 4), which are located near the contact of the Bell Canyon–Castile. Since modern waters in much of the Castile and Bell Canyon formations are saturated with respect to hydrogen sulfide, and since the Castile has numerous native sulfur deposits near its contact with the Bell Canyon, it is not unreasonable to assume that these units may have been the source of hydrogen sulfide for the dissolution of Carlsbad Cavern.

However, hydrogen sulfide is common in and around the Delaware basin, and other sources of hydrogen sulfide and avenues for gas movement should be considered. An even larger quantity of hydrogen sulfide-saturated water exists in the lower units of the Delaware Mountain Group (lower Bell Canyon, Cherry Canyon, Brushy Canyon), and caves that are located further from the edge of the basin may have been dissolved by hydrogen sulfide gas moving into reef rocks from these lower units. For example, Lechuguilla Cave is located about 4 km shelfward from the reef edge and is developed in the backreef Yates and Seven Rivers formations, in the Goat Seep Limestone, and along the contact of the Goat Seep–Capitan Limestones (Jagnow, 1989; Figure 8). It is possible that hydrogen sulfide gas moved up along the upper two-thirds of the Cherry Canyon Formation which interfingers into the Goat Seep, or alternately, the gas

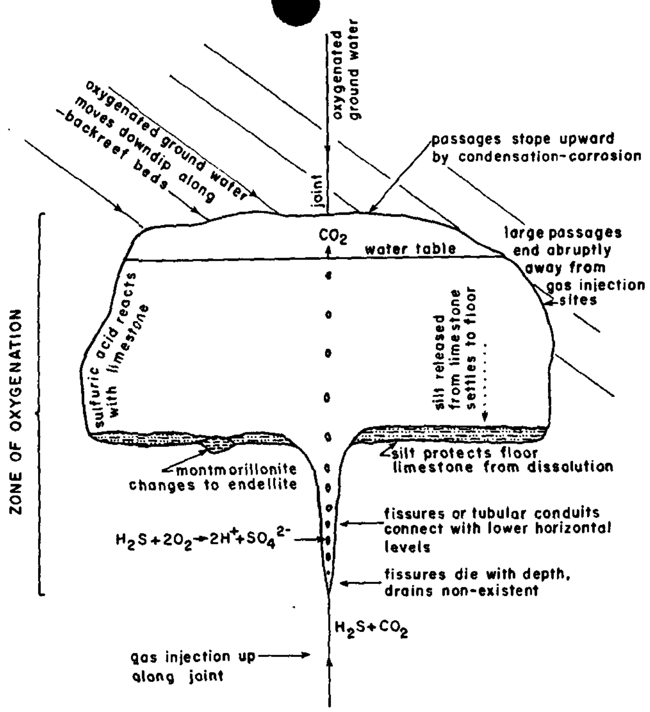

Figure 7—Model of hydrogen sulfide reaction with dissolved oxygen near the water table. Hydrogen sulfide from the basin ascended into the reef along injection points and reacted with oxygen in the zone of oxygenation to form sulfuric acid. Sulfuric acid was neutralized by the limestone away from injection points and therefore horizontal rooms end abruptly. The sulfuric acid reaction did not occur below the zone of oxygenation and hence vertical passages die with depth below large, horizontal rooms. With successive lowering of base level, new horizontal levels became connected with older horizontal levels by spring shafts and joint chimneys. From Hill (1987).

could have moved along the basal persistent tongue of the Cherry Canyon and then vertically upward into the porous Goat Seep reef (Figure 8). Large quantities of hydrogen sulfide from the Cherry Canyon could explain the position and extensiveness of Lechuguilla Cave, now over 80 km (50 mi) long (the fourth longest cave in the United States) and 477 m (1565 ft) deep (the deepest cave in the United States).

Other scenarios are also possible. Hydrogen sulfide generated in the backreef anhydrite (gypsum) could move downdip in solution and into the reef. Or, as proposed by DuChene (1986), it is possible that hydrogen sulfide could migrate updip into the Guadalupe Mountains along the Capitan reef from oil fields in the northern part of the basin. Other alternatives are that hydrogen sulfide originates in source rocks deep within the basin or that a combination of some or all of the above occurs.

TIMING OF HYDROGEN SULFIDE MIGRATION IN DELAWARE BASIN

From paleomagnetic dating of cave sediment and uranium-series and electron-spin-resonance dating of speleothems, Hill (1987) estimated the age of Guadalupe caves to be late Pliocene to Pleistocene, a judgment that agreed with the field evidence of King (1948). Thus, hydrogen sulfide migration from basin to reef has probably occurred during the last 3 m.y., in direct response to regional uplift. Late-stage speleothems in Carlsbad Cavern coated with canary-yellow sulfur crystals attest to the added possibility that migration has continued to recent times and that a sulfuric acid mode of dissolution may be going on today in caves presently developing at the water table.

Hill (1989) speculated that a similar migration of hydrogen sulfide gas from basin to reef provided the

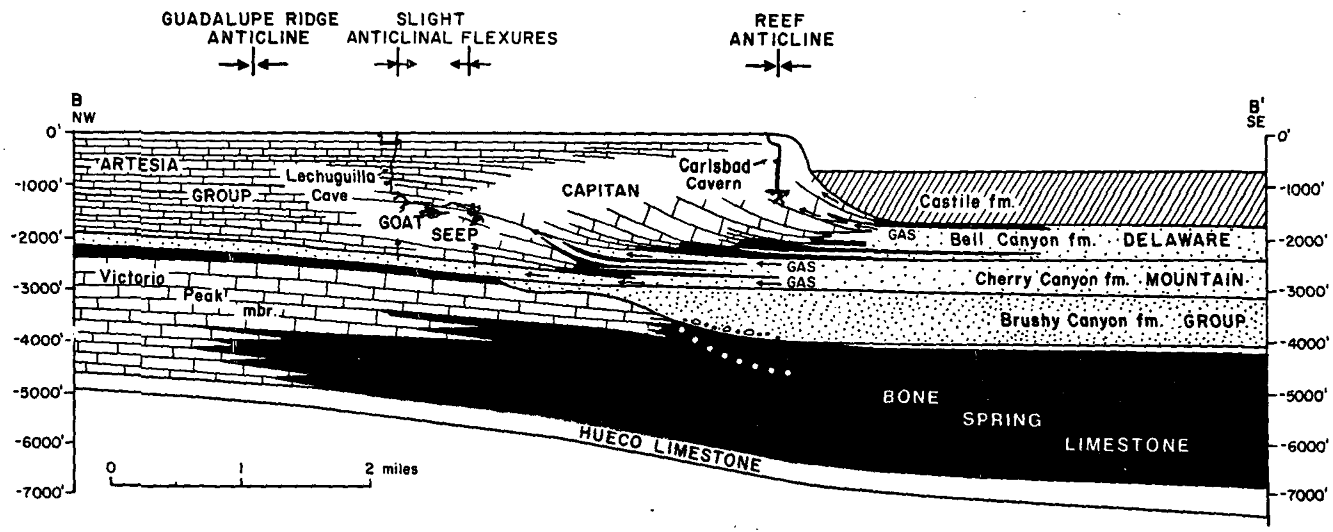

Figure 8—Possible avenues of hydrogen sulfide gas ascension for Carlsbad Cavern, located in the Capitan Limestone at the reef edge, and for Lechuguilla Cave, located in the Goat Seep Limestone about 4 km shelfward from the reef edge. Hydrogen sulfide may have moved updip along interfingerings of the upper Bell Canyon Formation to form Carlsbad Cavern and along interfingerings (or the basal tongue) of the Cherry Canyon Formation to form Lechuguilla Cave. Location of cross section B-B′ is shown on Figure 1. After Newell et al. (1953) and Jagnow (1989).

reduced sulfur necessary for Mississippi Valley-type (MVT) lead-zinc ore mineralization in the Guadalupe Mountains and also in the Apache Mountains, Glass Mountains, and Fort Stockton areas. MVT deposits in the Guadalupe Mountains are located in the same structural and stratigraphic position as are many of the caves; i.e., along the flanks or crests of positive structures and in rocks directly beneath the relatively impermeable siltstone of the Yates Formation. These ore deposits are not extensive but do consistently contain anomalous arsenic, barium, copper, iron, lead, molybdenum, and zinc. The MVT deposits are epigenetic: Sulfur isotope values for sulfides (e.g., pyrite, Guadalupe Mountains, Figure 3) are heavier than for syngenetic sulfides, and the deposits often display replacement textures. Hill (1989) placed the time of ore mineralization in the mid-Tertiary (30-40 Ma), during or just after the time of igneous intrusions and hydrothermal activity in the Delaware basin. If true, uplift, tilting, petroleum remobilization, and hydrogen sulfide migration from basin to reef may have occurred (at least intermittently) for the last 35 m.y. or so.

SULFURIC ACID KARST AROUND OTHER BASINS

The process of hydrocarbon-related, sulfuric acid karst generation is not unique to the Guadalupe caves and Delaware basin. Fiume Vento Cave, Italy, in the Apennine Mountains that rim the west side of the Adriatic Sea basin, is another example: Hydrogen sulfide can be smelled in the lowest level of the cave (near the water table) and gypsum blocks and the mineral endellite occur at higher levels (Hill, 1986). La Cueva de Villa Luz, Tobasco, Mexico, is a sulfuric acid cave related to hydrocarbons in the Gulf of Campeche: A milky-white river, with dissolved gypsum and sulfur, issues forth from the cave and sulfur crystals are growing in areas where drip water has a measured pH equal to 1 (Pisarowicz, 1988). The La Cueva de Villa Luz gypsum and sulfur are comparable to the Guadalupe cave gypsum and sulfur in their isotopic enrichment of ^{32}S.

