Deep Groundwater Exploration in the Empty Quarter (RAK) Using MT (Magnetotellurics)

By

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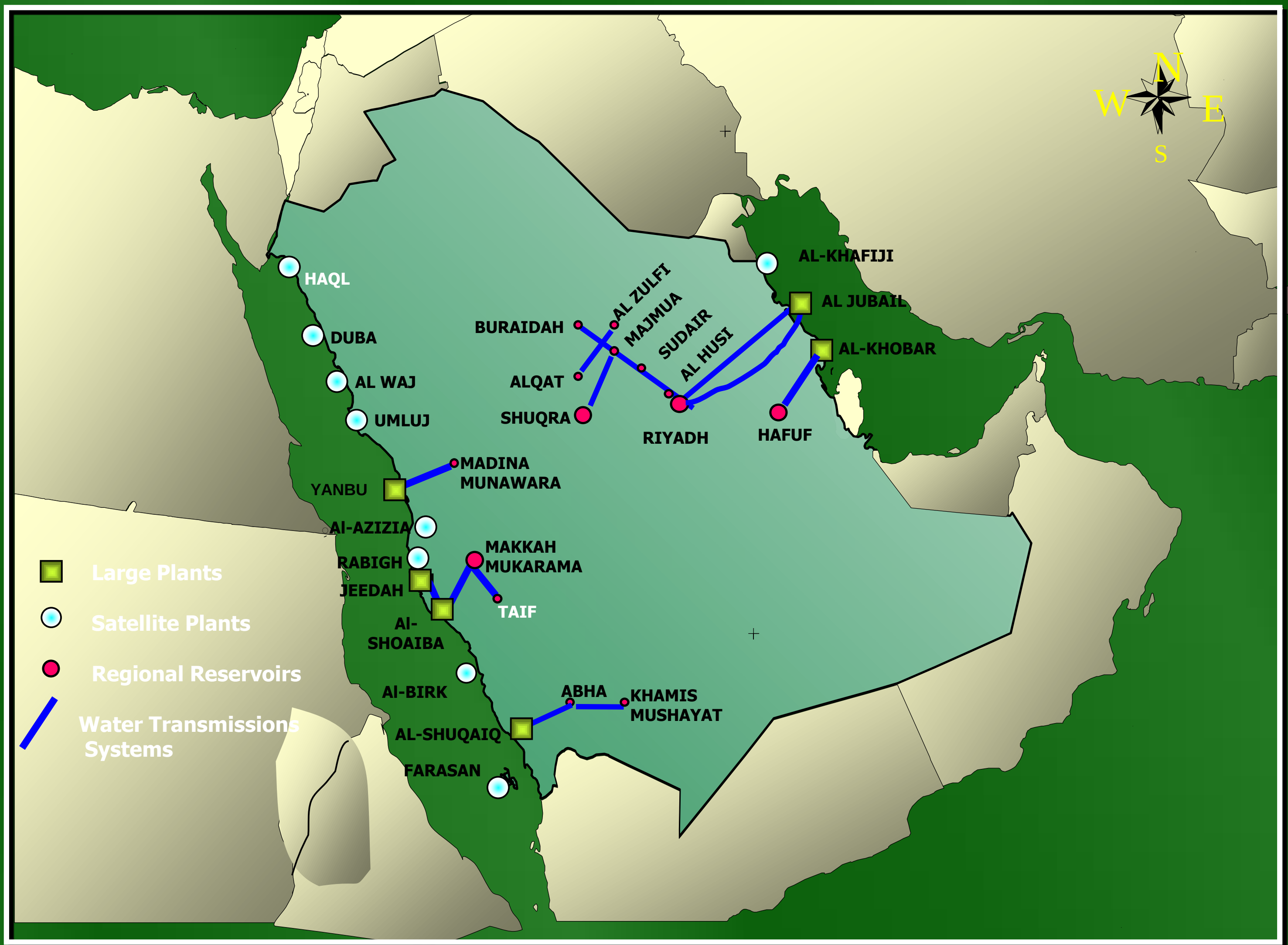
Outline

- KSA water consumption; aquifers vs. desalination
- Cost of desalination and tradeoffs compared to conservation, transportation, recycling, etc.
- Rationale for using sustainable aquifer recharge
- RAK aquifers and estimated recharge
- Deep geophysical survey (MT) to map RAK aquifers and recharge transport routes (best locations for recharge capture)
- Benefits

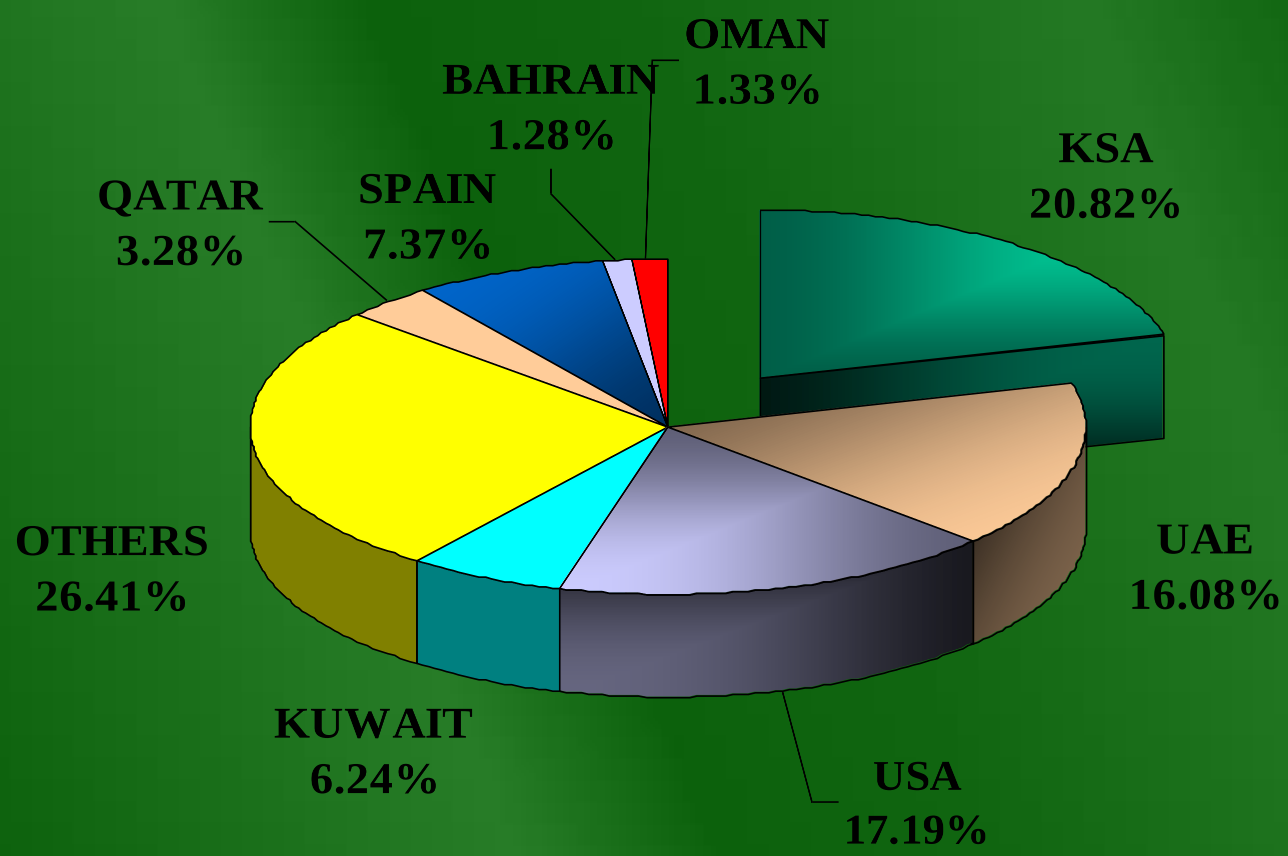
Water Requirements and Sources

- Total water consumption now ~22 x 10^9 m^3/yr
  - Aquifers: ~20 x 10^9 m^3/yr
  - Desalination: ~2 x 10^9 m^3/yr
- Rapidly growing population and demand
- Cost of multi-stage flash (MSF) desalination: ~US$1/$m^3$
  - Similar cost as lifting 2000 m or pipelining horizontally 1600 km
- Presently, desalinated water from Jubail is piped 320 km to Riyadh

Saline Water Conversion Corporation
Location of Main Generation and Transmission Assets

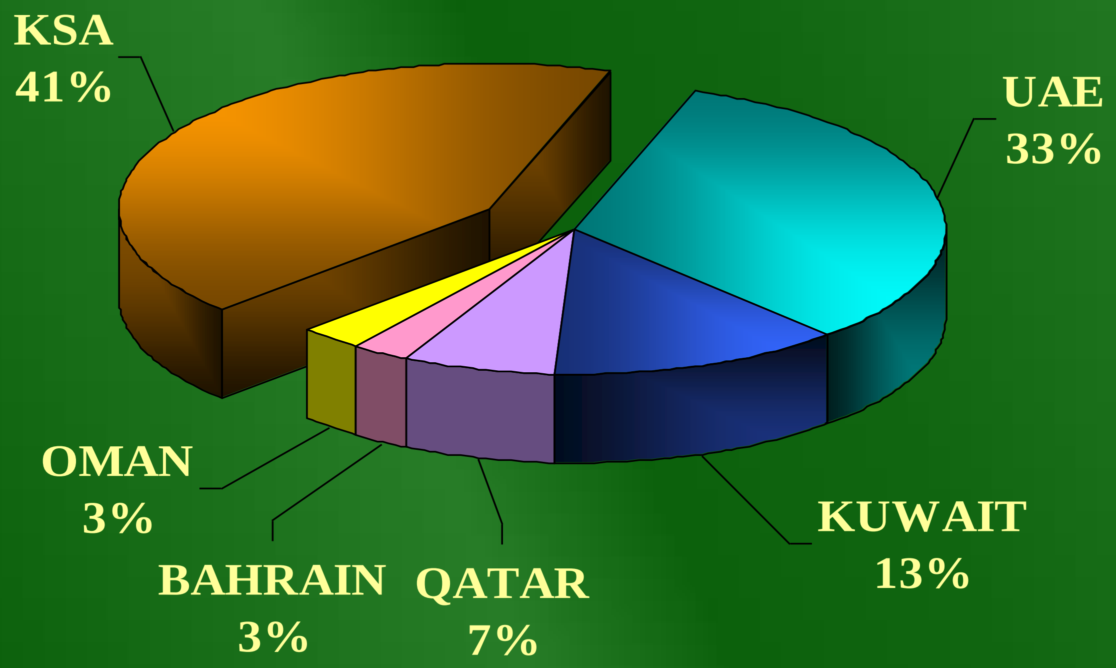


KSA Desalination Share in the World



Wang nick (IDA) Dec.31,2005

KSA Desalination Share in the GCC



Wang nick (IDA) Dec.31,2005

KSA Deep Aquifers

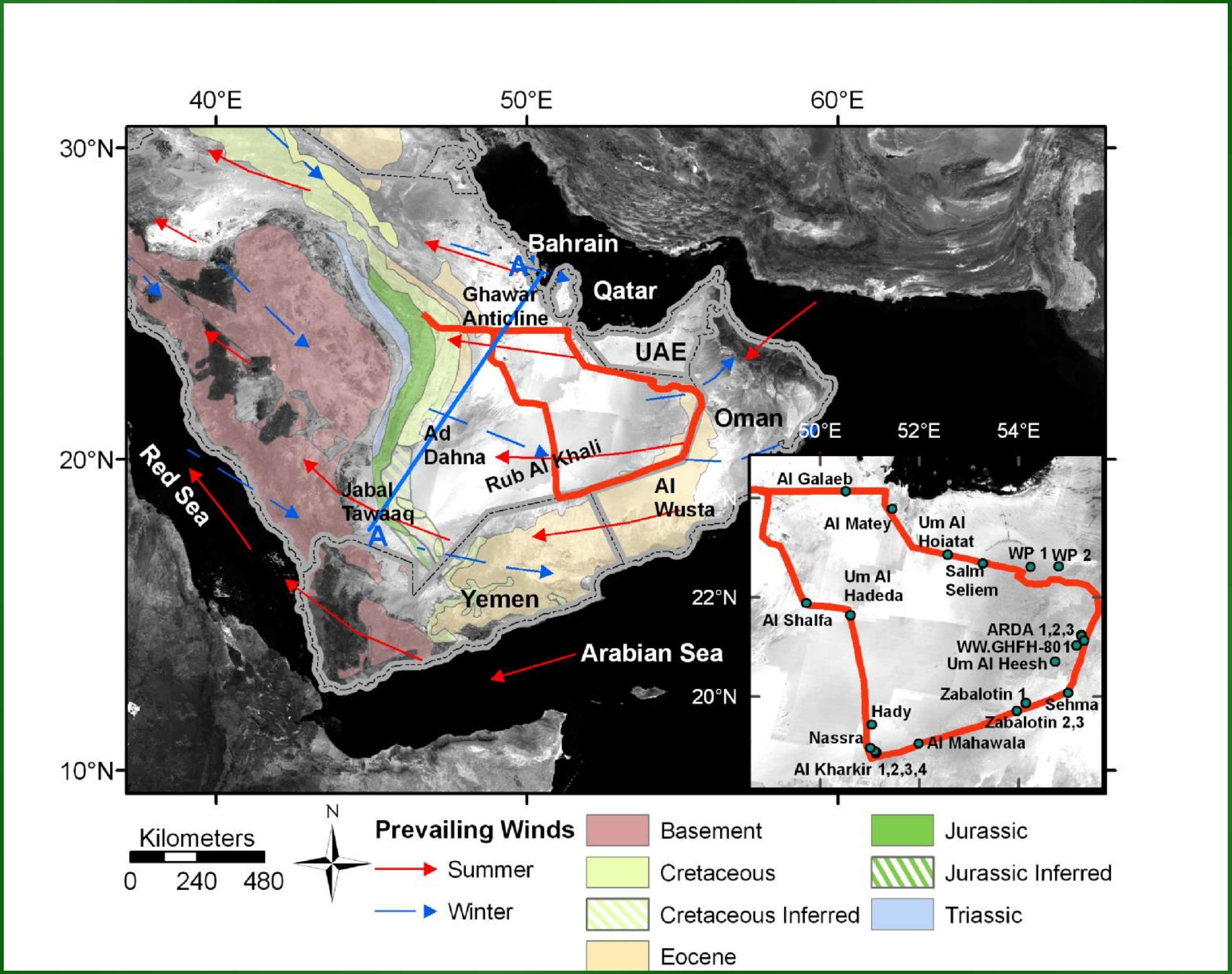
- Large fossil water resources exist in deep subsurface aquifers in desert areas including RAK
- Sustainable exploitation: capturing portion of recharge waters without drawdown of fossil waters
- Recharge waters may be fresh (<~1000 ppm TDS) or brackish (~1000–10,000 ppm TDS)

Rub' al Khali Aquifer System (RAKAS)

