From Organic Astrochemistry to Prebiotic Systems

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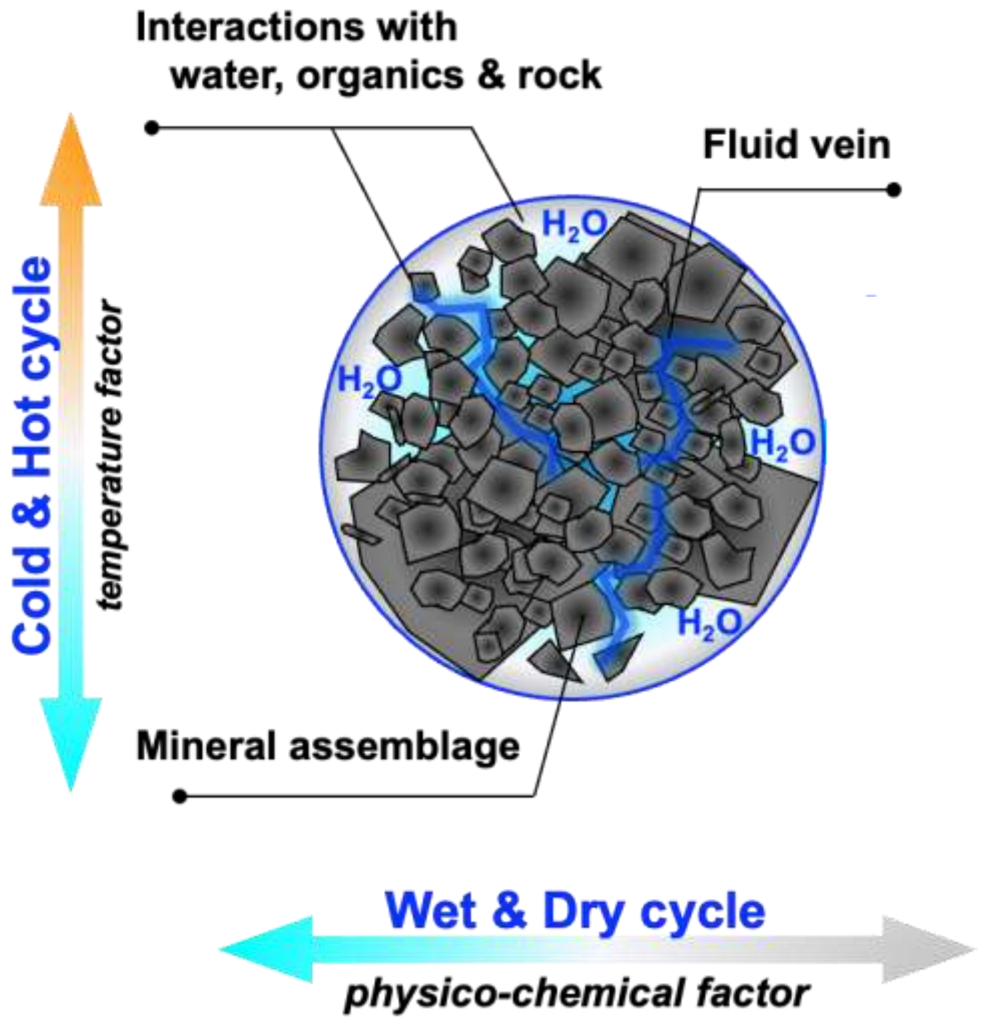
GSFC Astrobiology Analytical Lab http://science.gsfc.nasa.gov/691/analytical/

What Drove Organic Synthesis in Meteorites?

Parent-body aqueous and thermal alteration from melting of ices due to radiogenic decay, tidal forces, and impacts results in the formation of increasingly complex prebiotic molecules from:

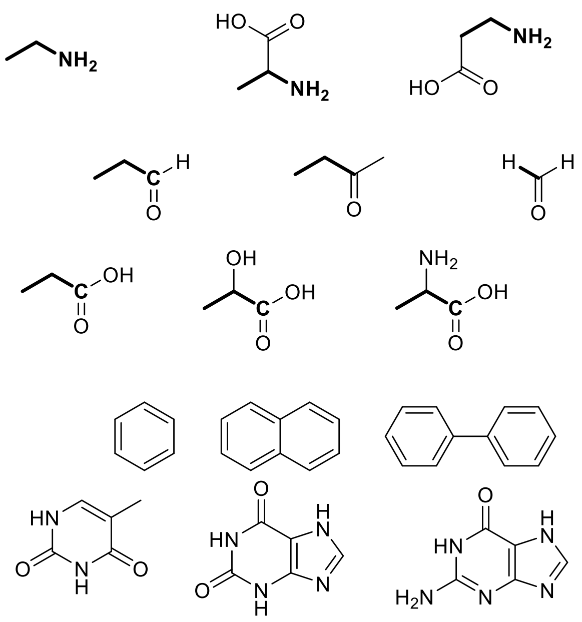
- Strecker synthesis
- Condensation reactions
- Michael addition
- HCN polymerization
- Fischer-Tropsch-type reactions
- etc.