OIL-FIELD KARST

"Oil-field karst" is a term used to describe oil and natural gas trapped in paleokarst reservoirs. In the world's most productive basin, the Persian Gulf, approximately 80% of the carbonate reservoirs are limestone (Ford and Williams, 1989), and much of the reservoir porosity is karstic. Significant oil-field karst also occurs in the newly discovered giant oil fields of the Gulf of Bohai basin, China (Han, 1990), and in many other oil fields in carbonate rock. Usually such karst has been attributed to marine-freshwater mixing zones (Ford and Williams, 1989), but it is also possible that such hydrocarbon-related paleokarst was originally dissolved by sulfuric acid in a manner similar to that discussed in this paper. Han (1990) partly attributed the Gulf of Bohai oil-field karst to acidic components generated from the bacterial reduction of sulfates.

In the Delaware basin, oil-field karst is present in early Paleozoic reservoirs and in Permian reservoirs. A good example of the many karst features found in early Paleozoic rock is the Devonian Dollarhide field, where oil is trapped in huge caverns comparable in size to Carlsbad Cavern (Stormont, 1949). Craig (1988) reported 285 caves encountered in 142 of 898 wells drilled in the San Andres Formation, Yates field, west Texas. An alternative to Craig's model of freshwater lenses being the agent of karstification is the possibility of sulfuric acid karst generation during periods of meteoric water influx sometime between the Permian and the present.

SUMMARY

(1) The Guadalupe caves were dissolved primarily by sulfuric acid rather than by carbonic acid. Sulfuric acid was responsible for dissolving huge chambers in limestone—chambers like the Big Room, Carlsbad Cavern.

(2) The sulfuric acid responsible for cave dissolution formed from the reaction of hydrogen sulfide with oxygenated meteoric groundwater. The hydrogen sulfide was most likely derived from the basin, and the oxygen-bearing meteoric water was derived as recharge water moving down along joints and dipping backreef beds.

(3) Avenues of ascent for hydrogen sulfide from basin to reef might have been northwest-trending joints or interfingerings of the Capitan forereef facies, upper Bell Canyon sandstones, or other members of the Delaware Mountain Group.

(4) The hydrogen sulfide responsible for the dissolution of Carlsbad Cavern could have originated at the base of the Castile Formation where hydrocarbons (primarily methane) reacted with sulfate anions to produce hydrogen sulfide, carbon dioxide, and the "castile" limestone.

(5) Carlsbad Cavern and other caves in the Guadalupe Mountains owe their origin to sulfuric acid formed from the oxidation of hydrogen sulfide which, in turn, was the result of the oxidation of methane and other hydrocarbons by sulfate ions. This connection of hydrocarbons and caves is supported by sulfur isotope data.

(6) Sulfuric acid dissolution should be considered as a possible mechanism for the development of oil-field karst in carbonate rock in and around petroleum-evaporite basins.

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fact, there would be no people; a sad (or not so sad?) truth!

Although the photosynthetic bacteria cannot be credited with contributing to the oxygen supply of our atmosphere, they certainly play a role, though doubtless only a "bit part", in the grand spectacle of world synthesis of organic compounds (Fig. 38.7). The microbic cosmos on which humanity depends works unseen and unheard, never goes on strike or receives wages and is beyond the control *even of Congress* (except very locally). The nation that first learns how to harness sunlight to synthesize its foodstuffs artificially, i.e., without plant life, on a commercially feasible basis can rule the world; "moon shots" or no moon shots!

38.4 SOME NONPHOTOSYNTHETIC ALGA-LIKE BACTERIA

"Sulfur Bacteria"

Inorganic sulfur is available to bacteria in various stages of oxidation and reduction, ranging from the most reduced, H_2S, through elemental S, thiosulfates and tetrathionates to the most oxidized form, sulfates. Any of these except sulfates may be oxidized as energy sources by various bacteria; and any except H_2S may be reduced as electron acceptors by other bacteria.

Bacteria that metabolize elemental sulfur or its inorganic compounds are often called *sulfur bacteria*. The term is used merely as a convenience and includes a heterogeneous group of species that have little else in common. We have already discussed photosynthetic sulfur bacteria. The relations of these and nonphotosynthetic sulfur bacteria are summarized in Table 38.3.

Habitat of Sulfur Bacteria. Nonphotosynthetic sulfur-utilizing bacteria, both sulfur-storing types, oxidizing and reducing, are common in sewage and other polluted waters, in decomposing organic matter and in swampy soils all over the world where putrefactive organisms are releasing H_2S from dead plants and animal wastes, or where sulfur-reducing species (*Desulfovibrio*) are reducing sulfates to H_2S. Some sulfur bacteria that are not at all like algae are found around free sulfur deposits, in other waters or in sulfur springs. Some occur in acid mine waters, others in garden soil. (See Table 38.3, Thiobacteriaceae, Chapter 43; also Table ...) The strictly anaerobic photosynthetic species, of course, thrive in the sunlit situations where oxygen has been removed by chemosynthetic organisms and where H_2S occurs.

Beggiatoales. We shall describe, as alga-like, some *nonphotosynthetic* sulfur bacteria of the order Beggiatoales (named for the Italian scientist, F. S. Beggiatoa). This order, as outlined in "Bergey's Manual" (1957) consists of four families:

Beggiatoaceae, Vitreoscillaceae, Leucothrichaceae and Achromataceae.

A great majority of species of Beggiatoales form long, multicellular threads called trichomes. A *trichome* (Gr. *trichos* = hair) is a single multicellular organism consisting of undifferentiated cells attached end-to-end like railway cars and clearly an entire multicellular structure. The term includes flagellate, nonflagellate and gliding organisms. It does not include chains of obviously independent cells such as streptococci, individual cells of which have clung together accidentally after fission. In two species of Beggiatoales, relatively large, single ovoid cells are typical. None of the Beggiatoales is ensheathed and none branches. Most of the filamentous species are structurally so very like the blue-green algae, *Oscillatoria*, that many authors regard the filamentous Beggiatoales as nonphotosynthetic variants of the *Oscillatoria*. In fact, some species are said to contain some photosynthetic pigments. Except the filamentous, heterotrophic Family Vitreoscillaceae, which oxidize organic compounds as energy sources, all usually

TABLE 38.3 RELATIONS OF THE SULFUR BACTERIA

Oxidize Sulfur and its Inorganic Compounds: Intracellular Sulfur Granules — Photosynthetic	Intracellular Sulfur Granules — Not Photosynthetic	No Intracellular Sulfur Granules — Photosynthetic	No Intracellular Sulfur Granules — Not Photosynthetic	Reduce Sulfates	Produce H_2S From Organic Sulfur Compounds
Thiorhodaceae	Beggiatoaceae (filamentous)	Chlorobacteriaceae*	*Thiobacillus*	*Desulfovibrio*	Various pathogenic and saprophytic (putrefactive) species: *Proteus*, *Serratia*, *Clostridium* sp.
	Achromatiaceae (non-filamentous)	Athiorhodaceae		*Sporovibrio* (?)	

*Free sulfur deposited extracellularly

live together in
is plentiful.
Only two fa
storers: the fila
nonfilamentous
and H_2S as sc
cording to the
2H₂S +
2S + 3O
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sulfates. Sulfate
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common in all s
containing H_2S
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world-wide in fresh, sea or brackish waters, especially waters rich in ferrous iron. Several species oxidize ferrous or manganous salts or organic compounds of iron or manganese as a source of energy and deposit $Fe(OH)_3$ or manganese oxides, not inside their cells but in *extracellular* structures. The yellow or reddish slime found on the mud and stones or water plants in iron-bearing waters is usually caused by ferric hydroxide in the sheaths or stalks or the gum of iron-accumulating bacteria growing there.

On the basis of the form of their extracellular structures three groups of these bacteria are recognized: (1) *sheaths* in the order Chlamydobacteriales (Gr. *chlamys* = cloak or covering); (2) *gummy, capsule-like masses* in the family Siderocapsaceae (Gr. *sideros* = iron; L. *capsa* = box or casing); (3) *stalks* in the family Caulobacteraceae (L. *caulis* = stalk).

The role of iron (or manganese) in the physiology of these organisms is interesting but is still under investigation. According to one view, the three groups of bacteria under discussion do not oxidize iron as a source of energy at all. They appear to utilize organic compounds containing iron but do not oxidize the iron itself.

For example, most Chlamydobacteriales and Siderocapsaceae can grow without gross amounts of iron or manganese, and then their sheaths or casings do not contain these metals. Young growths are free from iron or manganese. The deposition of the metals is a conspicuous and common feature of mature growths but clearly not an essential part of their physiology. The iron or manganese residue from the organism's metabolism remains outside the cell in the sheath, stalk or gum. According to one group of opinions, the metals are oxidized to ferric iron [or $Mn(OH)_3$] not by the cell but by free oxygen extraneous to the cell. The metals yield no energy to the cell. Such organisms are not true *iron bacteria* but might be called *iron-depositers.*

According to a logical view, only those organisms that oxidize *inorganic ferrous* iron compounds as a source of energy should be classed as true iron bacteria. A reaction often given to explain this process is:

$$4FeCO_3 + O_2 + 6H_2O \longrightarrow 4Fe(OH)_3 + 4CO_2$$

The iron is oxidized from the ferrous (Fe^{++}) to the ferric (Fe^{+++}) state. There are several such species but they are not at all alga-like. They occur especially in acid drainage waters of iron and coal mines and are discussed elsewhere. (See *Ferrobacillus,* Chapter 43.)

Functions of Iron-Depositing Bacteria. These organisms are not pathogenic but are of great economic importance as scavengers because they decompose organic matter in water. They are also important economic nuisances because they grow in water-distributing pipe systems and create obstructions. Some large geologic iron deposits ("bog-iron") may represent the accumulation of iron over long periods by these microorganisms.

