The origin of sulfur in shale oils, gases and spent matter as decoded by $\delta^{34}S$ monitoring and better knowledge gained on various pyrolysis driven processes

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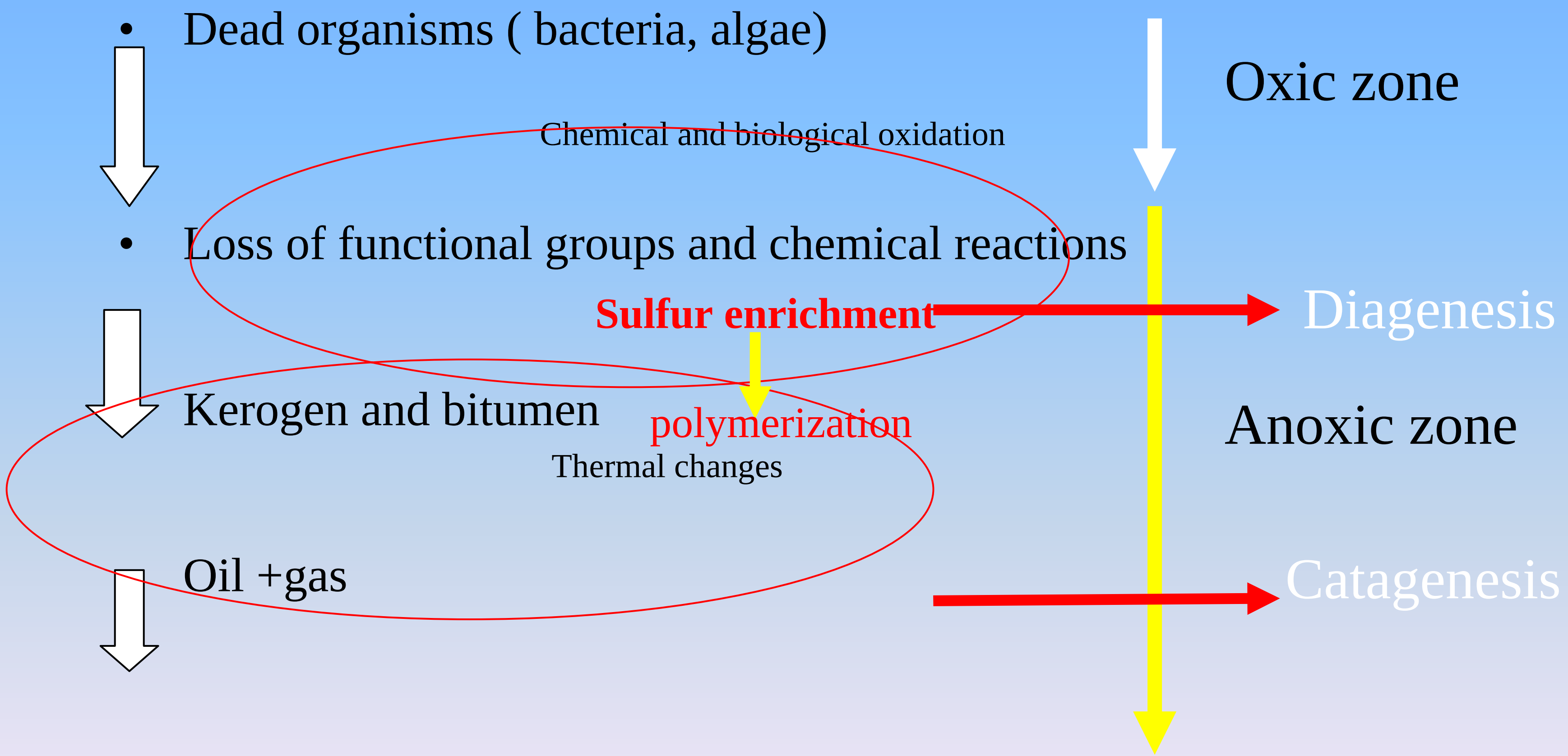
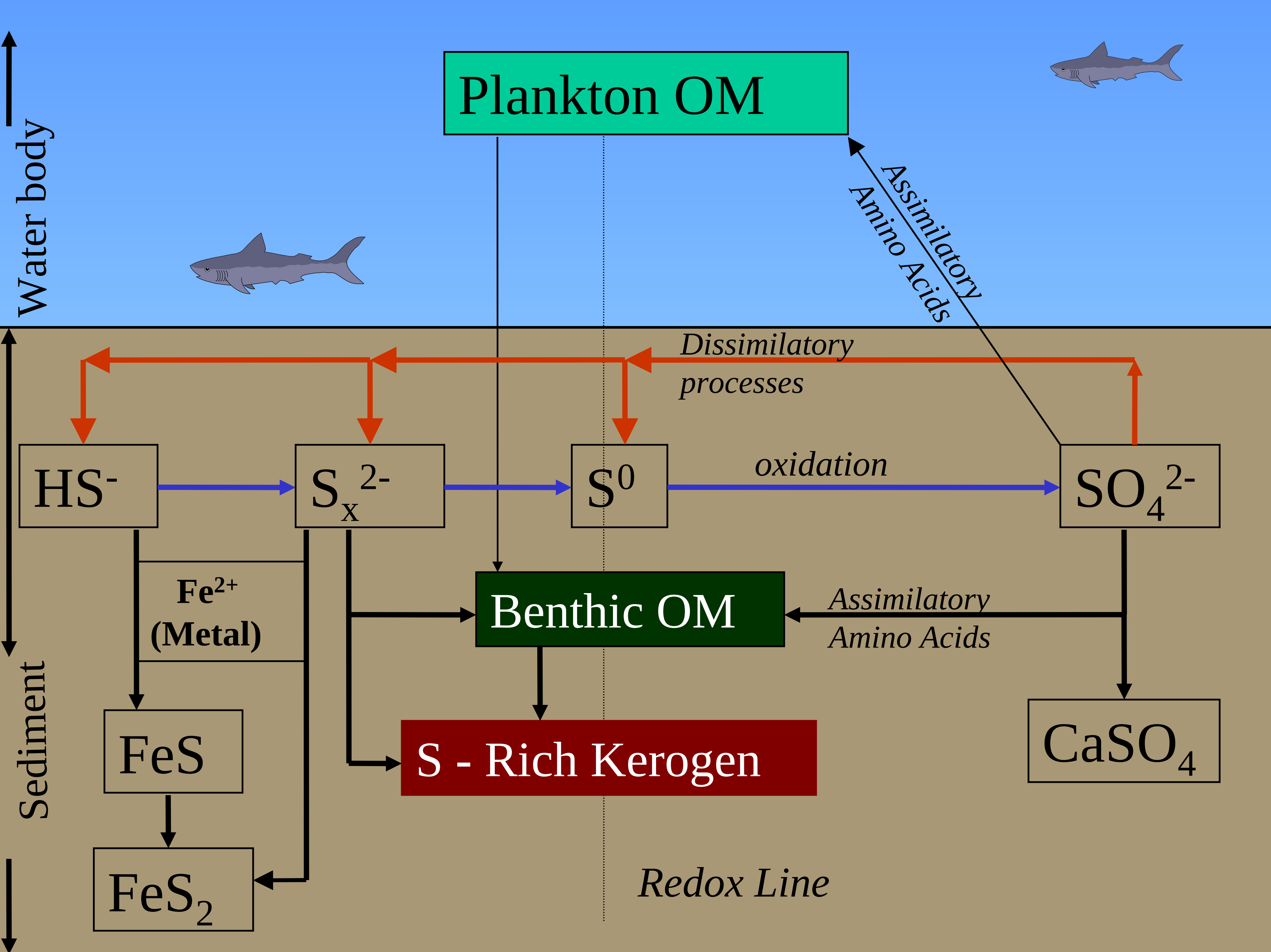
Main points