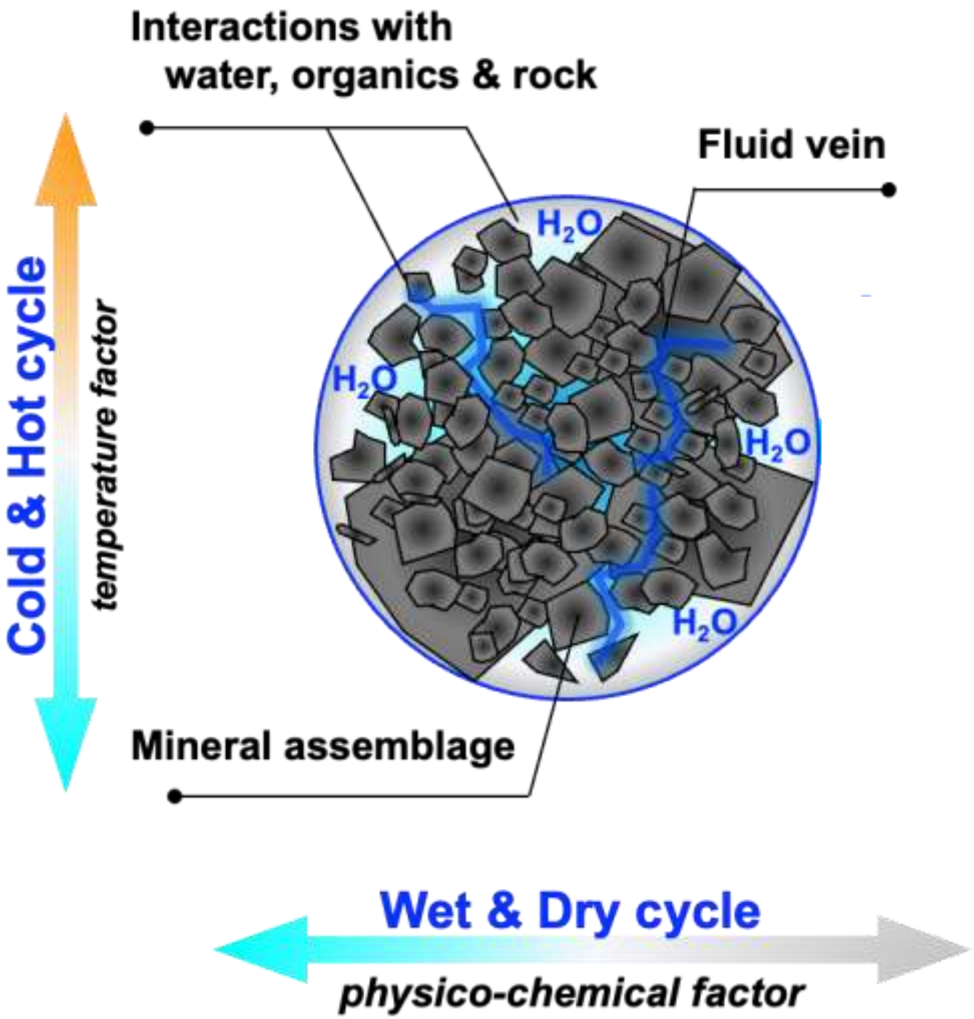
Modified from Takano et al., 2024

Organics in Carbonaceous Chondrites

Soluble Organic Matter (SOM) 1-3%



See Glavin et al., 2018



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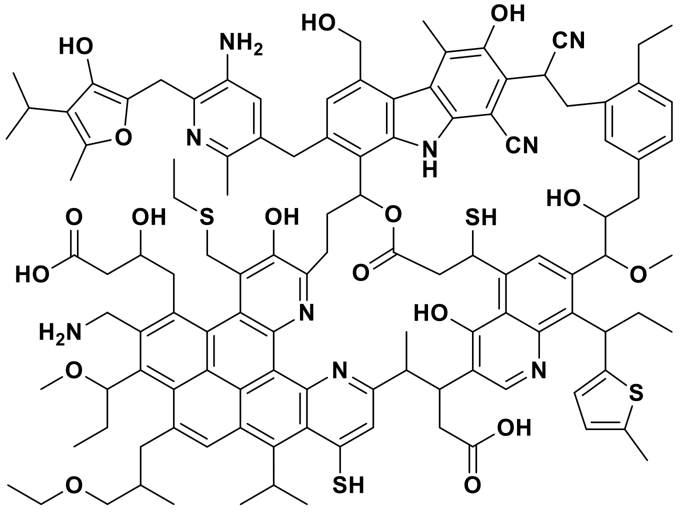
Insoluble Organic Matter (IOM) >50-70%



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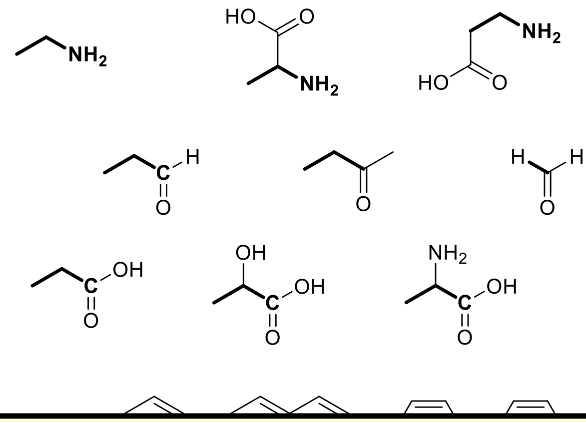
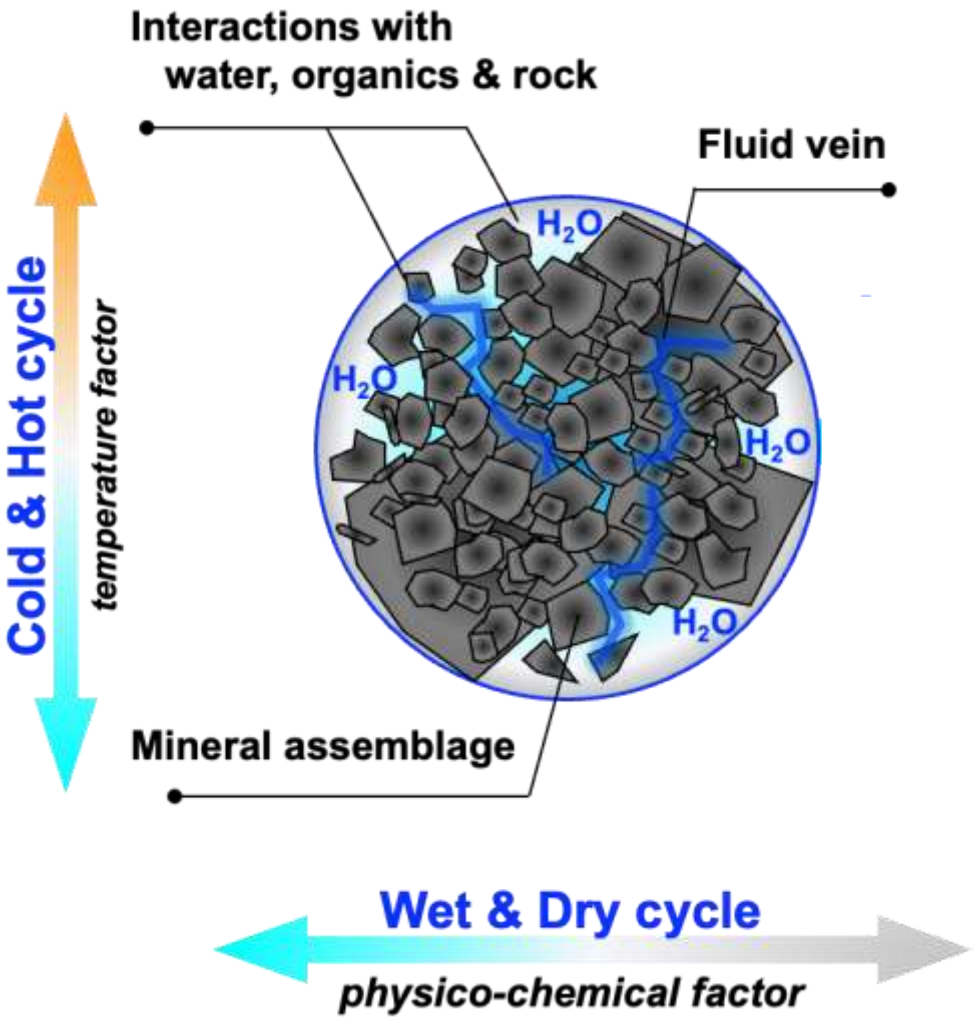


- Feedstock availability
- Reaction pathways
- Interstellar vs parent-body
- Degree of alteration

See Glavin et al., 2018



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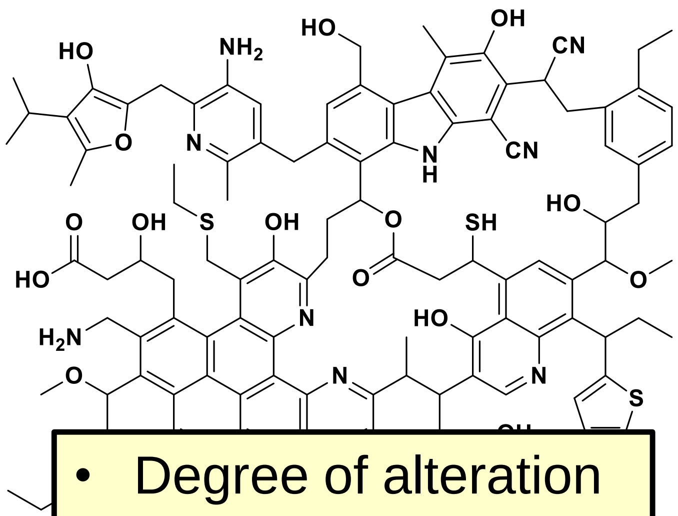


