Prepared in cooperation with the Ministry of Petroleum, Energy and Mines, Islamic Republic of Mauritania

Second Projet de Renforcement Institutionnel du Secteur Minier de la République Islamique de Mauritanie (PRISM-II)

Hydrogeologic Map of the Islamic Republic of Mauritania, Synthesis of Hydrologic Data, and Chemical Hydrologic Map of the Islamic Republic of Mauritania:

Phase V, Deliverables 56, 57, and Added Value

By Michael J. Friedel, Carol A. Finn, and John Horton

Open-File Report 2013–1280 Chapter C

U.S. Department of the Interior
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Suggested citation:
Friedel, M.J., Finn, C.A., and Horton, J.D., 2015, Hydrogeologic map of the Islamic Republic of Mauritania (phase V, deliverable 56), Synthesis of hydrologic data (deliverable 57), and chemical hydrologic map of the Islamic Republic of Mauritania (added value), chap. C *of* Taylor, C.D., ed., Second projet de renforcement institutionnel du secteur minier de la République Islamique de Mauritanie (PRISM-II): U.S. Geological Survey Open-File Report 2013–1280-C, 23 p., 2 pl., scale 1:1,000,000, http://dx.doi.org/10.3133/ofr20131280. [In English and French.]

Multiple spellings are used in various literatures, and may be reflected in the text.

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or for stratigraphic nomenclature.

The report is being released in both English and French. In both versions, we use the French-language names for formal stratigraphic units.

ISSN 2331-1258 (online)

Synthesis of Hydrologic Data

Summary

A hydrogeologic study was conducted to support mineral-resource assessment activities in Mauritania, Africa. Airborne magnetic depth estimates reveal two primary groundwater basins: the porous coastal Continental Terminal Basin (fill deposits); and the interior, fractured interior Taoudeni Basin. In the Continental Terminal Basin, there is uniform vertical recharge and localized discharge that is coincident with groundwater pumping at Nouakchott. This pumping center induces eastward flow of groundwater from the Atlantic Ocean resulting in a salinity gradient that diminishes quality over 100 km. Groundwater also flows southward into the basin from Western Sahara. By contrast, an interbasin exchange occurs as fresh groundwater flows westward from the Taoudeni Basin. In the Taoudeni Basin, zones of local recharge occur in three areas: northwest at the edge of the Rgueïbat Shield; at the city of Tidjikja; and near the center of the basin. Groundwater also flows across international boundaries: northward into Western Sahara and westward into Mali. At the southern country boundary, the Senegal River serves as both a source and sink of fresh groundwater to the Continental Terminal and Taoudeni basins. Using a geographical information system, thirteen hydrogeologic units are identified based on lateral extent and distinct hydraulic properties for future groundwater model development. Combining this information with drilling productivity, groundwater-quality, and geophysical interpretations (fracturing and absence of subsurface dikes) three potential water-resource development targets were identified: sedimentary rocks of the Jurassic, Cretaceous, and Quaternary Periods; sedimentary rocks of Cambrian and Ordovician Periods; and sedimentary rocks of Neoproterozoic age.

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
decimeter (dm)	0.32808	foot (ft)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
hectare (ha)	2.471	acre
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
metric ton per day	1.102	ton per day (ton/d)
megagram per day (Mg/d)	1.102	ton per day (ton/d)
metric ton per year	1.102	ton per year (ton/yr)
	Pressure	
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.01	bar
	Energy	
joule (J)	0.0000002	kilowatt hour (kWh)

ppm, parts per million; ppb, parts per billion; Ma, millions of years before present; m.y., millions of years; Ga, billions of years before present; 1 micron or micrometer (μor μm) = 1×10^{-6} meters; Tesla (T) = the field intensity generating 1 Newton of force per ampere (A) of current per meter of conductor

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
Coordinate information is referenced to the World Geodetic System (WGS 84)

Acronyms

AMT	Audio-magnetotelluric
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BIF	Banded iron formation
BLEG	Bulk leach extractable gold
BGS	British Geological Survey
BRGM	Bureau de Recherches Géologiques et Minières (Mauritania)
BUMIFOM	The Bureau Minier de la France d'Outre-Mer
CAMP	Central Atlantic Magmatic Province
CGIAR	CSI Consultative Group on International Agricultural Research-Consortium for Spatial Information
DEM	Digital Elevation Model
DMG	Direction des Mines et de la Géologie
EMPA	Electron Microprobe Analysis
EM	Electromagnetic (geophysical survey)
EOS	Earth Observing System
eU	Equivalent uranium
GGISA	General Gold International
GIF	Granular iron formation
GIFOV	Ground instantaneous field of view
GIS	Geographic Information System
HIF	High grade hematitic iron ores
IHS	Intensity/Hue/Saturation
IAEA	International Atomic Energy Agency
IOCG	Iron oxide copper-gold deposit
IP	Induced polarization (geophysical survey)
IRM	Islamic Republic of Mauritania
JICA	Japan International Cooperation Agency
JORC	Joint Ore Reserves Committee (Australasian)
LIP	Large Igneous Province
LOR	Lower limit of reporting
LREE	Light rare-earth element
METI	Ministry of Economy, Trade and Industry (Japan)
MICUMA	Société des Mines de Cuivre de Mauritanie
MORB	Mid-ocean ridge basalt
E-MORB	Enriched mid-ocean ridge basalt
N-MORB	Slightly enriched mid-ocean ridge basalt
T-MORB	Transitional mid-ocean ridge basalt
Moz	Million ounces
MVT	Mississippi Valley-type deposits
NASA	United States National Aeronautics and Space Administration

NLAPS	National Landsat Archive Processing System
OMRG	Mauritanian Office for Geological Research
ONUDI	(UNIDO) United Nations Industrial Development Organization
PRISM	Projet de Renforcement Institutionnel du Secteur Minier
PGE	Platinum-group elements
RC	Reverse circulation drilling
REE	Rare earth element
RGB	Red-green-blue color schema
RTP	Reduced-to-pole
SARL	Société à responsabilité limitée
SEDEX	Sedimentary exhalative deposits
SIMS	Secondary Ionization Mass Spectrometry
SNIM	Société National Industrielle et Minière (Mauritania)
SP	Self potential (geophysical survey)
SRTM	Shuttle Radar Topography Mission
SWIR	Shortwave infrared
TIMS	Thermal Ionization Mass Spectrometry
TISZ	Tacarat-Inemmaudene Shear Zone
TM	Landsat Thematic Mapper
UN	United Nations
UNDP	United Nations Development Program
US	United States
USA	United States of America
USGS	United States Geological Survey
UTM	Universal Transverse Mercator projection
VHMS	Volcanic-hosted massive sulfide
VisNIR	Visible near-infrared spectroscopy
VLF	Very low frequency (geophysical survey)
VMS	Volcanogenic massive sulfide deposit
WDS	Wavelength-dispersive spectroscopy
WGS	World Geodetic System

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1 Introduction

Government officials of Mauritania are interested in developing long-term and stable water supplies for agricultural, domestic, and mining use (BURGÉAP, 2006). The preferred approach for evaluating long-term, stable water supplies is to perform quantitative analysis using numerical models. Currently there are four national water-resource priorities: (1) protecting and expanding the groundwater supply for Nouakchott, (2) increasing mineral industry water supplies, (3) increasing rural water supplies, and (4) devising groundwater recharge strategies. While computer software is available for simulating groundwater flow and transport, there currently is no national hydrogeologic framework for Mauritania and limited data exist for conceptualization, parameterization, and calibration of numerical models. To facilitate future groundwater modeling activities, this study reports on the physical setting, hydrogeologic data, hydrogeology (groundwater basins, hydraulic properties, hydrostratigraphic units, groundwater flow, and water-quality), water-resource targets, and model development strategies.

2 Physical Setting

The Islamic Republic of Mauritania is located in northwestern Africa. It has the shape of an indented rectangle measuring about 1,500 km from north to south and about 1,000 km from east to west (fig. 1). It is bordered to the northwest by the Western Sahara, to the northeast by Algeria, to the east and southeast by Mali, and to the southwest by Senegal. Its Atlantic Ocean coastline, to the west, extends for 700 km from the delta of the Senegal River northward to the Cap Blanc Peninsula. The capital is Nouakchott.

Both land relief and drainage are influenced by the aridity that characterizes the greater part of Mauritania. The impression of immensity given by the landscape is reinforced by its relative flatness; the coastal plains are at or lower than an elevation of approximately 45 m above mean sea level (amsl) and the higher plains of the interior generally vary from about 180 to 230 m amsl. The interior plains form a plateau that is broken into mesas joined by long, gentle slopes of about 2 degrees. The flat topography is accented in places by vestiges of cliffs, as the sloping plains terminate in steep cliffs or faulted scarps that may reach heights of as much as 274 m, or more rarely by inselbergs (steep-sided residual hills), of which the highest is Mount Ijil at 915 m.

3 Hydrogeologic Data Compilation Methods

The creation of maps and groundwater models of hydrogeologically complex regions requires data management and quality control. The identification, acquisition, and conversion of suitable hydrogeologic data, and proper processing and analysis procedures for these data, were part of the characterization and conceptualization efforts. The hydrogeologic data were largely retrieved from the SIPPE2 Access database (Dassargues, 2006).