SHEATHED BACTERIA (CHLAMYDOBACTERIALES)

There are numerous types of sheathed "iron" organisms. Their taxonomy is under active investigation. Some of the many "species" are undoubtedly variants of a few central species. Two main types are *Leptothrix* and *Sphaerotilus.*

Sphaerotilis natans. *S. natans* is a common, much-studied and representative species.

It occurs world-wide in sewage and other polluted waters and becomes especially recognizable when those waters contain organic iron. It is aerobic or microaerophilic, organotrophic and nonsporeforming.

The sheath of *S. natans* is flexible, looking and behaving much like a clear, cellophane or paper tube such as a drinking straw. Chemically, it is a protein-polysaccharide-lipid complex without muramic acid. It is neither cell wall nor capsule; a unique structure (Fig. 38.10).

The individual cells inside the sheath are of the same order of size as typical rod-shaped bacteria (1 μ by 2 to 10 μ), though the trichomes may be several millimeters in length. The rods when motile possess one or more *polar* flagella. When the growth of *S. natans* is young, the filaments may resemble hyphae of coenocytic molds, though bacterial in diameter (1 to 3 μ). As the growth matures, the protoplast becomes more obviously divided into bacilli with lophotrichous flagella. These cells multiply by binary fission. The resulting motile bacilli, often called *swarm cells,* slip out at the ends of the sheaths or are liberated at the sides as the sheaths disintegrate. Sometimes the young cells cling to the outside of the sheath of origin and grow off at an angle. This is called *false branching.* In one variety, called *S. dichotomus* (possibly identical with *S. natans*), the false branching appears to be dichotomous.

S. natans usually does not accumulate much iron in the sheath except in matured filaments. *Leptothrix ochracea,* a species similar in several respects, deposits much larger amounts until it forms dense, ochre-colored masses. Some workers have regarded *L. ochracea* as matured *S. natans.*

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Figure 38.10 *Sphaerotilis natans*. *A*, Sheaths and bacillus-like cells within sheaths. Note also empty sheaths (about × 1000). *B*, Young colonies on nutrient agar after 24 hours at 28° C. (about × 50). (From Dondero, Phillips and Heukelekian: Appl. Microbiol., vol. 9.)

It is of interest to note that *S. natans* has also been described as a sulfur bacterium, depositing sulfur granules like *Beggiatoa alba*. *S. natans* also synthesizes prominent granules of poly-beta-hydroxybutyric acid.

S. natans is a tremendous nuisance when, because of its excessive growth, the tangled, filamentous masses cause blockage ("bulking") in the flow of sewage in disposal plants that use activated sludge. (See Chapter 42.)

STALK-FORMING BACTERIA (CAULOBACTERACEAE)

Gallionella ferruginea. *G. ferruginea* is a common and representative species of the stalk-forming family. Similar organisms are *Siderophacus* and *Nevskia*. Each cell of *Gallionella* forms a stalk which, as the plant matures, becomes encrusted with $Fe(OH)_3$. *Gallionella* does *not* form a sheath. It is said by some observers to be a true iron-oxidizing bacterium, but this is doubted by others. However, it grows only in waters bearing reduced iron (i.e., iron that can be oxidized as a source of energy). A curious metabolic feature is that all species require vitamin B_{12} (cyanocobalamin).

The cells of this organism are bean- or kidney-shaped and about 0.5 by 2 μ in size. Like other bacteria, they multiply by transverse binary fission. When motile, they resemble *Pseudomonas* and have polar flagella. From the concave side or end of each cell a flat, mucilaginous ribbon or stalk is excreted. This is attached by the distal end to some solid object. As each cell divides, dichotomy of the stalk occurs, so that complex tangles or rosettes of long stalks streaming from a common object are formed. The stalks are sometimes 0.2 to 0.3 mm. in length (Fig. 38.11).

From the complex fibrillar structure of these stalks and their occasional independence of the cell, it is inferred by some workers that these stalks or their fibers may possibly be living matter and play a role in the life cycle of the organism.

The stalks of *Gallionella* have the remarkable habit of twisting so that they resemble a loosely coiled rubber band. Large amounts of $Fe(OH)_3$ are later deposited in these stalks, giving them the appearance of a series of loops or string of beads. The twisting habit renders identification of *Gallionella* easy, since no other organism of similar character is known to twist in just this way. As stated by Thimann: ". . . the gallionellas are more notable for their excreta than for themselves."

Gallionella is found in nature as widely distributed as *Sphaerotilus*. Like other iron-accumulating bacteria, *Gallionella* can multiply in water pipes and often causes extensive deposits and incrustations of iron which may eventually occlude the pipes. It is also responsible in part for the fouling of ship bottoms.

Caulobacter vibrioides. *C. vibrioides* and tinct stages, each stage carried out by different genera. The first stage, the oxidation of ammonia to nitrites, is sometimes called *nitrosification:*

$$2NH_3 + 3O_2 \longrightarrow 2HNO_2 + 2H_2O + 79{,}000 \text{ cal.}$$

Oxidation of Ammonia to Nitrite. *Nitrosomonas* and *Nitrosocystis* (representative genera) are very small oval rods, each with a single, polar flagellum. They are strictly aerobic and are very sensitive to acidity. Since oxidation of ammonia, and especially of ammonium sulfate, creates acidity caused by HNO_2 and H_2SO_4, *Nitrosomonas* and *Nitroscystis* soon cease growth unless a soil is well limed or otherwise buffered. The optimum pH is around 8.6.

These species are chemolithotrophic and can be cultivated in a solution of minerals such as the following:

Ingredient	*Per Cent*
$(NH_4)_2SO_4$ (source of energy and nitrogen)	0.20
K_2HPO_4 (buffer)	0.10
$MgSO_4$	0.05
$FeSO_4$	0.04
NaCl	0.04
$CaCO_3$	0.10
$MgCO_3$	0.10

This medium may be solidified with silica gel but not with agar, since all Nitrobacteraceae are strict autotrophs.

Some of these bacteria, notably *Nitrosocystis oceanus,* a marine species, exhibit very complex intracellular and pericellular membranous structures or organelles that are suggestive of the photosynthetic structures in eucaryotic chloroplasts or bacteria (Fig. 43.10).

Oxidation of Nitrite to Nitrate. This process is called nitrification. Both nitrosification and nitrification are sometimes spoken of together as nitrification. Most higher plants cannot utilize nitrites as their source of nitrogen. In fact, nitrites are toxic to many plants and animals. The most immediately useful form of nitrogen for agricultural purposes is nitrate. Since nitrate does not commonly occur spontaneously in soil, its development is dependent on the presence of the Genus *Nitrobacter,* which oxidize nitrites to nitrates:

$$HNO_2 + \tfrac{1}{2}O_2 \longrightarrow HNO_3 + 21{,}600 \text{ cal.}$$

A difficulty with nitrates as fertilizers is that they are very soluble and are quickly leached from the soil.

Nitrobacters are nonmotile rods. They occur in soil, rivers and streams, and are world-wide in distribution. Under laboratory conditions they grow well only in the entire absence of organic matter. *Nitrobacter* may be cultivated in solutions such as the preceding by substituting sodium nitrite for ammonium sulfate as a source of energy.

Other Nitrogen Oxidizers. In addition to the Nitrobacteraceae, certain heterotrophic bacteria have been shown to oxidize ammonia to nitrite (e.g., *Streptomyces* and *Nocardia* species). Nitrification as a sole source of energy appears to be carried out only by species of *Nitrobacter* and *Nitrocystis* (do not confuse with *Nitrosocystis*). However, several species of eucaryotic fungi (*Aspergillus flavus, Penicillium* sp., *Cephalosporium* sp.) carry out both steps, oxidizing *organic* nitrogen (possibly first forming ammonia from it?) to nitrite and nitrate.

43.8 THE SULFUR CYCLE

In many respects the sulfur cycle is analogous to the nitrogen cycle. Sulfur is as essential to protoplasm* as nitrogen and undergoes similar alternations between organic and elemental states and between oxidation and reduction. Like nitrogen also, sulfur is most available to green plants in its most oxidized form, i.e., as sulfates. Sulfur is commonly added to agricultural soils as gypsum or as ammonium sulfate. In nature sulfur is often found in the elemental state or in volcanic ("medicinal") waters as hydrogen sulfide (H_2S) and other sulfides. It is released from organic compounds (e.g., proteins) by anaerobic decomposition (putrefaction) in its most reduced state, H_2S, analogous to ammonia (NH_3). Sulfates are also reduced to H_2S by certain bacteria. Like nitrates, fully oxidized sulfur (sulfate) is expensive and quickly leached (dissolved) from soil by rains.

Oxidation of Sulfur

We have already discussed photosynthetic bacteria (Chapter 38) that oxidize various forms of sulfur, especially hydrogen sulfide, to sulfates. Other important sulfur oxidizers are grouped in the Family Thiobacteriaceae of the Order Pseu-

*If sulfur becomes a vital part (say, part of a chromosome) of a living cell, is the sulfur then alive? Is *any* element or substance, no matter how complex, that is part of a living organism, alive? If not, then just what part of us *is* actually alive? What differentiates the *alive* part from the *not-alive* part? What is meant by "alive"?

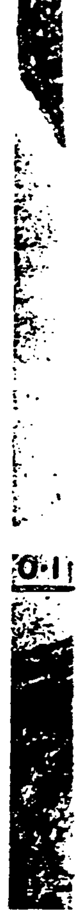

Figure 43.10 orate and orderly eucaryotic and pr cell: in the Nitrob In the upper elect whose origin, stru enlarged below. T triplet layer of the

domonadales. Thiobacteriaceae are single, independent, gram-negative, cocci, straight or curved rods, or spirals, generally about 0.5 μ by 10.0 μ in dimensions. Motile species have polar flagella. Many are strict or facultative chemolithotrophs. Some interesting representatives are found in the Genus *Thiobacillus.*

Genus *Thiobacillus.* Thiobacilli thrive in mud, sea water, sewage, boggy places, coal-mine drainage, sulfur springs and so on where sulfur and its reduced compounds occur naturally or as a result of microbial metabolism.