- Recharge in Red Sea Hills
  - estimated at $\geq 4 \times 10^9\ m^3/yr$
- Paleozoic, Jurassic, Cretaceous, Eocene ages
- Total thickness of aquifers > 1500 m
- Depth as great as 2000 m
- General west to east flow
- Increasing salinity, shallow to deep, west to east

Traverse – Sample Locations

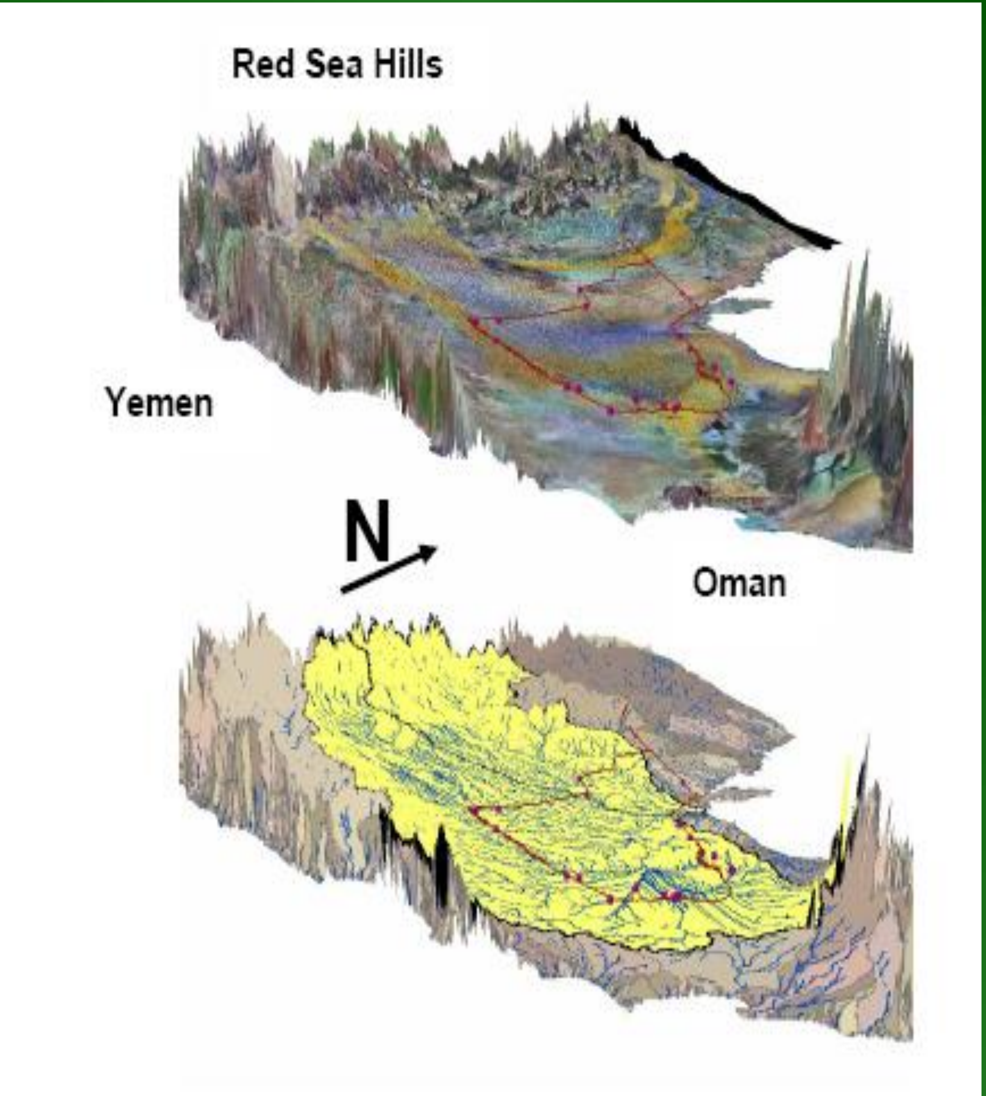
خط السير ومواقع العينات



(1) Water Collection System

- A major E-W watershed channels precipitation from Red Sea hills towards the RAK

وجود حوض تصريف ضخم (شرق-غرب) يصرف المياه المتساقطة على جبال البحر الأحمر في اتجاه الربع الخالي.



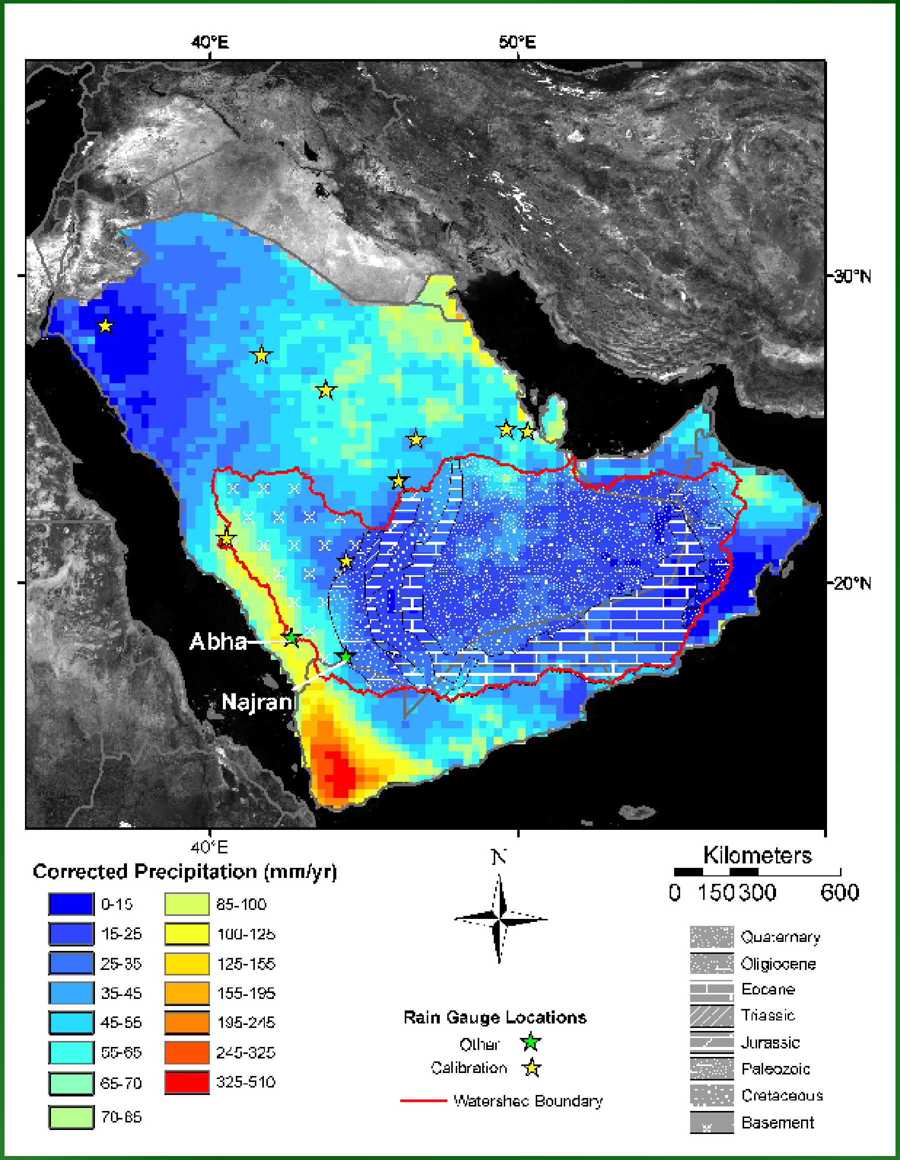
(2) Precipitation relatively high

27% of the average annual precipitation ($150 \times 10^9 m^3$) over the Arabian Peninsula is channeled toward the recharge areas in the RAK

27% من المعدل السنوي لتساقط مياه الأمطارفي شبة الجزيرة العربية تتجه نحو الربع الخالي

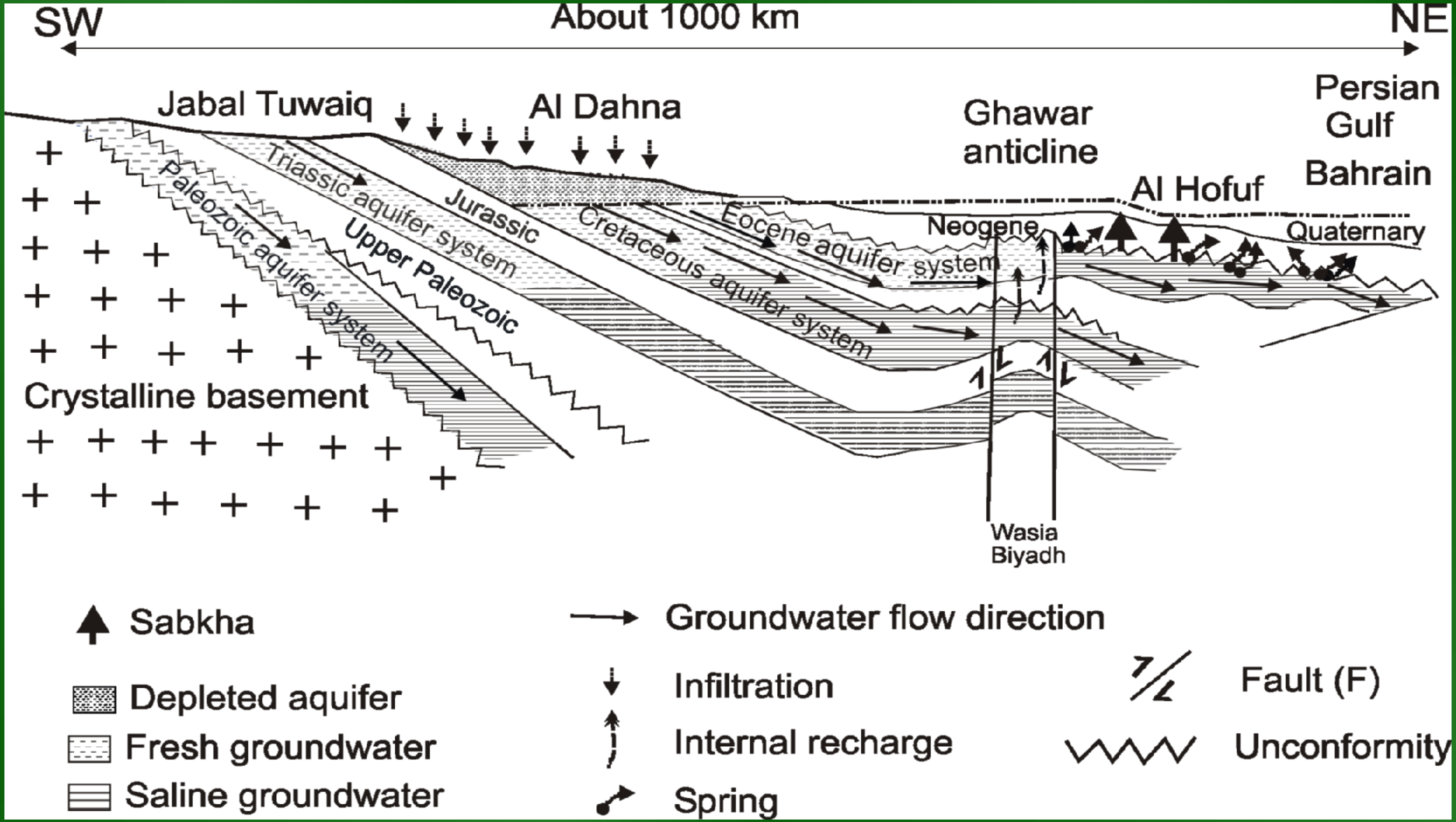
An estimated 4×10^9 m^3 a^{-1} to 10×10^9 m^3 a^{-1} of this water is partitioned as recharge to the RAK aquifer system.

تم تقدير 4×10^9 m^3 a^{-1} to 10×10^9 m^3 a^{-1} من هذه المياه تغذي خزانات المياه الجوفية بالربع الخالي



(3) Recharge areas at foothills of the Red Sea Hills

مناطق التغذية في سفوح جبال البحر الأحمر



(4) Groundwater flow from W to E

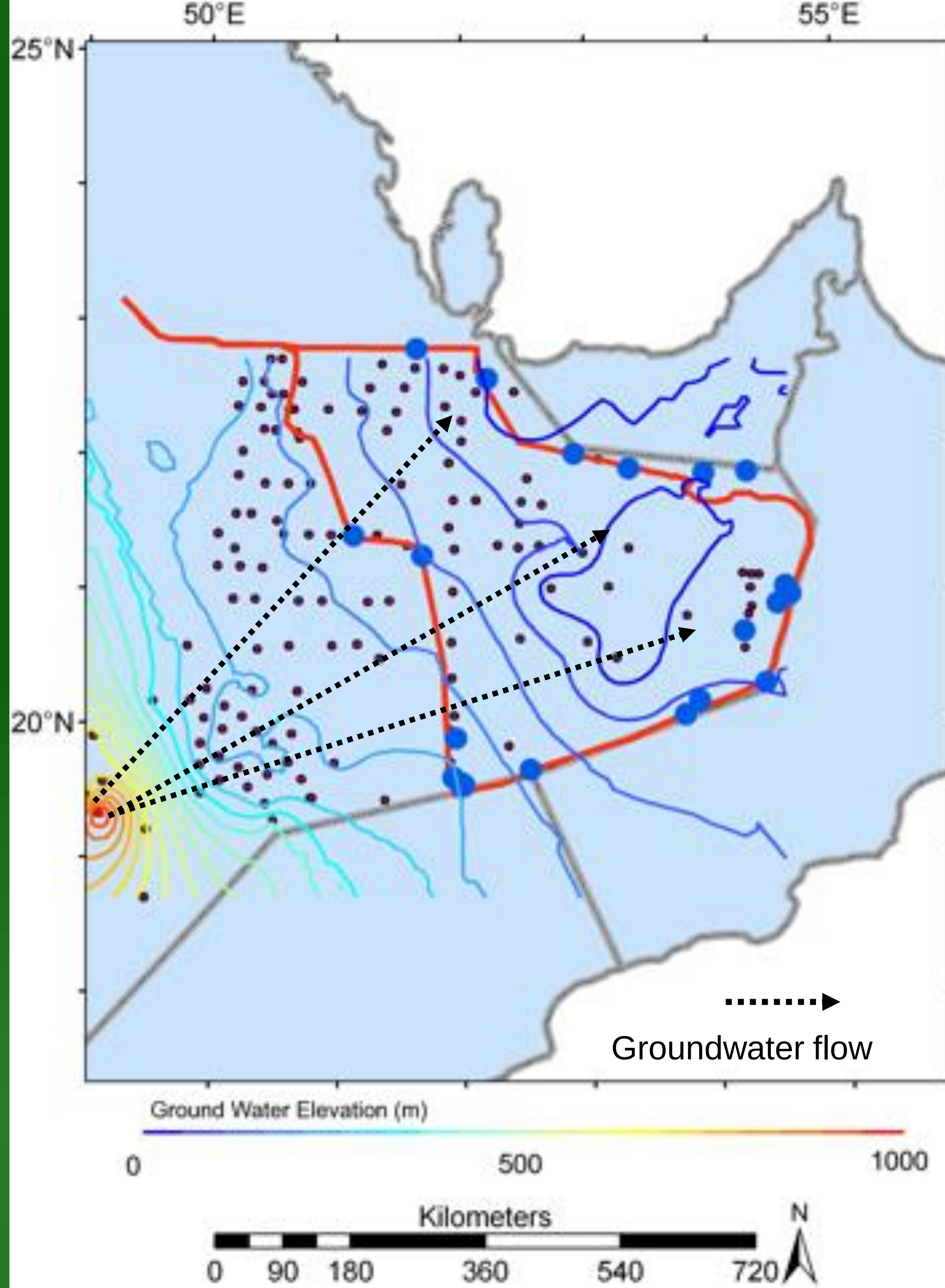
سريان المياه الجوفية من الغرب إلى الشرق

- Groundwater flow from W (Red Sea Hills) to E (Gulf)