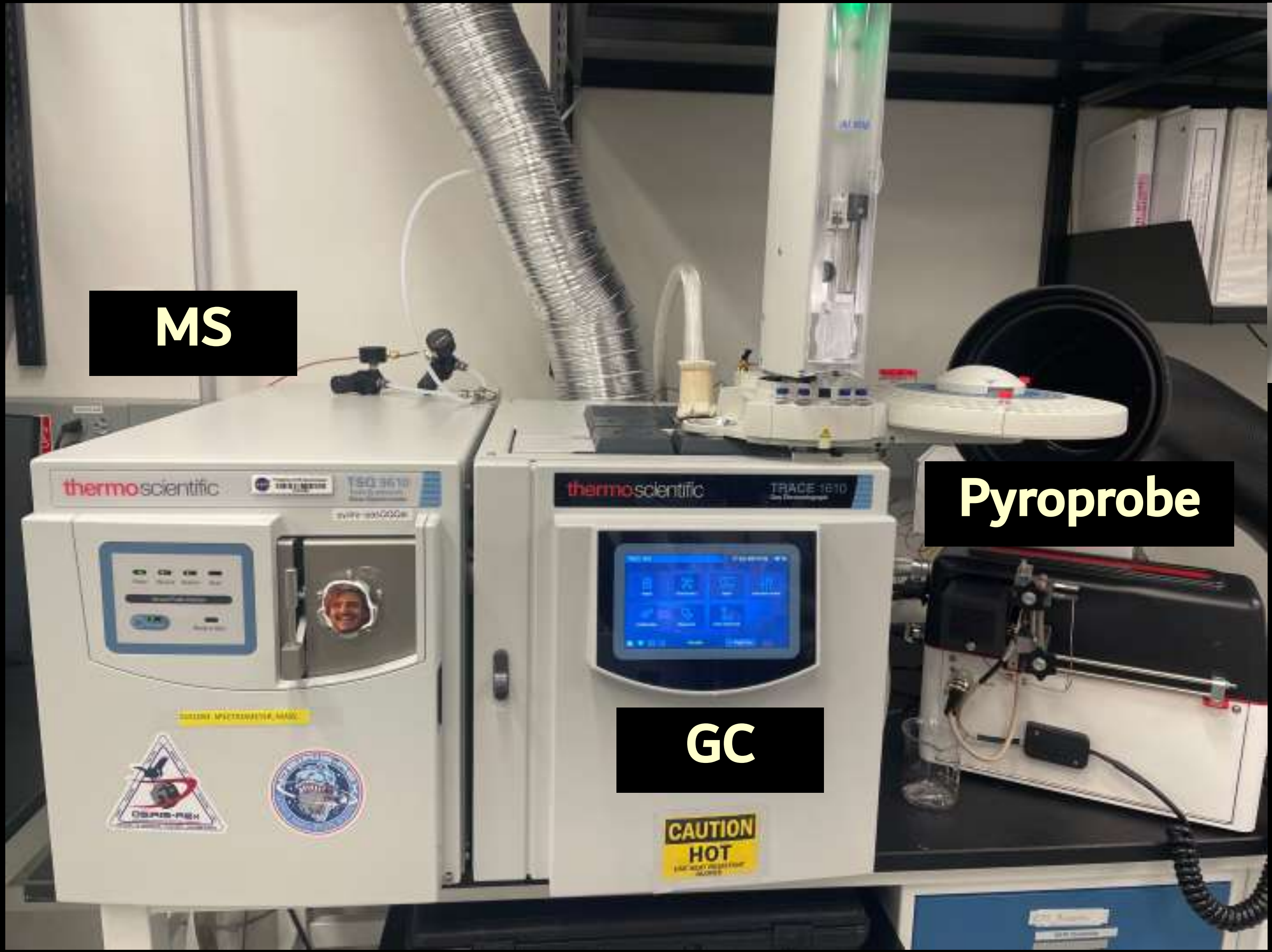
- Degree of alteration
- Aqueous vs thermal

See Glavin et al., 2018

Bulk Sample Analysis by pyrolysis-GC-MS

Pyrolysis-gas chromatography-mass spectrometry (py-GC-MS) characterizes complex organic mixtures

<u>Bulk solid samples</u> without chemical pretreatments
IOM + SOM



~1 mg of sample

Standard Pyrolysis

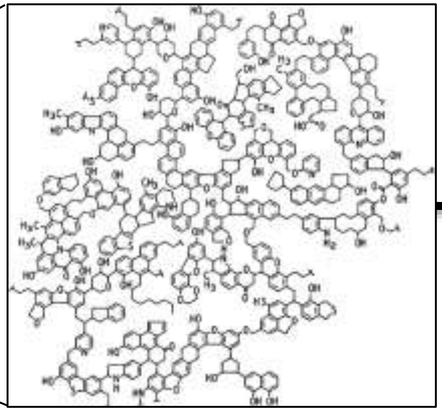
unknown solid sample
(*mixture of SOM and IOM*)

600 °C

volatilized **SOM***

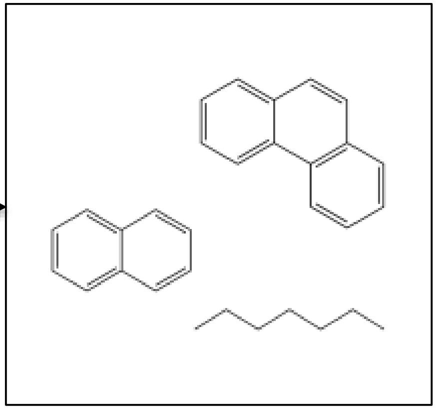
cracked **IOM** macromolecule*

Sample



(insoluble & complex macromolecule)

heat



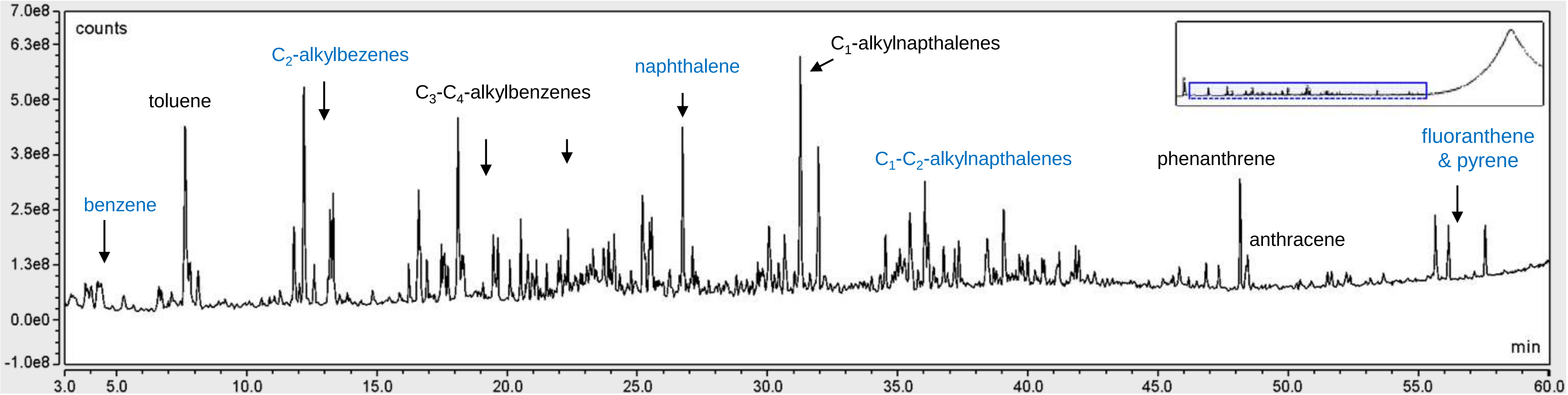
Results from standard pyrolysis: mixture of *discrete* volatile organic compounds thermally extracted from macromolecule

Reasoning: IOM wt.% is larger than soluble organics.
Pyrolysis signals represent the stable hydrocarbon fraction from the thermal breakdown of IOM.

