FUNDAMENTAL CRITERIA TO EXPLORE GEOTHERMAL RESOURCES OF YEMEN

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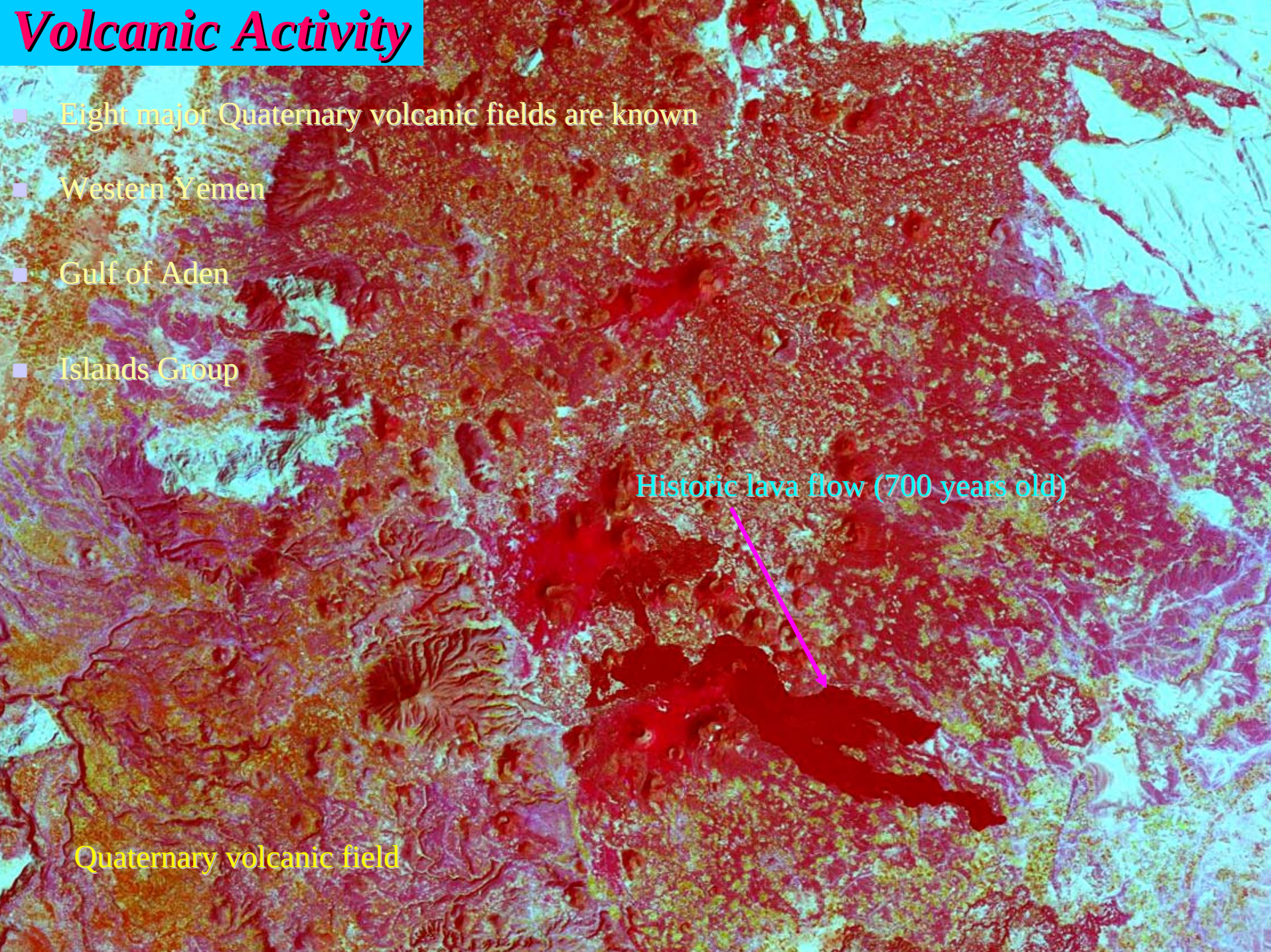
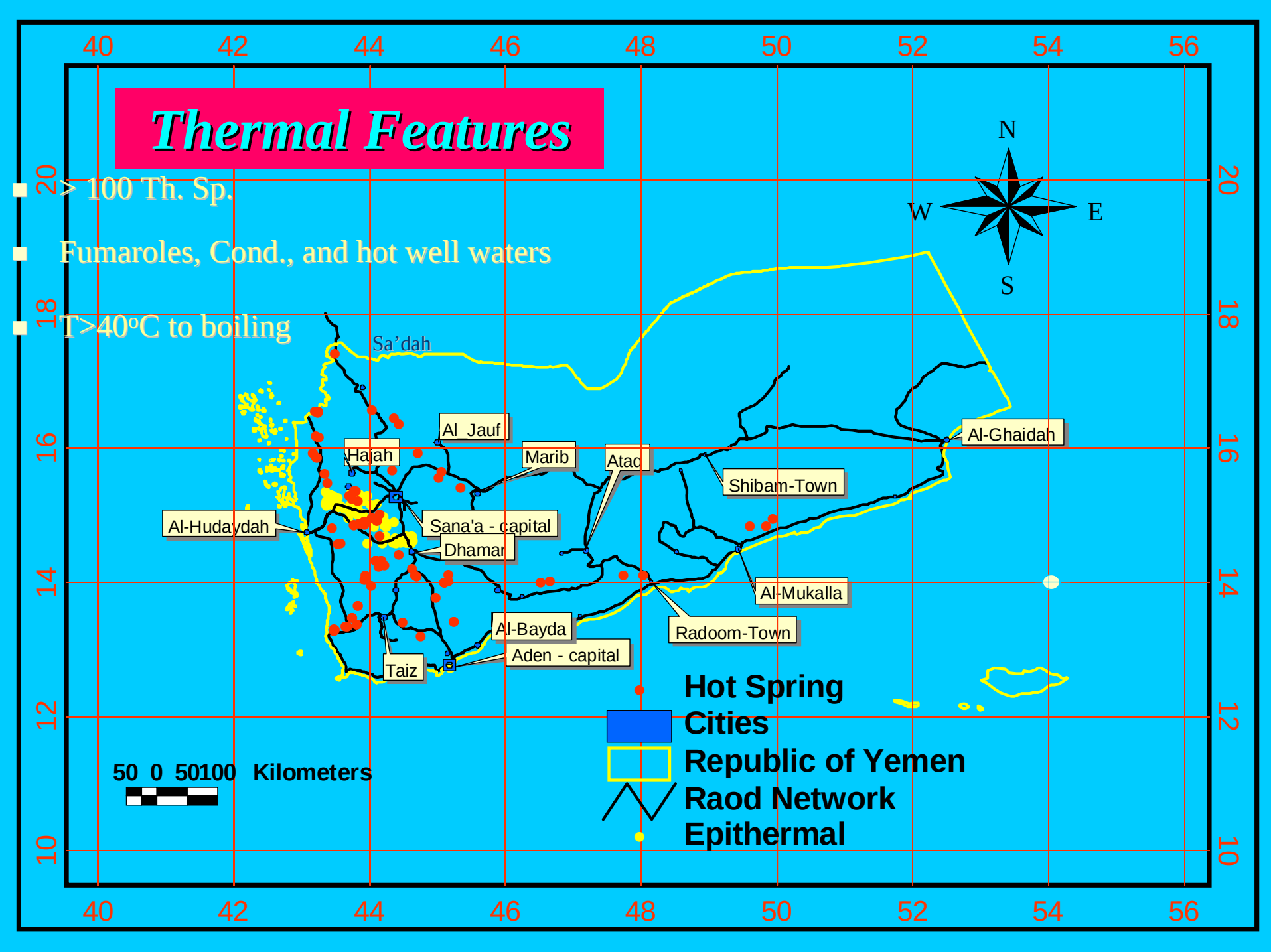
GOALS OF THIS STUDY

- 1. Evaluation of the physical-chemical processes,
- 2. Assessment of the quality of the thermal waters,
- 3. Developing physical-therapeutic and touristic resorts,
- 4. Developing industrial and hydrogeological aspects, and
- 5. Evaluation of the geothermal potential of Yemen.

Volcanic Activity

- Eight major Quaternary volcanic fields are known
- Western Yemen
- Gulf of Aden
- Islands Group

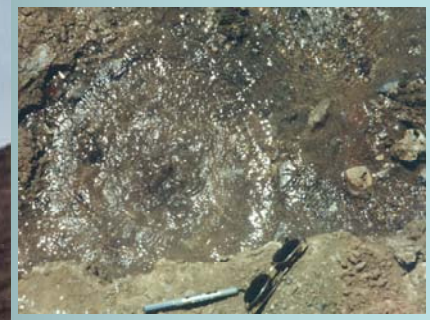



Thermal Features
> 100 Th. Sp.
Fumaroles, Cond., and hot well waters
T>40°C to boiling
N
W
E
S
Sa'dah
Al_Jauf
Hajah
Marib
Atad
Al-Ghaidah
Shibam-Town
Al-Hudaydah
Sana'a - capital
Dhamar
Al-Mukalla
Radoom-Town
Al-Bayda
Aden - capital
Taiz
50 0 50100 Kilometers
Hot Spring
Cities
Republic of Yemen
Raod Network
Epithermal
40
42
44
46
48
50
52
54
56
20
18
16
14
12
10