سريان المياه الجوفية من الغرب (جبال البحر الأحمر) إلى الشرق (الخليج العربي)

Ground Water Levels (Aramco data set)

مستويات المياه الجوفية (بيانات أرامكو السعودية)



Hydrogen & Oxygen Isotope Data

بيانات نظائر الأكسجين والهيدروجين

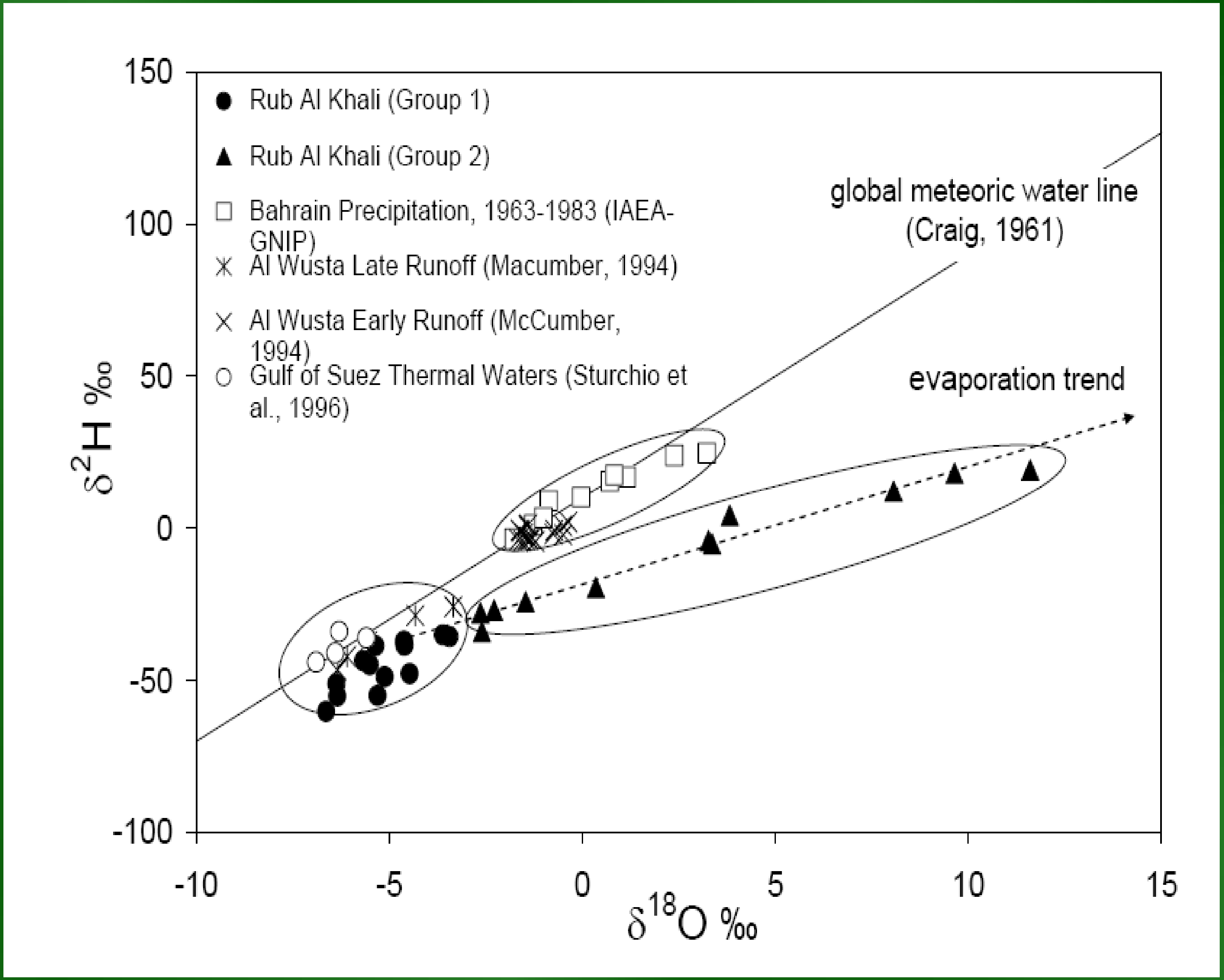
Hydrogen and oxygen isotope ratios are expressed in the conventional δ (delta) notation, where

$$\delta = [(R_{sample}/R_{standard}) - 1] \times 1000$$

R: Ratio of D/H or $^{18}O/^{16}O$

S: Standard Mean Ocean Water

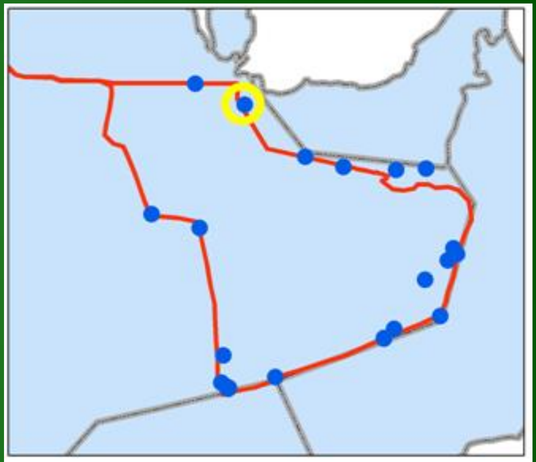
O & H Isotopic Compositions



Group I

- Mostly from flowing artesian wells & springs & pumped wells

يتدفق معظمها من من الآبار الإرتوازية والينابيع و آبار الضخ.



- Isotopically depleted

δ^2H: –60‰ to -35‰

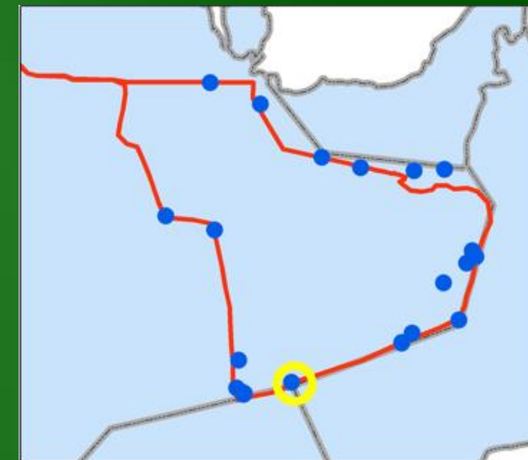
TDS 1300 up to 76,000 mg/L

- Hot waters

At Matty Hot spring

Continue Group I

Al Mohawaleh



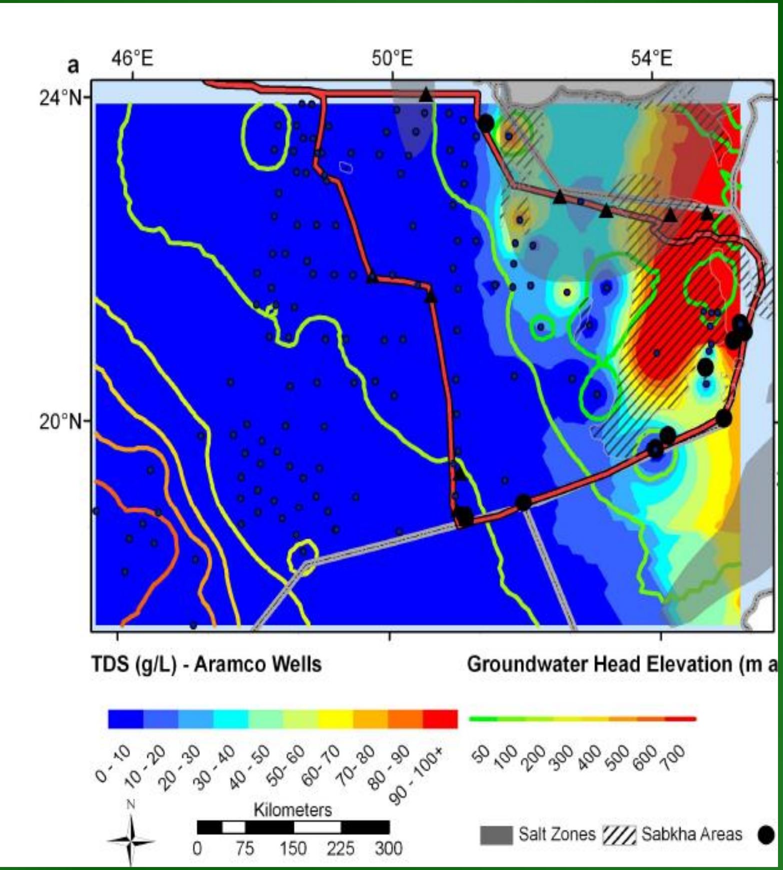
Al Heesh

من أين أكتسبت المجموعة الأولى الملوحة؟

From where did Group 1 acquire salinity?

Hormuz Series

- Upper Proterozoic sedimentary sequence (2 km thick) underlies all major oil fields in the Persian Gulf area: Bedded salt, gypsum, anhydrite, with thick interbeds of dolomite, shale, and sandstone



Edgel, H.S, 1991, Precambrian Research, 54, pp 1-14

Origin – Group I

- Unlikely to have originated as modern precipitation

احتمال ضعيف لتكونها من مياه امطار حديثة

- More likely, represents paleowater precipitated during moist intervals in Pleistocene

أحتمال كبير أن تكون نشأة المياه الجوفية بفعل تساقط مياه أمطار قديمة (البليستوسين).

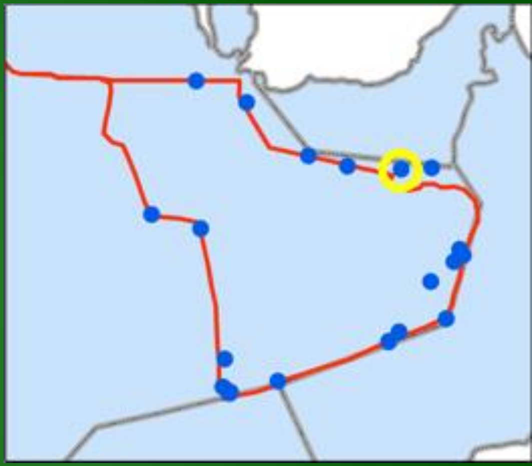
- Or High elevation recharge from mountainous areas (Red Sea Hills)

أو من تساقط الأمطار على مرتفعات جبال البحر الأحمر.

- Salinity acquired from subsurface dissolution of Hormuz series

الملوحة من ذوبان مجموعة هرمز التحت سطحية.

