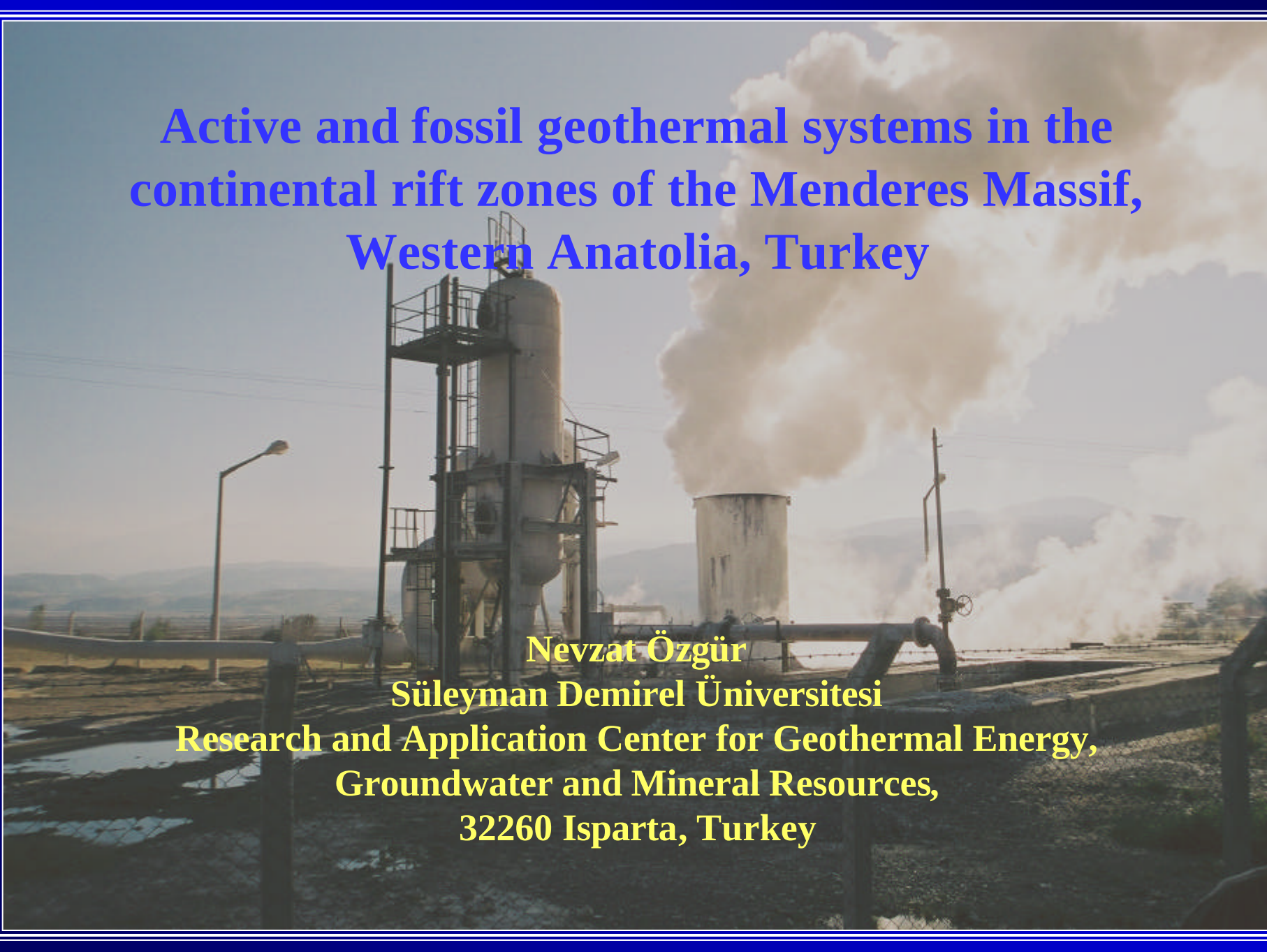
Active and fossil geothermal systems in the continental rift zones of the Menderes Massif, Western Anatolia, Turkey



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The aims of the investigation:

- **Geological and petrographic investigations to describe the relationship between active and fossil geothermal waters, tectonic features, and volcanics in the rift zones of the Menderes Massif, western Anatolia, Turkey.**

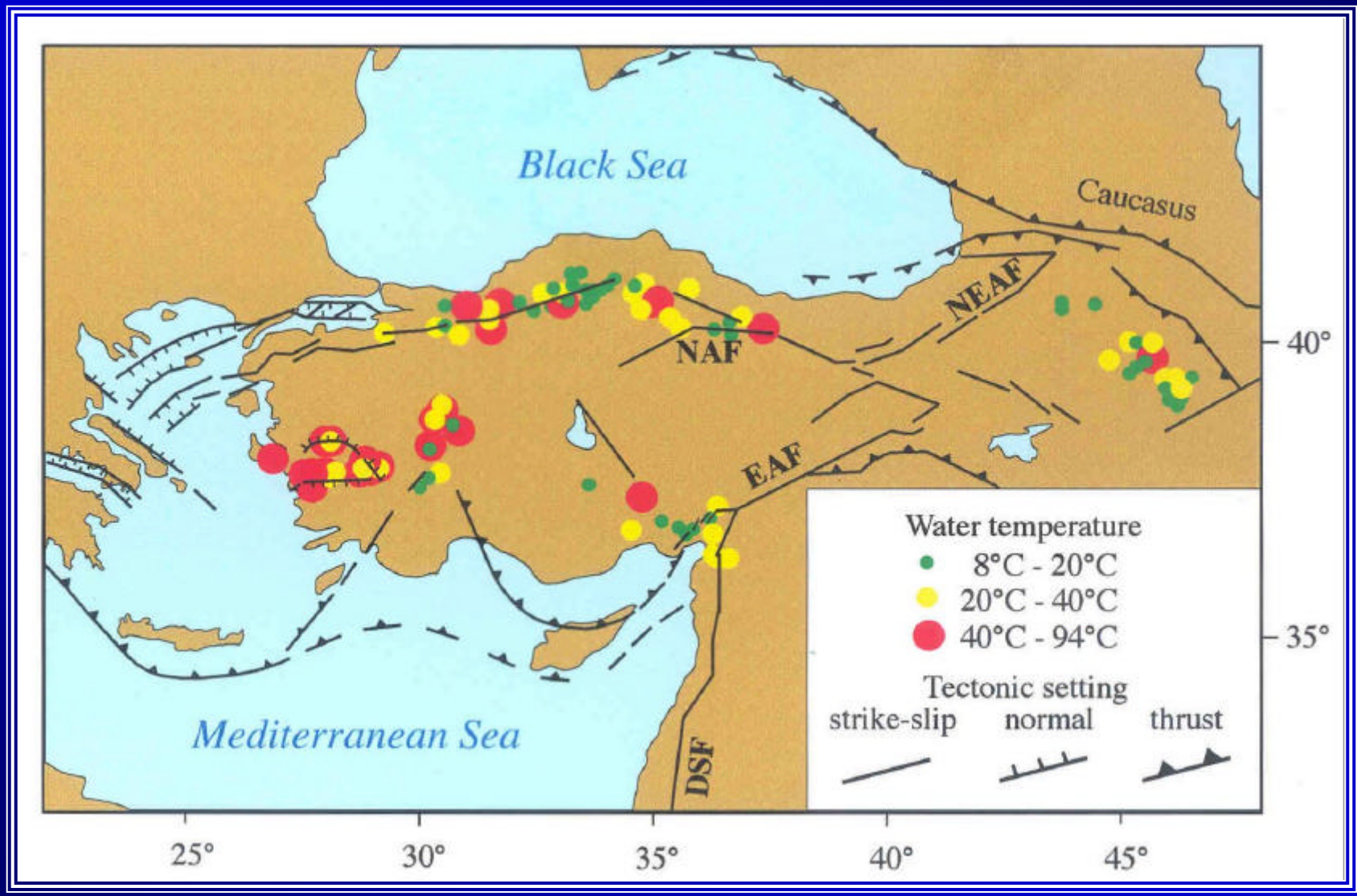
- **Petrographic, geochemical and isotope geochemical investigations to describe the fluid-rock interaction in the active and fossil thermal fields of the rift zones in the Menderes Massif.**

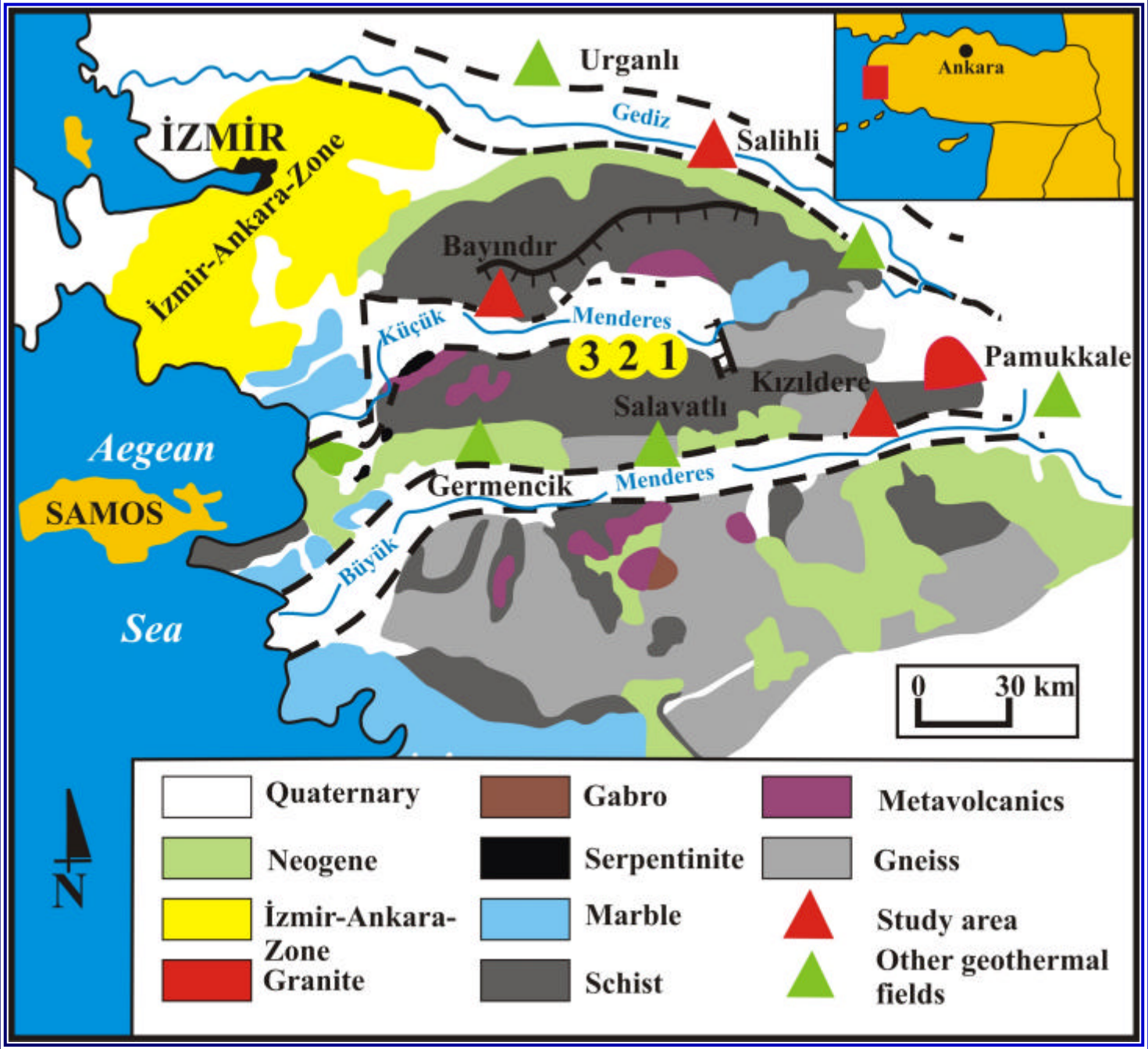
- **Microscopic and microthermometric investigations to understand the ore and alteration mineral assemblage of fossil geothermal systems and mineral precipitations of active geothermal systems in the rift zones of the Menderes Massif.**