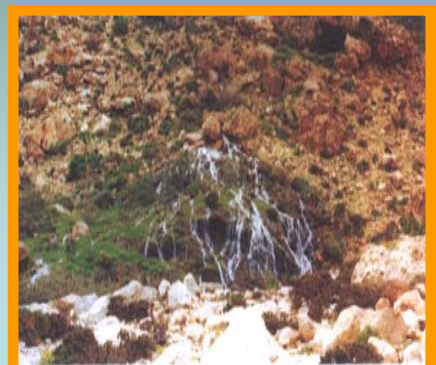


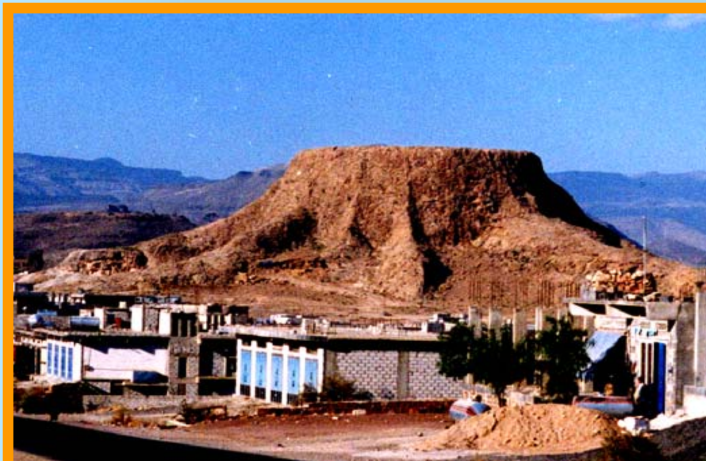


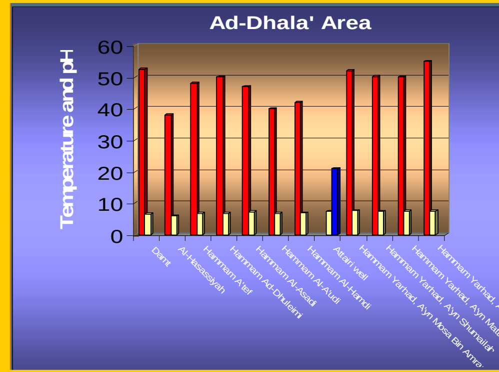




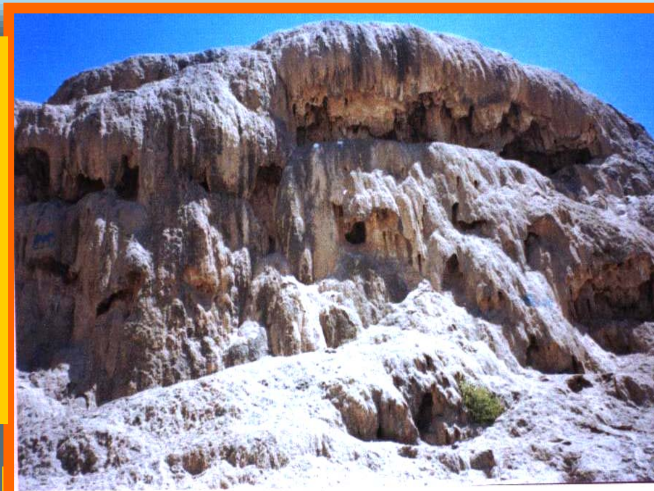


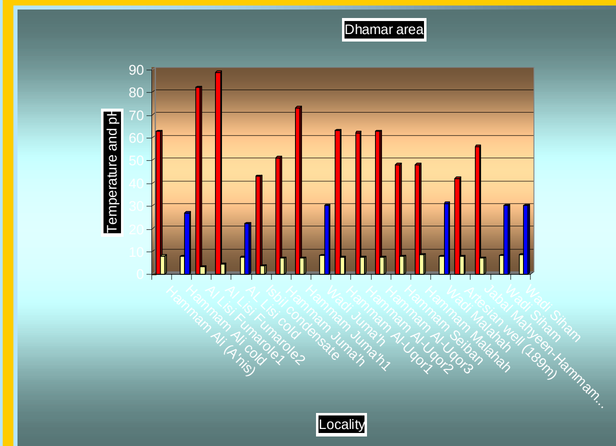




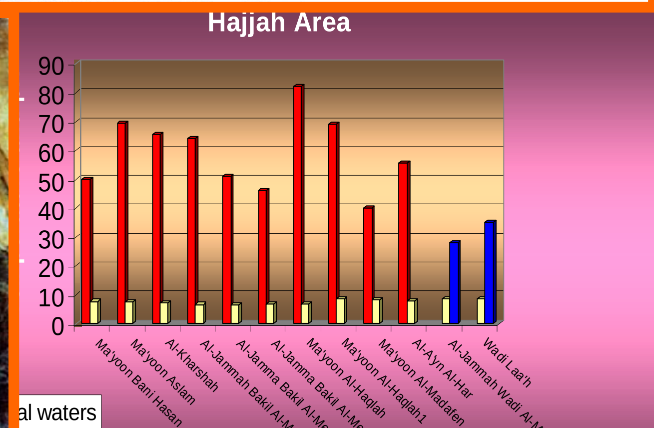


Ad-Dhala' Area
Temperature and pH
Damt
Al-Hasassiyah
Hammam A'tef
Hammam Ad-Dhuleimi
Hammam Al-Asadi
Hammam Al-A'udi
Hammam Al-Hamdi
Attairi well
Hammam Yarhad, A'yn Mosa Bin Amra
Hammam Yarhad, A'yn Shumailah
Hammam Yarhad, A'yn Mattas

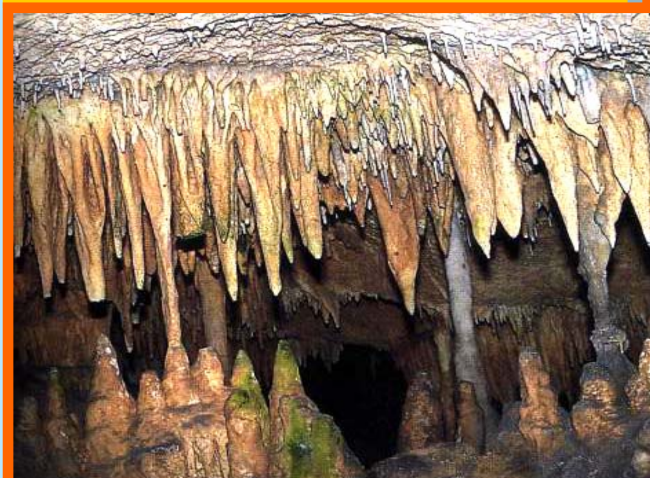


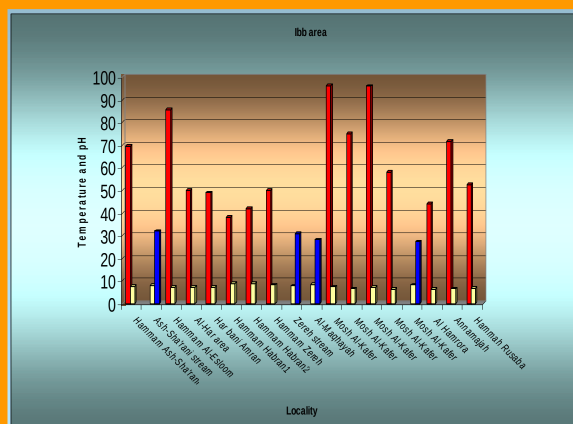


Dhamar area
Temperature and pH
Hammam Ali (A'nis)
Hammam Ali cold
Al Lisi Fumarole1
Al Lisi Fumarole2
AL Lisi cold
Isbil condensate
Hammam Juma'h
Hammam Juma'h1
Wadi Juma'h
Hammam Al-Uqor1
Hammam Al-Uqor2
Hammam Al-Uqor3
Hammam Seiban
Hammam Malahah
Wadi Malahah
Artesian well (189m)
Jabal Mahyeen-Hammam...
Wadi Siham
Wadi Siham
Locality



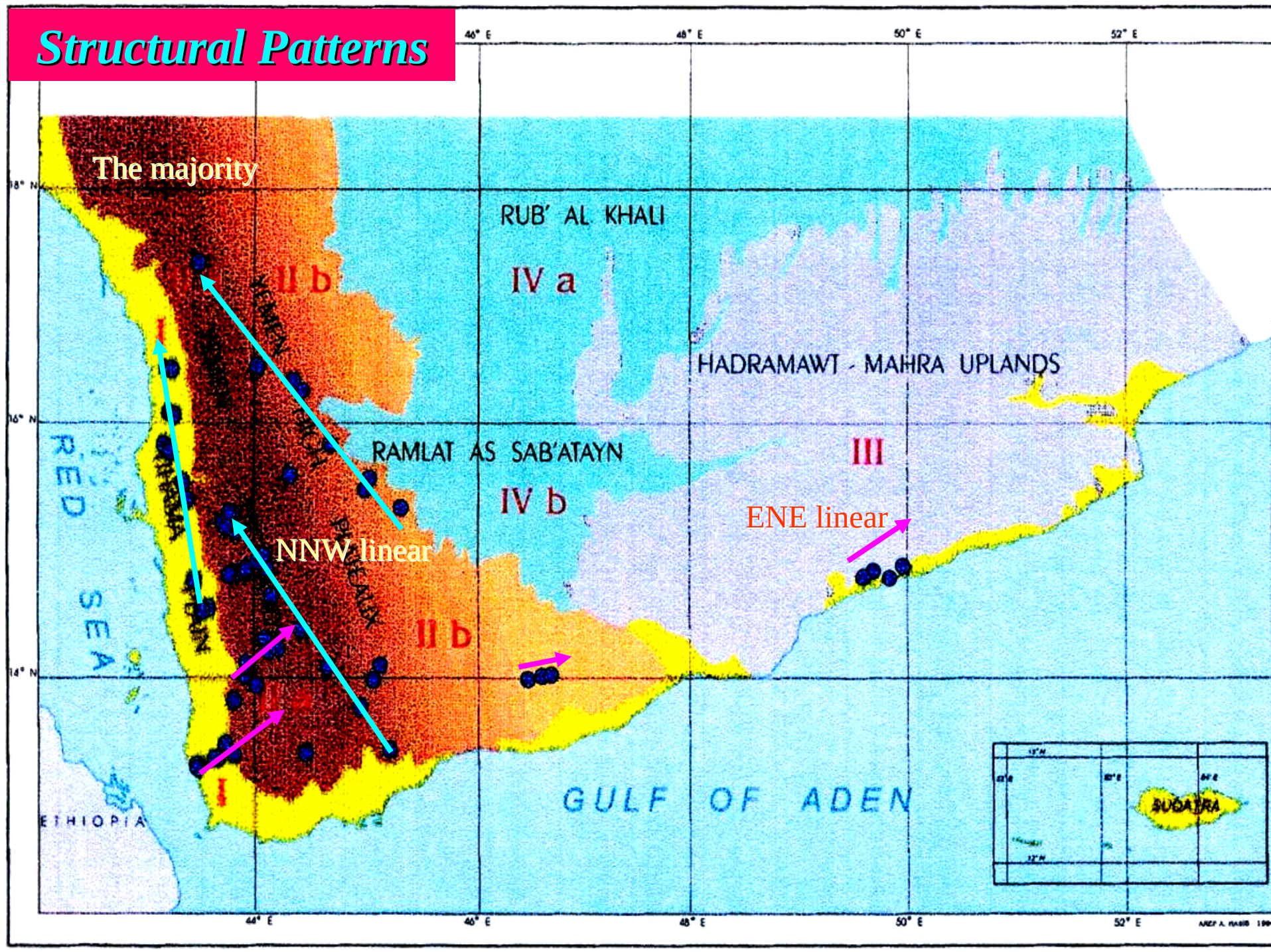
Hajjah Area
Ma'yoon Bani Hasan
Ma'yoon Aslam
Al-Kharshah
Ma'yoon Al-Haqlah
Ma'yoon Al-Haqlah1
Ma'yoon Al-Madafen
Al-Ayn Al-Har
Wadi Laa'h
al waters