Group II



المجموعة الثانية معظمها من الآبار اليدوية الضحلة

- Mostly from shallow hand dug wells

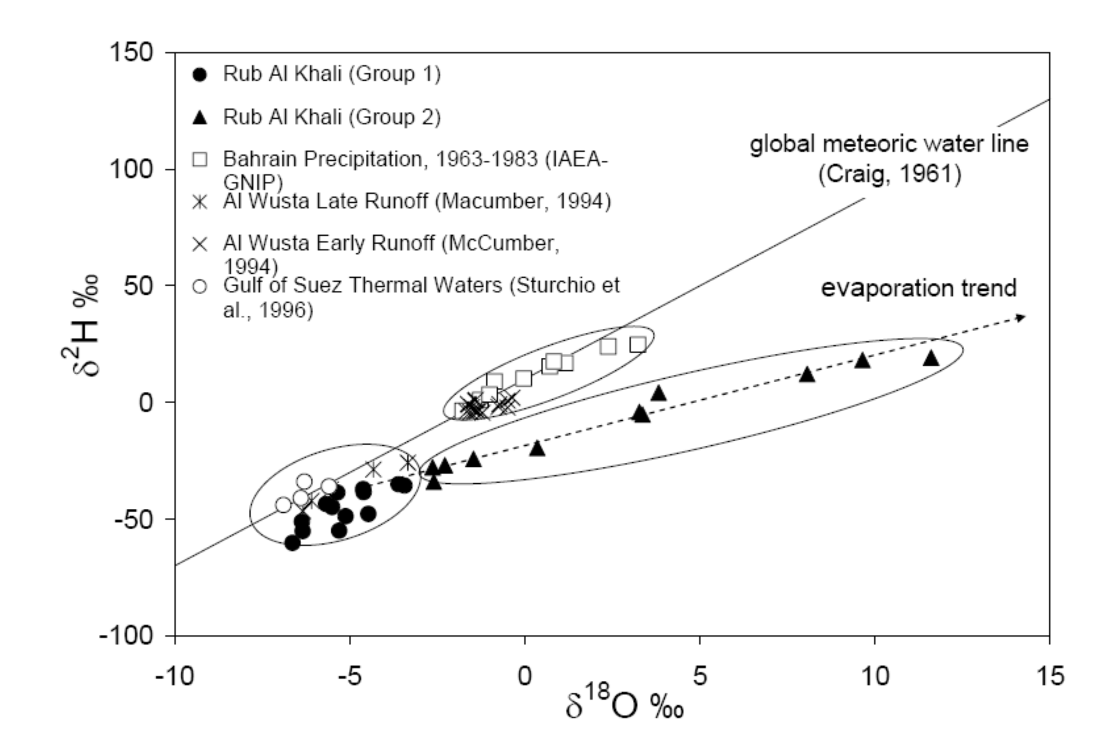
Sheba water point

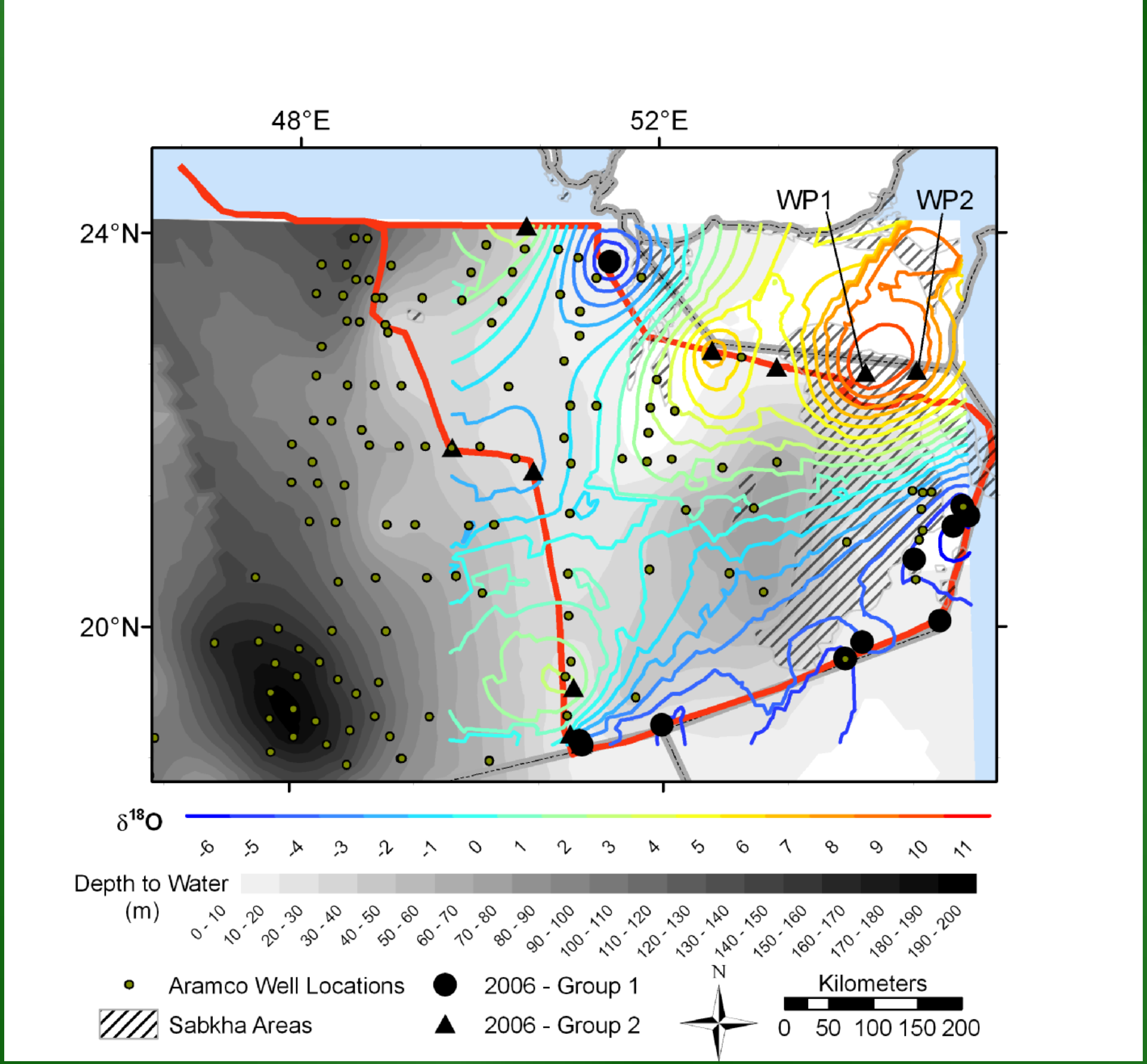
Group II

- Plots along an evaporation line that extends upward from Group I samples
- Significant evaporation & salinization

δ2H: –43‰ to +19‰

TDS > 92,000 mg/L

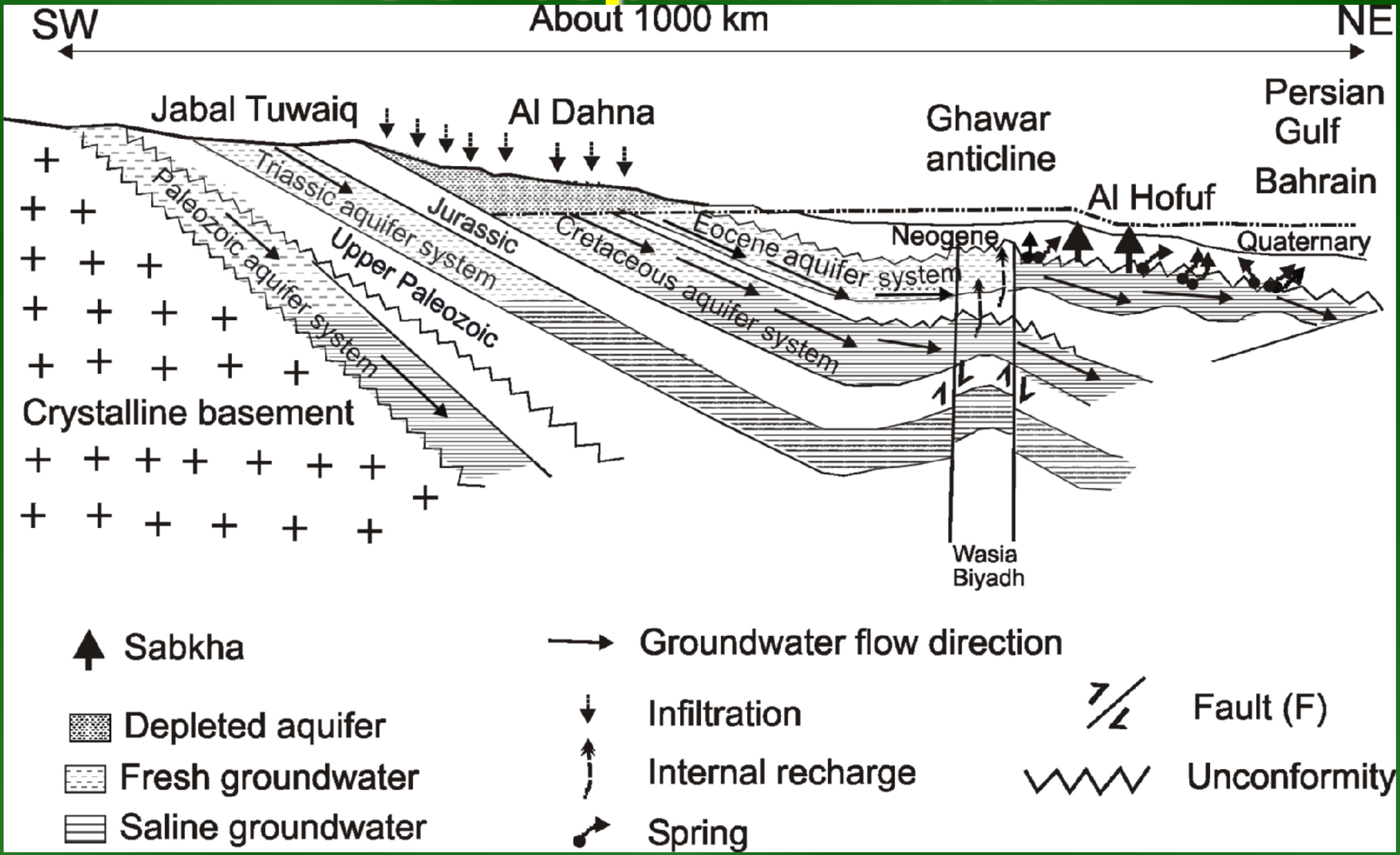




Distribution of Group II wells correlates with that of sabkha and shallow groundwater

توزيع آبار المجموعة الثانية مرتبط بتوزيعات السبخات والمياه الجوفية الضحلة

Conceptual Model



Origin of Group II

- Group II are Group I samples that were subjected to evaporation at lowlands and dissolution of evaporative salts at surface of sabkha areas and salt domes in subsurface

المجموعة الثانية هي عينات المجموعة الأولى التي خضعت للتبخر في المناطق المنخفضة و ذوبان أملاح المتبخرات على سطح مناطق السبخات والقبب الملحية التحت سطحية.

- Sabkhas are areas of groundwater discharge

السبخات هي مناطق تصريف المياه الجوفية.

Conclusions

- Many of natural discharge areas may have gone undetected
  العديد من مناطق التصريف الطبيعية قد تكون غير مكتشفة.
- For the RAK aquifer system natural discharge is occurring over extensive areas resulting in salinization of groundwater
  التصريف الطبيعي لخزان الربع الخالي يحدث فوق مناطق شاسعة مما أدى إلى زيادة ملوحة المياه الجوفية.
- Groundwater should be intercepted prior to reaching discharge areas.
  المياه الجوفية يجب إعتراضها قبل وصولها إلى مناطق التصريف الطبيعية.

Conclusions

- The RAK aquifer system was largely recharged in previous wet climatic periods yet is still receiving modest modern meteoric contributions

  خزان الربع الخالي تم تغذيته بالمياه سابقا من خلال فترات مناخية رطبة ولا يزال يتلقى مساهمات متواضعة من الأمطار الحديثة.

- Careful utilization of the RAK aquifer system can result in sustained development of such system.

  الإستخدام الرشيد لخزان الربع الخالي يمكن أن يؤدي إلى تحقيق التنمية المستدامة لهذا الخزان.

- Future studies could demonstrate that the RAK is one of the most promising sites for groundwater exploration in the Arabian Peninsula.

  الدراسات المستقبلية يمكن أن تثبت أن الربع الخالي هو واحد من أكثر المواقع الواعدة لاستكشاف المياه الجوفية في شبه الجزيرة العربية

Future studies الدراسات المستقبلية

- Integrated (geochemical, isotopic [stable, radiogenic], geophysical, modeling [groundwater flow, rainfall-runoff], RS/GIS) studies on:

الدراسات المتكاملة (الجيوكيميائية، النظائر (المشعة والغير مشعة), والجيوفيزيائية، والنماذج الرياضية (سريان المياه الجوفية, وتساقط الأمطار والجريان السطحي), الإستشعار عن بعد ونظم المعلومات الجغرافية) عن:

  - recharge rates,

    معدلات التغذية

  - natural discharge rates

    معدلات التصريف الطبيعي

  - groundwater ages,

    أعمار المياه الجوفية

  - water quality issues,

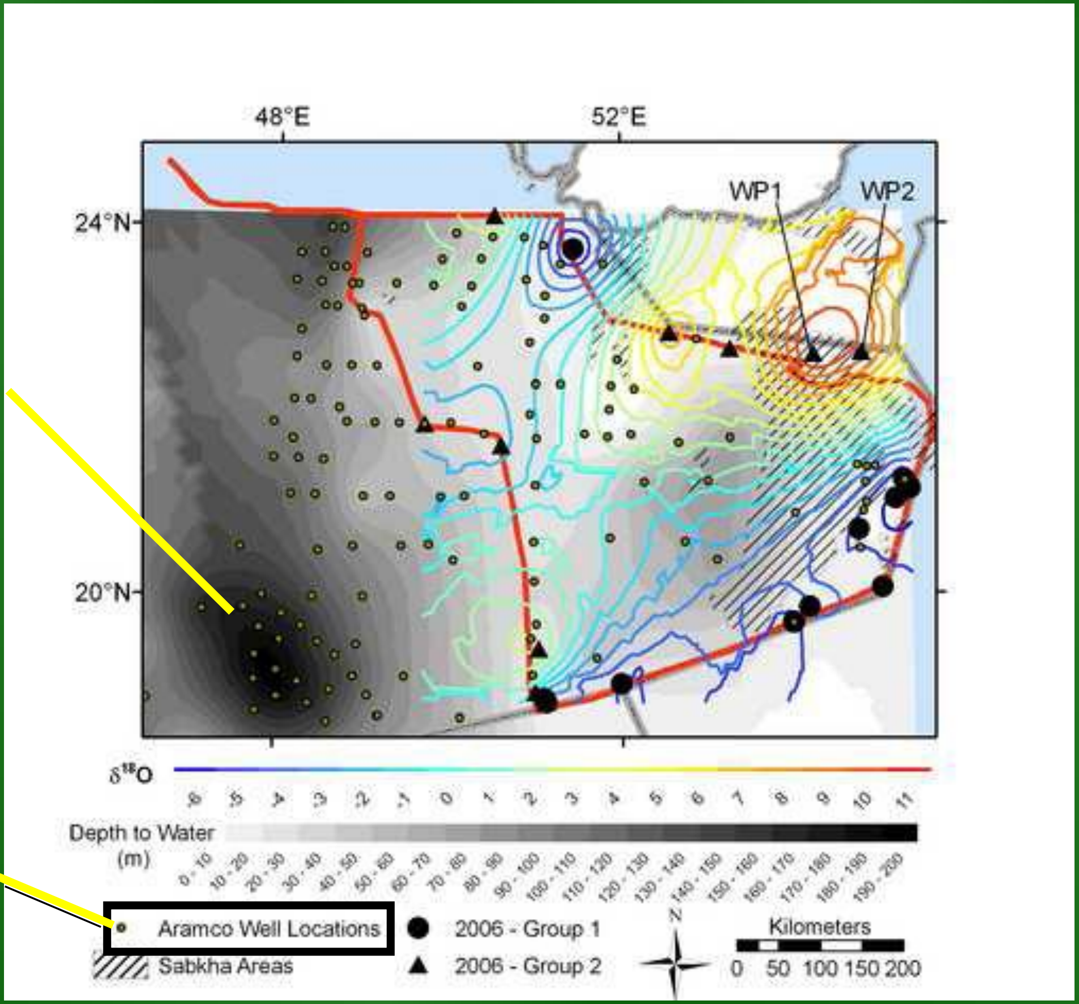
    قضايا نوعية المياه

  - Sustainability

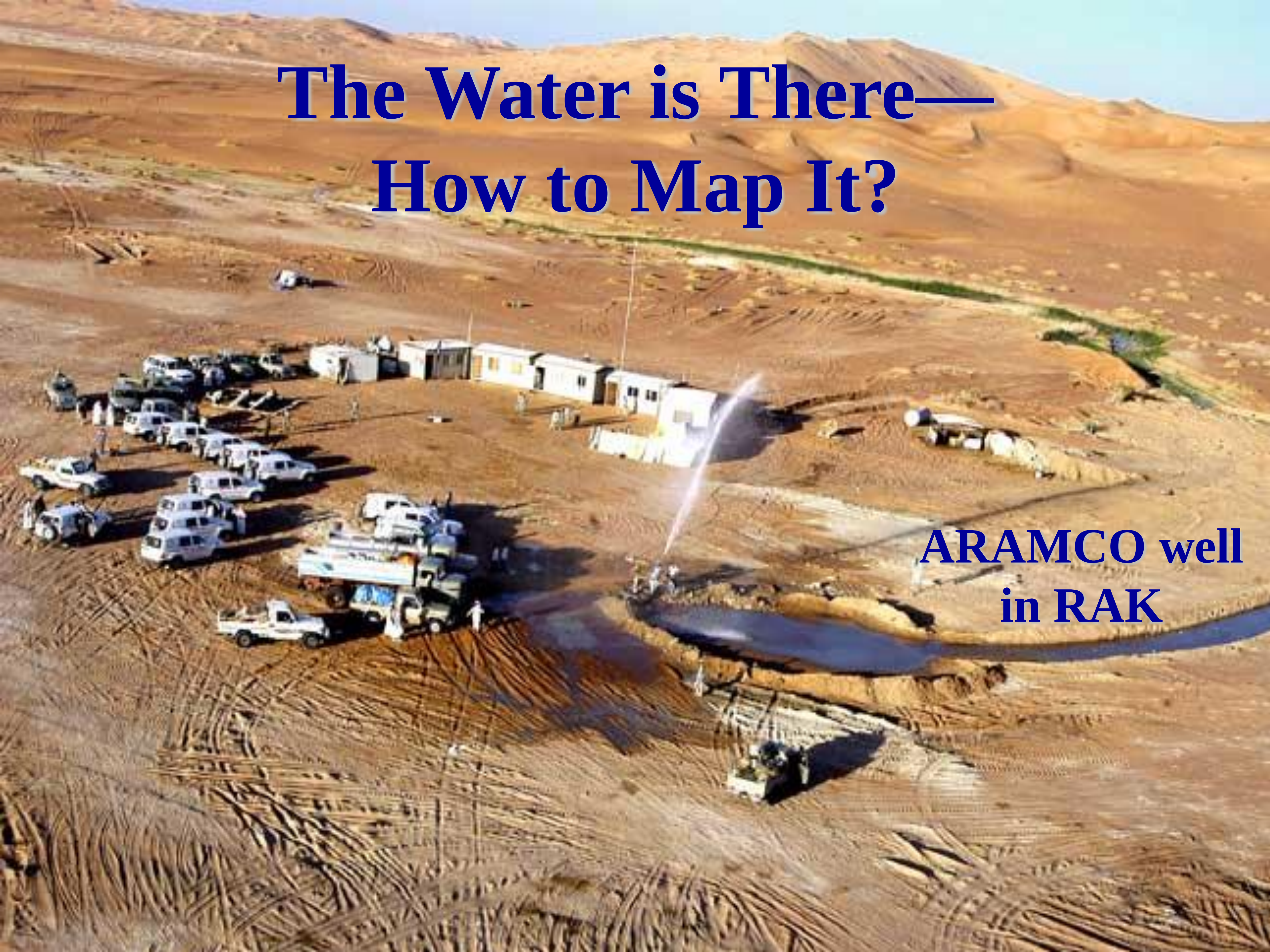
ARAMCO Wells Verify Presence of Aquifers