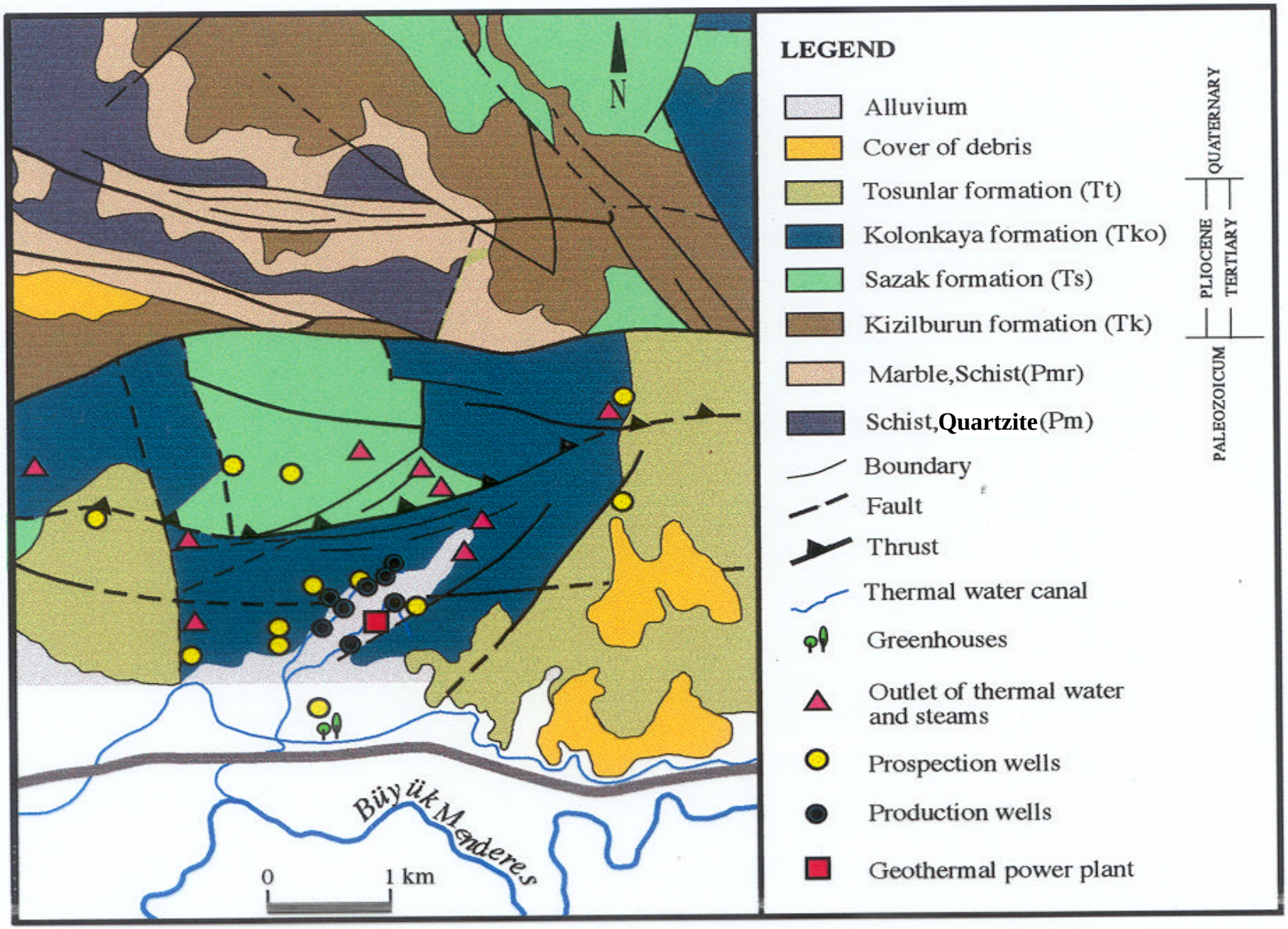
- **Geochemical distributions of the major and trace elements in the rocks and ores of the fossil geothermal systems, and the element contents in the recent mineral precipitations from the thermal waters.**

- **Hydrogeological, hydrogeochemical and isotope geochemical investigations to describe the origin and genesis of the thermal waters.**

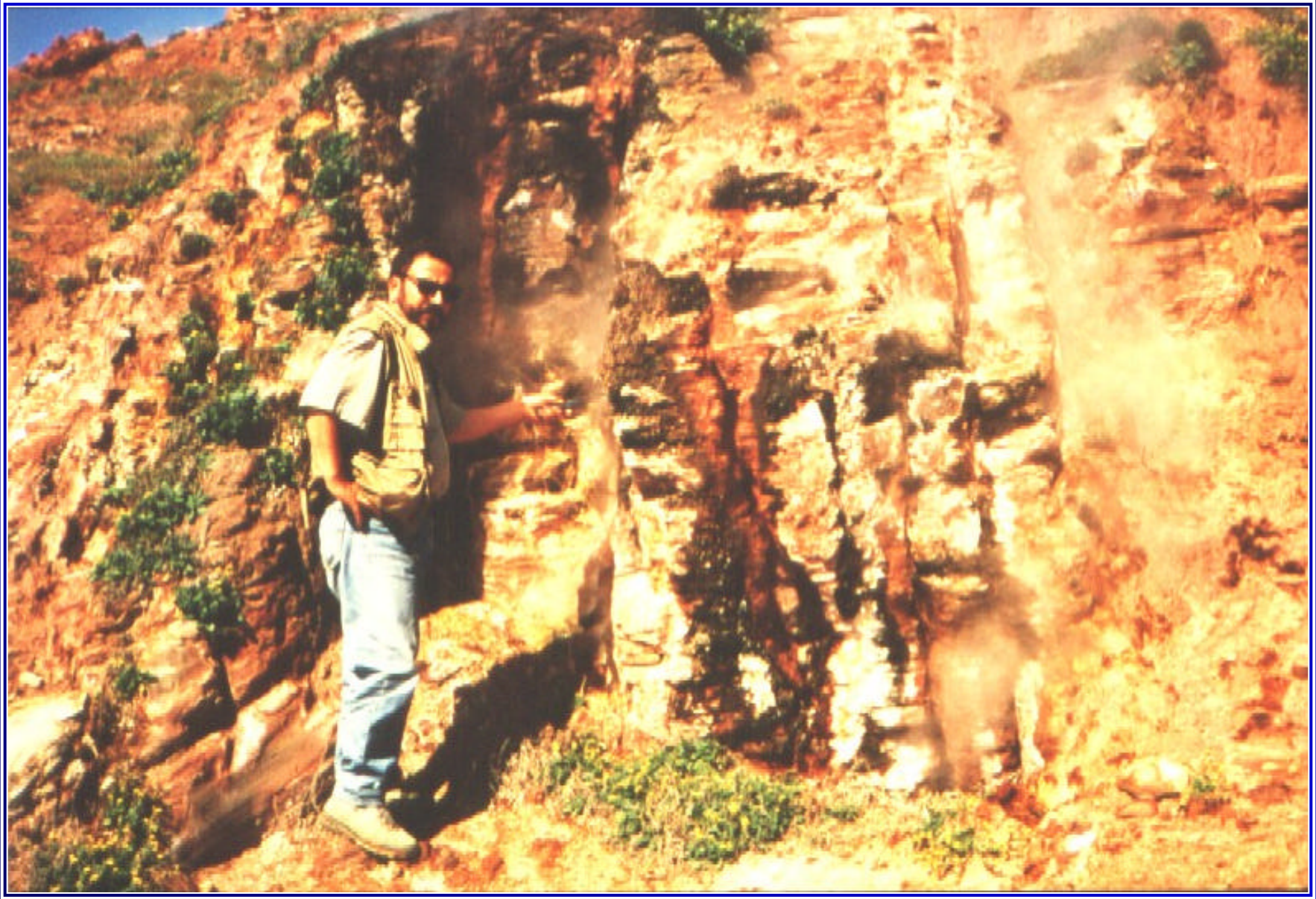
- **Hydrogeochemical modelling of fluid-rock interaction in thermal systems and short consideration of active and fossil geothermal systems.**

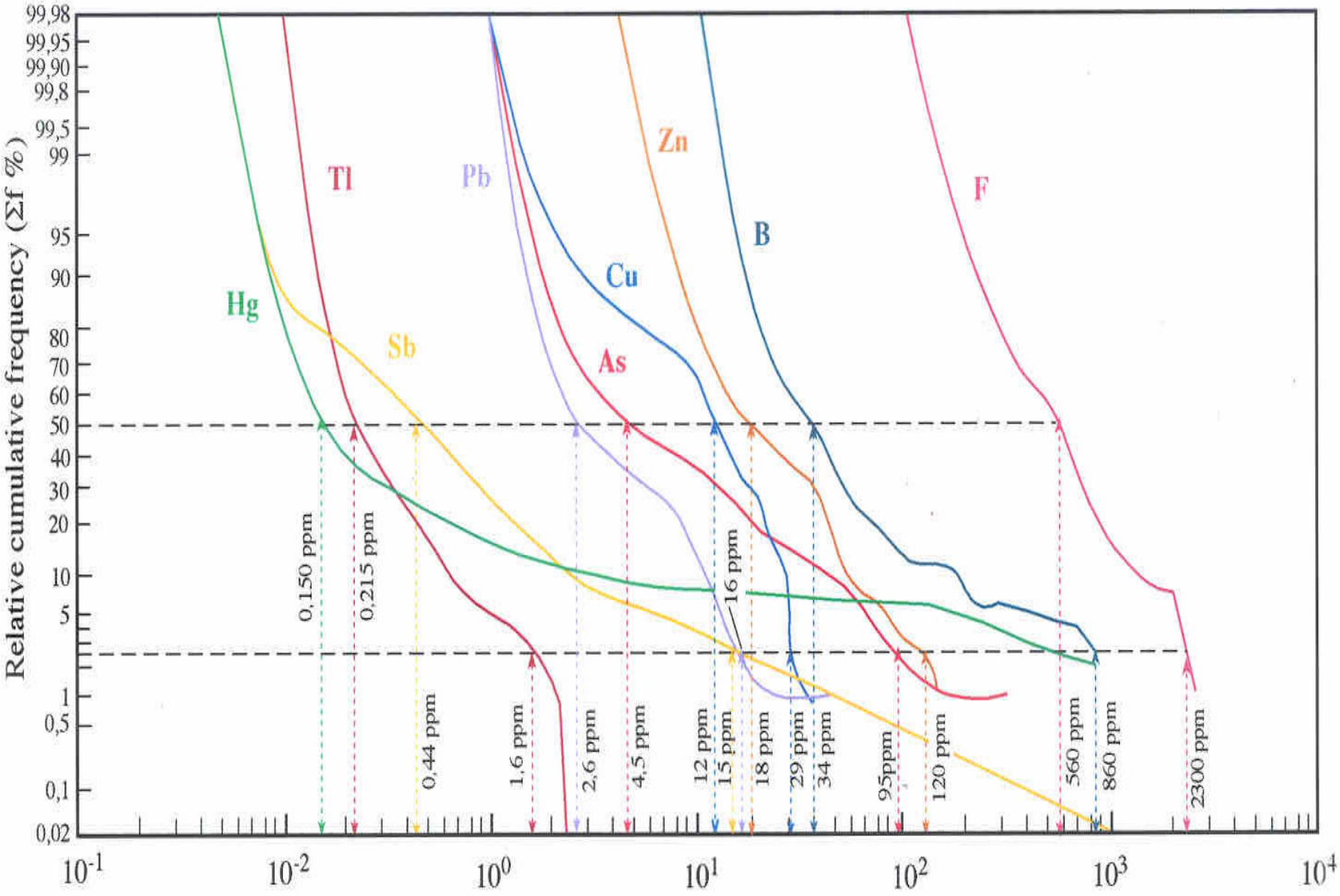

Black Sea
Caucasus
NEAF
NAF
EAF
DSF
Mediterranean Sea
Water temperature
8°C - 20°C
20°C - 40°C
40°C - 94°C
Tectonic setting
strike-slip
normal
thrust
40°
35°
25°
30°
35°
40°
45°

