Significance of Ground-Water Chemistry in Performance of North Sahara Tube Wells in Algeria and Tunisia

---

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1757-M

Prepared in cooperation with
the Governments of
Algeria and Tunisia

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

SIGNIFICANCE OF GROUND-WATER CHEMISTRY IN PERFORMANCE OF NORTH SAHARA TUBE WELLS IN ALGERIA AND TUNISIA

Shallow water lift, Tunisia

Significance of Ground-Water Chemistry in Performance of North Sahara Tube Wells in Algeria and Tunisia

By FRANK E. CLARKE *and* BLAIR F. JONES

CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA
AND THE MEDITERRANEAN REGION

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1757-M

Prepared in cooperation with
the Governments of
Algeria and Tunisia

A contribution to the International
Hydrologic Decade

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1972

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress catalog-card No. 72-600275

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 55 cents (paper cover)
Stock Number 2401-00256

CONTENTS

ILLUSTRATIONS

TABLES

CONTRIBUTIONS TO THE HYDROLOGY OF AFRICA AND THE MEDITERRANEAN REGION

SIGNIFICANCE OF GROUND-WATER CHEMISTRY IN PERFORMANCE OF NORTH SAHARA TUBE WELLS IN ALGERIA AND TUNISIA

By FRANK E. CLARKE and BLAIR F. JONES

ABSTRACT

Nine ground-water samples from the principal shallow and deep North Sahara aquifers of Algeria and Tunisia were examined to determine the relation of their chemical composition to corrosion and mineral encrustation thought to be contributing to observed decline in well capacities within a UNESCO/UNDP Special Fund Project area. Although the shallow and deep waters differ significantly in certain quality factors, all are sulfochloride types with corrosion potentials ranging from moderate to extreme. None appear to be sufficiently supersaturated with troublesome mineral species to cause rapid or severe encrustation of filter pipes or other well parts. However, calcium carbonate encrustation of deep-well cooling towers and related irrigation pipes can be expected because of loss of carbon dioxide and water during evaporative cooling.

Corrosion products, particularly iron sulfide, can be expected to deposit in wells producing waters from the deep aquifers. This could reduce filter-pipe openings and increase casing roughness sufficiently to cause significant reduction in well capacity. It seems likely, however, that normal pressure reduction due to exploitation of the artesian systems is a more important control of well performance. If troublesome corrosion and related encrustation are confirmed by downhole inspection, use of corrosion-resisting materials, such as fiber-glass casing and saw-slotted filter pipe (shallow wells only), or stainless-steel screen, will minimize the effects of the waters represented by these samples. A combination of corrosion-resisting stainless-steel filter pipe electrically insulated from the casing with a nonconductive spacer and cathodic protection will minimize external corrosion of steel casing, if this is found to be a problem. However, such installations are difficult to make in very deep wells and difficult to control in remote areas.

Both the shallow waters and the deep waters examined in this study will tend to cause soil salinization because their salt contents are relatively high, and both have sodium absorption ratios which are unfavorable to sodium-sensitive soils and vegetation. Proper drainage and soil treatment are the only means of overcoming these problems during irrigation.

INTRODUCTION

This study of ground-water qualities was made at the request of the United Nations Education, Scientific and Cultural Organization (UNESCO) (written commun. to U. S. Geol. Survey, Apr. 9, 1969) to determine if the waters from the principal North Sahara aquifers of Algeria and Tunisia are likely to cause corrosion and mineral encrustation of well casings and filter pipes and thus contribute to observed reduction in discharge and quality changes in irrigation wells. The field study was made during the period September 15 through September 30, 1969, as part of UNESCO/UNDP (United Nations Development Project) Special Fund Project "Survey of Groundwater Resources in the Northern Sahara." This report is based on the field observations and extensive laboratory studies of well waters and water-formed deposits collected during the investigation. Preliminary findings were reported during the data processing (F. E. Clarke, written commun., December 1969, and consultant rept., April 1970).

SCOPE OF STUDY

The nine test wells were located in the northeast quadrant of the 800,000—km^2 (square kilometers) area covered by the UNDP special project. Six Algerian wells, three each near Ouargla and Touggourt, were situated along the northwestern boundary of the great eastern dune field (Grand Erg Oriental). The remaining three wells were located in the environs of Gabès, Tunisia, to the northeast of the dune field and the great internal drainage basin, Chott Djerid. Two actually were in the margin of the chott. One of the three (well ICM 3) was only a few kilometers from the Gulf of Gabès. Locations are shown on the map in figure 1.

The test wells along this route from Ouargla to Touggourt (both in Algeria) to Gabès were selected to provide water quality information on artesian aquifers of the shallow Continental Terminal and the deep Continental Intercalary aquifers shown in the lithologic cross section of figure 2. These are the principal water-bearing formations of the project area. Except for a relatively small amount of unconfined water near the surface utilized by phreatophytic plants and drawn with simple lifts (see frontispiece), these formations constitute the major source of water for irrigation and general-purpose use. The test series in the Ouargla-Touggourt sector of Algeria included three wells each in the Miocene and Pliocene formation of the Continental Terminal and the formation of Albian age of the Continental Intercalary. The Tunisian wells included two in the Miocene and Pliocene and one in the formation of Barremian age which underlies the outcropped Albian in this area. Tests of a geothermal well (CF 3), which bottoms in the still deeper formation of Neocomian age of the Continental Intercalary's Lower Cretaceous near El Hamma, were abandoned on September 25 because of a persistent record-breaking storm and resulting flood.

ACKNOWLEDGMENTS

This study was made at the request of the United Nations Education, Scientific and Cultural Organization (UNESCO) and in cooperation with the Governments of Algeria and Tunisia. Messrs. J. A. da Costa, N. Bouchin, R. Ackermann, UNESCO, Paris, and Mrs. Elizabeth Meechan, UNESCO, New York, provided valuable background information and assistance in planning for the work. Messrs. S. Anderson and Linner, Resident Representatives of United Nations in Algeria and Tunisia, respectively, and members of their staffs, particularly Mr. Corry and Madam Yannaki, in Algeria, and Madam Campo, in Tunisia, gave careful attention to details of local travel which made the investigation pleasant as well as scientifically profitable.

Mr. Carlo Chenevart, Manager of UNESCO/UNDP Special Fund Project "Survey of Groundwater Resources in the Northern Sahara" (REG. 100), traveled with the senior author throughout the field studies. His able assistance and excellent knowledge of geology, hydrology, and well technology made it possible to complete the planned work in the short time available. Messrs. Simonot, Schoute, and Perrier, and Mesdames Loubet-Rousseab and Pontanier of his staff also were quite helpful.

Offices of the Ministry of Public Works, Algeria, and the Ministry of Agriculture, Tunisia, provided essential logistic and technical support. Particular appreciation is expressed to Mr. M. Inal, General Manager of the Organization for Reclamation of Arid Lands (OCI) Algeria, and Mr. R. Rouatbi, Comanager of the UNESCO/UNDP project in Tunisia.

GENERAL CHARACTERISTICS OF TEST WELLS

The test wells fell into two distinctly different classes determined primarily by the depth of the formation penetrated. All occurred in areas of relatively low topographic relief, and the wellhead elevations declined slightly and uniformly from 158 meters above sea level at Ouargla, Algeria, to 12 meters in the coastal region of Gabès, Tunisia. Depths of the five shallow test wells ranged from 65 meters below land surface in the Miocene-

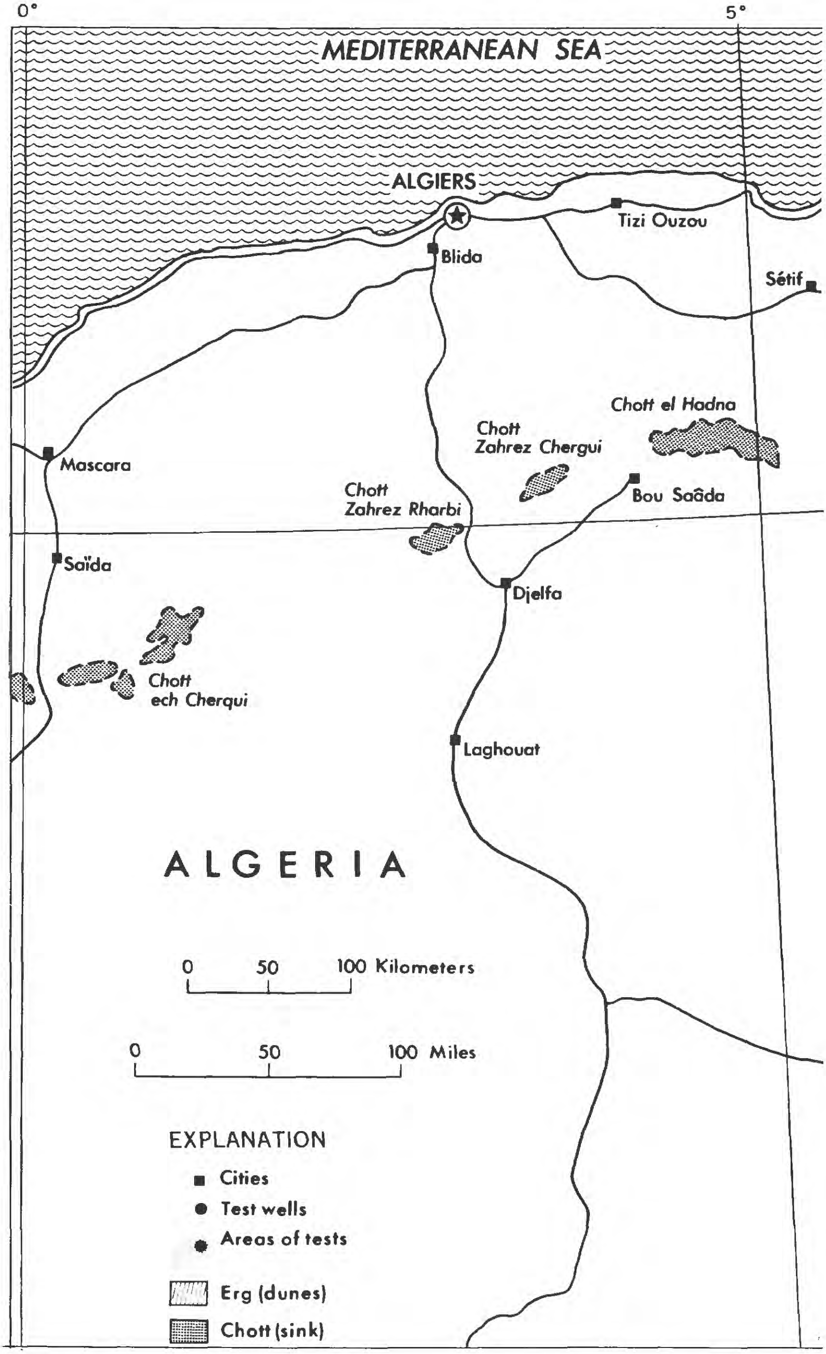
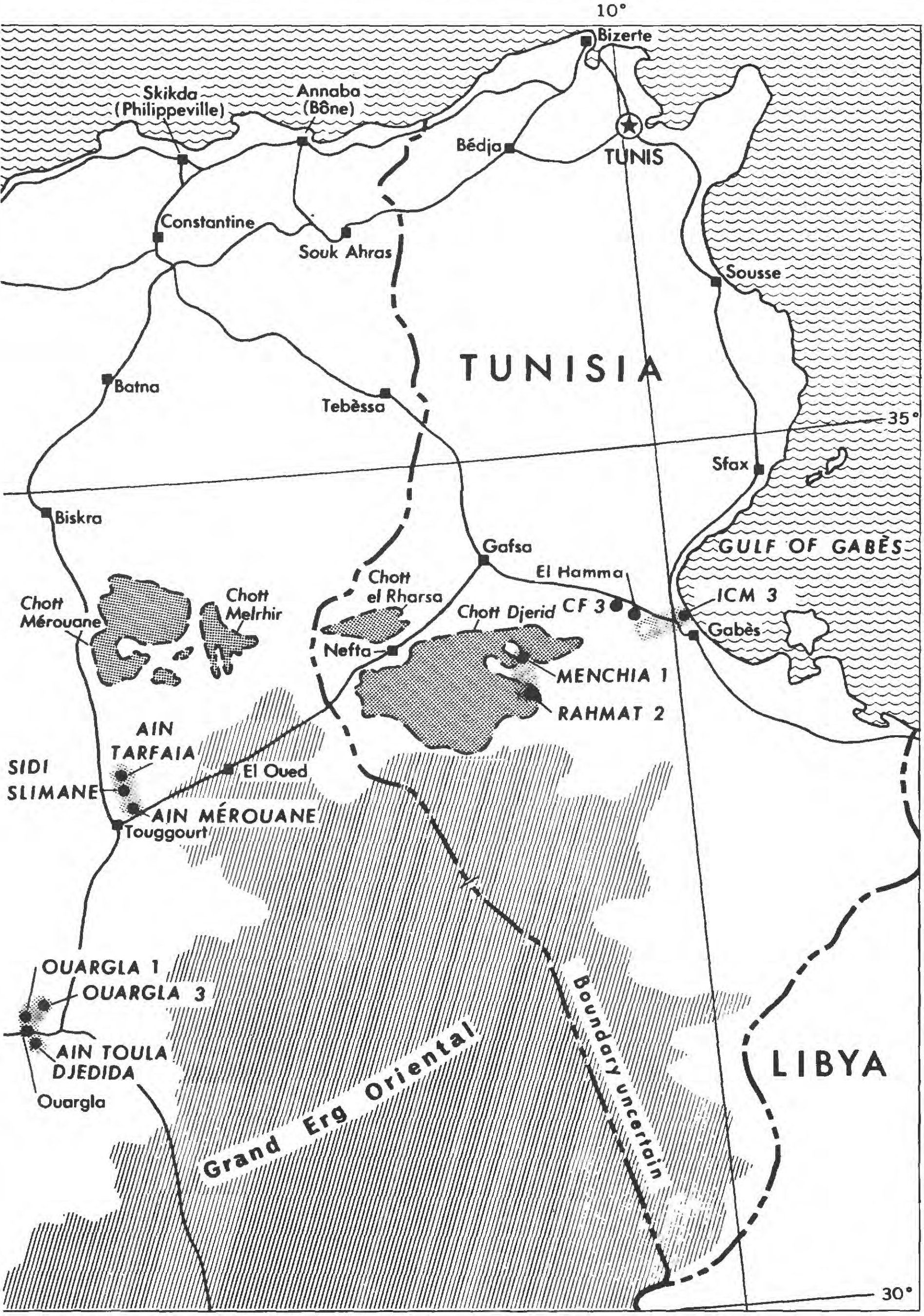


FIGURE 1.—Test



well locations.