Depth to water greatest in the west

> 150 wells

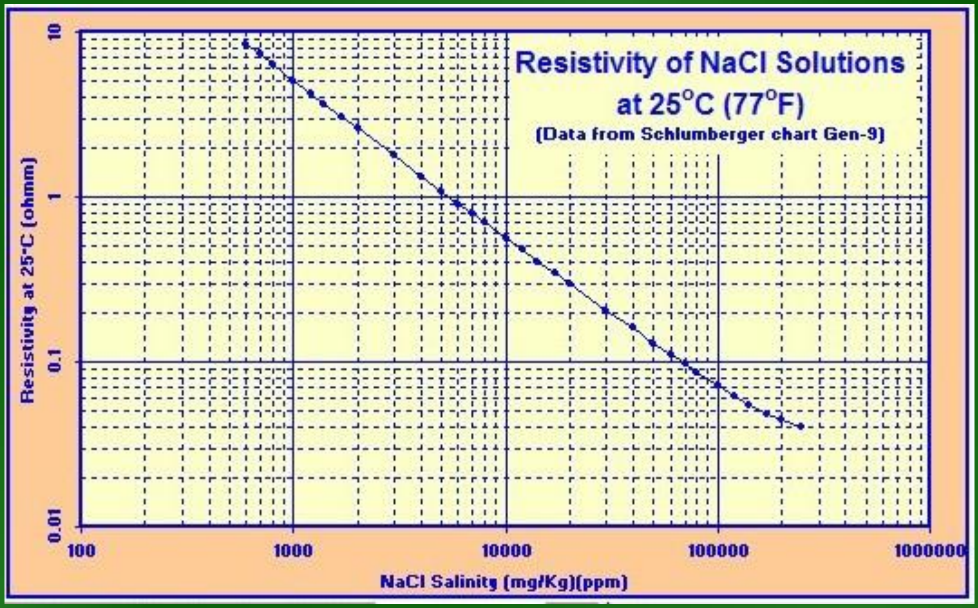


The Water is There— How to Map It?



What Method to Use?

- Seismic?
  - Maps density contrasts, structure
  - Not sensitive to fluid content or
    resistivity (1/conductivity)
- EM methods?
  - Very sensitive to conductivity
  - Resistivity varies strongly with fluid content and salinity
  - Well suited to and used extensively for groundwater mapping



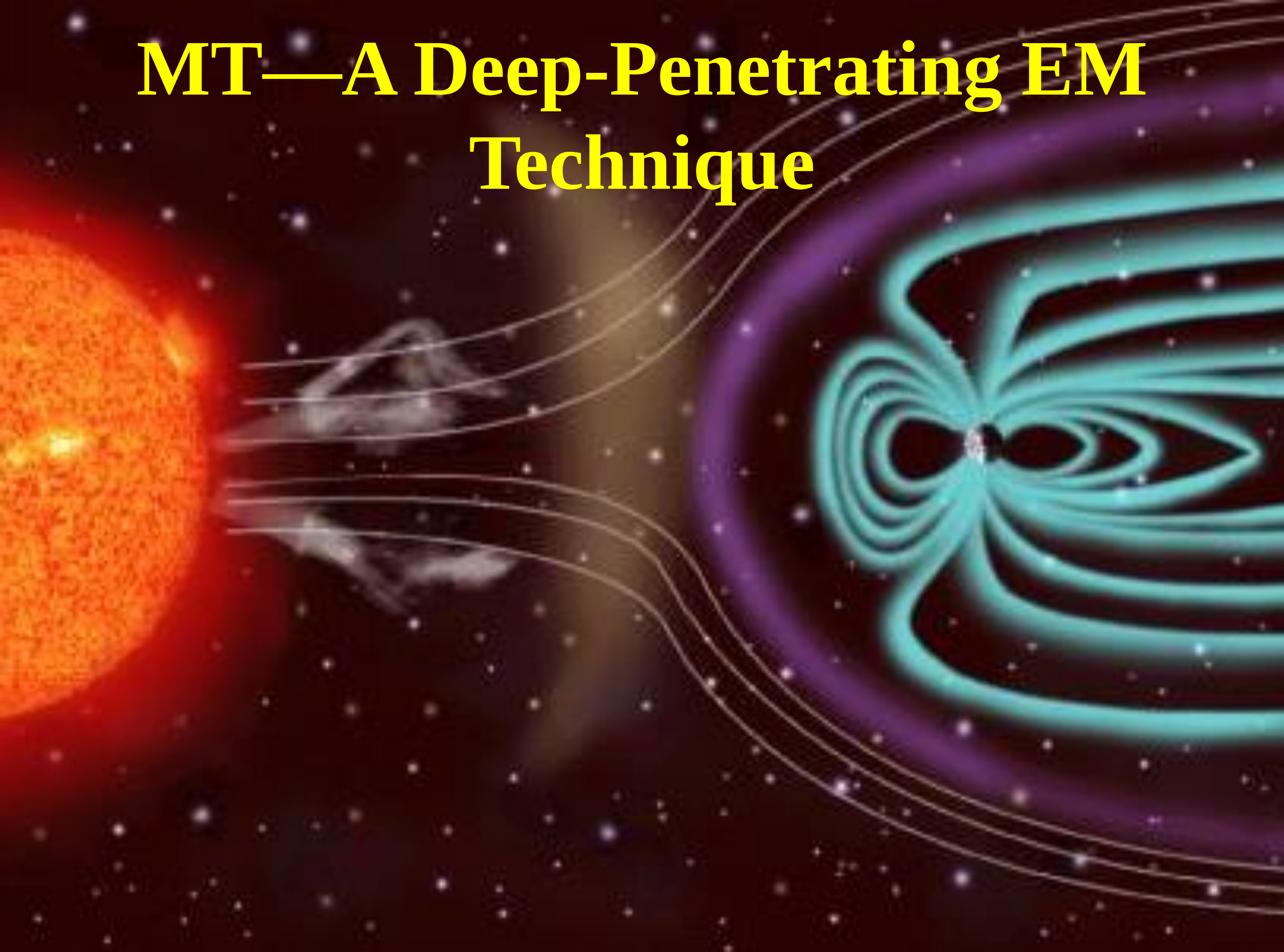
Which EM Technique?

- Controlled Source?
  - Requires transmitter, motor generator for man-made signal
  - Depth of investigation limited by transmitter power, quality of electrode ground contact
  - Not practical in RAK
- Natural Source?
  - Signal is natural fluctuation of earth’s magnetic field
  - Great depth of investigation
  - A practical and proven method: MT

MT - Source Field

- High frequencies (>1 Hz) = Spherics
  - thunderstorm activity world-wide
- Low frequencies (<1 Hz) = Micropulsations
  - Solar wind interacting w/ magnetic field
- Vary on hourly, daily, yearly cycles

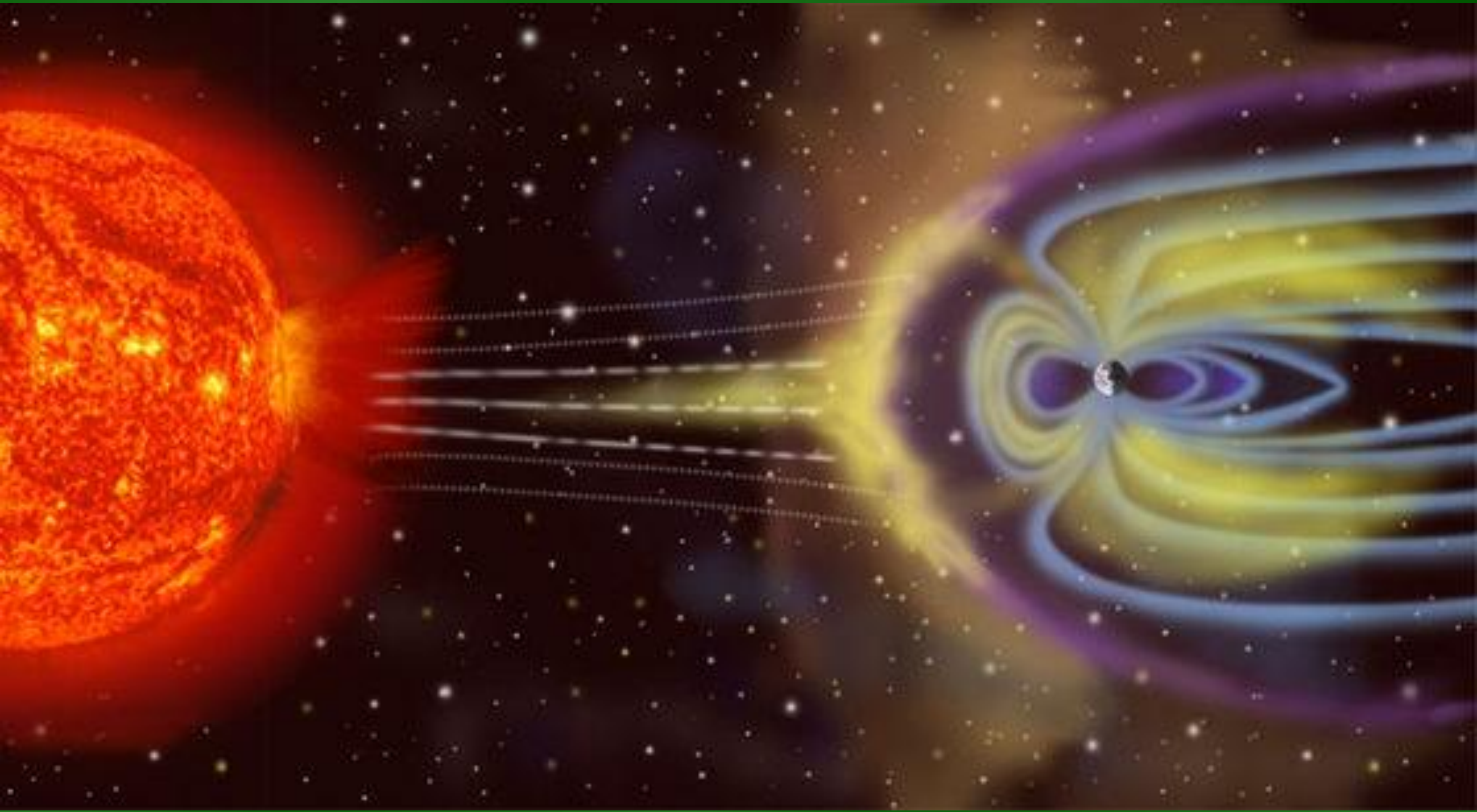
MT—A Deep-Penetrating EM Technique



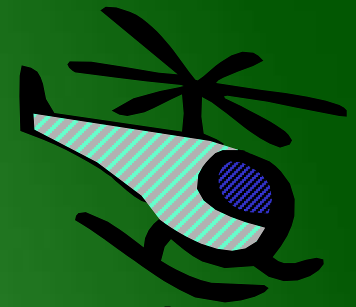
Magnetotellurics (MT)

- Detects subsurface resistivity, the physical property most diagnostic of groundwater
- Commonly used for groundwater detection, mapping of geothermal fluid and of saline water intrusion in coastal zones
- Has sufficient depth of investigation for this task
- Uses natural source (fluctuating magnetic field)
  - No man-made signal required

