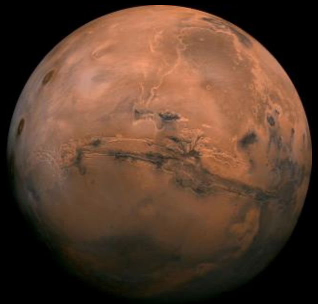
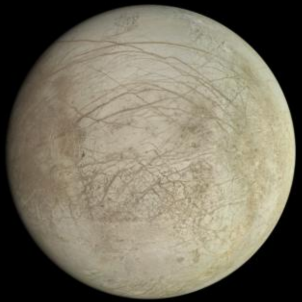
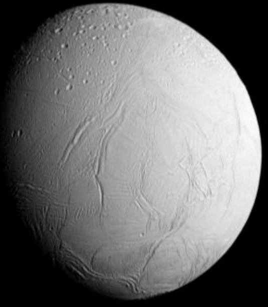
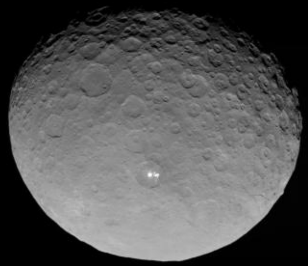
# Cycling Of Organic Molecules

Kirt Robinson

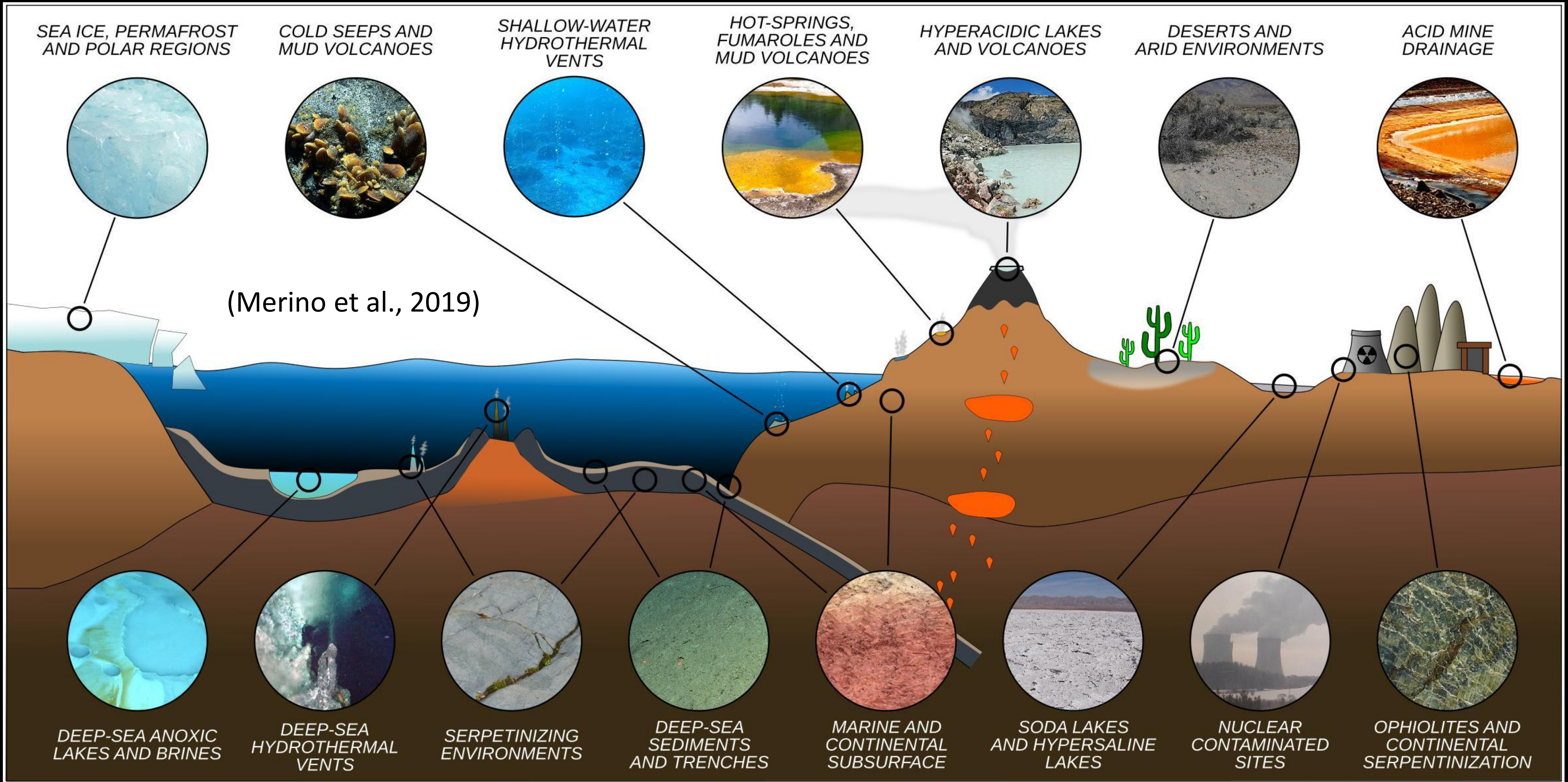
KISS: Next Frontiers in the Investigation of Extraterrestrial Organics

December 1st, 2025



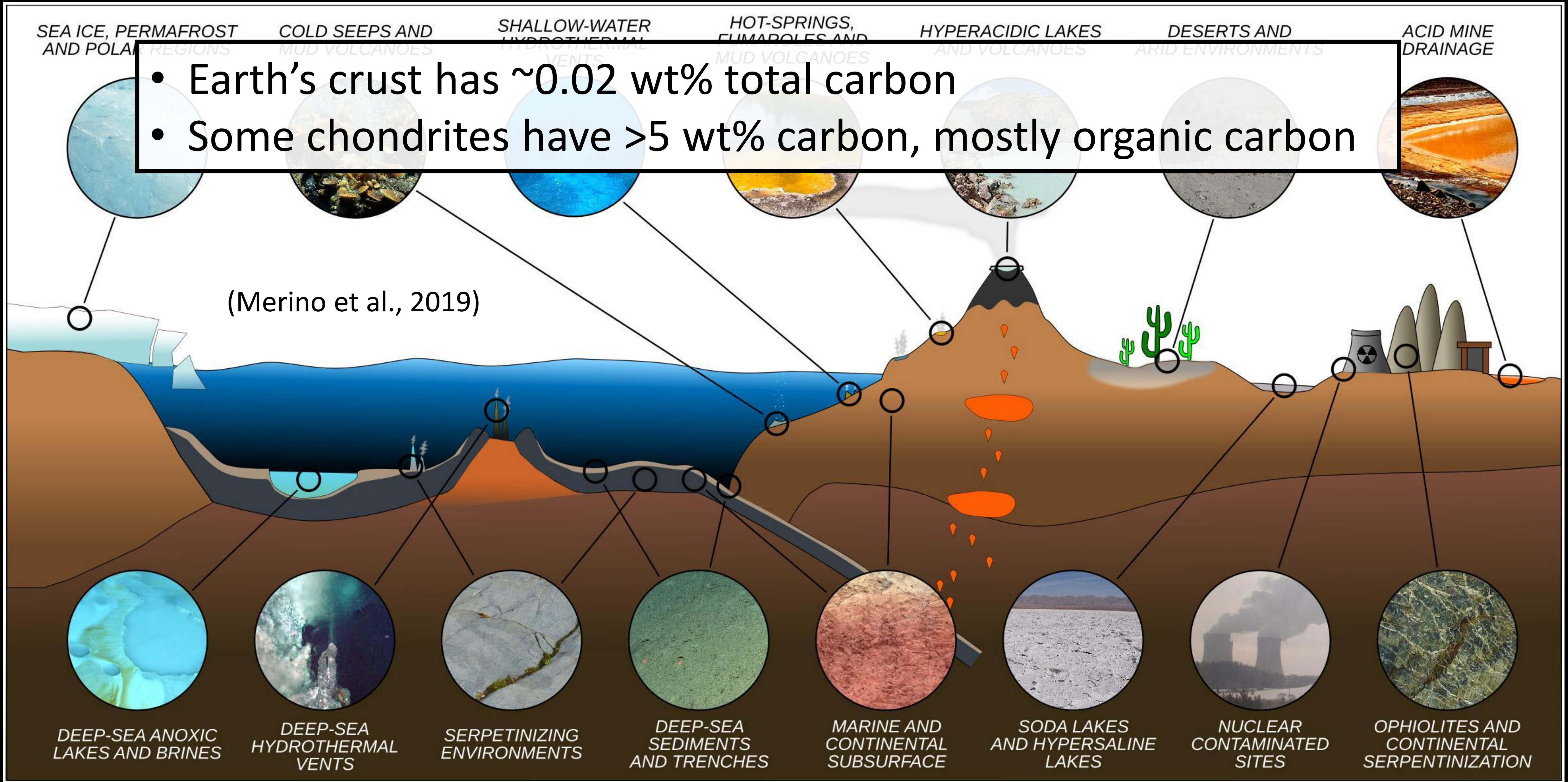
# Earth is a complicated analog



# Earth is a complicated analog

- Earth's crust has ~0.02 wt% total carbon
- Some chondrites have >5 wt% carbon, mostly organic carbon

(Merino et al., 2019)



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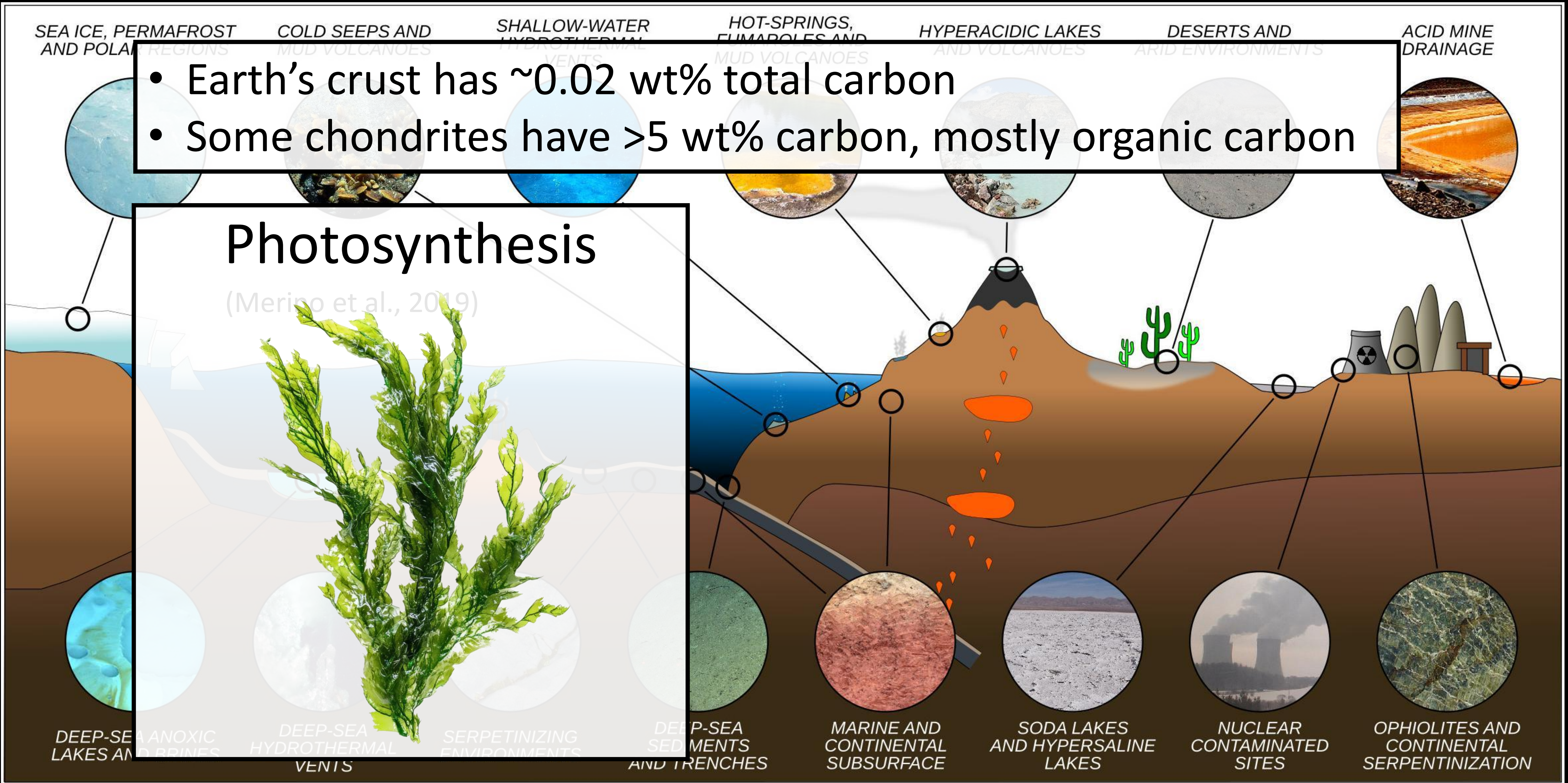


Photosynthesis

(Merino et al., 2019)

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Photosynthesis

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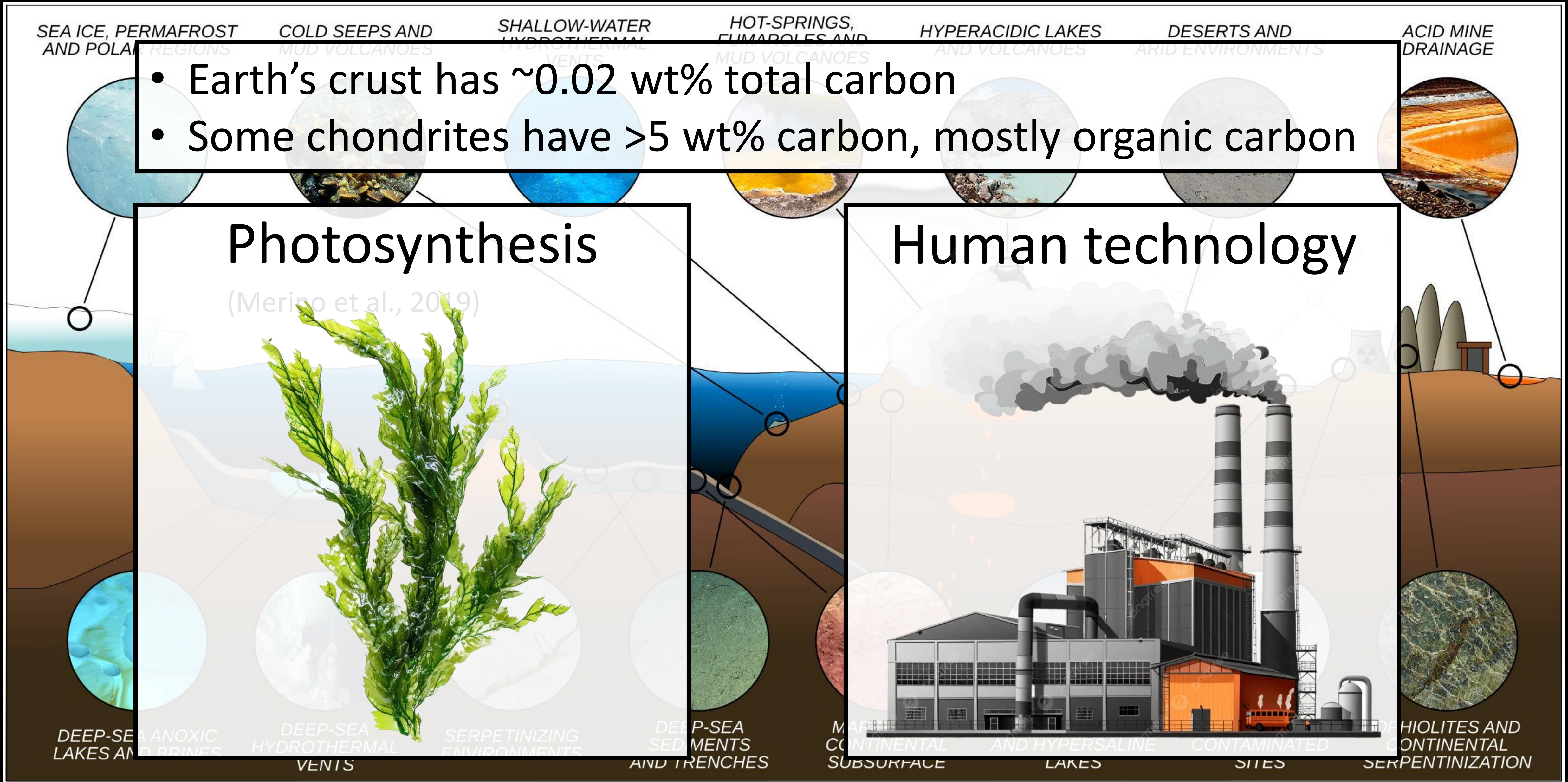
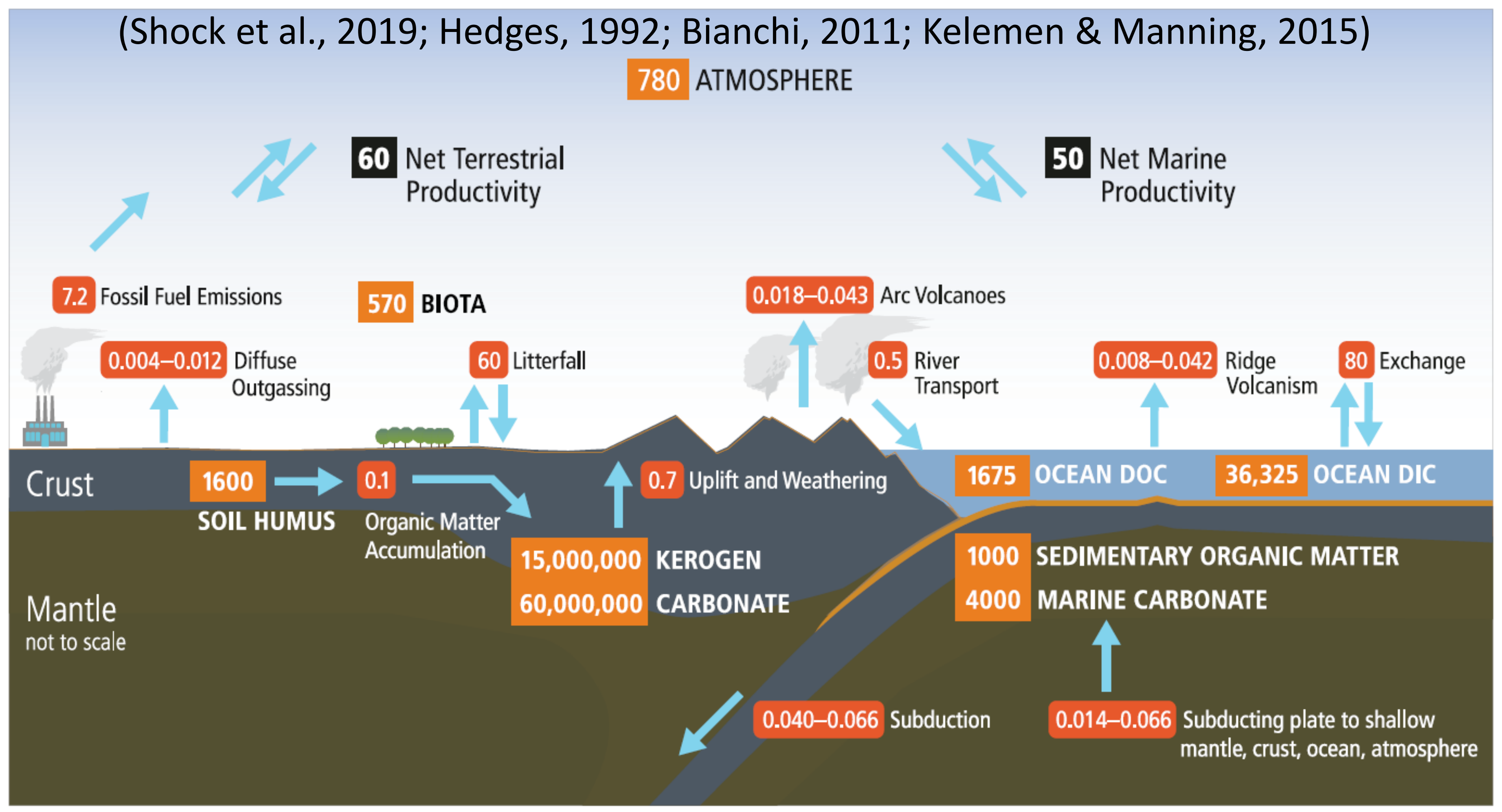
Human technology