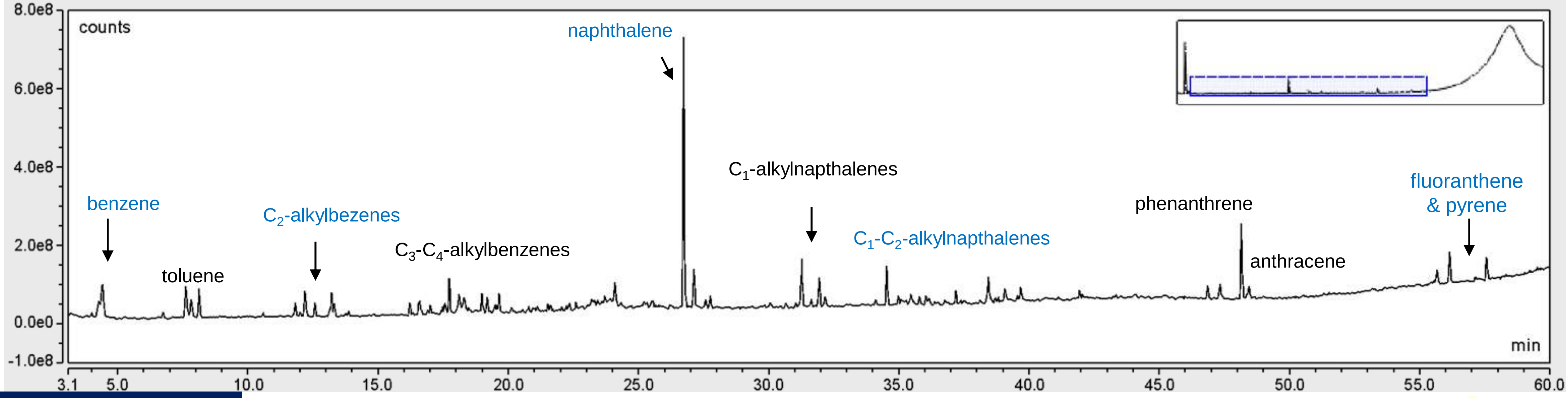
*Thermally unstable compounds may undergo dehydration, decarboxylation, etc. at the chosen pyrolysis temperature.

Pyrolysis Total Ion Chromatogram

OREX-800055-112
angular



Murchison



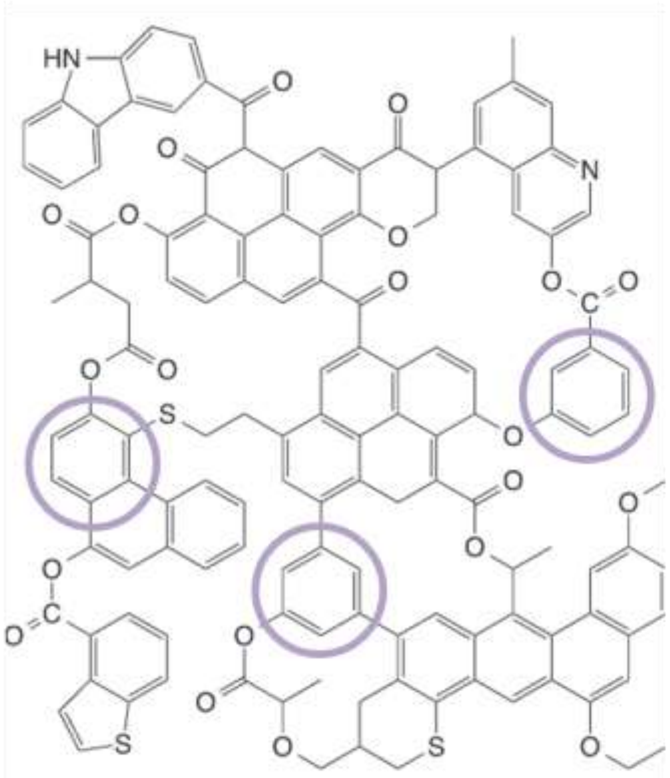
Mojarro et al. (2025) *PNAS* e2512461122

Comparison of PAH in Meteorites

Mojarro et al. (2025) *PNAS* e2512461122

IOM *conceptual* structure

(Glavin et al., 2013)



Hypothesis: Distribution of alkylated benzenes, heterocycle, & PAH isomers may reveal IOM alteration history

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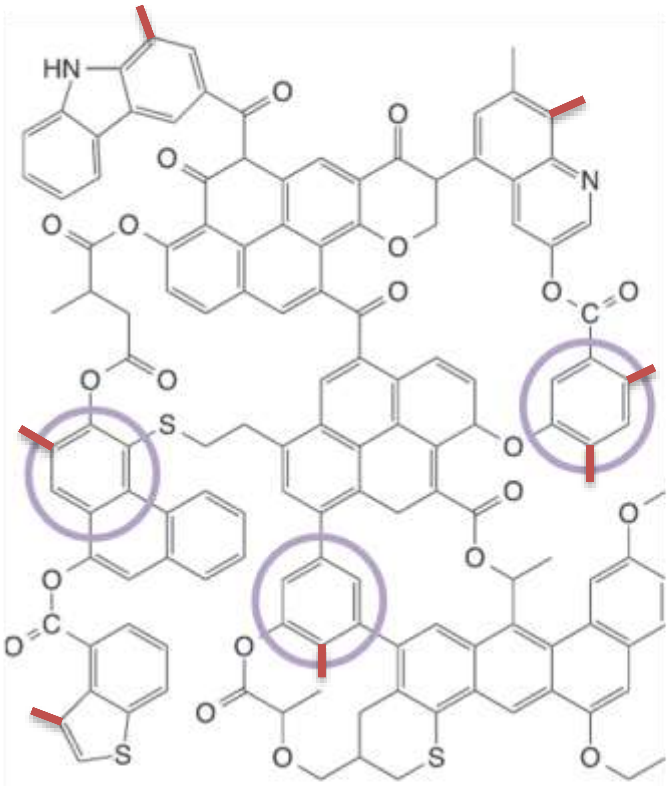

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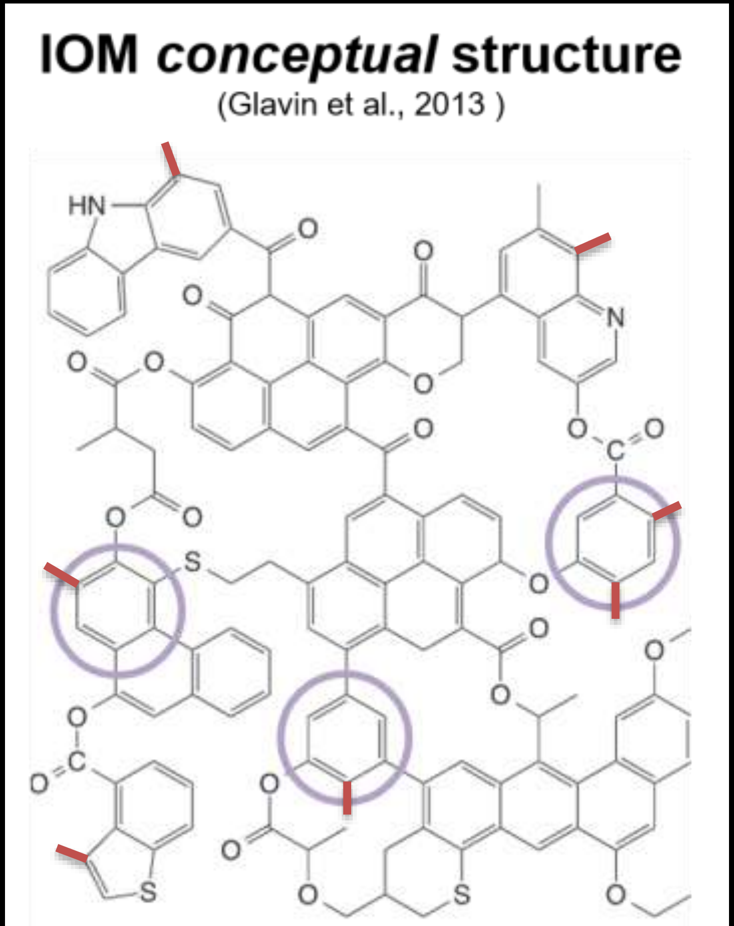