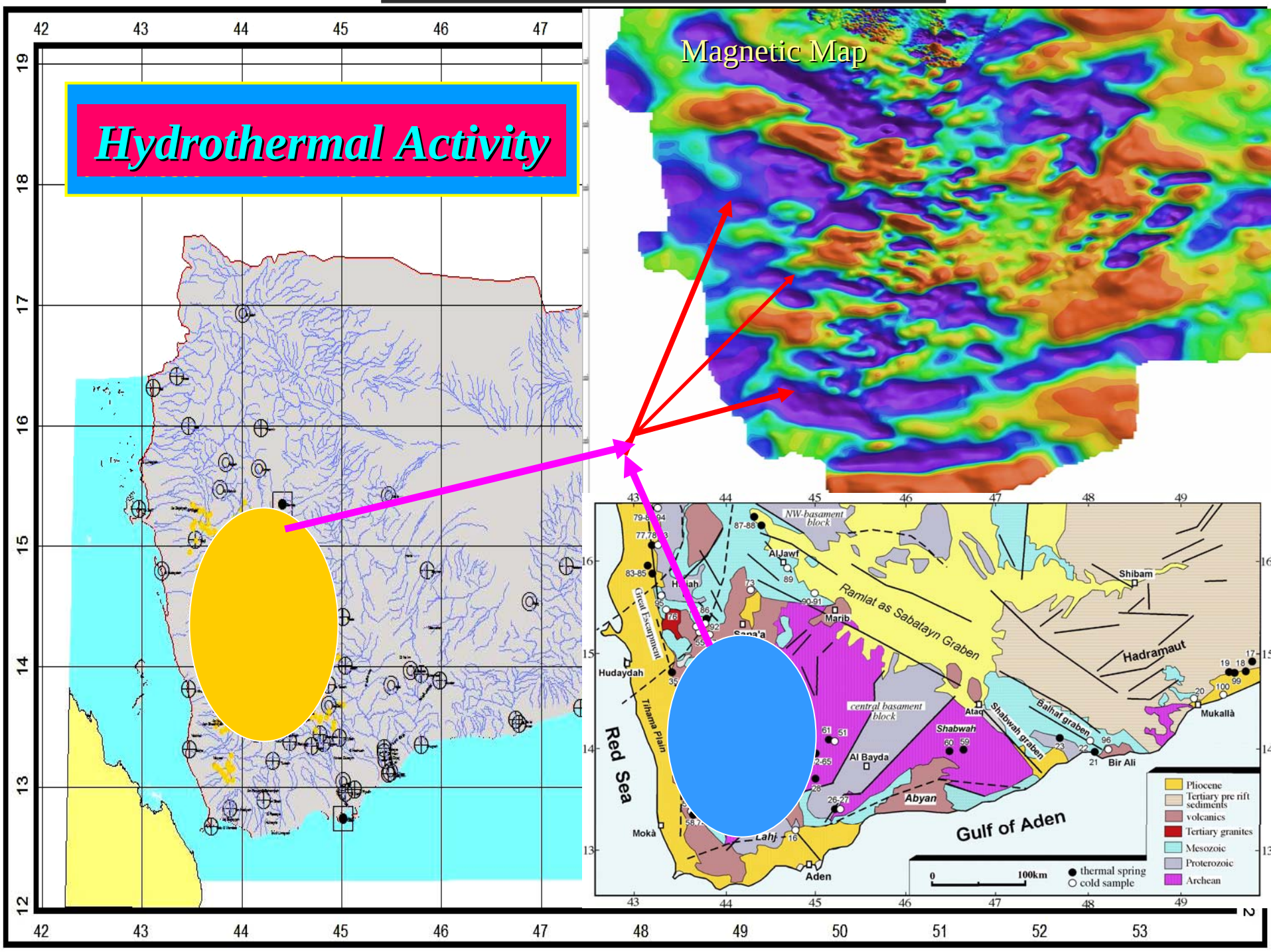


Ibb area
Temperature and pH
Hammam Ash-Sha'ran
Ash-Sha'rani stream
Hammam Al-Esloom
Al-Har area
Har bani Amran
Hammam Habran1
Hammam Habran2
Hammam Zereh
Zereh stream
Al-Maqhayah
Mosh Al-Kafer
Mosh Al-Kafer
Mosh Al-Kafer
Mosh Al-Kafer
Mosh Al-Kafer
Al Hamrora
Annamajah
Hammah Rusaba
Locality