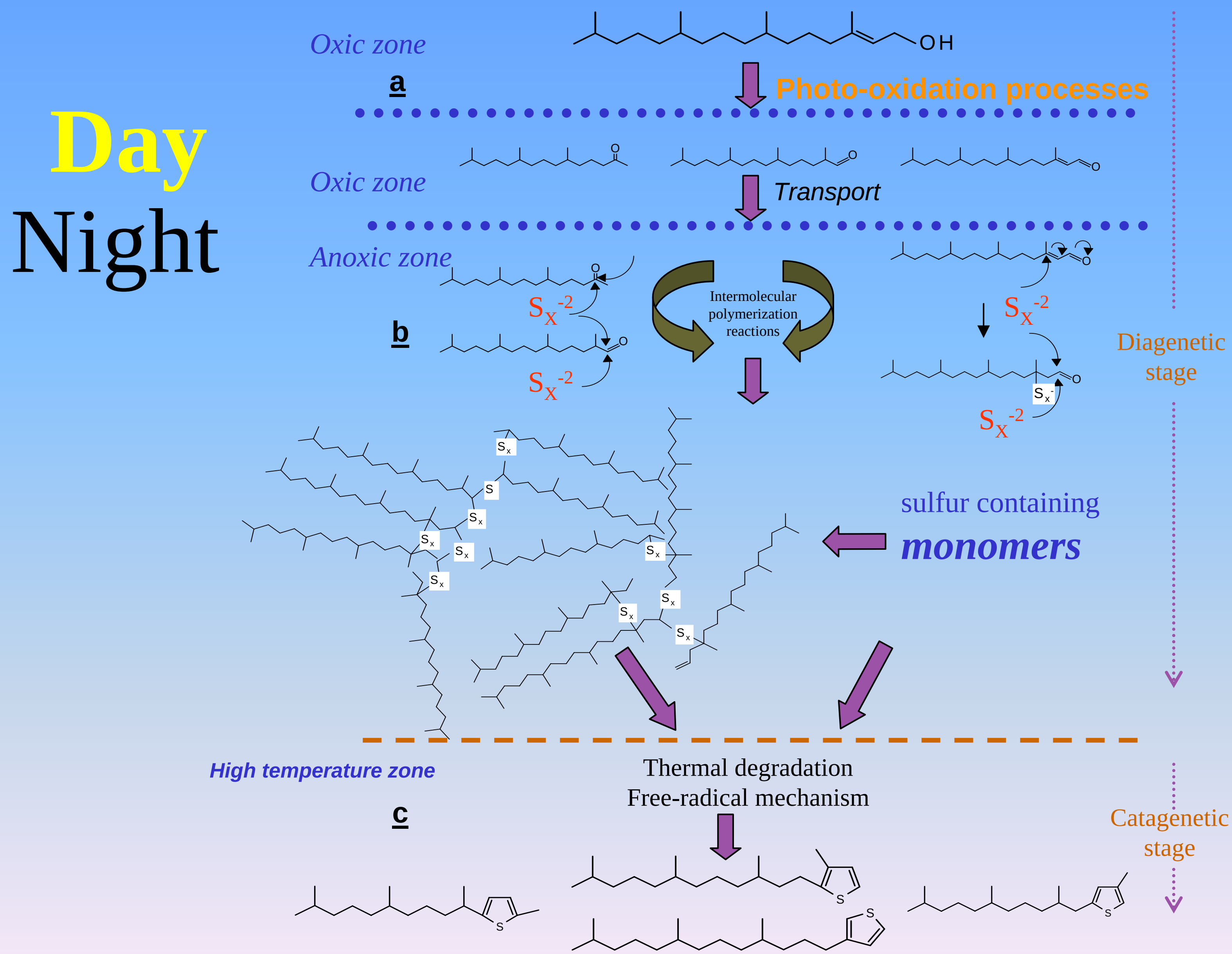
- The use of sulfur stable isotopes for recognition of sedimentation conditions and Diagenetic processes.
- Assimilatory and dissimilatory sources of organically bonded sulfur isotope imprint.

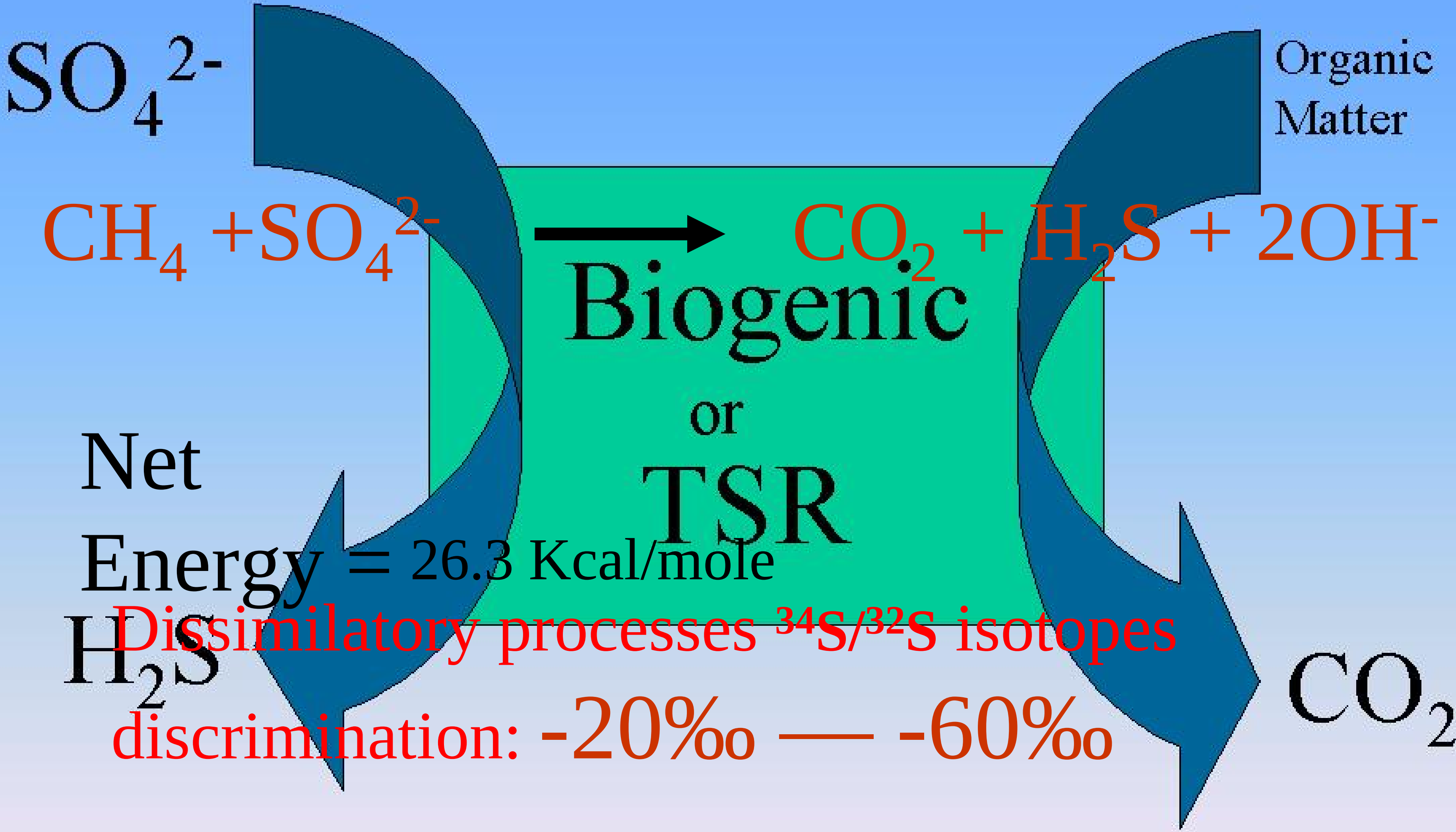
The formation of oil in marine sediments





Plankton OM
Water body
Assimilatory
Amino Acids
Dissimilatory
processes
HS⁻
S_x 2-
S0
oxidation
SO4 2-
Fe2+
(Metal)
Benthic OM
Assimilatory
Amino Acids
FeS
S - Rich Kerogen
CaSO4
FeS2
Sediment
Redox Line