Low Frequency Source: Solar Wind

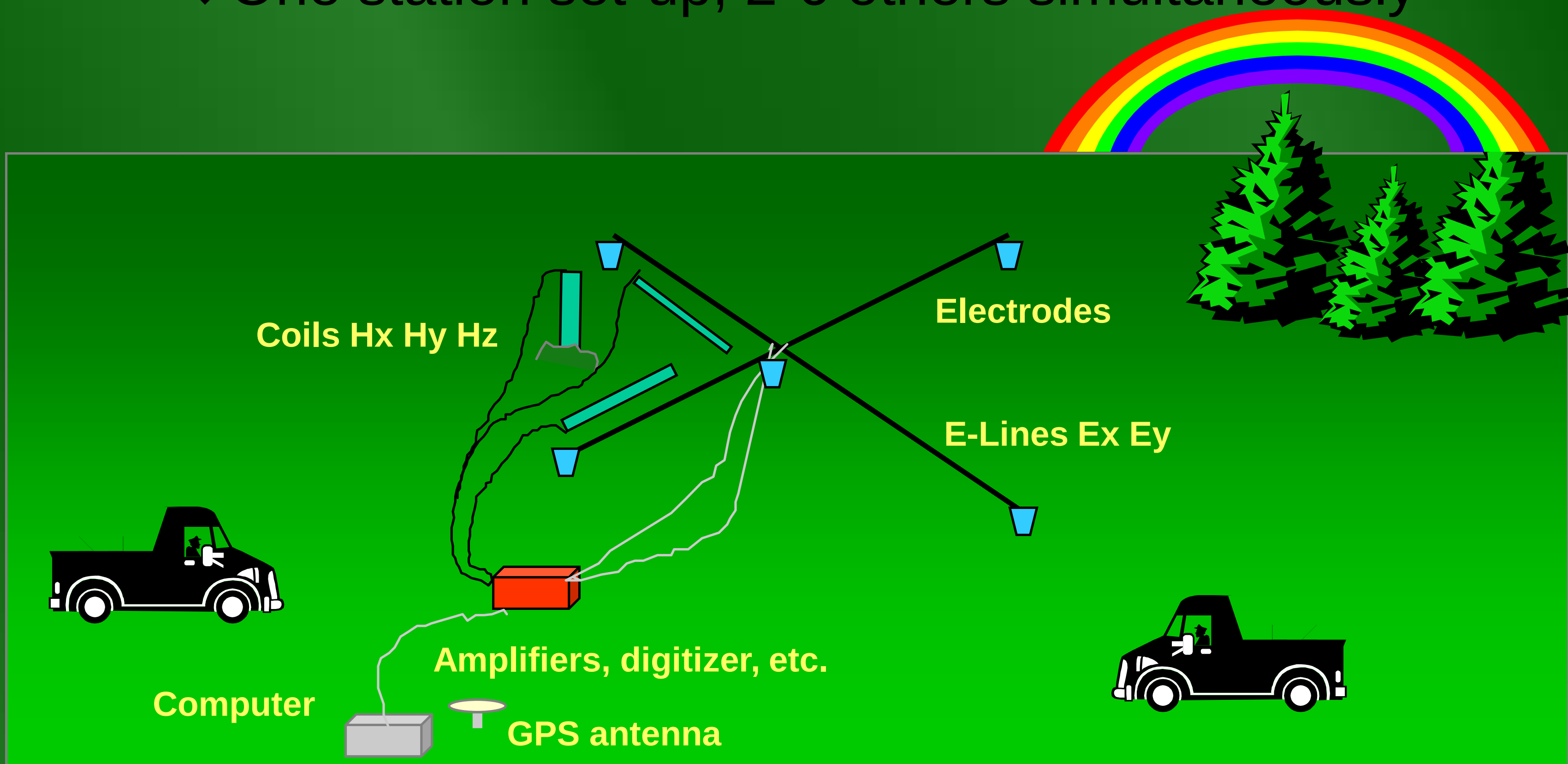



High Frequency Source



MT Acquisition

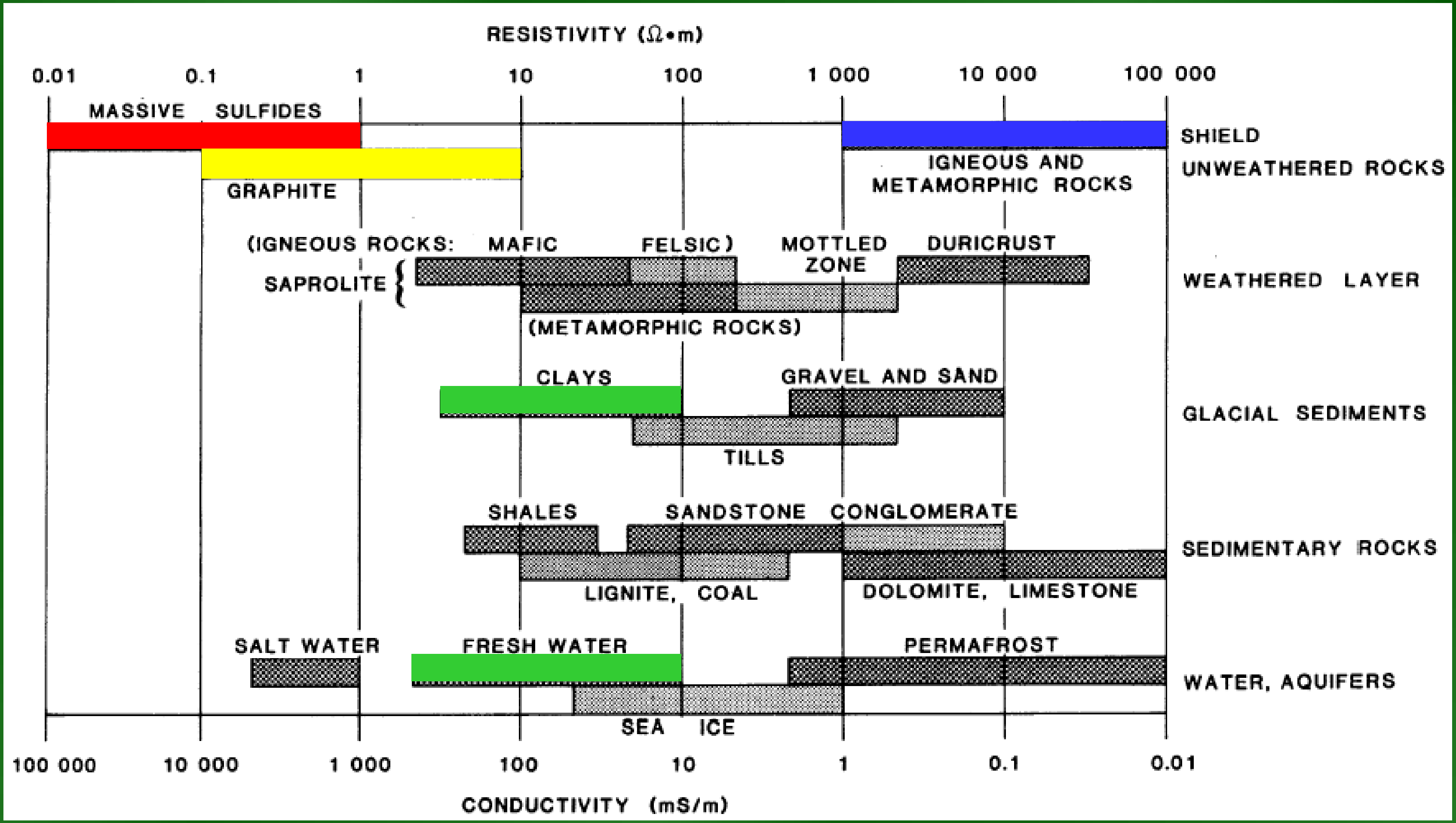
- One station set-up; 2-6 others simultaneously



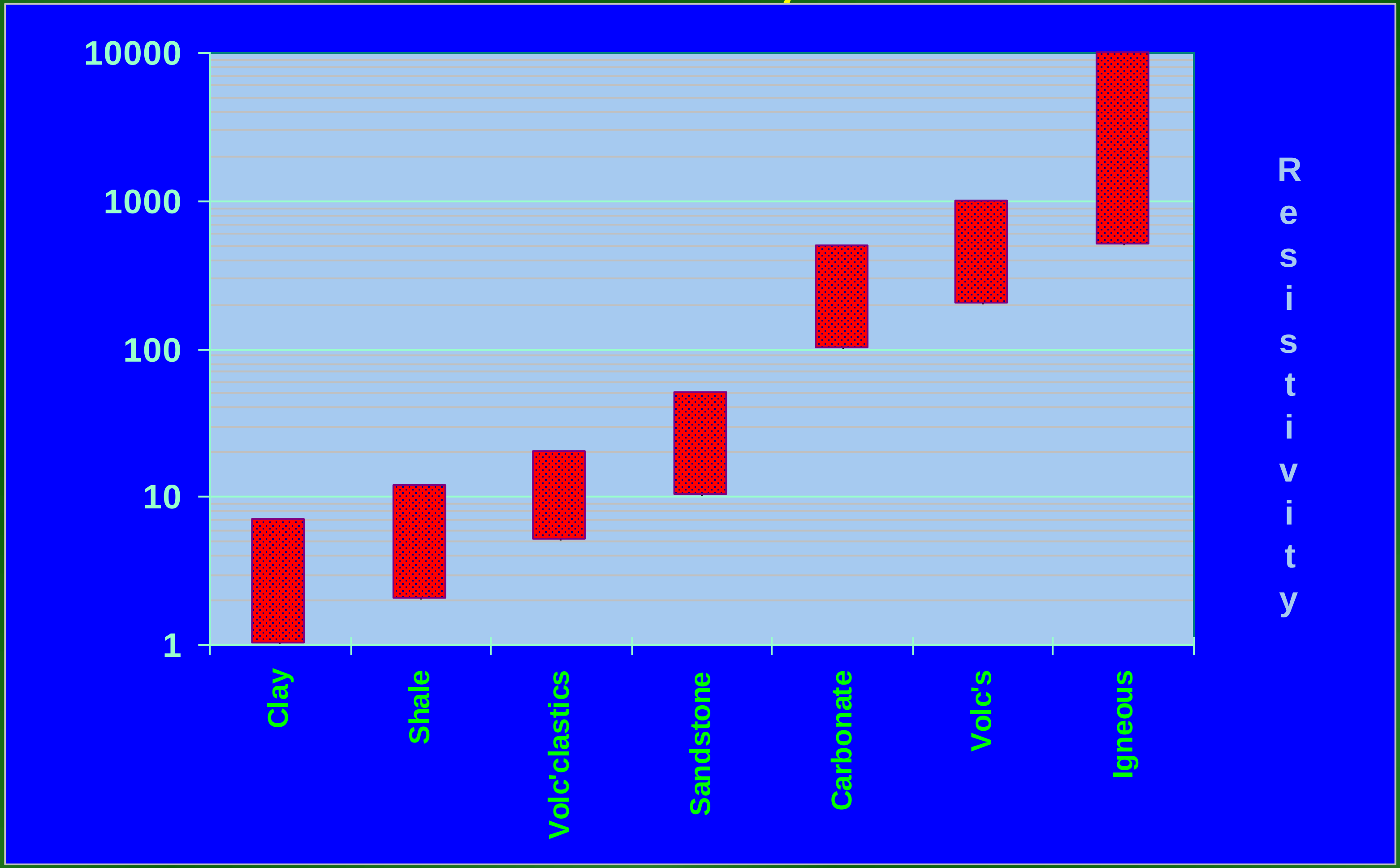
Resistivity Contrasts

- There must be a significant resistivity contrast within the depth of investigation for the method to be useful
- Contrast of 5:1 or greater
- Resolution depends on thickness and depth of unit being mapped
  - About 5% of depth e.g. the top of a horizon at 10000’ can be mapped to +- 500’

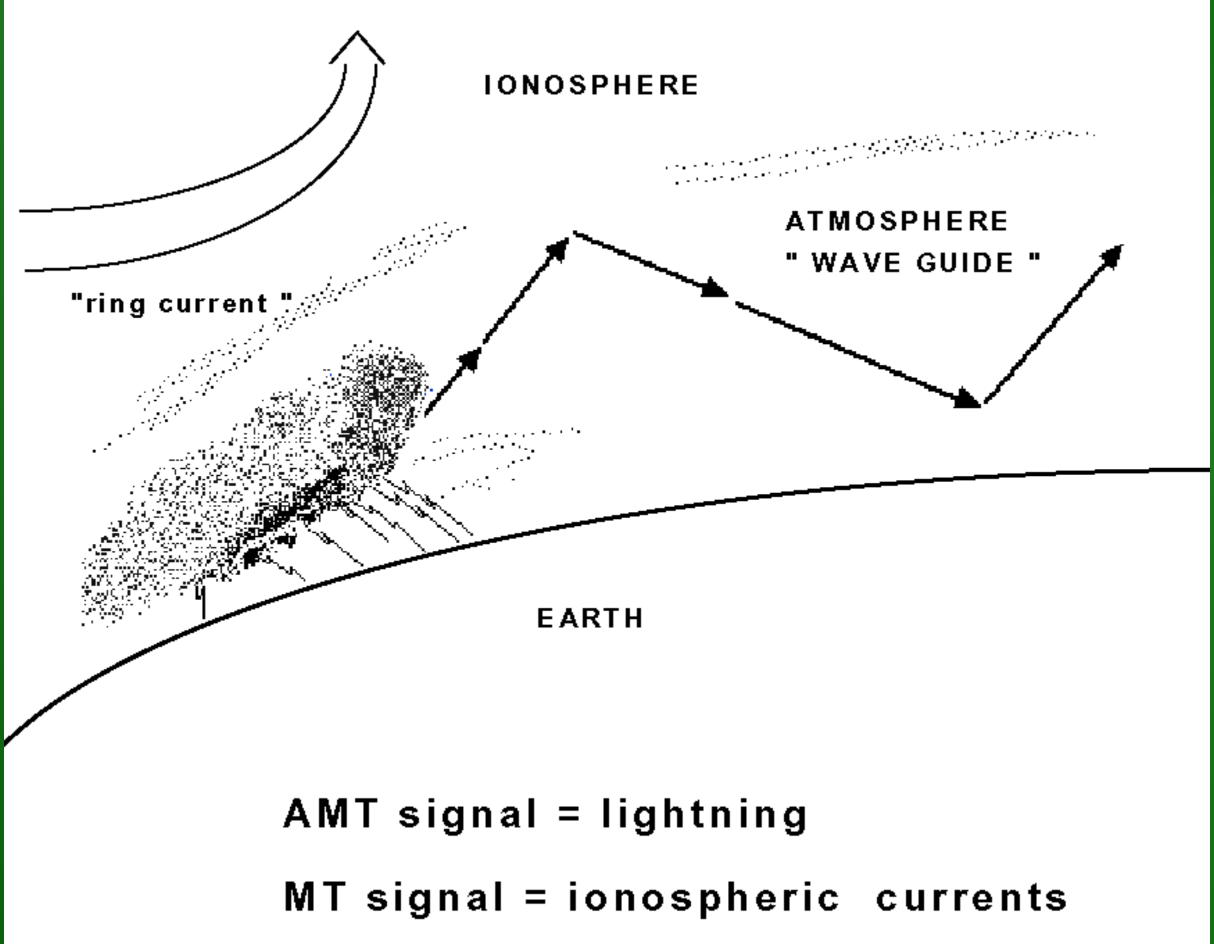
Typical Resistivities



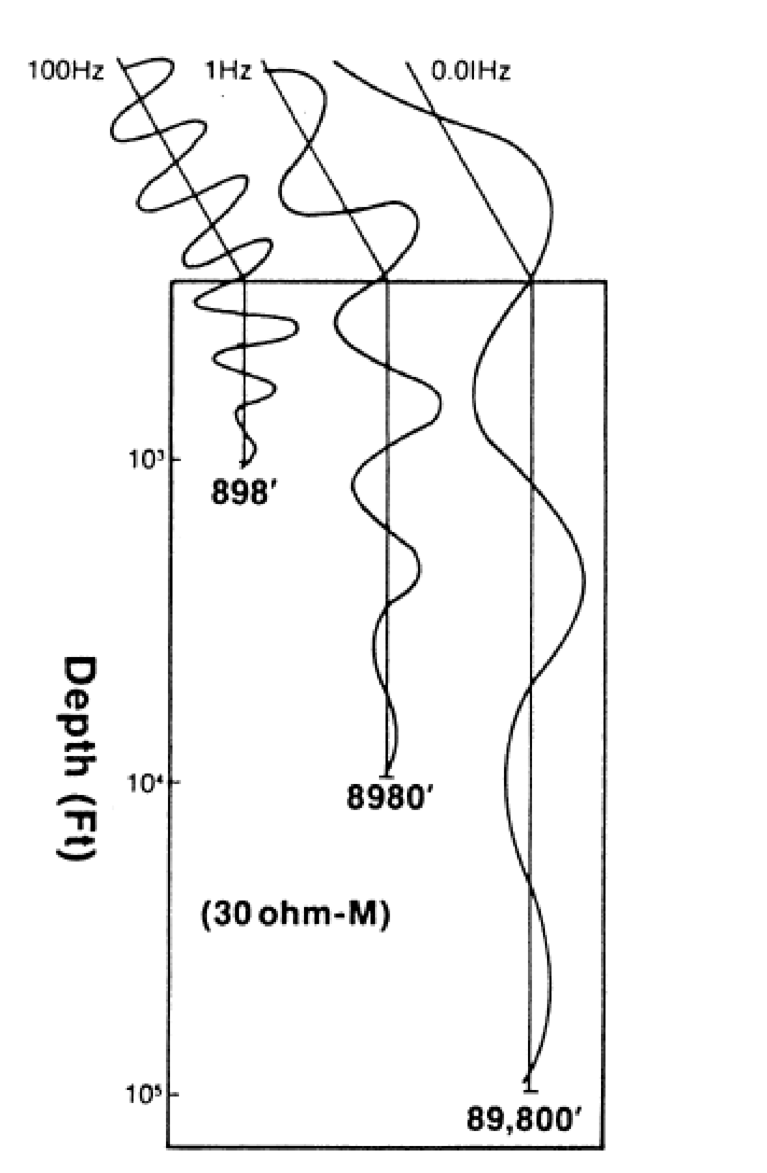
Resistivity Values



MT and AMT Signal Sources



Frequency vs. Depth



Depth of Investigation

"Skin Depth"