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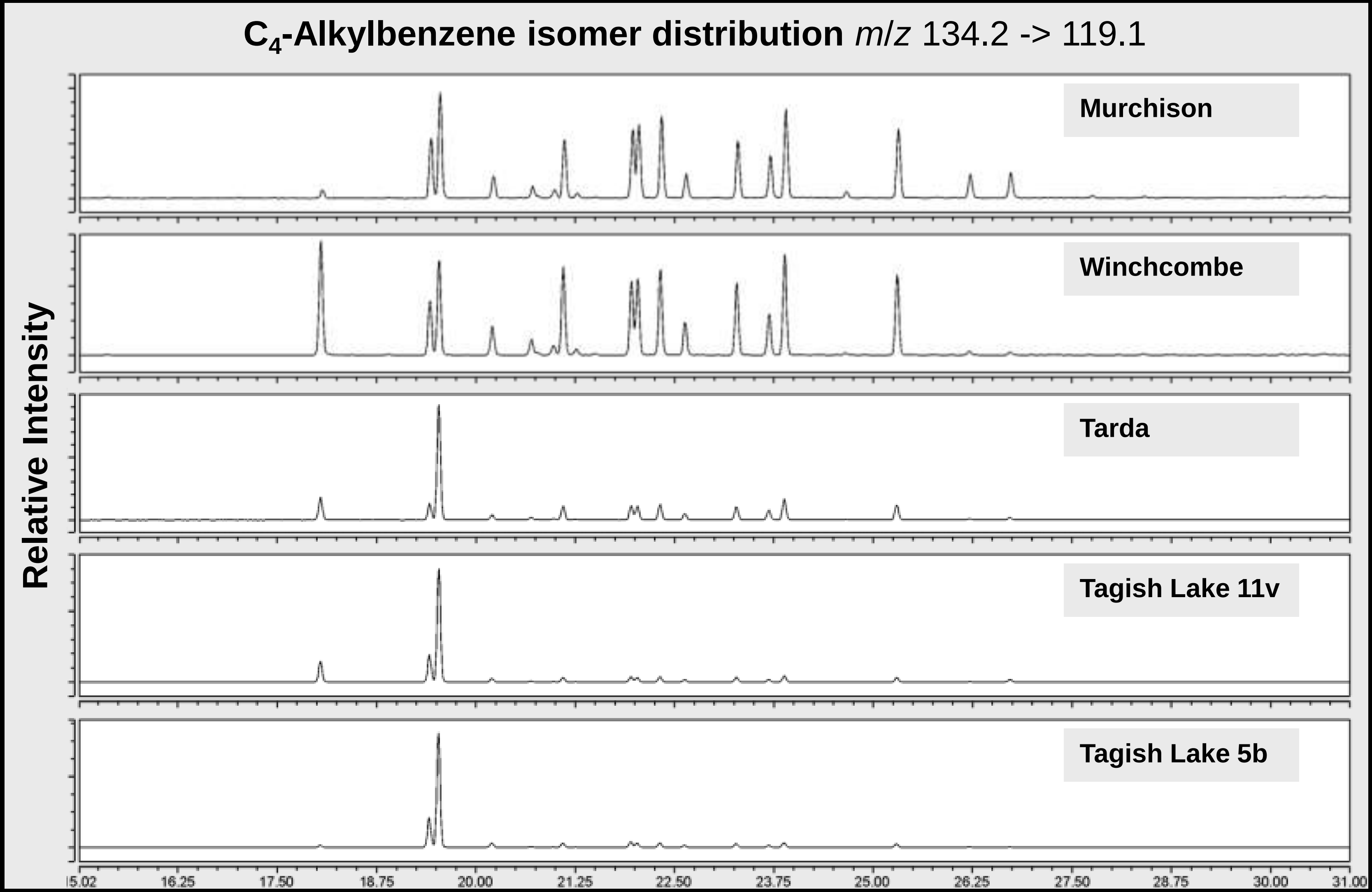