Thiobacilli oxidize sulfur or its reduced inorganic compounds as energy sources in a variety of ways depending on species:

1. $5Na_2S_2O_3 + H_2O + 4O_2 \longrightarrow 5Na_2SO_4 + H_2SO_4 + 4S$
2. $2Na_2S_2O_3 + \frac{1}{2}O_2 + H_2O \longrightarrow Na_2S_4O_6 + 2NaOH$

The sulfur in equation 1 above may be further oxidized by other thiobacilli to sulfuric acid.

3. $2S + 3O_2 + 2H_2O \longrightarrow 2H_2SO_4$

All thiobacilli are strict autotrophs. Aqueous solutions such as the following meet all of their nutritive requirements.

Ingredients	*Per Cent*
S	1.000
$Na_2S_2O_3$	0.500
$(NH_4)_2SO_4$	0.030
KH_2PO_4	0.025
$CaCl_2$	0.050
$FeSO_4$	0.001
KCl	0.050
$MgSO_4$	0.020
$Ca(NO_3)_2$	0.050

Note the absence of carbon source. This diet and metabolism are truly marvellous when compared with the complex organic requirements of heterotrophic bacteria or man. Instead of lipids, carbohydrates and proteins and their derivatives as sources of energy and cell substance, thiobacilli use a few minerals. Instead of complex organic wastes in urine and feces, these organisms excrete corrosive H_2SO_4!

The metabolism of *Th. denitrificans* is of special interest, since this represents one of the factors responsible for losses of fertility in certain anaerobic (swampy) soils (*denitrification,* or reduction of nitrates):

$$5S + 6HNO_3 + 2H_2O \longrightarrow 5H_2SO_4 + 3N_2\ (+\epsilon)^*$$

*ϵ = energy.

Thiobacillus thiooxidans oxidizes sulfur and thiosulfates to sulfuric acid *aerobically.* As sulfuric acid is formed in considerable amounts, it might be thought that the organisms would quickly inhibit their own further growth. This species, however, is of interest in having a great resistance to acid. It is "distinctive in that it is able not only to tolerate but to produce higher concentrations of acid than any other living organism yet known" (*Starkey*). Some growth is said to occur at a pH of 1, and it grows readily at pH 3. Another species, *Th. intermedius,* requires both organic and reduced inorganic sulfur for best growth (Fig. 43.11).

An interesting physiological question arises, and remains unanswered, as to how sulfur particles, water-insoluble, pass through the bacterial cell wall and membrane. In spite of their strange properties these organisms have the same general structures as familiar, heterotrophic, gram-negative bacteria. Could pinocytosis operate in a cell coated by a cell wall?

An important aspect of acid formation by any microorganism lies, on the debit side, in the corrosive and destructive properties of the acids on industrial steel, pipes, and other acid-sensitive products. On the credit side is the very desirable solvent action of acids on phosphate rocks that contain the indispensable element phosphorus in otherwise insoluble forms. (See Phosphorus Cycle, page 547.)

Thiobacillus ferrooxidans, a species closely similar to *Th. thiooxidans,* is found in acid drainage waters of iron and bituminous coal mines. *Th. ferrooxidans* can oxidize ferrous iron salts as well as sulfur:

$$4FeSO_4 + 2H_2SO_4 + O_2 \longrightarrow 2Fe_2(SO_4)_3 + 2H_2O$$

$$Fe_2(SO_4)_3 + 6H_2O \longrightarrow 2Fe(OH)_3 + 3H_2SO_4$$

Similar species called *Ferrobacillus ferrooxidans* and *Fer. sulfooxidans* have been described. These are all true "iron bacteria," i.e., they oxidize iron as a source of energy (Fig. 43.12).

43.9 BACTERIAL REDUCTION OF SULFUR

Sulfate-reducing species of bacteria are few but they are widely distributed, especially in sewage and other polluted waters, the sea and marine muds from pole to pole, in oil wells and in the bovine rumen. There are two general types; one, Genus *Desulfotomaculum,* includes sporeforming rods, one species of which was formerly known as *Clostridium nigrificans;* the

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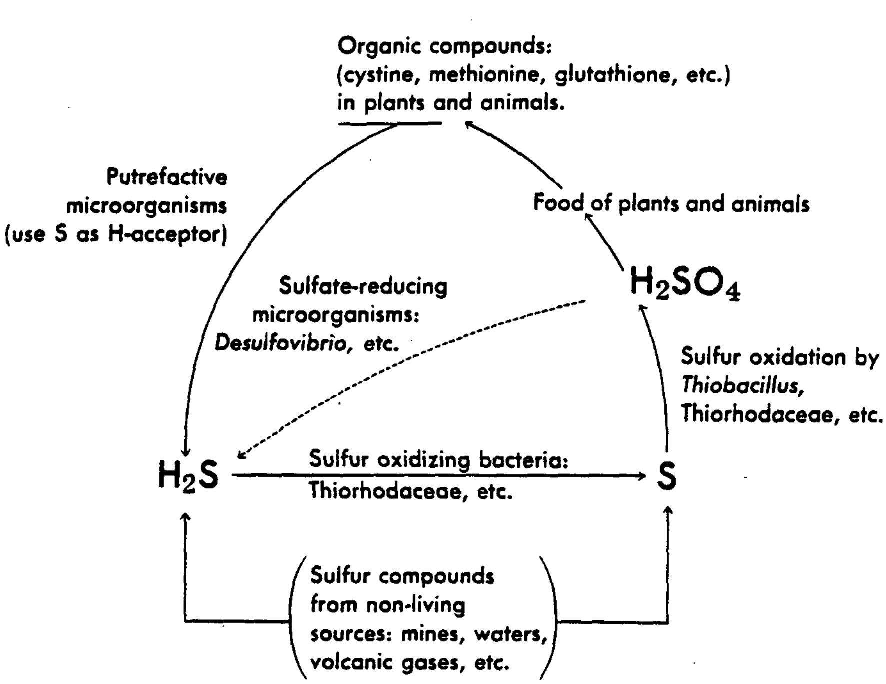

Figure 43.11 The sulfur cycle. At left, H_2S enters the cycle from nonliving sources (bottom) and from living sources (top). It is oxidized to sulfur (right) by various sulfur-oxidizing microorganisms. Sulfur also enters the cycle from inorganic sources (bottom). Sulfur is oxidized by microorganisms to H_2SO_4 which may enter organic structures in plants and animals (top) or be reduced to H_2S (left) by sulfate reducers.

Figure 43.12 Colonies of *Ferrobacillus sulfooxidans*, an autotrophic, sulfur- and iron-oxidizing bacterium. The colonies are on a wholly inorganic nutrient agar (pH 4) containing $FeSO_4 \cdot 7H_2O$ as the sole source of energy. Note the red (dark) central areas of oxidized iron in the larger colonies (× 50). (From Kinsel: J. Bact., vol. 80.)

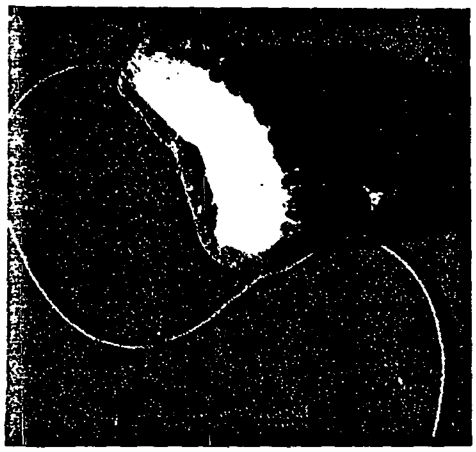

Figure 43.13 Electron micrograph of *Desulfovibrio desulfuricans* (× 18,540). (From Campbell, Frank and Hall: J. Bact., vol. 73.)

other is a group of pleomorphic, curved-rod (vibrio-like) organisms classified as *Desulfovibrio.* Like other vibrios they are motile with polar flagella (Fig. 43.13). Of these, *Desulfovibrio desulfuricans,* the best known species, is anaerobic though it has cytochrome systems like oxidative organisms. Like all typical anaerobes it requires low O-R potentials and must have iron for its cytochrome. Organic materials are dehydrogenated and the hydrogen is transferred to sulfites, sulfates and thiosulfates, which are reduced to H_2S.

$$2CH_3 \cdot CHOH \cdot COONa + H_2SO_4 \longrightarrow$$
Sodium lactate

$$2CH_3 \cdot COONa + H_2S + 2CO_2 + 2H_2O$$
Sodium acetate

Some sulfate reducers can use molecular hydrogen in the reduction of sulfate:

$$4H_2 + H_2SO_4 \longrightarrow H_2S + 4H_2O$$

43.10 THE CARBON CYCLE

Carbon is introduced into the organic system from its most oxidized state, carbon dioxide, and is reduced in organic combination, mainly by photosynthesis. A lesser amount of carbon is taken as atmospheric CO_2 into some species of chemosynthetic bacteria and some other cells. As a result of these various biological synthetic activities involving carbon, and in the passage of hundreds of millions of years, vast quantities of carbon are stored in coal, peat, petroleum oils and gases ("fossil fuels") and in coral, limestones, marble and other carbonate rocks to say nothing of the carbon in today's living organisms (and to say still less of the carbon in diamonds!). In all of these forms, carbon is more reduced than it is as CO_2. A number of anaerobic bacteria use organically combined carbon as an electron (H) acceptor and reduce it still further to methane (CH_4). As mentioned elsewhere, methane is a major component of natural gas, including marsh and sewer gases, being produced by such species as *Methanobacterium, Methanococcus* and some species of *Clostridium.* Note that these are methane *producers.*

If all existing supplies of CO_2 in the atmosphere or dissolved in the waters of the earth were to be continuously removed from the atmosphere and combined in organic matter or in carbonate rocks, life on the earth would cease in a generation or so. But carbon is continuously reoxidized and returned to the atmosphere, and thence to the seas, as CO_2 in a variety of familiar ways: mainly by combustion of coal and organic fuels and biooxidations, and also by volcanic activities, all of which liberate CO_2. Biological activities include not only fermentations that yield CO_2, but metabolism by certain rare bacteria that oxidize methane as a source of energy, e.g., *Pseudomonas* or *Methanomonas methanica.* Some of these are *wholly dependent* on the *methyl* group as in methane or methanol, e.g. *Methylococcus capsulatus.* CO_2 is released from carbonate rocks by acids resulting from geological action and also by acids formed during fermentations and by such bacteria as the species in the nitrogen and sulfur cycles that produce HNO_3 and H_2SO_4.