$$\delta = 503m \times \sqrt{\frac{\rho_a}{\text{frequency}}}$$

$1/e$ of initial amplitude

Apparent Resistivity (ρ_a)

$$\rho_a = \frac{1|E|^2}{5f|H|^2}$$

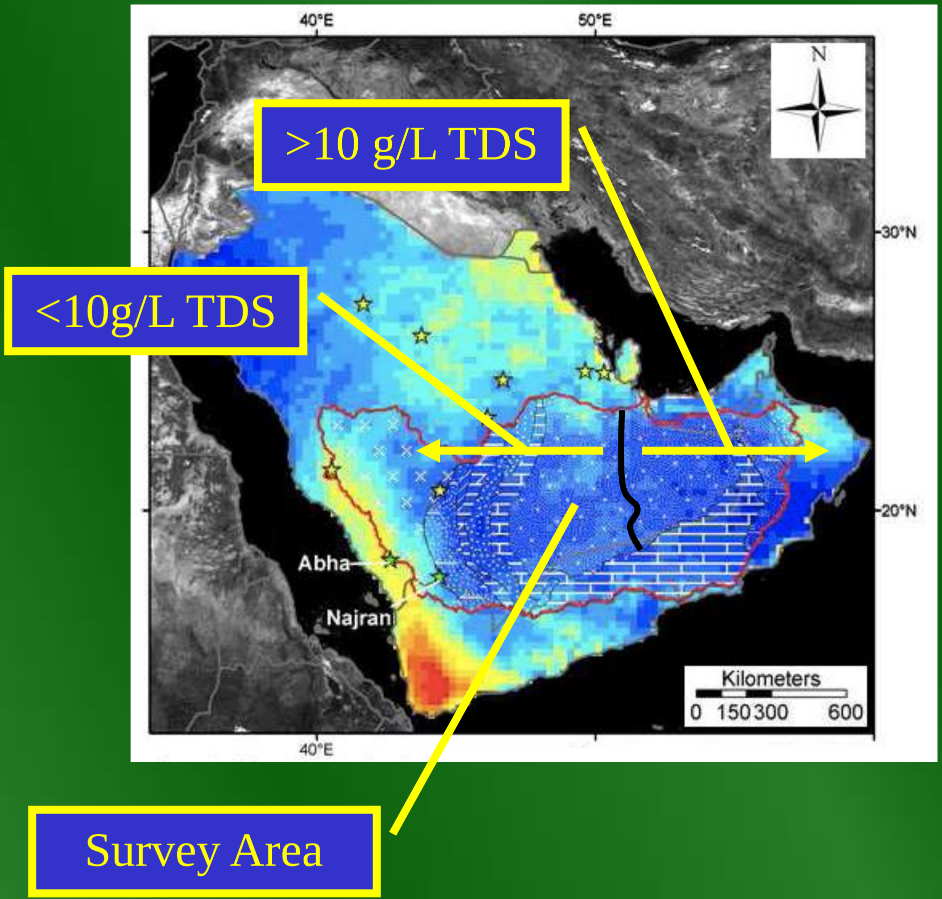
Magnetotellurics (MT)

- Portable equipment, low power requirement
  - could use solar power in RAK
- Small footprint, no environmental impact
- Rich information content, including dimensionality indicators
- Well-developed technology and software; used in oil & gas exploration for over 50 years

State-of-the-Art: MTU-net

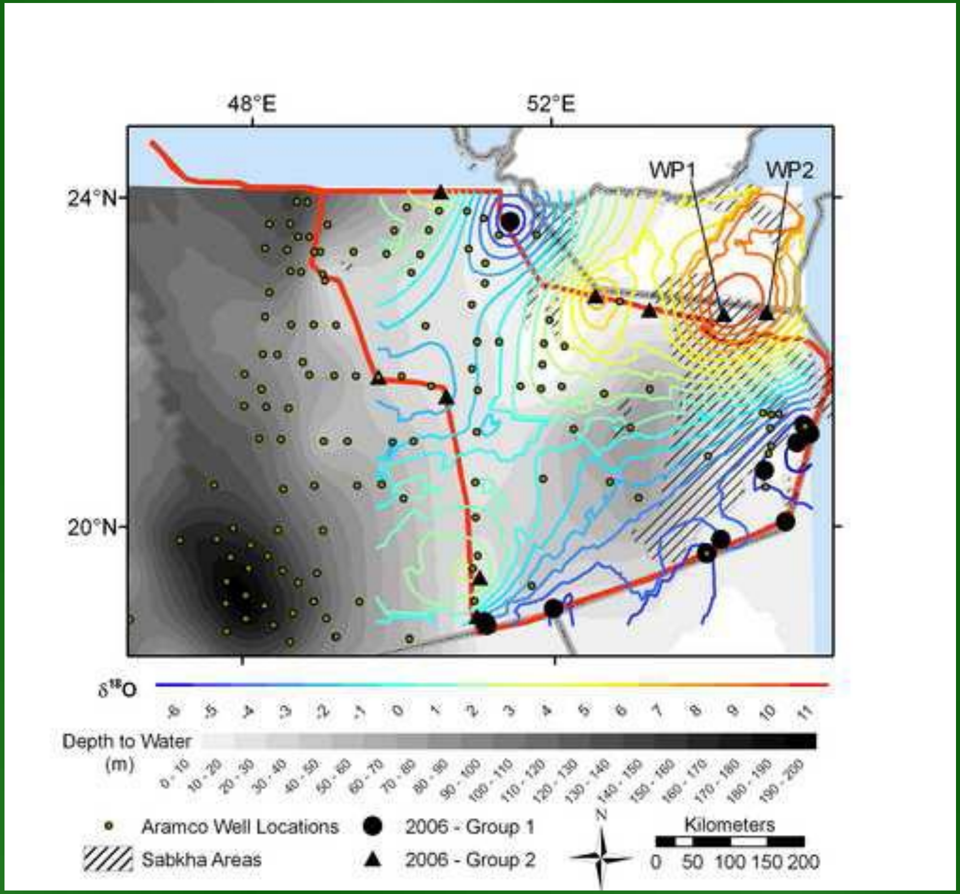
- Introduced in 2009
- Evolution of proven technology
- WiFi, browser-based control, real-time QA
- Satellite data up-link to processing & interpretation HQ

Suggested MT Survey Area in Western RAK



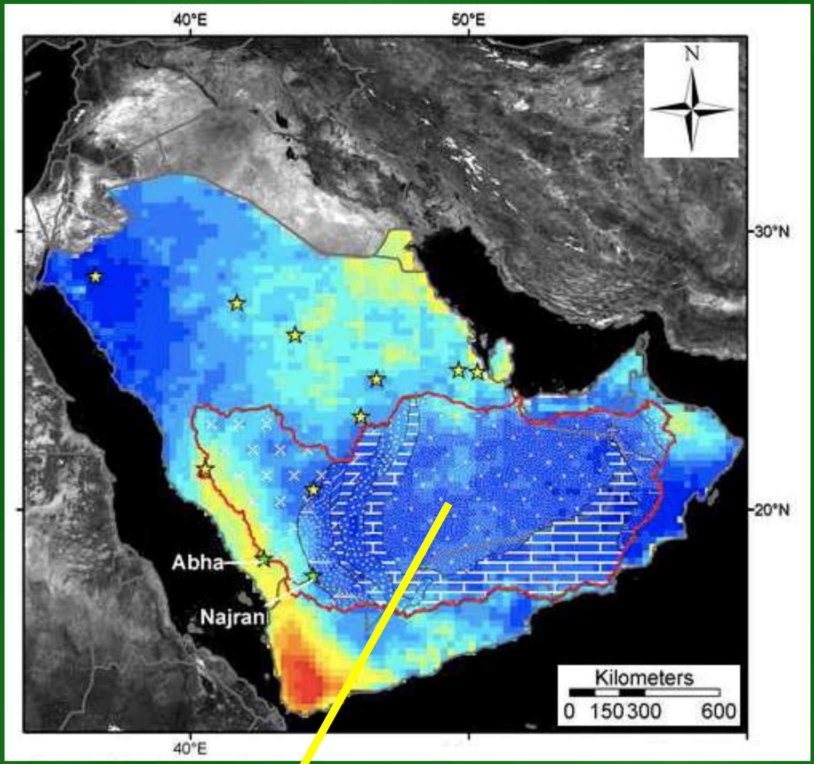
- Net of profiles in area of freshest RAKAS water
  - Line spacing ~30 km
  - Station spacing ~500 m
- If 11 lines, then 6600 km, 13,200 MT stations
- Incorporate data from ARAMCO wells

Use ARAMCO Well Data to Calibrate



- >150 wells: some could be used to calibrate deep geophysical survey
- Well spacing is 30–50 km
- Need to study between wells

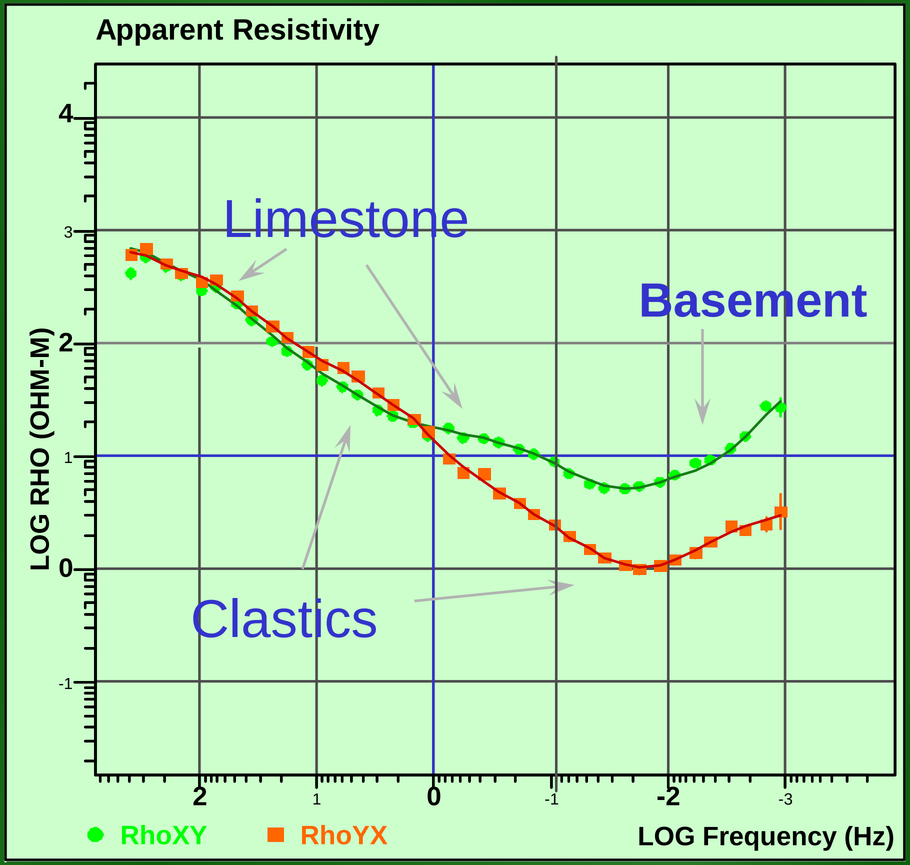
MT Survey: Area



Survey Area

- Actual subsurface drainage system unknown (channels, fractures, etc.)
- Estimate thickness of aquifers, salinity
- Best targets are channels of highest flow
- Lateral resistivity boundaries (e.g., subsurface channels) are detected by MT vertical magnetic field

MT Data Curves



- Apparent resistivity
- Two curves, xy and yx
- Qualitative view of subsurface changes in resistivity
- Used with phase data for interpretation

Similar Project, Different Objective — *Project Paleorift* (Uzbekistan, 2002)