# The carbon cycle



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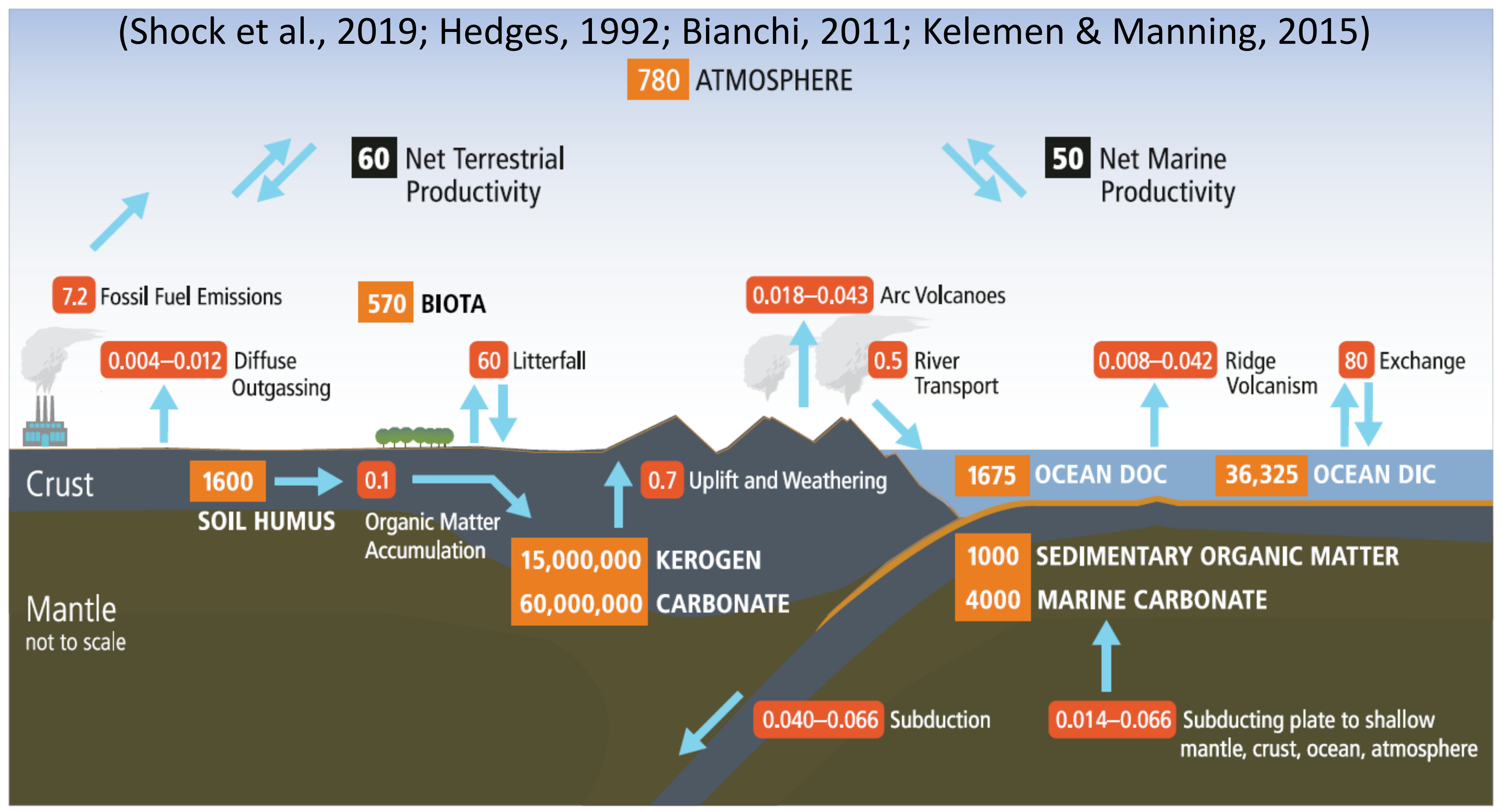



>> 99.9% of organic carbon is in the subsurface.

# Organics entering the subsurface

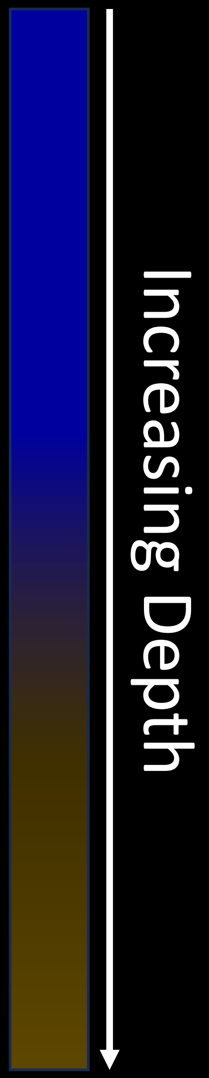
cellular detritus

↓

proteins, lipids, carbohydrates

↓

amino acids, fatty acids, simple sugars




Underlined structures may persist longer.

(Leeuw & Largeau, 1993)

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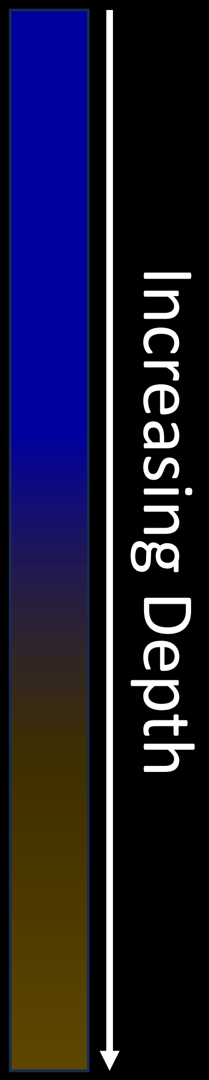


Example organic groups:

Amino (R-$NH_2$), Carboxyl (R-COOH), Hydroxyl (R-OH), Phenyl ()

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# Organics entering the subsurface

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proteins, <u>lipids</u>, carbohydrates

amino acids, <u>fatty acids</u>, simple sugars

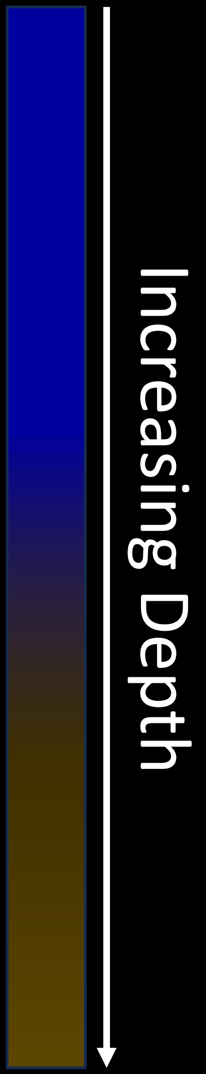
fulvic and humic acids (still soluble)*

kerogen (insoluble)

<u>Underlined structures may persist longer.</u>

*not comprehensive, e.g., lignin

(Leeuw & Largeau, 1993)

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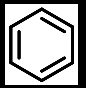
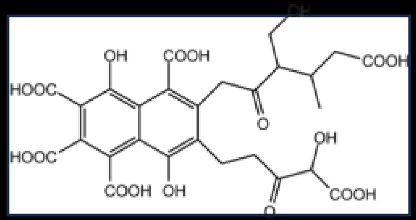
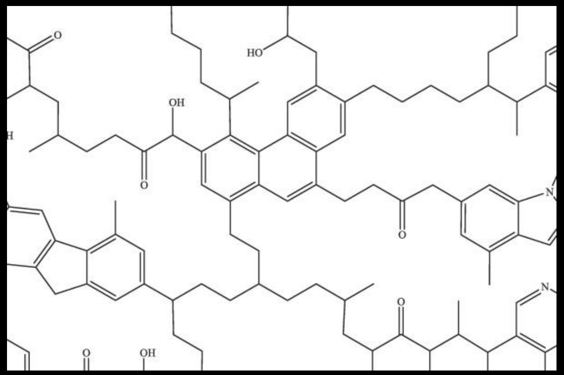
Amino ($R-NH_2$), Carboxyl (R-COOH), Hydroxyl (R-OH), Phenyl ()



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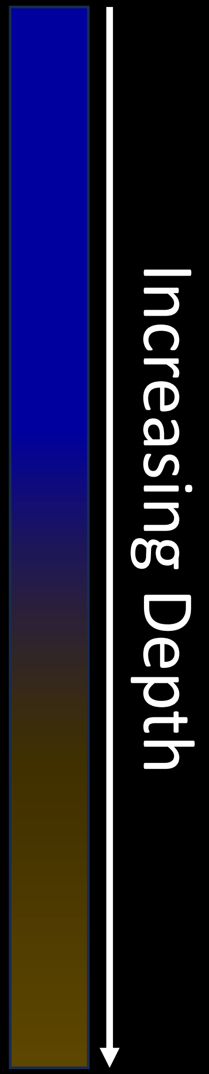


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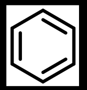
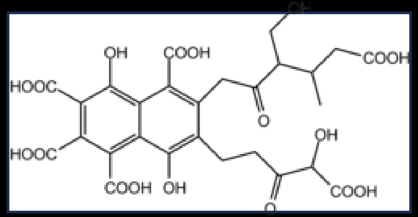
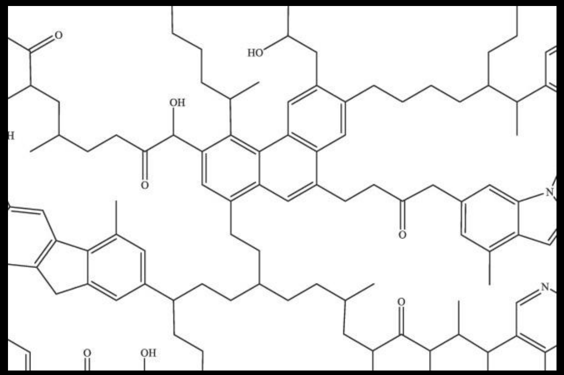
Amino ($R\text{-}NH_2$), Carboxyl (R-COOH), Hydroxyl (R-OH), Phenyl ()



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Increasing Depth

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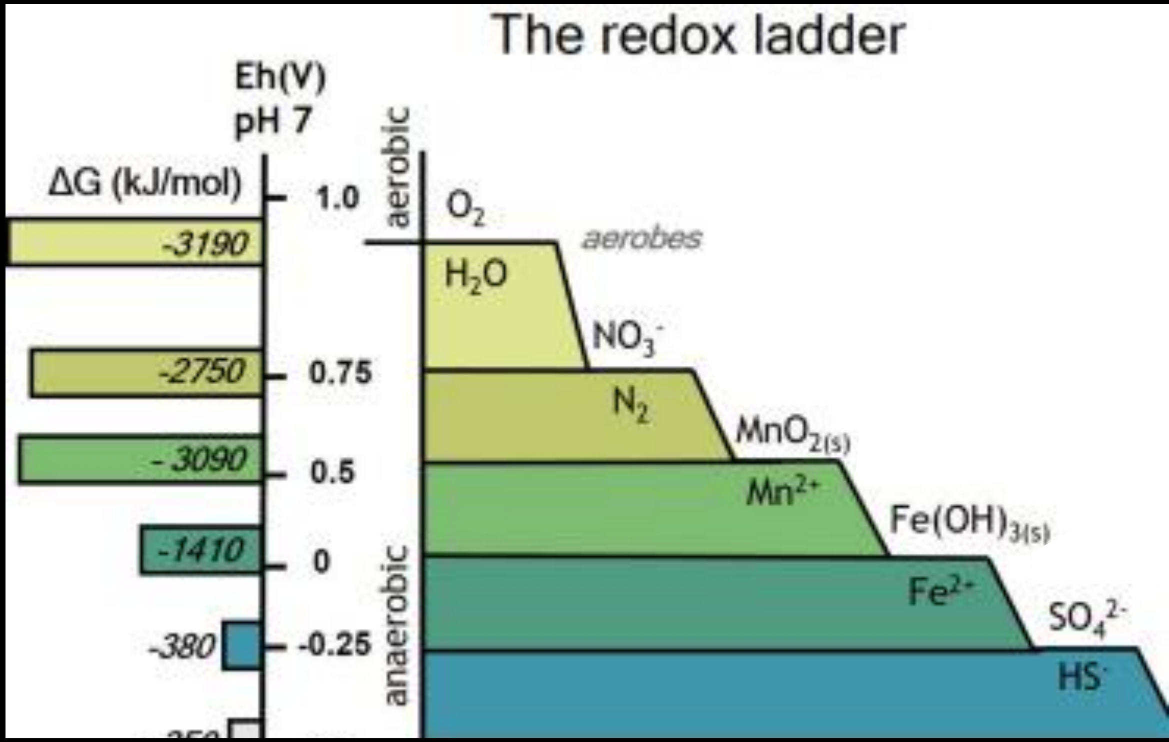

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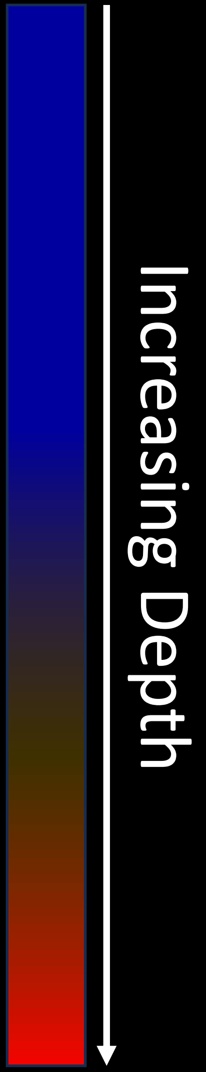


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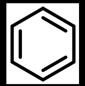
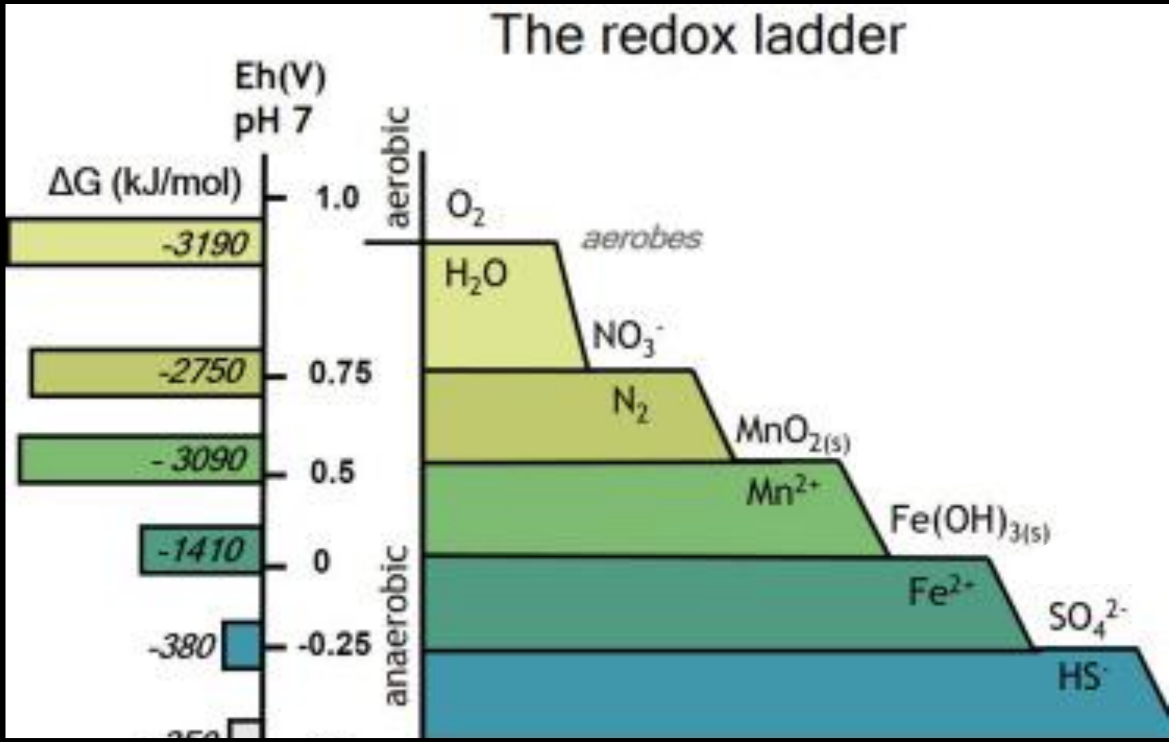
Amino (R-$NH_2$), Carboxyl (R-COOH), Hydroxyl (R-OH), Phenyl ()



# Relearning organic chemistry

Synthetic organic chemistry

Exotic, reactive, high-purity reagents

Ideal conditions: room T & P

Avoid water!