Carbon monoxide is a relatively rare gas under ordinary conditions and results commonly

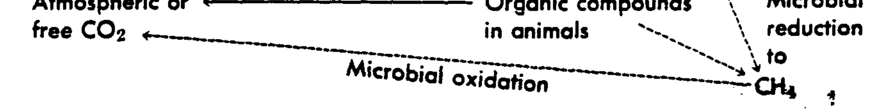

Figure 43.14 The carbon cycle. Atmospheric or free CO_2 (lower left) is combined as organic matter by photosynthesis (upper left). These organic compounds either remain as plant material (upper right) or are taken up by animals (lower right, solid lines). In either case the carbon is eventually released to the atmosphere again by combustion, metabolism of higher plants or animals, or by microbial decomposition of plant and animal wastes and remains (diagonal solid line). The dash lines at lower right show a sort of extraneous cycle carried on by anaerobic microorganisms which either *reduce* carbon to CH_4 in bio-oxidation or *oxidize* CH_4 to CO_2 as a source of energy in bio-oxidation.

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from partial combustion. Exceedingly poisonous for most aerobic organisms including man, it is relished as a source of energy and carbon by at least one autotrophic bacterial species, *Carboxydomonas oligocarbophila*, that oxidizes CO to CO_2. So the carbon "goes 'round and 'round," alternating between organic and inorganic, reduced and oxidized, like sulfur and nitrogen (Fig. 43.14).

43.11 THE PHOSPHORUS CYCLE

The phosphorus cycle involves an alternation in form of phosphorus between soluble and insoluble as well as between organic and inorganic. No organisms are known that reduce phosphates or oxidize phosphorus as a source of energy. Phosphorus enters the soil in relatively insoluble, inorganic forms as phosphates in the rock from which the soil is derived. It is added to agricultural soils as $Ca_3(PO_4)_2$ in the form of *bone meal* and in commercial fertilizers as *rock phosphates.*

Phosphorus is liberated from such insoluble compounds [e.g., $Ca_3(PO_4)_2$] by acids formed during nitrification and during oxidation of sulfur (and also by fermentations) in the soil as follows:

$$Ca_3(PO_4)_2 + 2HNO_3 \longrightarrow 2CaHPO_4 + Ca(NO_3)_2$$

$$Ca_3(PO_4)_2 + 4HNO_3 \longrightarrow Ca(H_2PO_4)_2 + 2Ca(NO_3)_2$$

$$Ca_3(PO_4)_2 + H_2SO_4 \longrightarrow 2CaHPO_4 + CaSO_4$$

Decomposing vegetable and animal materials liberate *soluble* compounds of phosphorus such as DNA and RNA, ADP and ATP.

The soluble forms of phosphorus are used by both higher plants and microorganisms.

43.12 THE RHIZOSPHERE

The rhizosphere is a zone of increased microbial growth and activity in the soil around the roots of plants. Sometimes the microorganisms form a sort of living mantle close around the roots. The rhizosphere may extend several inches into the soil around the roots. There are many interrelationships and interactions between plant roots and soil microorganisms. Some are favorable to plants, some indispensable; some are unfavorable, others lethal.

We know, for example, that some bacteria or fungi make nitrogen available to plants as nitrates or in organic form. Sulfur oxidizers make sulfur available as sulfates. Heterotrophic metabolism makes carbon available as carbon dioxide for photosynthesis. Production of acids by microbial action makes rock or bone phosphorus available as soluble phosphates. Some bacteria synthesize auxins or phytohormones (e.g., indole-acetic acid) which greatly stimulate root growth, and certain fungi (*Gibberella* species) synthesize the growth auxin, *gibberellic acid* (Fig. 43.15).

Plant roots reciprocate in kind. The roots of leguminous plants secrete soluble, organic nitrogenous compounds into the soil around them

Figure 43.15 Effect of gibberellin on plant growth. The first (left) lima bean seedling was grown from seeds dusted with plain talc. The talc used to dust the seeds of seedlings 2, 3 and 4 contained, respectively, 10, 20 and 40 gm of gibberellic acid. (Courtesy of Boyce Thompson Institute for Plant Research Inc.)

Regional Area

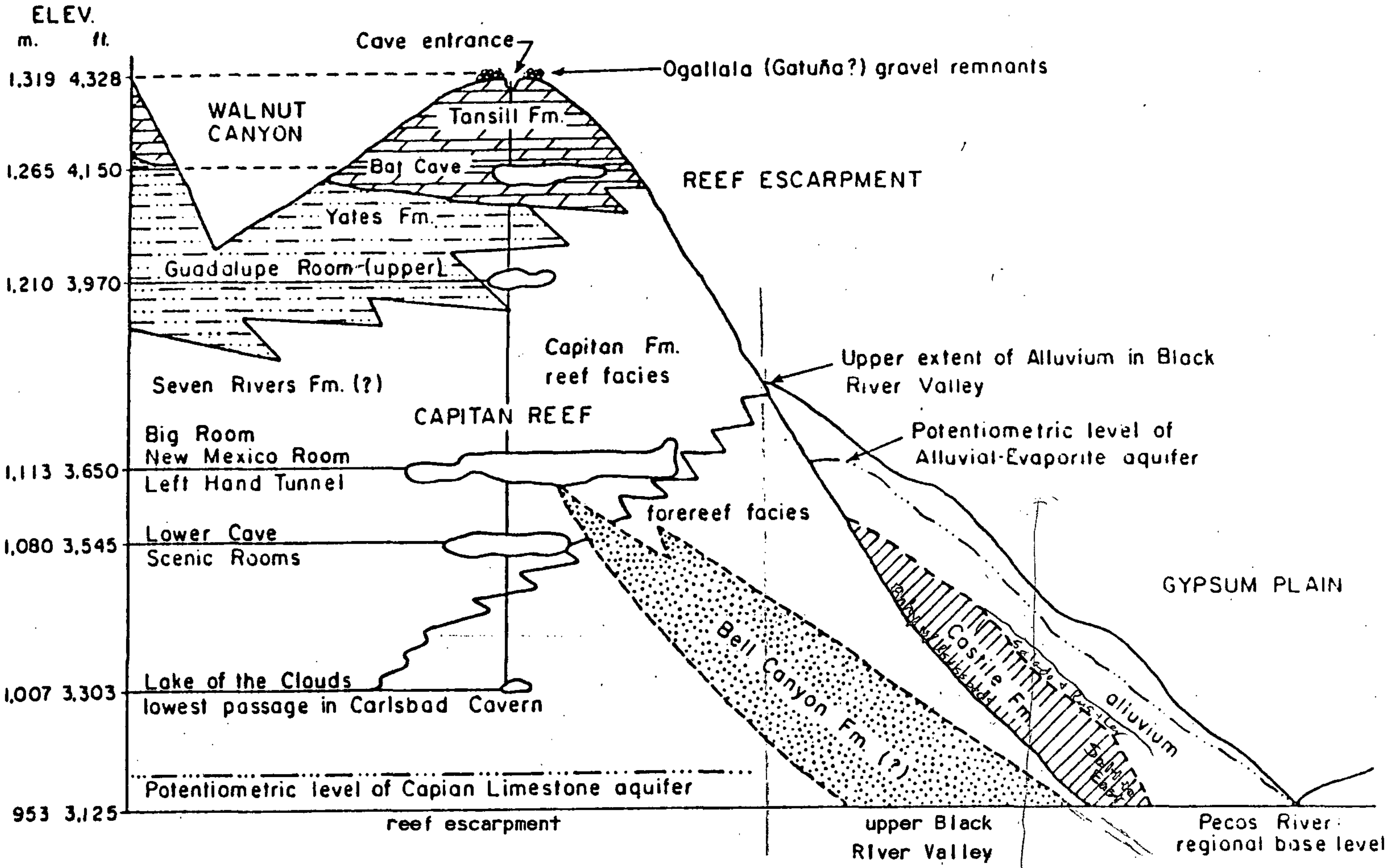


Figure 2. Geologic Cross-Section for the Upper Black River Valley and Adjacent Guadalupe Mountains (Adapted from Hill 1987).