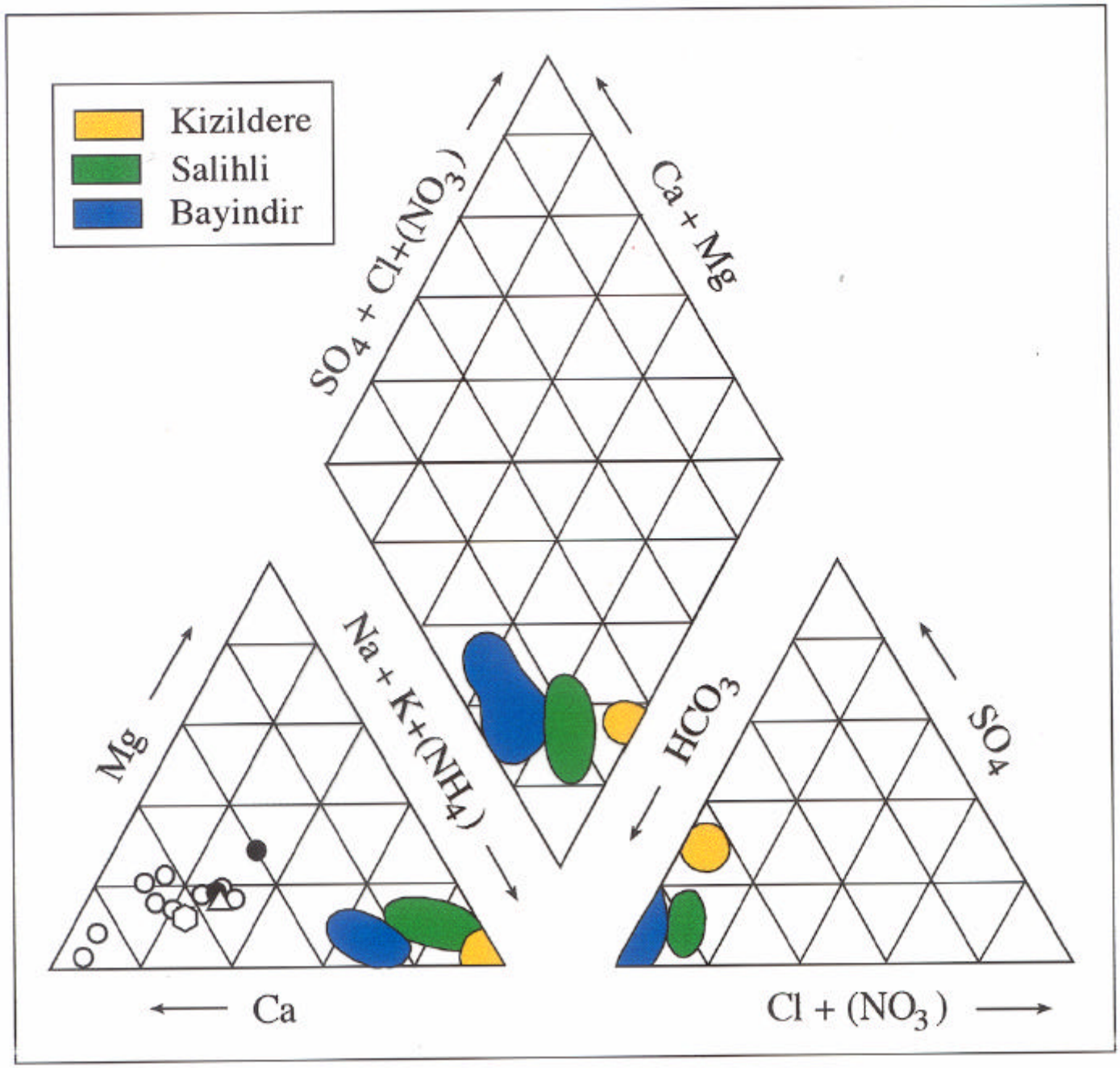

Urganlı
Gediz
Salihli
İZMİR
İzmir-Ankara-Zone
Bayındır
Küçük
Menderes
3 2 1
Kızıldere
Pamukkale
Salavatlı
Aegean
SAMOS
Germencik
Menderes
Büyük
Sea
Ankara
0 30 km
N
Quaternary
Neogene
İzmir-Ankara-Zone Granite
Gabro
Serpentinite
Marble
Schist
Metavolcanics
Gneiss
Study area
Other geothermal fields

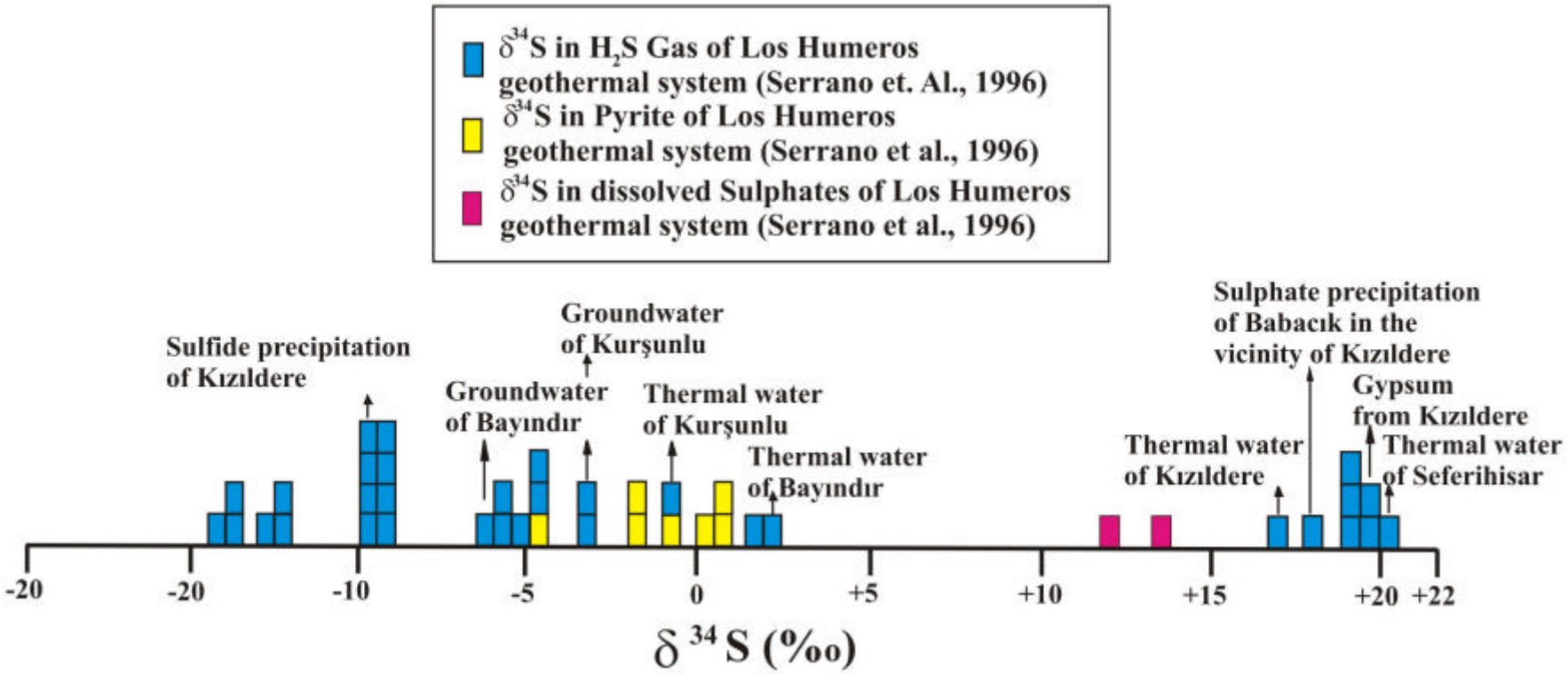

N
LEGEND
Alluvium
Cover of debris
Tosunlar formation (Tt)
Kolonkaya formation (Tko)
Sazak formation (Ts)
Kizilburun formation (Tk)
Marble,Schist(Pmr)
Schist,Quartzite(Pm)
Boundary
Fault
Thrust
Thermal water canal
Greenhouses
Outlet of thermal water and steams
Prospection wells
Production wells
Geothermal power plant
QUATERNARY
PLIOCENE
TERTIARY
PALEOZOICUM
Büyük Menderes
0
1 km