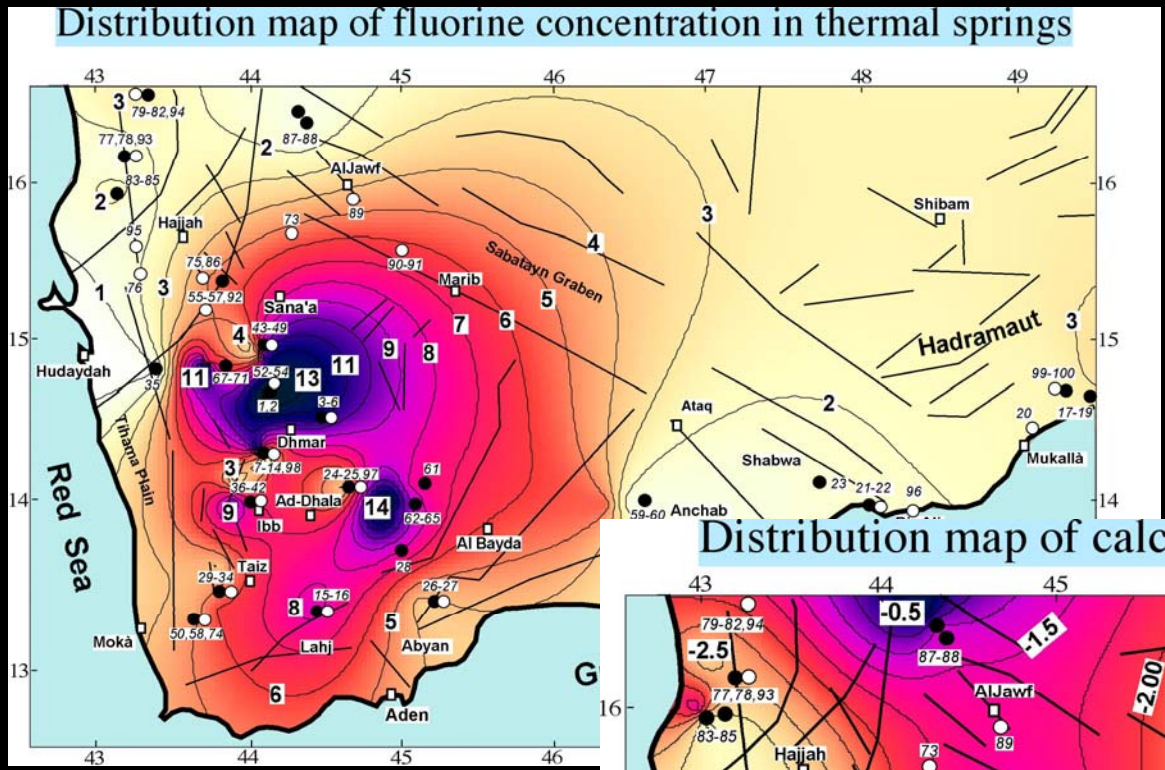
Structural Patterns



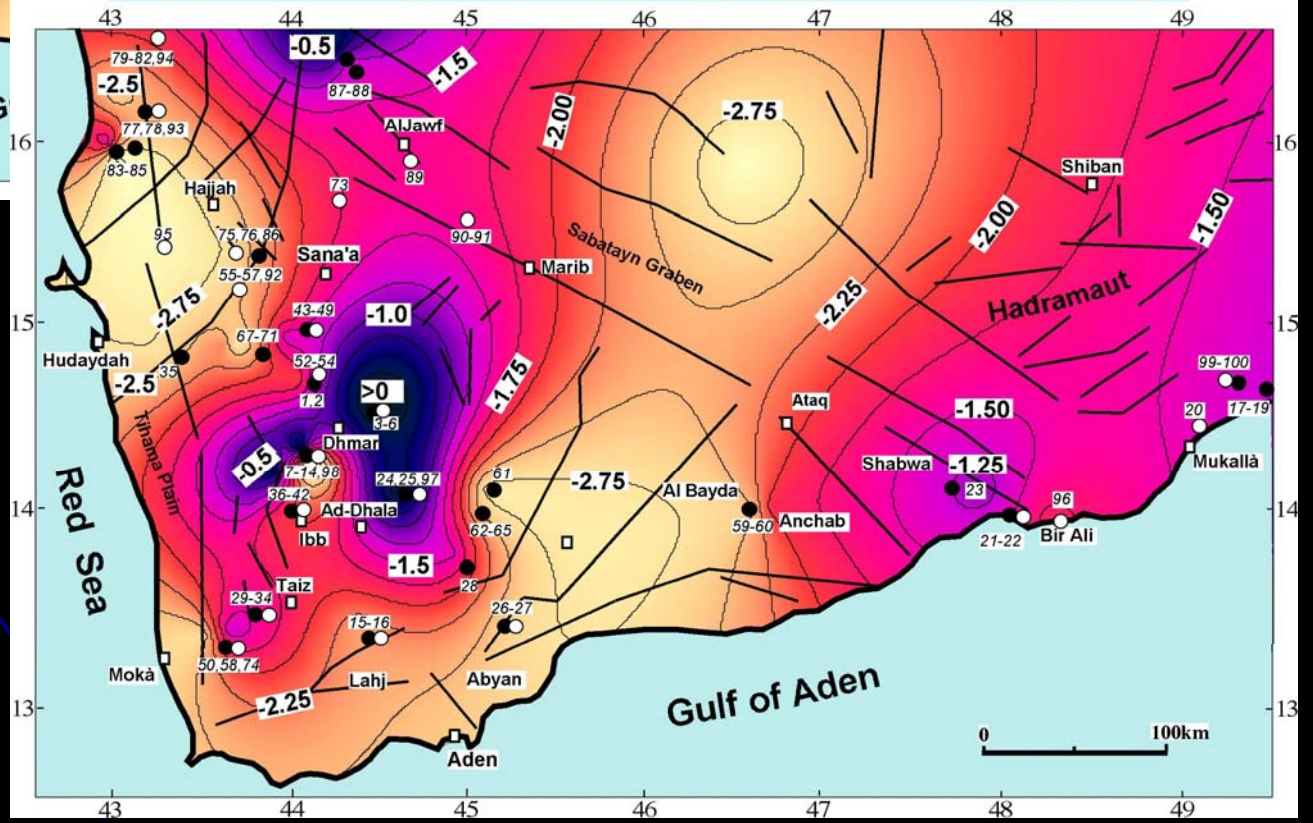
Hydrothermal Activity



Distribution map of fluorine concentration in thermal springs



Distribution map of calculated pCO_2 in thermal springs

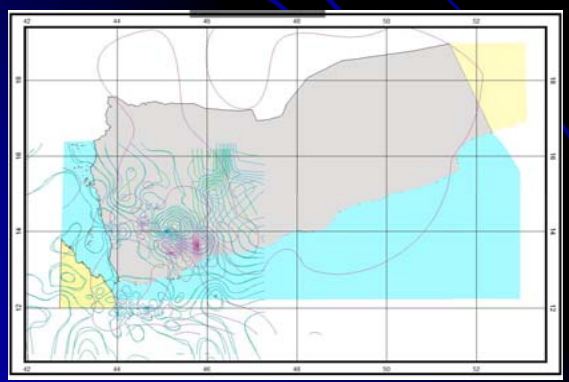


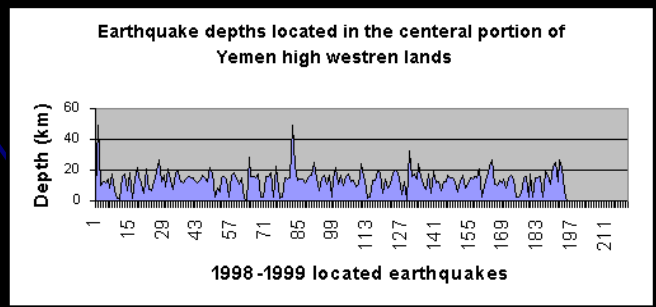
Seismic Activity

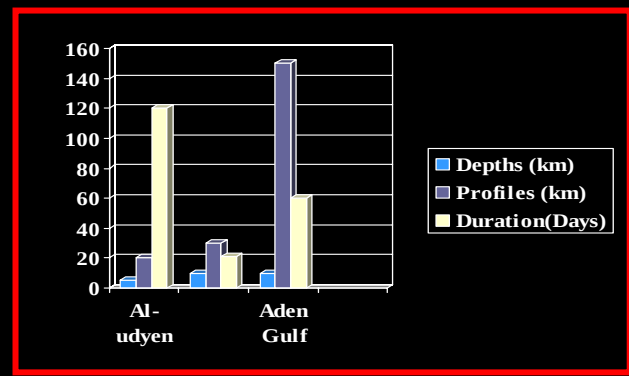
Several Historic EQ

Recent Activity

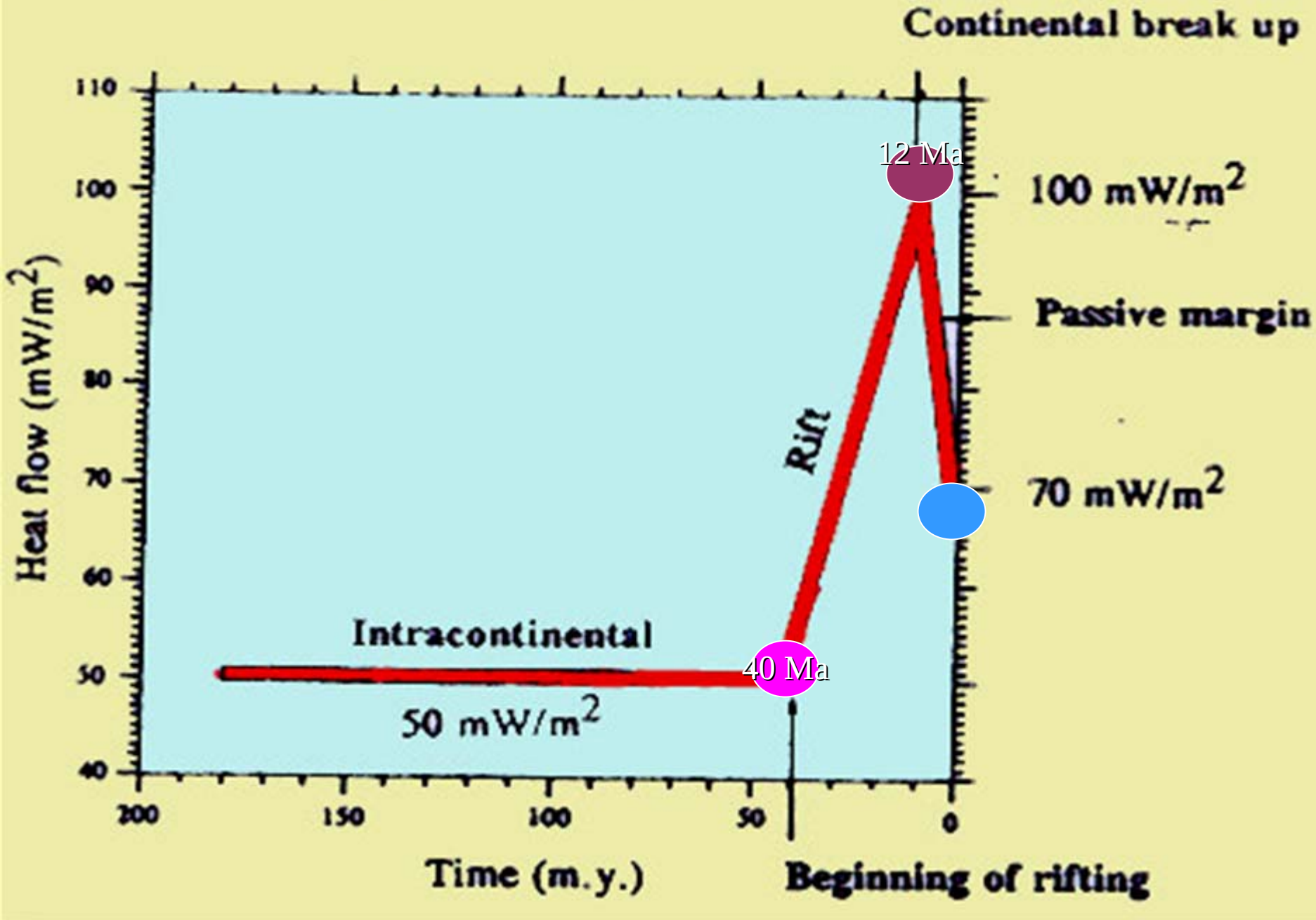
EQ are CC.