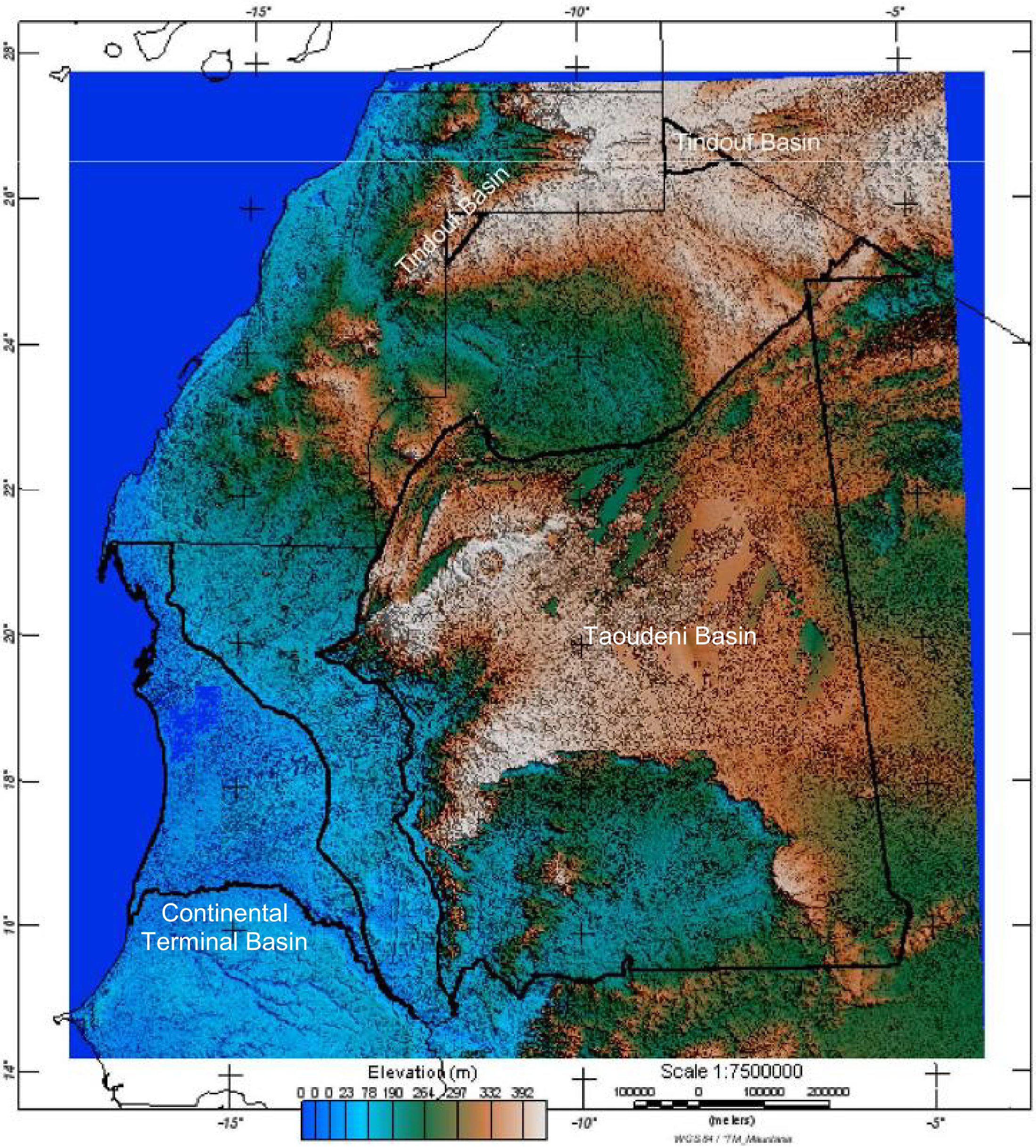

Figure 1. Color-shaded relief image of topography using shuttle radar tomography data.

The queries used to retrieve and format data tables were developed as part of the Phase 1 inventory of hydrogeologic data (Friedel, 2008). Examples of some database information used in this study include locations of cities, lithology (rock type), stratigraphy (geologic age), aquifer type (fractured versus porous) and nature (confinement), productivity, depth of production, hydrologic properties (transmissivity and hydraulic conductivity values), aquifer tests, static water level, and groundwater quality (dissolved bicarbonate, oxygen, nitrate, sodium, sulfate, and parameters such as electrical conductivity and temperature). These data tables were imported and projected using a geographic information system (GIS) to create layer files for combining and display. The GIS was used to manage, store, and analyze the digital data used to develop the hydrogeologic maps. Other data found in PRISM-II annexes 1–3 (Dassargues, 2006) included group and formation names by location, and the percentage range of productivity, which is the drilling success of encountering flow rates of water equal to or exceeding 1 m^3 hr^{-1} (success measurements are: poor, 0–5 percent, fair, 5–45 percent, good, 45–65 percent, very good, 65–80 percent, excellent, 80 percent and above). The spatial productivity and information on roads and cities were also available and in some cases used as GIS layers.

4 Hydrogeology

Conceptualization of a groundwater flow system requires the identification and assessment of various system elements that include: (1) definition of groundwater basins, (2) distribution of hydraulic properties, (3) definition of hydrogeologic units, (4), groundwater flow, and (5) groundwater-quality. Each of these system elements are described in more detail in the following sections.

4.1 Groundwater Basins

A recent inventory of hydrogeologic data in Mauritania revealed a lack of information about the thickness and extent of rock units (Friedel, 2008). Geophysical data are used here to determine the extent of groundwater basins and identify potential barriers to groundwater flow. For example, aeromagnetic data merged with previous United Nations (UN) data identified the coastal Continental Terminal and interior Taoudeni Basins (BURGÉAP, 2006; and Dassargues, 2006). Basin depth estimates from these data were calculated across most of Mauritania (fig. 2*A*) using the extended Euler method (Phillips, 2002) with a structural index of 0 (magnetic contact) and a window of 7. While results of the two aeromagnetic data sets are in general agreement, the estimated depths over the coastal Continental Terminal Basin are about 1 km deeper than those estimated using the newer data. Hence, there is uncertainty in the true depth estimates for the Continental Terminal Basin. By contrast, depth estimates calculated over the Continental Terminal Basin are about 0.1 km along its eastern edge, about 2–3 km at its center, and about 3–4 km along the western Atlantic coast.

In the interior Taoudeni Basin, the magnetic depth estimates reveal increases from about 500 m to 1 km at the basin's edge to greater than 2 km at about 25 km from the edge toward the basin's center (fig. 2A). Estimates of the greatest depths are about 6 km in areas not covered by dolerite sills. The calculated minimum depth to magnetic basement at the center of the basin is about 3 km, which was confirmed during drilling of the Abolag-1 well (Islamic Republic of Mauritania, Ministry of Mines and Industry, 2007). Processed seismic reflection data from that same report indicates the Taoudeni Basin reaches a