pyGC-MS: Σ C_1-MeNp / Ph Ratio

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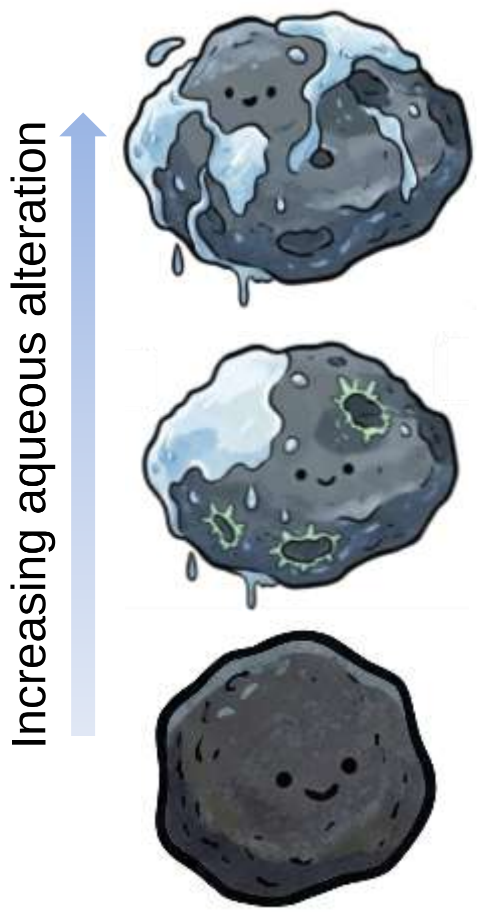
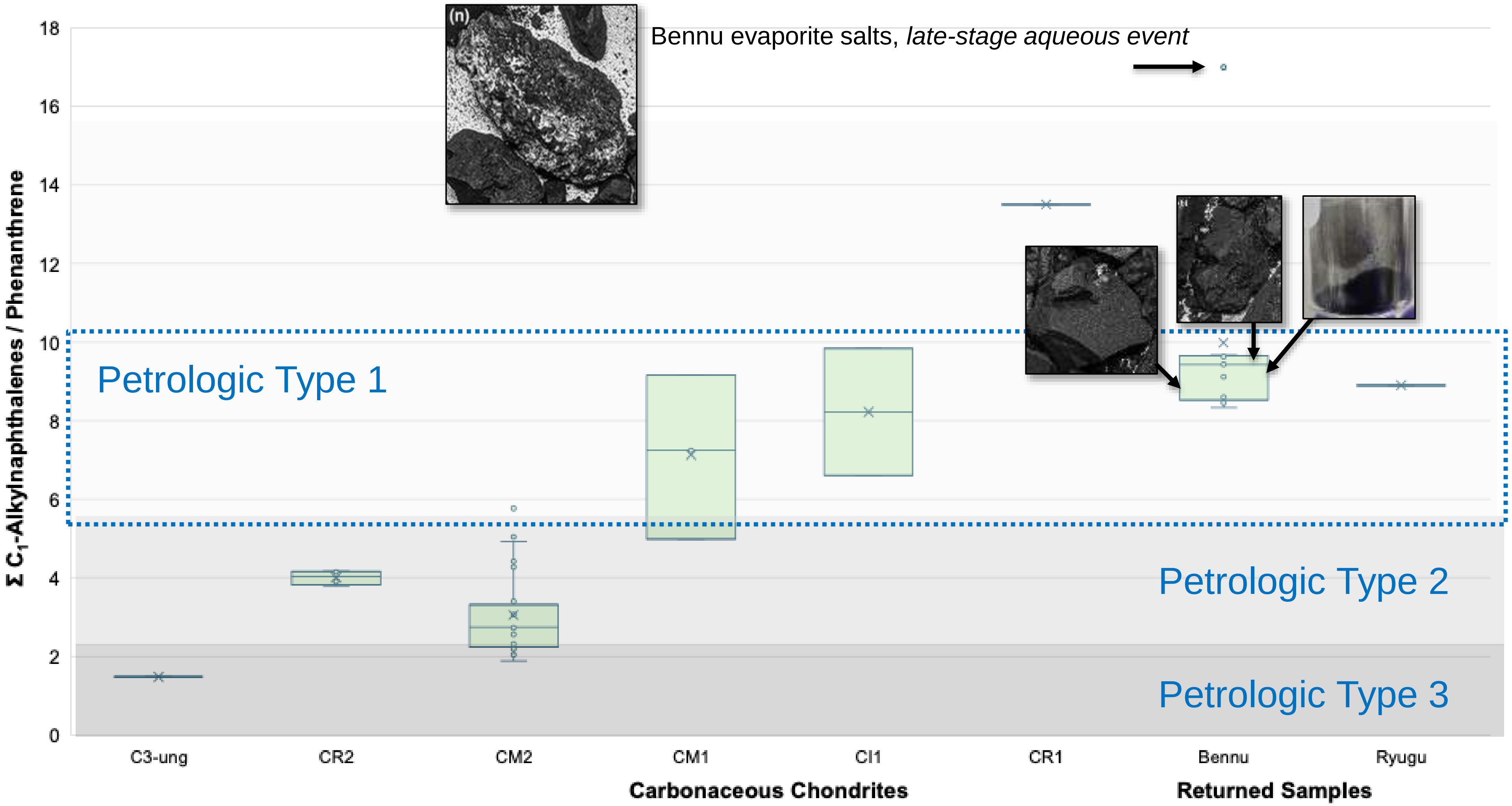
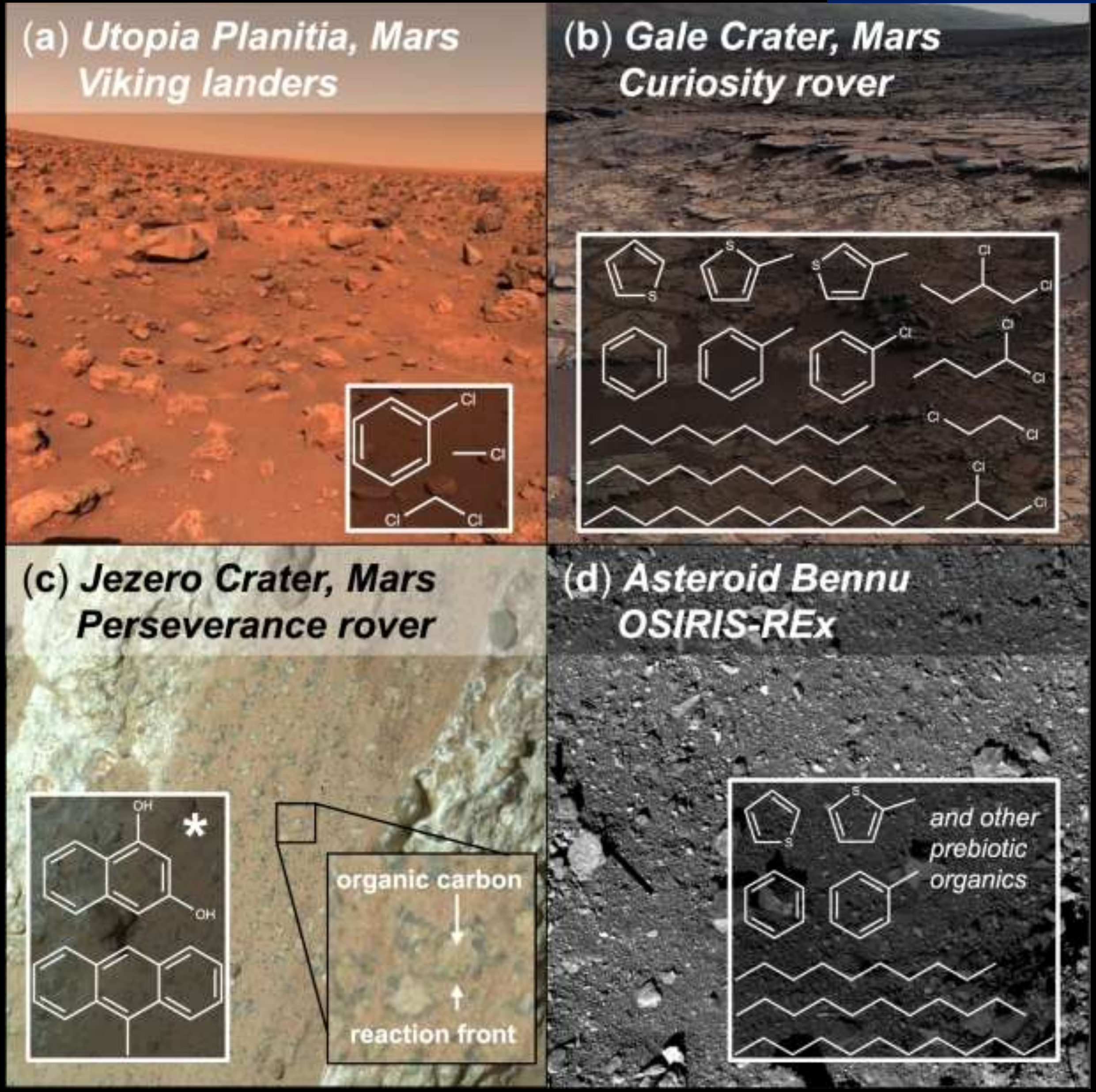




one-way ANOVA testing of petrologic type 1 (CI1, CM1) type 2 (CR2, CM2), and type 3 (C3ung) indicates there is a significant difference between group means.

pyrolysis-GC-MS Applied to Martian Organics

Buckner & Mojarro (2026)