# Relearning organic chemistry

Synthetic organic chemistry

Hydrothermal organic geochemistry

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# Relearning organic chemistry

Synthetic organic chemistry

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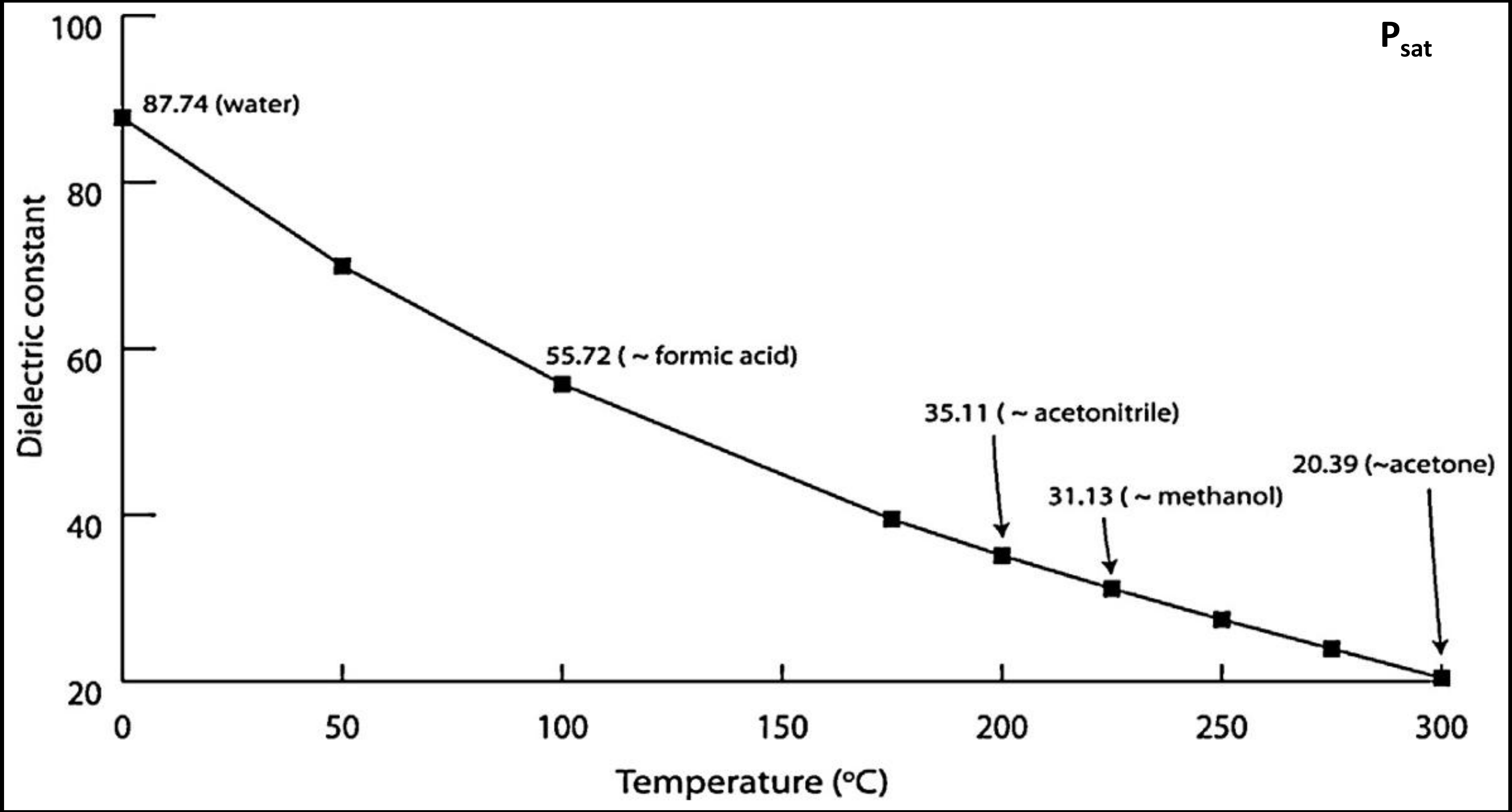
Hydrothermal organic geochemistry

Water-rock-organic systems

Higher temperatures

Higher pressures

# Properties of hot water




(Luong et al., 2015)

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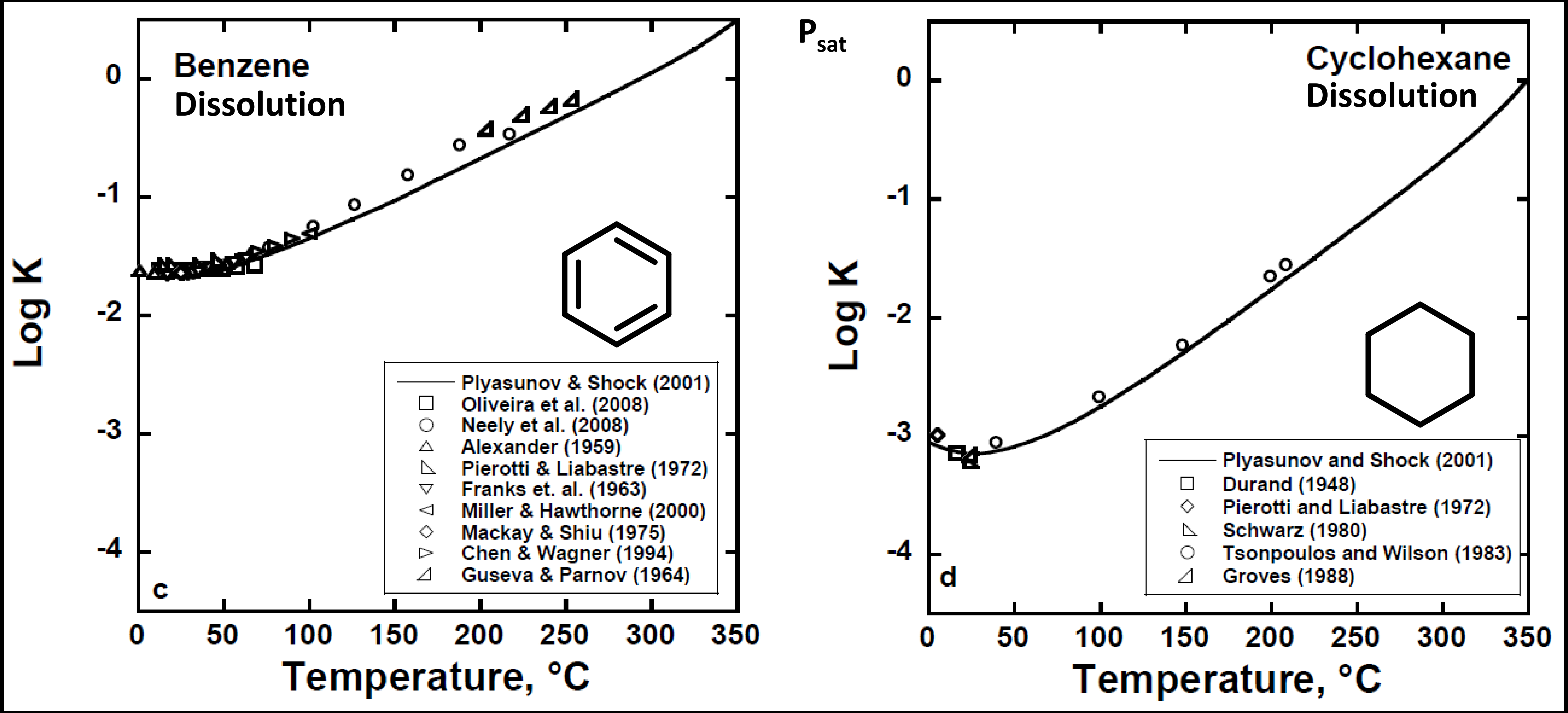


(Shock et al., 2013)

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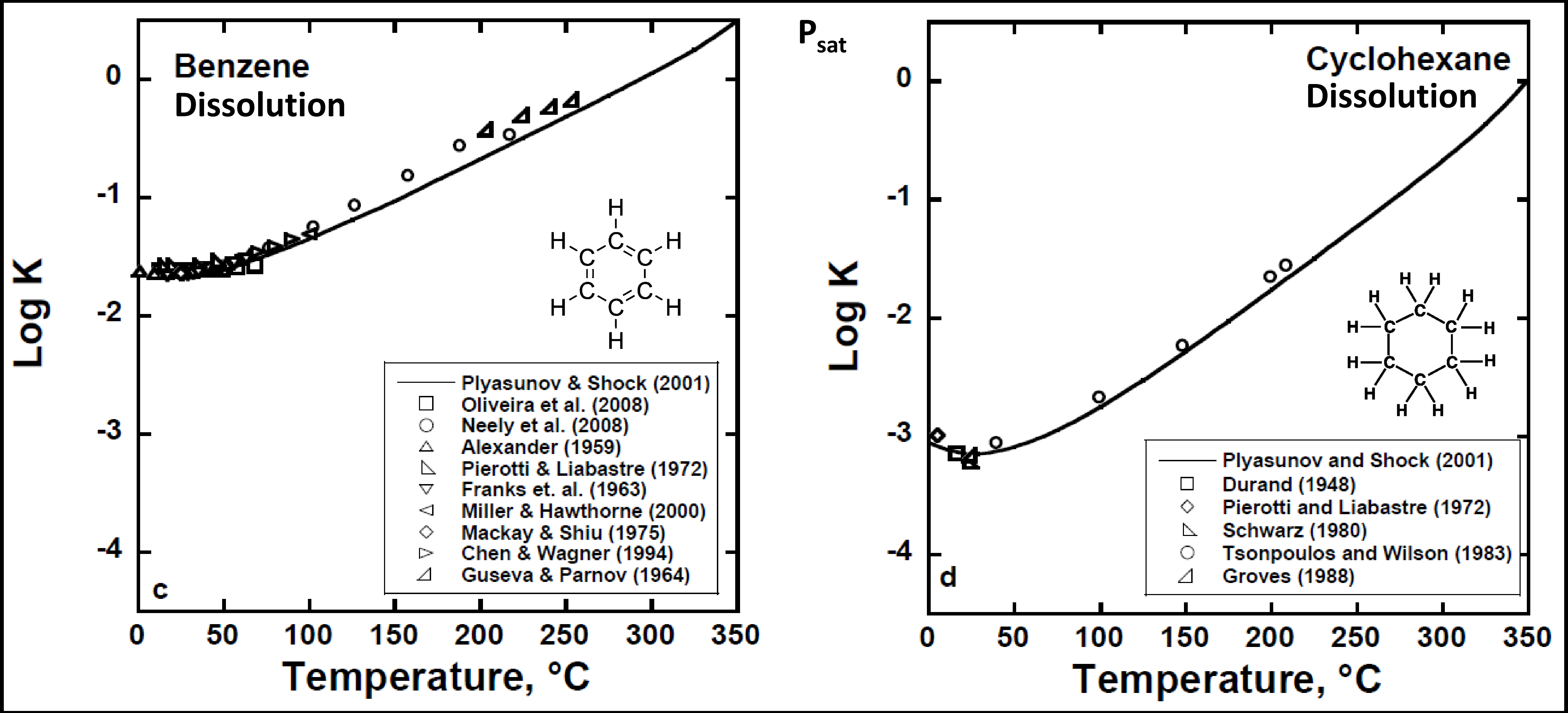


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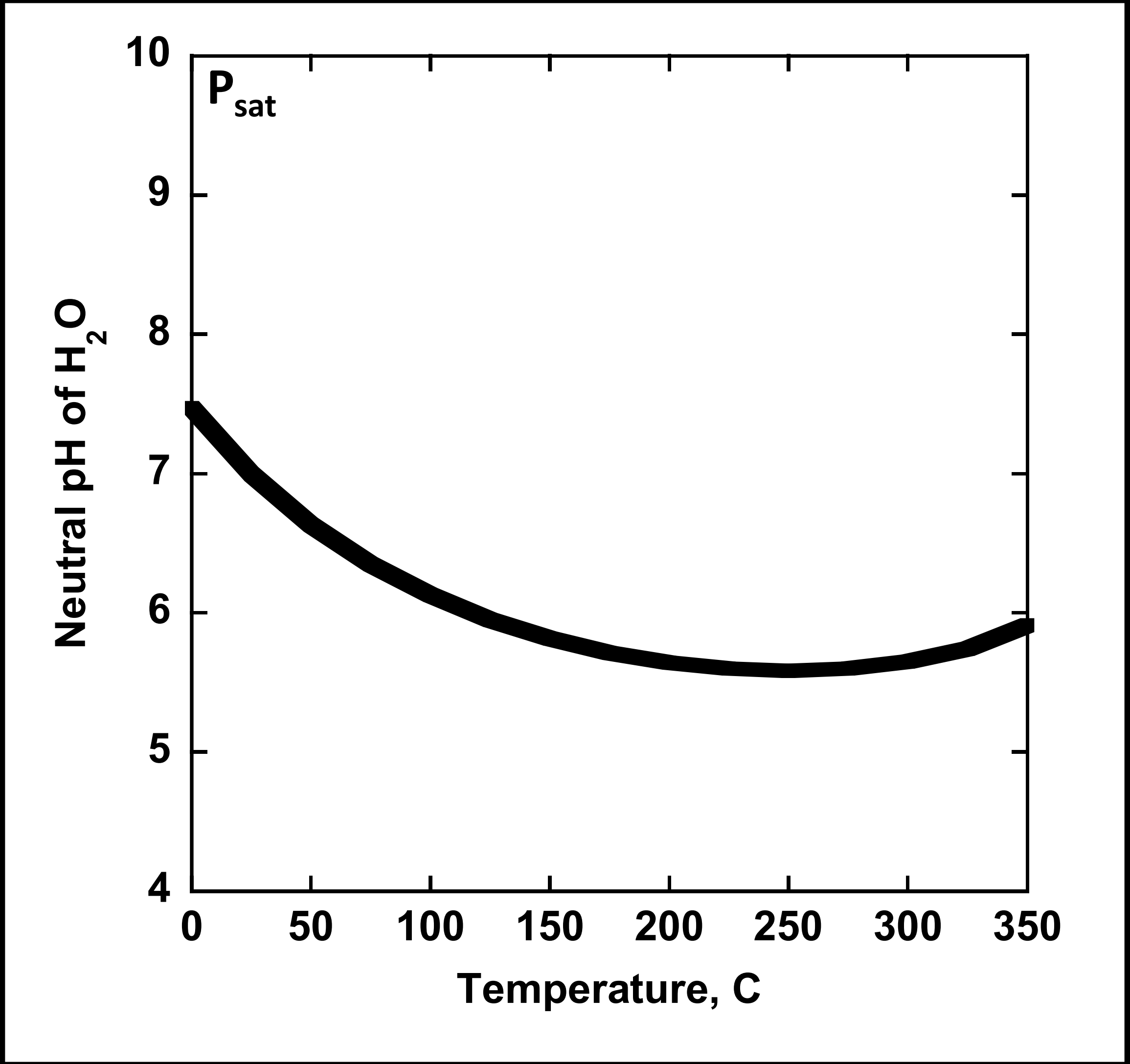


(Boyer et al., 2024a; Dick, 2019)

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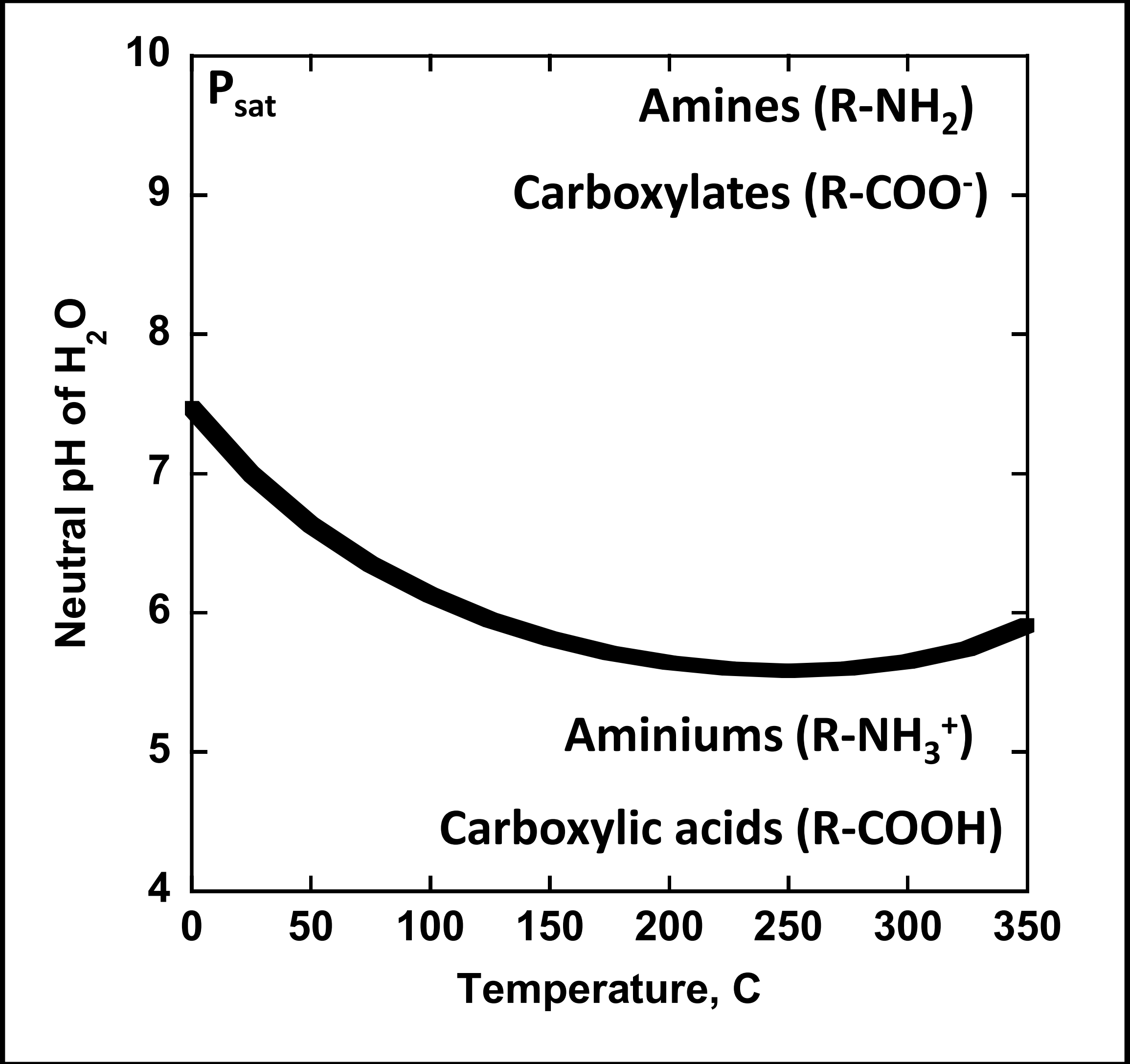


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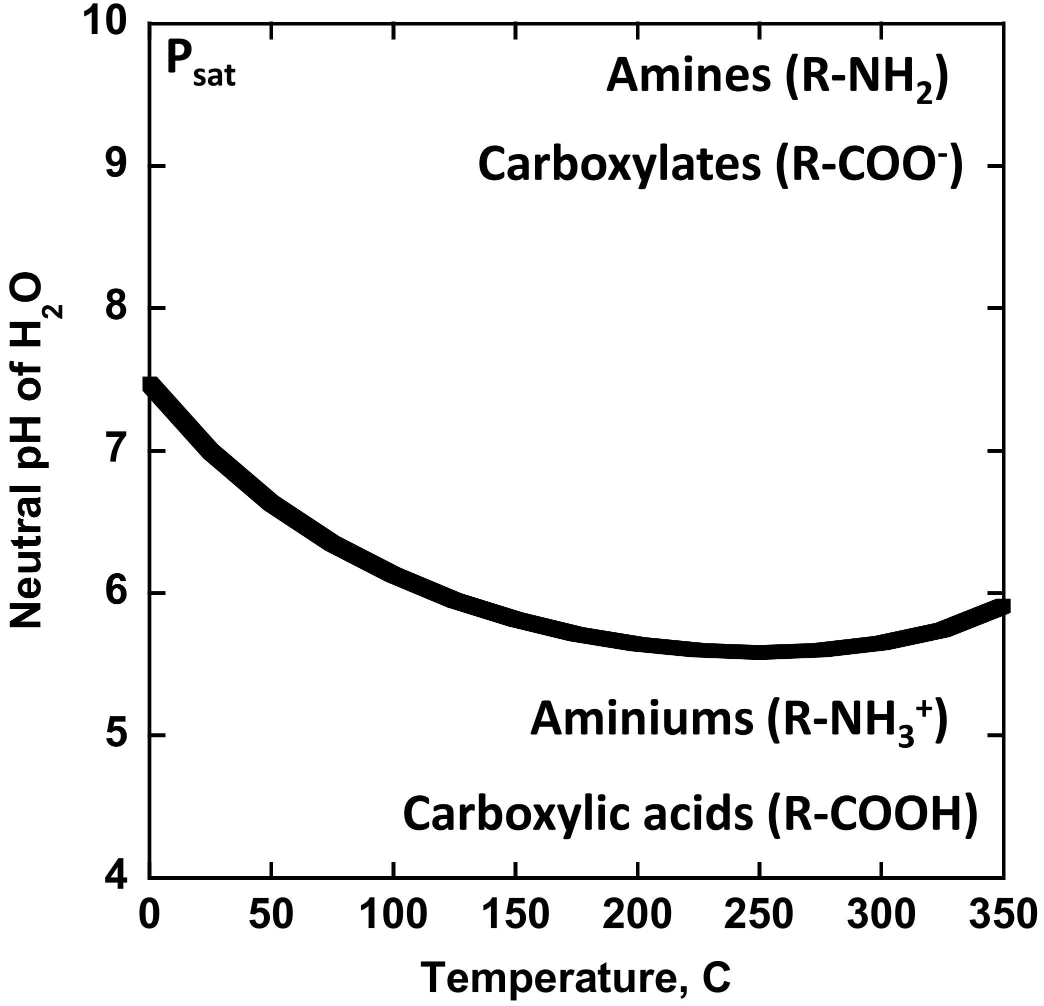