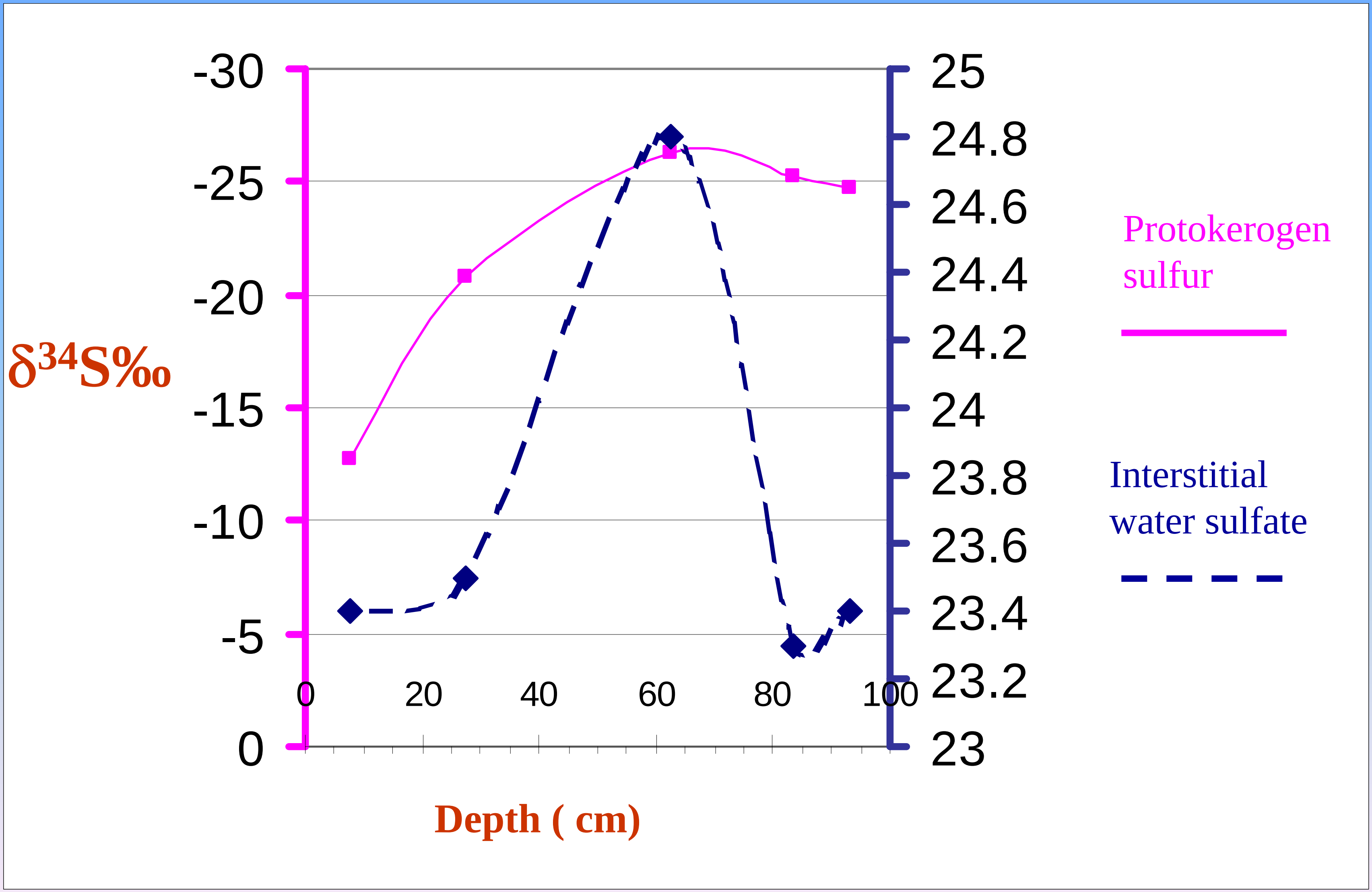

Day
Night
Oxic zone
OH
a
Photo-oxidation processes
Oxic zone
Transport
Anoxic zone
Intermolecular polymerization reactions
b
Sx-2
sulfur containing
monomers
Diagenetic stage
High temperature zone
Thermal degradation
Free-radical mechanism
c
Catagenetic stage



$CH_4 + SO_4^{2-} \rightarrow CO_2 + H_2S + 2OH^-$

Net Energy = 26.3 Kcal/mole

Dissimilatory processes $^{34}S/^{32}S$ isotopes discrimination: -20‰ — -60‰



δ34S‰
-30
-25
-20
-15
-10
-5
0
25
24.8
24.6
24.4
24.2
24
23.8
23.6
23.4
23.2
23
0
20
40
60
80
100
Depth (cm)
Protokerogen sulfur
Interstitial water sulfate

$\delta^{34}S$ Changes during Catagenetic processes, thermally induced

- Thermal maturation and influence of Open *versus* Closed systems.
- The possible role of mineral matrix.
- Application to evaluation of sulfur role In utilization of *in-situ /ex-situ* designed Processes.

Theoretic chemical $^{34}S/^{32}S$ isotopes

discrimination: -25‰

Assimilatory processes $^{34}S/^{32}S$ isotopes

discrimination: up to -3‰

Dissimilatory processes $^{34}S/^{32}S$ isotopes

discrimination: -20‰ — -50‰

kinetics isotopes effect :