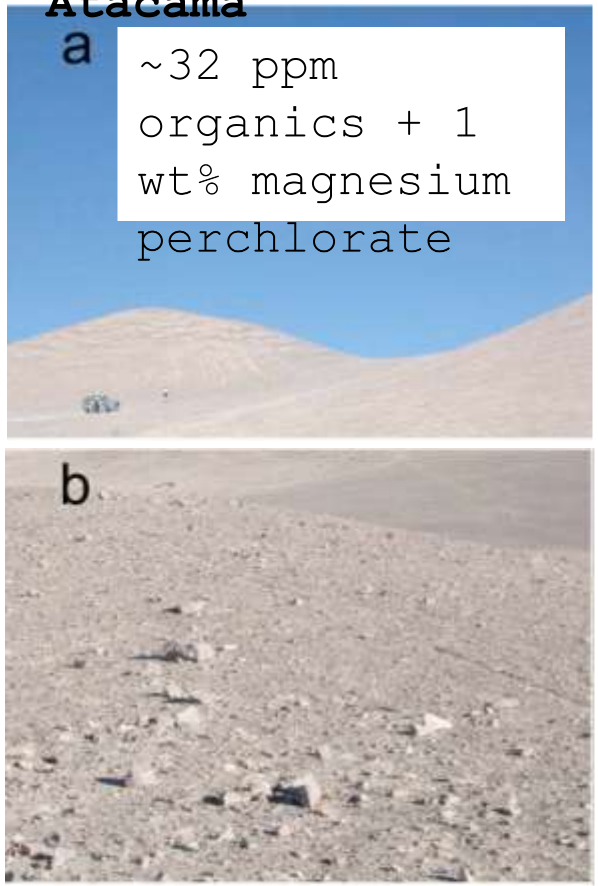
Reanalysis of the Viking Results Suggests Perchlorate and Organics at Midlatitudes on Mars

Table 1. Detection of Chlorohydrocarbons in Martian Soils by the Viking TV-GC-MS[a]

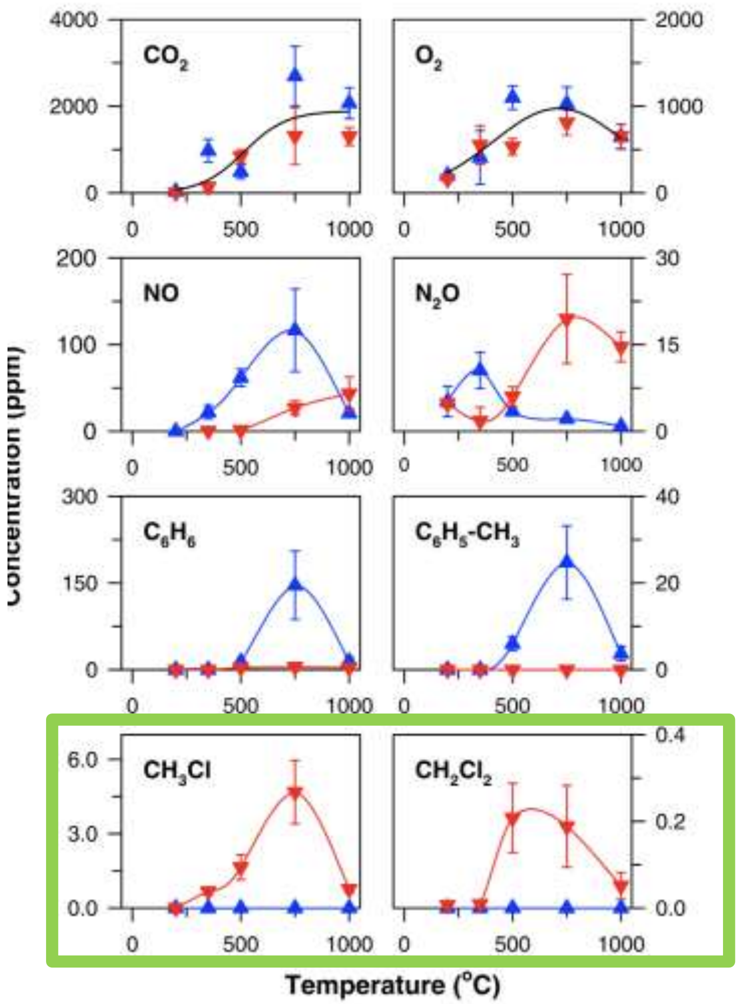
Sample	T (°C)	Injection Mode[b]	Compound	Abundance (ppb)
VL-1				
Blank	500	CO_2	CH_3Cl	ND
Sample 1	200	CO_2	CH_3Cl	15
	500	CO_2	CH_3Cl	ND
Sample 2	200	CO_2	CH_3Cl	ND
	350	CO_2	CH_3Cl	ND
	500	CO_2	CH_3Cl	ND
VL-2				
Blank	500	CO_2	CH_2Cl_2	ND
Sample 1	200	H_2	CH_2Cl_2	ND
	350	H_2	CH_2Cl_2	6–14
	500	H_2	CH_2Cl_2	6–14
	500	CO_2	CH_2Cl_2	2–6
Sample 2	50	H_2	CH_2Cl_2	ND
	200	H_2	CH_2Cl_2	0.04–0.08
	350	H_2	CH_2Cl_2	10–20
	500	H_2	CH_2Cl_2	<4
	500	CO_2	CH_2Cl_2	20–40

[a]From *Biemann et al.* [1977]. GC, gas chromatography; MS, mass spectrometry; ND, not determined; TV, thermal volatilization; VL-1 and VL-2, Viking Landers 1 and 2, respectively.
[b]Gases and volatiles released by TV are swept away from the oven into the gas chromatograph by a stream of either $^{13}CO_2$ or H_2.

Yungay region Atacama



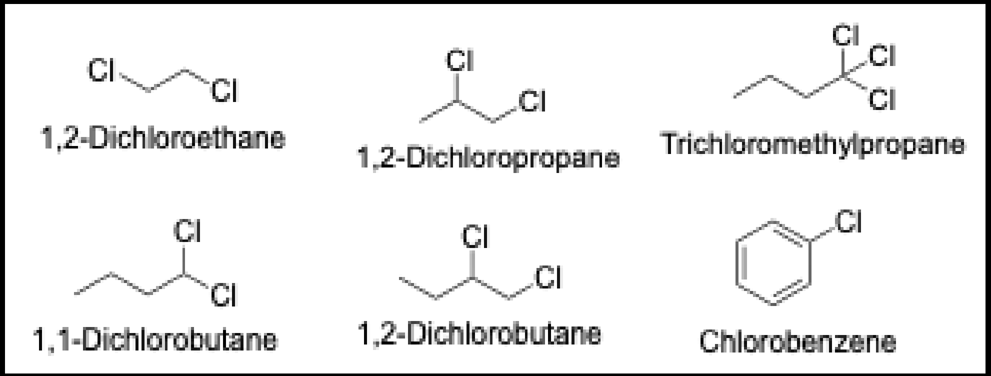
from Navarro-Gonzalez et al., 2010



SAM Confirmed Chlorinated Compounds Are Indigenous

- The Sample Analys at Mars (SAM) instrument aboard the curiosity rover is a more sophisticated ***py*GC-MS**.