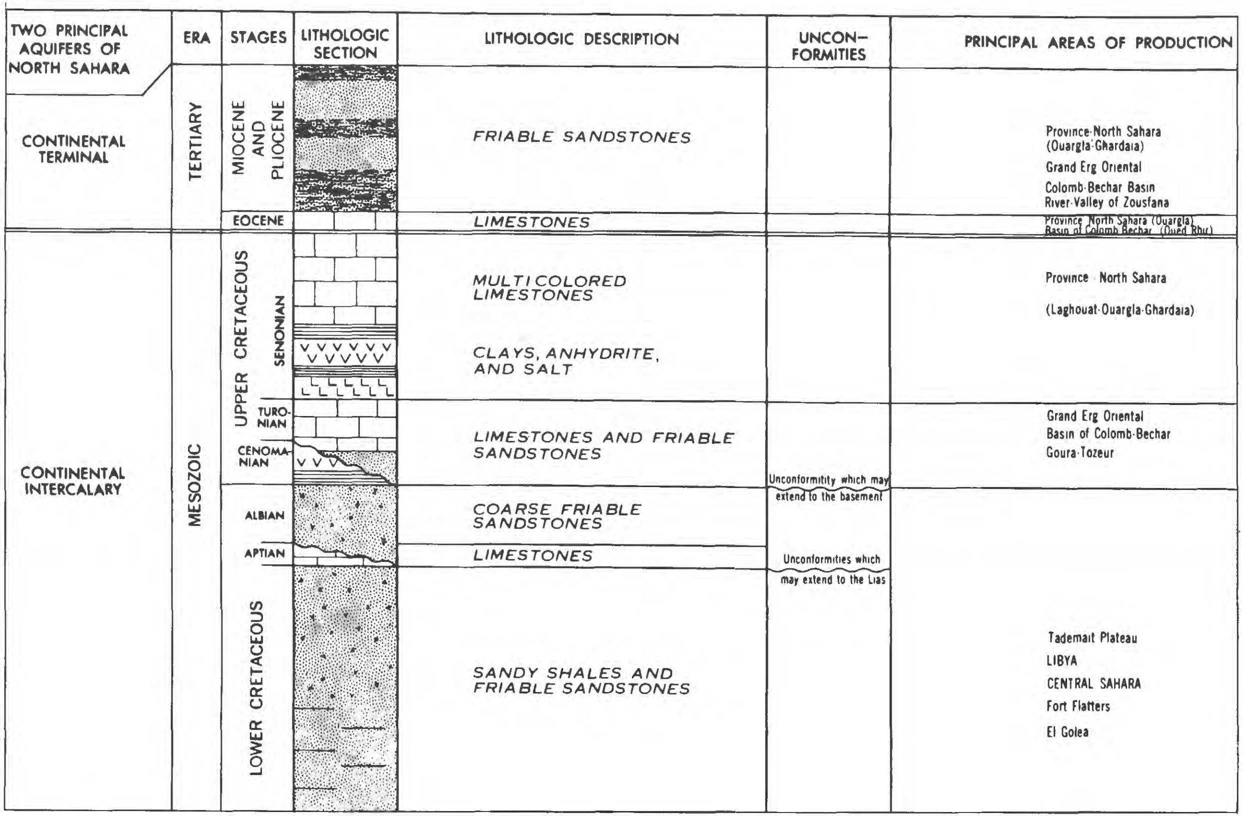


FIGURE 2.—Lithology of principal aquifers of the North Sahara. From sketch prepared by Carlo Chenevart.

Pliocene horizon near Ouargla to 185 meters in the Upper Cretaceous near Gabès. Deep wells of the Albian and Barremian ranged in depth below land surface from 1,126 to 1,571 meters. With the exception of the well bottomed in the Barremian (Menchia), all the deep well waters reached the surface with relatively high pressures of 24 to 27 kg/cm^2 (kilograms per square centimeter), temperatures of 49° to 57°C (Celsius), and discharge rates of 60 to 345 l/sec (liters per second). Menchia 1 well water was in the same temperature range (50°C) as one would expect for its depth, but the well's 7.4 kg/cm^2 pressure and 16.5 l/sec discharge were considerably lower than corresponding values in the other deep wells. Temperatures of the shallow well water ranged from 23° to 26°C, and pressures and discharges of the corresponding wells were 0.1 to 2 kg/cm^2 and 2 to 65 l/sec, respectively.

The wells are cased and equipped with filter pipes (screens) of a variety of sizes and types of materials and components. Plain carbon steel predominates as the construction material in both casings and filter pipes, and most of the filter pipes are of louvered design. Two of the wells are equipped with stainless-steel filter pipes of German origin (composition unknown), and one well was reported to have saw-slotted plain carbon steel filter pipe. All wells which bottom in the deeper horizon are externally cemented above the producing aquifer. Available data failed to show if this is true of shallow wells tapping the Miocene and Pliocene rocks.

The three shallow test wells in Algeria were flowing without throttling at the time of test, and this appears to be the general practice. The deep Algerian wells discharge through cooling towers or cascade coolers, like that shown in figure 3, to reduce irrigation water to the tolerance temperature of date palms. Provision is made for throttling these wells, and in some instances, for bypassing the coolers. With the exception of Ouargla 1, which is within the city of the same name, the deep wells are typically in sparsely populated desert areas and are either equipped or are in the process of being equipped with distributors for relatively long-distance transport of irrigation water. The shallow wells generally are in or near villages or date palm oases associated with villages.

Table 1 provides a summary of general information on the nine test wells.

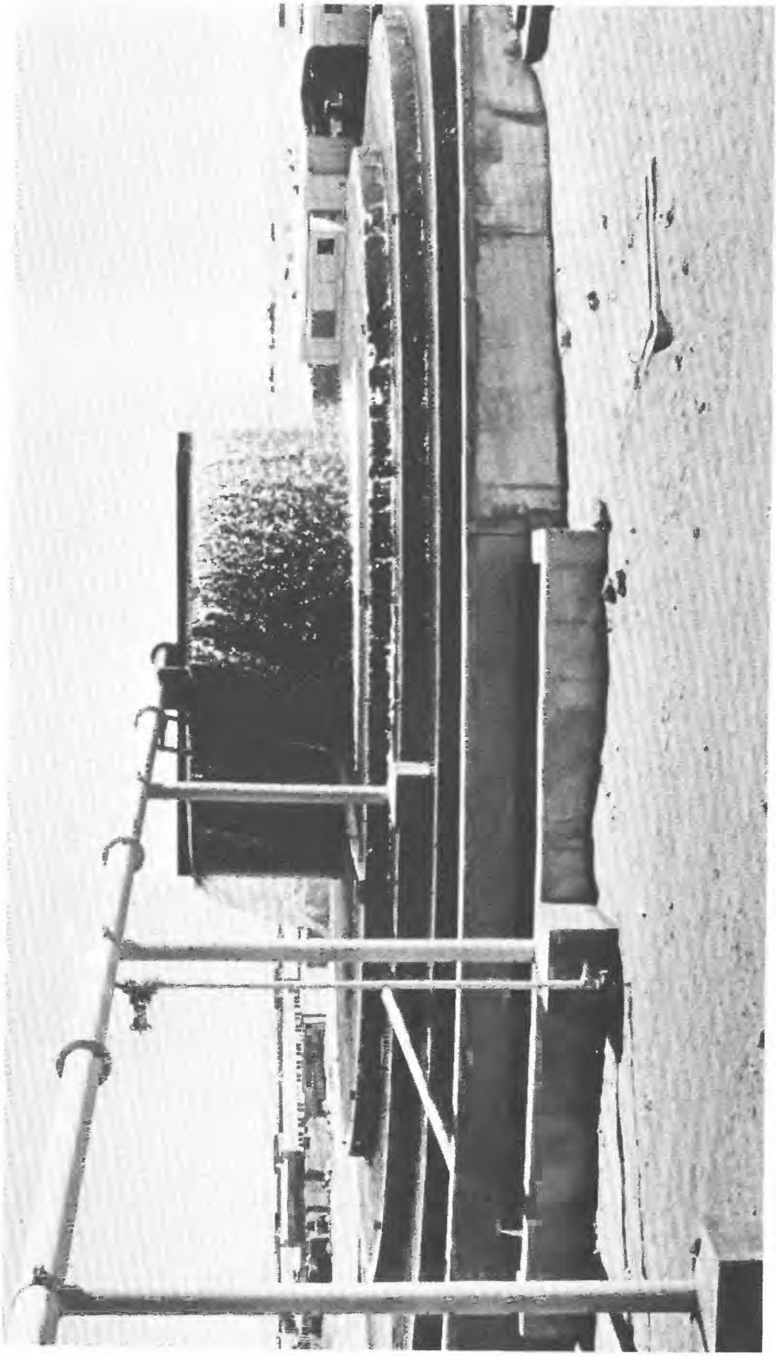


FIGURE 3.—Cascade cooler, deep well near Ouargla, Algeria.

FIELD TESTS

Because of the difficulty of transporting and maintaining equipment in desert areas, field tests were made only of water components and characteristics likely to change or be lost in transporting samples to the laboratory. These included tests for temperature, pH (hydrogen ion activity), Eh (platinum electrode potential), corrosion rate, dissolved iron, and bicarbonate ion, and qualitative tests for sulfide compounds. All these tests were made on water discharging from the wellheads, except that several temperature and dissolved iron measurements and semiquantitative tests for aqueous (free) carbon dioxide were made on water taken from the cooler outlets of the deep wells. The carbon dioxide test was made by direct titration with standard sodium hydroxide to phenolphthalein endpoint.

A solid state specific ion meter was used in conjunction with glass and calomel (reference) electrodes, both for measuring pH and for detecting the endpoints in the sulfuric acid titrations of bicarbonate ion. In both tests, the pH electrode system was calibrated with pH 4 and pH 7 standard buffer solutions maintained as closely as possible to well water temperature by suspending their plastic containers in the well's discharge.

Eh, a measure of oxidation-reduction characteristics of water, also was measured with the specific ion meter. The electrodes were mounted in the special stainless-steel flow cell shown in figure 4. This electrode system was calibrated with a solution of known oxidation-reduction potential (Zobell solution). Water discharging from the wellhead was flushed through the flow cell by means of a closed tube, and flow was maintained through the cell for up to an hour, until a steady potential was achieved. Because of practical limitations on redox measurements resulting from such processes as oxygen or ferric hydroxide colloid sorption on noble metal electrode surfaces (considered in some detail by Doyle, 1968), only the data for the deep wells can be treated in any quantitative manner. At the same time, errors related to spurious and mixed potentials plus long-term drift may be imposed on further evaluation of redox-controlled solution species, such as those of iron. Nevertheless, the gross correlation between Eh data and the mineralogy of corrosion products (Clarke and Barnes, 1969) supports the general value of such measurements.