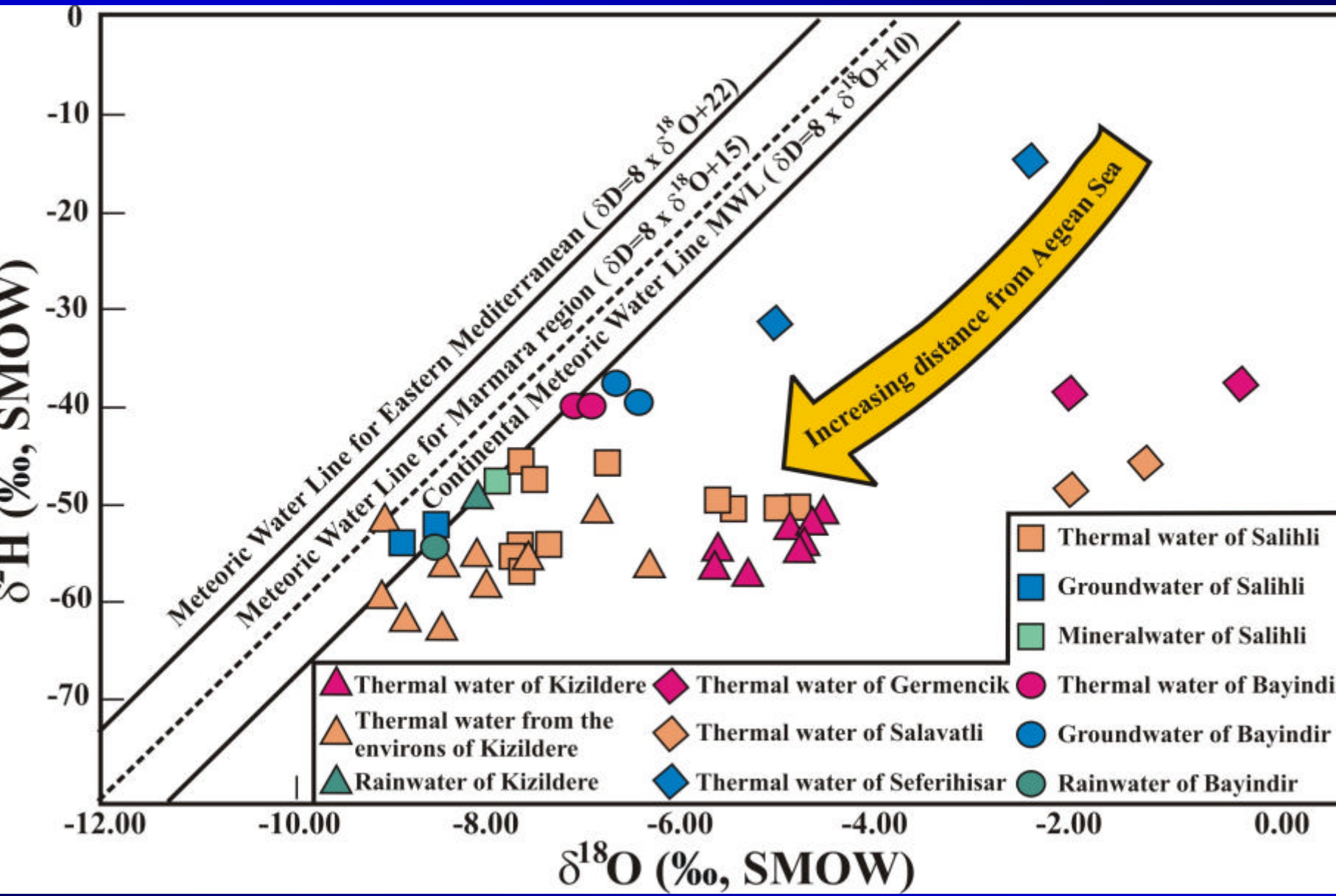
Geothermal field of Kizildere

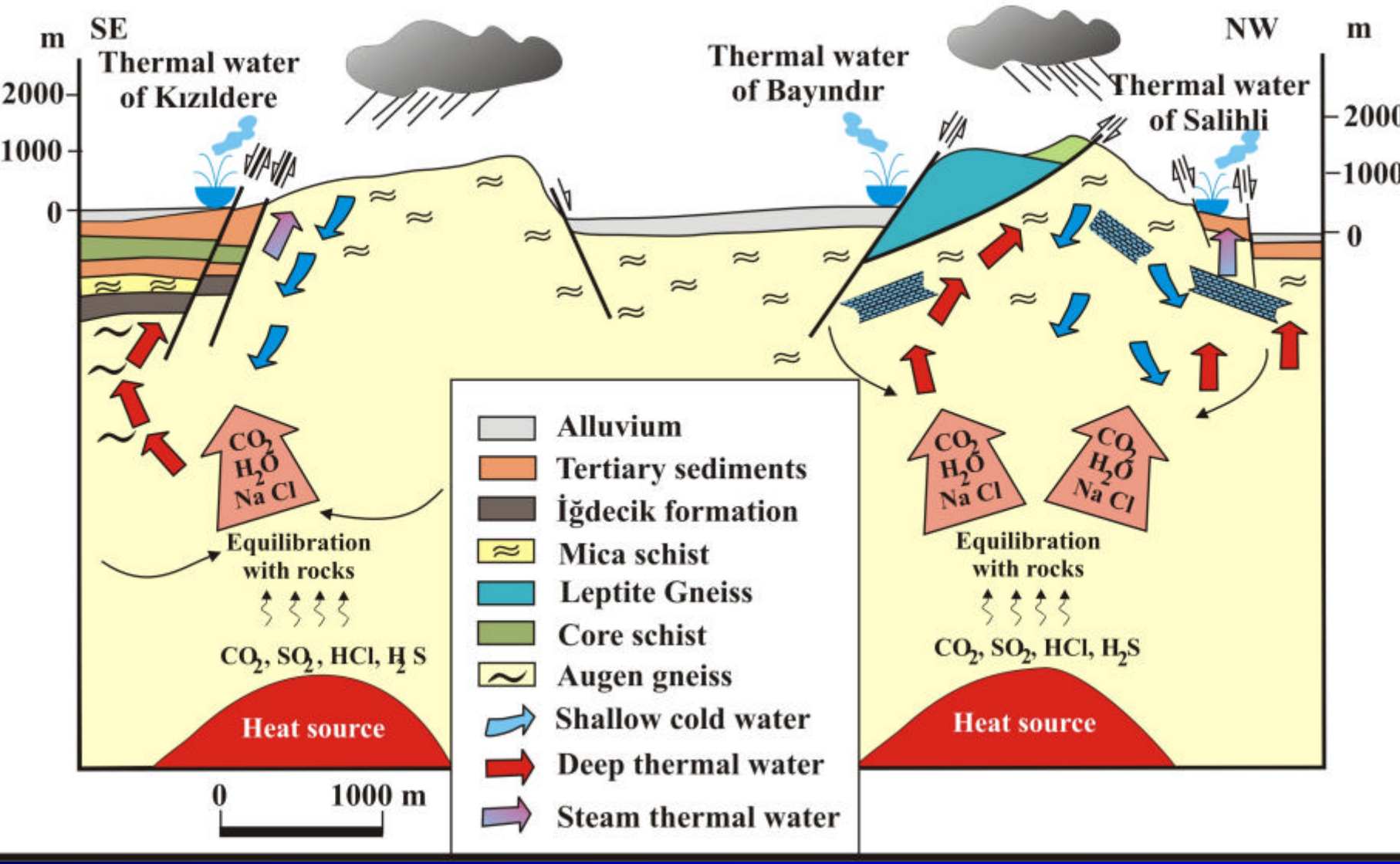


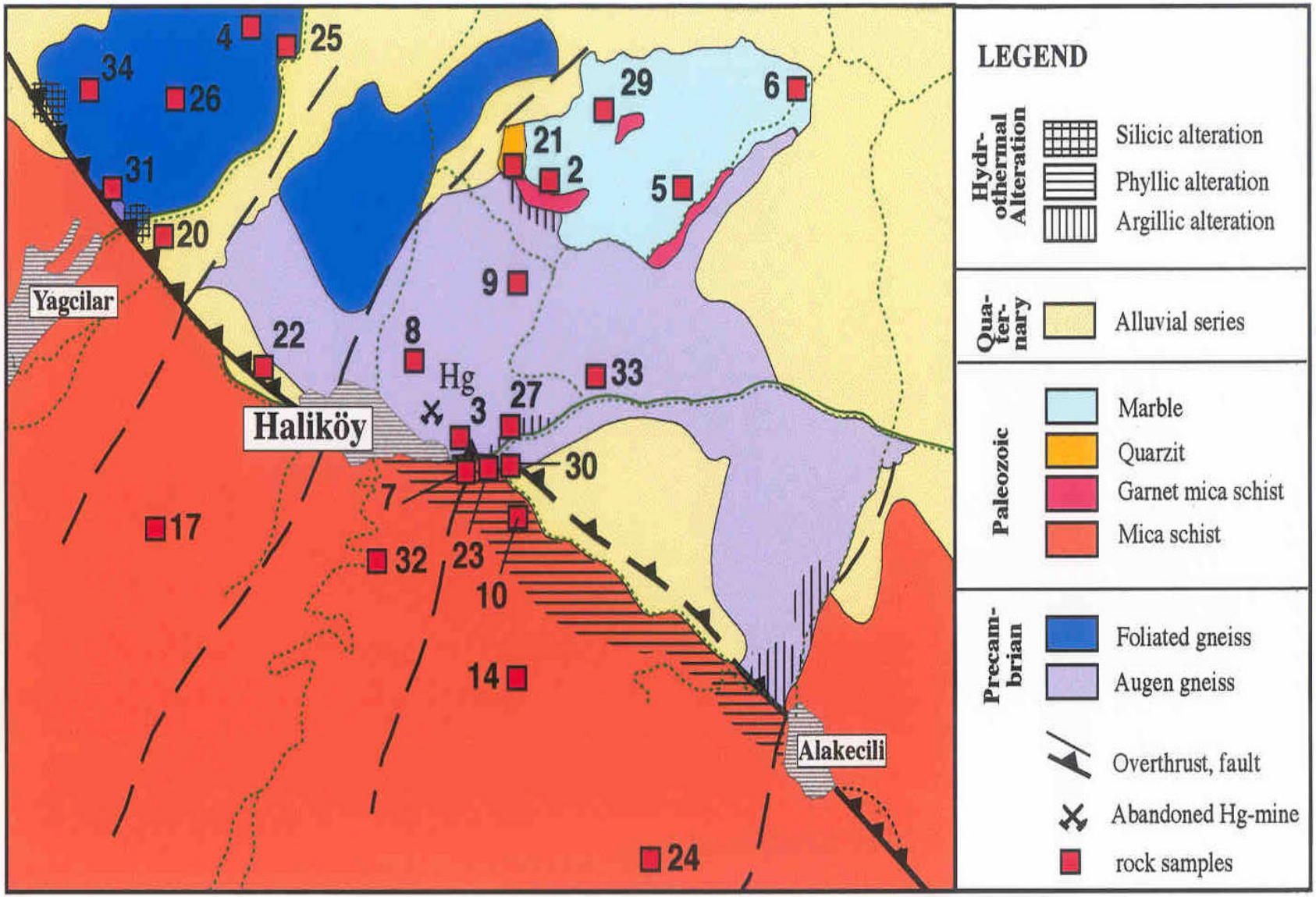

Relative cumulative frequency (Σf %)
99,98
99,95
99,90
99,8
99,5
99
95
90
80
70
60
50
40
30
20
10
5
1
0,5
0,1
0,02
Hg
Tl
Pb
Zn
F
B
Cu
As
Sb
0,150 ppm
0,215 ppm
0,44 ppm
1,6 ppm
2,6 ppm
4,5 ppm
12 ppm
15 ppm
16 ppm
18 ppm
29 ppm
34 ppm
95ppm
120 ppm
560 ppm
860 ppm
2300 ppm
10-1
10-2
100
101
102
103
104

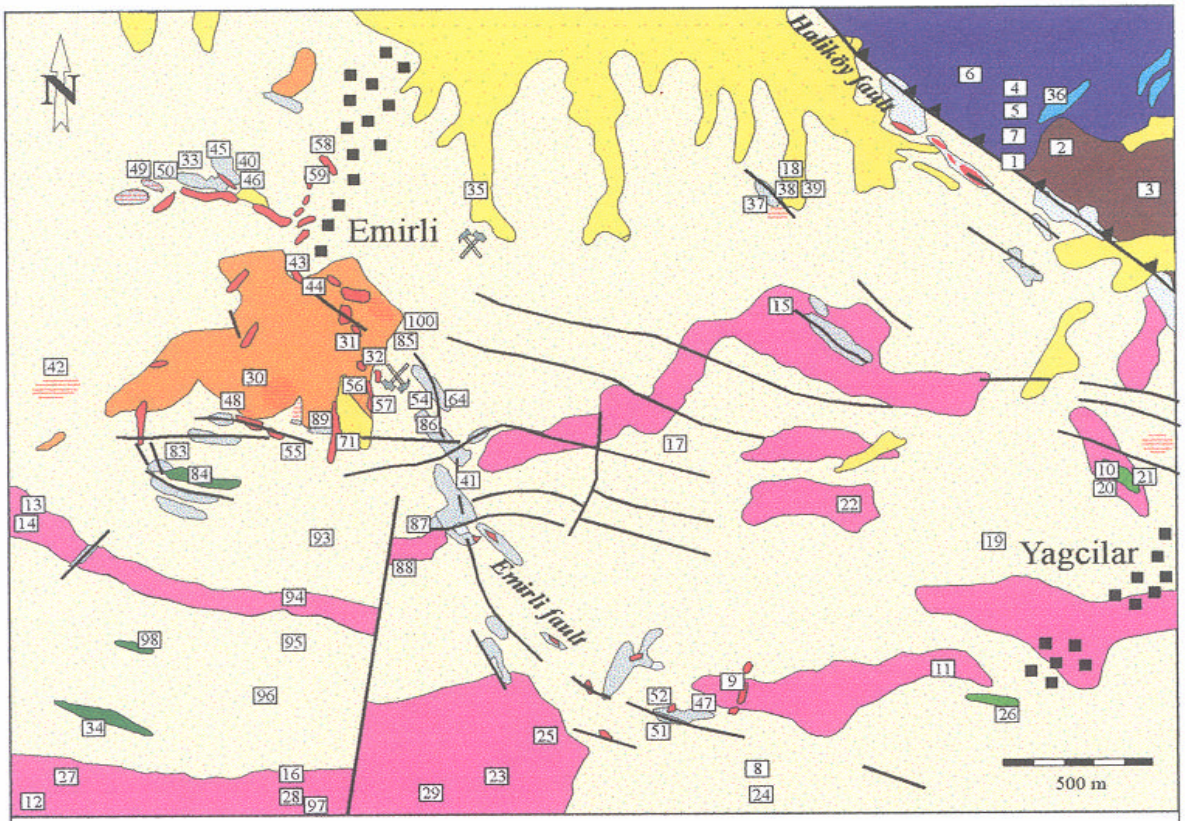

Kizildere
Salihli
Bayindir
$SO_4 + Cl + (NO_3)$
$Ca + Mg$
$Na + K + (NH_4)$
Mg
Ca
HCO_3
SO_4
$Cl + (NO_3)$


δ34S in H2S Gas of Los Humeros geothermal system (Serrano et. Al., 1996)
δ34S in Pyrite of Los Humeros geothermal system (Serrano et al., 1996)
δ34S in dissolved Sulphates of Los Humeros geothermal system (Serrano et al., 1996)
Sulfide precipitation of Kızıldere
Groundwater of Kurşunlu
Groundwater of Bayındır
Thermal water of Kurşunlu
Thermal water of Bayındır
Sulphate precipitation of Babacık in the vicinity of Kızıldere
Gypsum from Kızıldere
Thermal water of Kızıldere
Thermal water of Seferihisar
-20
-20
-10
-5
0
+5
+10
+15
+20
+22
δ 34 S (‰)


Meteoric Water Line for Eastern Mediterranean (δD=8 x δ18O+22)
Meteoric Water Line for Marmara region (δD=8 x δ18O+15)
Continental Meteoric Water Line MWL (δD=8 x δ18O+10)
Increasing distance from Aegean Sea
Thermal water of Salihli
Groundwater of Salihli
Mineralwater of Salihli
Thermal water of Kizildere
Thermal water of Germencik
Thermal water of Bayindi
Thermal water from the environs of Kizildere
Thermal water of Salavatli
Groundwater of Bayindir
Rainwater of Kizildere
Thermal water of Seferihisar
Rainwater of Bayindir
0
-10
-20
-30
-40
-50
-60
-70
δ2H (‰, SMOW)
-12.00
-10.00
-8.00
-6.00
-4.00
-2.00
0.00
δ18O (‰, SMOW)


m
SE
Thermal water of Kızıldere
2000
1000
0
Thermal water of Bayındır
NW
m
Thermal water of Salihli
2000
1000
0
CO2 H2O Na Cl
Equilibration with rocks
CO2, SO2, HCl, H2S
Heat source
CO2 H2O Na Cl
CO2 H2O Na Cl
Equilibration with rocks
CO2, SO2, HCl, H2S
Heat source
Alluvium
Tertiary sediments
İğdecik formation
Mica schist
Leptite Gneiss
Core schist
Augen gneiss
Shallow cold water
Deep thermal water
Steam thermal water
0
1000 m


LEGEND
Hydr-othermal Alteration
Silicic alteration
Phyllic alteration
Argillic alteration
Qua-ter-nary
Alluvial series
Paleozoic
Marble
Quarzit
Garnet mica schist
Mica schist
Precam-brian
Foliated gneiss
Augen gneiss
Overthrust, fault
Abandoned Hg-mine
rock samples
Yağcilar
Haliköy
Hg
Alakecili
4
25
34
26
31
20
29
6
21
2
5
9
22
8
33
27
3
30
7
17
32
23
10
14
24