Detailed Area

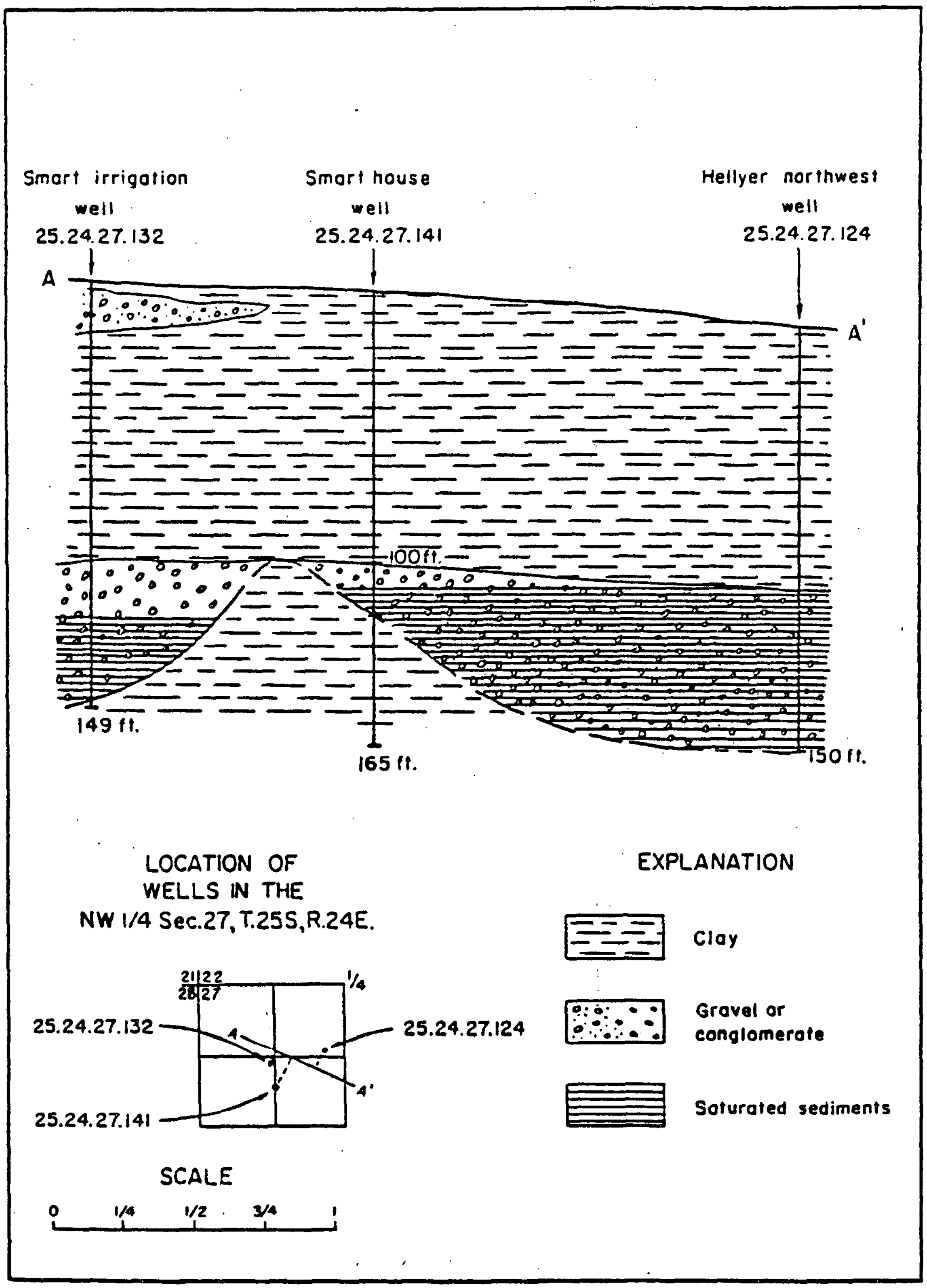


Figure 5. **Groundwater Levels and the Existence of a Subsurface Barrier Between the Smart House and Irrigation Wells** (from Hale 1955).

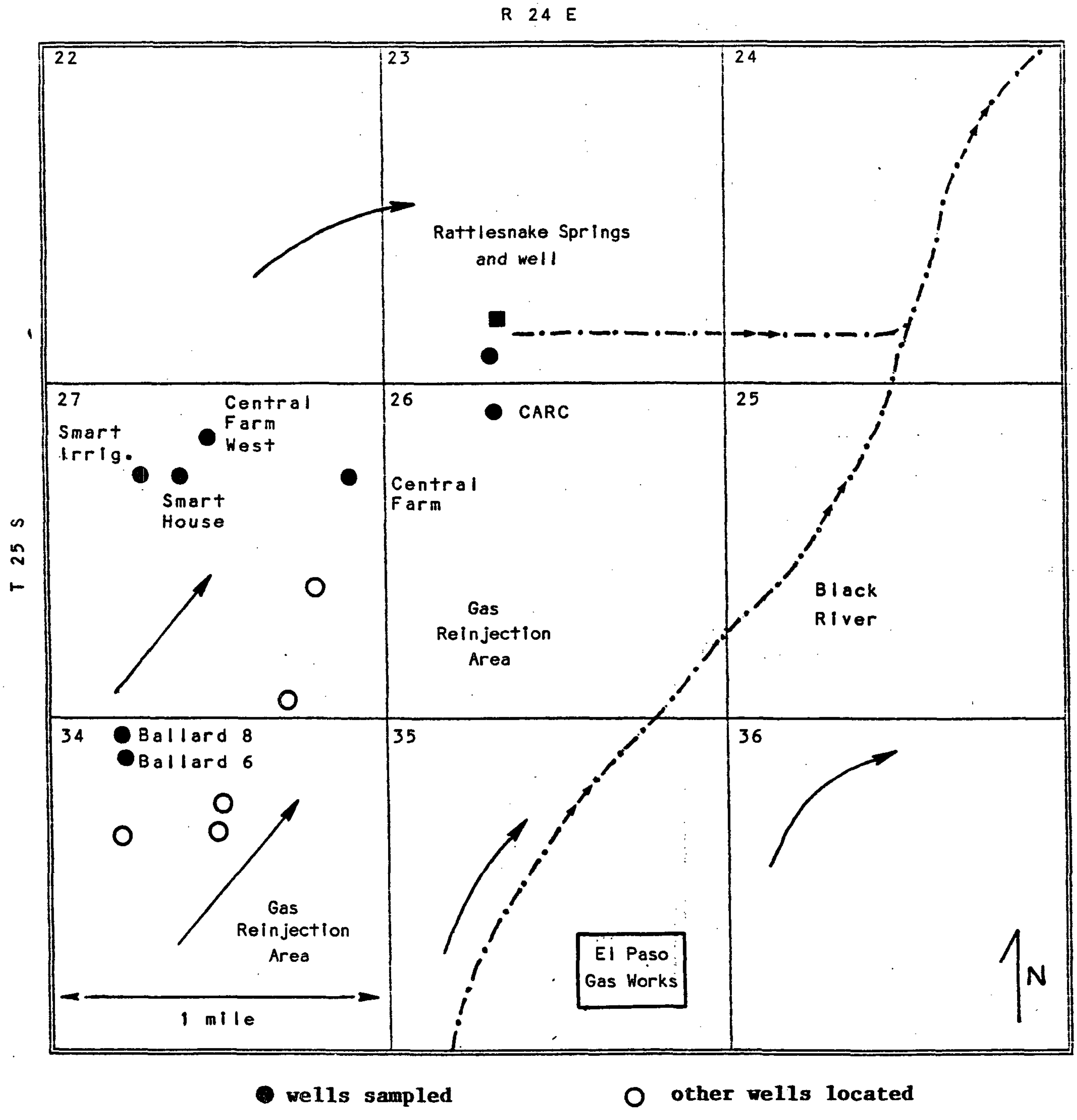
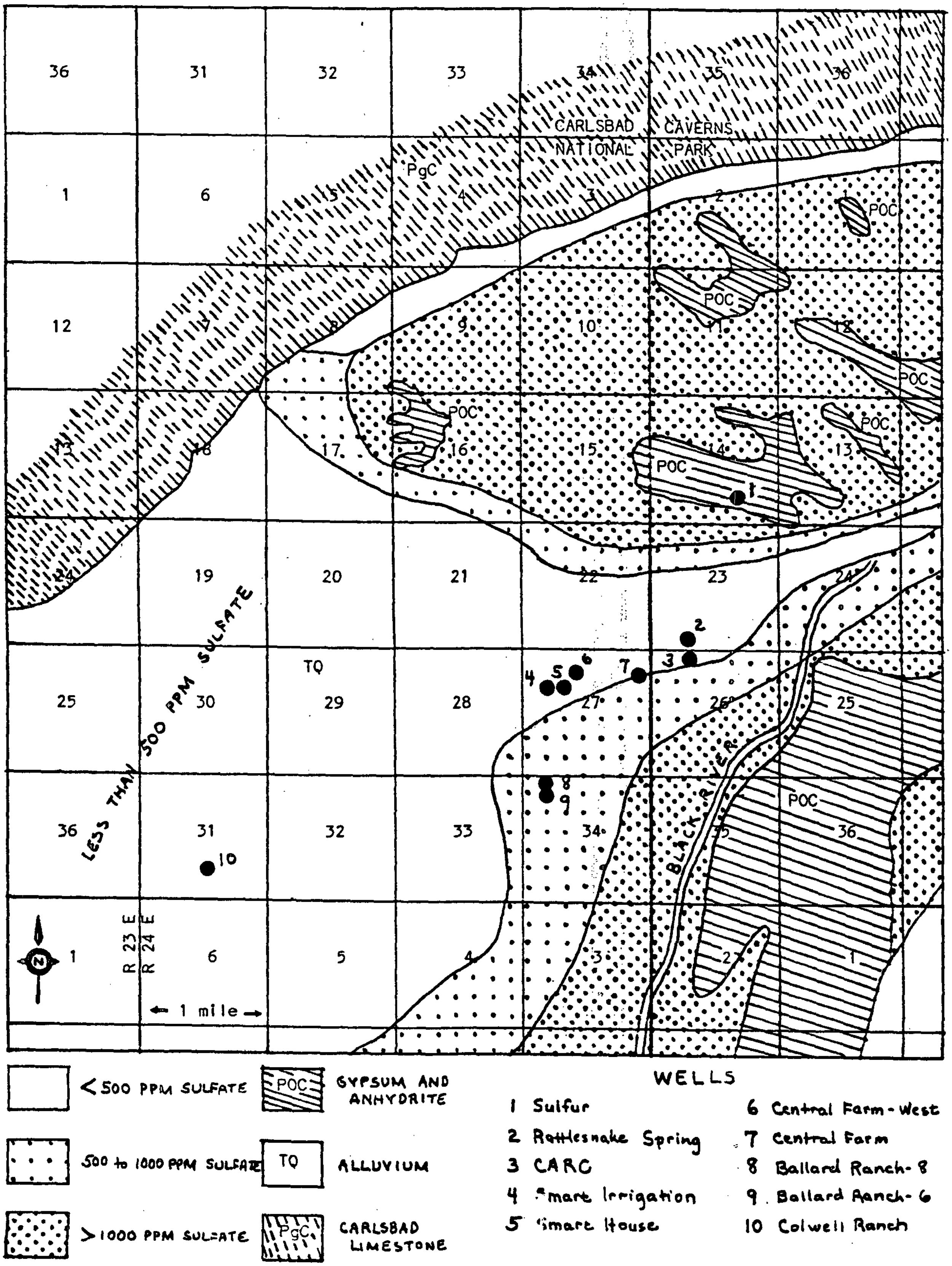
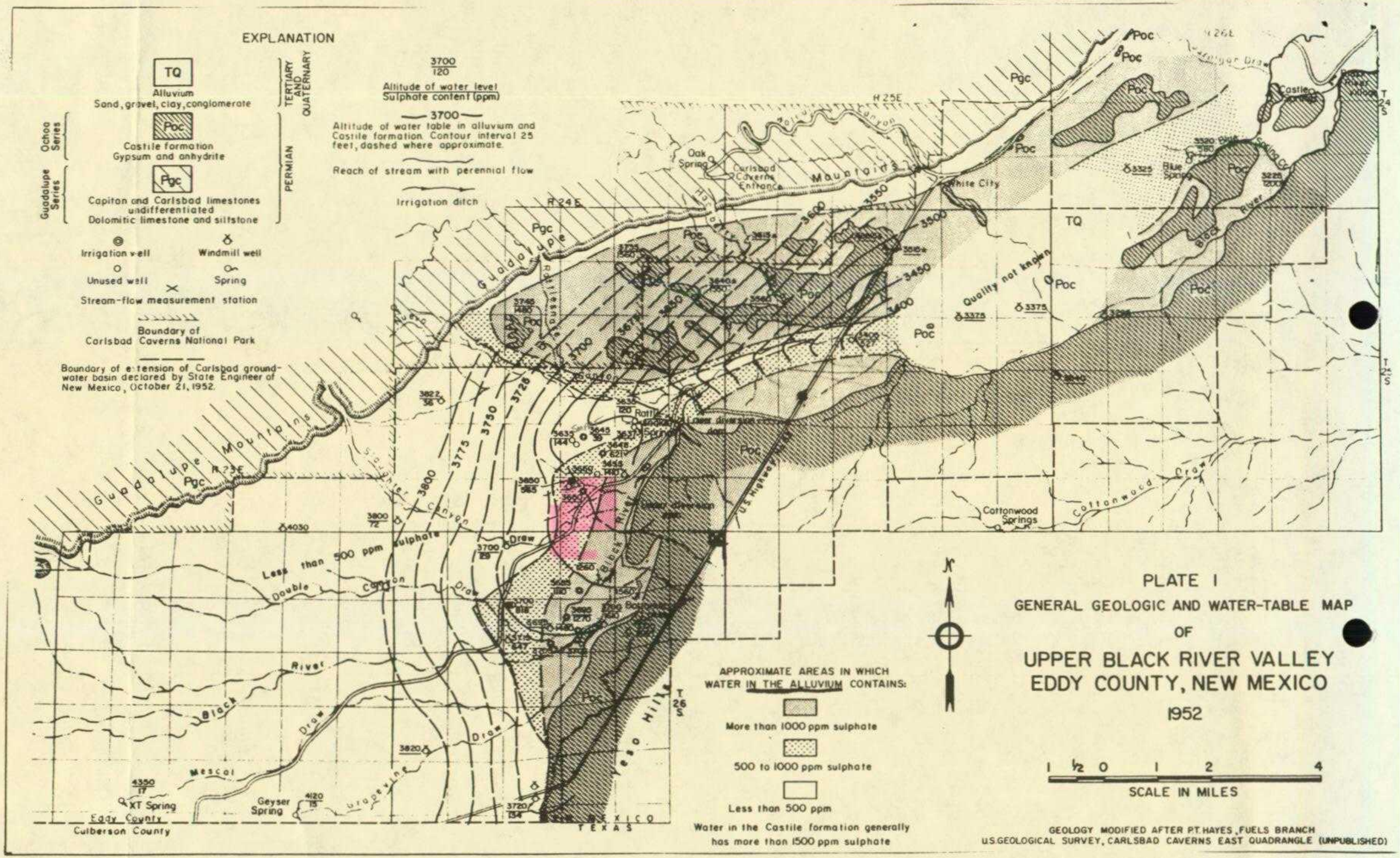