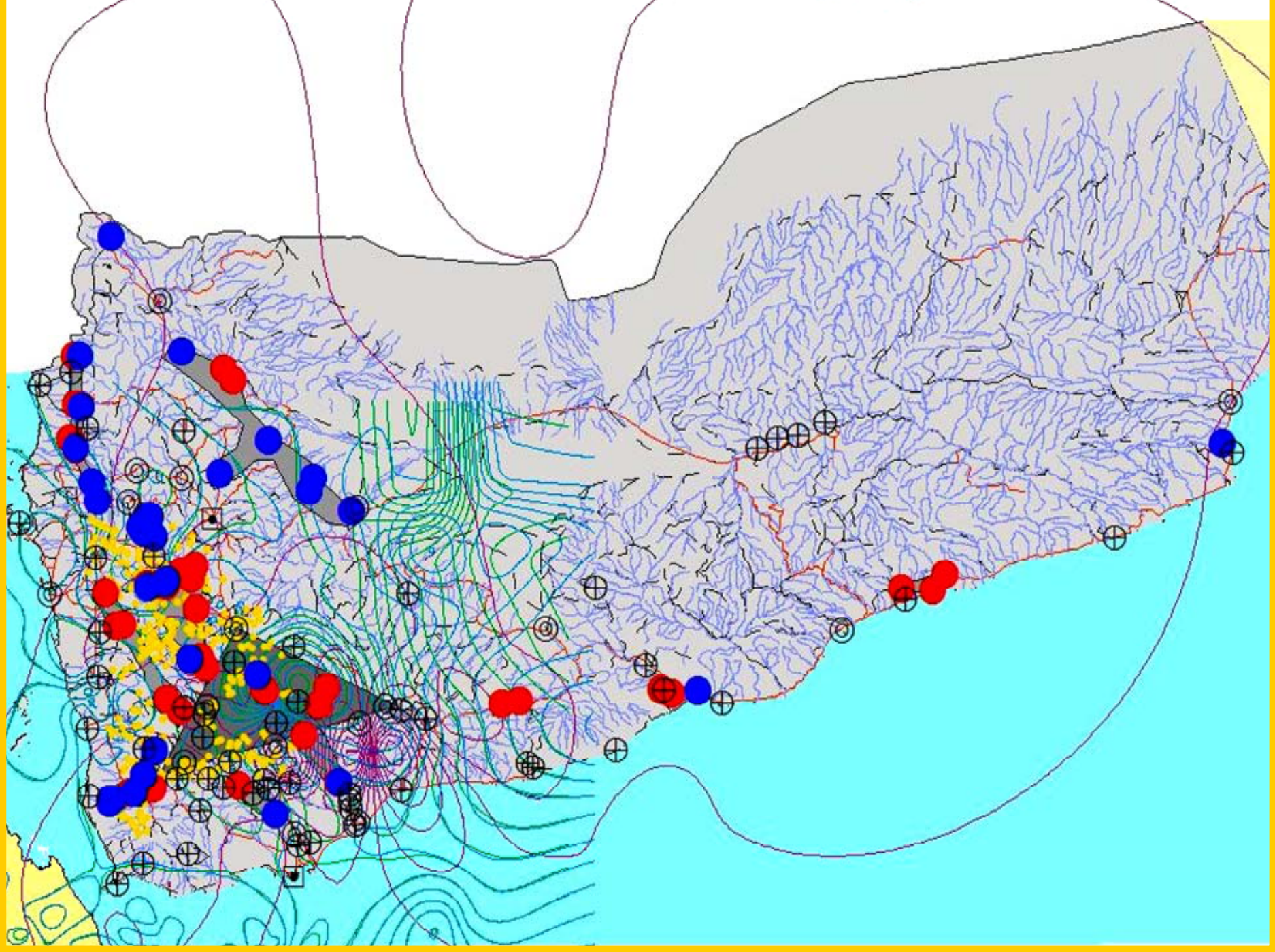


Heat Flow History

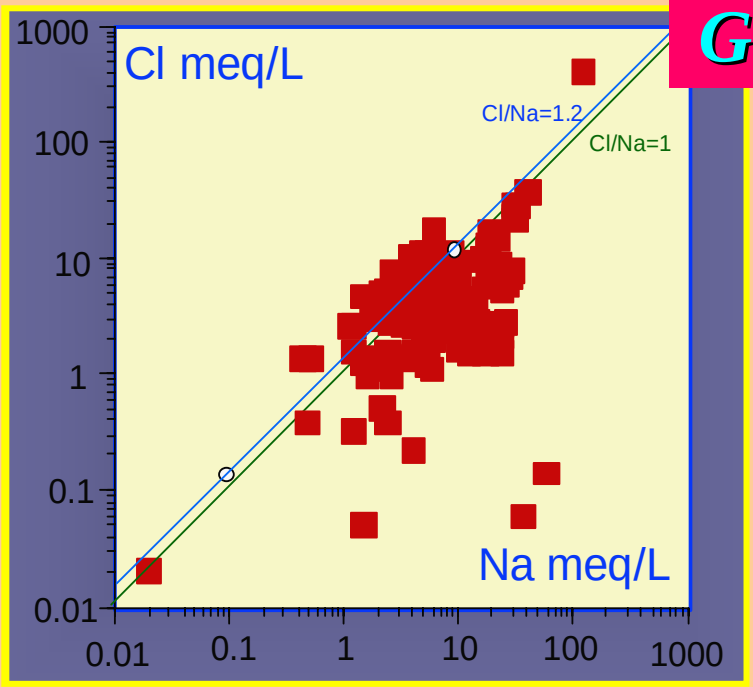


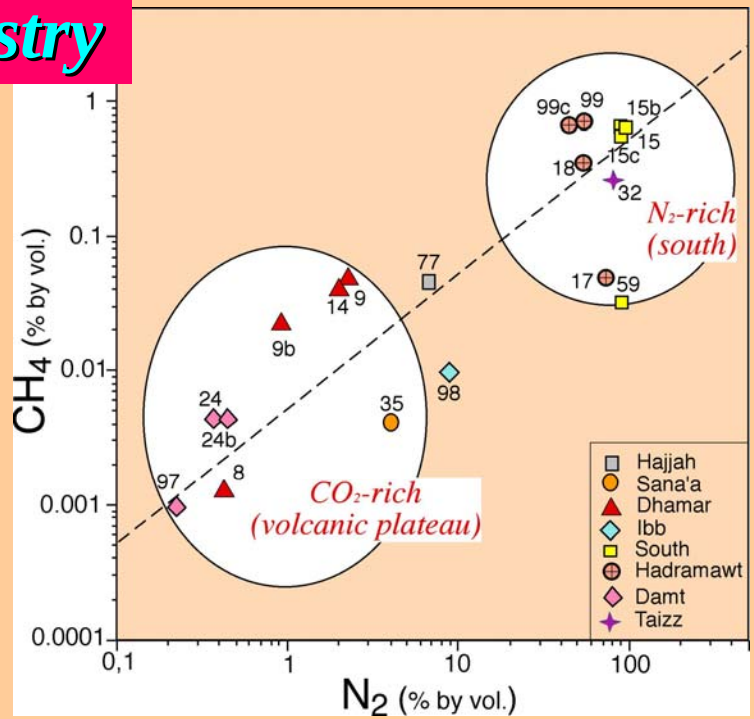
Country	State	Area	Geothermal gradient °C/km	Heat flow mW/m^2	Maximum surface T (°C)	Estimated T (°C)
USA	Oregon	Grande Ronde Valley	30 to 70	60-80	80	100-125
USA	Oregon	Alvord Valley	47 to 295	52-295	97	150-200
Yemen	Hadramawt	Gulf of Aden		70	65	80-120
Yemen	Western part	Red Sea	50-77	94-154	96.3	150-180
India	Cambay	-	70			
India	Tattapani	-	90			
Intercontinental	Continental	Active rifts	60-90			
World	Average value	Normal	30			

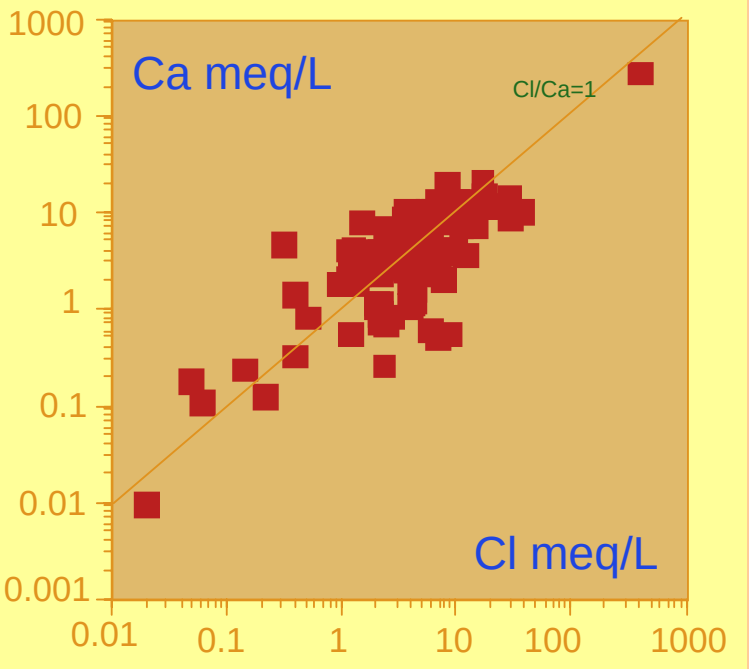
Well name	Depth (m)	Maximum T (°C) recorded	Equilibrium gradient	Projected depth to 200 (°C)	Estimated heat flow HFU	Reference
Zaydiah 1	3018	152	50	3480	2.50	Mecom
Kathib1	2459	167	70	2490	4.00	Shell
Al-Auch 1	2812	170	54	3220	2.75	Shell
Abbas1	3414	174	50	3480	2.75	Shell

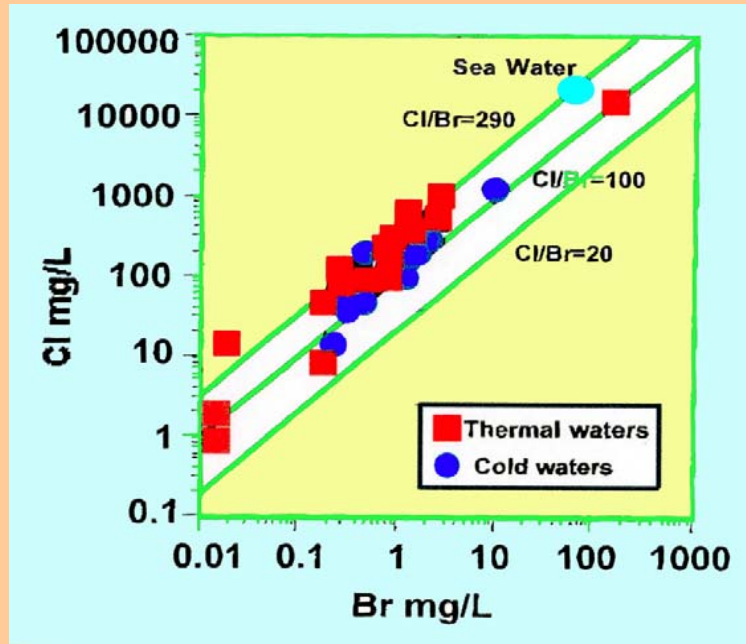


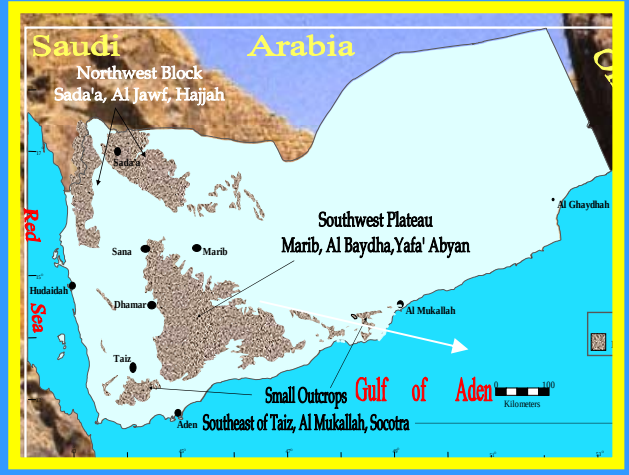
Geochemistry

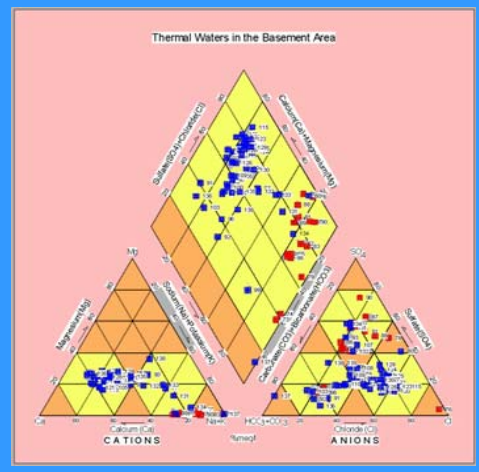


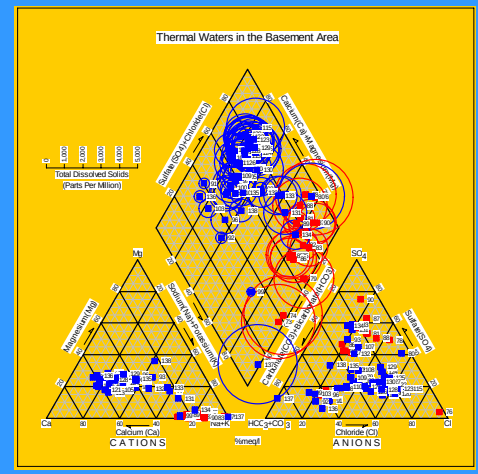


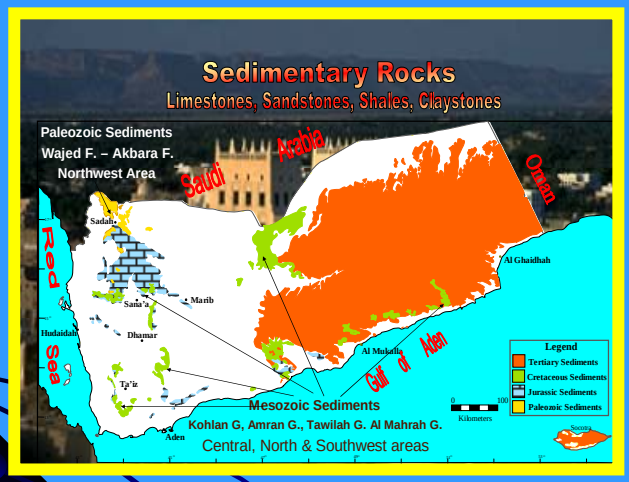


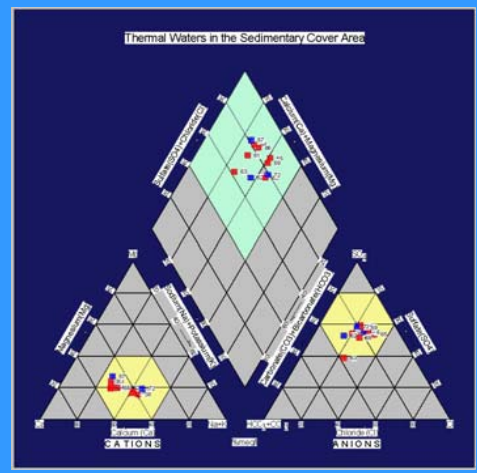


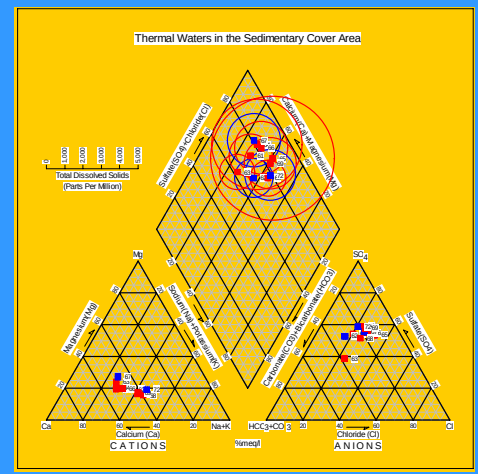

Saudi Arabia
Northwest Block
Sada'a, Al Jawf, Hajjah
Sadaa
Red Sea
Southwest Plateau
Marib, Al Baydha,Yafa' Abyan
Sana
Marib
Hudaidah
Dhamar
Taiz
Al Ghaydhah
Al Mukallah
Small Outcrops
Gulf of Aden
Aden
Southeast of Taiz, Al Mukallah, Socotra
Kilometers