Quaternary

- Alluvium

Ordovician

Paleozoic

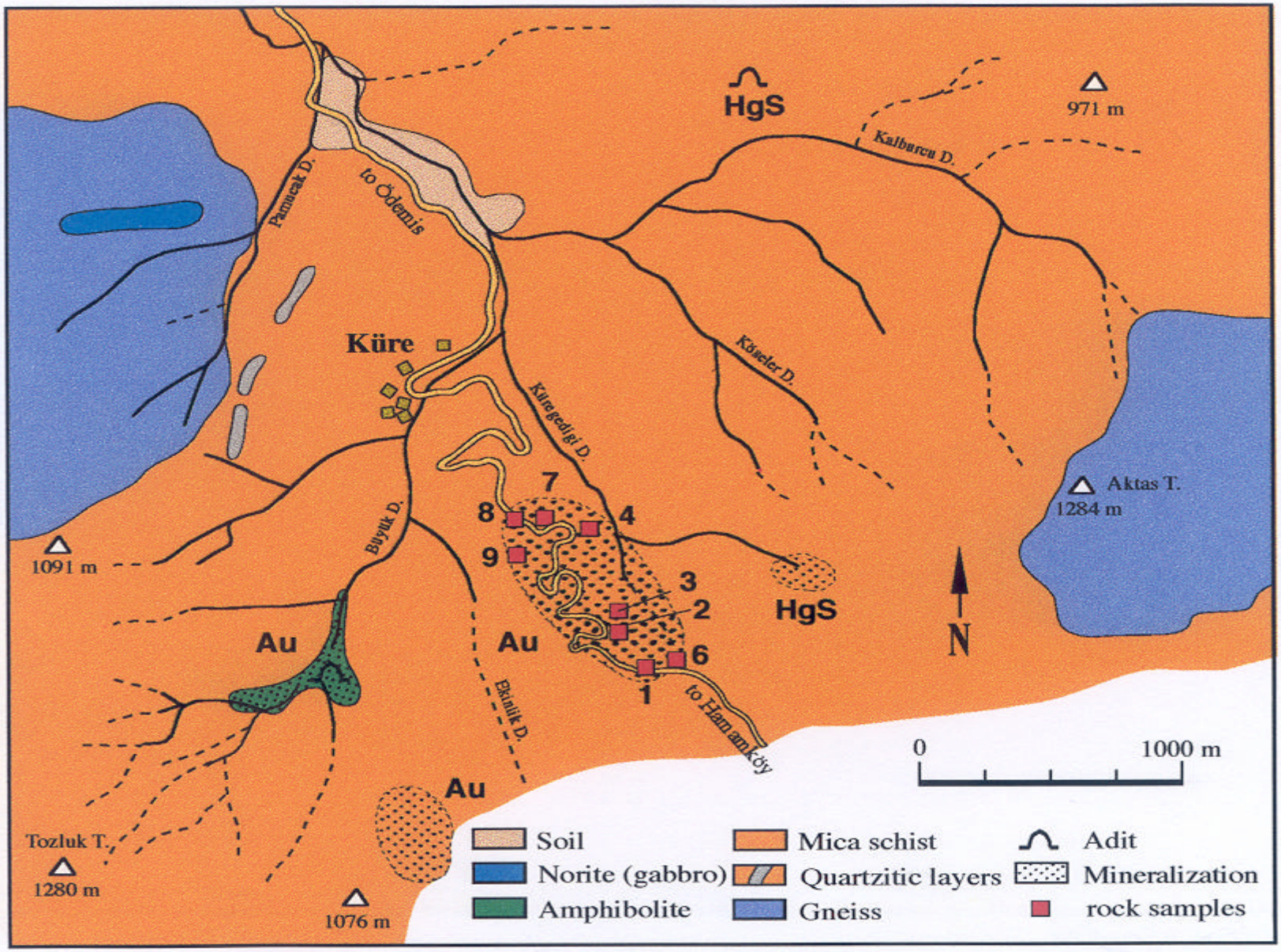
- Quartzite
- Amphibolite-chlorite schist
- Mica schist
- Chlorite schist
- Biotit-chlorite schist

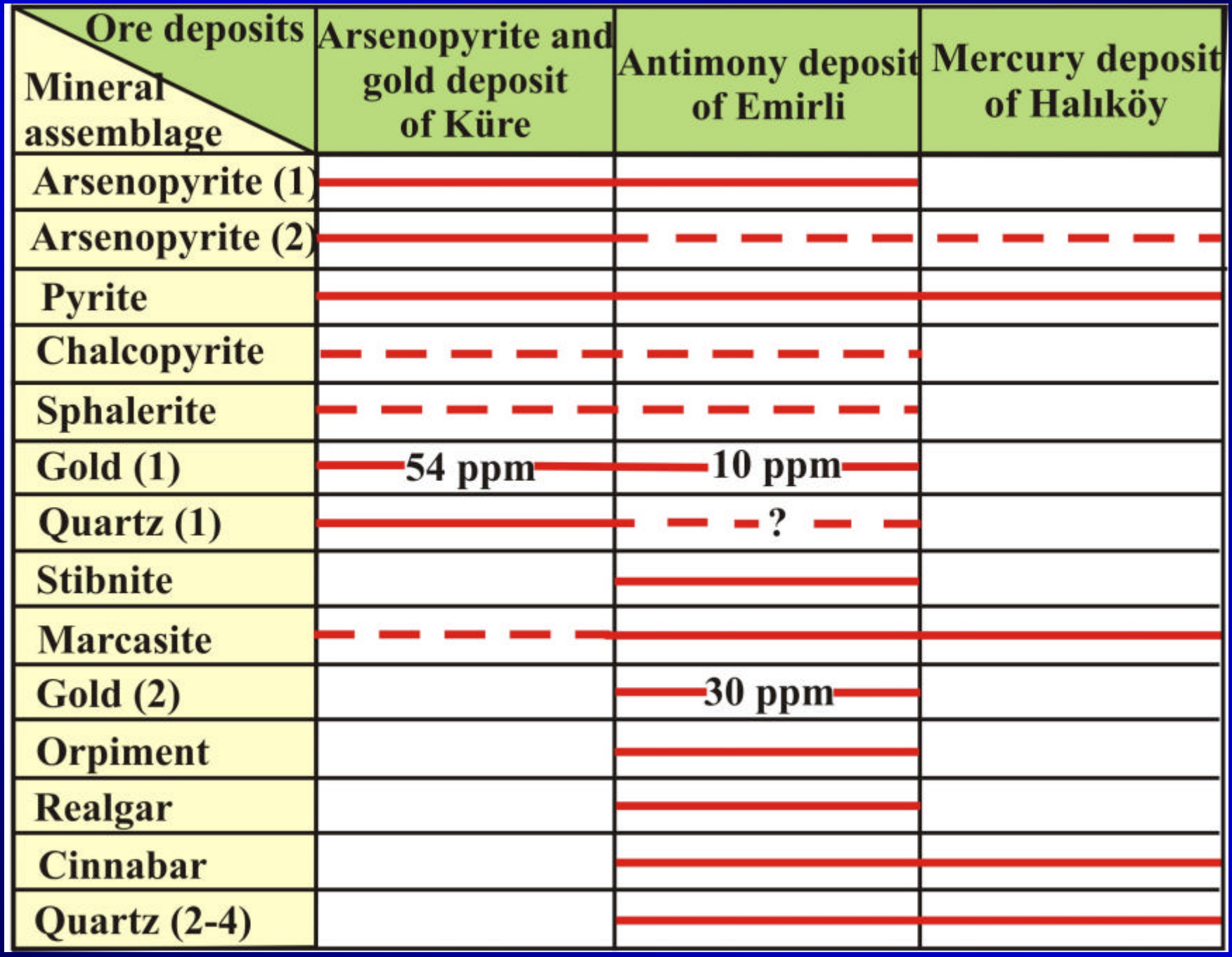
Precambrian/Cambrian

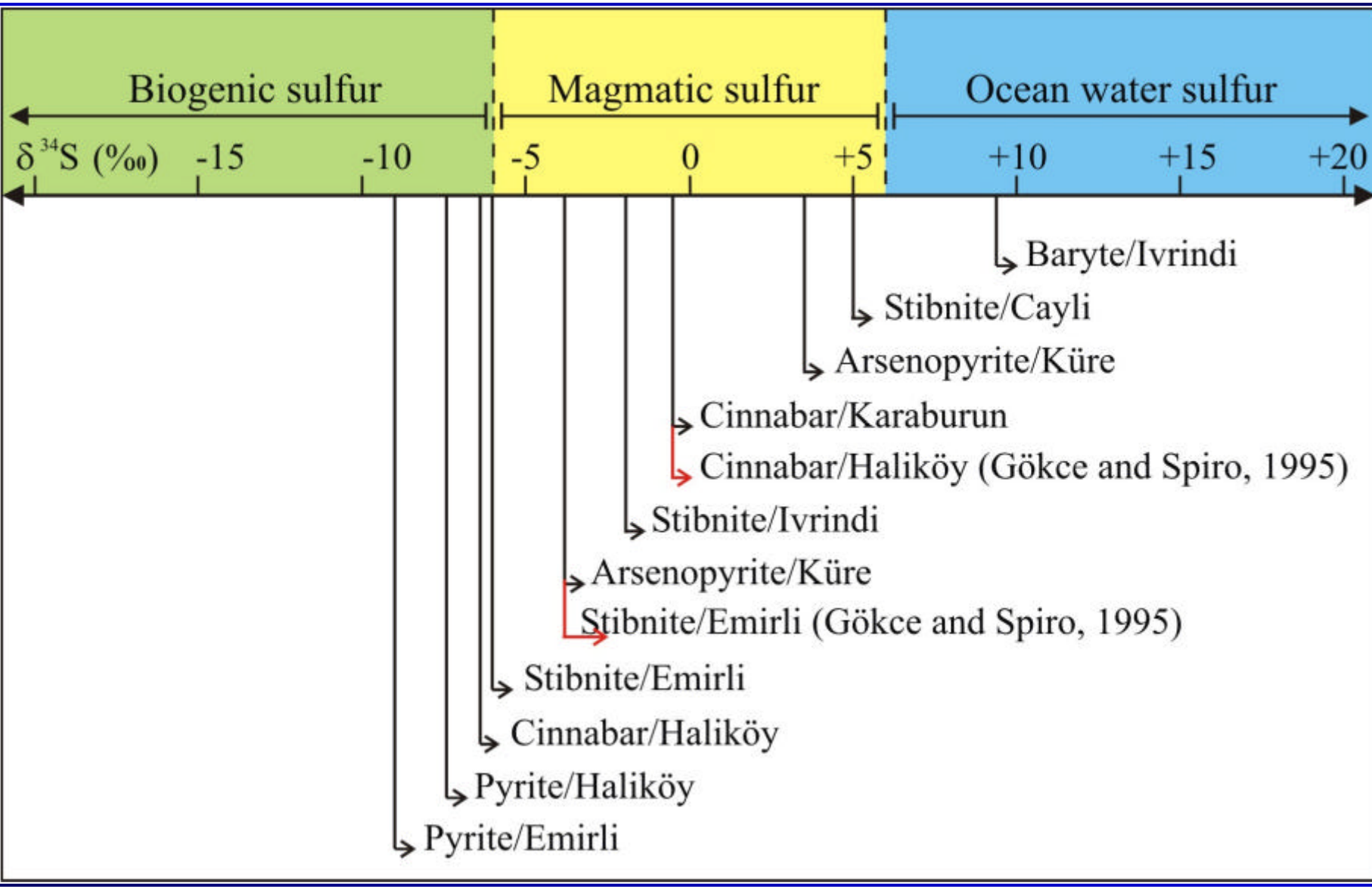
- Foliated gneiss
- Granite gneiss
- Augen gneiss