Ferrous and ferric ion were measured colorimetrically by standard bipyridine and orthophenanthroline methods using fields kits specially designed for the purpose (precision 0.05 mg/l). Qualitative tests for sulfide were made by checking each well for the

TABLE 1.—*General information,*

Well designation (and location)	Date completed	Elevation of land surface above sea level (m)	Well depth (m)	Producing formation	Casing size[1]
Algeria					
Ouargla 1 [replacement well], Ref. No. S.E.S. 447J10.	1956	138.1	1,350	Albian	13⅜ in. (0 to 409.2 m). 9⅝ in. (409 to 1,048 m). 6⅝ in. (1,048 m to bottom, five sections).
Ain Toula Djedida, Ref. No. S.E.S. D4F 77 (oasis near Ouargla).	1968	139.4	65	Miocene and Pliocene.	13⅝ in
Ouargla 3, Ref. No. S.E.S. 511J10 (desert, 15 km from Ouargla).	1961	158	1,126.4	Albian	13⅝ in
Ain Mérouane, D29F 73 (Meggarine Oasis, Guedima, Touggourt).	1952	59	169.45	Miocene and Pliocene.	8 in. (0 to 160.1 m)
Ain Tarfia, D25F 12 (oasis near Touggourt).	1964	55.14	120.25	Miocene and Pliocene.	12 in. (0 to 11 m). 8 in. (11 to 101 m).
Sidi Slimane (desert project, about 20 km from Touggourt).	1960	64	Initial: 1,774. Present: 1,571.	Albian	Initial: 13⅜ in. (to 1,559 m). 9⅝ in. (1,542 to 1,565 m; 1,765 to 1,774 m). Present: 9⅝ in. (1,426 to 1,556 m.).
Tunisia					
Rahmat 2, 5692/5 (100 km west of Gabès).	1951	25.8	185	Upper Cretaceous (?).	13⅜ in. (0 to 63.8 m)
Menchia 1, 9346/5 (about 100 km west of Gabès).	1967	30	1,458	Barremian (Lower Cretaceous).	9⅝ in
ICM 3, 9251/5 (10 km north of Gabès).	1968	12	150	Miocene and Pliocene.	13⅜ in

1. All steel, depth given when available.

characteristic odor and by making semiquantitative color tests with lead acetate paper when sulfide compounds appeared to be present.

Corrosion rates were determined by immersing a dual electrode probe assembly in the water and impressing a predetermined voltage across the electrodes, which are made of low-carbon steel like the casings. The resulting current flow is proportional to the corrosivity of the water. Direction of current flow is reversed periodically to avoid errors from polarization and unavoidable differences in the electrode pair. Corrosion rate is estimated by averaging readings and comparing the data with calibration curves based on specific resistivity equal to that of the water being tested. Reliability of this measurement is influenced by dif-

water wells Algeria and Tunisia

Screen size	Screen type[2]	Pressure head at land surface (kg/cm^2)	Discharge[3] (l/sec)	Remarks
8½ in., four sections (1,119 to 1,314.75 m) (total, 102.2 m perforated).	INOX stainless steel louver (German).	Initial: 26.7. Present: 24.3.	Initial: 258. Present: 200.	Sampled corrosion product; cooling tower encrusted.
9⅝ in. (40 to 65 m)	INOX steel louver (German).	0.2	9.5	Severe corrosion of horizontal discharge line.
9⅝ in. (1,219.29 to 1,421.10 m).	NSMC steel louver.	Initial: 26.5. Present: 24.6	60	
6 in. (160.1 to 169.45 m)	Steel "APS 20A" louver (4 to 8 mm opening).	0.1	25.9	In oasis surrounded by water-logged salinized area.
6⅝ in. (101 to 120. 25 m)	Steel "APS 20A" louvre.	0.11	2.2	
Initial: 9⅝ in. (1,565 to 1,765 m). Present: 9⅝ in. (1,556 to 1,571 m).	See "Remarks."	Initial: 27. Present: unknown	1960: 416.6. 1962: 364.6. 1964: 345.5.	The steel screen blew out of this well in 1964. It was recased from 1,426 to 1,556 m with 9⅝ in. API "1003" steel and was rescreened from 1,556 to 1,571 m with INOX stainless-steel louvered screen (German).
9⅝ in. (63.8 to 185 m)	Steel louver	1.56	Initial: 39. present: 4.0.	
8 in	Steel louver	7.4	16.5	
9⅝ in	Steel saw slot (Nold, Germany).	2.06	(?) 65	

[2] Aperture size given when available.
[3] Some of the unlabeled figures may be initial values.

ferences in geometry between the electrodes and the well parts being studied. This can have significant effects, depending on the corrosion mechanism. Nevertheless, the corrator is an excellent rapid field tester for estimating corrosion rates of well parts, particularly for comparing corrosiveness of several well waters to a particular steel or the corrosion resistances of a variety of metals to a particular well water.

Corrosion measurements were made on the deep wells and some of the shallow wells by drilling and tapping (threading) the outlet pipes to receive the threaded probe assembly. In several shallow wells it was necessary to remove the cap from the vertical well casing and handhold the probe in the overflowing water. In

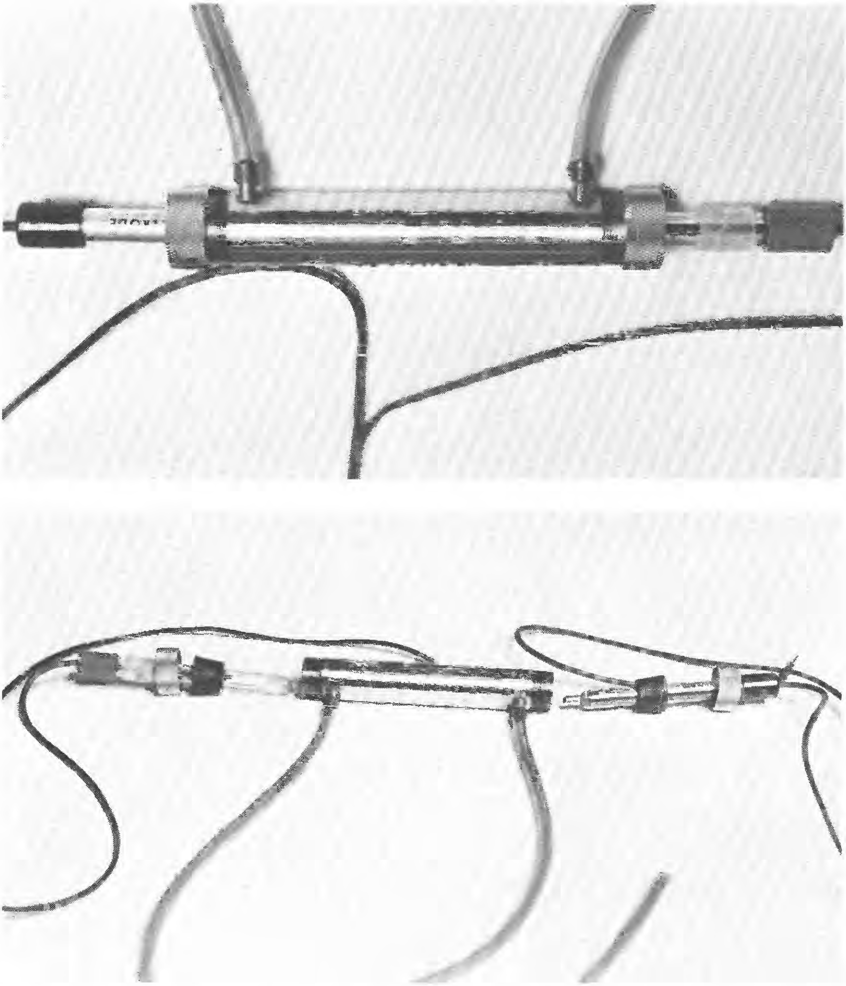


FIGURE 4.—Stainless-steel flow cell for oxidation-reduction measurement. Assembled view (upper photograph) and disassembled view (lower photograph).

every case tests were continued until stable readings were obtained. The time required ranged from 30 minutes to 2 hours.

HYDROCHEMISTRY

The pH values of the test wells were uniformly in the range 7.1 to 7.3 regardless of depth and location, except for the two shallow Tunisian wells (pH 6.75 and 7.55). Aqueous (free or agressive) carbon dioxide contents were low in all wells—6.0 to 14.9 mg/l (milligrams per liter)—except for Tunisian shallow well ICM 3 (38.2 mg/l). Except for Algerian shallow well Ain Tarfaia, silica concentrations were uniformly rather high (15 to 26 mg/l). Corrosion rates were less uniform, as would be expected considering the variety of factors involved in corrosion processes; however, only two were in the range of severe to extreme metal damage. Both of these were in Tunisia (table 2).

All wells contained significant amounts of boron, fluoride, and nitrate ions. In several shallow wells, the concentration of fluoride approached the level at which mottling of teeth might occur (2 mg/l). In Algeria, these minor constituents were more prevalent in the shallow aquifer.

In all other respects, the wells fell into two groups with distinctly different properties related to depth of formation. The expected temperature differences already have been discussed. Eh

TABLE 2.—*Water-quality data, Algerian and Tunisian wells*

[Determinations in milligrams per liter unless unit of measurement is specified. Specific conductance: resistance (ohms) given in parentheses. Qualitative sulfide data not included; sulfide odor noticed in all deep wells. Temperature, pH, Eh, corrosion rate, CO_2, total iron, Fe^{+2}, and HCO_3, determined in the field. Data for total solids and ionic concentrations are based on laboratory analyses by Donald Fisher, U.S. Geological Survey. Data for Tunisian well CF 3 not included as test was abandoned because of persistent storm]

	General determinations					
Well designation (and location)	Temp (°C)	pH	Eh (mv)	Specific conductance (mhos)	Corrosion rate (in. per yr)	CO_2
Algeria						
Ouargla 1 [replacement well], Ref. No. S.E.S. 447J10	49	7.25	+22	3,010 (332.2)	0.006 (moderate)	12.3
Ain Toula Djedida, Ref. No. S.E.S. D4F 77 (oasis near Ouargla)	24	7.2	+357	3,710 (296.5)	0.012 (moderate)	9.2
Ouargla 3, Ref. No. S.E.S. 511J10 (desert, 15 km from Ouargla)	49	7.3	+22	2,630 (380)	0.016 (moderate)	11.6
Ain Mérouane, D29F 73 (Meggarine Oasis, Guedima, Touggourt)	26	7.05	+412	6,400 (156)	0.024 (moderate to severe)	13.8
Ain Tarfia, D25F 12 (oasis near Touggourt)	26	7.1	+402	5,610 (178)	0.018 (moderate)	8.9
Sidi Slimane (desert project, about 20 km from Touggourt)	57	7.2	−108	2,800 (357)	0.025 (moderate to severe)	14.9
Tunisia						
Rahmat 2, 5692/5 (about 100 km west of Gabès)	23	7.55	+442	2,310 (433)	0.012 (moderate)	6.0
Menchia 1, 9346/5 (about 100 km west of Gabès)	50	7.15	−133	7,030 (142)	0.043 (severe)	6.2
ICM 3, 9251/5 (10 km north of Gabès)	24.5	6.75	+452	4,250 (235)	0.083 (extreme)	38.2

TABLE 2.—*Water-quality data, Algerian and Tunisian wells*—Continued

Well designation (and location)	General determinations—Continued			Cations					
	SiO_2	Total Fe	Total solids by evaporation at 180°C	Al	Ca	Mg	Na	K	Fe^{+2}
Algeria									
Ouargla 1 [replacement well], Ref. No. S.E.S. 447J10	21	------	1,990	0.2	188	76	352	31	0.9
Ain Toula Djedida, Ref. No. S.E.S. D4F 77 (oasis near Ouargla)	15	0	2,560	0.2	228	97	436	25	0
Ouargla 3, Ref. No. S.E.S. 511J10 (desert, 15 km from Ouargla)	23	1.9	1,740	0.1	167	76	266	30	1.0
Ain Mérouane, D29F 73 (Meggarine Oasis, Guedima, Touggourt)	20	------	4,920	0.3	532	163	735	40	0
Ain Tarfia, D25F 12 (oasis near Touggourt)	10	0	4,100	0.3	428	142	675	35	0
Sidi Slimane (desert project, about 20 km from Touggourt)	26	4.2	1,980	0.2	221	93	218	43	3.8
Tunisia									
Rahmat 2, 5692/5 (about 100 km west of Gabès)	19	0	1,570	0.1	146	69	220	14	0
Menchia 1, 9346/5 (about 100 km west of Gabès)	25	2.8	4,700	0.2	458	91	970	38	2.7
ICM 3, 9251/5 (10 km north of Gabès)	21	0	3,100	0.2	355	107	441	35	0

Well designation (and location)	Anions							
	Mn	B	Cl	F	HCO_3	CO_3	SO_4	NO_3
Algeria								
Ouargla 1 [replacement well], Ref. No. S.E.S. 447J10	0.2	0.19	564	0.7	188	0	580	0.6
Ain Toula Djedida, Ref. No. S.E.S. D4F 77 (oasis near Ouargla)	0	0.37	708	1.2	132	0	748	29
Ouargla 3, Ref. No. S.E.S. 511J10 (desert, 15 km from Ouargla)	0.02	0.19	446	0.7	188	0	539	0.2
Ain Mérouane, D29F 73 (Meggarine Oasis, Guedima, Touggourt)	0	0.39	1,250	1.8	130	0	1,640	3.2
Ain Tarfia, D25F 12 (oasis near Touggourt)	0	0.44	1,080	1.8	136	0	1,370	31
Sidi Slimane (desert project, about 20 km from Touggourt)	0.3	0.25	474	0.7	190	0	640	8.0
Tunisia								
Rahmat 2, 5692/5 (about 100 km west of Gabès)	0.02	0.19	432	0.8	140	0	422	28
Menchia 1, 9346/5 (about 100 km west of Gabès)	0	0.75	1,680	0.8	125	0	1,090	0.5
ICM 3, 9251/5 (10 km north of Gabès)	0	0.66	696	1.6	156	0	1,170	9.0

values were consistently high in the shallow aquifer (+357 to +452 mv (millivolts)) and consistently low in the deep aquifers (+22 to −133 mv). There appeared to be a slight but rather uniform decline in the Eh value of the deep waters from Ouargla through Touggourt to Gabès, but more extensive testing would be required to confirm this.