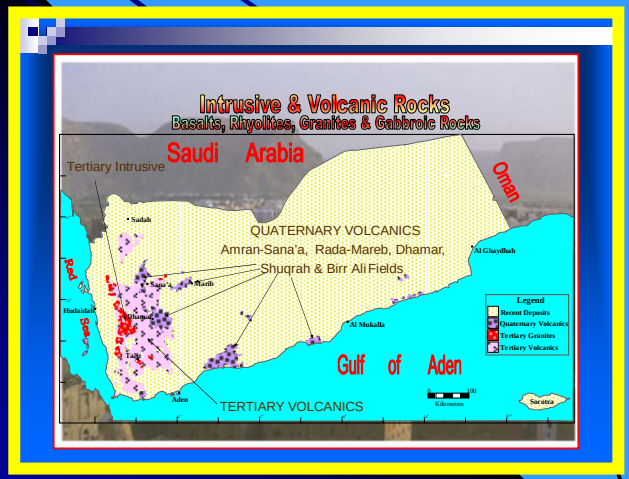

Thermal Waters in the Basement Area
CATIONS
ANIONS

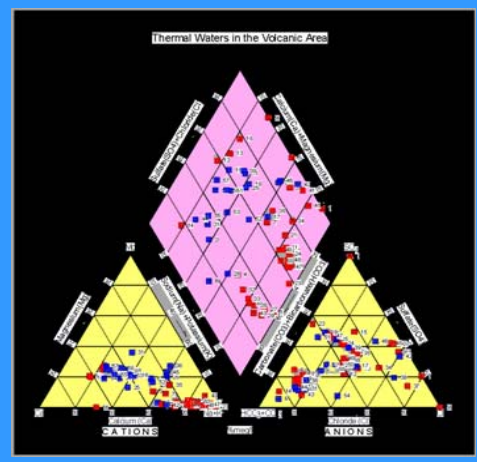

Thermal Waters in the Basement Area
Total Dissolved Solids
(Parts Per Million)
Calcium (Ca)
Chloride (Cl)
CATIONS
ANIONS

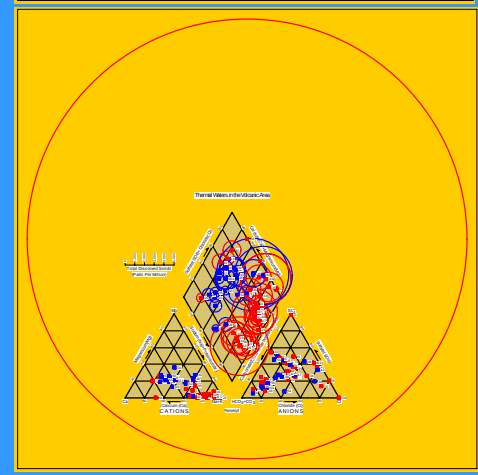

Sedimentary Rocks
Limestones, Sandstones, Shales, Claystones
Paleozoic Sediments
Wajed F. – Akbara F.
Northwest Area
Saudi Arabia
Oman
Red Sea
Gulf of Aden
Mesozoic Sediments
Kohlan G, Amran G., Tawilah G. Al Mahrah G.
Central, North & Southwest areas
Legend
Tertiary Sediments
Cretaceous Sediments
Jurassic Sediments
Paleozoic Sediments


Thermal Waters in the Sedimentary Cover Area
CATIONS
ANIONS

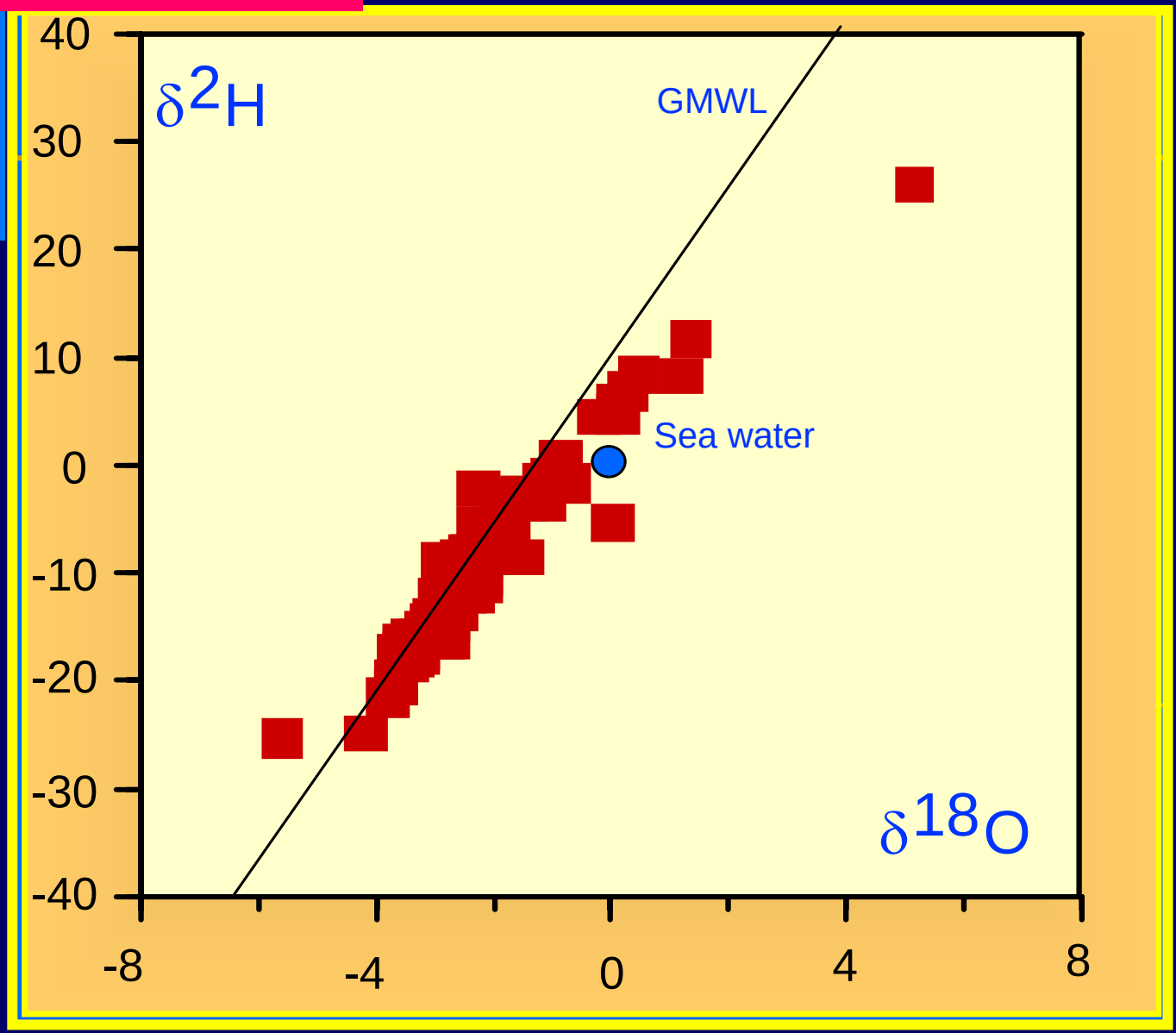

Thermal Waters in the Sedimentary Cover Area
Total Dissolved Solids
(Parts Per Million)
Calcium (Ca)
Chloride (Cl)
CATIONS
ANIONS


Intrusive & Volcanic Rocks
Basalts, Rhyolites, Granites & Gabbroic Rocks
Saudi Arabia
Oman
Tertiary Intrusive
QUATERNARY VOLCANICS
Amran-Sana'a, Rada-Mareb, Dhamar,
Shuqrah & Birr Ali Fields
Red Sea
Gulf of Aden
TERTIARY VOLCANICS
Legend
Recent Deposits
Quaternary Volcanics
Tertiary Granites
Tertiary Volcanics