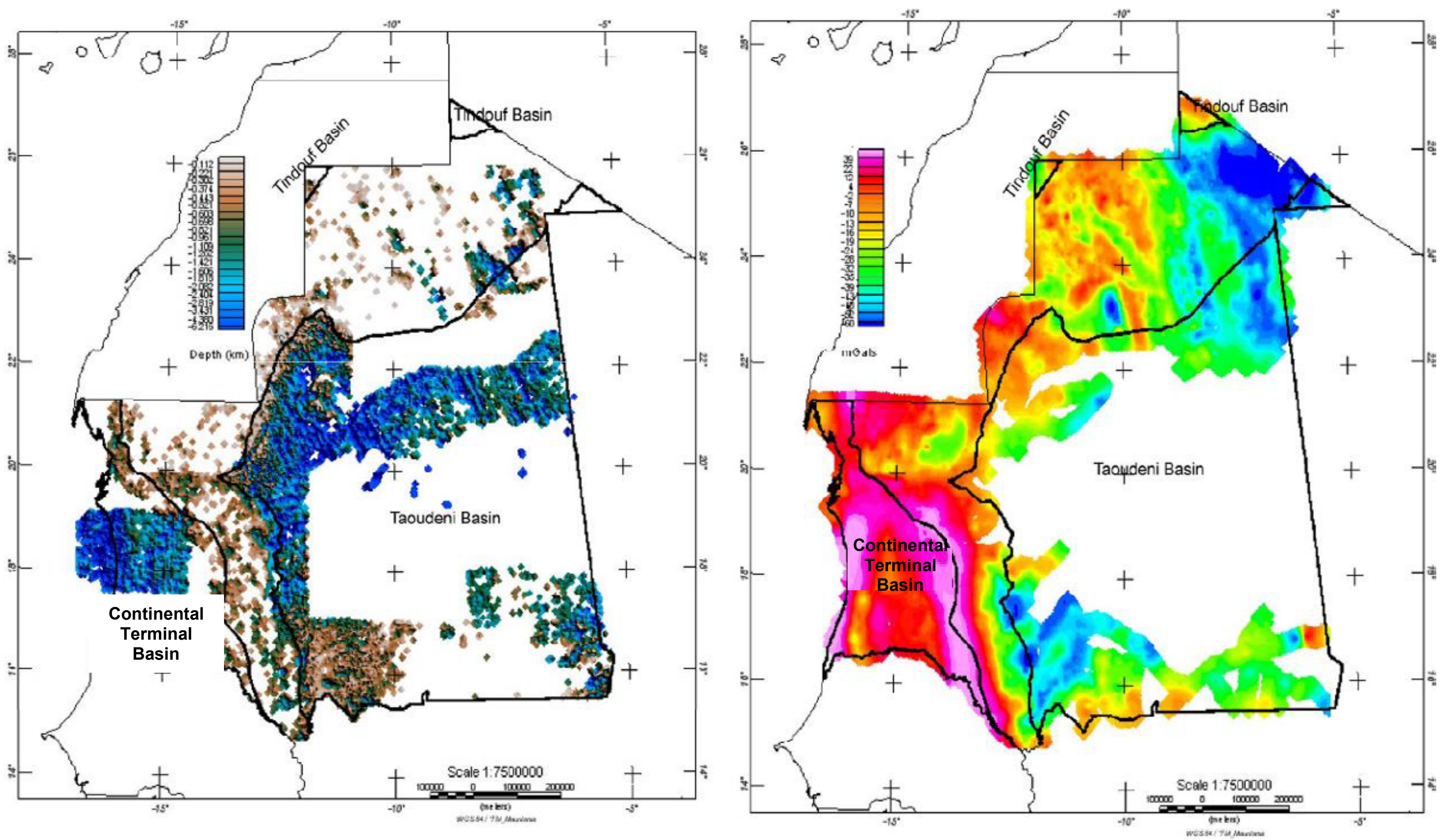

Figure 2. Geophysical imaging: *A*. Color-shaded relief image of gridded depth estimates. *B*. Simple Bouguer gravity map of Mauritania.

maximum depth of about 6 km at the central eastern border of Mauritania. In contrast, the report shows depths to the top of Jurassic dolerite sills that are about 0.5 to 1.5 km, in reasonable agreement with the seismically determined thickness of the Devonian section over which the sills lie. These seismic and drilling data also reveal a Devonian-Silurian ridge in the Taoudeni Basin.

Proprietary gravity data, obtained from a French agency (M. Albouy, written commun, 2006), provided confirmation and additional insight into the character of the two primary Mauritanian groundwater basins (fig. 2*B*). For example, there are several approximately 40-km-wide, linear, 20–35 mGal gravity lows that occur over the Continental Terminal Basin. These gravity lows correspond to the location of pumping centers in the basin and are interpreted as less-dense sediments. Gravity lows over the Rgueïbat Shield indicate density variations within the Precambrian terrane and not groundwater basins. Several linear northeast-trending gravity lows over the southwestern edge of the Taoudeni Basin in the Mauritanides are co-oriented with magnetic lows and are interpreted to be caused by the Precambrian basement (Roussel and Lesquer, 1991). A positive gravity anomaly in the north-central Mauritanide belt reveals a relatively shallow high-density Precambrian basement that may restrict regional flow between the coastal and interior basins. The persistence of a gravity-high along the Mauritanide belt to the north and south coincides with highly fractured regions, suggesting the possibility for preferential fracture flow of limited depth from the interior to coastal basin. The other prominent gravity high in the Continental Terminal Basin along the Atlantic Coast coincides with the center of a salt water plume migrating toward the primary pumping center (fig. 2*B*). The high gravity anomaly is not likely caused by low-density salt water but rather by higher-density gravels and (or) basement rocks. Further study of these relations is required to confirm the source of this gravity anomaly.

4.2 Hydraulic Properties

A literature search on the hydrologic properties of rocks in Mauritania was carried out as part of PRISM-II (Dassargues, 2006). This search revealed various site-specific, in-situ field tests (Blanchot, 1975), that measured hydrologic properties ranging over several orders of magnitude. For example, hydraulic conductivity ranges over three orders of magnitude with a minimum of 1.0E-06 m hr^{-1} for schist and maximum of 5.8E-03 m hr^{-1} for shelly sand. Similarly, transmissivity values range over 4 orders of magnitude with a minimum of 1.50E-06 m^2 hr^{-1} for dolerites and pelites and maximum of 6.94E-02 m^2 hr^{-1} for shelly sand. The hydraulic characteristics of many geologic rock units are unknown and therefore warrant further study. A summary of available conductivity and transmissivity values for various rock types is presented in table 1. The in-situ coastal and interior Taoudeni Basin field tests also indicated differences in hydraulic characteristics. In the coastal Continental Terminal Basin tests, the results were characteristic of an equivalent porous media, whereas results for the interior Taoudeni Basin were characteristic of fractured-rock hydrology. Other hydrologic properties such as porosity and storativity were not available for any rock types.

Hydrogeologic investigations in Mauritania lack any quantitative assessment of the hydraulic role of faults. As a result, information is unavailable on the influence of regional fault zones on groundwater flow patterns. Because anecdotal information suggests that the regional groundwater flow system may be influenced by deeper flow paths, another aspect

Table 1. Hydraulic characteristics.

Formation lithology	Age	Transmissivity[a,b] ($m^2\ hr^{-1}$)			Conductivity[c] ($m\ hr^{-1}$)		
		Minimum	Maximum	Median	Minimum	Maximum	Median
Dolerite		1.50E-06	9.31E-04	7.95E-05	6.69E-04	6.69E-04	6.69E-04
Dolomitic limestone		1.50E-04	1.50E-04	1.50E-04	1.00E-05	1.00E-05	1.00E-05
Granite		1.00E-02	1.00E-02	1.00E-02	unknown	unknown	unknown
Gravel		1.73E-04	2.20E-02	6.55E-04	1.49E-05	1.25E-03	1.05E-04
Jasper		5.00E-04	5.00E-05	5.25E-04	unknown	unknown	unknown
Limestone		1.10E-02	2.30E-03	6.65E-03	1.10E-04	3.10E-04	
Pelite	Other	1.50E-06	9.31E-04	7.95E-05	unknown	unknown	unknown
	Proterozoic	3.10E-04	3.10E-04	3.10E-04	4.57E-06	1.77E-05	8.43E-06
Quartzite	Other	2.38E-05	2.38E-05	2.38E-05	unknown	unknown	unknown
	Proterozoic	6.83E-04	6.83E-04	6.83E-04	unknown	unknown	unknown
Sand		4.87E-05	1.40E-02	1.02E-03	4.00E-06	1.76E-04	5.00E-05
Sandstone		2.31E-06	2.80E-02	1.25E-04	1.89E-06	1.89E-06	1.89E-06
	Cambrian-Ordovician	4.40E-04	8.20E-03	1.95E-03	1.10E-05	3.10E-04	1.10E-04
Schist	Cambrian-Ordovician	1.90E-03	1.90E-03	1.90E-03	1.00E-04	1.00E-06	5.05E-05
		2.80E-04	1.15E-03	6.82E-04			
	Proterozoic	7.29E-04	5.50E-05	3.92E-04	unknown	unknown	unknown

[a] Transmissivity = hydraulic conductivity * total thickness of permeable units.
[b] Transmissivity values (149) retrieved from SIPPE2 Access database.
[c] Permeability values (84); 79 were located in the coastal Continental Terminal Basin.

not previously studied but worth considering is the effect of depth on hydrologic properties. For example, one hypothesis is the likelihood of increased jointing or fracturing near the surface, caused by stress released from erosional unloading and weathering, may yield larger hydraulic conductivity values for rocks at shallow depths. Because most well tests are measured at shallow depths (<150 m), other hydrologic property data were evaluated from similar arid systems elsewhere, such as the Death Valley, California, regional aquifer (Bedinger and others, 1989). The available data, along with anecdotal information, were used to reach the following conclusions:

- Weathering and fractures (due to release of confining pressures by erosional unloading) probably are not significant at depths below 300 m.
- At increased depths, overburden pressures tend to decrease the apertures of joints or fractures and the size of pores, and therefore porosity and intrinsic permeability tend to decrease.
- Surface faults and fractures are good indicators of the orientation and position of permeable zones at depths up to 1,000 m.
- In some areas, solution-type voids and relict cavernous features may withstand overburden pressures in crystalline carbonate rocks, allowing these features to remain open at depths up to 2,000 to 3,000 m.

Large, regional crustal fault zones are good indicators of areas with significantly increased hydraulic conductivity at great depths. The regional hydraulic conductivity resulting from fractures is dependent not only on the presence of open fractures, but also on the rock type, fracture orientation, and regional history of tectonic stress.