The shallow wells of Algeria tested in this study had consistently higher dissolved solids than the deep wells (2,560 to 4,920 mg/l versus 1,740 to 1,990 mg/l), but the wells tested in Tunisia did not conform to this pattern. Significant quantities of iron and manganese were present in all deep wells except Menchia 1 in Tunisia, which had no manganese. The shallow wells were free of these mineral constituents except for a trace of manganese in Rahmat 2.

Table 2 summarizes the data obtained in field tests and laboratory analyses.

The trilinear diagram of figure 5 shows the waters to have a distinct similarity in ionic characteristics, regardless of depth and geographic location of the wells and dissolved-solids contents. The percentage plots of chemical equivalents of principal ions and ionic combinations indicate the waters to be all sulfochloride type, quite low in carbonate-bicarbonate species, and rather evenly balanced between alkalies and alkaline-earths. This suggests that both deep and shallow waters were derived from sources of similar chemical composition, or that there has been considerable mixing of the deep and shallow waters.

Although the trilinear diagram does not reveal much variation in ionic combinations, individual ion ratios provide good indications of solute source and mechanisms for chemical change. A plot of major cation concentrations versus chloride (fig. 6) suggests a close correlation for sodium and supports an NaCl source, probably evaporitic. Similarly, the good correlation of calcium and sulfate reflects the solution of gypsum and (or) anhydrite. Large departures of points in figure 6 from the general trends for Na and Ca versus Cl and SO_4 can be attributed to the reduction of sulfate or the addition of $CaSO_4$; the sample from Menchia 1 illustrates reduction, while the waters from Sidi Slimane and ICM 3 illustrate additional solution of calcium sulfate.

Values of the sodium to chloride ratio for seven of the nine well samples range from close to the 0.86 of sea water (0.89 at Menchia 1) to nearly the 1.0 (0.98 at ICM 3) expected for the simple dissolution of pure halite. The NaCl content of the samples can be approximated by dilution of sea water sodium and chloride concentrations from 15 times at Ain Mérouane to 45 times at Rahmat 2. But even if the source of the NaCl is ultimately all marine, the North Sahara well waters require not only solution of $CaSO_4$ in proportions greater than in the ocean, but also the means to pick up magnesium and lose potassium relative to the chloride content of the sea. The most likely source of magnesium is the solution of dolomitic carbonates, whereas K^+

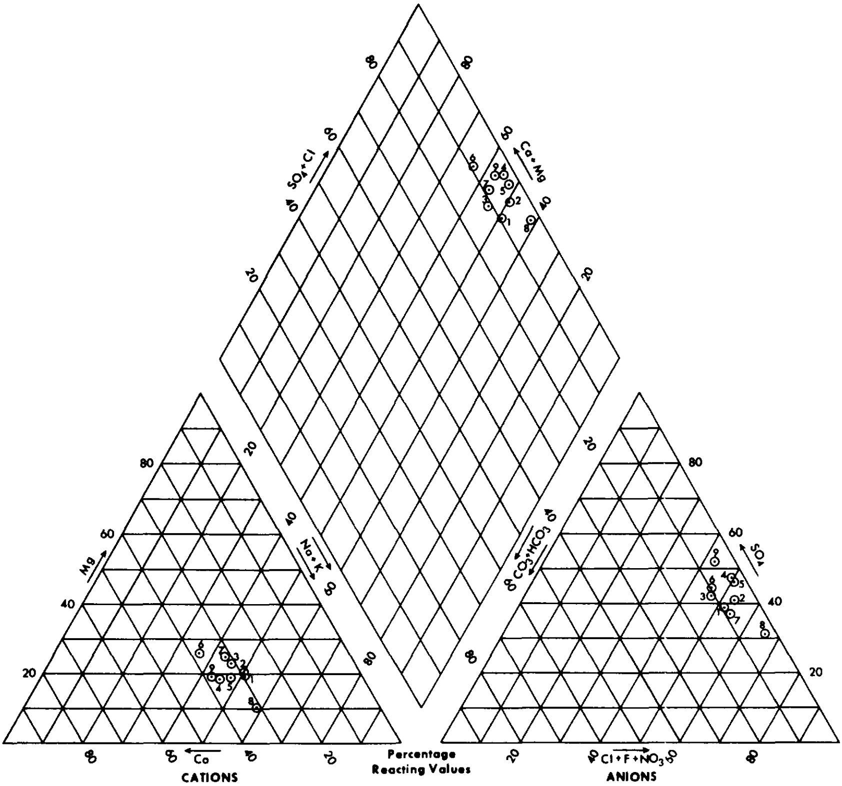


FIGURE 5 (above and right).—Chemical composition of waters from North Sahara wells. Prepared by William Back, U. S. Geological Survey.

is most probably lost by sorption on clay minerals.

In two of the well samples, Sidi Slimane and Rahmat 2, the Na/Cl ratio is less than the value for normal sea water. This suggests a solute source in residual liquors of marine evaporites, or the effect of other processes on the chemistry of these waters. A reasonable explanation may lie in limited recharge from the North Sahara playas or chotts. Rapid evaporative concentration of waters draining marginal marine evaporite sequences including dolomite and $CaSO_4$ will reprecipitate calcium and carbonate completely as $CaCO_3$ because of kinetic restrictions on the formation of dolomite. Sulfate will be redeposited as Na_2SO_4 and residual fluids will be enriched in $MgCl_2$; similar solutions from the Mojave Desert of the U.S.A. and the Great Kavir of Iran have been analyzed (B. F. Jones, unpub. data). Indeed, the two North Sahara well waters noted above are among the highest in Mg/Cl

Country ..ALGERIA and TUNISIA..

Subarea ..OUARGLA and TOUGGOURT, ALGERIA — GABÈS ENVRONS, TUNISIA.....

		DESIGNATION	DATE SAMPLED	DISSOLVED SOLIDS (mg/l)	AQUIFER
OUARGLA ALGERIA	1.	OUARGLA I S E S 447J10	9/17/69	1,990	ALBIAN
	2.	AIN TOULA DJEDIDA D4F 77	9/18/69	2,560	MIOCENE AND PLIOCENE
	3.	OUARGLA 3 NO. S. E. S. 511J10	9/19/69	1,740	ALBIAN
TOUGGOURT ALGERIA	4.	AIN MÉROUANE D29F 73	9/20/69	4,920	MIOCENE AND PLIOCENE
	5.	AIN TARFAIA D25F 12	9/21/69	4,100	MIOCENE AND PLIOCENE
	6.	SIDI SLIMANE	9/22/69	1,980	ALBIAN
TUNISIA	7.	RAHMAT 2 5692/5	9/24/69	1,570	UPPER CRETACEOUS
	8.	MENCHIA 1 9346/5	9/24/69	4,700	BARREMIAN (LOWER CRETACEOUS)
	9.	ICM 3 9251/5	9/25/69	3,100	MIOCENE AND PLIOCENE

ratio. However, similar but much smaller solute contributions to other waters may have gone unnoticed. None of the well waters analyzed had an Na/Cl ratio greater than 1.0; presumably, any contribution from chemical weathering of more stable lithologic components is completely obscured by readily soluble constituents.

REACTION STATES

A comparison of stability constants (*K*) for representative mineral species was made with activity products (*AP*) that were computer calculated from chemical analyses of the well waters; due allowance was made for activity coefficients and solute complexing. The departure of an actual solution composition from an equilibrium state with respect to any particular phase can be expressed in terms of free energy as

$$\Delta G_R = RT \ln \frac{AP}{K},$$

where ΔG_R is the Gibbs free energy of reaction ($\Delta G_R = 0$ at equi-

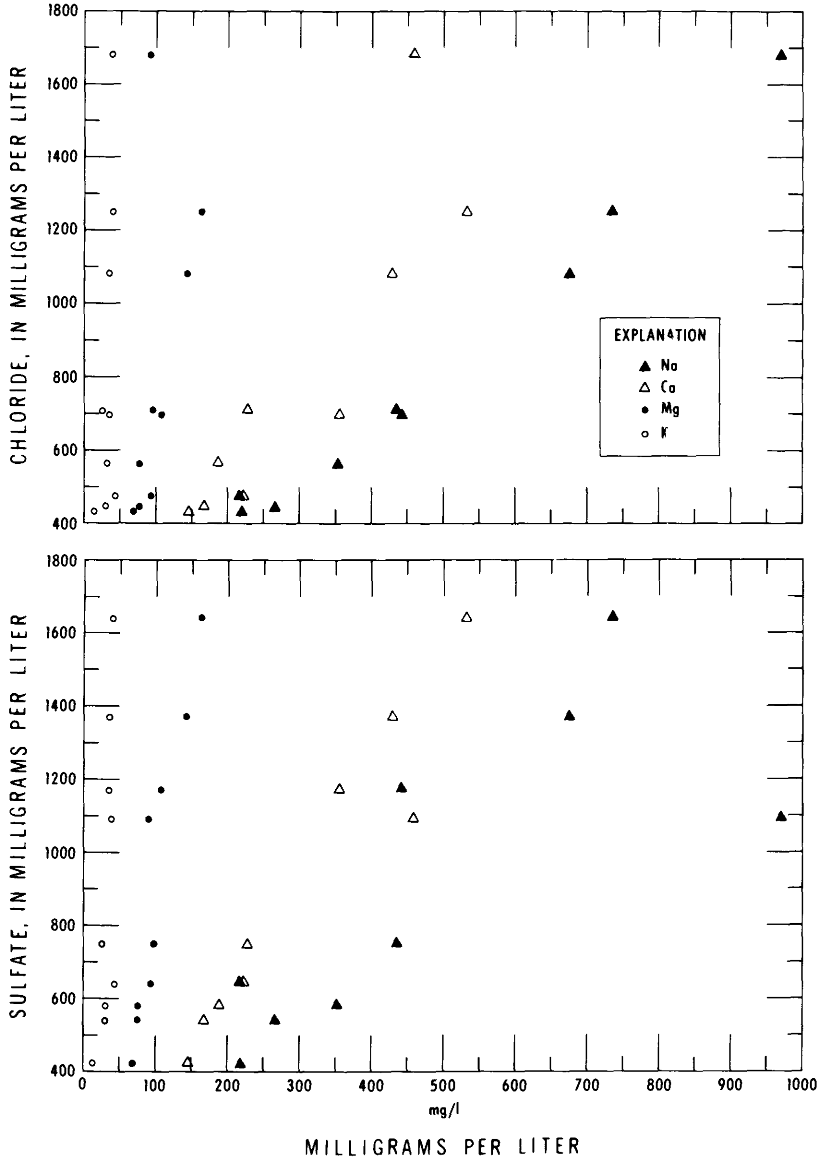
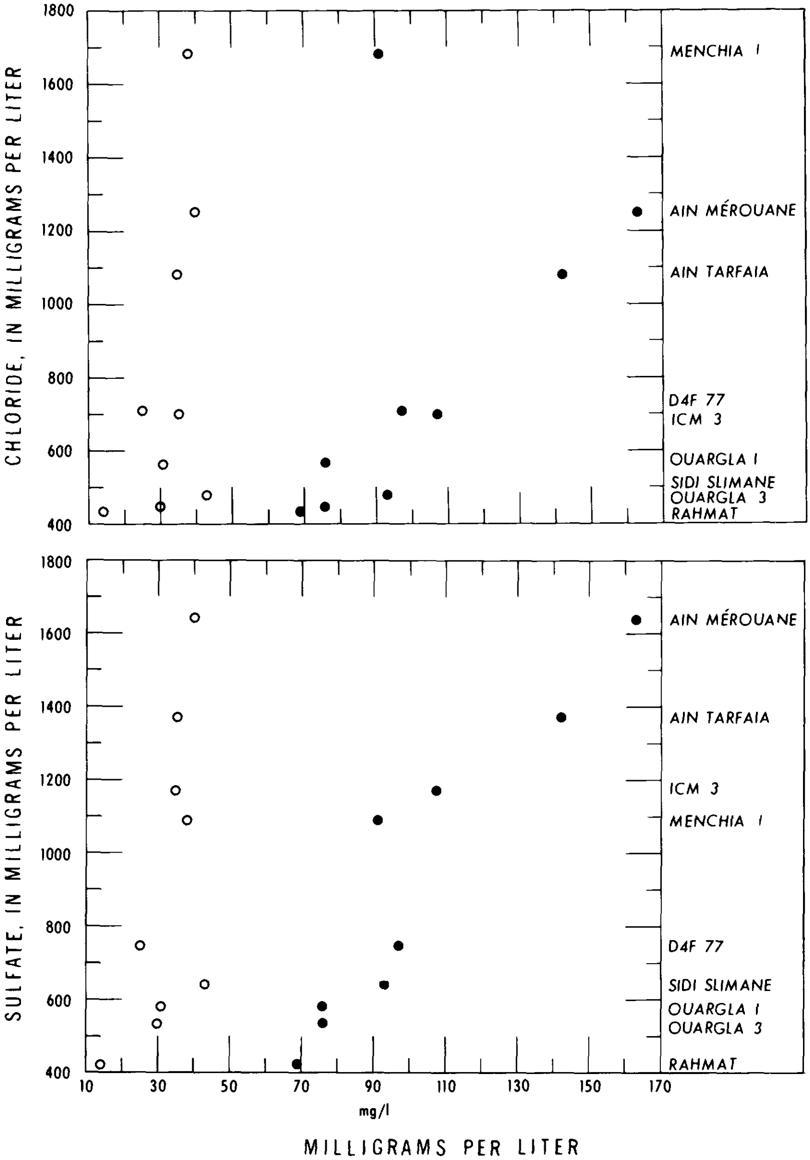