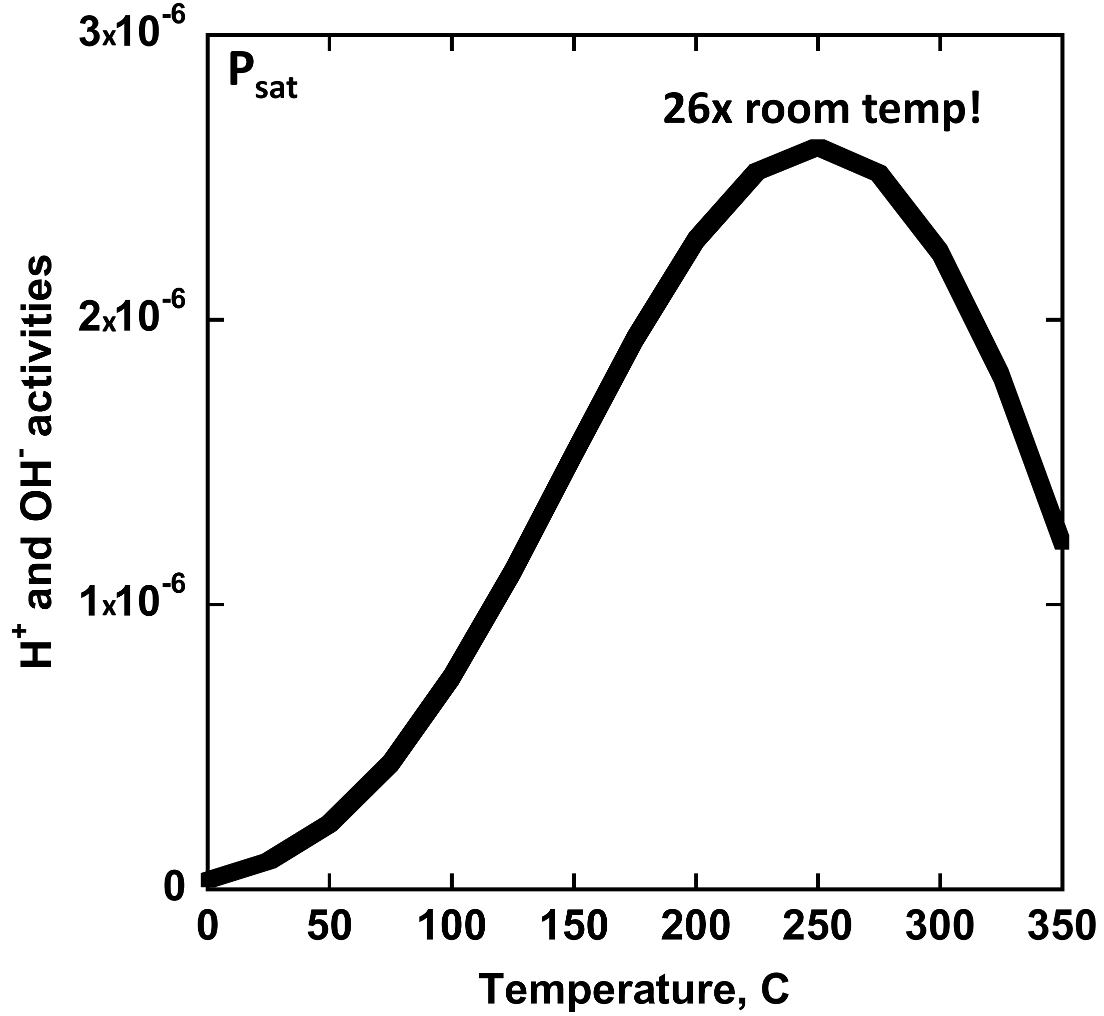


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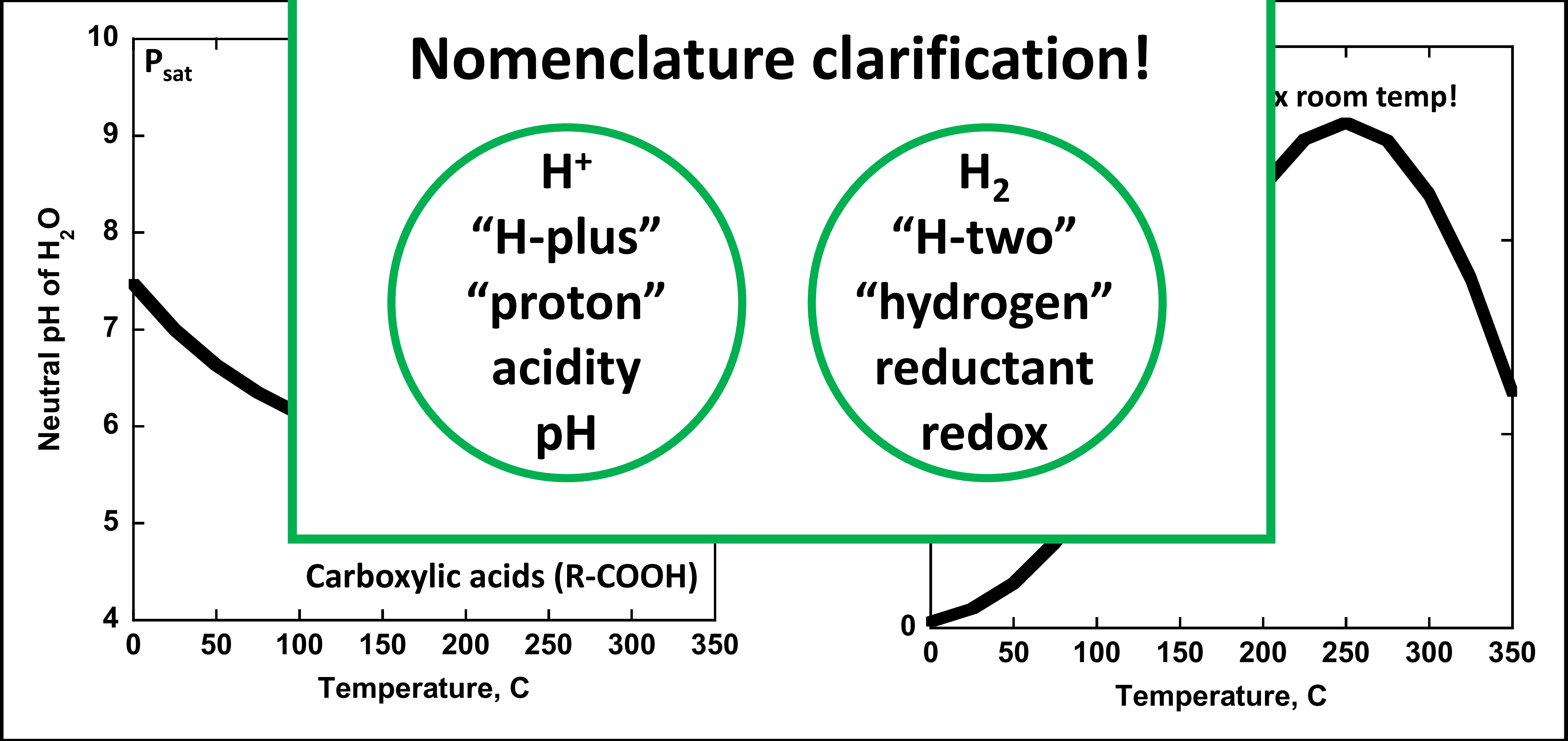



## Nomenclature clarification!

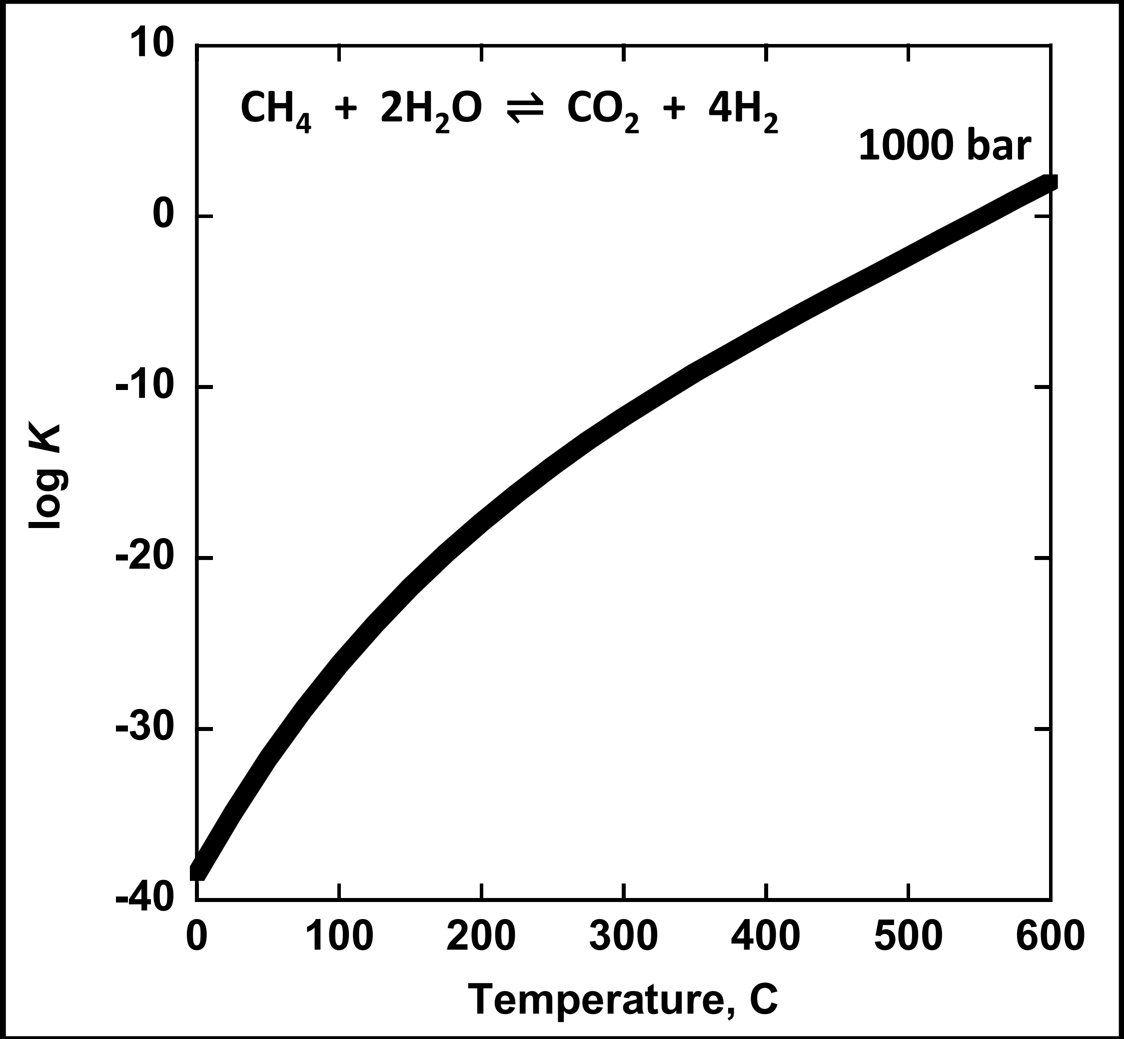
$H^+$
"H-plus"
"proton"
acidity
pH

$H_2$
"H-two"
"hydrogen"
reductant
redox

(Boyer et al., 2024a; Dick, 2019)

# Organic transformations driven by geochemistry

# What happens across T, P, x?

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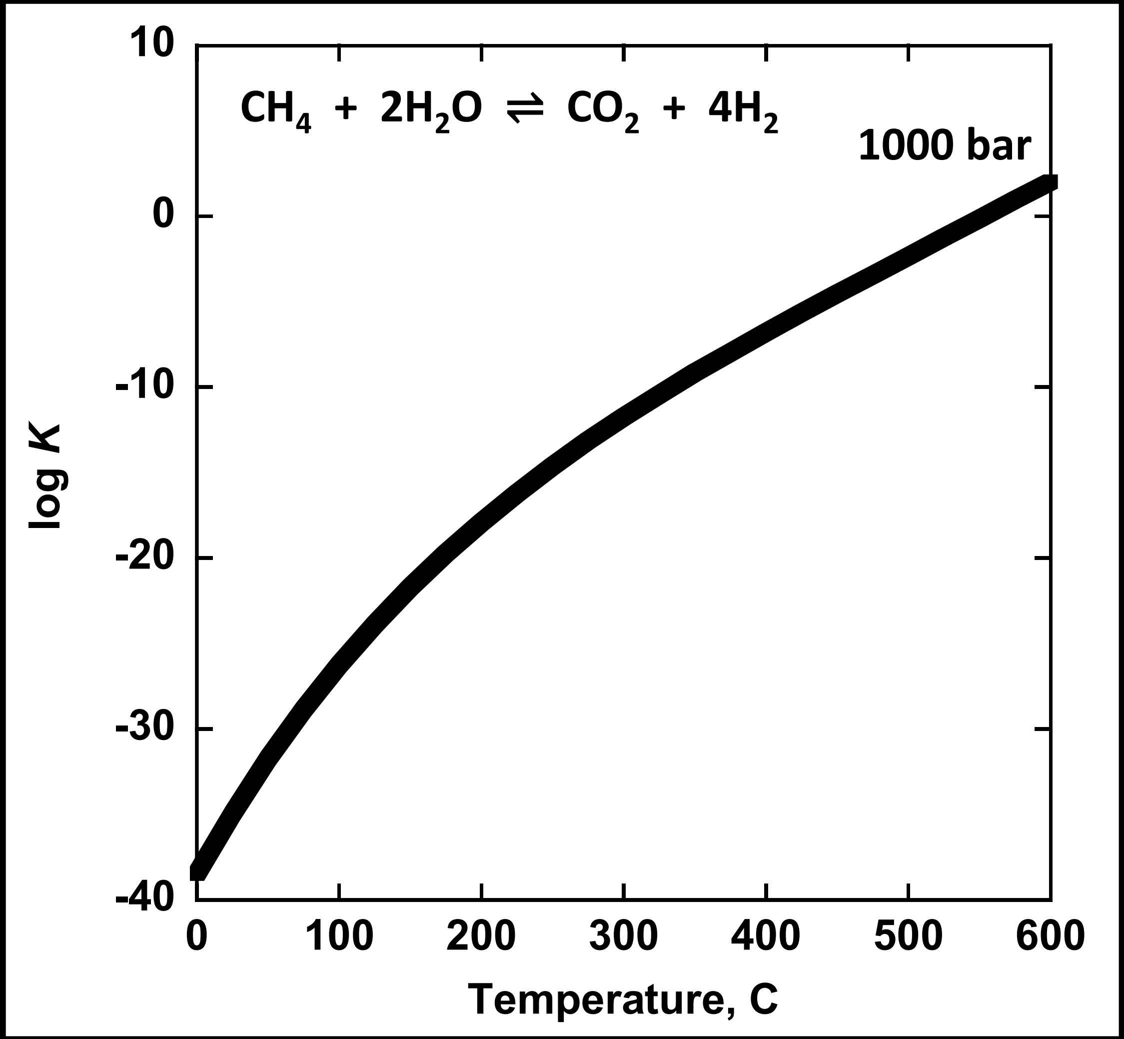


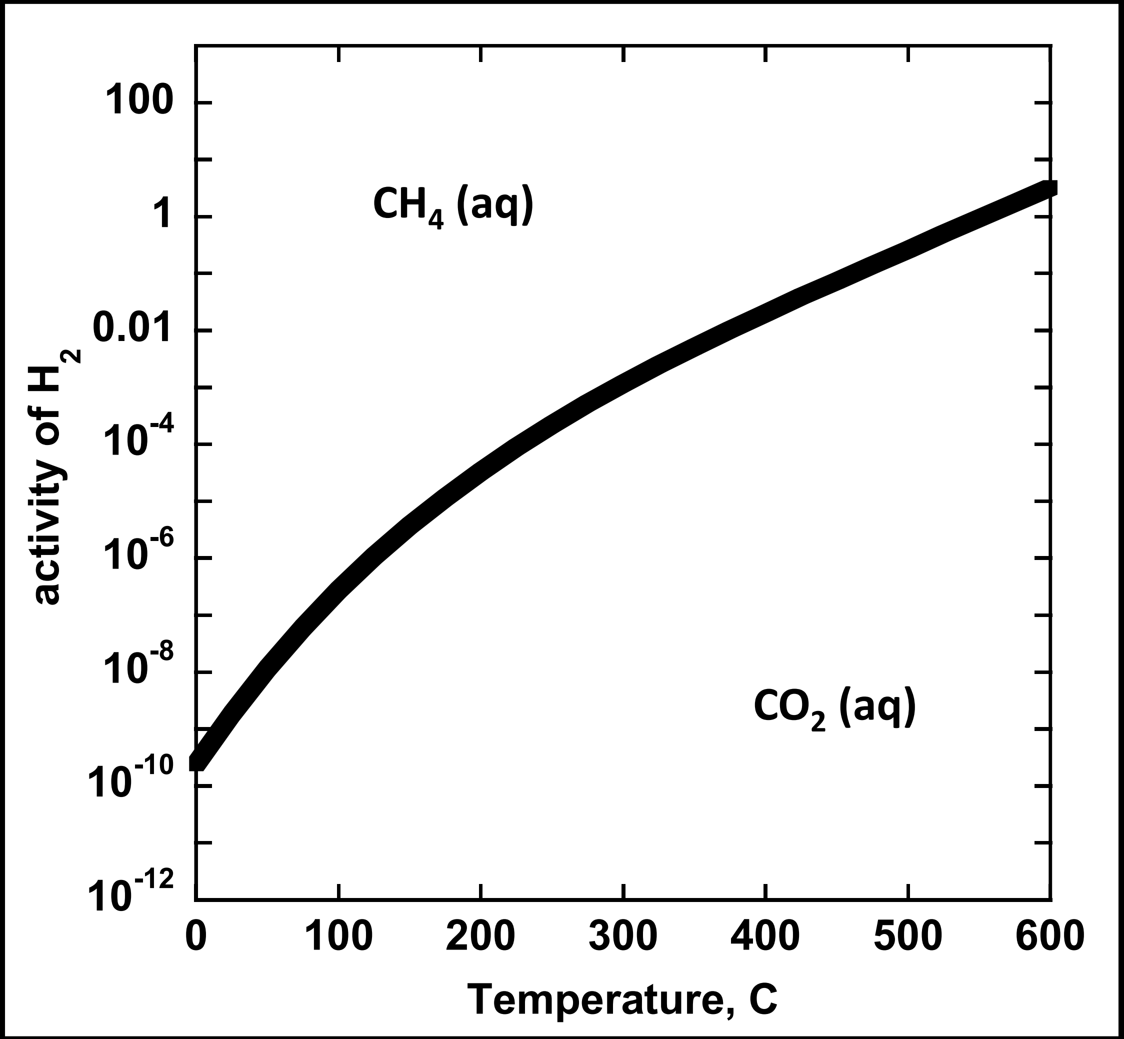


(Boyer et al., 2024a; Dick, 2019)