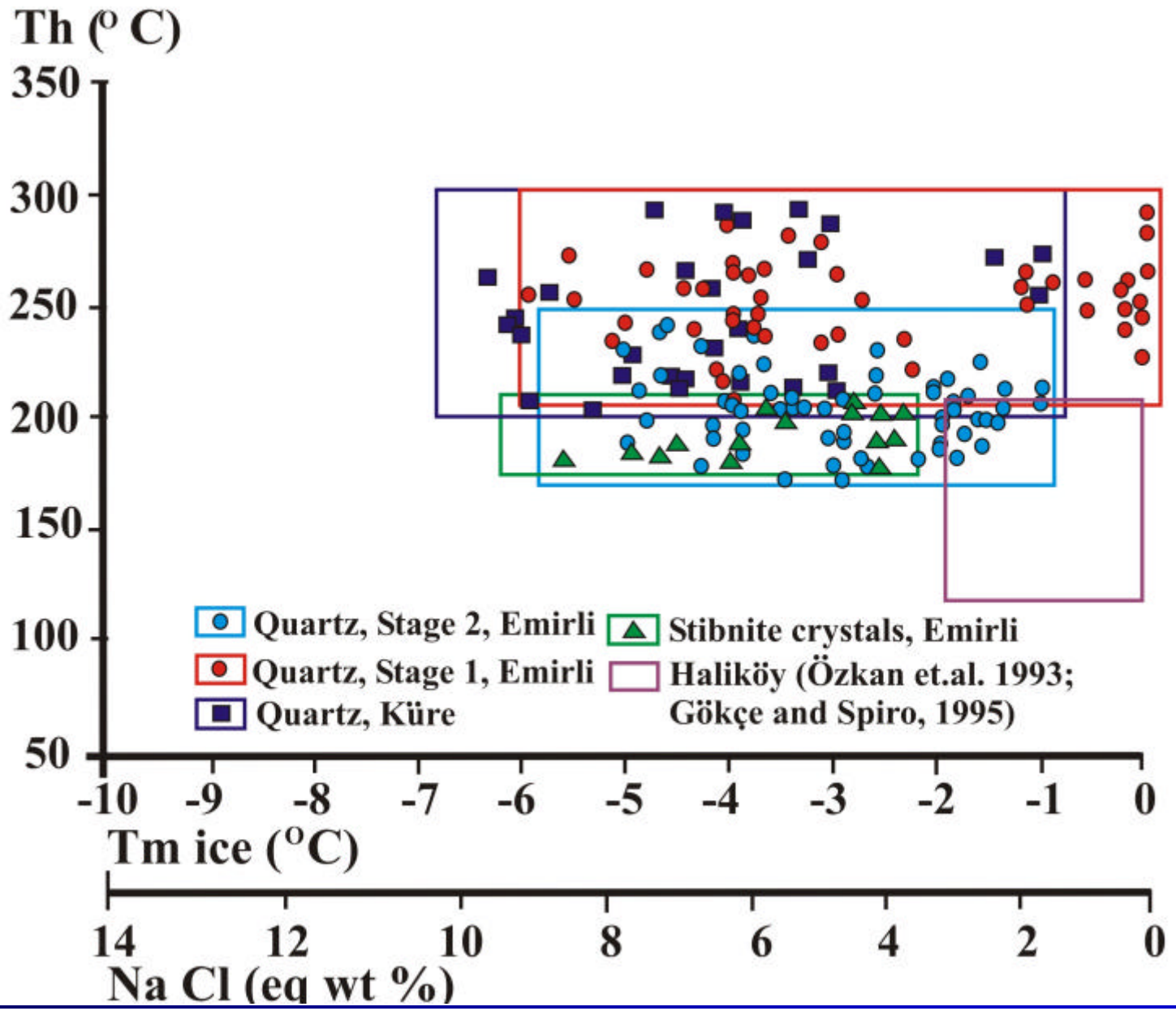
Hydrothermal alteration

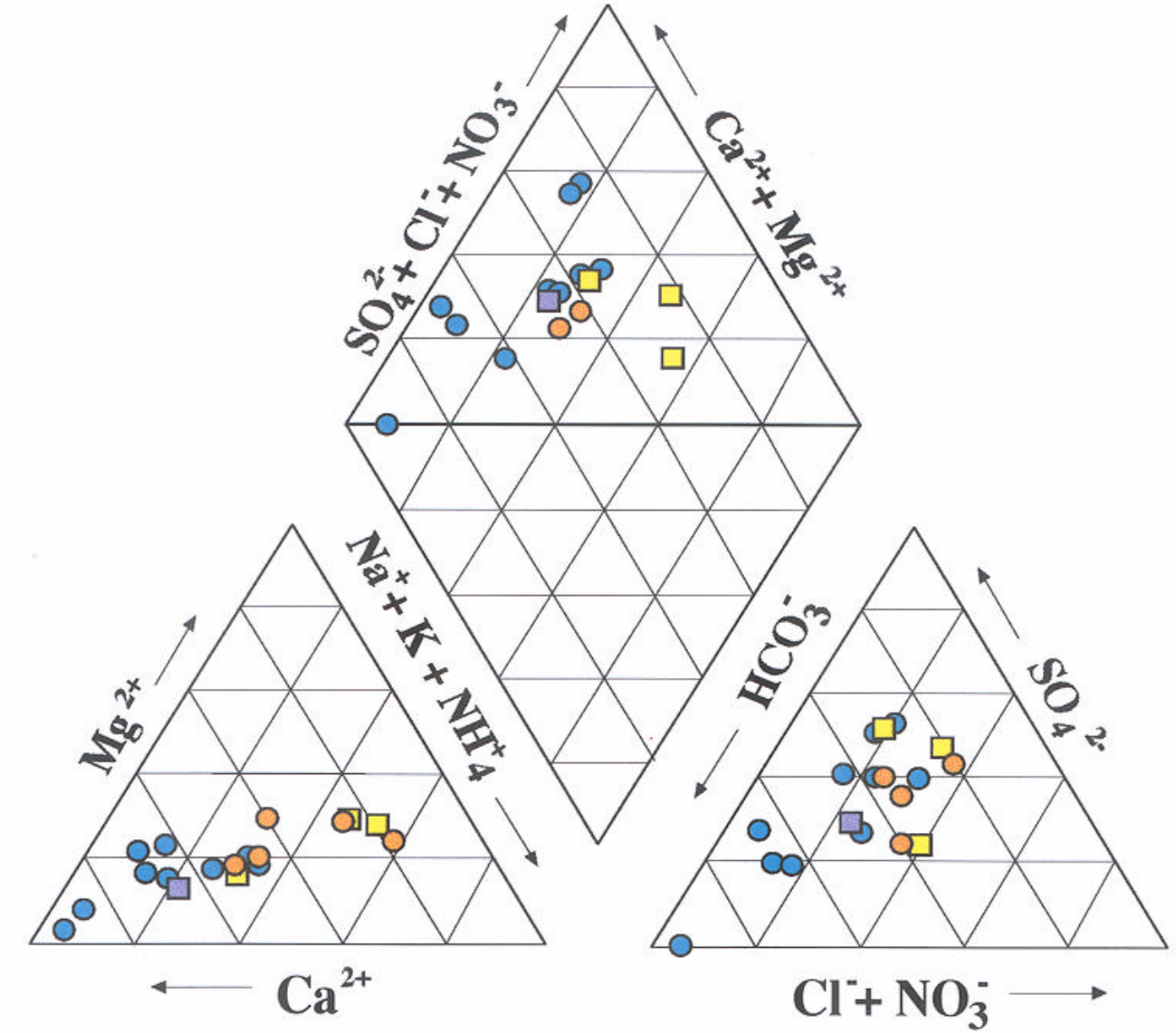
- Silicic alteration ± haematitization
- Phyllic alteration
- Argillic alteration

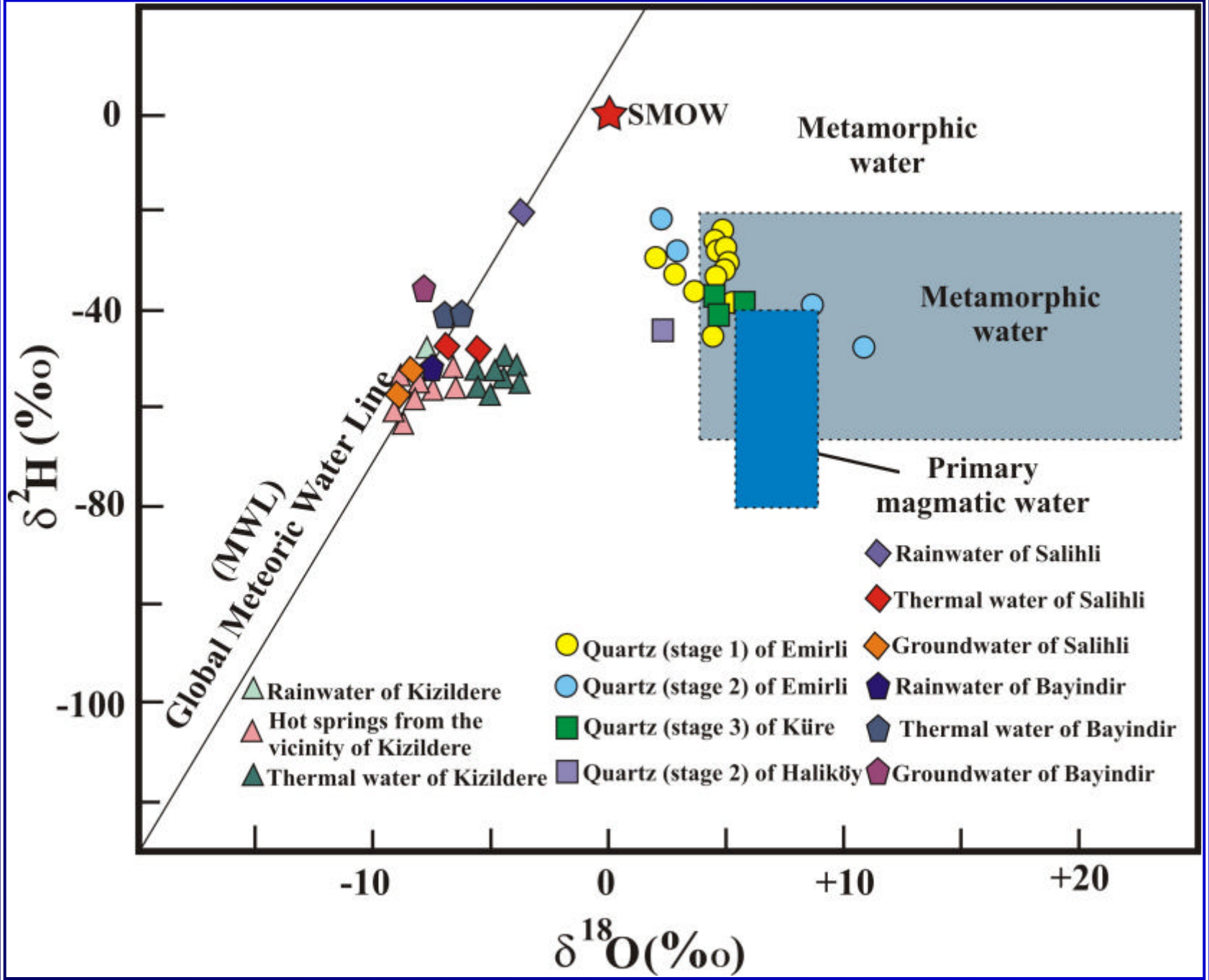

HgS
971 m
Kalburcu D.
Pamucak D.
to Ödemis
Küre
Köseler D.
Küregedigi D.
Aktas T.
1284 m
1091 m
Büyük D.
7
8
4
9
3
2
HgS
N
Au
Au
6
1
to Hamamköy
Ekinlik D.
0
1000 m
Au
Tozluk T.
1280 m
1076 m
Soil
Norite (gabbro)
Amphibolite
Mica schist
Quartzitic layers
Gneiss
Adit
Mineralization
rock samples