FIGURE 6 (above and right).—Major cations versus chloride and sulfate concentrations in North Sahara well waters. Relations for Mg^{+2} and K^{+} shown in the part of the figure above are expanded in the right-hand part.

librium), R is the gas constant, and T is the absolute temperature. For a reaction of the type $aA+bB=cC+dD$, the activity



product is expressed:

$$AP = \frac{(a_C)^c \ (a_D)^d}{(a_A)^a \ (a_B)^b},$$

with the activity defined by $a_i = m_i \gamma_i$, where m is the molality of the ith species as calculated from the chemical analyses, and γ_i is

TABLE 3.—*Calculated data on reaction states for*

[Activity products calculated as indicated in text: values have been rounded to three significant through reference to stability constants from sources

Well	Temperature (°C)	Ionic strength	p ion HSO_4^-	P_{CO_2} (atm) $\times 10^{-3}$	Siderite, $FeCO_3$		Calcite, $CaCO_3$	
					log *AP*	ΔG_R	log *AP*	ΔG_R
Ouargla 1	49	0.038	7.6	12.4	—10.8	2.0	—8.29	0.4
Ouargla 1	36	.039	7.8	10.2	----	1.6	—8.32	.2
D4F 77	24	.049	7.9	5.6	----	--	—8.48	—.1
Ouargla 3	49	.033	7.7	12.0	—10.7	2.1	—8.29	.4
Ouargla 3	44	.34	7.7	11.2	—10.4	2.4	—8.30	.3
Ain Mérouane	26	.090	7.4	8.3	----	--	—8.44	.0
Ain Tarfaia	26	.078	7.6	5.7	----	--	—8.27	.2
Sidi Slimane	57	.037	7.4	15.8	—9.87	3.5	—8.28	.5
Sidi Slimane	43	.038	7.6	13.4	—10.4	2.3	—8.52	.3
Rahmat 2	23	.030	8.2	15.8	----	--	—8.33	.1
Menchia 1	50	.086	7.6	15.7	—10.2	2.8	—8.11	.7
ICM 3	24.5	.060	7.1	3.7	----	--	—8.81	.6

the activity coefficient computed for charged species from an extended form of the Debye-Hückel equation (Helgeson, 1969) and for uncharged species from a modified form of the Setchenov relation (Truesdell and Jones, 1969). Oxidation-reduction reactions have been treated in the same manner as hydrolysis, with the Eh measurement converted to the negative logarithm of the electron activity, pE, analogous to pH (Truesdell, 1968). The free energy of reaction (ΔG_R) is an indication of reaction tendency toward dissolution or precipitation of a phase. Supersaturation is reflected in positive numbers, while undersaturation is indicated by negative numbers. Such calculations are completely dependent on the stability constants employed for reference and bear no direct quantitative relation to corrosion or encrustation because of kinetic and catalytic effects.

Table 3 presents activity products and free energies of reaction computed from the analyses of the North Sahara well waters for a number of important mineral phases. The data indicate that carbonate saturation is more prevalent in the deep wells. Three of the five shallow holes apparently are undersaturated with calcite, and the values for the remaining waters are low enough to suggest that $CaCO_3$ may not nucleate. All the deep well waters show significant reduction in saturation on cooling. However, this will be compensated by loss of CO_2 accompanying evaporation; the P_{CO_2} (partial pressure of CO_2) of the deep well waters exceeds atmospheric values by nearly two orders of magnitude (table 3). Only the well at Gabès, Tunisia, is close to atmospheric equilibrium.

The free energies of reaction calculated for dolomite follow a similar pattern to those for calcite. Although kinetic barriers to precipitation probably will not be overcome, it is unlikely that the deep waters will derive much additional Mg from this source.

minerals important to North Sahara well waters

figures. Free energies of reaction (ΔG_R) are given to nearest 0.1 kilocalorie and are obtained compiled by Truesdell and Jones (1969)]

Dolomite, $Ca_{.5}Mg_{.5}CO_3$		Gypsum, $CaSO_4 \bullet 2H_2O$		Amorphous, $Al(OH)_3$		Halloysite, $Al_2Si_2O_5(OH)_4$		Amorphous, $Fe(OH)_3$		Greenalite, $Fe_3Si_2O_5(OH)_4$	
log *AP*	ΔG_R	log *AP*	ΔG_R	log *AP*	ΔG_R	log *AP*	ΔG_R	log *AP*	ΔG_R	log *AP*	ΔG_R
—16.8	0.7	—5.39	—0.8	—31.4	—0.9	—31.9	—1.5	4.39	2.5	—5.87	0.6
—16.9	.3	—5.35	—.7	—31.4	—.2	—32.0	.2	4.21	2.1	—6.07	.3
—17.2	—.3	—5.19	—.5	—31.4	.3	—32.6	1.1	--	--	--	--
—16.8	.8	—5.45	—.9	—31.8	—1.4	—32.4	—2.3	4.54	2.7	—5.83	.7
—16.8	.6	—5.43	—.9	—31.7	—1.1	—32.5	—1.6	4.74	2.9	—5.82	.7
—17.3	—.4	—4.69	.2	—31.3	.4	—32.0	1.7	--	--	--	--
—16.9	.1	—4.81	.1	—31.3	.4	—32.0	1.6	--	--	--	--
—16.8	.9	—5.32	—.7	—31.4	—1.1	—31.5	—1.9	3.23	.8	—5.53	1.2
—16.8	.6	—5.28	—.6	—31.4	—.5	—31.6	—.3	2.45	—.4	—5.86	.7
—16.8	.2	—5.49	—.9	—31.8	—.2	—33.2	.5	--	--	--	--
—16.8	.8	—4.96	—.2	—31.6	—1.1	—32.0	—1.8	3.00	.4	—5.57	1.1
—18.0	—1.4	—4.88	.0	—31.9	—.3	—33.2	.3	--	--	--	--

The sample from the deep well at Menchia was apparently the most supersaturated with alkaline-earth carbonate of any water analyzed. This well also gave the most positive qualitative test for sulfide. These factors probably can be interrelated by a schematic equation for sulfate reduction resulting from decomposition of carbohydrate, such as:

$$2CH_2O + SO_4^{-2} = H_2S + 2HCO_3^-.$$

Reduction is reflected in the relatively low concentration of sulfate in relation to total solutes in the Menchia water.

With the exception of the samples from the shallow wells near Touggourt, most of the North Sahara well waters analyzed were undersaturated with gypsum. In figure 7, the activity products for gypsum and calcite are plotted against ionic strength, which adjusts the total solute concentration for the effect of differing ionic charge and complexing, chiefly major ion pairs. The corresponding pH changes are shown for reference. The regular increase of the activity product for gypsum with total concentration suggests that solution of gypsum or anhydrite is a principal source of calcium and sulfate.

The total amount of sulfate available for reduction may be a factor in the well corrosion. Free energies of reaction calculated from field estimates of the total sulfide concentration in the deep well waters are compatible with precipitation of any form of iron sulfide (table 4), although estimates of sulfide concentrations based on computation for inorganic reduction alone (from Eh and SO_4^{-2}) are much too low. To test the effect of pH and SO_4^{-2} content, the negative log of the HSO_4^- species molality was calculated and plotted against the corrosion rate measured in the field. A rough relation appears to exist (fig. 8).

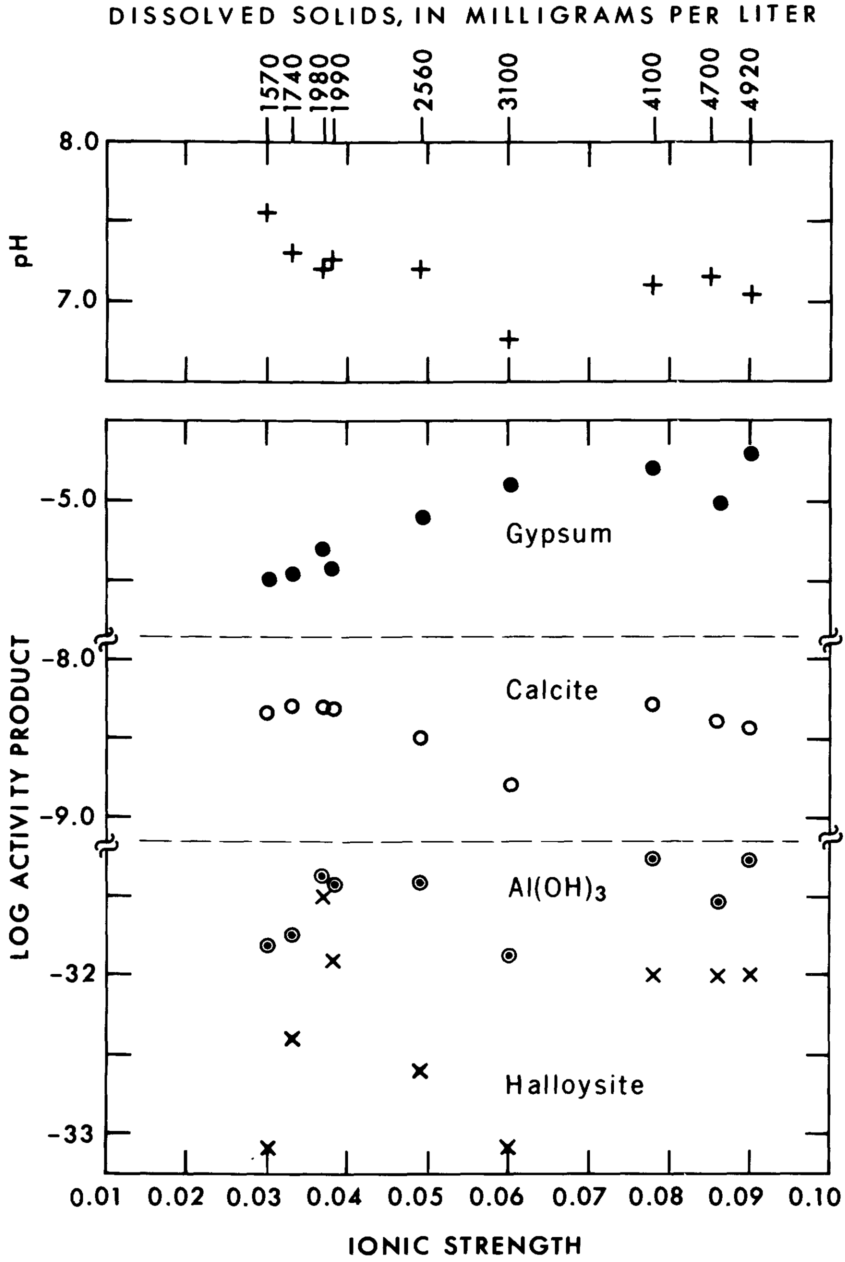


FIGURE 7.—Important ion activity products versus ionic strength for North Sahara well waters.

TABLE 4.—*Calculated data on reaction states for iron sulfide in North Sahara wells*

Well	Estimated total H_2S (mg/l)	ΔG_R calculated from estimates of total reduced sulfur			$a\text{HS}^-$ calculated from Eh and $a\text{SO}_4^{-2}$ (p ion)[1]
		Mackinawite	Gregite	Pyrite	
Ouargla 1	0.1	1.43	5.95	10.7	40.3
Ouargla 3	.1	1.57	6.10	10.8	40.6
Sidi Slimane	.1	3.00	5.63	8.0	24.4
Menchia 1	.5	4.70	7.72	10.0	21.9

[1] p denotes negative $\log_{10}$, as in pH.