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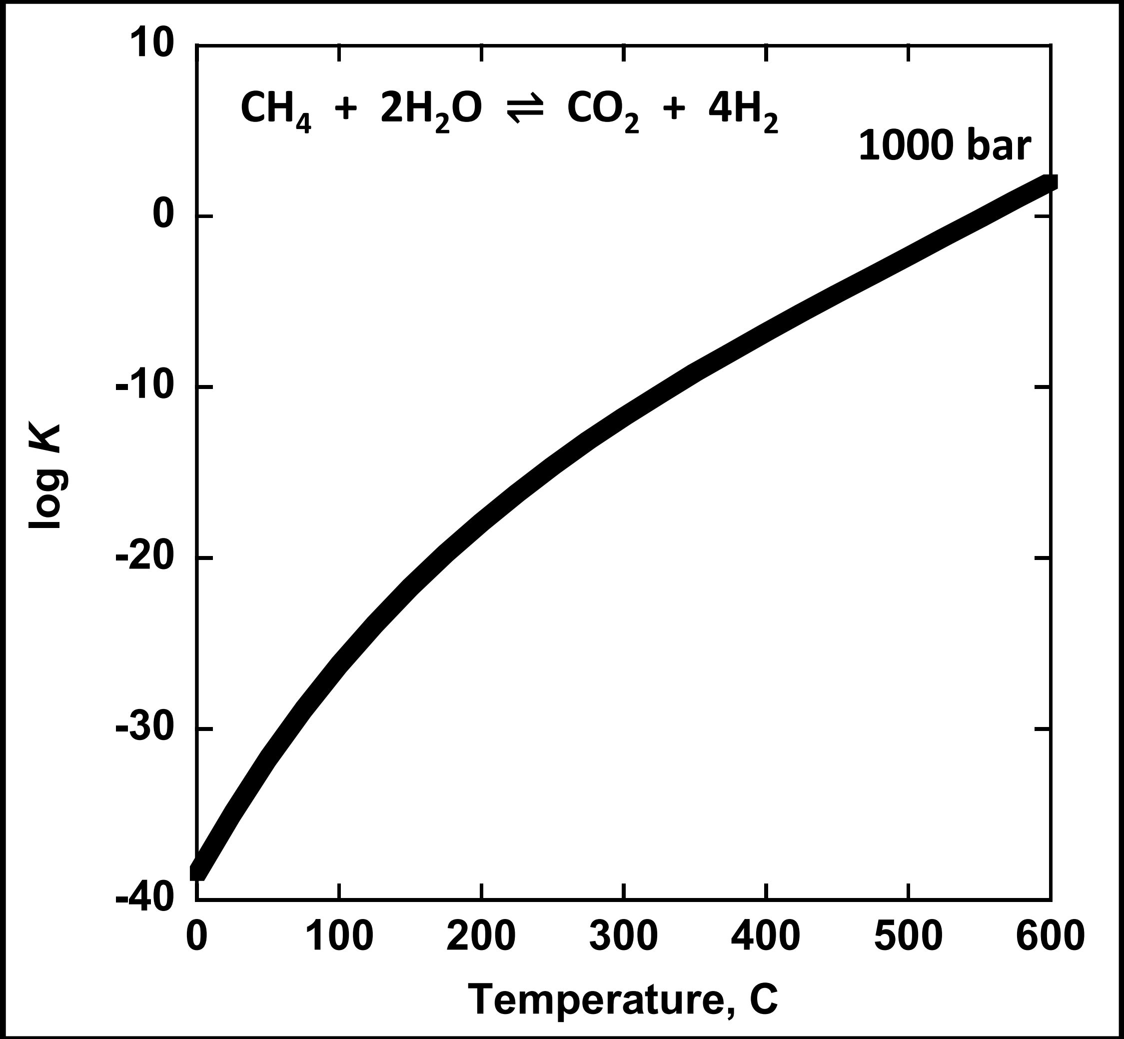


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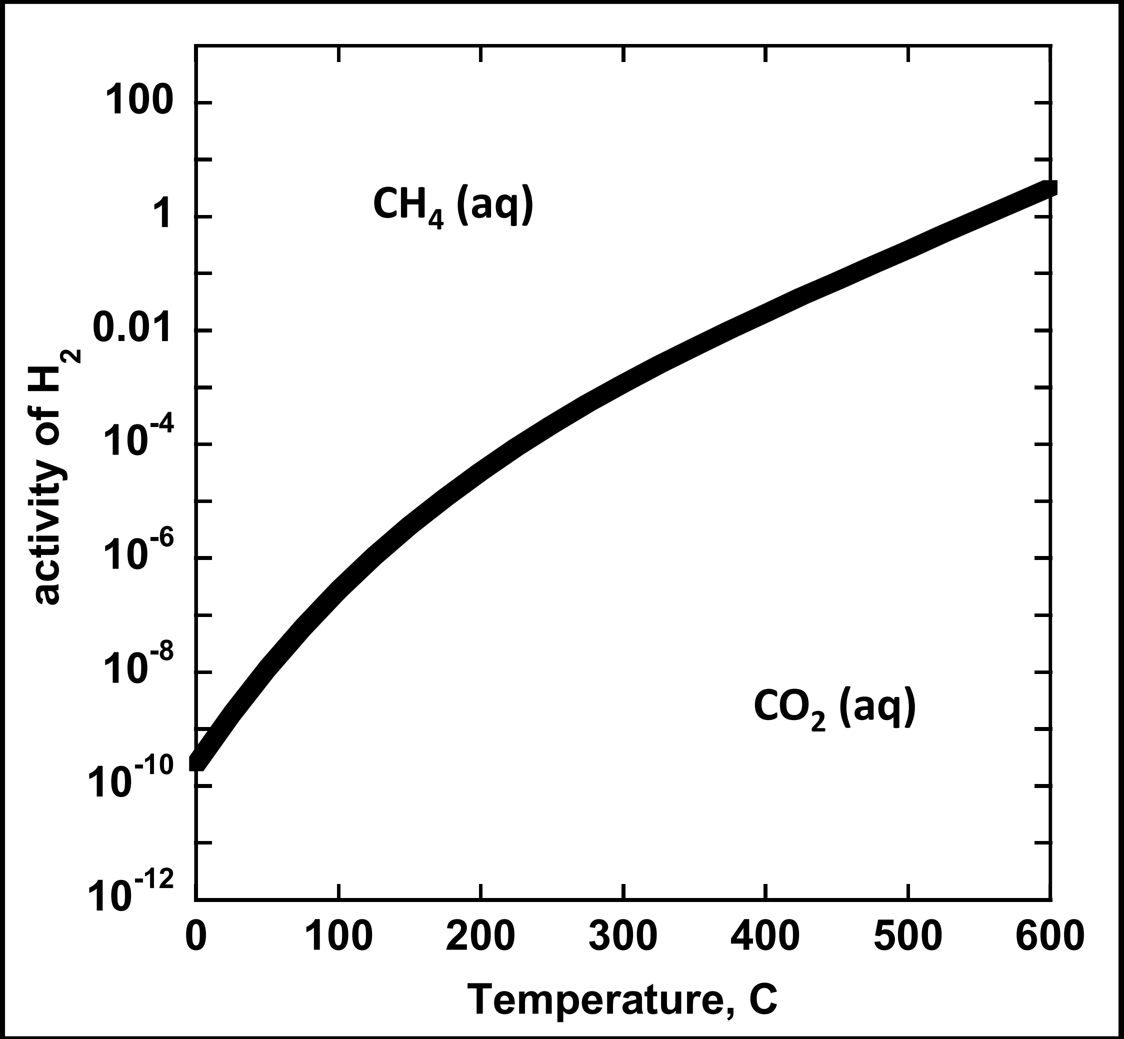


**Thermo consistent with natural gas vs. volcanic gas**

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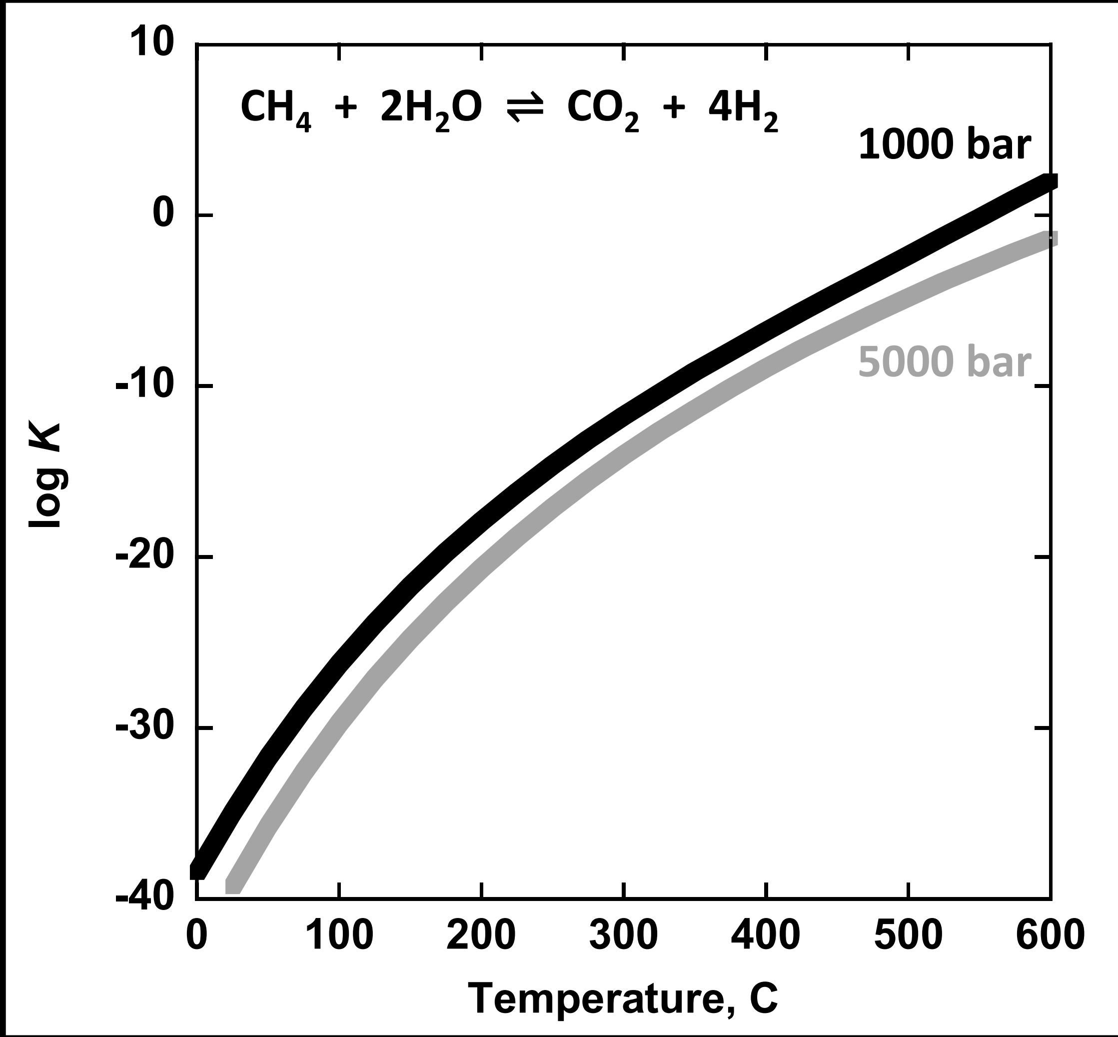


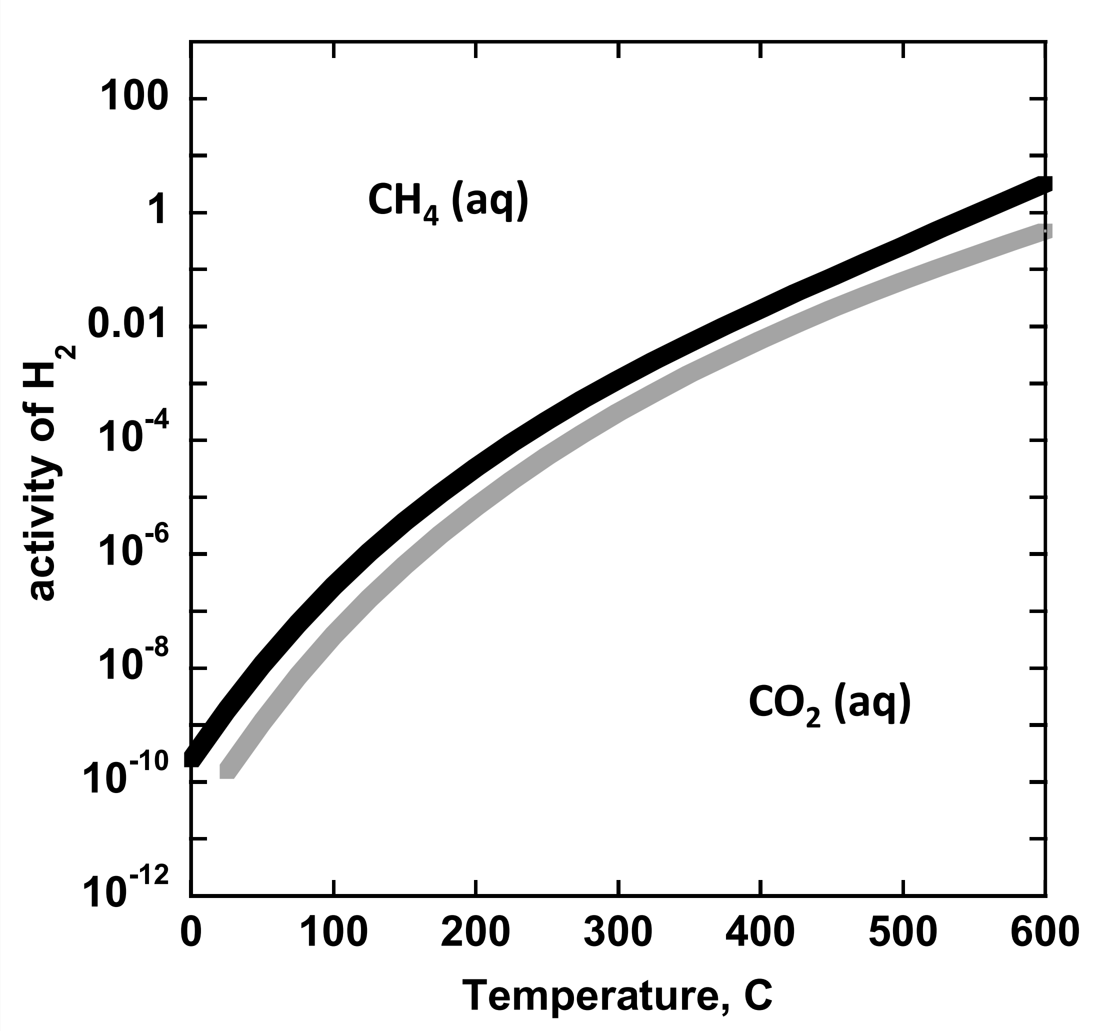


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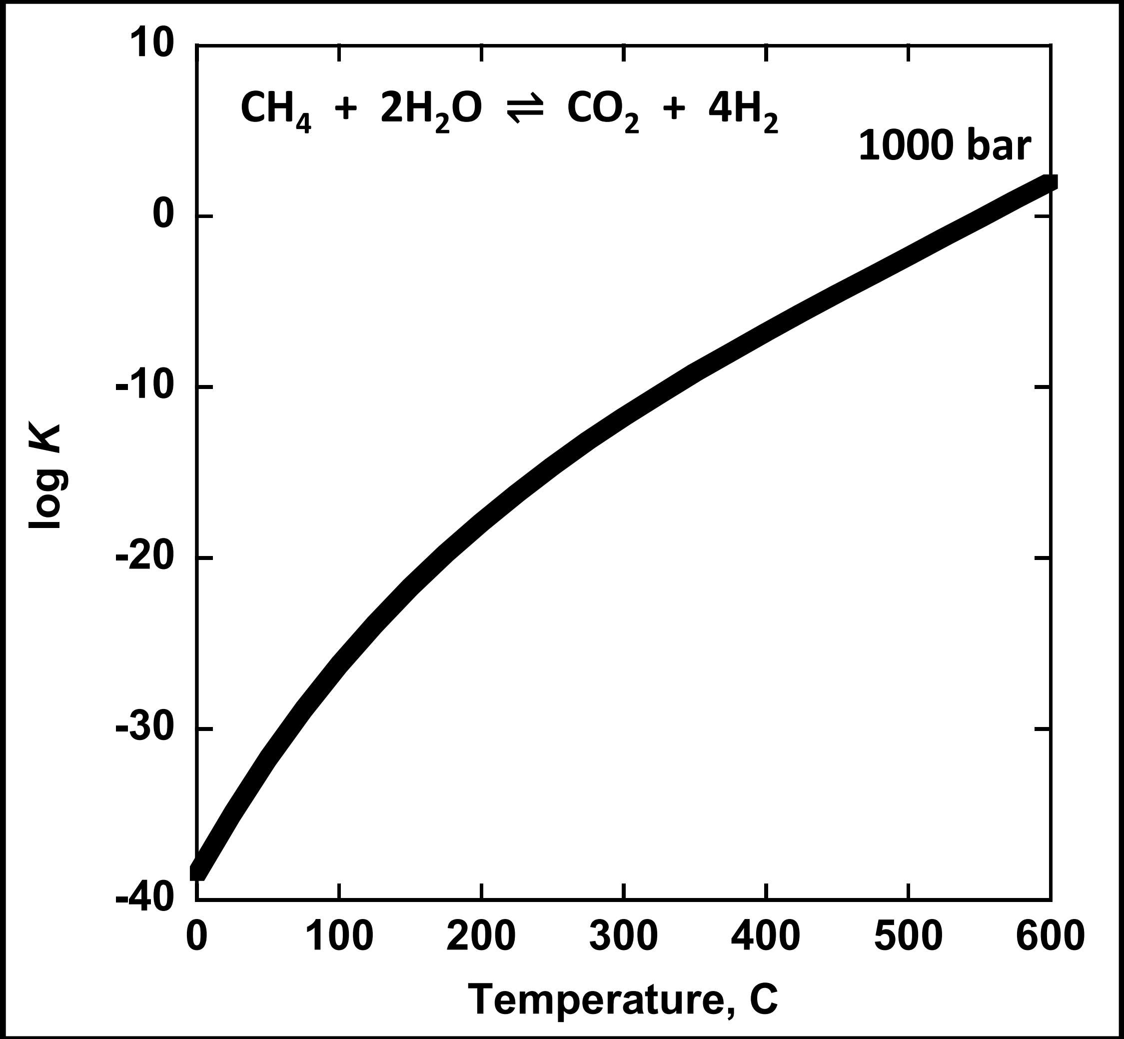