Figure 4. Location of Wells in the Vicinity of Rattlesnake Springs and Generalized Groundwater Flow in the Area.

Figure 3. Major Geologic Features and Sulfate Content of Groundwaters in the Upper Black River Valley (modified from Hale 1955).





Washington Ranch Gas Storage Project

WASHINGTON RANCH
CONTAMINATION STUDY UPDATE

October 17, 1991

Talked with Phil Baca about analysis from the fluids obtained from Well No. 9. El Paso obtained an aqueous phase, but State Lab could not find an aqueous phase. Still have same basic conclusion - oil.

El Paso has $560,000 in the 1992 budget to workover 4 wells at WR. Exact work plans still undecided. On Well No. 3 pulled tubing, ran a caliper log, and replaced the tubing (cost $141,000). El Paso engineers are afraid to perf and squeeze cement into surface/casing annulus because of the nature of the geology. Because of the large fractures and cavities encountered during drilling and cementing (ie. lost circulation), afraid they may not be able to squeeze cement if encounter fractures/cavities, and this would make the situation even worse. May consider running a noise/temperature log to determine any fluid movement outside of the casing. Have run this log on 4 wells already (No.s 10, 17, 3, ?). El Paso also believes that some of the numerous P/A wells could also be the culprit - records show lost circulation when the wells were P/A. Example of this is the Cities Service Well in Section 28 where records show lost circulation during P/A.

The OCD needs to request that El Paso address the cement problems in their workover plans. Will send letter out.

WASHINGTON RANCH STORAGE PROJECT

AUGUST SAMPLING TRIP

Meet Phil Baca (El Paso) on August 27, 1991 at 9:00 am at WRSP. Sampling technician (out of Jal) is Joe Tuten. The plant superintendent is Frank Floyde.
Plant phone number ???

Directions to WRSP: Drive southwest out of Carlsbad on SR 62. About 3-4 miles past White City turn right at the turnoff for Washinton Ranch/New Cave/Rattlesnake Springs. Road meanders for about 3-4 miles and then you will be at the plant.

rsvp for hotel
boots, hat
call brine wells for inspection
district office

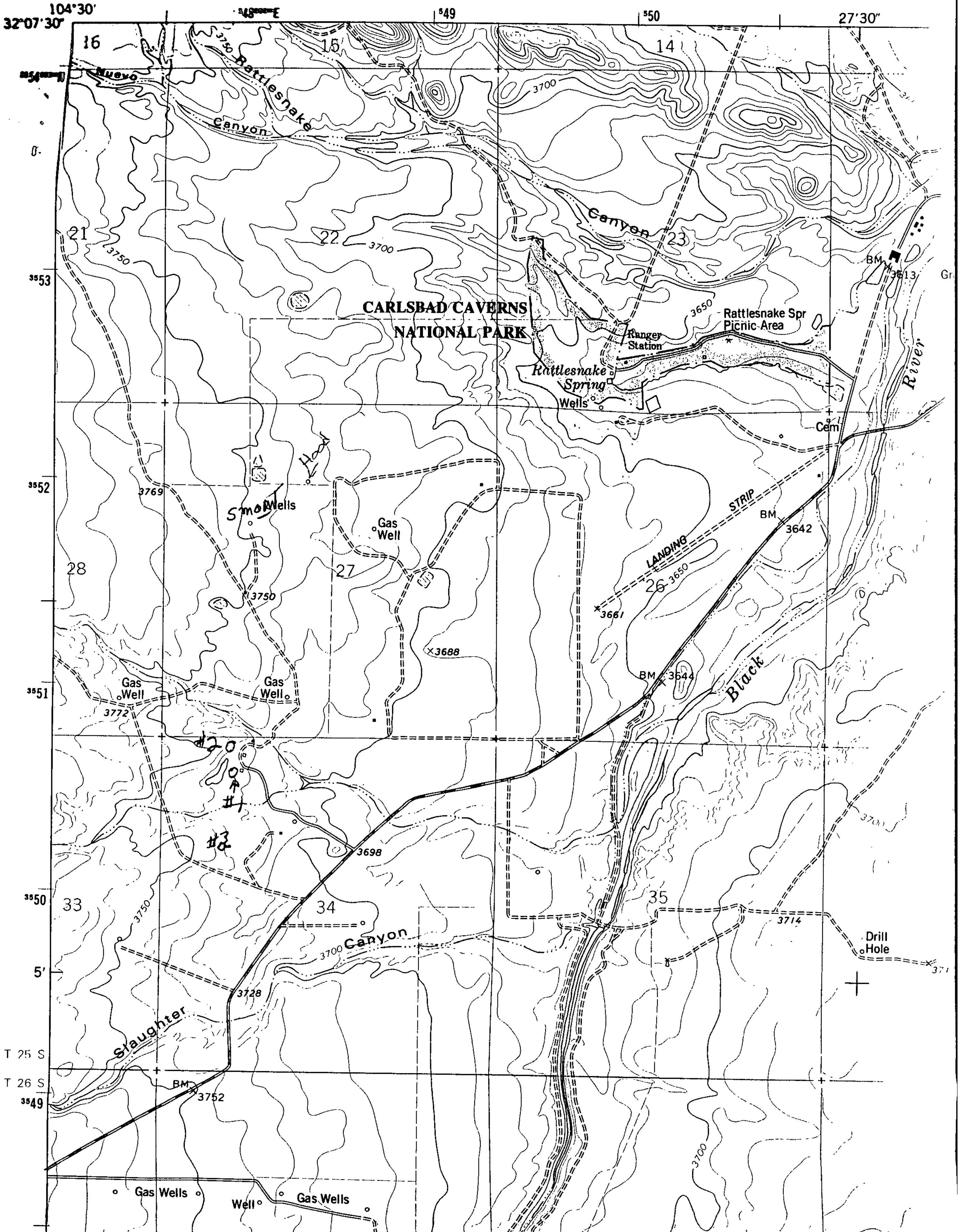
August 27, 1991

Sampled Surface/Production Casing Annulus on Well No.s 12, 7, 16, 9, 22, 19

No. 12: 105 psi, No H_2S, No liquids
No. 7 105 psi, No H_2S, No liquids
No. 16 95 psi, No H_2S, No liquids
No. 9 25 psi, 240 ppm H_2S liquids - looks like oil
Sample 9108271100
No. 22 0 psi, 0 ppm H_2S, ~~[illegible] gas sam~~ No liquids
No. 19 105 psi, No H_2S, No liquids