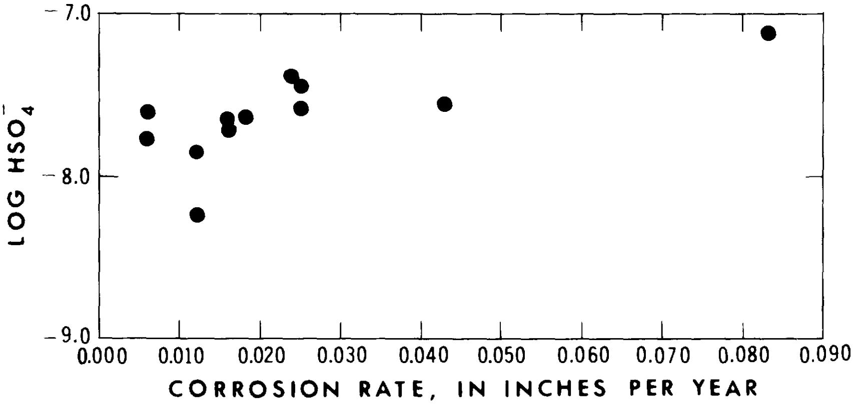


FIGURE 8.—Combined effects of total SO_4^{-2} and pH on corrosion rate as illustrated by calculated HSO_4^- content.

Iron was found only in the deep well waters and all of these were supersaturated with siderite ($FeCO_3$). Like calcite (fig. 7) and the other carbonates, the variation of the activity product with total solute concentration closely follows the pH and, to some extent, the temperature. Where significant amounts of sulfide compete for the iron, as in water from Menchia 1, the carbonate saturation is somewhat reduced.

Calculation of free energies of reaction indicates that all the deep well waters exceed the stability limits for amorphous $Fe(OH)_3$ (although the water from Sidi Slimane becomes undersaturated on cooling) and are substantially supersaturated with the less hydrous oxides, such as goethite or hematite. The reducing conditions found in both the Sidi Slimane and Menchia 1 waters reduce the activity products for all ferric oxide species, such as $Fe(OH)_3$, which are linearly dependent on the Eh. The deep well waters are all also supersaturated with iron silicate, as approximated by the iron serpentine, greenalite; reducing conditions favor this ferrous iron phase.

In addition to binary salts and iron componds, free energies of reaction were calculated for amorphous aluminum hydroxide and aluminosilicate clay. The results for halloysite (hydrated kaolin) (stability data from Kittrick (1969) and Hem and others (1972)), which is the most probable cation-free species to form from natural waters, suggests supersaturation in all the shallow wells and also cooled waters from Ouargla 1. The three shallow waters in Algeria are even supersaturated with $Al(OH)_3$, suggesting that clogging may become a problem as flow rates diminish. This condition is heavily dependent on the pH of the solutions (fig. 7), as the silica and aluminum concentrations are relatively constant. Actually the cation content of all well waters is high enough to expect interaction with 2:1 layer-silicates, but insufficient data are available for an estimate of composition or the free energy of reaction.

EVIDENCE OF CORROSION AND ENCRUSTATION

Concern about corrosion and encrustation of well casings and filter pipes results primarily from observed decline in surface pressures and discharge volumes of the North Sahara wells and uncertainty concerning the relative contributions of corrosion and aquifer exploitation to this problem. Diemer (1965) mentioned an important increase of salt content of water from a well (designated as "Tamenlhat") 9 years after its drilling and suggested that imperfect cementation of the casing and resulting solution of formation salt, cavitation, and collapse, together with possible internal or external corrosion, probably contributed to this well's deterioration.

The corrosion tubercles, laminated corrosion deposits, and pits present in the used wellhead pipe from Ouargla 1 shown in figure 9 indicate clearly that some internal corrosion has occurred in this deep anaerobic well, and surface roughening of this kind over the entire length of the casing would be expected to have detectable effects on surface friction and on well discharge.

The circumferential tubercles shown near the top of the shallow well casing in figure 10 probably are not typical of internal conditions over the full length of the casing's interior. More likely these scars result from surges in water level related to barometric changes and consequent rise and fall of the air-water interface.

Slimy iron-stained crusts on the exteriors of the cooling towers, occasional crystalline stalactites on the tower surfaces, and mineral

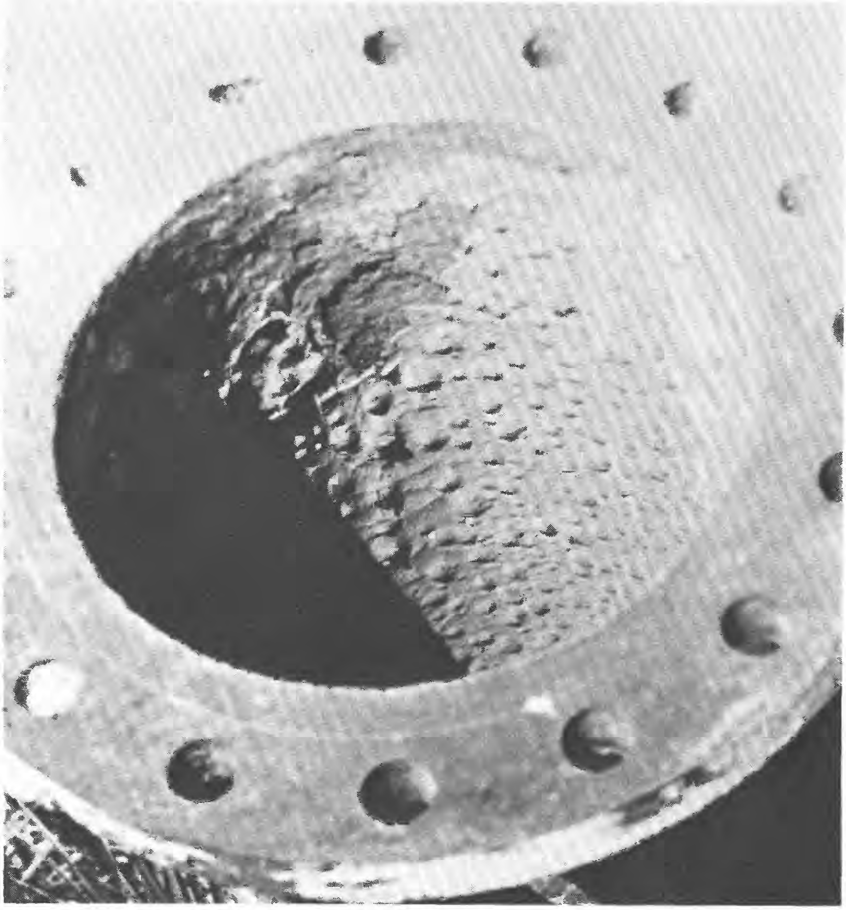


FIGURE 9.—Corroded wellhead pipe, Ouargla 1, Algeria.

clogged asbestos-cement irrigation pipes at a deep-well site near Touggourt, Algeria, indicate clearly that deep-well hot waters have significant encrusting tendency once water volume and the partial pressure of carbon dioxide have been reduced by aeration and related evaporation. Because no systematic downhole measurements have been made with mechanical calipers or other borehole devices, there is little evidence of either serious corrosion or serious encrustation at depths in the wells investigated. Corrosion rate data in table 2 suggest significant attack on steel parts, but only four wells, Sidi Slimane, Ain Mérouane, Menchia 1, and ICM 3, exceed the corrosion rate generally considered to be the upper limit of moderate attack, and only the rate in ICM 3 would be considered extreme.

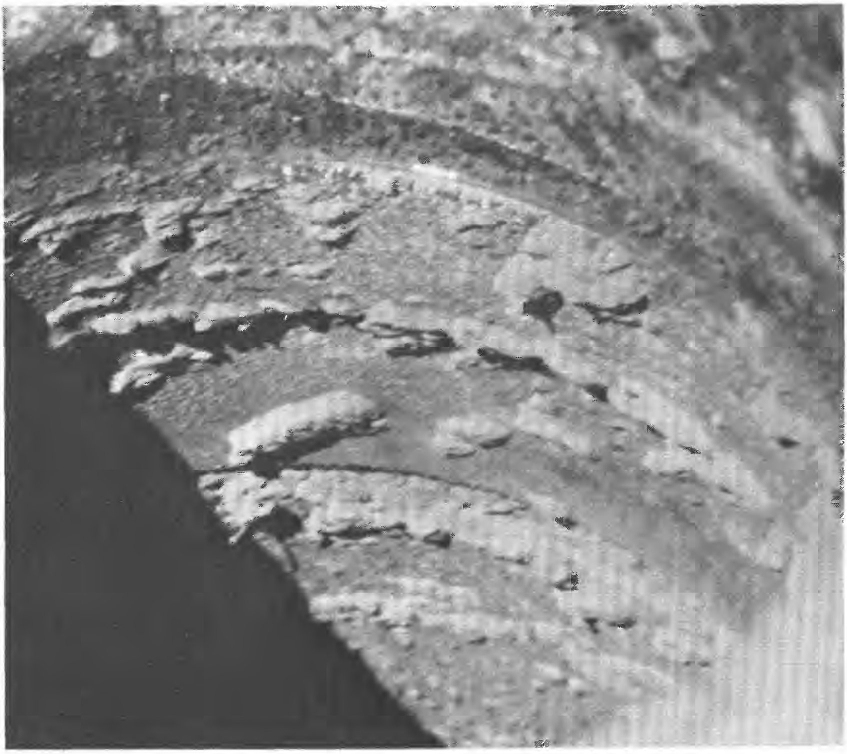


FIGURE 10.—Corroded casing in shallow well near Ouargla, Algeria.

POSSIBLE CAUSES OF CORROSION AND ENCRUSTATION

BASIC ELECTROLYTIC EFFECTS

All corrosion of steel in aqueous media is electrochemical in nature, and it involves solution of iron in the anodic areas to form soluble ferrous ion and flow of electrons to adjacent cathodic areas, where they neutralize negative ions in the surrounding water. The reaction eventually is blocked by accumulation of atomic hydrogen and other deposits on cathodic areas (polarization) unless depolarization actions occur. Positively charged anodic areas and negatively charged cathodic areas are abundant on steel surfaces of water wells. They can result from slight differences in metal surfaces, such as nonuniform stress or metal inclusions; from nonuniformity of the fluid which contacts the metal, such as might result from differences in temperature, linear velocity, or concentration of dissolved salts; and from long-line electrical currents generated by exposure of one length of the casing to an environment different from another length (for example, two aquifers of different salt contents). Stray electrical currents from improperly installed pumps or transmission lines and galvanic effects created by coupling dissimilar metals also can set up anodic-cathodic corrosion cells. Whatever the source of the electrolytic cell, the conductivity of the surrounding water influences the rate of current flow and therewith the extent of metal loss.

In mildly corrosive waters, the cathodic and anodic areas are sharply defined and corrosion occurs as local pitting, like that shown in figure 10. In more aggressive waters, such as those of high acidity, electrolytic patterns change continually and result in more general metal loss. More complex patterns can result from peculiarities in fluid flow, sand erosion, and cavitation related to high dissolved-gas content.

EFFECTS OF OXYGEN, BACTERIA, AND CHLORIDE ION

Dissolved oxygen from solution of air in water is the most common depolarizing agent of cathodic areas in corrosion cells as far as surface waters are concerned. However, well waters rarely have significant dissolved-oygen content, because this component generally has reacted with earth materials. The Eh data of table 2 suggest that dissolved oxygen is absent in the deep wells, and there appears little likelihood that it exists in the shallow wells except where sluggish flow to the surface-discharge pipes allows back diffusion of air into the near-surface water.

Bacterial reduction of sulfate ion is a common depolarization process for corrosion cells in anaerobic (air-free) wells, and qualitative tests showed sulfide to be present in all of the deep wells included in this study. Corrosion deposits removed from used discharge pipe at Ouargla contained both iron sulfide and free sulfur deposits as evidence that sulfate reduction contributed to corrosion of the steel. Sulfate-reducing bacteria can enter wells during drilling operations but also can originate from dormant bacterial cysts in the aquifers regardless of their depth and age. Such bacteria thrive in environments with Eh values below +200 mv, which would agree with their presence in the deep wells but not in shallow wells. Sulfate-reducing bacteria do not actually consume metal but simply catalyze combination of the protective hydrogen film with sulfate ion in the surrounding water. The resulting hydrogen sulfide creates secondary effects by combining with iron to form iron sulfide (FeS), which is a voluminous encrustant and is cathodic to steel, so that both filter-pipe clogging and secondary corrosion result from its formation.