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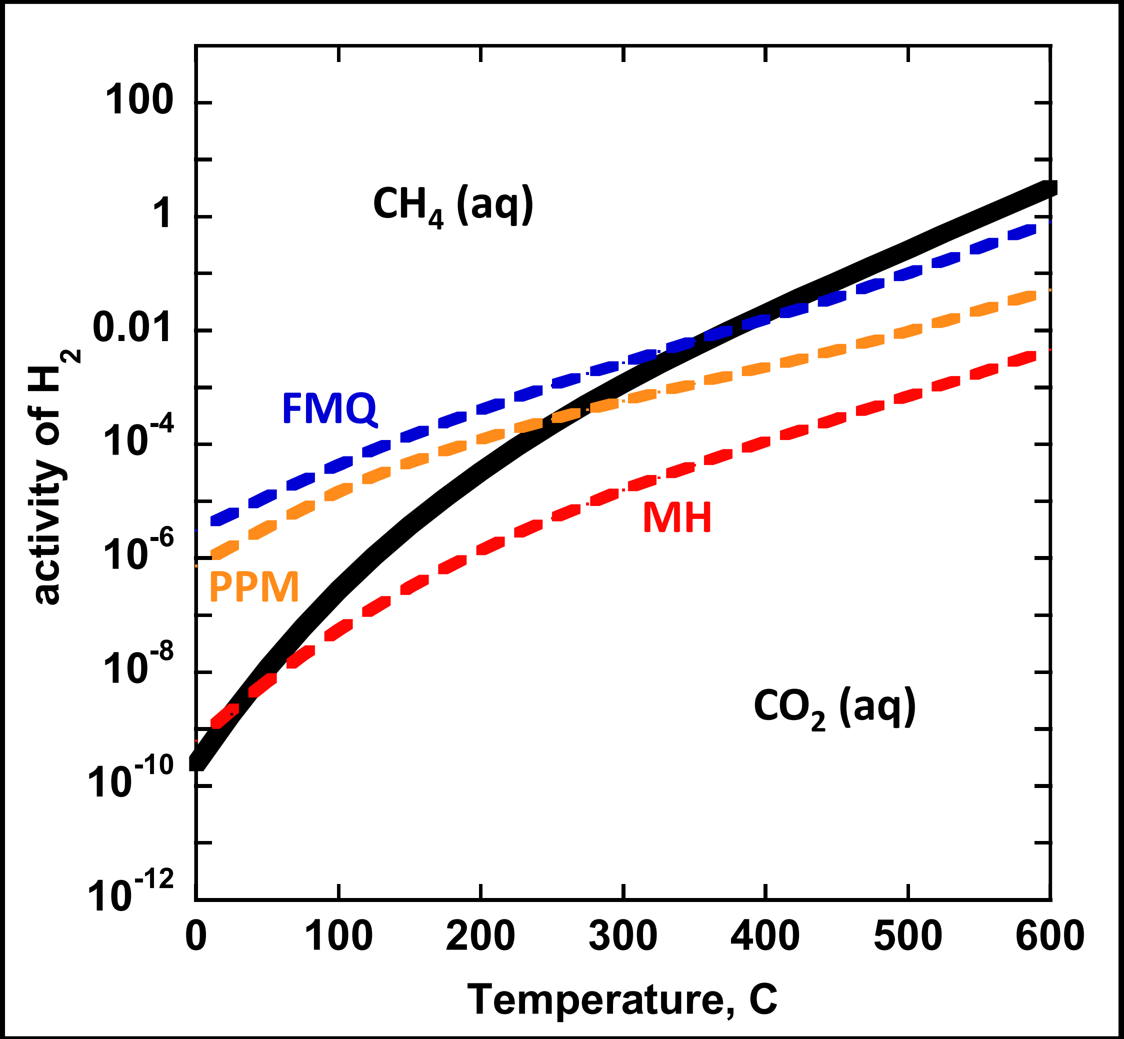
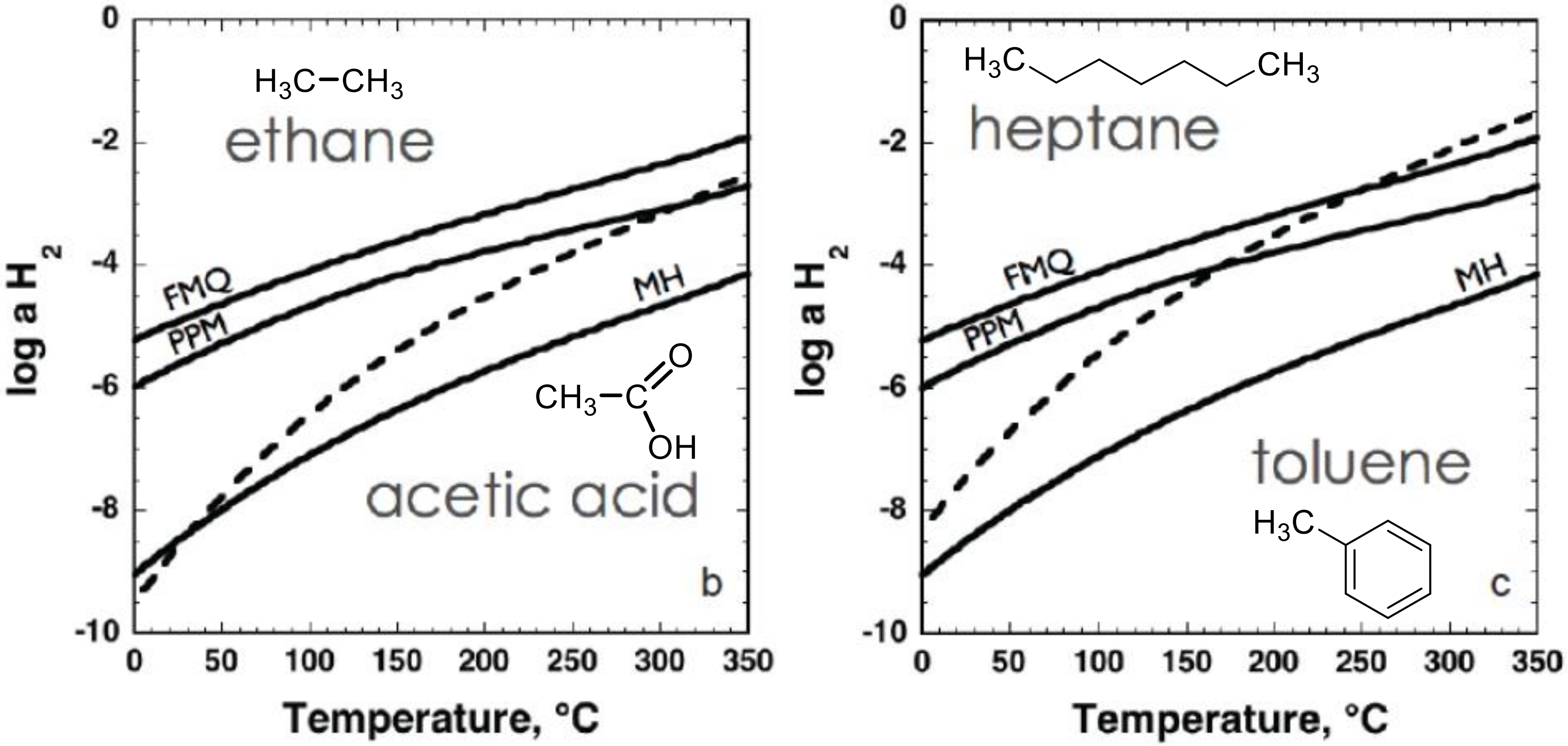



(Shock et al., 2013)

# More oxidations, similar trend

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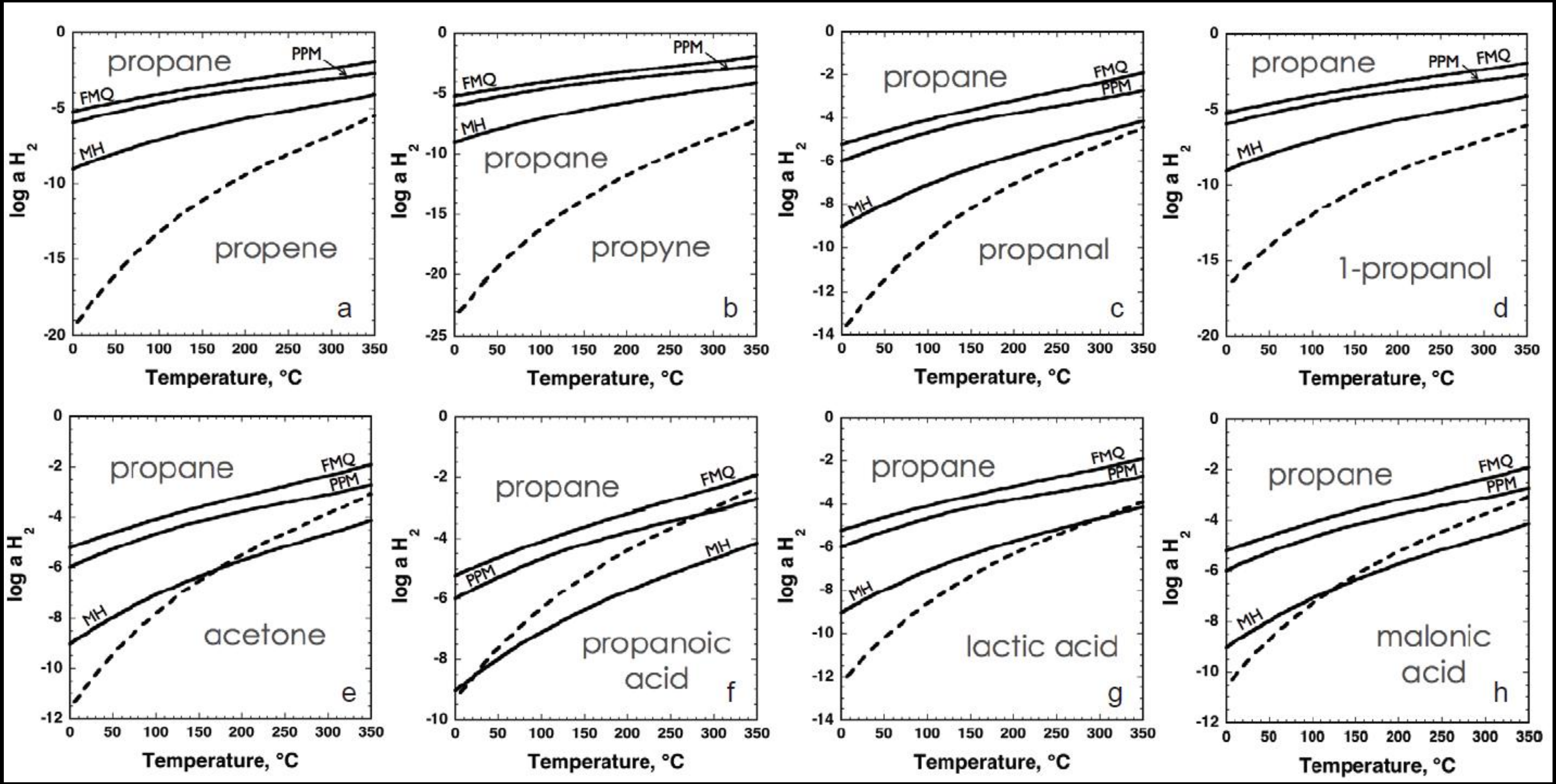


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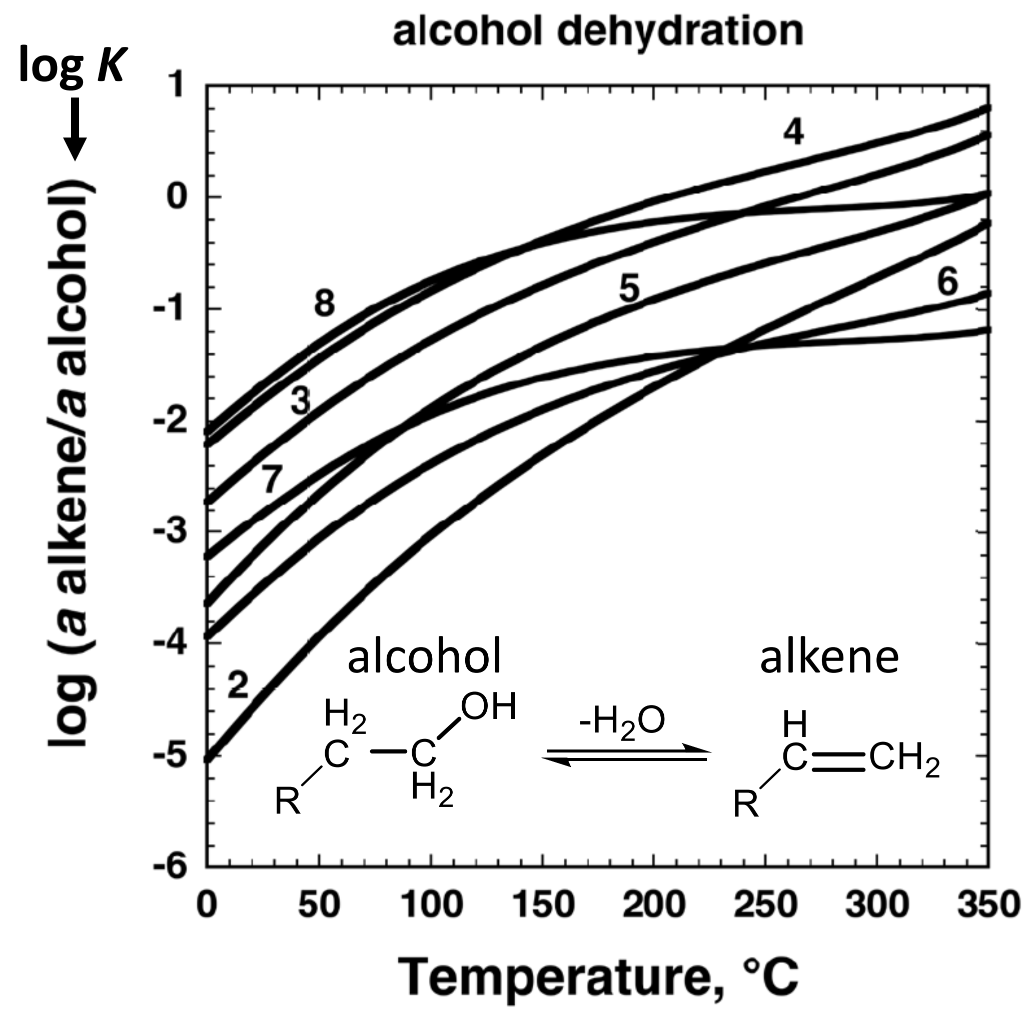
# Loss of O and N in heated organics

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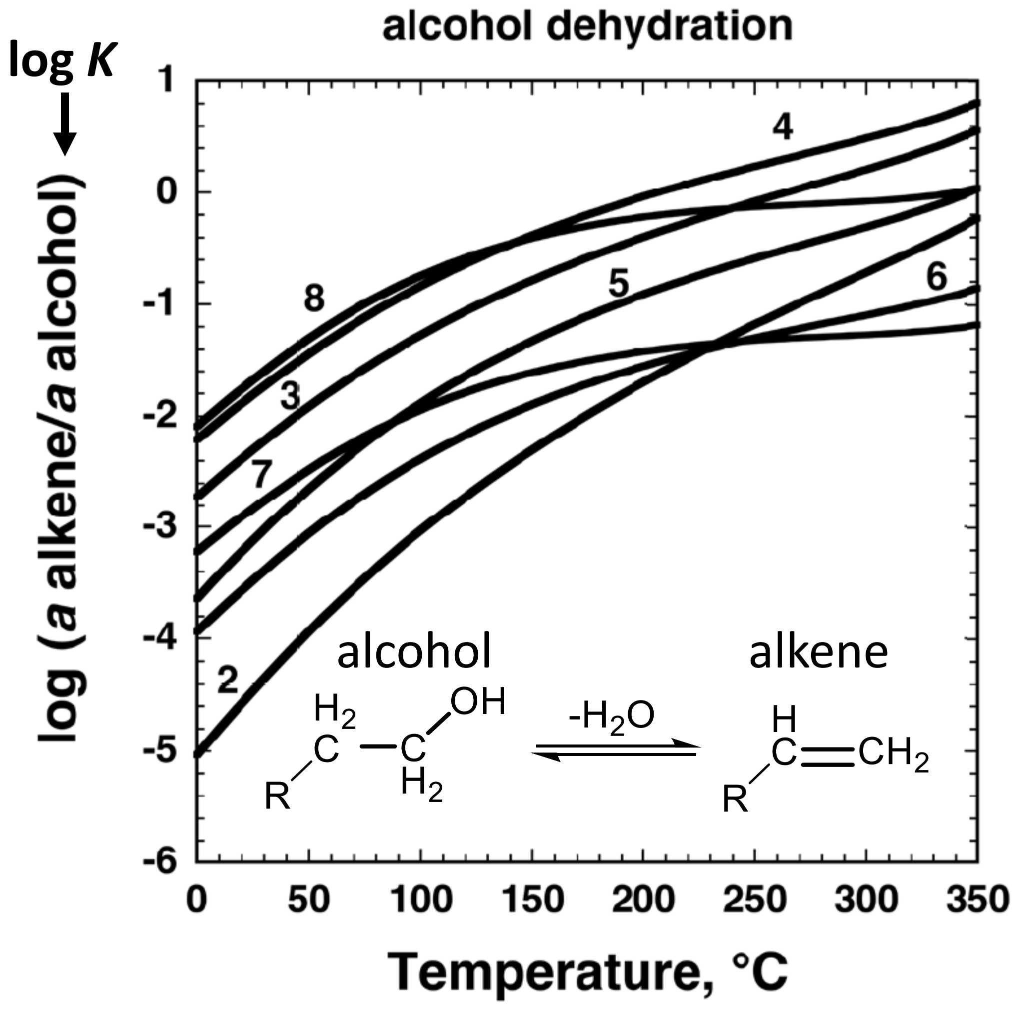


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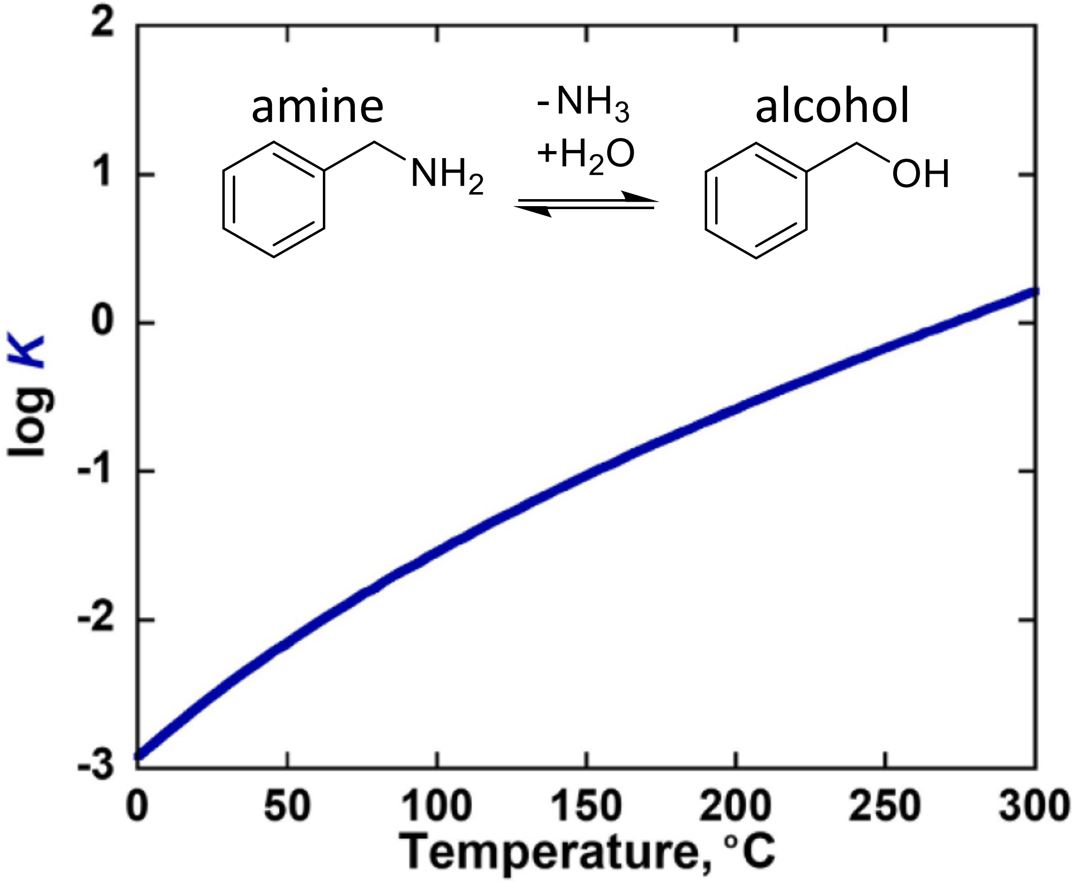


(Robinson et al., 2024)

Thermodynamics tells us what can happen, not what will happen.