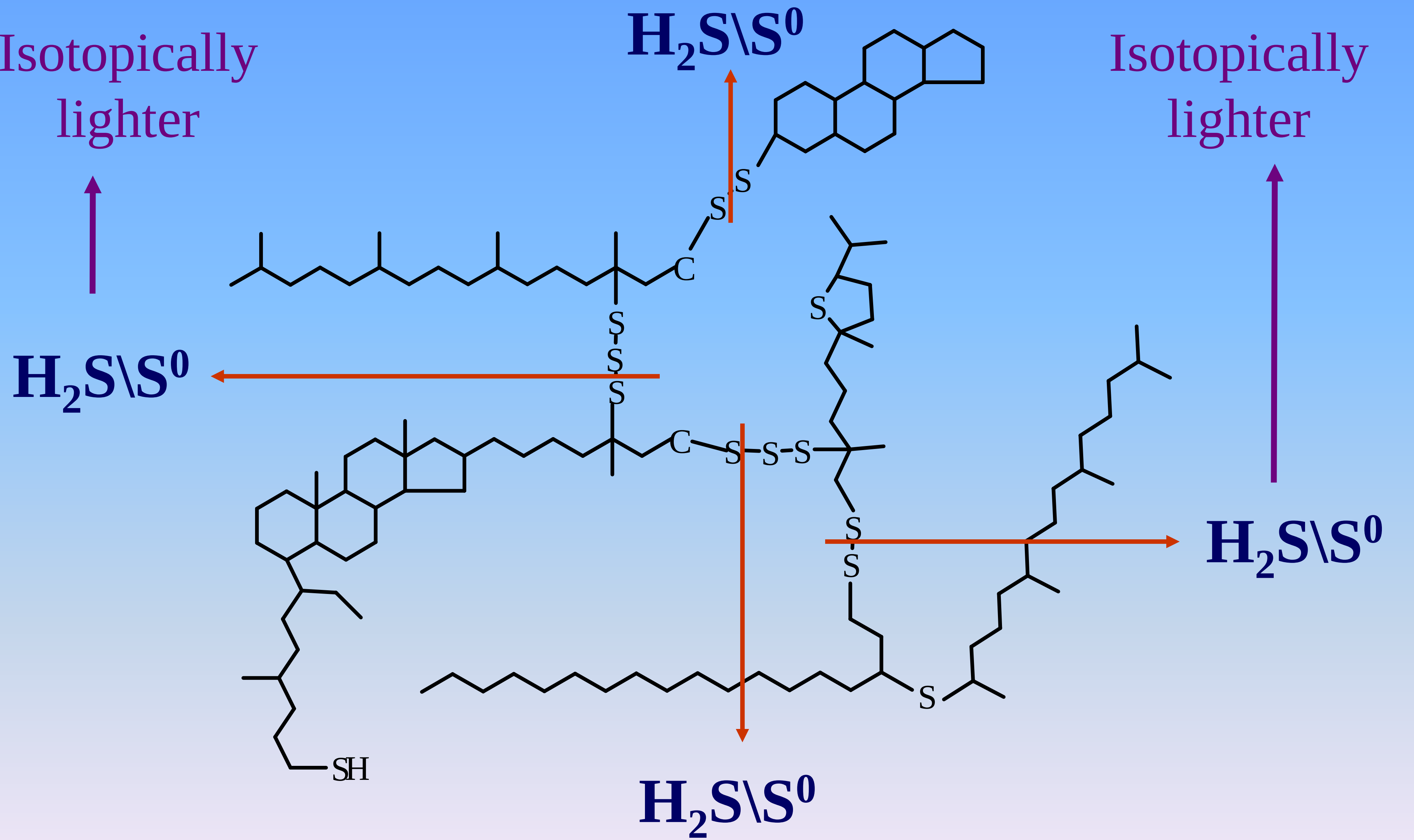
Open system

Closed system

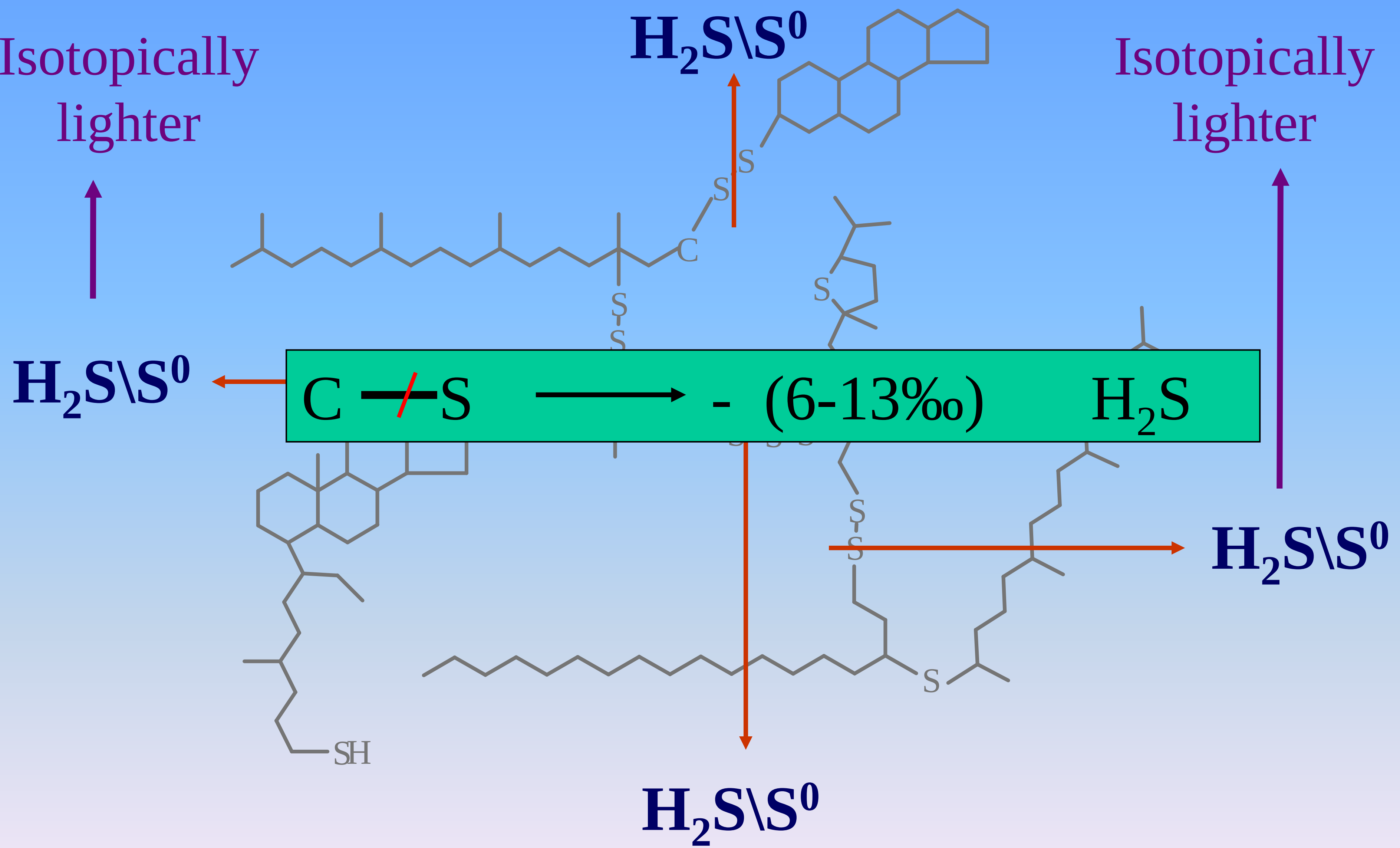
TSR

Data TRS discrimination

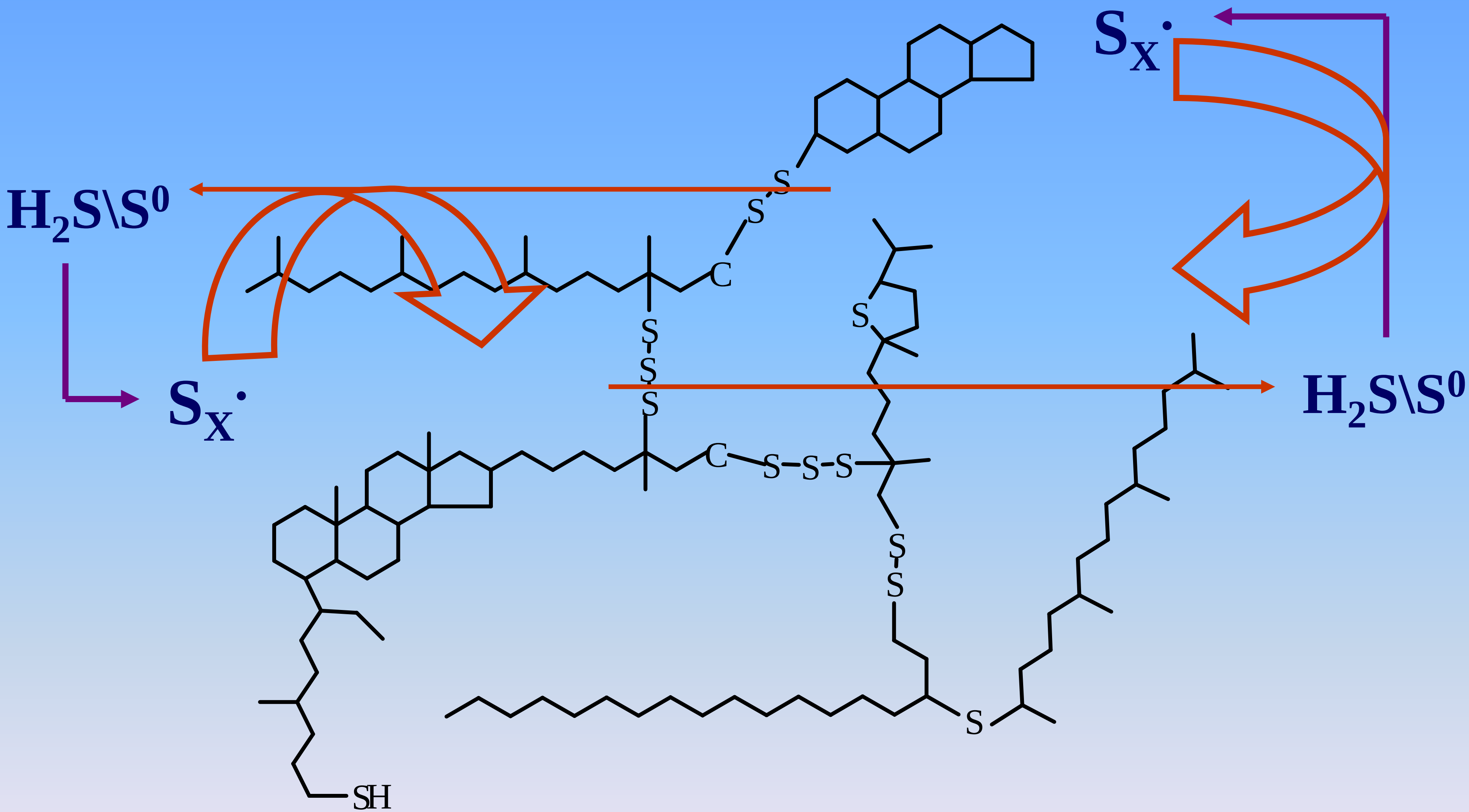
Open system- Isotopes discrimination



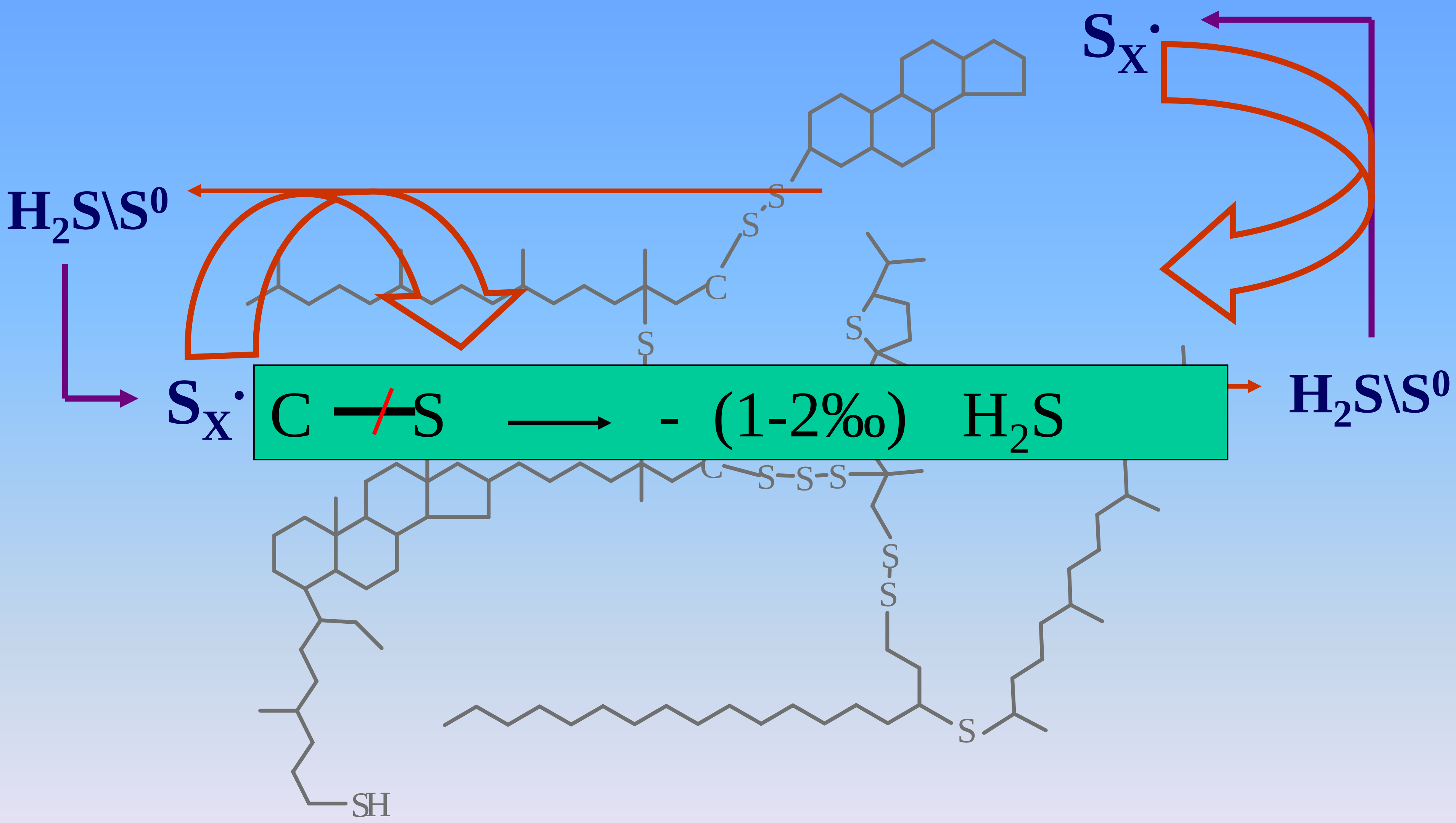
Open system- Isotopes discrimination