4.3 Hydrogeologic Units

Rock units with considerable lateral extent and distinct hydrologic properties can be classified into hydrogeologic units (Maxey, 1968). The term hydrogeologic unit is synonymous with hydrostratigraphic unit. Because a study objective was to develop an understanding of the hydrogeology in Mauritania at a 1:1,000,000 scale, the hydrogeologic units characterize generalized aquifers and aquitards. Although the major geological features were retained, many smaller rock units were combined by generalizing both lithologic and hydrologic properties (such as, nature, type, productivity, and transmissivity) of the bedrock geology units. In applying these criteria, 107 rock units (Bradley and others, 2015) were grouped into 13 hydrogeologic units (tables 2 and 3). Abbreviations for the hydrogeologic units are arbitrary, being fashioned after group and formation age (era or period). The surface expression of these hydrogeologic units mapped across Mauritania, together with principal streams, lakes, annual rainfall, and cities, are shown in a physical hydrogeologic map (fig. 3). Numerous limitations are inherent in the creation of these digital map files. Specifically, the maps are accurate to the scale of updated digitized geologic maps; in this case 1:200,000. In addition, the rock units under the Sahara Dune field are interpreted based on surface expression, borehole sampling, geophysical data, and information in various reports (Dassargues, 2006). The following section describes the geologic and hydrologic characteristics of each hydrogeologic unit. A summary of the hydrogeologic units and their characteristics is provided in tables 2 and 3.

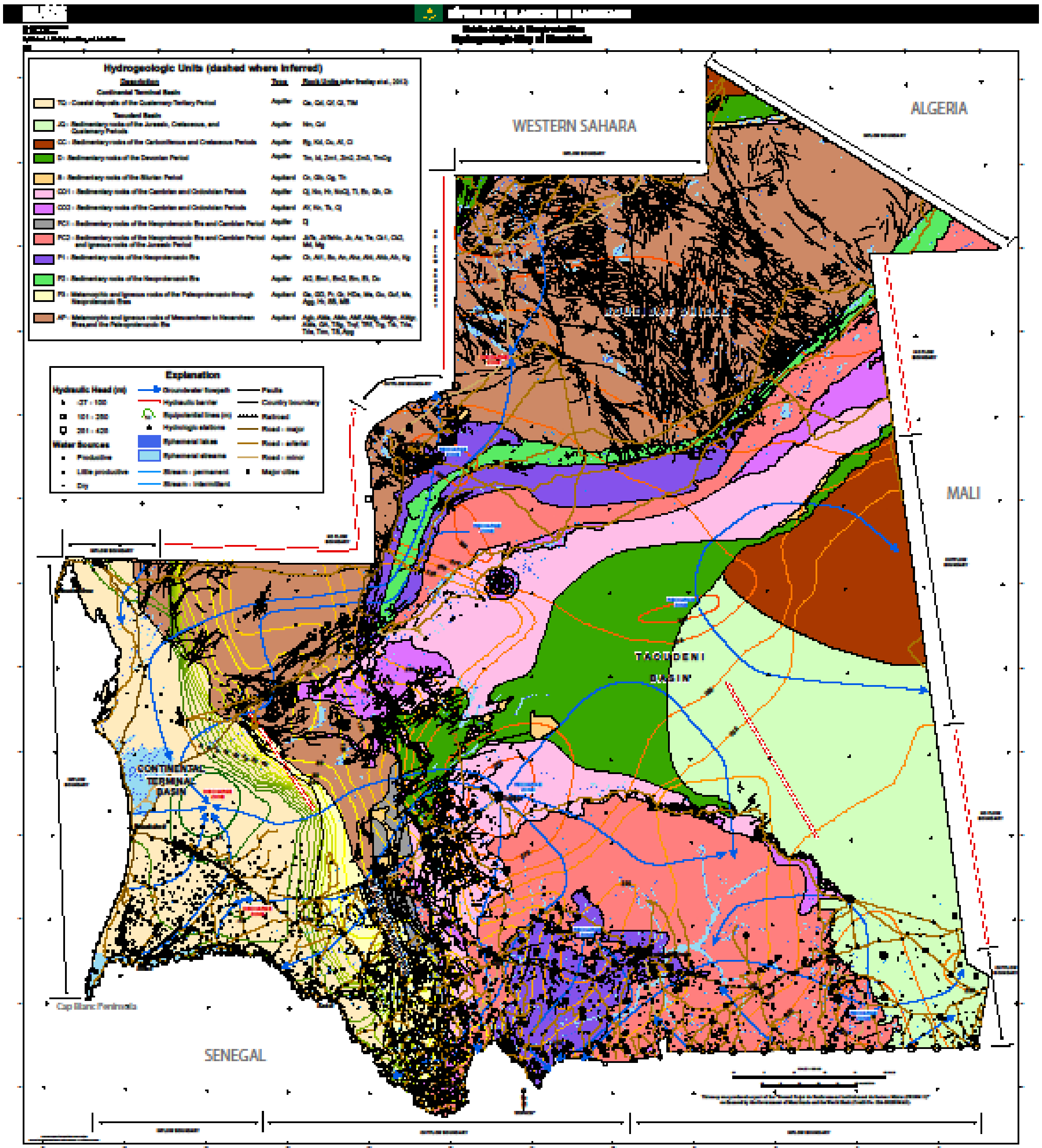

Figure 3. Physical hydrogeologic map showing hydrogeologic units, equipotentials of hydraulic head, groundwater flow paths, recharge and discharge zones, and flow conditions along country boundary.

4.3.1 Coastal Deposits of Quaternary to Tertiary Periods (TQ)

This hydrogeologic unit (TQ) is associated with alluvial sediments deposited during the Quaternary and Tertiary Periods (rock units: Qa, Qd, Qf, Ql, Tm). This heterogeneous mixture of coarse gravels, fine to shelly sand, sandstone, and caliche is likely to exhibit matrix (porous) flows that vary greatly (from 10 $m^3\ hr^{-1}$ to 60 $m^3\ hr^{-1}$) over short distances, as does the degree of confinement (unconfined, semi-confined, and confined) and hydrologic properties (transmissivity: from 3.50E-05 to 2.57E-02 $m^2\ hr^{-1}$). These changes in hydraulic character, both laterally and vertically, reflect the abrupt changes in grain size, degree of sorting, and consolidation. The likelihood of flows exceeding 1 $m^3\ hr^{-1}$ is about 100 percent (excellent).

The Continental Terminal Basin fill unit constitutes one of the two regional flow systems and is the most developed groundwater resource in Mauritania. The total fill ranges in thickness from tens of meters at the eastern edge (along the Mauritanides) to 4 km along Atlantic coast. Groundwater flows into this basin from the interior Taoudeni Basin to the east, the Atlantic Ocean from the west, and the Senegal River from the south. Groundwater leaves the basin primarily through evaporation and two well-fields pumping near the center of the basin (fig. 3). Whereas recharge may occur across the basin, the amount will probably be restricted to locally focused recharge and limited regionally due to low average precipitation (99 mm) and high average evaporation rate (>4,100 mm) (Friedel, 2008). Unfortunately, the induced cones of depression at the pumping centers appear to have enhanced inland migration of salt water from the Atlantic Ocean, characterized as a plume that degrades the quality of water for distances of more than 100 km inland from the coast (fig. 4).

4.3.2 Sedimentary Rocks of the Jurassic, Cretaceous, and Quaternary Periods (JQ)

This hydrogeologic unit (JQ) is associated with permeable sandstones of the Néma Group (rock unit: KJnm) and Adeïlé, Aïdiate, and Saïlé Formations. These rocks crop out parallel and east of the Mauritanide belt but are mostly covered by Sahara Desert dune sands (rock unit: Qd). In the north and north-central portions of this unit, the seismic reflection and drill core data reveal these rocks underlying the dune sands and overlying at least part of the Devonian rocks (Roussel and Lesquer, 1991; Islamic Republic of Mauritania, Ministry of Mines and Industry, 2007). In the south-central and southeast portions of this unit, the processed data from electrical resistivity and magnetic resonance soundings reveal the occurrence of these sandstones from Néma eastward to the Mali border (Bernard and others, 1999). A second electrical resistivity and magnetic resonance study reveals that sandstones in the eastern half of this region are water-bearing but the western half are dry (Bernard and Legchenko, 2003).

Table 2. Relation among hydrogeologic and productive rock units.