Free energy studies of the deep well waters indicate that sulfate reduction could have contributed to corrosion and sulfide deposition in the absence of sulfate-reducing bacteria. All of these waters were compatible with precipitation of any form of iron sulfide, and their negative logs of HSO_4^- correlate roughly with corrosion rate.

Both solute composition and concentration can have marked effects on corrosion of steel well parts. In the absence of the more common depolarizing agents, dissolved oxygen and sulfate-reducing bacteria, uncharged water molecules tend to cluster on the metal surface with their oxygen atoms oriented toward the surface and their hydrogen atoms oriented away from it, thus providing a passive condition. Negatively charged ions, such as sulfate and chloride, attracted to the anode by their negative charges, displace the film of water molecules. When the attracted anion has no inhibiting effect, as in the case of Cl^-, it tends to increase solution of anodic metal, which migrates outward to form metal hydroxide films and to promote deposition at the cathode. In other words, it is possible for chloride ion to depolarize corrosion cells and encourage corrosion even when no common depolarizing agent is present. The fact that waters high in chloride are particularly troublesome is well documented. The high salt content and sulfochloride character of the North Sahara ground water would be expected to increase corrosion. In shallow wells where neither dissolved oxygen nor sulfide is present, chloride might have been the major control responsible for the observed corrosion.

Regardless of the corrosion process and well depth, filter pipes (well screens) and threaded couplings are likely to be most seriously affected because both are stressed by cold working (anodic) and expose sharp edges to the water, thus exaggerating the damage because of their geometry. In the case of the filter pipe, corrosion is likely to be most severe where it is least tolerable. Either the openings enlarge to the point that they no longer serve the intended purpose of retaining the formation or gravel pack, or they are clogged by corrosion deposits and reduce the flow of the well.

EFFECTS OF Eh-pH RELATIONSHIPS AND CARBON DIOXIDE

The graphical relationship of Eh and pH provides a useful illustration of the behavior of the iron species and the stability of iron oxide protective films. These relationships for the North Sahara test wells are plotted in figure 11 on a stability field diagram modified from Hem (1970). The vertical lines which separate the species are determined from corresponding equilibrium constants. The nonvertical boundaries through the center of the diagram separate oxidized species above the line from reduced species below it. The dashed lines illustrate the shift in these boundaries over a representative range of total Fe concentrations to be expected in

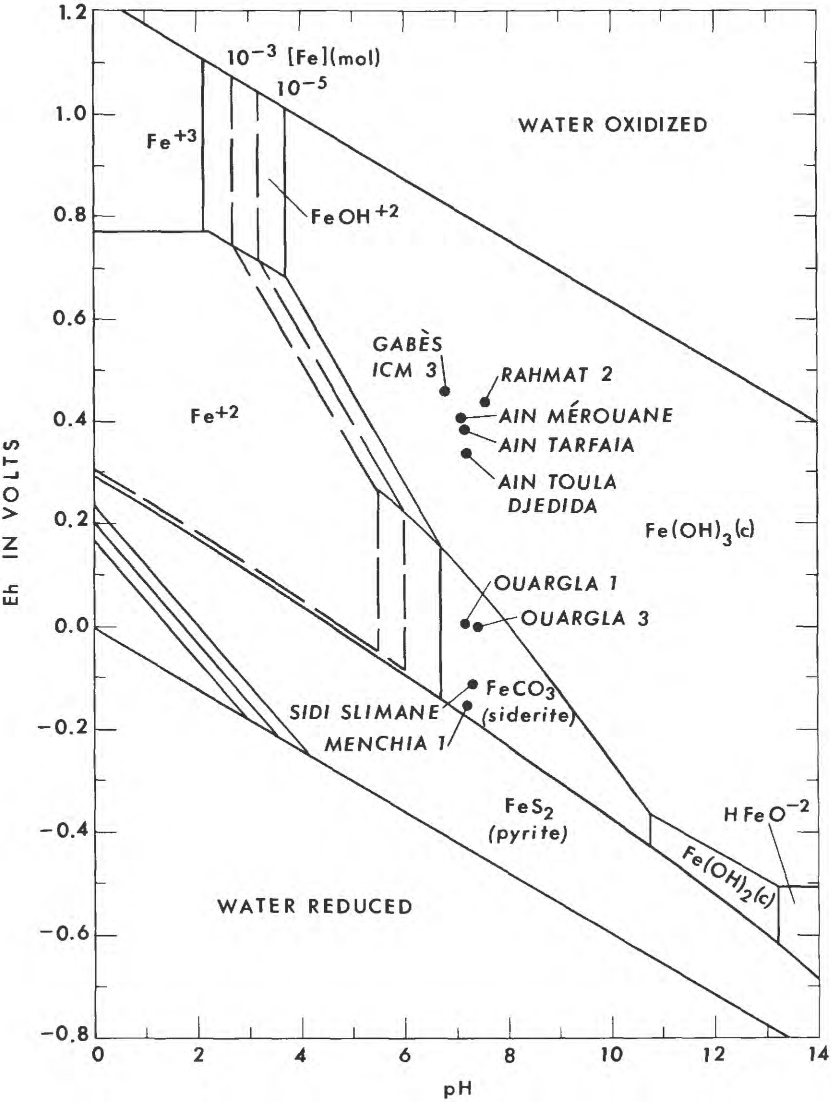


FIGURE 11.—Eh and pH of North Sahara well waters shown with respect to the stability fields of iron species at 25°C and 1 atmosphere of pressure. Total dissolved sulfur (reduced) equals 10^{-4} *m*; total CO_2 species equals 10^{-2} *m*. Modified from Hem (1970).

the North Sahara wells (0.06 to 6.0 mg/l). Well waters which are suitable for irrigation and general-purpose use generally have Eh and pH values which plot near the boundary of $Fe(OH)_3$ and the lower Fe^{+2} stability fields. The former is representative of a condition of relative passivity of steel. Waters which plot in the fields of reduced iron species are likely to be more aggressive to steel and to prevent retention of protective oxide films on the metal surface. It is evident in figure 11 that waters from the deep test wells plot in this reduced field, whereas all shallow well waters fall in the zone of oxidation.

The siderite field in figure 11 has been drawn for a total CO_2 species concentration about three times larger than that measured in any of the wells examined but at a convenient upper limit for waters of this type. It is apparent from the points representing the deep well waters that iron carbonate encrustation is more dependent on the total Fe in solution than on the bicarbonate content. Also shown in the diagram is a stability field for pyrite, the most stable form of iron sulfide.

EFFECTS OF FLUID VELOCITY AND TEMPERATURE

Linear velocity has significant effects on corrosion of metals for a variety of reasons and may be either beneficial or detrimental, depending on the particular metal and the velocity. Corrosion of steel increases significantly with increasing velocity, and surface velocities above 1 m/sec (meter per second) generally are considered undesirable. Velocities in the deep flowing wells of this study are above 1 m/sec.

No matter what chemical mechanism is responsible for corrosion, the rate of corrosion is likely to double for each 10°C rise in temperature of the fluid system. This means that one would expect the deep warm waters to be considerably more corrosive than the cool shallow well waters, if other factors are equal.

CHARACTERISTICS OF CORROSION DEPOSITS

The deposit from Ouargla well 1, pictured in figure 9 and shown in cross section in the photomicrograph (fig. 12) and sketch (fig. 13), probably is typical of corrosion products forming within the

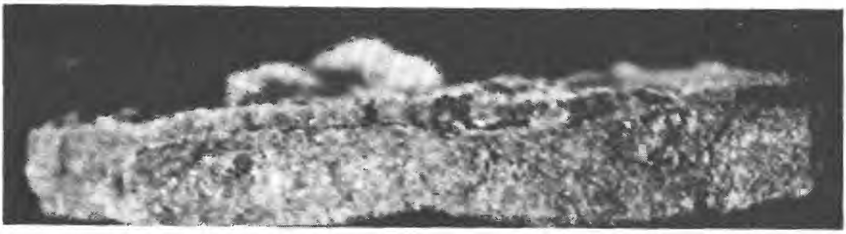


FIGURE 12.—Photomicrograph of corrosion deposit (× 16) from Ouargla 1. Algeria.

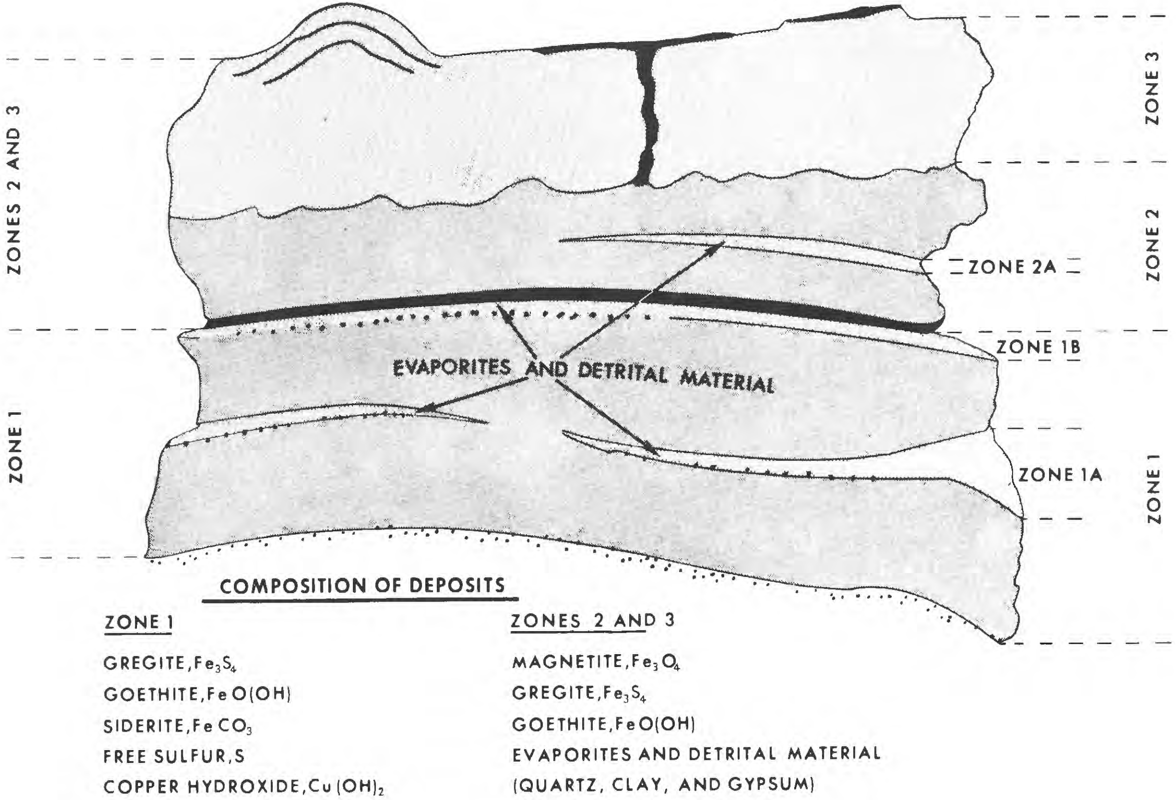


FIGURE 13.—Cross section of deposit shown in figure 12. Zones identified by Ruth Deike, U.S. Geological Survey.

casings of the deep wells, except for the small amount of mixed salts which presumably were deposited during the drying process. The metal side of the deposit (zone 1) was dark reddish-blue-black and was found, by x-ray diffraction examination, to contain major amounts of the primary corrosion products goethite, FeO(OH); gregite, Fe_3S_4; and minor amounts of siderite, $FeCO_3$; free sulfur, S; and copper hydroxide, $Cu(OH)_2$. This is the basic type of deposit one would expect in a steel-cased anaerobic well where the principal corrosive agents are chloride ion and sulfate-reducing bacteria. Traces of copper are commonly present in such deposits and can be derived from either the related earth materials or the steel of the wellpipe. In this well, no copper was found in the water samples.

The central part of the deposit (zone 2) differed from the metal-side layer in that it contained no sulfur compounds and was primarily a mixture of the iron minerals goethite, magnetite, and gregite.

Outermost zone 3 was essentially identical to zone 2 except that it had a yellowish-brown wash which contained significant amounts of residual evaporite and detrital material including quartz and clay. Similar products of evaporation were imbedded elsewhere in the deposit, presumably in crevices resulting from the drying process (zones 1A, 1B, and 2A, fig. 13).

Spectrographic analysis of the deposit detected trace amounts of manganese, copper and nickel, and a normal suite of trace elements. Composition of the deposit is shown in table 5.

TABLE 5.—*Composition of corrosion deposit, Ouargla 1 wellhead pipe, Ouargla, Algeria, in 1969*

[Analyses by Edward Dwornik, Irving May, John Marienko, Paul Elmore, Hezekiah Smith, Ruth Deike, Marian Schnepfe, and Ellen Lillie, all of the U.S. Geological Survey]

Determination	Percent	Determination	Percent
Silica, SiO_2	3.90	P_2O_5	.34
Al_2O_3	2.10	CO_2	.86
Na_2O	.33	Total sulfur, S	[1]12.60
MgO	.14	FeO	14.60
CaO	.38	Fe_2O_3	[2]51.60
K_2O	.10	H_2O	12.00
MnO	.24	Organic carbon	1.00
TiO_2	.12		

[1] Includes 7.20 percent free sulfur.