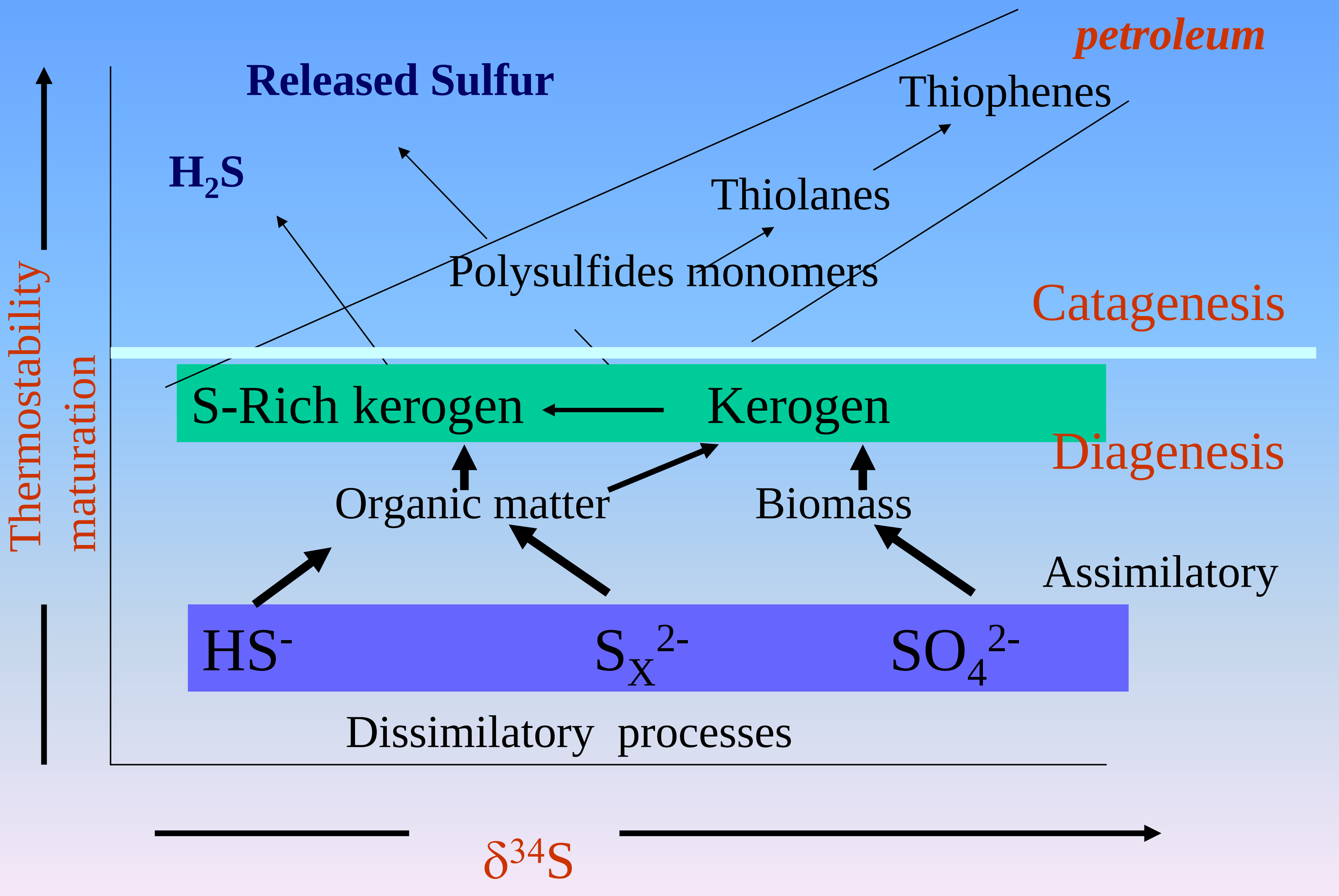


Closed system - isotopes mixing



Closed system - isotopes mixing

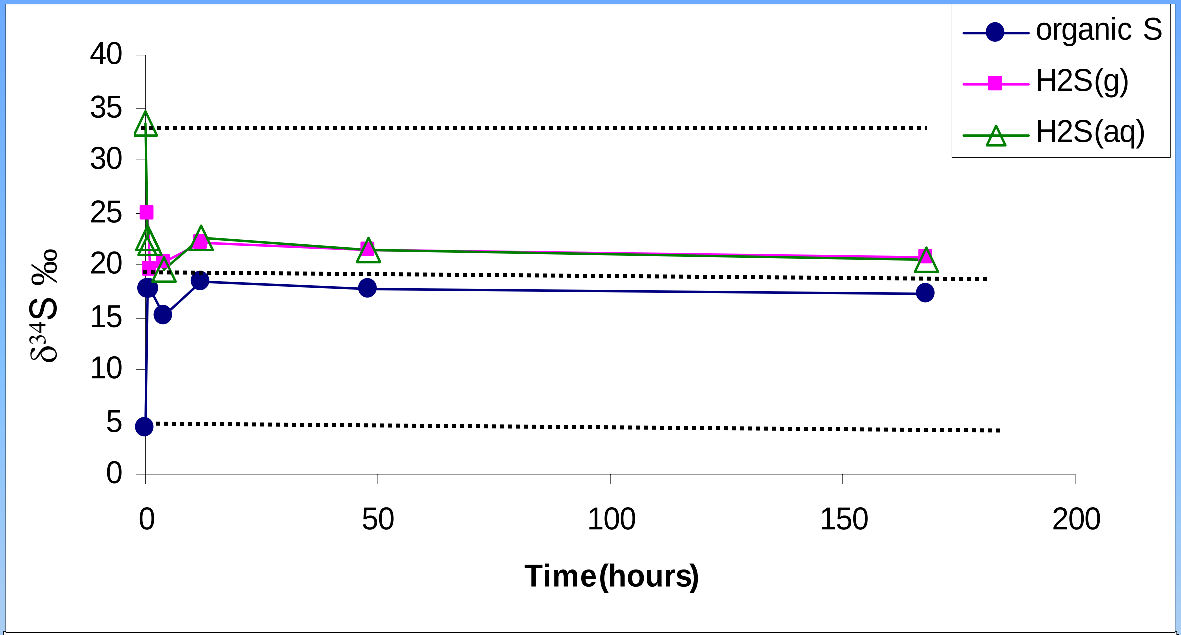


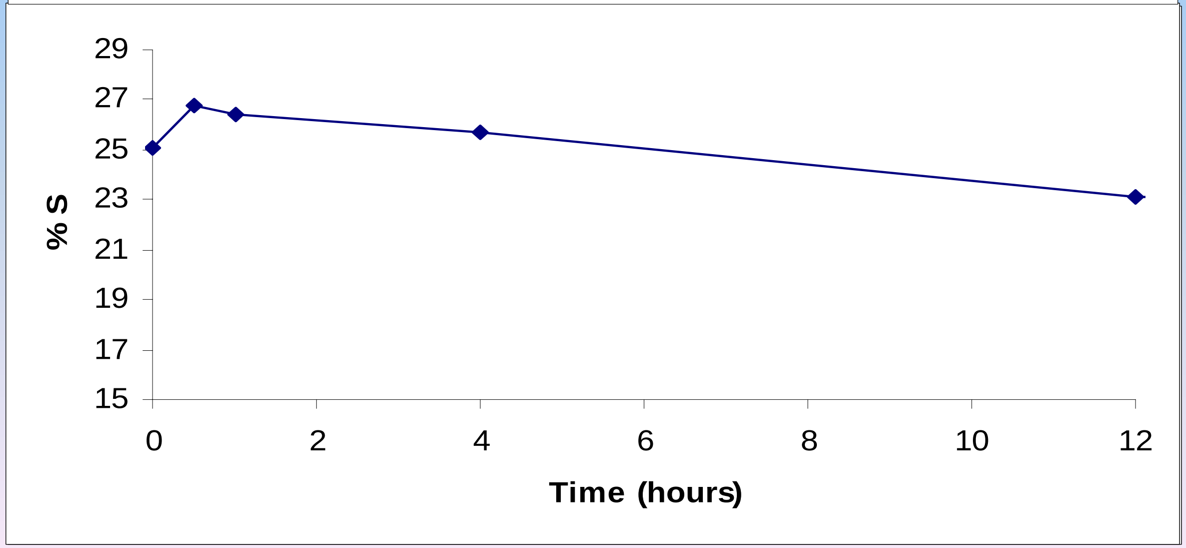

petroleum
Released Sulfur
Thiophenes
H2S
Thiolanes
Polysulfides monomers
Catagenesis