Hydrogeologic units		**Rock units**
Description	Type	(after Bradley and others, 2015)
Coastal deposits of the Quaternary-Tertiary Period (TQ)	Aquifer	Qa, Qd, Qf, Ql, Tm
Sedimentary Rocks of the Jurassic, Cretaceous, and Quaternary Periods, (JQ)	Aquifer	KJnm, Qd
Sedimentary Rocks of the Carboniferous and Cretaceous Periods (CC)	Aquifer	Ceg, Ckd, Cou, Kai, Kci
Sedimentary rocks of the Devonian Periods (D)	Aquifer	Dtm, Did, Dzm1, Dzm2, Dzm3, Dstmog
Sedimentary rocks of the Silurian Periods (S)	Aquitard	Scn, Sgb, Sog, Sth
Sedimentary rocks of the Cambrian and Ordovician Periods (CO1)	Aquifer	_oj1, _no, _Ohrt, _Ohrtq, Oti, Otikd, _Oojno, Oec, Ogh, Ooh, _Ooj
Sedimentary rocks of the Cambrian and Ordovician Periods (CO2)	Aquitard	_ay, _kn, _tk, Ooj2
Sedimentary rocks of the Neoproterozoic era and Cambian Periods (PC1)	Aquifer	Nedj, Nedjd
Sedimentary rocks of the Neoproterozoic era and Cambian Period and Igneous Rocks of the Jurassic Period (PC2)	Aquitard	_Ntet, _NFnotejb, NFjb, NGaz, NGjb, NGte, NEck1, NEck2, Jmd, Jmg
Sedimentary Rocks of the Neoproterozoic Era (P1)	Aquifer	MGch, MGat1, MGso, NEan, NEahzr, NEahtt, NEahtb, NEah, Nkg
Sedimentary rocks of the Neoproterozoic Era (P2)	Aquifer	MGat2, MGem1, MGem2, MGemam, Mget, Mgdo
Metamorphic and Igneous Rocks of the Paleoproterozoic through Neoproterozoic Eras (P3) - Mauritanide belt	Aquitard	NFga, NFgdg, NGfr, NGfrb, NGfrk, NGgre, NGgref NGgrm, NGgro, NGhda, NGmsb, NGmsbs, NGmso, NGmsos, NGgu, NGguf, Nmsdj, Nmsn, NPagg, NPhrs, NPhrt, NPhrtq, NFtb, Nmb
Metamorphic and Igneous Rocks of Mesoarchean to Neoarchean Eras, and the Paleoproterozoic Era (AP)—Rgueïbat Shield	Aquitard	Agb, AGamam, AGamcp, AGamch, AGamfe, AGamga, AGamgn, AGamgn1, AGamgn2, AGtsmg, AGtsmf, AItspg, AItslc, Altrf, Altrgh, Altrkh, Altrmi, AGtrqf, Altrla, Altrle, Apg

Table 3. Hydrogeologic unit characteristics.

Hydrogeologic unit[1]	Formation lithologies[2]	Basin	Nature[3]	Production[5] %	Type	Transmissivity[6] ($m^2 hr^{-1}$)		
						Minimum	Maximum	Median
Coastal sedimentary deposits of Quaternary-Tertiary ages (TQ)	Continental Terminal sandstones, sand, gravel, caliche	Coastal	Porous	100	Aquifer	3.5E-05	2.6E-02	3.0E-03
Sedimentary rock of Jurassic age (JS)	Sandstone	Interior	Fractured	Unknown	Unknown	Unknown	Unknown	Unknown
Sedimentary sequence of rocks of Carboniferous, Triassic-Cretaceous, and Quaternary ages and rhyolite of Cambrian age (CR1)	Dolorite sills[#]	Interior	Fractured	Unknown	Aquitard	1.0E-08	2.5E-02	5.2E-06
	Sandstones[#]	Interior	Fractured	Unknown	Aquifer	2.3E-06	2.8E-02	1.2E-04
	Shales	Interior	Fractured	Unknown	Aquitard	1.0E-08	1.0E-07	5.5E-08
Sedimentary sequence of rocks of Carboniferous, Triassic-Cretaceous ages (CR2)	Dolorite sills[#]	Interior	Fractured	Unknown	Aquitard	1.9E-06	2.5E-02	5.2E-06
	Sandstones[#]	Interior	Fractured	Unknown	Aquifer	2.3E-06	2.8E-02	1.2E-04
	Shales	Interior	Fractured	Unknown	Aquitard	1.0E-08	1.0E-07	5.5E-08
Sedimentary rocks of Silurian and Devonian ages (SD)	l'Oued Group: sandstones (includes ferruginous), schists, argillites, mudstones; Tenemouj Group: sandstones, siltstones, argillites	Interior	Fractured	5–45	Aquifer	Unknown	Unknown	Unknown

Table 3. Hydrogeologic unit characteristics.—Continued

Hydrogeologic unit[1]	Formation lithologies[2]	Basin	Nature[3]	Production[5] %	Type	Transmissivity[6] ($m^2 hr^{-1}$)		
						Minimum	Maximum	Median
Sedimentary rocks of Cambrian and Ordovician ages (CO)	d'Oujeft Group: graywackes, jaspers, pelites (50%), quartzites, sandstones (50%); de la falaise d'Atar Group: limestones (80%); Nouati Group: sandstones, pelites (60%), shales, dolomites (Superior) (100%); Teniagouri Group: jasper, schist, sandstone (local) siltstone, and mudstone	Interior	Fractured	65–85	Aquifer	4.4E-04	1.9E-03	1.2E-03
Sedimentary rocks of Neoproterozoic to Cambrian ages (N1)	Des Jbeliat Group:	Interior	Fractured	5–45	Aquitard	Unknown	Unknown	Unknown
Sedimentary rocks of Neoproterozoic age (N2)	l;Affolle Group: sandstones the Atrouss and Aioun Groups (84%), basal (62%), others; l'Assabet el Hassian Group: shale, siltstone, quartzite, schist	Interior	Fractured	45–65	Aquifer	5.8E-05	9.3E-04	8.0E-05
	Dolorite sills (south)	Interior			Aquitard	1.5E-06	9.3E-04	8.0E-05
Sedimentary rocks of Neoproterozoic age (N3)	Sandstone, pelite, dolorite	Interior	Fractured	80	Aquifer	2.3E-06	2.8E-02	1.2E-04

Table 3. Hydrogeologic unit characteristics.—Continued

Hydrogeologic unit[1]	Formation lithologies[2]	Basin	Nature[3]	Production[5] %	Type	Transmissivity[6] ($m^2 hr^{-1}$)		
						Minimum	Maximum	Median
Carbonate rocks of middle Mesoproterozic age (PC1)	Atar Group: dolomite and limestone (80%)	Interior	Karst	45–65	Aquifer	Unknown	Unknown	Unknown
Sedimentary rocks of Mesoproterozoic age; metasedimentary, metabasalt, metarhyolite, and mafic intrusive rocks of Neoproterozoic age (PC2)	Atar Group: shale, quartzite, siltstone	Interior	Fractured	45–65	Aquifer in north and south; Aquitard central	2.8E-04	1.2E-03	6.8E-04
Metavolcanic and sedimentary rocks of Mesoarchean and Neoarchean ages; andesite, gneiss, granitoid, metasedimentary, and undifferentiated sedimentary rocks of Paleoproterozoic age (PC3)	Known as the Rgueïbat Shield Char Group: schist, dolomite, siltstone, sandstones	Interior	Fractured	0–5	Aquitard	2.8E-04	1.2E-03	6.8E-04
Unknown sequence of rocks of (U1)	Unknown	Interior	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Unknown sequence of rocks of (U2)	Unknown	Interior	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Mauritania (all data)						4.0E-06	6.9E-02	2.1E-03

[1] Equivalent rock units in parenthesis.

[2] Annex 1: Echelles stratigraphiques.

[3,4] Type and nature of aquifer determined based on near-surface (<100 m depth) pump tests; information retrieved from SIPPE2 Access database.

[5] Productivity percentage of drillholes that produce water greater than 1 $m^3 hr^{-1}$.

[6] Transmissivity values (149) retrieved from SIPPE2 Access database.

[7] Transmissivity values characteristic of dolorites retrieved from SIPPE2 Access database.

[8] Transmissivity values characteristic of pellites retrieved from SIPPE2 Access database.

[9] Presence of dolorites interpreted using filtered aeromagnetic images.

Currently, there is no information available on the hydraulic characteristics of this unit.

4.3.3 Sedimentary Rocks of the Carboniferous and Cretaceous Periods (CC)

This hydrogeologic unit (CC) is associated with sandstones and limestones of the El Guettara (rock units: Ceg, Ckd) and Ouarkziz (rock unit: Cou) Groups and Carboniferous Period; and sandstones (rock units: Kai, Kci) of the Continental Intercalaire Group and Jurassic Period. These rocks crop out in the northern Taoudeni Basin, but there is no information available on their hydraulic characteristics or the degree to which exploitation of groundwater occurs.

4.3.4 Sedimentary Rocks of the Devonian and Silurian Periods (S, D)

These hydrogeologic units are associated with rocks that were deposited during the Devonian (D) and Silurian (S) Periods. Productive water-bearing rocks are associated with the Tenemouj and Zemmour Groups of the Devonian Period (rock units: Dtm, Did, Dzm1, Dzm2, Dzm3, Dstmog). Outcrops of this hydrogeologic unit, bound the Sahara Desert to the north and south, overlie impermeable Silurian rocks (rock units: Sog, Sth) at the central Taoudeni Basin, centered on the eastern border. Whereas the hydraulic characteristics of the fracture-dominated Devonian unit are unknown, the likelihood for developing wells with flows greater than $1 m^3 hr^{-1}$ in the near-surface rocks (<60m), such as at Zemmour, is considered good (60 percent). By contrast, the l'Oued Chig and Tenemouj Groups of the Silurian Period (rock units: Scn, Sgb, Sog, Sth) host argillites, mudstones, and siltstones which provide an impermeable base to rocks of the Devonian Period and a cap to rocks of the Cambrian-Ordovician Periods (BURGÉAP, 2006).