[2] In percentage of whole deposit, probably about 2.25 percent iron carbonate and 12.5 percent iron sulfide.

Although representative corrosion deposits from the shallow wells were not available for study, it appears reasonably certain that they would be composed primarily of iron oxyhydroxide, because corrosion in these wells apparently results primarily from chloride depolarization rather than from sulfate-reducing bacteria.

CONTROL OF CORROSION

Cementing and cathodic treatments.—Exteriors of steel well casings immersed in aggressive waters can be protected against corrosion by complete cementing, by partial cementing used in conjunction with chemical inhibitor solution placed in the annulus above the cement, by cathodic protection with impressed electrical current to balance corrosion current, and by combinations of these several methods. Because the casing exterior may be exposed to different levels of aeration and different concentrations and types of salt solutions in several water-bearing horizons from the shallow water-table aquifers through the Continental Terminal formation to the deep Continental Intercalary, long-line corrosion currents will flow from one vertical point to another and result in giant corrosion cells. This will cause external corrosion unless the casing's exterior is completely protected by one or more of the methods discussed above. Partial protection of casing exteriors with fluids in the annular space, such as that mentioned by Diemer (1965), are effective if properly compounded to cope with the type of ground water involved. However, the fluids may be diluted to ineffective concentrations by movement of ground water, and there is some risk of their entering the casing or filter pipe and contaminating the supply. Thus, there is need to monitor both the annular space and the well discharge periodically if inhibitor is used. Generally speaking, such treatment is intended primarily for protection of oil wells and waste-disposal wells rather than water wells. Even when the chemical inhibitor is nontoxic, economic considerations and engineering difficulties preclude its use inside the casing. Cathodic devices will not protect internal surfaces.

Anodic protection of casing interior.—Theoretically, it is possible to protect the interiors of casings and filter pipes by installing sacrificial electrodes (anodic protection). However, such systems are difficult and costly to install and maintain in deep wells and are not uniformly protective unless they are properly spaced within the casing. Also, external corrosion of the casing and corrosion of the filter-pipe openings are likely to be more troublesome than corrosion of the casing interior.

Corrosion-resisting materials.—Filter pipes and screens of water wells are particularly susceptible to corrosion because of resultant stresses from cold working (sawing, drilling, or punching) and absence of protective oxides on the cut surfaces. Use of corrosion-resisting materials, such as stainless steels, copper-bearing alloys, and plastics (where practicable), is the only satisfactory means of minimizing filter-pipe corrosion. Protective cements and fluids cannot be used to protect filter pipes for obvious reasons, and experience has shown that the best type of metal coating is short lived in the filter-pipe openings, where they are most needed.

CONTROL OF MINERAL ENCRUSTATION

It is unlikely that water of the quality covered by this study will precipitate large amounts of such common mineral encrustants as calcium carbonate and ferrous carbonate on the filter pipe or within the casing. Although all the deep well waters apparently are supersaturated with siderite and calcite, concentrations are low, and in most cases supersaturation with calcium carbonate is probably not sufficient for extensive nucleation.

The mineral encrustations observed in cooling towers and on the interior surfaces of irrigation pipes are almost entirely the result of loss of water and carbon dioxide during evaporative cooling. Water loss is estimated to be about 2 percent of the flow to the towers for prevailing conditions of humidity, wind, and temperature reduction. Several tests indicated almost total loss of free carbon dioxide in the cooling process. No practical way exists to prevent calcium carbonate from depositing on evaporation surfaces of towers under these conditions. Providing a retention pond at the cooler discharge to allow time for precipitation of calcium carbonate from the cooled saturated water may reduce the amount of encrustation in irrigation pipes. Use of open discharge channels instead of pipes would minimize the encrustation problem, but of course this would increase evaporation loss.

The small amount of iron hydroxide precipitated by aeration in the cooling towers is relatively unimportant as compared with the deposition of calcium carbonate in the tower and irrigation pipes. Calcium sulfate encrustation should not occur with evaporation loss in the cooling towers, because the original concentration in the deep well waters was well below saturation. Concentration from high evaporation loss, of course, can cause precipitation of even the most soluble compounds.

OTHER WATER QUALITY CONSIDERATIONS

Although the principal purpose of this investigation was to study the likelihood of corrosion and encrustation in North Sahara wells, other troublesome effects might arise from use of waters of qualities observed. The high dissolved-solids content of the shallow waters in both Algeria and Tunisia (with the exception of Tunisian well Rahmat 2) eventually can be expected to cause troublesome soil salinization effects unless excellent drainage is provided in the irrigation systems, and this is not always possible because of low topographic relief and impermeability of the gypsum-encrusted land surfaces. The result already is quite evident in the near-sea-level area at Touggourt shown in figure 14.

FIGURE 14.—Salinized soil near Touggourt, Algeria.

Even the deep wells have sufficient dissolved solids to cause significant salinization problems in semiarid regions of this kind, where evaporation rates are high and rates of infiltration are relatively slow.

Although the high ratios of Ca^{+2} and Mg^{+2} to HCO_3^-, together with the high gypsum content of the soil, would prevent black alkali formation, all the wells in this test series—both shallow and deep—have sodium adsorption ratio (SAR) values above 4. This value is generally considered to be the upper limit acceptable for sodium-sensitive soils and sodium-sensitive vegetation.

An attempt was made to calculate how much evaporative concentration of the well-water samples would bring about precipitation of gypsum. Assuming that the calcium content of the waters will be controlled by calcite precipitation, further evaporation must act primarily to increase the sulfate concentration sufficiently to exceed the stability constant for gypsum at a calcium level fixed by calcite saturation. The equation employed was

$$\text{concentration factor} = \frac{(AP/K)_{\text{calcite}} \cdot K_{\text{gypsum}}}{(\alpha \mathrm{Ca}^{+2} \cdot \alpha \mathrm{SO}_4^{-2})/0.4},$$

where 0.4 is assumed to be the mean activity coefficient of solute $CaSO_4$ at saturation with gypsum. The activities of calcium and sulfate, plus the *AP/K* ratio for calcite, were calculated from the chemical analyses of the well waters as explained earlier. The results are given in table 6.

TABLE 6.—*Data employed for computing minimum concentration factor for gypsum precipitation*

Well	Temp[1] (°C)	$(AP/K)_{\text{calcite}}$	$^{a}\mathrm{SO}_4^{-2}$ ($\times 10^3$)	$^{a}\mathrm{Ca}^{+2}$ ($\times 10^3$)	Concentration factor
Ouargla 1	36	1.43	2.24	1.98	11.86
D4F 77	24	.81	2.80	2.34	4.42
Ouargla 3	44	1.72	2.09	1.78	16.88
Ain Mérouane	26	.92	4.71	4.37	1.59
Ain Tarfaia	26	1.36	4.22	3.70	3.11
Sidi Slimane	43	1.74	2.28	2.33	11.97
Rahmat 2	23	1.13	1.74	1.85	12.50
Menchia 1	50	2.89	2.96	3.74	9.62
ICM 3	24.5	.45	3.29	4.04	1.03

[1] Cooling tower temperatures were used for deep wells.

The approximate nature of the calculation (principally due to the effects of other constituents) is indicated by comparison with the more detailed analysis given earlier (table 3). In table 6 waters from the shallow wells near Touggourt appear slightly undersaturated with gypsum, whereas the earlier computations suggested slight supersaturation was more likely. Nevertheless, it is clear that with evaporation it will be only a short time until even the most dilute of the deep well waters threaten salinization of the soil.

If used as domestic supply, all the waters of the deep wells contain sufficient iron or manganese, or both, to cause troublesome stains in laundry operations and on plumbing fixtures. Both the shallow and deep wells would be expected to cause corrosion and troublesome mineral encrustation of domestic water systems, or industrial water systems, because of their high chloride content and their great potential for depositing calcium carbonate and calcium sulfate. Unlike the problems related to irrigation, the problems in domestic and industrial use can be overcome by conventional treatments, except for certain minor effects related to high dissolved-solids content (for example, objectionable taste). Possible effects of fluoride ion already have been mentioned.

SUMMARY AND CONCLUSIONS

North Sahara ground waters from the relatively shallow Continental Terminal formation and the relatively deep Continental Intercalary differ significantly in temperatures, total dissolved-solids contents, oxidation-reduction characteristics, and certain chemical-quality factors, notably iron, manganese, and sulfide components. Oxidation-reduction potentials and, with two exceptions, dissolved-solids contents are markedly higher in the shallow wells, whereas the pressures, discharge rates, and temperatures are considerably lower in all but one of these wells. All the deep wells are relatively high in pressure and discharge, low in oxidation-reduction potential, and contain significant quantities of dissolved iron, manganese, and sulfide ion.

All the waters studied, both shallow and deep, have similar ionic characteristics. They are sulfo-chloride types, low in bicarbonate species, and evenly balanced between alkali and alkaline earth components. All have favorable ratios of calcium and magnesium to bicarbonate ion, which reduces the probability of alkalizing irrigated soils. However, all have rather unfavorably high sodium-adsorption ratios, which could be troublesome to sodium-sensitive soils and plants. All have a dissolved-solids content that is high enough to cause relatively rapid salinization of soil in poorly drained environments, and the shallow wells would be significantly more troublesome in this respect.

The similarity in chemical composition of the shallow and deep waters suggests a common source or intermixing of the two. Sodium to chloride ratios suggest that most can be considered diluted sea waters which have derived $CaSO_4$ and magnesium ion from, and lost potassium ion to, the formation materials.

Although the deep waters are supersaturated with both siderite and calcite, none of the waters appear to be supersaturated to the extent that they will cause serious well encrustation with these minerals. Encrustation of cooling towers and irrigation pipes and canals with calcium carbonate and minor amounts of iron deposits is to be expected because of loss of carbon dioxide and water during aeration in the cooling process. Provision of retention ponds on the cooler outlets to allow time for some separation of calcium carbonate before distributing the water, and use of open canals instead of small-diameter distributor pipes might reduce the problem significantly. Both shallow well waters and deep well waters will develop crusts of gypsum and calcium carbonate on whatever soils they irrigate.

Because of their sulfo-chloride compositions and the relatively high chloride and total salt content, all nine of the tested wells will be at least moderately corrosive to steel. Corrosion related to sulfate reduction adds to this effect in the deep wells, as indicated by the water chemistry and presence of sulfide deposits. It is possible that sulfate-reducing bacteria contribute to this process.

Corrosion measurements showed five of the nine well waters to be moderately corrosive and two others to be slightly above this range. Such corrosion is not likely to cause sudden serious damage to casings and filter pipes made of steel, but it could cause general metal loss and general roughening of the surface with corrosion deposits. Also, development of voluminous deposits on slowly wasting metal surfaces can cause significant reduction in filter pipe openings, and eventually, it might affect well capacity. This is more likely to occur in the deep wells because of sulfate reduction and resulting iron sulfide deposits.

Because most of the waters tested in this study would not be expected to cause rapid encrustation of well parts, it is likely that normal hydraulic response of the confined aquifers to development is a significant factor in observed changes in well performances.

REFERENCES

Diemer, E., 1965, Examen des problèmes de corrosion des puits sahariens produisant l'Albien: Paris Service Etudes et Methodes de Flopetrol, 30 p.

Doyle, R. W., 1968, The origin of the ferrous ion-ferric oxide Nernst potential in environments containing dissolved ferrous iron: Am. Jour. Sci., v. 266, p. 840–859.

Clarke, F. E., and Barnes, Ivan, 1969, Evaluation and control of corrosion and encrustation in tube wells of the Indus Plains, West Pakistan: U.S. Geol. Survey Water-Supply Paper 1608–L, 63 p.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water [2d ed.]: U.S. Geol. Survey Water-Supply Paper 1473, 363 p.

Hem, J. D., Roberson, C. E., Lind, C. J., and Polzer, W. L., 1972, Chemical interactions of aluminum with aqueous silica at 25°C: U.S. Geol. Survey Water-Supply Paper 1827–E. (In press.)

Helgeson, H. C., 1969, Thermodynamics of hydrothermal systems at elevated temperatures and pressures: Am. Jour. Sci., v. 267, p. 729–804.

Kittrick, J. A., 1969, Soil minerals in the Al_2O_3-SiO_2-H_2O system and the theory of their formation: Clays and Clay Minerals, v. 17, p. 157–167.

Truesdell, A. H., 1968, The advantages of using pE rather than Eh in redox equilibrium calculations: Jour. Geol. Education, v. 16, p. 17–20.

Truesdell, A. H., and Jones, B. F., 1969, Ion association in natural brines: Chem. Geology, v. 4, p. 51–62.

U. S. GOVERNMENT PRINTING OFFICE : 1972 O - 487-185