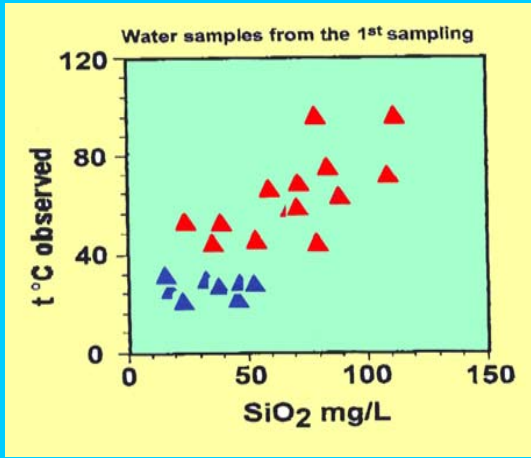

Thermal Waters in the Volcanic Area
CATIONS
ANIONS

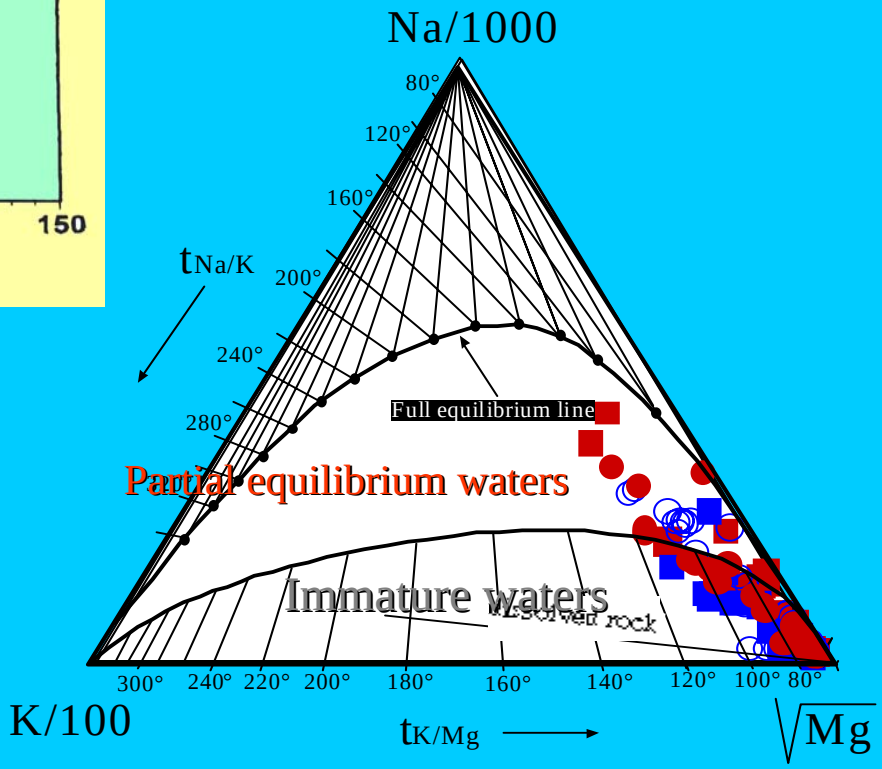

Thermal Waters in the Volcanic Area
CATIONS
ANIONS

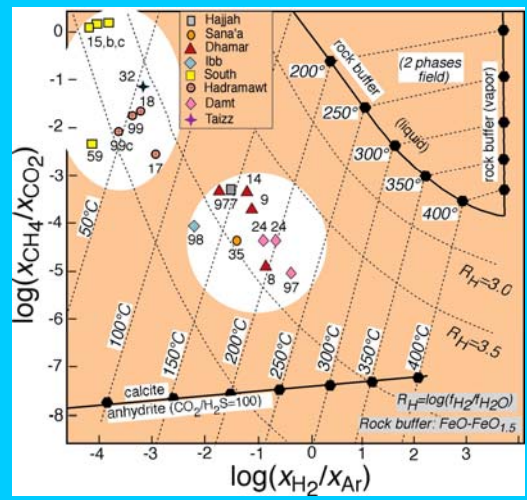
Oxygen and Deuterium



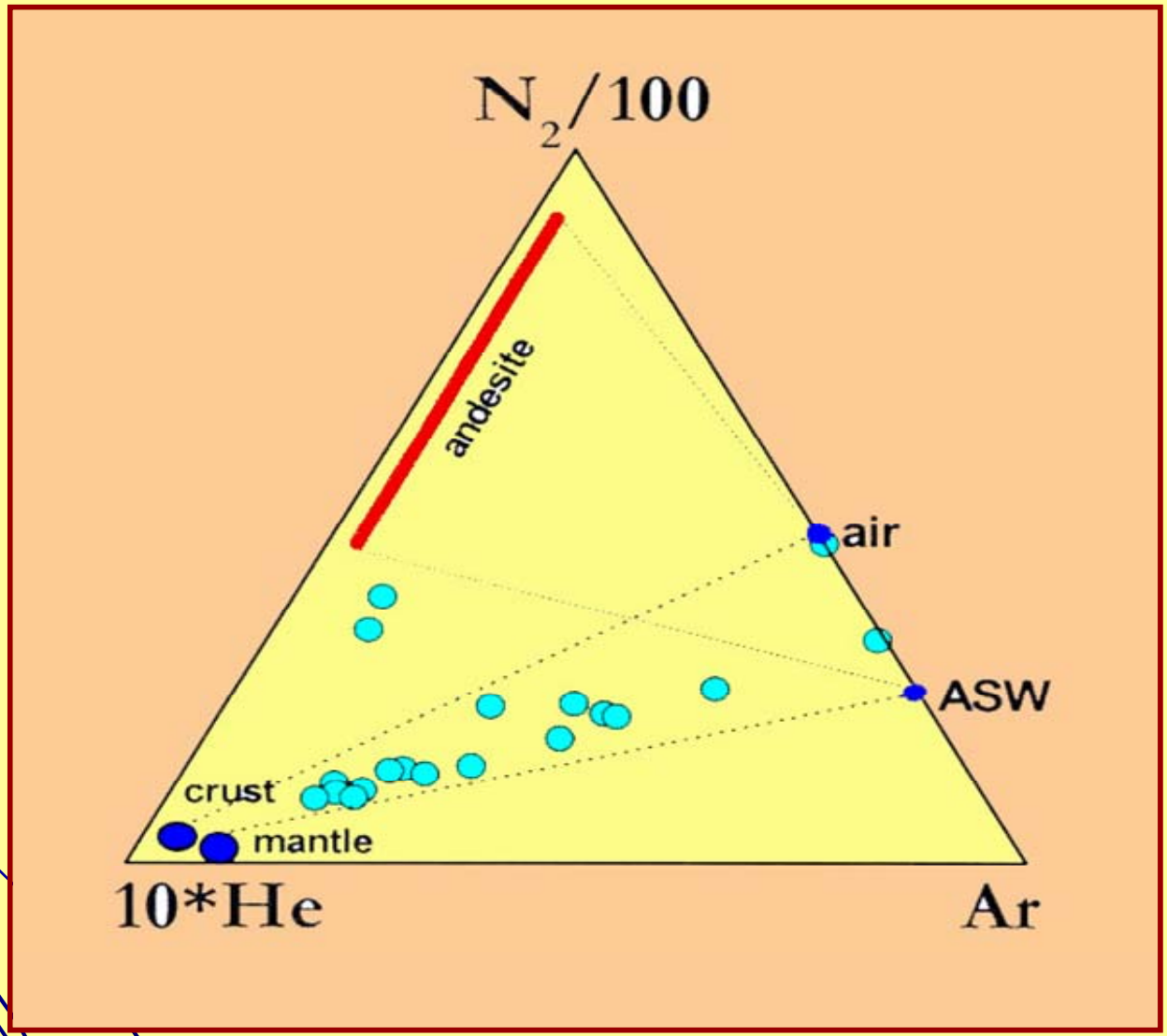
Geothermometry





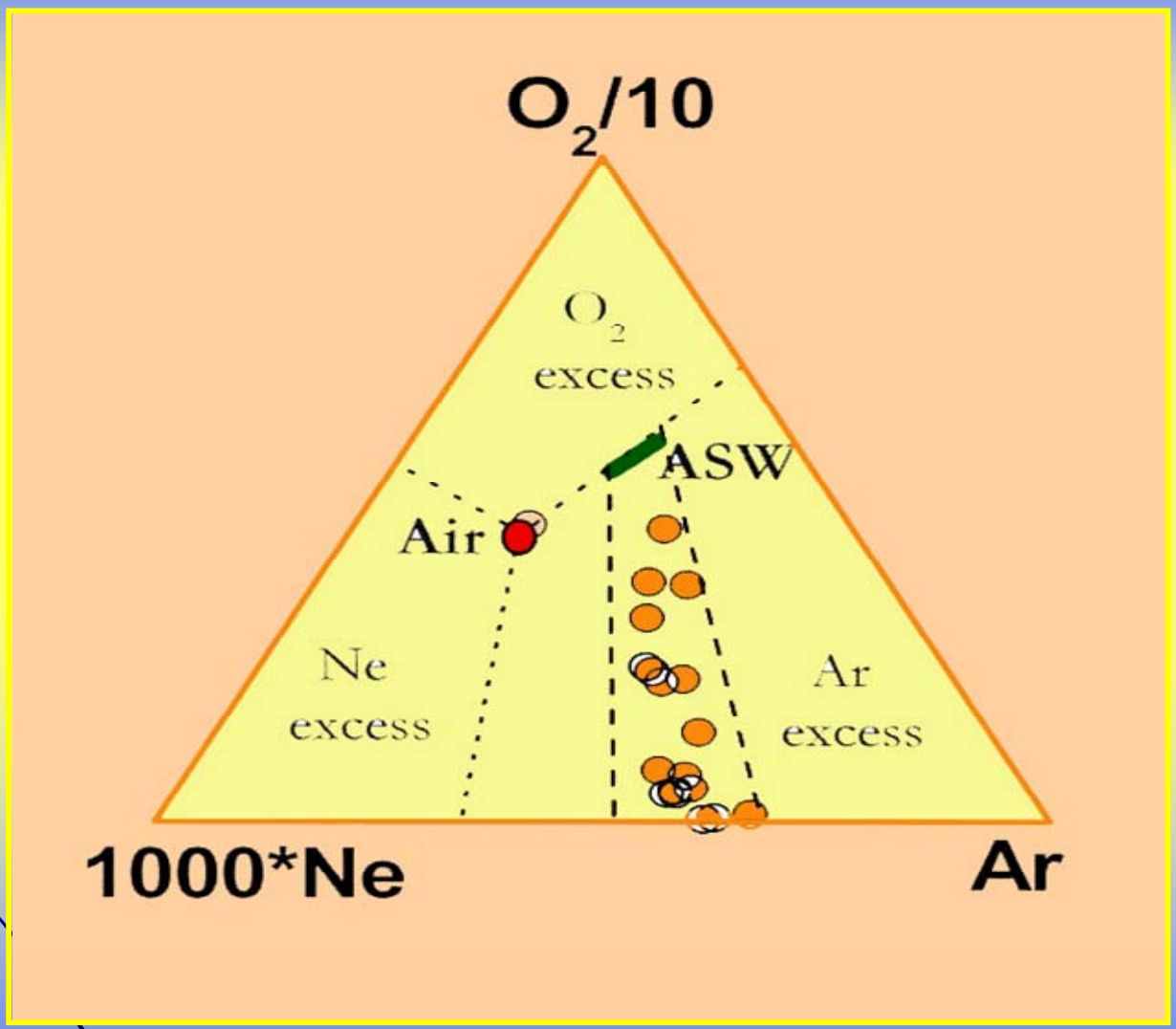


The composition of gases is dominated by two species, CO_2 and N_2, being their sum >95% in vol.%. The presence of CO_2 is probably related to thermometamorphic reactions on carbonate formations.



N_2 has atmospheric origin, as indicated by N_2/Ar ratios, which are comprised between air (82) and air saturated water (ASW=40) values.

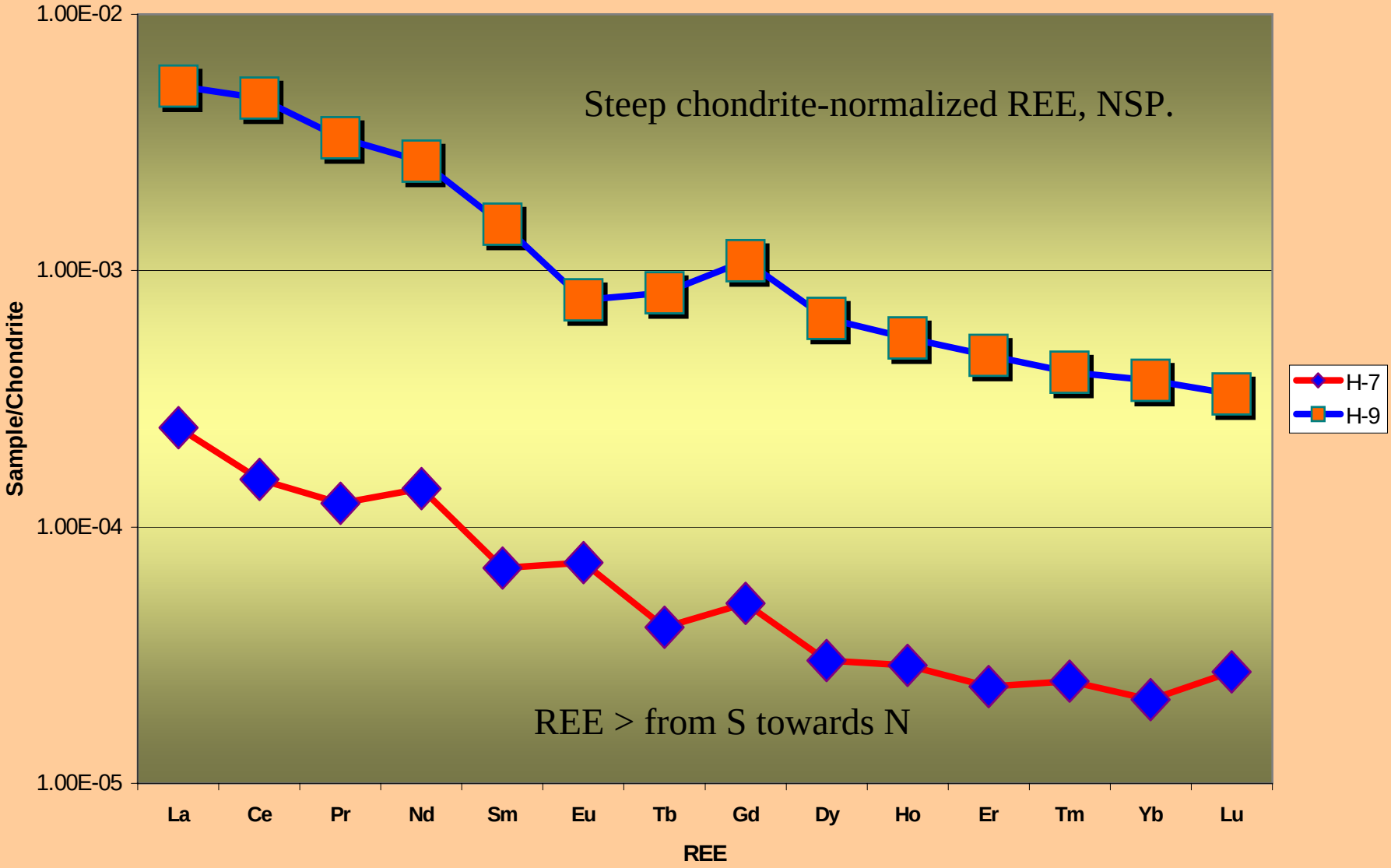
The other atmospheric compounds, such as O_2 , Ar and Ne, are present in considerable amounts, although only Ar and Ne have maintained their original relative contents (Ne/Ar ratios are comprised in the area of AWS values.