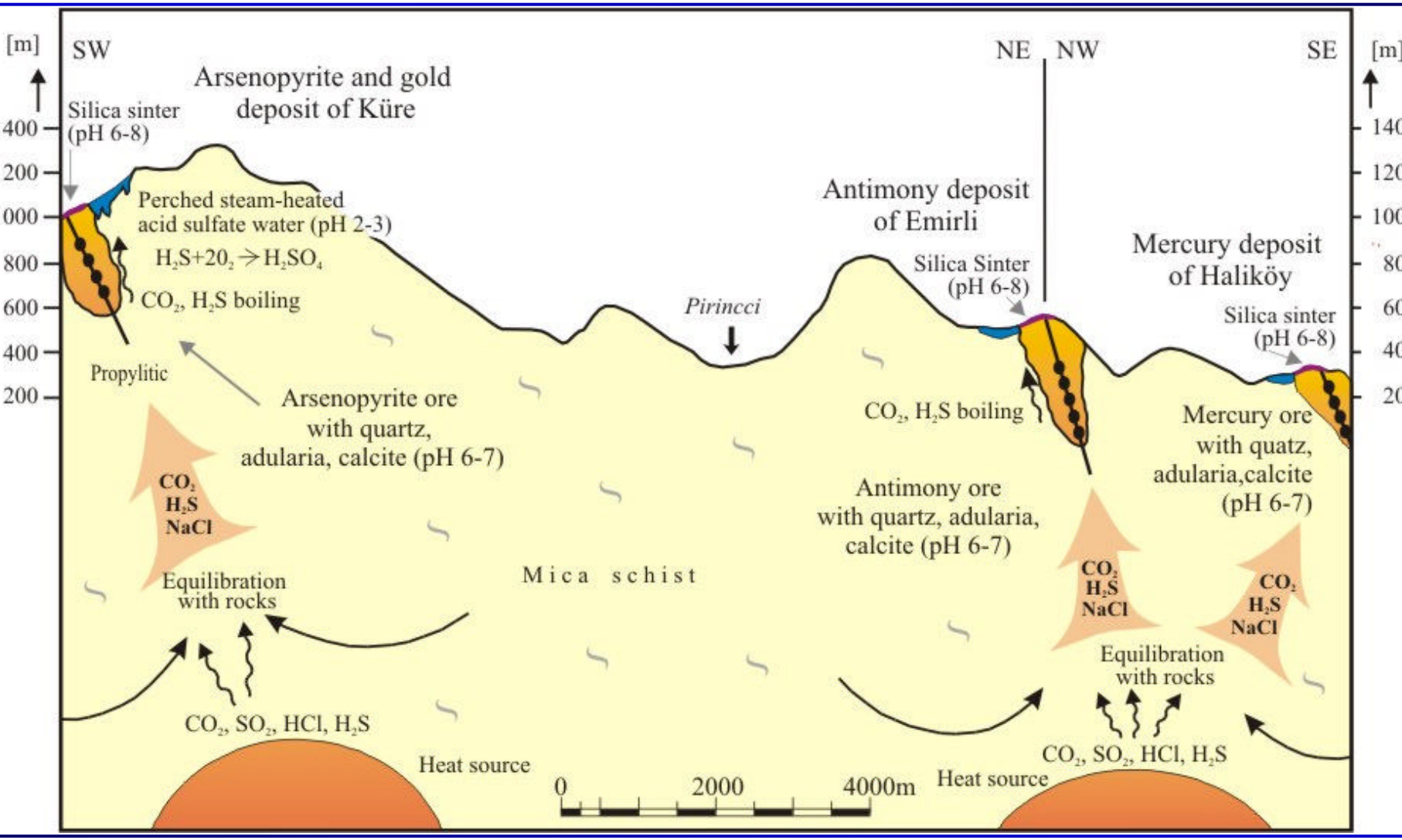

Ore deposits
Mineral assemblage
Arsenopyrite and gold deposit of Küre
Antimony deposit of Emirli
Mercury deposit of Halıköy
Arsenopyrite (1)
Arsenopyrite (2)
Pyrite
Chalcopyrite
Sphalerite
Gold (1)
54 ppm
10 ppm
Quartz (1)
?
Stibnite
Marcasite
Gold (2)
30 ppm
Orpiment
Realgar
Cinnabar
Quartz (2-4)

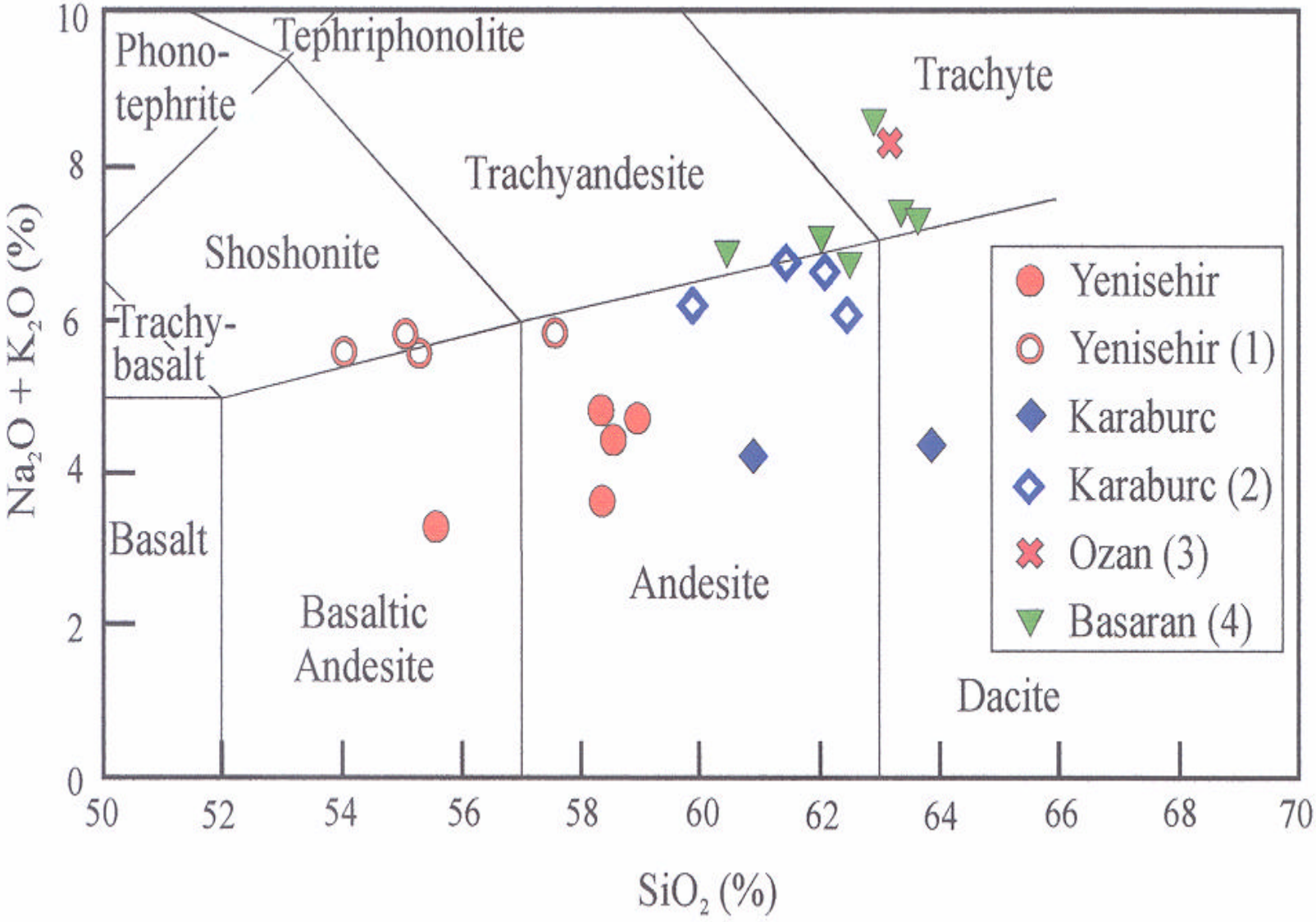

Biogenic sulfur
Magmatic sulfur
Ocean water sulfur
δ 34S (‰)
-15
-10
-5
0
+5
+10
+15
+20
Baryte/Ivrindi
Stibnite/Cayli
Arsenopyrite/Küre
Cinnabar/Karaburun
Cinnabar/Haliköy (Gökce and Spiro, 1995)
Stibnite/Ivrindi
Arsenopyrite/Küre
Stibnite/Emirli (Gökce and Spiro, 1995)
Stibnite/Emirli
Cinnabar/Haliköy
Pyrite/Haliköy
Pyrite/Emirli

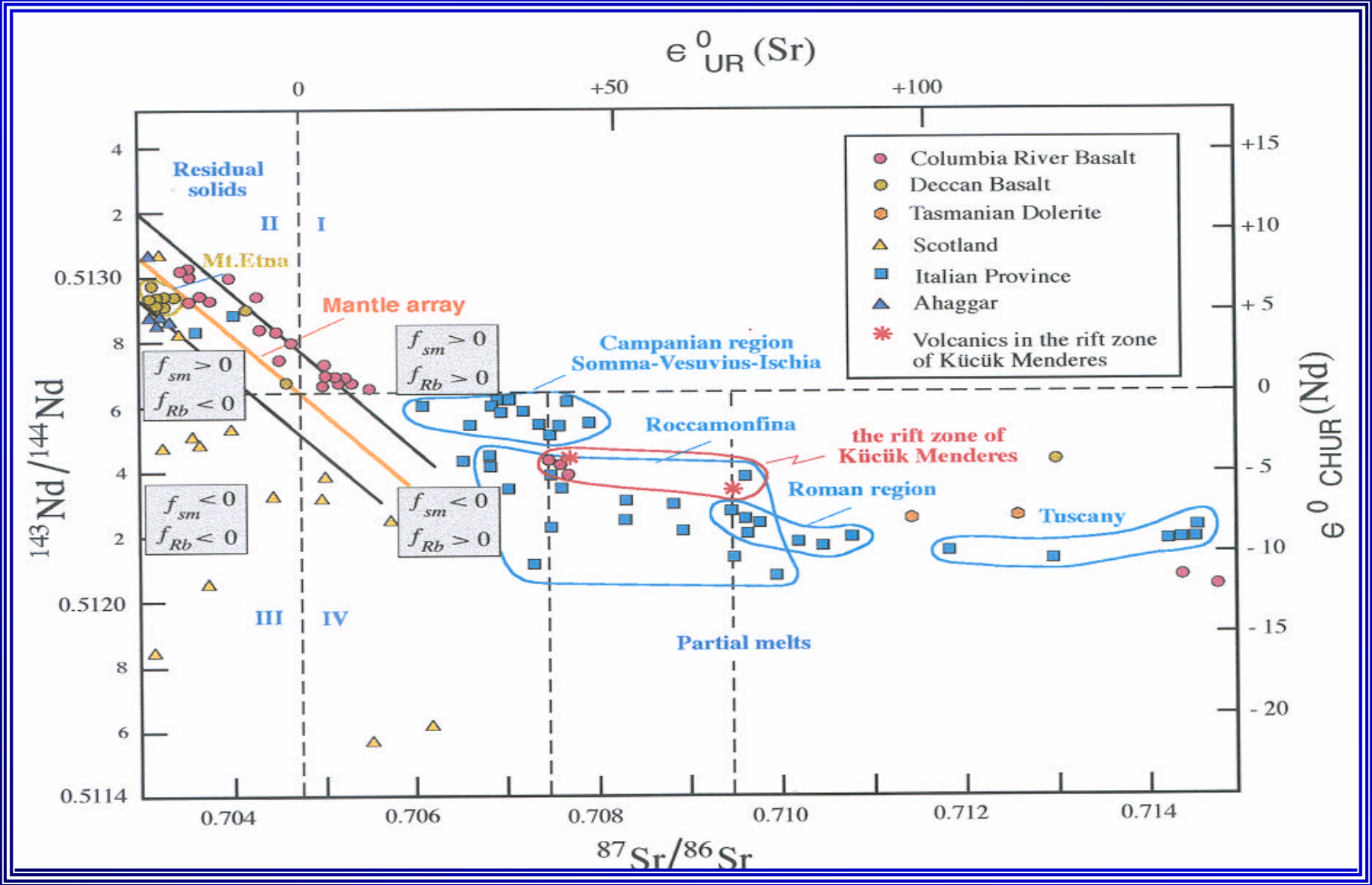

Th (º C)
350
300
250
200
150
100
50
Quartz, Stage 2, Emirli
Quartz, Stage 1, Emirli
Quartz, Küre
Stibnite crystals, Emirli
Haliköy (Özkan et.al. 1993;
Gökçe and Spiro, 1995)
-10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0
Tm ice (°C)
14 12 10 8 6 4 2 0
Na Cl (eq wt %)