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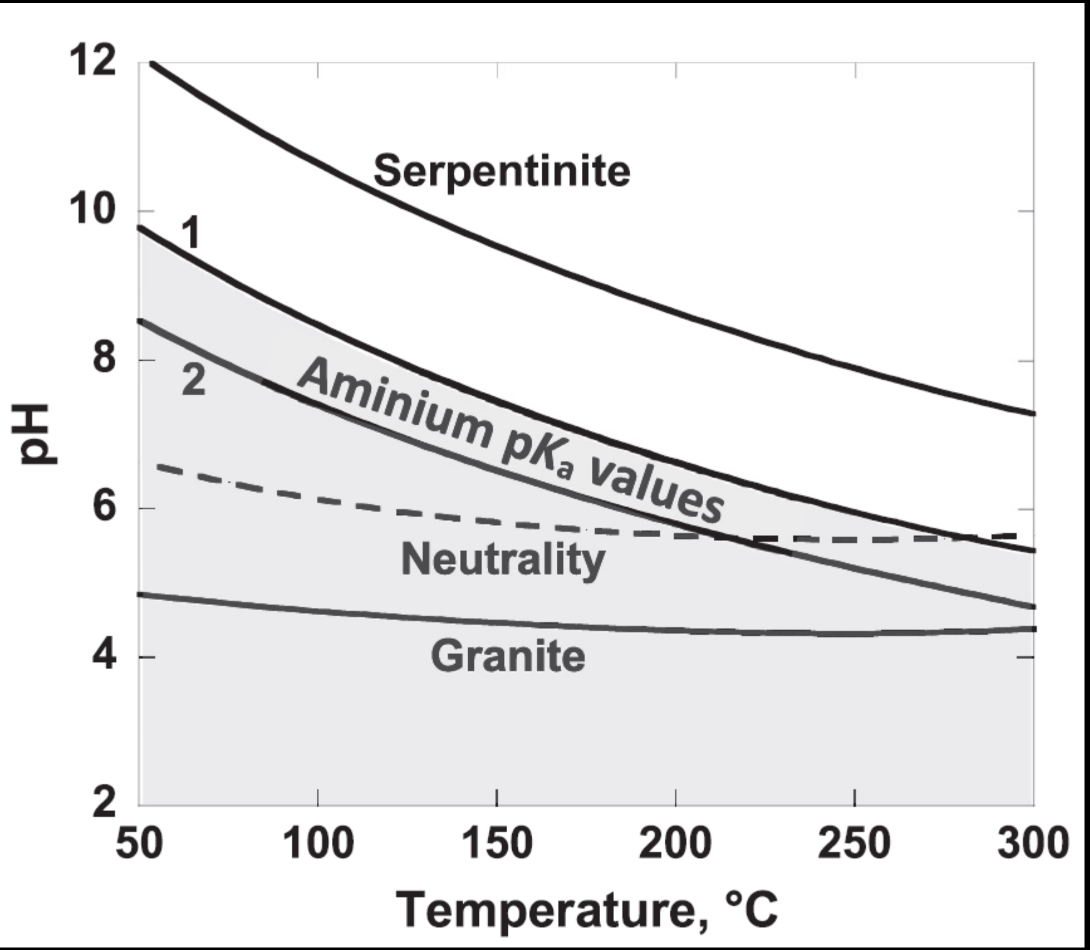
Kinetics studies needed!

# Effect of pH on kinetics: Speciation

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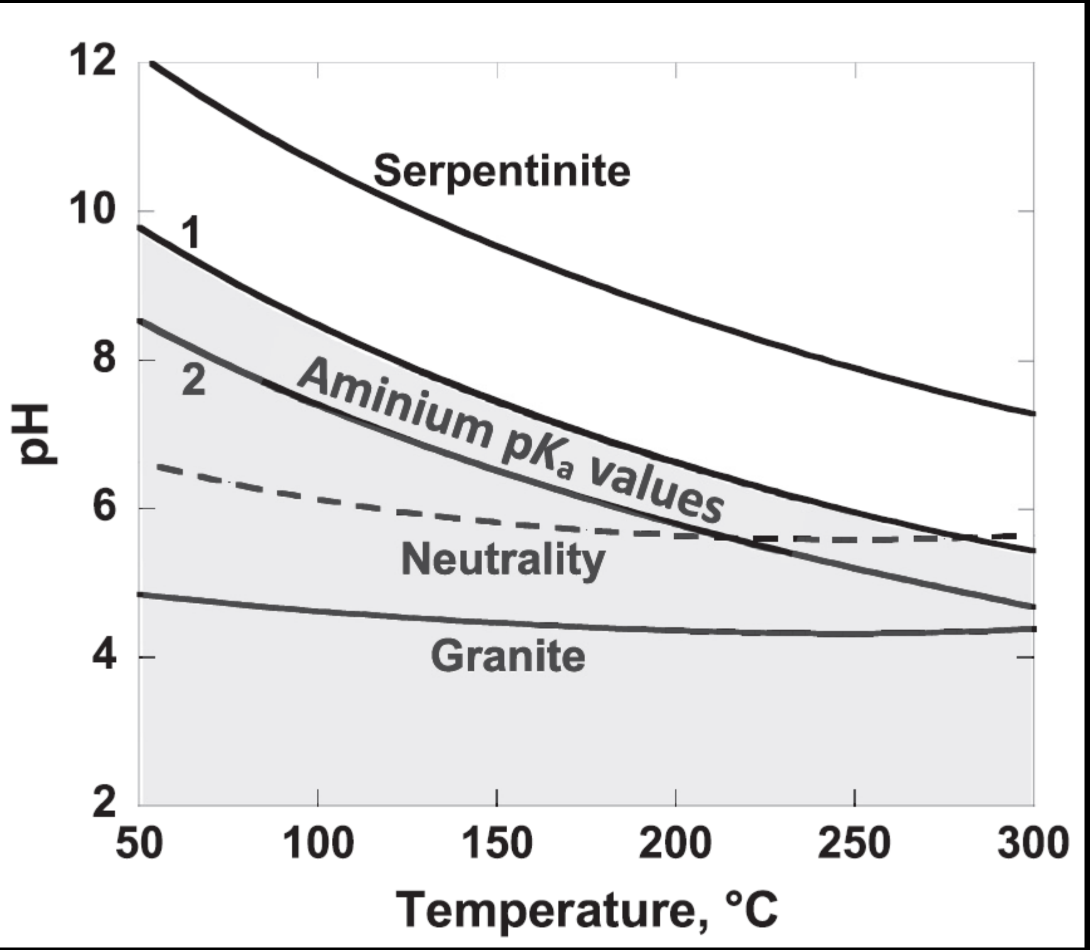


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Glycinate dominates ($NH_2$-$CH_2$-$COO^-$)

pH-dependent speciation

Glycine dominates ($^+NH_3$-$CH_2$-$COO^-$)

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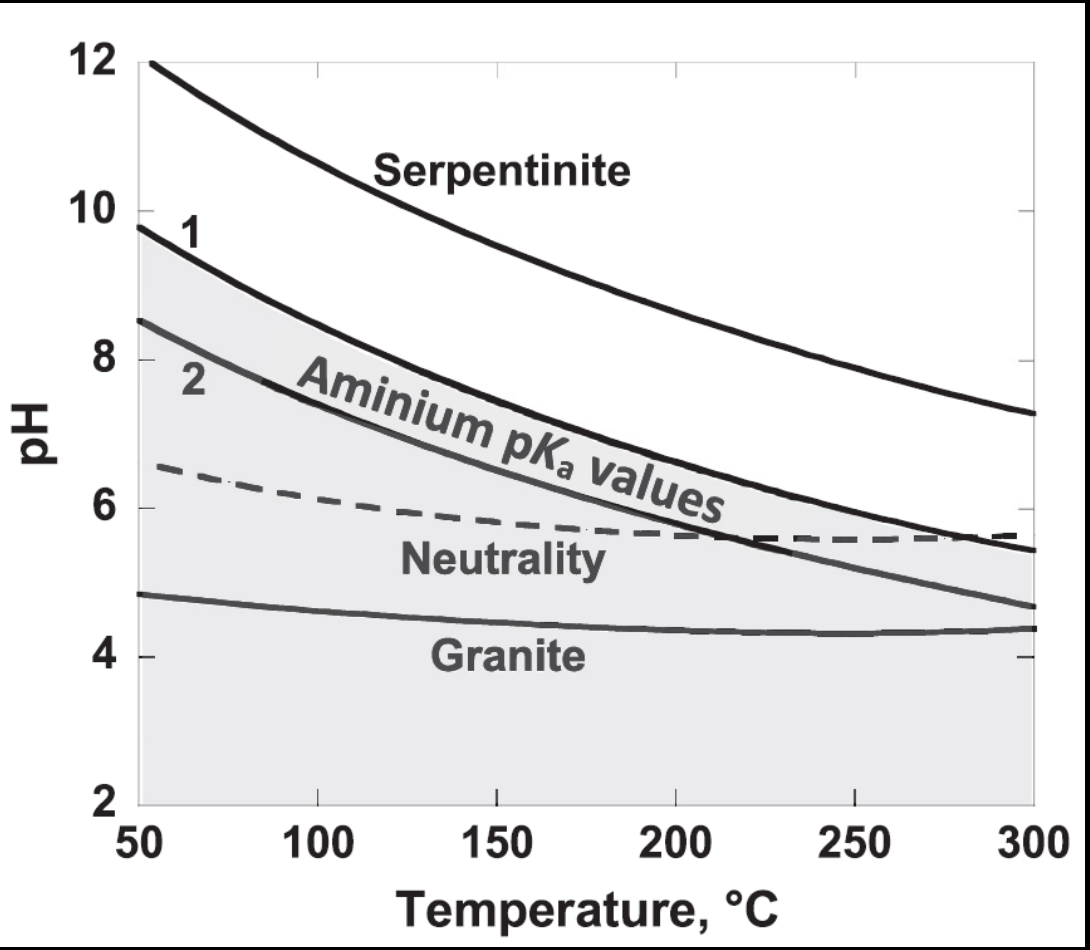


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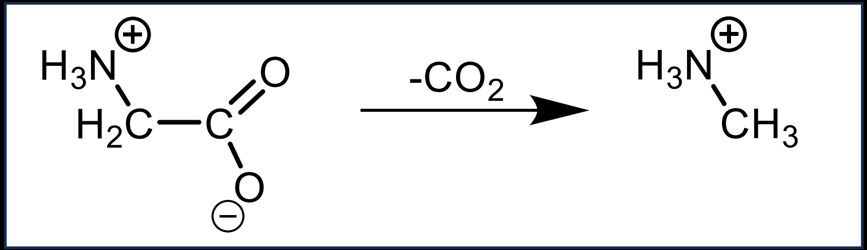
>1000x decarboxylation rate



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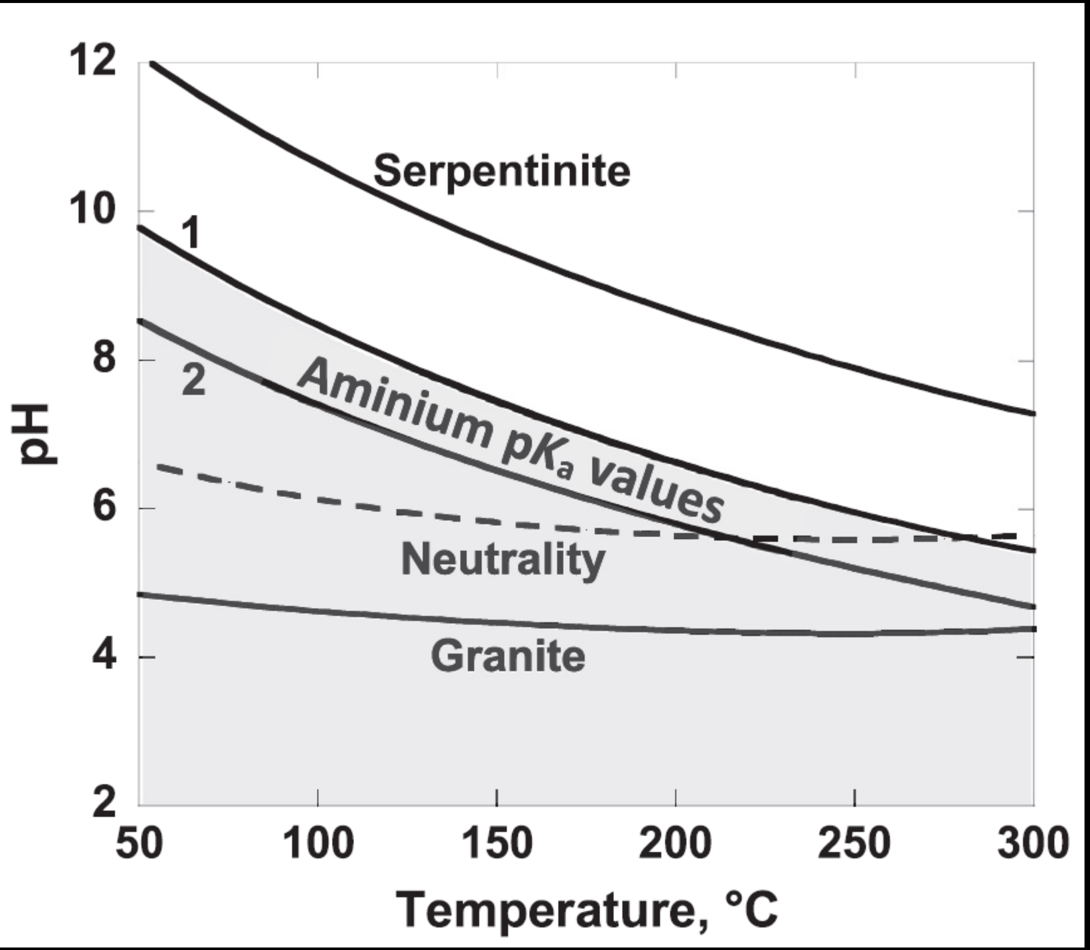


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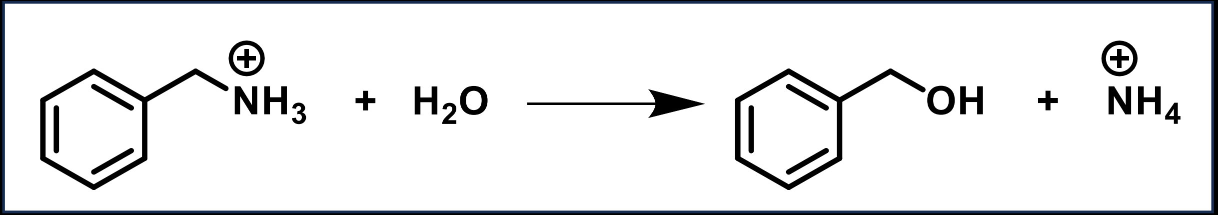
Amines dominate (R-$NH_2$)

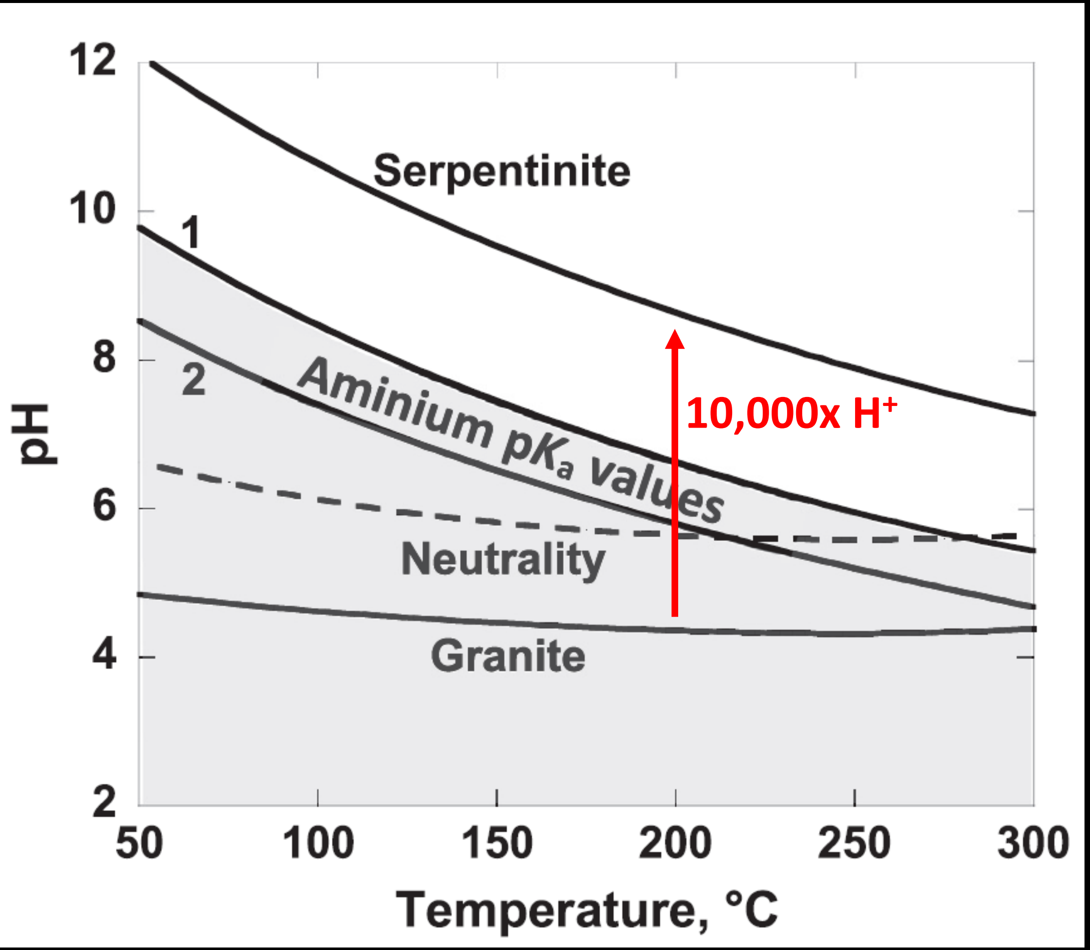
pH-dependent speciation

Aminiums dominate (R-$NH_3^+$)

>10x deamination rate



# Effect of pH on kinetics: Catalysis

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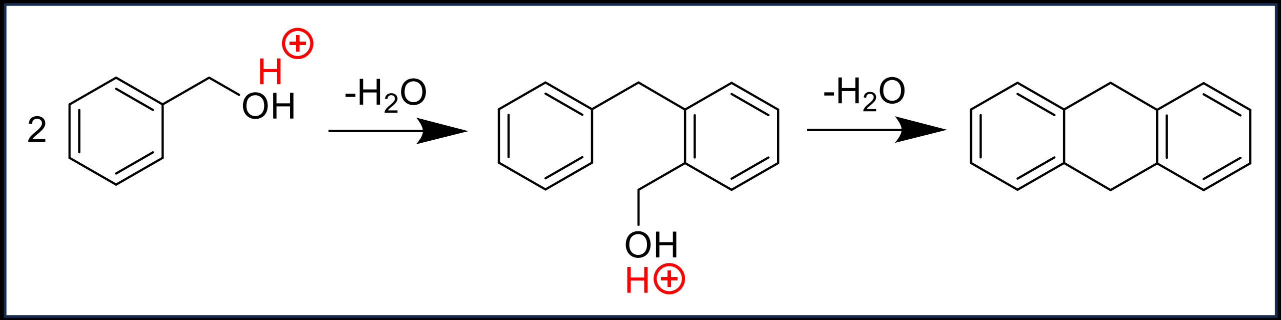
## Acid catalysis