4.3.5 Sedimentary Rocks of Cambrian to Ordovician Periods (CO1, CO2)

These two hydrogeologic units are associated with sedimentary rocks deposited during the Cambrian and Ordovician Periods. Outcrops are oriented parallel to the Mauritanide belt and bound the Sahara Desert to the north and south. The first hydrogeologic unit (CO1) is characterized by permeable rocks of the Cambrian, Cambrian to Ordovician, and Ordovician Periods. Rocks of the Cambrian Period are associated with the d'Oujeft Group (geologic unit: _oj1) including sandstones of the Beddamez Formation, sandstones and quartzites of the Chinguetti Formation, sandstones and conglomerates of the Moudjéria Formation; and the Nouatil Group (geologic unit: _no) including dolostones and limestones of the d'Achram and d'Amogjar Formations. Similarly, water-bearing rocks of the Cambrian to Ordovician Periods are associated with conglomerates, schists, quartizites, and siltstones of the d'El Harach Group (rock units: _Ohrt, _Ohrq). In the Ordovician Period, sandstones and quartizites of the Tichit Group (geologic unit: Oti, Otikd) are productive units. The hydraulic characteristics of this fracture-dominated unit include transmissivity values in the range of 4.4E-04 to 1.9E-03 $m^2 hr^{-1}$. The likelihood of flows greater than $1 m^3 hr^{-1}$ in these rocks is excellent (80 percent) for limestones of the de la falaise d'Atar Group; good (60 percent) for pelites and fair for dolomites (9 percent) of the Nouatil Group; pelites (50 percent), sandstones (50 percent), and dolomites (76 percent) of the d'Oujeft Group; and conglomerates and quartzites (43 percent) of the d'El Harach Group. The second hydrogeologic unit (CO2) comprises impermeable argillites, argillaceous sandstones, and mudstones (BURGÉAP, 2006) of the Nouatil (_ay, _kn, _no, _tk) Group and Cambrian Period; and argillaceous sandstones and quartzites associated with the Foum Nbeïka, de Terguent, d'Aghaoujeft, and d'Oued Touerga Formations from the Ordovician (inferior) Period (rock unit: Ooj2). Despite being impermeable, their discontinuous and fractured nature may result in semi-confined conditions with leakage between overlying and underlying units.

4.3.6 Sedimentary Rocks of the Neoproterozoic Era to Cambrian Period and Igneous Rocks of the Jurassic Period (PC1, PC2)

These two hydrogeologic units consist of sedimentary rocks deposited during the Neoproterozoic Era to Cambrian Period. Their fractured-rock units appear to crop out parallel to the Rgueïbat Shield in the north and as a rectangular region adjacent to the Senegal River in the south. The first hydrogeologic unit (PC1) forms an aquifer comprising conglomerates, pelites, quartzites, sandstones, and schists of the Djonaba Group (geologic unit: Nedj, Nedjd) with a 56 percent (good) likelihood to produce water. The hydraulic characteristics of this unit include transmissivity values in the range of 2.3E-6 to 2.8E-2 $m^2 hr^{-1}$. By contrast, the second hydrogeologic unit (PC2) forms an aquitard that comprises argillaceous sandstones and quartzites which belong to the l'Azlaf, Jbéliat and Téniagouri Groups (rock units: _Ntet, _NFnotejb, NFjb, NGaz, NGgre, NGjb, NGte); and intrusive Jurassic rocks, such as dolerites and diorites (rock units: Jmd, Jmg) which are largely impermeable (BURGÉAP, 2006). The character of these rocks is generally massive, but where fractured they have a 38 percent likelihood to produce water of which 75 percent are expected to exceed 10 $m^3 hr^{-1}$. Also, the fractured and discontinuous nature of these rocks may give rise to semi-confined conditions with leakage between overlying and underlying units. The range of transmissivity for this unit is based on the dolerite sills: 1E-8 to 2.5E-2 $m^2 hr^{-1}$.

4.3.7 Sedimentary Rocks of the Neoproterozoic Era (P1, P2)

These two hydrogeologic units consist of sedimentary rocks deposited during Neoproterozoic Era. The first hydrogeologic unit (P1) consists primarily of sandstones that crop out in the southern Taoudeni Basin which was subject to syntectonic uplift. The likelihood for successful well production ranges from 43 to 89 percent (good to excellent) but varies by group and formation. For example, the likelihood for producing flows exceeding 1 $m^3 hr^{-1}$ is about 75 percent in the Aioun Group (rock unit: NEan), 43 percent in the Assabet El Hassiane Group (Taleb Formation) (rock units: NEahzr, NEahtt, NEahtb, NEah), 88 percent in the Atar Group (rock unit: MGat1) including Formations Foum Chor; 50–89 percent in the Char Group (geologic unit: MGch) including the Agueni Formation; (rock unit: MGch), and 48 percent in the Khaang Naam Group including the El Aguer Formation (rock unit: Nkg). The hydraulic characteristics of these sandstones include transmissivity values in the range of 2.3E-6 to 2.8E-2 $m^2 hr^{-1}$. The second hydrogeologic unit (P2) consists mostly of limestones and dolomites that are associated with two Groups: Atar (rock unit: MGat2) including the d'Azougui, Tawaz, Tod, Touiderguilt, Tifounke, and Terrariat Formations,; and El Mreïti (rock units: MGem1, MGem2, MGemam, MGet) including the ‘Aguel el Mabha, Touirist, Tenoumer, Khatt, Gouamir, and Nesoar Formations. This karstic rock unit only crops out in the north, parallel to the Rgueïbat Shield. Hydraulic tests indicate the likelihood of flows greater than 1 $m^3 hr^{-1}$ are about 25–100 percent (good to excellent) for the d'Atar, 50–89 percent (good to very good) for the Char, and 38 percent (good) for the d'El Mreïti groups (Blanchot, 1975).

4.3.8 Metamorphic and Igneous Rocks of the Paleoproterozoic to Neoproterozoic Eras (P3)

This hydrogeologic unit, known as the Mauritanide Belt, consists primarily of northwest-southeast trending metamorphic and igneous rocks from the Paleoproterozoic to Neoproterozoic Eras. In the northern part, there are schists, metavolcanics, and rhyolites; in the southern part, there are schists with granitic intrusions. The general hydraulic character of this unit is a barrier to regional flow, such as over a distance of about 150 km near its center where groundwater is forced to flow north or south.

Where geologic conditions promote flow through fractures, the respective likelihood for flows exceeding 1 m^3 hr^{-1} in schists and granites is 48 percent and 65 percent with salinity <1g/l. The hydraulic characteristics of localized, fracture-dominated permeability include transmissivity values in the range of 2.8E-04 to 6E-03 m^2 hr^{-1}. Important water-producing schists include those from the El Fadra (rock units: NGfr, NGfrb, NGfrk, NGgre, NGgrm, NGgro), El Ghabra (rock units: NGgrm, NGgref), El Harach (rock units: NPhrs, NPhrt, NPhrtq), Gadel (geologic unit: NFga), El Mseigguem (rock units: NGmsb, NGmsbs, NGmso, NGmsos, Nmsdj, Nmsn), Gueneiba (rock units: NGguf, NGgu) Groups which exhibit a 40–47 percent success rate of flows exceeding 1 m^3 hr^{-1}. Other rocks exhibiting local groundwater production success rates of 21 and 51 percent include metasedimentary, metacarbonate, and metavolcanic rocks associated with the El Ghabra (rock units: NGgre), Hajar Dekhen – Kleouat (geologic unit: NGhda). Similarly, the likelihood of success for producing water in the metabasic intrusive complex of the Cortège de Guidamaka (geologic unit: NFgdg, NPagg) is about 19–41 percent.

4.3.9 Metamorphic and Igneous Rocks of the Mesoarchean to Neoarchean Eras, and the Paleoproterozoic Era (AP)—Rgueïbat Shield

This hydrogeologic unit, known as the Rgueïbat Shield, comprises a western Archean terrane dominated by gneisses and granitic rocks, and an eastern terrane largely made up of Paleoproterozioic metasedimentary rocks. Despite the intense fracturing of this unit, most of the fractures appear to be randomly connected, resulting in heterogeneous productivity with likelihood of success from about 0–45 percent. Where the unit is productive, the transmissivity values range from 2.8E-4 to 1.2E-3 m^2 hr^{-1}. In most areas there is no productivity, probably due to hydraulic properties of the order 1E-8 m^2 hr^{-1}. For this reason, this hydrogeologic unit is considered an aquitard at the base of the central interior Taoudeni Basin centered on the eastern border of Mauritania.