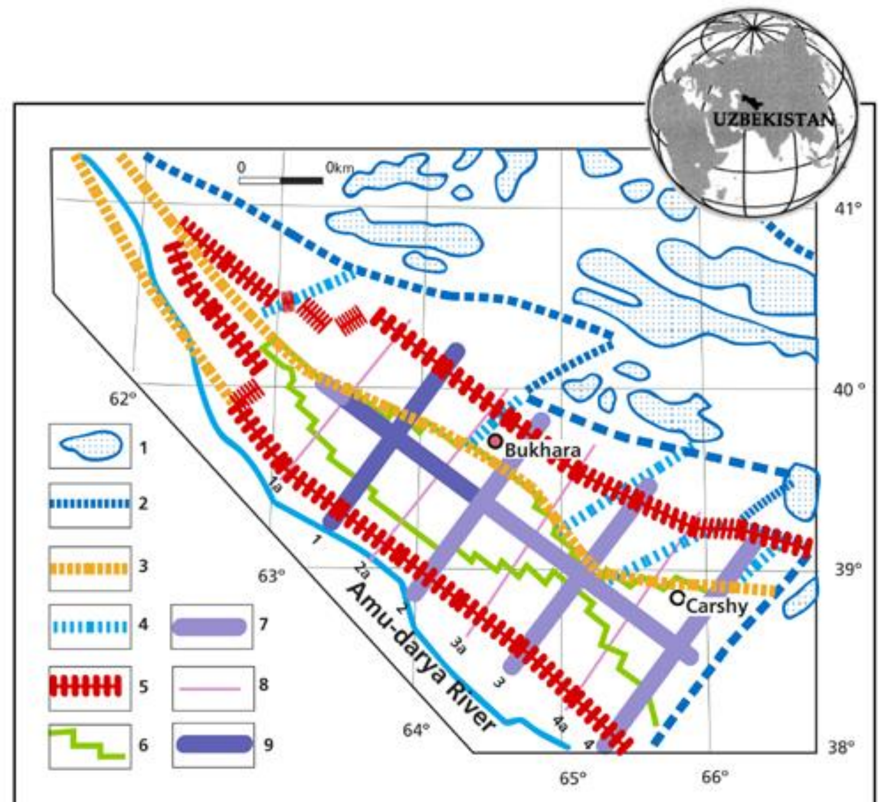
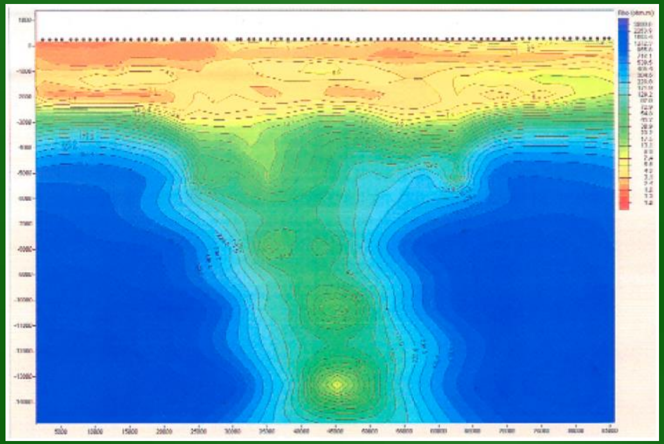
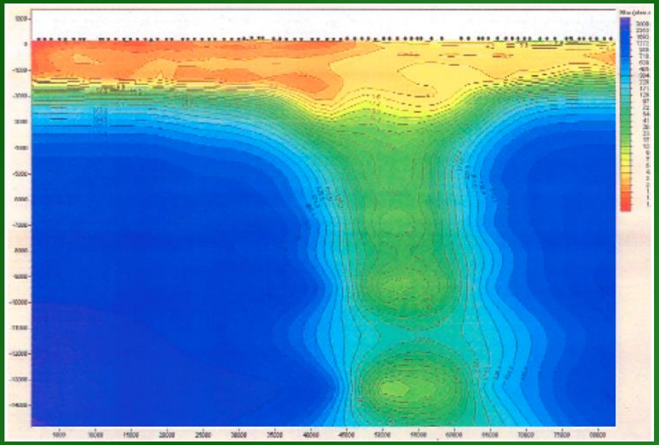


Figure 1: Map of regional profiles crossing Bukharo-Khivinsky Paleorift
1. Outcrops of Paleozoic rocks; 2. Boundaries of Lithosphere plates: 3. Boundaries of tectonic steps; 4. Boundaries of basement blocks; 5. Paleorift boundaries; 6: Central graben boundaries; 7. Main profiles; 8. Secondary profiles; 9. Calibration profiles.

- Pilot study to map paleorift in co-operation with Uzbekneftegaz
- >500 stations at 500 m spacing
- Resistivity cross-sections obtained through inversions

MT Inversions Along Parallel Reconnaissance Profiles in Uzbekistan



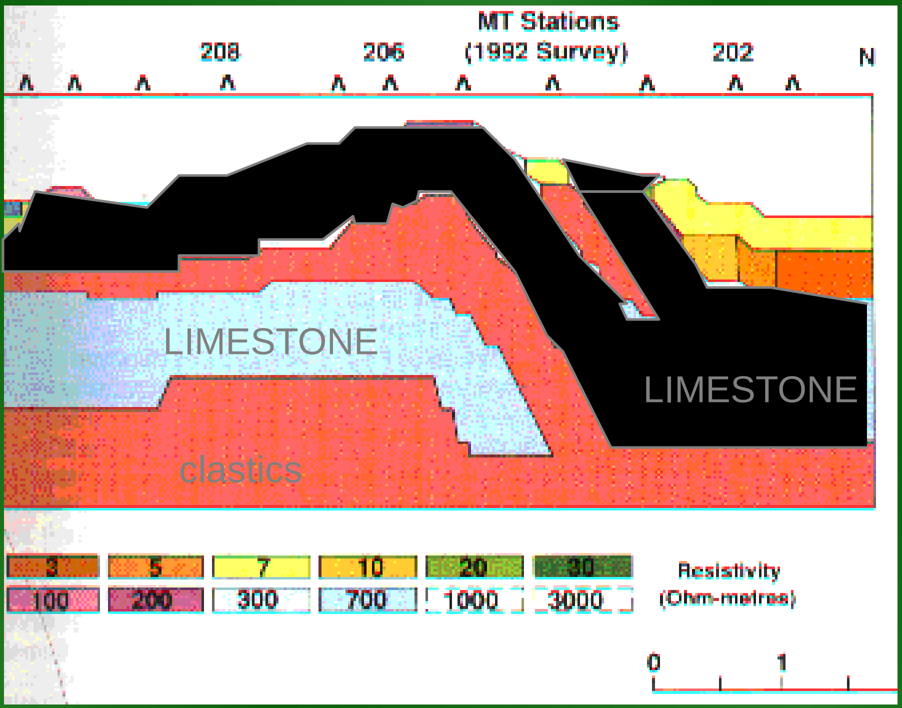


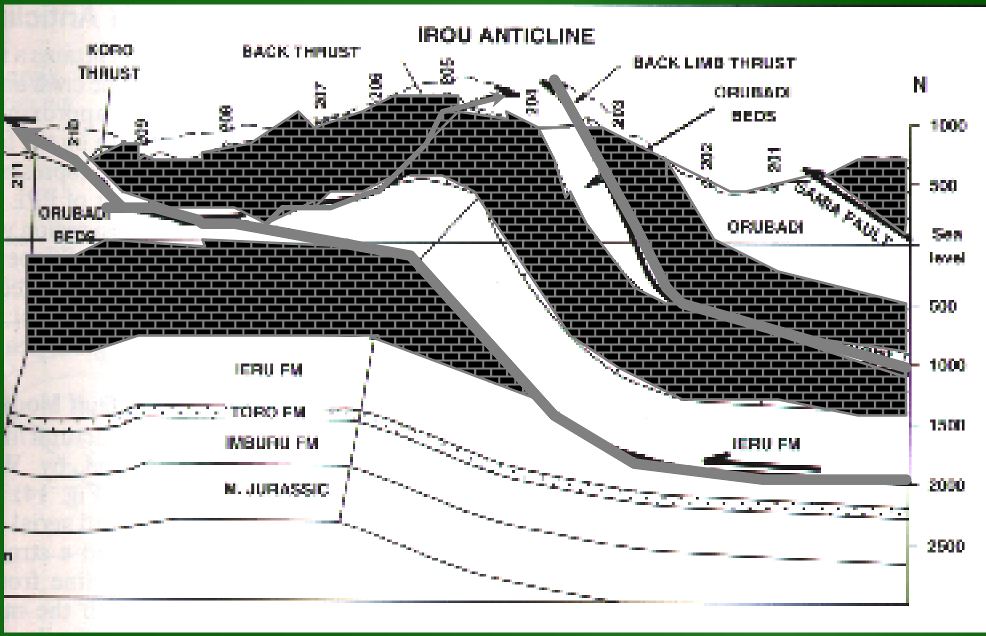
- Profiles ~82 km long
- ~30 km apart
- Resistivity shown to a depth of ~15 km
- Clear indication of highly resistive rocks on either side of conductive rocks in rift

Irou, PNG

MT

Geology based on MT and dips





VE=1:1

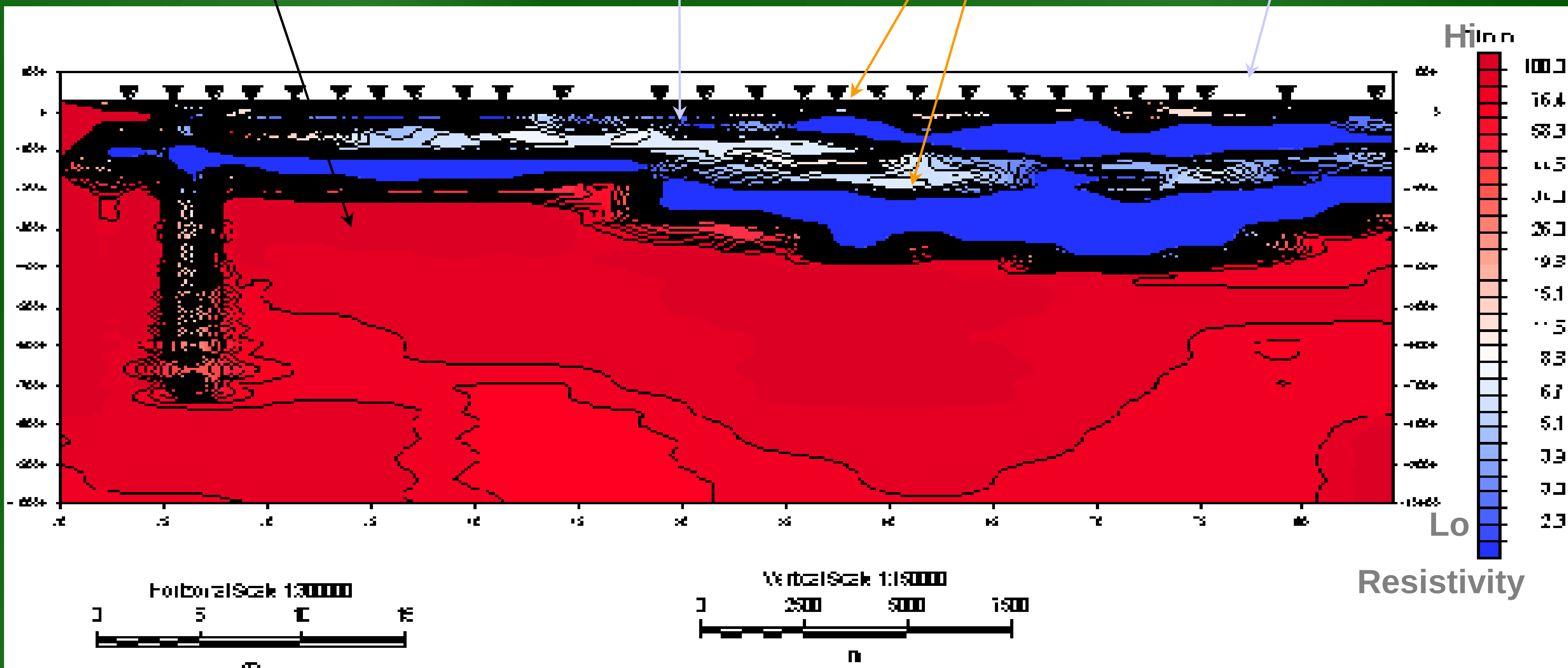
MT in N. Africa

HIGH RESISTIVITY
METAMORPHIC BASEMENT

DOLOMITE+ANHYDRITE:
POTENTIAL RESERVOIR UNIT

LOW RESISTIVITY
SHALE

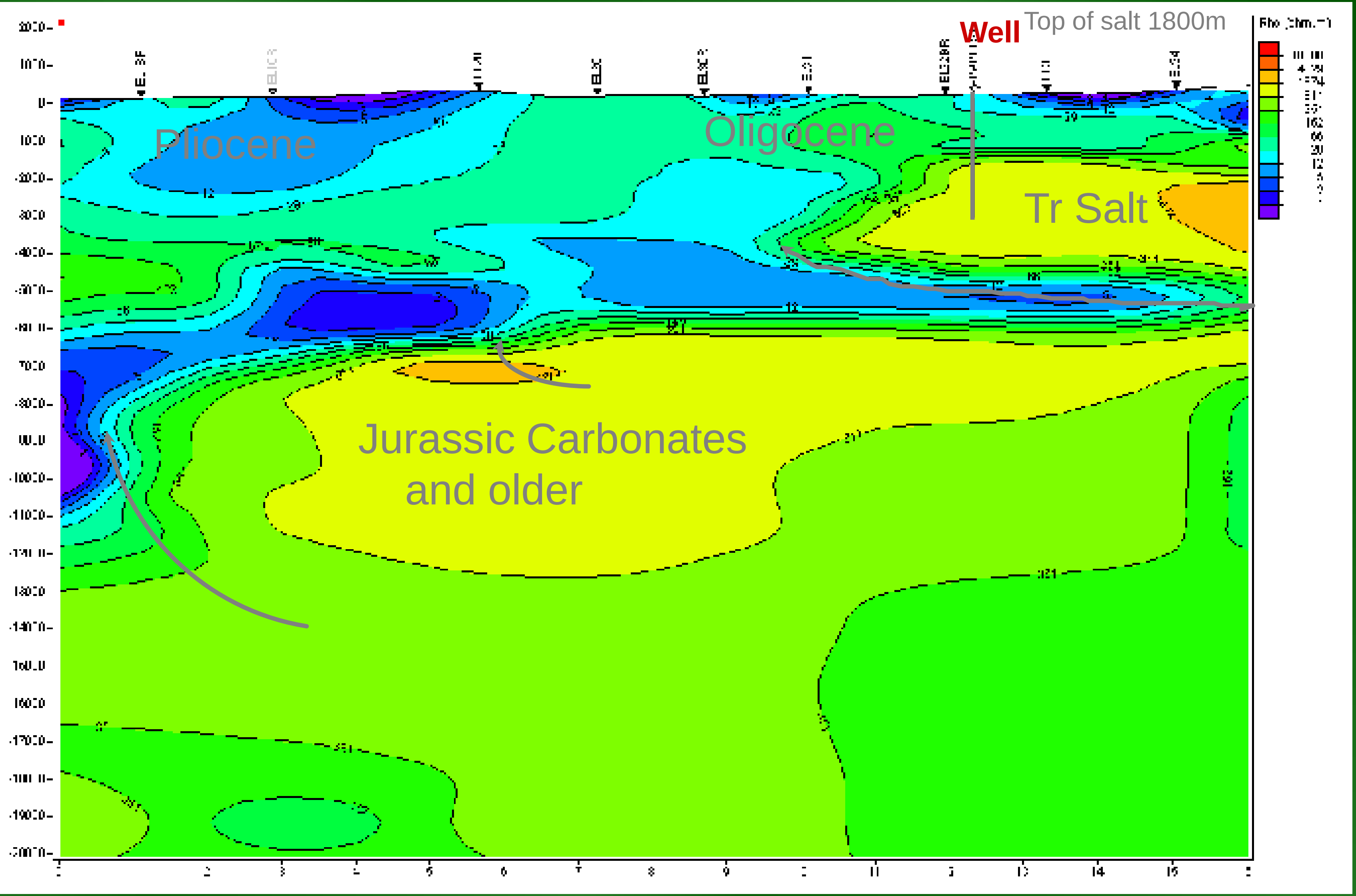
BASALT &
SAND DUNES



VERTICAL EXAGGERATION=2.0.

GEOSYSTEM

Salt Problem



GEOSYSTEM