Alcohol dehydration rate
proportional to the activity of H+



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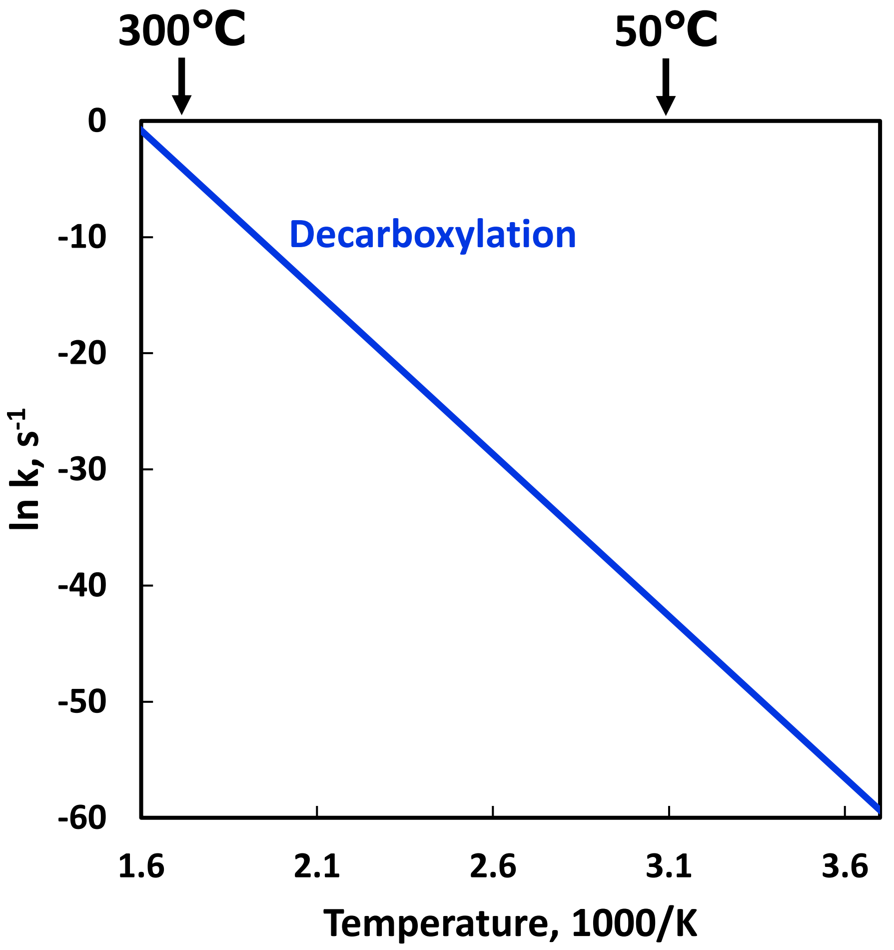


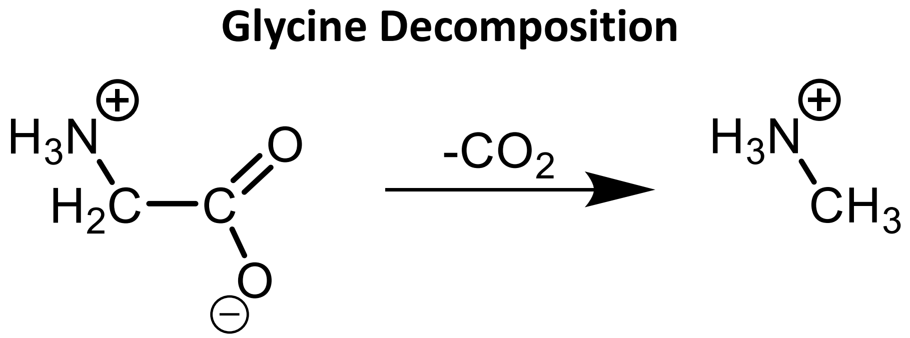


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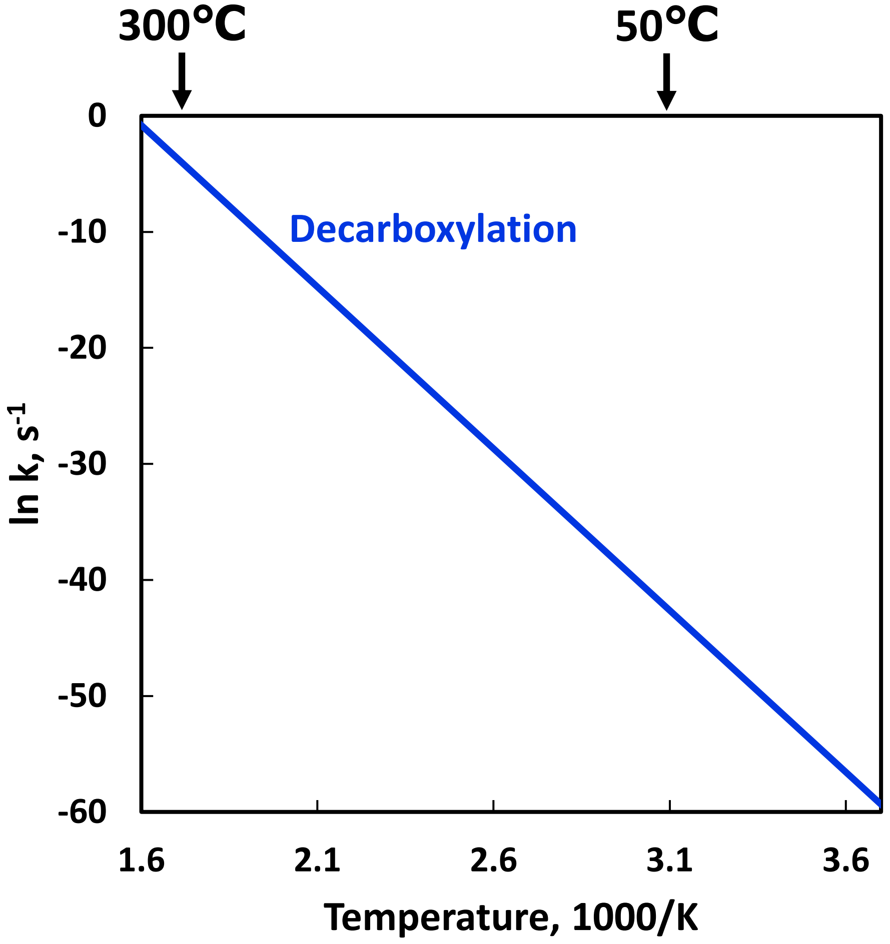
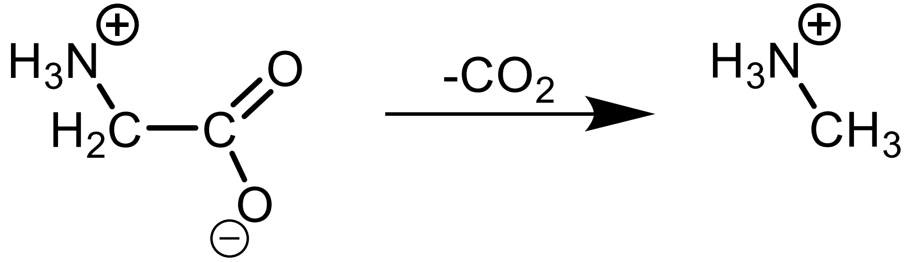



**Glycine Decomposition**




<u>**Half-life at 50°C**</u>

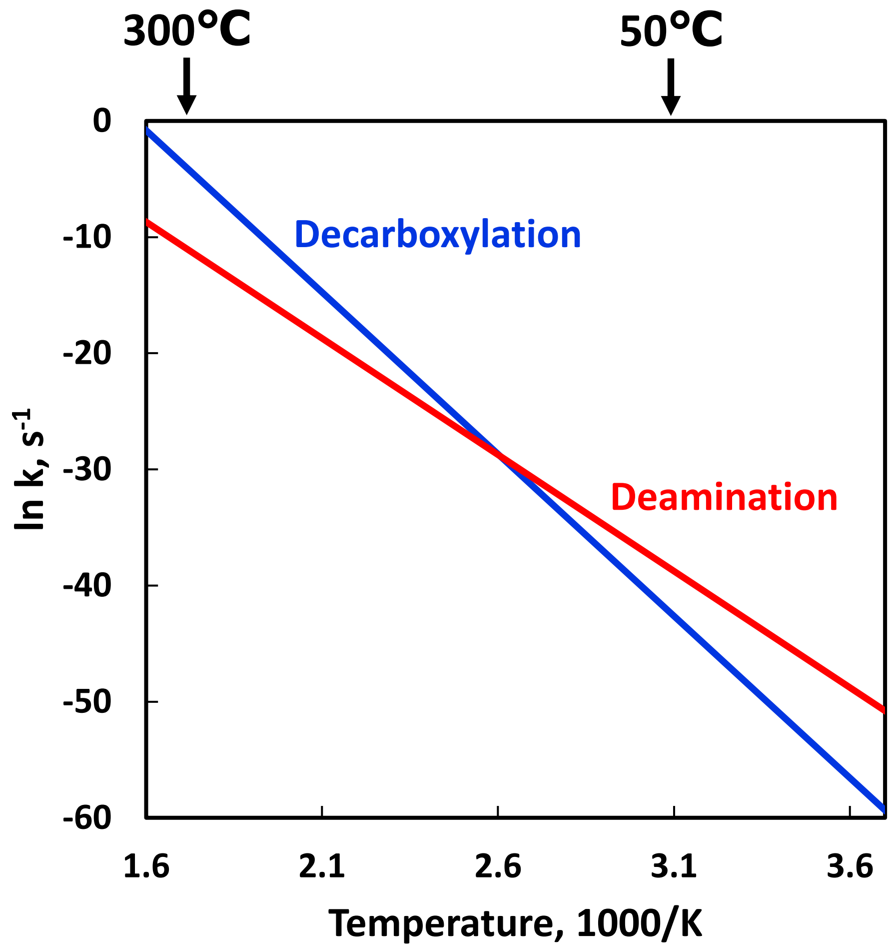
**Decarboxylation:** **~60 billion years**

<u>**Half-life at 300°C**</u>

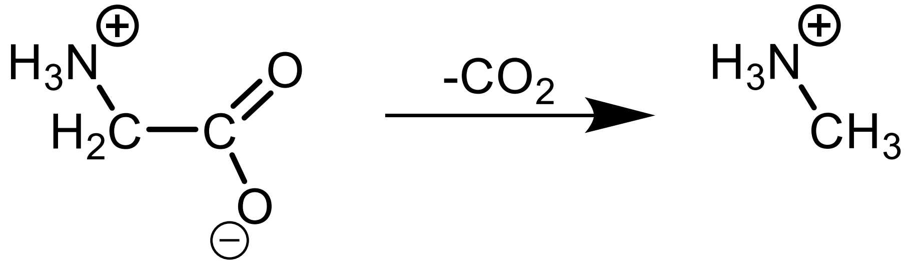
**Decarboxylation:** **~40 seconds**

(Johnson-Finn et al., 2020; Robinson et al., 2019; Shock et al., 2019; Truong et al., 2019; and refs therein)

# Effect of temperature on kinetics




**Glycine Decomposition**




**Half-life at 50°C**

| | |
|---|---|
| Ignore mechanism: | ~60 billion years |
| Both reactions: | ~1 billion years |

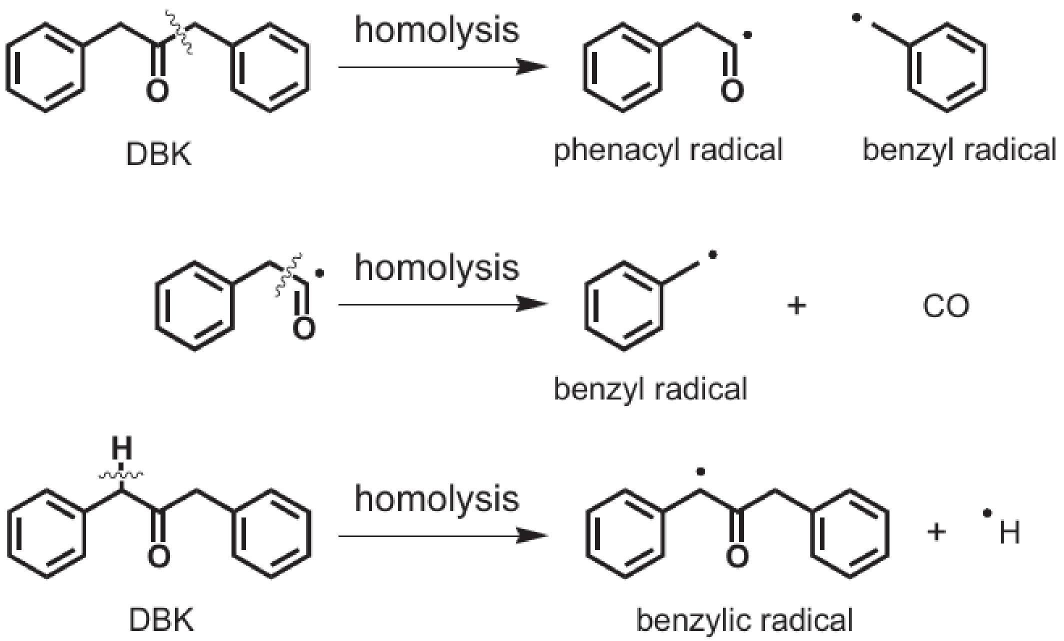
**Half-life at 300°C**

| | |
|---|---|
| Ignore mechanism: | ~40 seconds |
| Both reactions: | ~40 seconds |

(Johnson-Finn et al., 2020; Robinson et al., 2019; Shock et al., 2019; Truong et al., 2019; and refs therein)

# Effect of minerals on kinetics

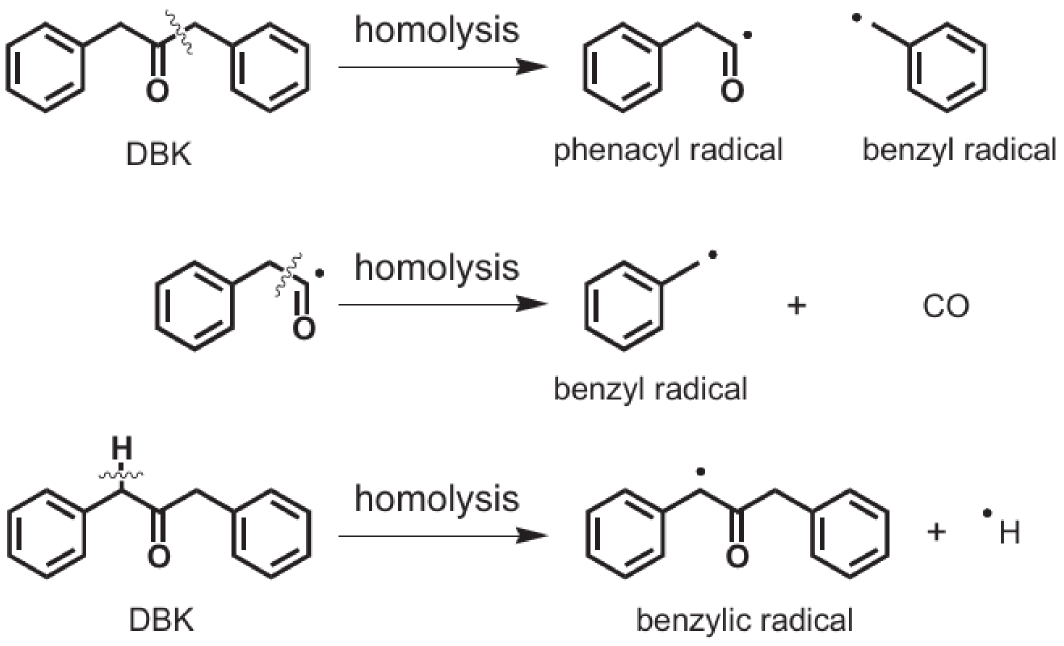
300ºC, 1000 bar

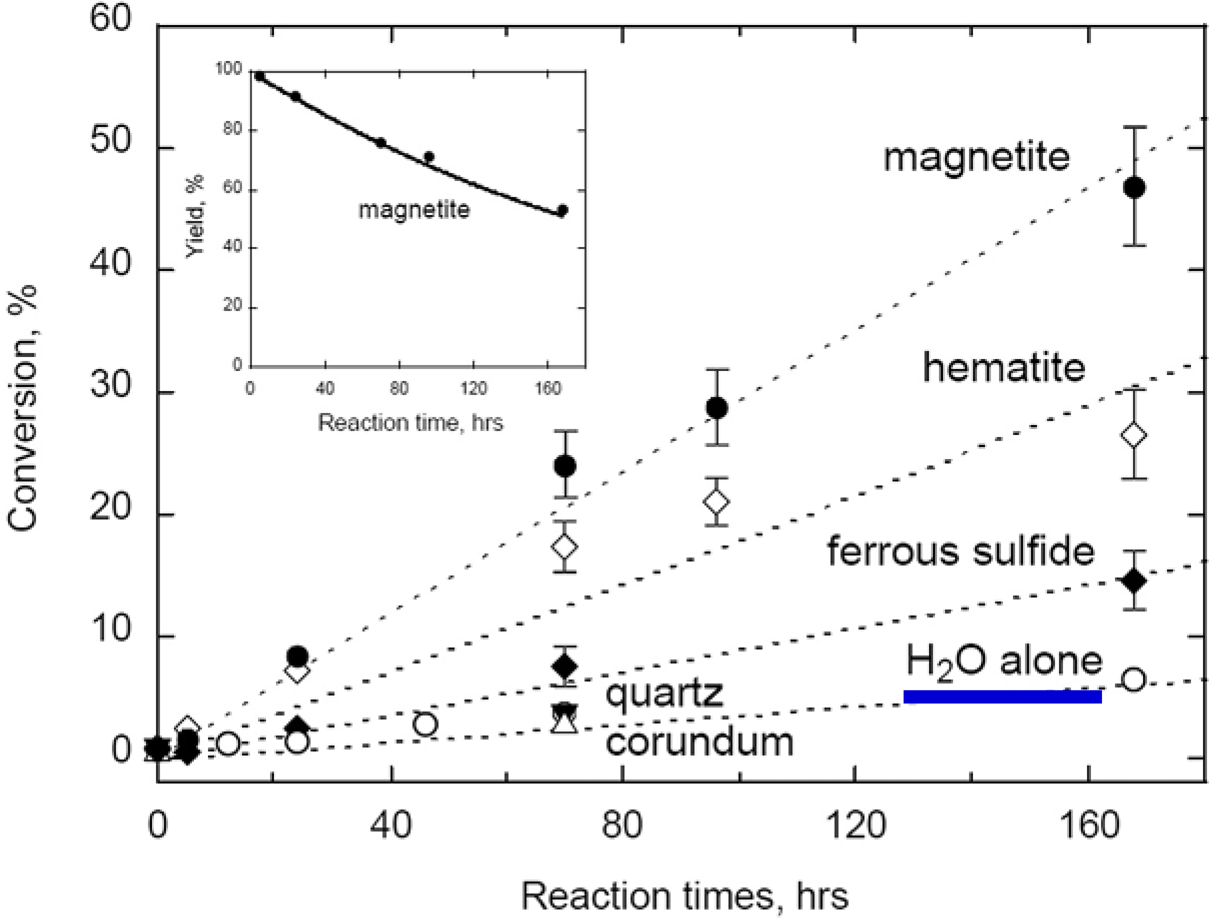



(Yang et al., 2018)

# Effect of minerals on kinetics

300°C, 1000 bar




(Yang et al., 2018)

# Summary

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- Life, Photosynthesis ($O_2$), Technology

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But we can still utilize models that work on Earth and are not system-specific to understand extraterrestrial organics.

- Fundamental chemistry: thermodynamics and kinetics.

Some major drivers of organic transformations:

- Temperature, pressure, water properties, pH and redox state

Generally established by minerals in Earth's subsurface, but may not be the case across planetary environments.