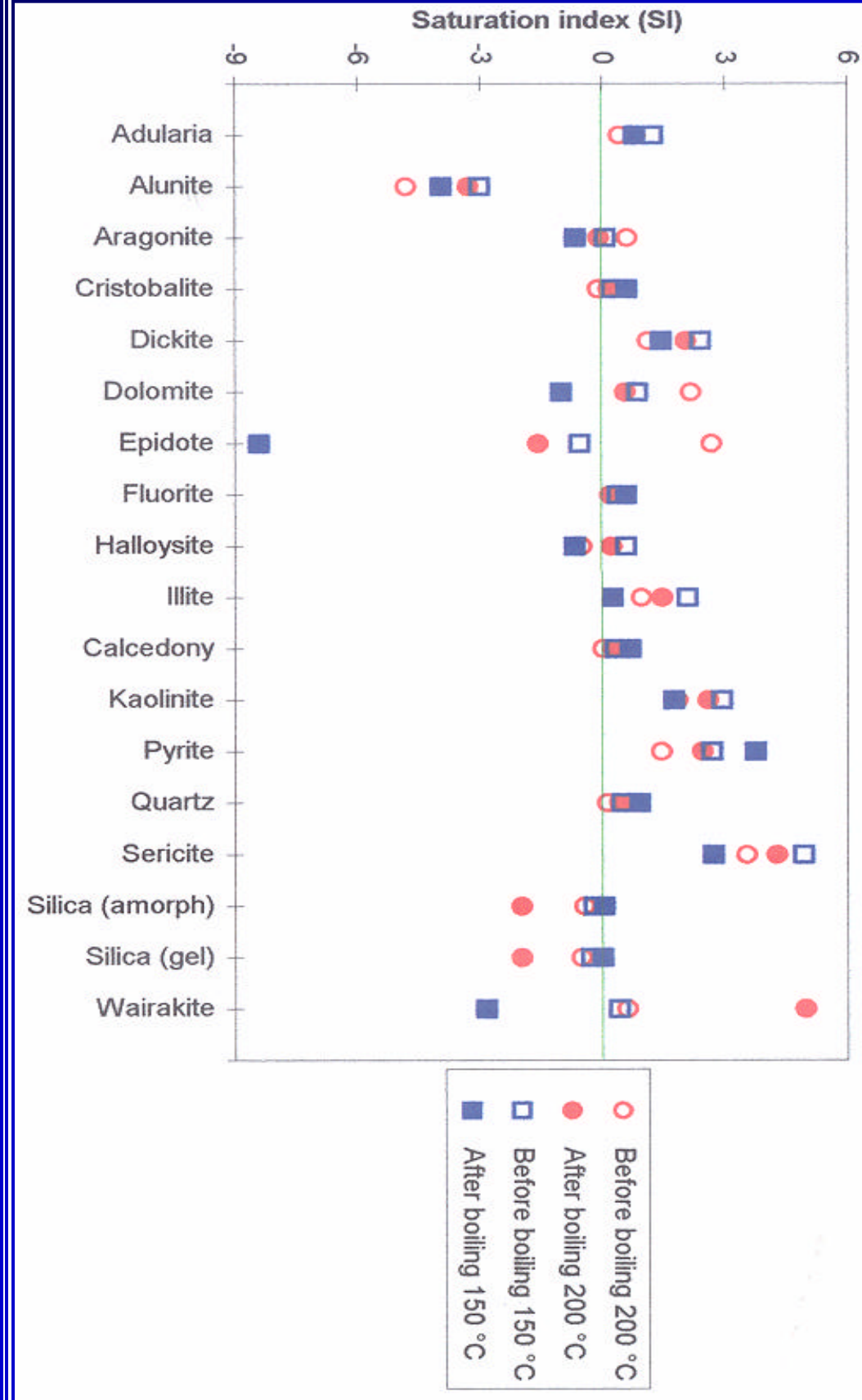

$SO_4^{2-} + Cl^- + NO_3^-$
$Ca^{2+} + Mg^{2+}$
Mg^{2+}
$Na^+ + K + NH_4^+$
Ca^{2+}
HCO_3^-
SO_4^{2-}
$Cl^- + NO_3^-$
Quartz (stage 1) of Sb deposit of Emirli
Quartz (stage 2) of Sb deposit of Emirli
Quartz (stage 2) of Au deposit of Küre
Quartz (stage 2) of Hg of Haliköy

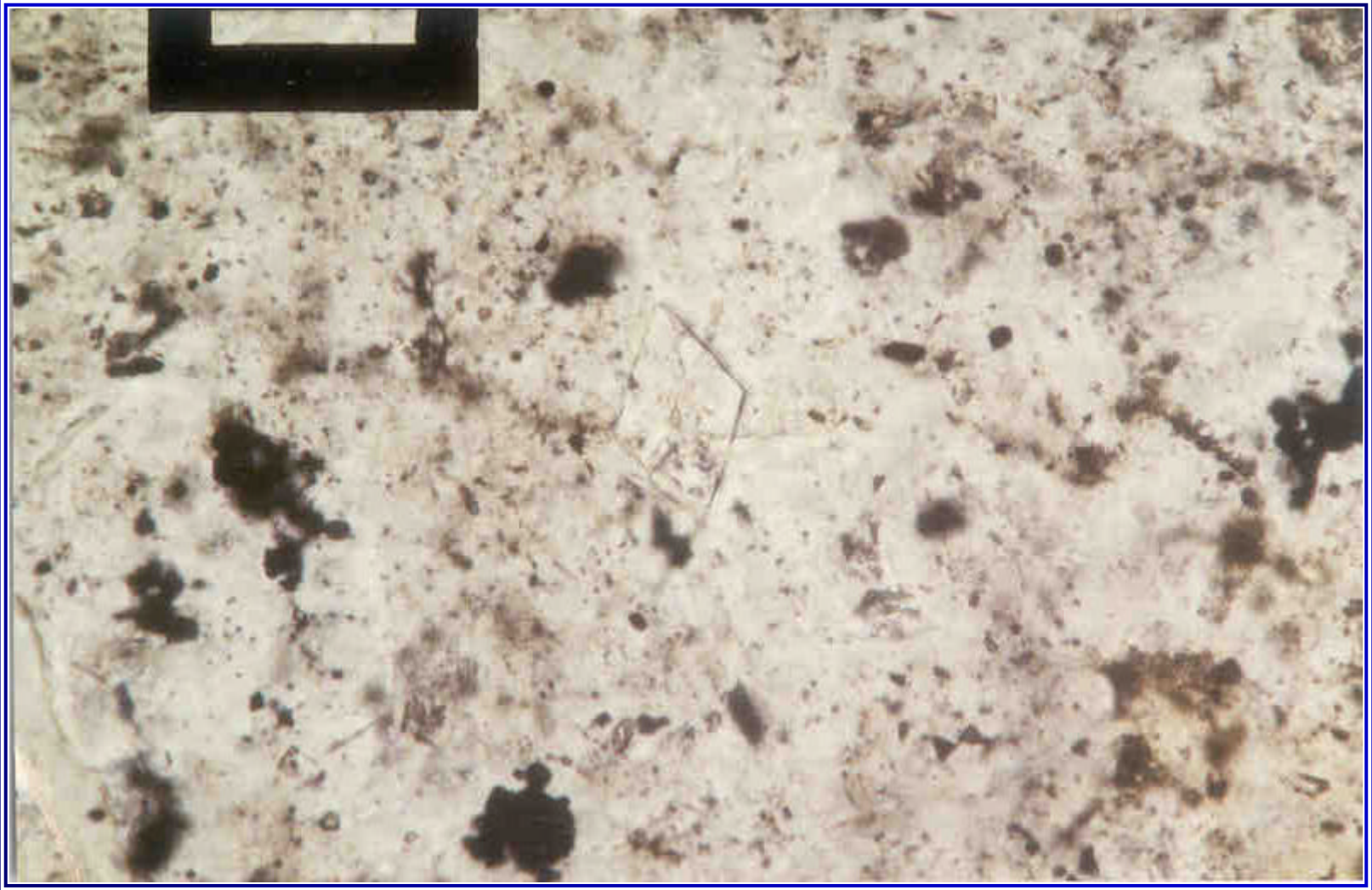

0
-40
-80
-100
δ^2H (‰)
-10
0
+10
+20
$\delta^{18}O$(‰)
SMOW
Global Meteoric Water Line (MWL)
Metamorphic water
Metamorphic water
Primary magmatic water
Rainwater of Kizildere
Hot springs from the vicinity of Kizildere
Thermal water of Kizildere
Quartz (stage 1) of Emirli
Quartz (stage 2) of Emirli
Quartz (stage 3) of Küre
Quartz (stage 2) of Halıköy
Rainwater of Salihli
Thermal water of Salihli
Groundwater of Salihli
Rainwater of Bayindir
Thermal water of Bayindir
Groundwater of Bayindir


[m]
SW
NE
NW
SE
[m]
Arsenopyrite and gold deposit of Küre
Silica sinter (pH 6-8)
400
200
000
800
600
400
200
Perched steam-heated acid sulfate water (pH 2-3)
$H_2S+2O_2 \rightarrow H_2SO_4$
CO_2, H_2S boiling
Propylitic
Arsenopyrite ore with quartz, adularia, calcite (pH 6-7)
CO_2 H_2S NaCl
Equilibration with rocks
CO_2, SO_2, HCl, H_2S
Heat source
Mica schist
Pirincci
Antimony deposit of Emirli
Silica Sinter (pH 6-8)
CO_2, H_2S boiling
Antimony ore with quartz, adularia, calcite (pH 6-7)
CO_2 H_2S NaCl
Equilibration with rocks
CO_2, SO_2, HCl, H_2S
Heat source
Mercury deposit of Haliköy
Silica sinter (pH 6-8)
Mercury ore with quatz, adularia,calcite (pH 6-7)
CO_2 H_2S NaCl
140
120
100
80
60
40
20
0
2000
4000m


Phono-
tephrite
Tephriphonolite
Trachyte
Trachyandesite
Shoshonite
Trachy-
basalt
Basalt
Basaltic
Andesite
Andesite
Dacite
Yenisehir
Yenisehir (1)
Karaburc
Karaburc (2)
Ozan (3)
Basaran (4)
$Na_2O + K_2O$ (%)
SiO_2 (%)
0
2
4
6
8
10
50
52
54
56
58
60
62
64
66
68
70


ε^{0}_{UR} (Sr)
0
+50
+100
Residual solids
II
I
Mt.Etna
Mantle array
$f_{sm} > 0$ $f_{Rb} < 0$
$f_{sm} > 0$ $f_{Rb} > 0$
Campanian region Somma-Vesuvius-Ischia
Roccamonfina
the rift zone of Kücük Menderes
Roman region
Tuscany
$f_{sm} < 0$ $f_{Rb} < 0$
$f_{sm} < 0$ $f_{Rb} > 0$
III
IV
Partial melts
Columbia River Basalt
Deccan Basalt
Tasmanian Dolerite
Scotland
Italian Province
Ahaggar
Volcanics in the rift zone of Kücük Menderes
$^{143}Nd/^{144}Nd$
0.5130
0.5120
0.5114
0.704
0.706
0.708
0.710
0.712
0.714
$^{87}Sr/^{86}Sr$
+15
+10
+ 5
0
- 5
- 10
- 15
- 20
ε^{0}_{CHUR}(Nd)


Saturation index (SI)
-9
-6
-3
0
3
6
Adularia
Alunite
Aragonite
Cristobalite
Dickite
Dolomite
Epidote
Fluorite
Halloysite
Illite
Calcedony
Kaolinite
Pyrite
Quartz
Sericite
Silica (amorph)
Silica (gel)
Wairakite
Before boiling 200 °C
After boiling 200 °C
Before boiling 150 °C
After boiling 150 °C



Conclusions

- There is relationship between geothermal systems, tectonic features, and volcanics in the rift zones of the Menderes Massif, western Anatolia, Turkey.

- In the active and fossil geothermal systems, the hydrothermal alteration is noticeable at the surface which is distinguished by phyllic, argillic, and silicic ±heamatitization alteration zones. There are also similarities in both systems due to hydrothermal alteration features.

- The geochemical temperatures of the active geothermal waters indicate a range from 220 to 260 ^{o}C which can be compared with the homogenization temperatures of quartz and stibnite crystals from 180 to 300 ^{o}C.

- The active geothermal waters can be considered as Na-(SO_4)-HCO_3-type which may be compared with the fossil fluids of epithermal Hg, Sb, and Au deposits.

- According to stable isotopes, the active geothermal waters show a meteoric origin. In comparison, the stable isotopes in the fluids of epithermal ore deposits are enriched by fluid-rock interaction and indicate the mixing of these fluids.

- The active and fossil geothermal systems are distinguished by an enrichment of these elements Hg, Sb, As, Au, Tl, and Ag on the surface. In comparison, the analyses of the drill cores show that the elements Cu, Pb, and Zn are enriched at depth. These can be attributed to (i) preferred mobilization of Hg, Sb, As, Tl, Au, and Ag by hydrothermal fluids and (ii) the low salinity of fluids due to transport of metals such as Cu, Pb, and Zn.

- **Therefore, the present-day epithermal Hg, Sb, and Au deposits of Haliköy, Emirli, and Küre in the rift zone of the Küçük Menderes may be considered as fossil deposits of formerly active geothermal systems.**

- **The epithermal mineralizations of Haliköy, Emirli, and Küre can be compared to the other Hg, Sb, and arsenopyrite and Au ore mineralizations in the rift zones of the Menderes Massif, similar to the epithermal Sb and Au deposits in the metallotect of Jiangnan, PR China and active and extinct geothermal systems of New Zealand, and considered as fossil equivalents of active geothermal systems.**