Important water-bearing units include the Neoarchean to Mesoarchean granites and granodiorites of the Tasiast Group (rock units: AItspg, AItslc, AGtsmg, AGtsmf) with a likelihood for productivity (exceeding 1 m^3 hr^{-1}) between 0 to 45 percent (depths: 47 to 72 m; quantity: 0.6 to 3 m^3 hr^{-1}; salinity: 3 to 37 g/l); Mesoarchean gneisses and schists associated of the Tiris Complex (rock units: Altrf, Altrgh, Altrkh, Altrmi, AGtrqf, Altrla, Altrle) with a 17 percent likelihood for productivity (depths: 15 to 131 m; quantity: 8 to 20 m^3 hr^{-1}; salinity: 5 to 60 g/l), and gneisses, granitoids and metamorphic rocks of the Amsaga Complex (rock units: AGamgn2, AGamgn1, AGamgn, AGamga, AGamfe, AGamcp, AGamch, AGamam, Apg, Agb) Groups with a 21 percent likelihood for productivity (depths: 21 to 58 m; salinity: <2 g/l). Important water bearing gneisses and granites, metasedimentary, and undifferentiated sedimentary rocks of the Paleoproterozoic Era (rock units: AlPan, AlPpx) include rhyolites of the Blekhzaymat Group (rock units: Plbzam1, Plbzam2, PIPGbzam3, PGbzam4) that have a 40 percent likelihood for productivity (depths: unknown; quantity: unknown; salinity: unknown), and granites of the Bir Moghreïn Group that have a 40 percent and 28 percent likelihood for productivity (depths: 15 to 131 m; quantity: 8 to 20 m^3 hr^{-1}; salinity: 5 to 60 g/l).

4.4 Groundwater Flow

Groundwater movement in Mauritania was characterized based on flow paths oriented orthogonally to equipotential lines of hydraulic head (fig. 4). Values of hydraulic head (n=978) were computed by subtracting the observed static water levels from co-located elevations. Whereas observed water levels obtained from the SIPPE2 database (Friedel, 2008) were given specific coordinates, the location of elevation values were interpolated from a digital elevation model with 90-m resolution. These estimated values of hydraulic head were plotted and analyzed using the GIS to identify spatial statistical relations. The lack of any spatial statistical relation among hydraulic head prevented the development of a model variogram and determination of a kriging estimation variance.

A review of groundwater flow paths provided information on the location of recharge and discharge areas, and flow boundary conditions (such as areas of no flow, groundwater divides, and hydraulic barriers). Collectively, these features confirmed that the groundwater flow system in Mauritania is best described as two interconnected regional systems: the coastal porous Continental Terminal Basin, and the interior, fractured sedimentary Taoudeni Basin. Groundwater from five separate recharge areas flows out of the Taoudeni Basin in three general directions: east toward Mali, west toward the Continental Terminal Basin, and south toward the Senegal River. Groundwater flows into the Continental Terminal Basin from the Atlantic Ocean and from two interior Taoudeni Basin recharge areas. One of these recharge areas is located northeast of Atar at the northwestern edge of the Rgueïbat Shield (hydrogeologic unit PC2), and the other is centered at the city of Tidjikja (hydrogeologic unit CO1). The transfer of groundwater from the Taoudeni Basin to the Continental Terminal Basin occurs along two primary flow paths that deflect around a 150-km-long hydrologic barrier and trend northwest-southeast along the axis of the Mauritanide belt (hydrogeologic unit P3) east of Akjoujt. Some groundwater from the second recharge area flows northwest, then turns south near another hydrologic barrier. This northwest-southeast-trending barrier is about 200 km long (hydrogeologic unit JQ) and coincides with the structural high of a Silurian-Devonian ridge separating the Maqteir Depression from the Taoudeni Basin Low that straddles the border between Mauritania and Mali. A third groundwater recharge area in the Taoudeni Basin is in the south (hydrogeologic unit PC2) between the cities of Kiffa and ‘Ayoun el Atrous. Groundwater from here flows south eventually discharging to the Senegal River. The fourth and fifth recharge areas contribute water to the Taoudeni Basin Low and eventually to Mali: one is at the center of the country in the Sahara Desert and another is in its southeastern corner. The groundwater that is being withdrawn at two Continental Terminal Basin (hydrogeologic unit TQ) water-supply well fields appears as discharge areas: 100 km east of Nouakchott and 165 km southeast of Nouakchott. During this study, there were no pumping records provided for the wells in Mauritania.

4.5 Groundwater Quality

A chemical hydrogeologic map was constructed to illustrate the occurrence and distribution of water quality in Mauritania (fig. 4). Selected dissolved water-quality indicators and basic aqueous parameters were analyzed for their occurrence and distribution across the country. The chemical constituents included bicarbonate, nitrate, and sulfate, and the aqueous parameters evaluated included electrical conductivity (salinity) and dissolved oxygen. A summary table of statistics is provided for each mapped element and aqueous parameter (table 4). The data are limited in number and spatially biased, with most samples taken from the Continental Terminal Basin and southern portions of exposed hydrogeologic units in the Taoudeni Basin.

An important objective of this study was to identify potential regions of suitable water quality for use as public water supplies. Toward that end, the occurrence and distribution of salinity in Mauritanian groundwater was mapped. Because the majority of the groundwater monitoring sites (n=796) measured electrical conductivity (EC) but not total dissolved solids (TDS), these EC values were converted to an equivalent value of salinity using a regression relation. The relation used to convert EC to TDS was based on application of the regression process to fit an equation to EC measurements (n=128) that were concurrently sampled and analyzed for TDS. After converting the values of EC to TDS, they were plotted and contoured, revealing a prominent salt water intrusion from the Atlantic Ocean into the Continental Terminal Basin (hydrogeologic unit TQ). A gradient of salinity occurs inland over a distance of about 100 km and spans a range of categories: fresh (<1,000 mg L^{-1}), brackish (1,000–5,000 mg L^{-1}), highly brackish (5,000–15,000 mg L^{-1}), saline (15,000–30,000 mg L^{-1}), seawater (30,000–40,000 mg L^{-1}) and brine (40,000–300,000 mg L^{-1}). Two other smaller areas also reveal elevated salinity concentrations. These areas of brackish water are in the south-central Taoudeni Basin (hydrogeologic unit PC2) west of Kiffa, and between Kiffa and 'Ayoun el Atrous (hydrogeologic unit P1). The elevated salinity contours appear elongated in a north-south trend that coincides with flow paths discharging to the Senegal River. Apart from these three areas, the majority of Mauritania's groundwater is fresh.

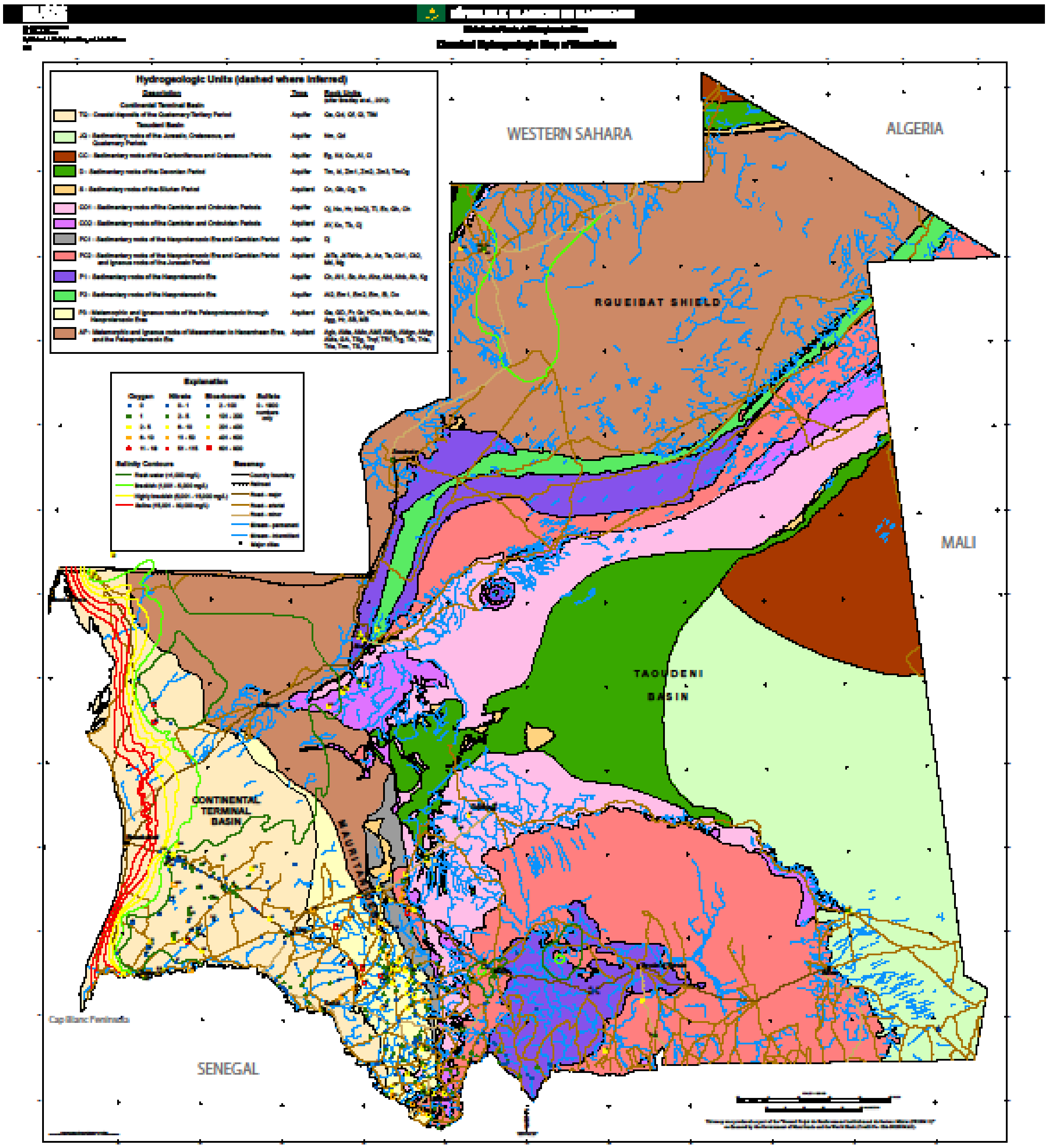

Figure 4. Chemical hydrogeologic map showing the occurrence and distribution of water quality in Mauritania.