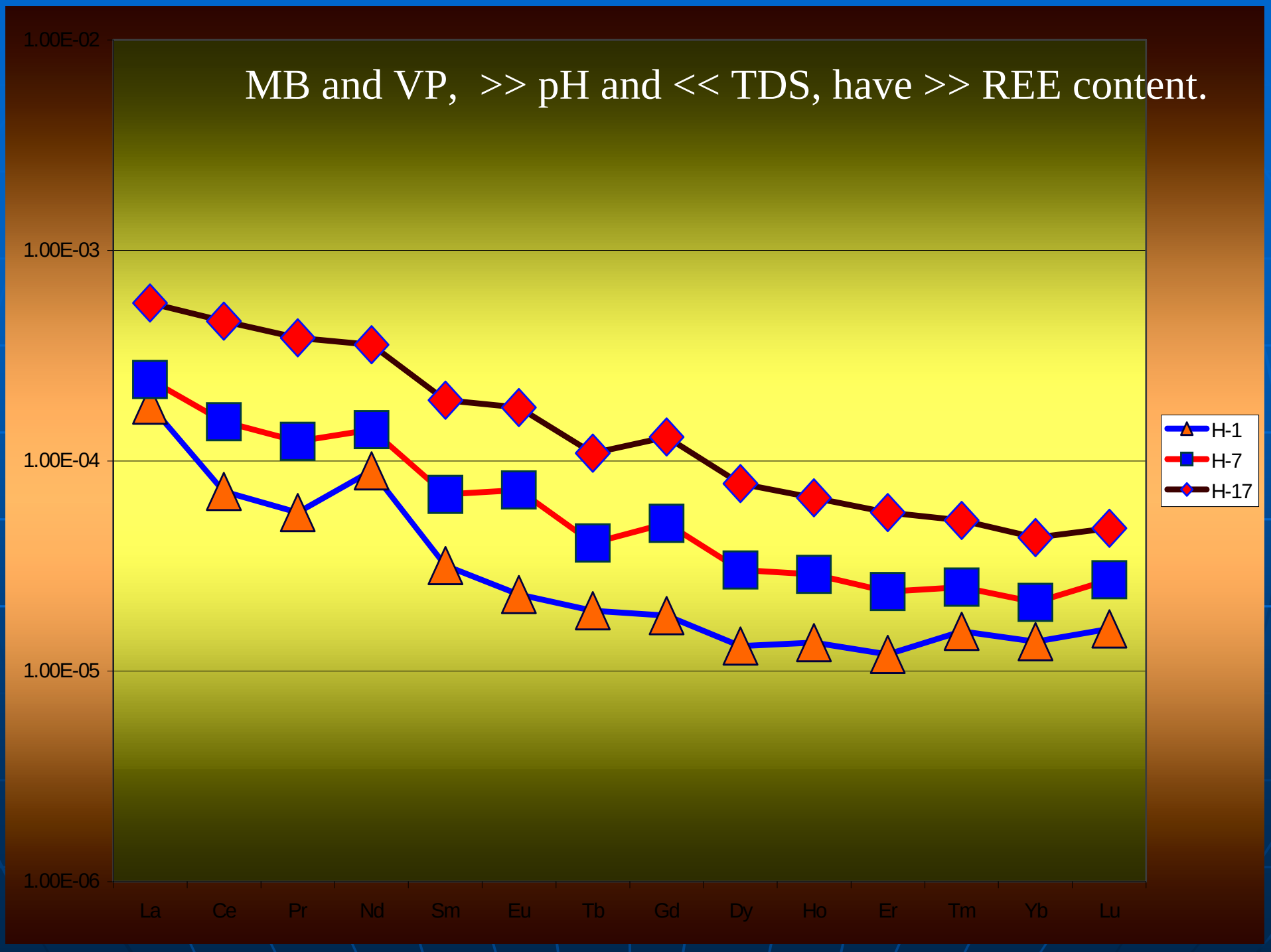


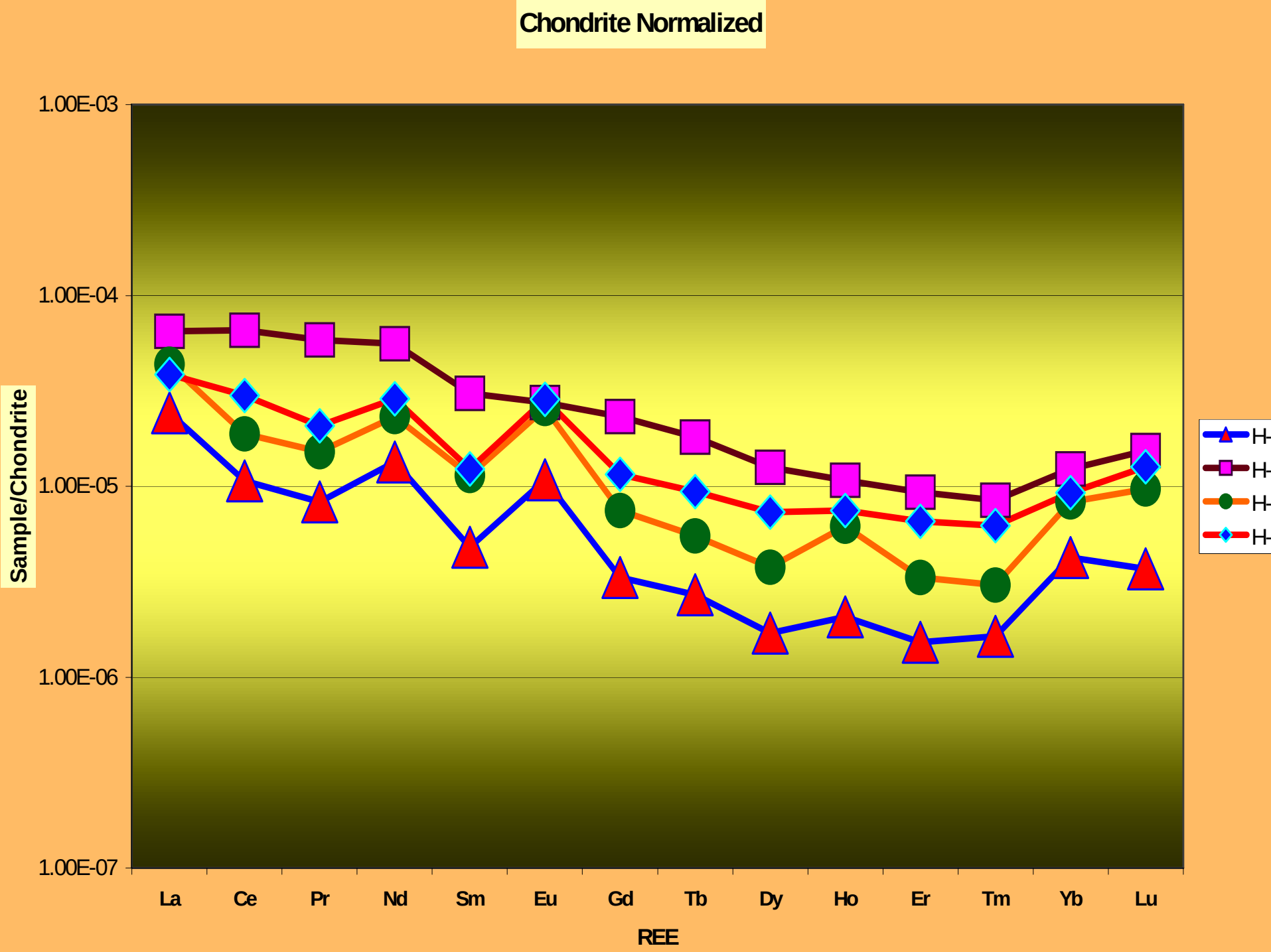
Differently O_2/Ar and O_2/Ne ratios are lower with respect to AWS values, probably due to O_2 consumption during redox reactions.

Rare Earth Elements

Yemen Data 2
Chondrite Normalized




MB and VP, >> pH and << TDS, have >> REE content.
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
La
Ce
Pr
Nd
Sm
Eu
Tb
Gd
Dy
Ho
Er
Tm
Yb
Lu
H-1
H-7
H-17


Chondrite Normalized
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
Sample/Chondrite
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
REE
H-
H-
H-
H-

GEOTHERMAL APPLICATIONS

* Geothermal (heating, cooling and small-scale industry).

* Thermal and thermomineral (therapeutic thermal treatment, and producing mineral waters).

* Hydrologic (agriculture) applications, and

* Production of electricity.

CONCLUSIONS

* Low enthalpy resources (60-80 °C) in the areas covered by sedimentary rocks.

* Medium enthalpy resources (100-140 °C) in the metamorphic basement areas.

* High enthalpy resources (>140<250 °C) are associated with the western Yemen volcanic province.

CONCLUSIONS

- * It is possible to predict high-enthalpy potential in some regions of the country and this is indicated by:

- * The fumaroles at Dhamar (Al-Lisi area), and the high surface T at Al-Qafr area.

- * The high geophysical conductive thermal anomaly beneath the Yemeni rift related area.

CONCLUSIONS

- * The high heat flow in the Red Sea area,
-
- * The positive Eu anomaly from some hot springs areas may indicate higher T exceeding 200 °C,
- * The relatively high He and Ar isotopic ratios,
- * The shift found in the Oxy.-D disc. Diag.

ACKNOWLEDGEMENTS

- Ministry of Oil and Minerals, Yemen,
- CIES, Washington DC, U. S. A,
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- Idaho and Washington State Universities,
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- BGR, Hannover-Germany (Katrin Kessler, in particular),
- GEF (particularly Mr. Bernard), and
- The Organizing Committee of this Conference (mainly Dr. Messeret).

Thank you very much for your kind attention