S-Rich kerogen
Kerogen
Diagenesis
Organic matter
Biomass
Assimilatory
HS-
Sx2-
SO42-
Dissimilatory processes
Thermostability
maturation
δ34S

Isotopic Mixing

Graphic picture of our experiments

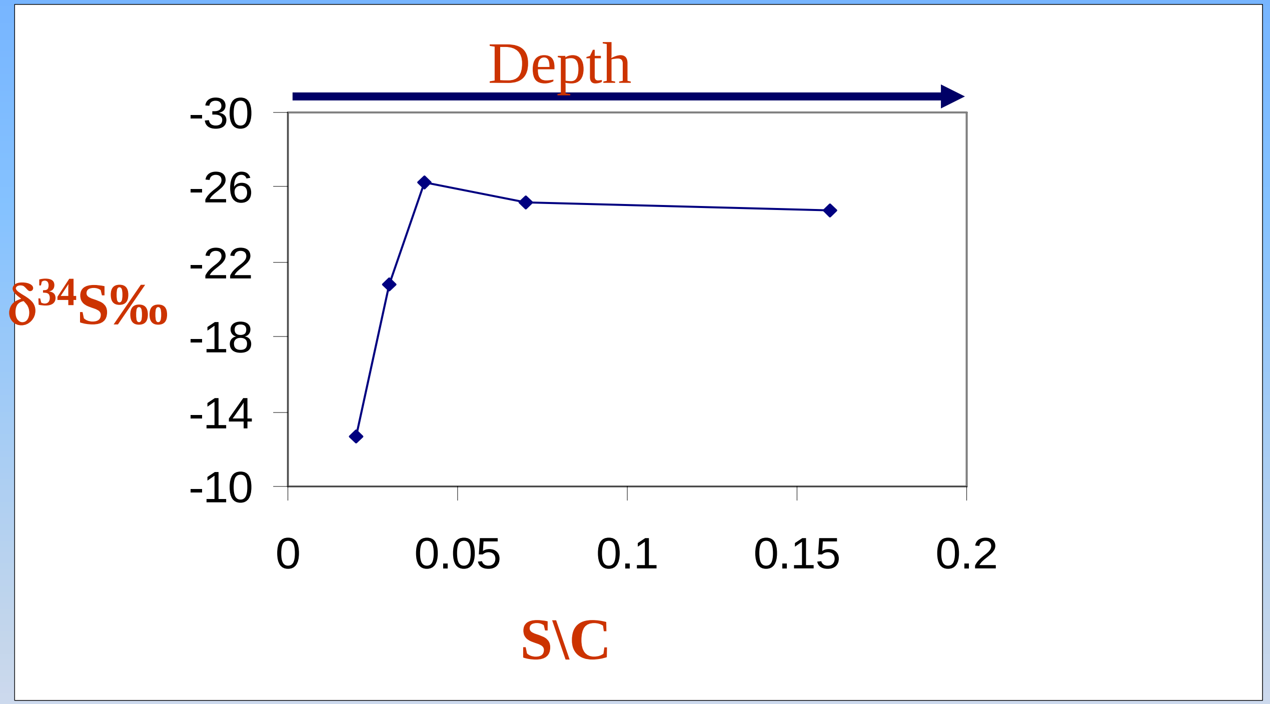
Polymer-S + $S_{(aq)}$ $\xrightarrow{200^{o}C}$