Table 4. Water-quality characteristics.

	Dissolved Element				Parameter
Statistic	Bicarbonate	Nitrate	Sulfate	Dissolved solids[a]	Dissolved oxygen
Number of samples	281	391	196	746	22
Minimum ($mg\ L^{-1}$)	2	0 (11)[b]	0 (14)	1	0 (3)
Maximum ($mg\ L^{-1}$)	896	115	1,900	35,000	17.6
Mean ($mg\ L^{-1}$)	242.2	4.9	96.8	3,952	4.6
Standard deviation ($mg\ L^{-1}$)	44	11.8	195.3	9,867	3.8
Median ($mg\ L^{-1}$)	189	1.15	35.1	542	4

[a] Dissolved solids estimated using nonlinear regression relation established using for 285 samples.
[b] Parenthesis indicates number of values at or below limit of detection

5 Water Resource Targets

This section identifies new water-resource targets for potential development in support of mining and public supply needs in Mauritania. The selection of these targets is based on a combination of historical drilling productivity, geophysical interpretations including degree of fracturing, the absence of subsurface dikes, and the quality of water.

1. Sedimentary rocks of the Jurassic, Cretaceous, and Quaternary Periods (hydrogeologic unit: JQ)

There currently is no hydraulic or production information available for this hydrogeologic unit. However, geophysical and hydrogeologic studies in this hydrogeologic unit reveal several positive attributes suggesting it to be a primary water-resource target. First, the airborne magnetic study reveals the southeast to be comparatively shallow and free of dolerite sills. The fact that the sandstones underlie dune sands suggests that they may receive periodic recharge. Second, the electrical and nuclear magnetic resonance studies reveal the eastern half to be preferred as it appears saturated. Third, the water quality of this region appears to be fresh.

2. Sedimentary rocks of Cambrian and Ordovician Periods (hydrogeologic unit: CO1)

The combined regional gravity low associated with fracturing of this unit and lack of dikes indicated by the aeromagnetic map support this unit as a high-valued water-resource target. To the north, the gravity values increase, possibly indicating less intensity in fracturing; however, the thickness of this unit increases northward, enhancing the total potential volume to be explored..

3. Sedimentary rocks of Neoproterozoic age (hydrogeologic unit: P1)

Whereas the carbonate rocks associated with this hydrogeologic unit demonstrated the greatest productivity of all, little exploration has occurred in the north, possibly because of its remoteness and because much of it lies below dune sands. Given that the dune sands are comparatively thin (0 to 100 m) in areas adjacent to the Rgueïbat shield, production in the uncovered southern outcrop is about 80 percent, and hydraulic properties are among the greatest for fractured-rock units of the Taoudeni Basin. This is a good target for water resource exploration. The two prominent gravity lows in the south suggest relatively low-density rocks that are likely due to intense fracturing and/or local faulting; however, the estimated thickness is comparatively thin and the unit likely has intermediate resources compared to other hydrologic units.

6 Model Development Strategies

The future development of a groundwater flow and transport model will require several steps: conceptualization, parameterization, calibration, validation, and predictive analysis. In the present study, the conceptual development of a model for the coastal and interior groundwater basins is possible by reviewing the spatial extent of units in the hydrogeologic map. Depth estimates for various units can be obtained from the interpreted geophysical and borehole data. Model parameterization requires defining a numerical grid that accounts for spatial distribution of parameter values. Flow modeling requires the assignment of hydraulic property values (such as, transmissivity or hydraulic conductivity, and storativity). The solute transport model requires values of transport properties (such as porosity, distribution coefficients, dispersivities, and density). For these flow and transport parameter values, one suggestion is to generate a random spatial distribution for each known property, assuming a log-normal distribution to reflect the random and heterogeneous nature of fractured-rock production rates. A statistical description for some hydraulic property values are found in tables 1 and 4. Some hydraulic and transport property values are unknown and need to be determined from additional field tests or available literature.

Boundary conditions must be applied to grid cells so that the dependent variables change from static equilibrium. Some common spatial and temporal boundary conditions include recharge that is assigned to the uppermost model layer, constant head and/or flux along vertical boundaries, and pumping rates in wells. In Mauritania, a first-order steady-state approximation for recharge might reflect an annual negative value because evaporation is 1-2 orders of magnitude greater than precipitation. In actuality, however, some locations show regionally focused recharge in the Taoudeni Basin. Likewise, not all focused recharge may be evident because of the hydrogeologic map scale and assumptions made in its development. In both cases, however, further study is necessary to confirm the location, magnitude, and importance of focused recharge. The approximate vertical boundary flux also must be computed.

For a steady-state groundwater flow model, approximate values for vertical boundary flux conditions may be computed from the equipotential surface (see the hydrogeologic map) and the geometric mean of layer transmissivity values along that boundary. At the scale of the hydrogeologic map, only two discharge locations in the Continental Terminal Basin flow system are evident. These discharge locations must be specified in the model, and the annual pumping rates need to be determined from existing records and assigned as internal boundary conditions.

Following conceptualization and parameterization, the model needs to be calibrated and validated, and its prediction uncertainty analyzed. During calibration of the steady-state model, important dependent variables must be replicated to include the regional hydraulic head fields, the internal and boundary fluxes, and the water levels in assigned wells.

7 References

Bedinger, M.A., Sargent, K.A., and Langer, W.H., 1989, Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste-characterization of the Death Valley region, Nevada, and California: U.S. Geological Survey Professional Paper 1370–B, 43 p.

Bernard, J. Diagana, B., and Ricolvi, M., 1999, Combination of electrical resistivity and magnetic resonance sounding data for mapping an aquifer layer in Mauritania: Society of Exploration Geophysicists (SEG), Technical Program, expanded abstracts, v. 23(1).

Bernard, V. and Legchenko, A., 2003, Groundwater exploration with the magnetic resource sounding method, *in* ASEG 16th Geophysical Conference and Exhibition, Adelaide, Feb. 2003: Australian Society of Exploration Geophysicists, Extended Abstracts, no. 2, p. 1–5, doi:10.1071/ASEG2003ab013.

Blanchot, A., 1975, Plan minéral de la République Islamique de Mauritanie: Bureau de Rechereches Géologiques et Minièrs (BRGM), 564 p.

Bradley, D.C., Motts, H.A., Horton, J.D., Giles, Stuart, and Taylor, C.D., 2015, Geologic map of Mauritania (phase V, deliverables 51a, 51b, and 51c), chap. A1 *of* Taylor, C.D., ed., Second projet de renforcement institutionnel du secteur minier de la République Islamique de Mauritanie (PRISM-II): U.S. Geological Survey Open-File Report 2013–1280-A1, 3 pl., scale 1:1,000,000, http://dx.doi.org/10.3133/ofr20131280/. [In English and French.]

BURGÉAP, 2006, PRISM II—Second project of strengthening of the institutions of the Mining Sector—An evaluation of the hydrogeologic studies in Mauritania at 1:500,000, 86 p.

Dassargues, Alain, 2006, PRISM II: Second project of strengthening of the institutions of the Mining Sector—An evaluation of the hydrogeologic studies: Presentation at PRISM II meeting, Sabah Hotel, Nouakchott, Mauritania.

Friedel, M.J., 2008, Inventory and review of existing PRISM hydrogeologic data for the Islamic Republic of Mauritania, Africa: U.S. Geological Survey Open File Report, 2008–1138, 51 p.

Islamic Republic of Mauritania, Ministry of Mines and Industry, 2007, Hydrostratigraphic traps and reservoirs.

Maxey, G.B., 1968, Hydrogeology of desert basins: Groundwater, v. 6, no. 5, p. 10–22.

Phillips, J.D., 2002, Two-step processing for 3D magnetic source locations and structural indices using extended Euler or analytic signal methods, *in* SEG International Exposition and 72nd Annual Meeting, Salt Lake City, Utah, Oct. 6–11, 2002, expanded abstracts: Salt Lake City, Utah, Society of Exploration Geophysicists, 4 p.

Roussel, J., and Lesquer, A., 1991, Geophysics and the crustal structure of West Africa, *in* Dallmeyer R.D., and Lecorché, J.-P., eds., The West African orogens and circum-Atlantic correlatives: Berlin, Springer Verlag, p. 9–28.

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20131280