5048 II NE (SERPENTINE BENDS)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY



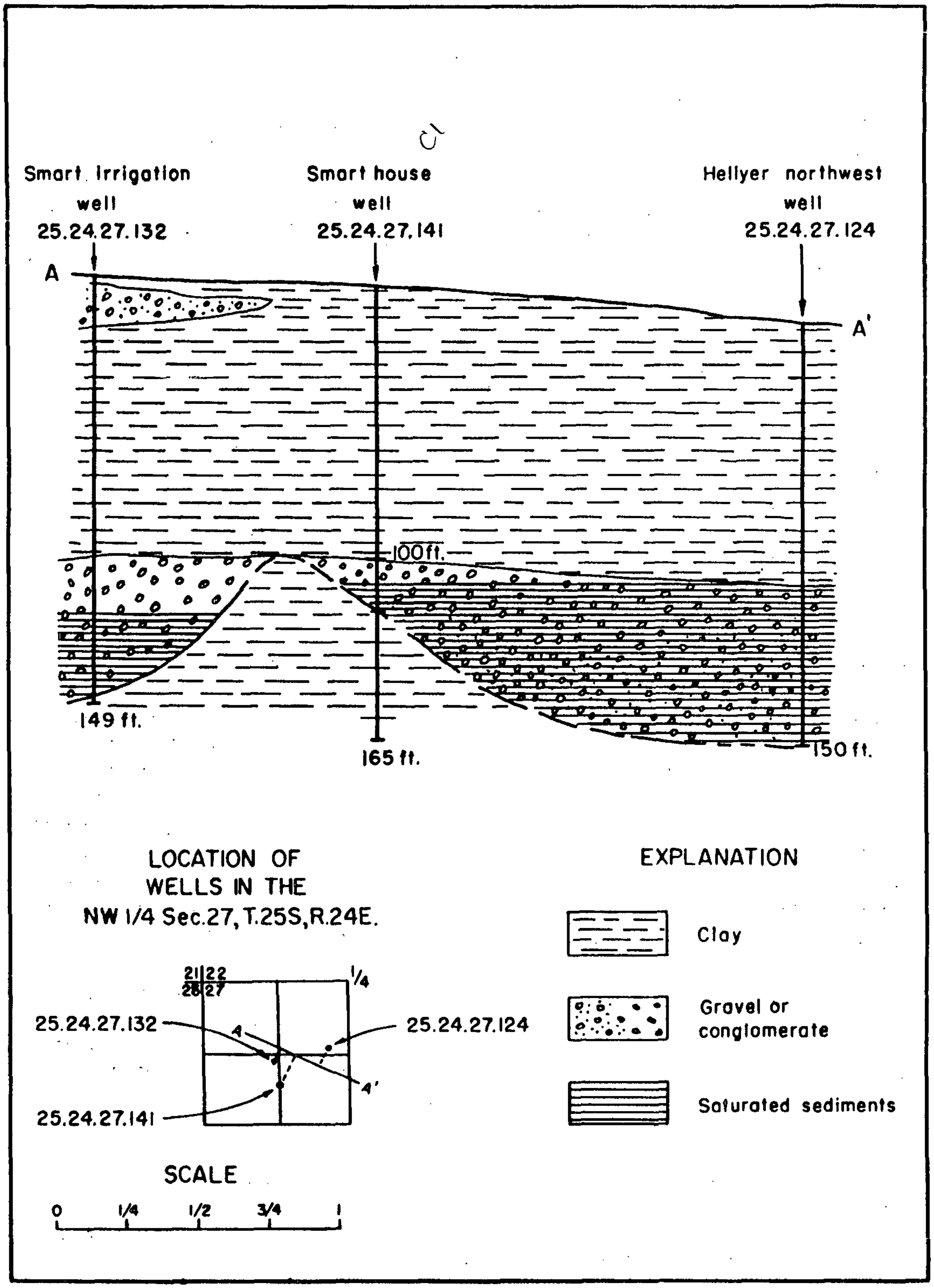


Figure 5.--Inferred relation between aquifers tapped by wells in sec. 27, T. 25 S., R. 24 E., Eddy County, N. Mex. (Based on driller's logs of three wells and results of production tests.)

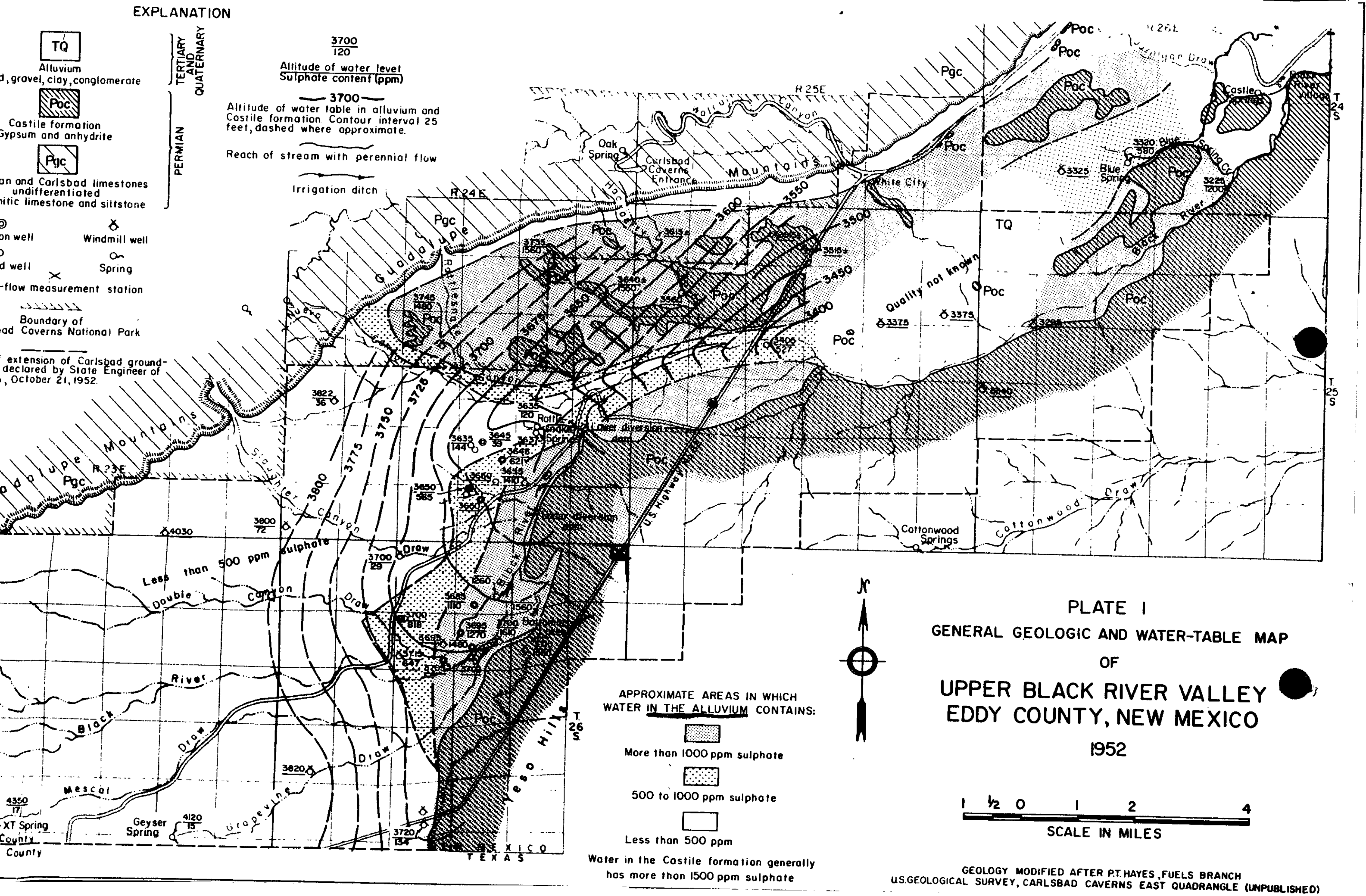


PLATE I
GENERAL GEOLOGIC AND WATER-TABLE MAP
OF
UPPER BLACK RIVER VALLEY
EDDY COUNTY, NEW MEXICO
1952

GEOLOGY MODIFIED AFTER P.T. HAYES, FUELS BRANCH
U.S. GEOLOGICAL SURVEY, CARLSBAD CAVERNS EAST QUADRANGLE (UNPUBLISHED)