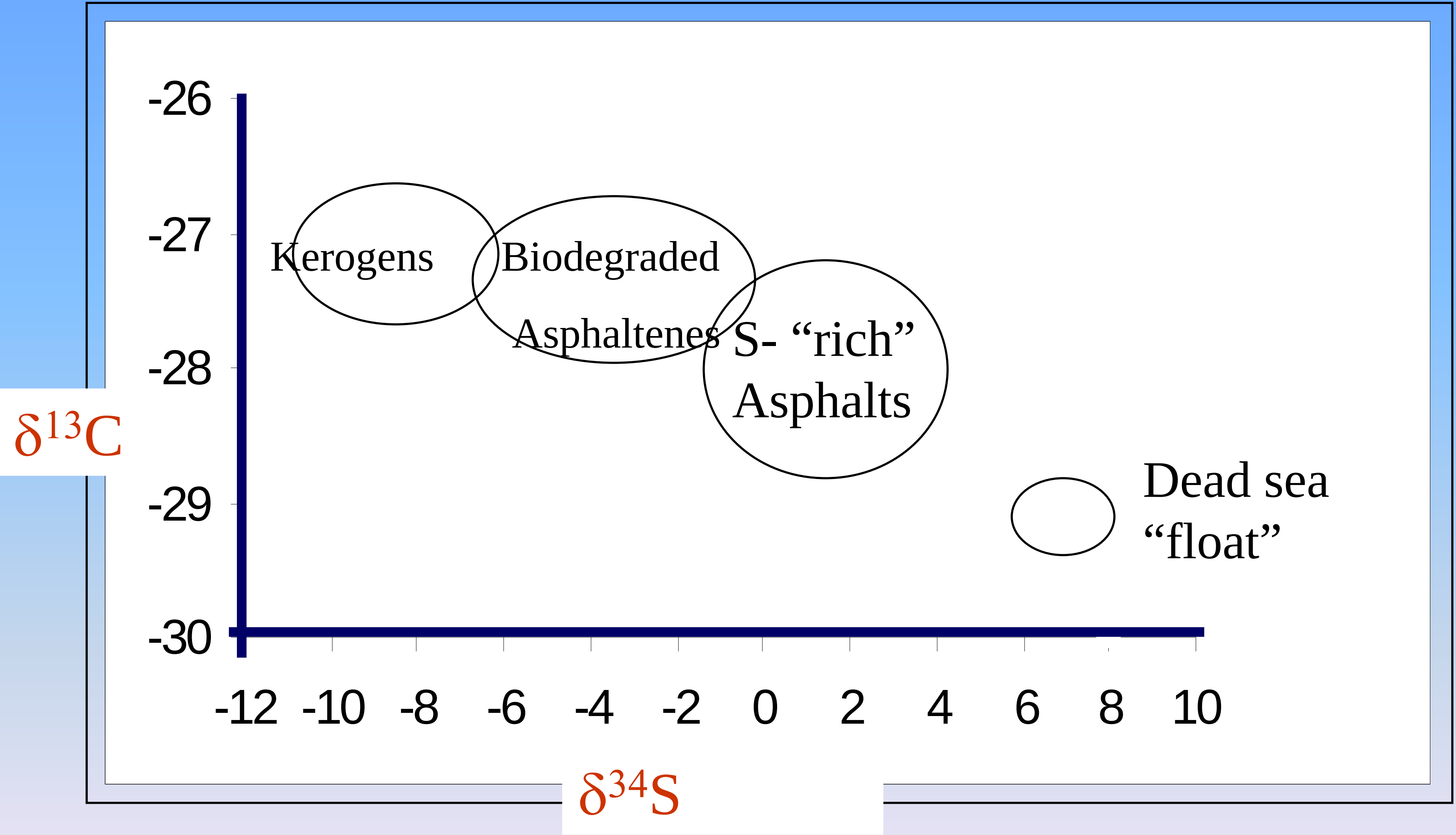


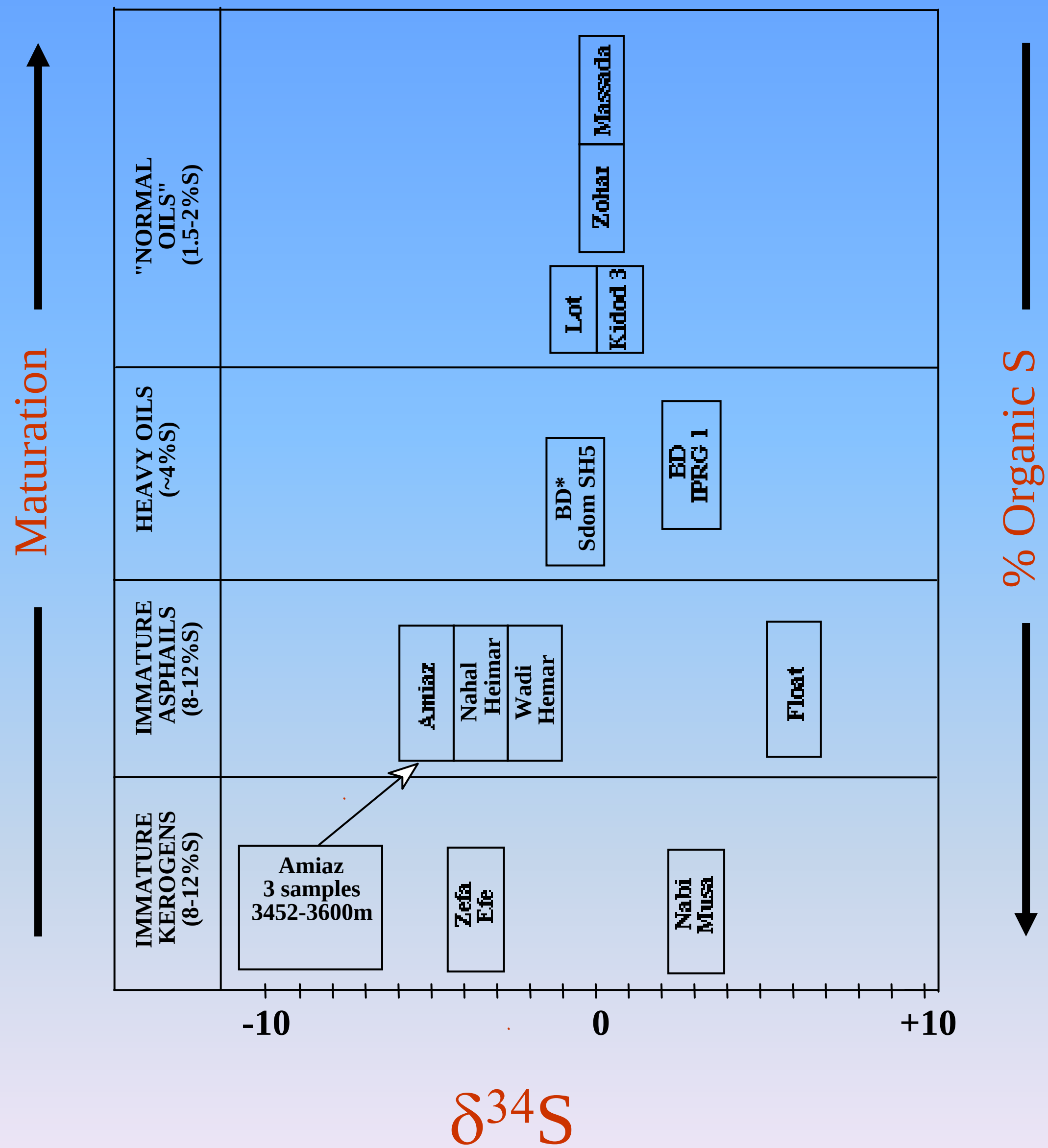


Reactant	Sulfur mole ratio reactant/organic S mole	Initial reactant $\delta^{34}S$(‰)	Initial organic S $\delta^{34}S$(‰)	Residual organic S $\delta^{34}S$(‰)	$H_2S_{(g)}$ $\delta^{34}S$(‰)	Binary isotope mass balance $\delta^{34}S$(‰)	Residual organic sulfur content %
$H_2S_{(g)}$	1:3	36	19	32.1	34	32	38.5
$H_2S_{(g)}$	1:1	60	4	30.4	29.1	32	34.3
S_8	1:1	-1.7	19	8.1	8.8	8.7	30±2

$\delta^{34}S$ values (error<0.4‰) and wt% for isotopes mixing experiments between polysulfide cross-linked polymer (25.1 wt% S) and $H_2S_{(g)}$ or S_8 at 200ºC for 48h


Depth
-30
-26
-22
-18
-14
-10
δ34S‰
0
0.05
0.1
0.15
0.2
S\C


-26
-27
-28
-29
-30
δ13C
Kerogens
Biodegraded
Asphaltenes
S- "rich"
Asphalts
Dead sea
"float"
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10
δ34S


Maturation
% Organic S
"NORMAL OILS" (1.5-2%S)
HEAVY OILS (~4%S)
IMMATURE ASPHAILS (8-12%S)
IMMATURE KEROGENS (8-12%S)
Massada
Zohar
Lot
Kidod 3
BD* Sdom SH5
BD IPRG 1
Amiaz
Nahal Heimar
Wadi Hemar
Float
Amiaz
3 samples
3452-3600m
Zefa Efe
Nabi Musa
-10
0
+10
δ34S

Conclusions - diagenetic stages

- **The largest pool of sulfur in the geosphere is sulfate SO_4^{2-}marine sulfates are $\delta^{34}S_{CDT}$ +20 ± 5‰ depending on geological era. The supply of sulfate open or closed systems determines the interstitial $\delta^{34}S$ recorded.**

- **The main source of reduced sulfur in sediments is the SRB dissimilatory process. The bacterial process has a marked isotopes selectivity -20 to -60‰, this is kinetically recorded by the formation of pyrite depending on iron availability.**

Conclusions- diagenetic stages

- S^{2-} and S^0 form (pH ~8-9) polysulfides of the S_x^{2-} structure (x=3,4,5) that are the most chemically active, these in turn react with the SOM to form sulfur rich-SOM. The isotopic signature of the organic bound sulfur has a wide range relating to some parameters discussed in the papers $\delta^{34}S$ recorded for the organically bound sulfur is on average +10‰ heavier then the pyrite.

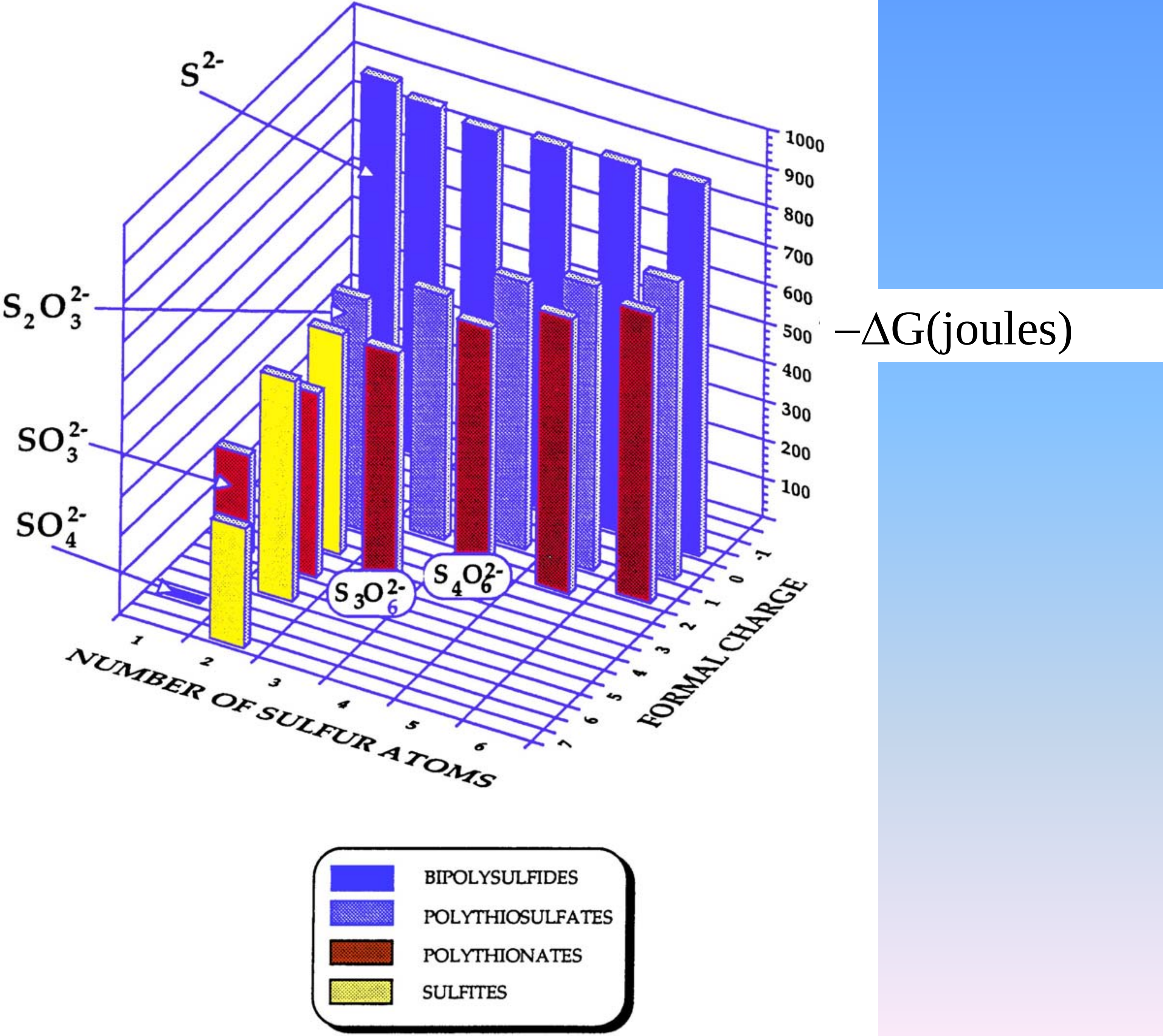
- Type II-S kerogens are formed by the secondary sulfur enrichment dominated by polysulfides, these reactions produce the poly-cross-linked-macromolecules (PCLM). The isotopic mixing and discrimination at each geological setting still needs further studies

Conclusions- catagenetic stages

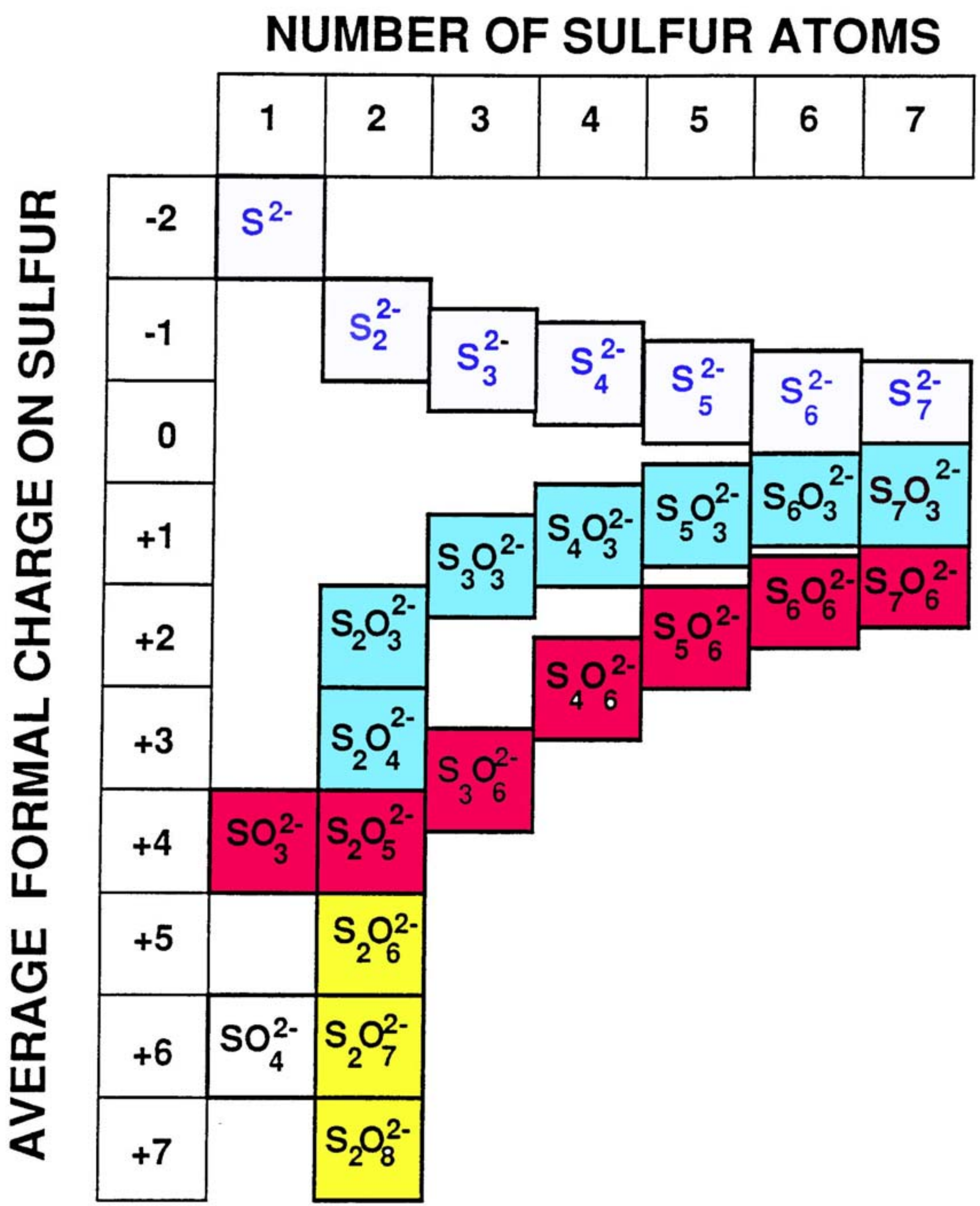
- The evolved H_2S from the kerogen is always ^{32}S -enriched. Very small, if any, pyritic light sulfur is contributed.
- On average the H_2S released is 5‰ lighter than the original $\delta^{34}S$ of the organic matter.
- All liquids are by +5 to +8‰ heavier ^{34}S than the original kerogen. The residual kerogen (isolated) is somewhat Isotopically heavier.
- In comparison to the carbon isotope changes with maturation from kerogen to petroleum the proposed scheme is reversed.

Catagenesis and TSR

- **The closed or open systems at the catagenesis stages (thermally controlled) transformations have a marked difference.**
- **TSR depends on mineral matrix, high temperatures and pH changes.**
- **Mixing of the various reduced species of sulfur is recorded by sulfur isotope ratio changes.**
- **The source of organically bonded sulfur under TSR conditions can derive from inorganic sulfur such is the case for Type I kerogens under *insitu* shale oil production.**



S^{2-}
$S_2O_3^{2-}$
SO_3^{2-}
SO_4^{2-}
$S_3O_6^{2-}$
$S_4O_6^{2-}$
1000
900
800
700
600
500
400
300
200
100
$-\Delta G$(joules)
NUMBER OF SULFUR ATOMS
1
2
3
4
5
6
FORMAL CHARGE
-1
0
1
2
3
4
5
6
7
BIPOLYSULFIDES
POLYTHIOSULFATES
POLYTHIONATES
SULFITES


NUMBER OF SULFUR ATOMS
1
2
3
4
5
6
7
AVERAGE FORMAL CHARGE ON SULFUR
-2
-1
0
+1
+2
+3
+4
+5
+6
+7
S^{2-}
S_2^{2-}
S_3^{2-}
S_4^{2-}
S_5^{2-}
S_6^{2-}
S_7^{2-}
$S_7O_3^{2-}$
$S_6O_3^{2-}$
$S_5O_3^{2-}$
$S_4O_3^{2-}$
$S_3O_3^{2-}$
$S_2O_3^{2-}$
$S_7O_6^{2-}$
$S_6O_6^{2-}$
$S_5O_6^{2-}$
$S_4O_6^{2-}$
$S_3O_6^{2-}$
$S_2O_4^{2-}$
SO_3^{2-}
$S_2O_5^{2-}$
$S_2O_6^{2-}$
SO_4^{2-}
$S_2O_7^{2-}$
$S_2O_8^{2-}$