- Chlorinated compounds detected above background levels:



Freissinet et al. 2015; Szopa et al. 2020

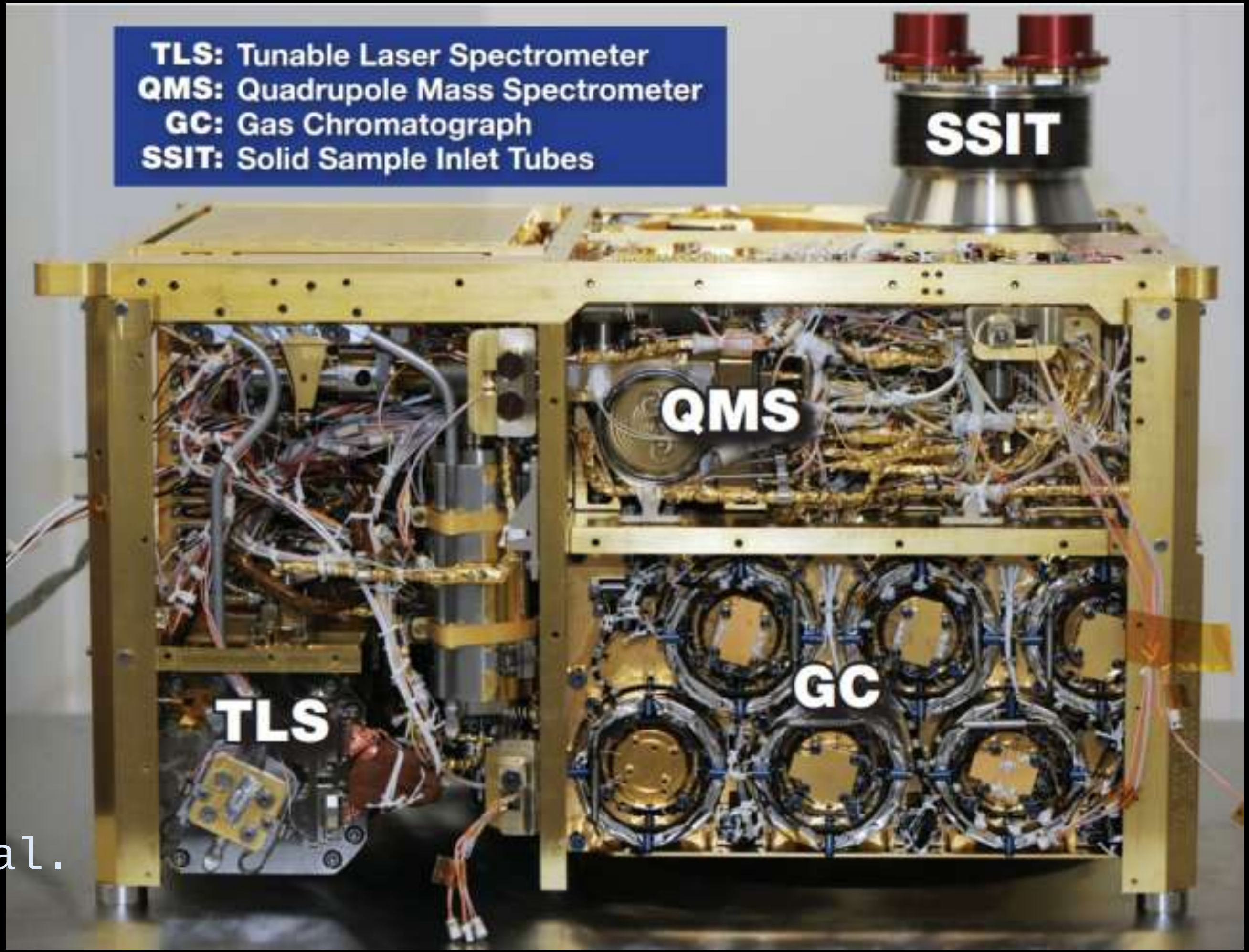


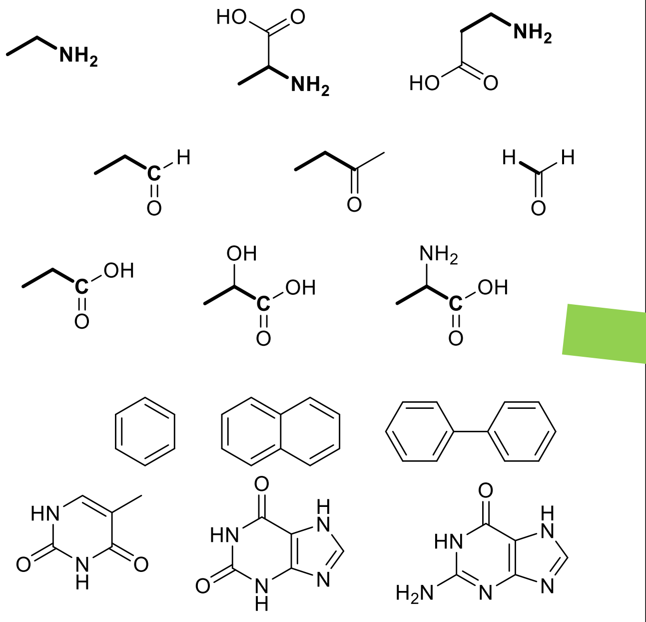
Image credit: NASA

Origin of the organic compounds (abiogenic or biogenic) remains uncertain.
<u>Determining the source of organic matter on Mars may ultimately require sample return to Earth laboratories</u>

https://svs.gsfc.nasa.gov/10274/

Organic Compounds in Martian Regolith

Soluble Organic Matter (SOM) / **Bitumen**



Solvent-extractable labile fraction more susceptible to degradation.

Sample

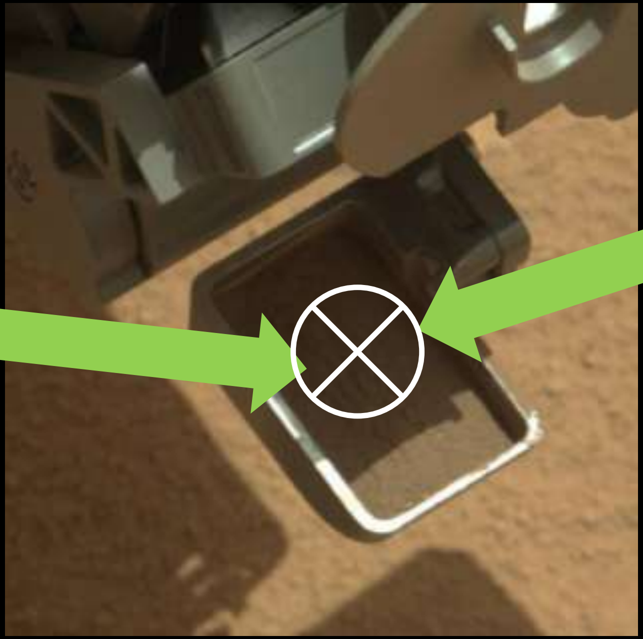
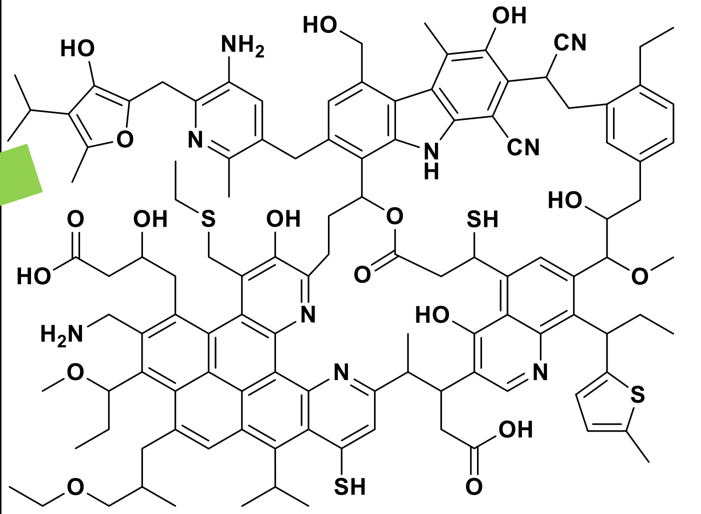


Image credit: NASA JPL

Insoluble Organic Matter (IOM) / **Kerogen**



Refractory fraction can persist through diagenesis on geological timescales.

(IOM from Glavin et al., 2013)

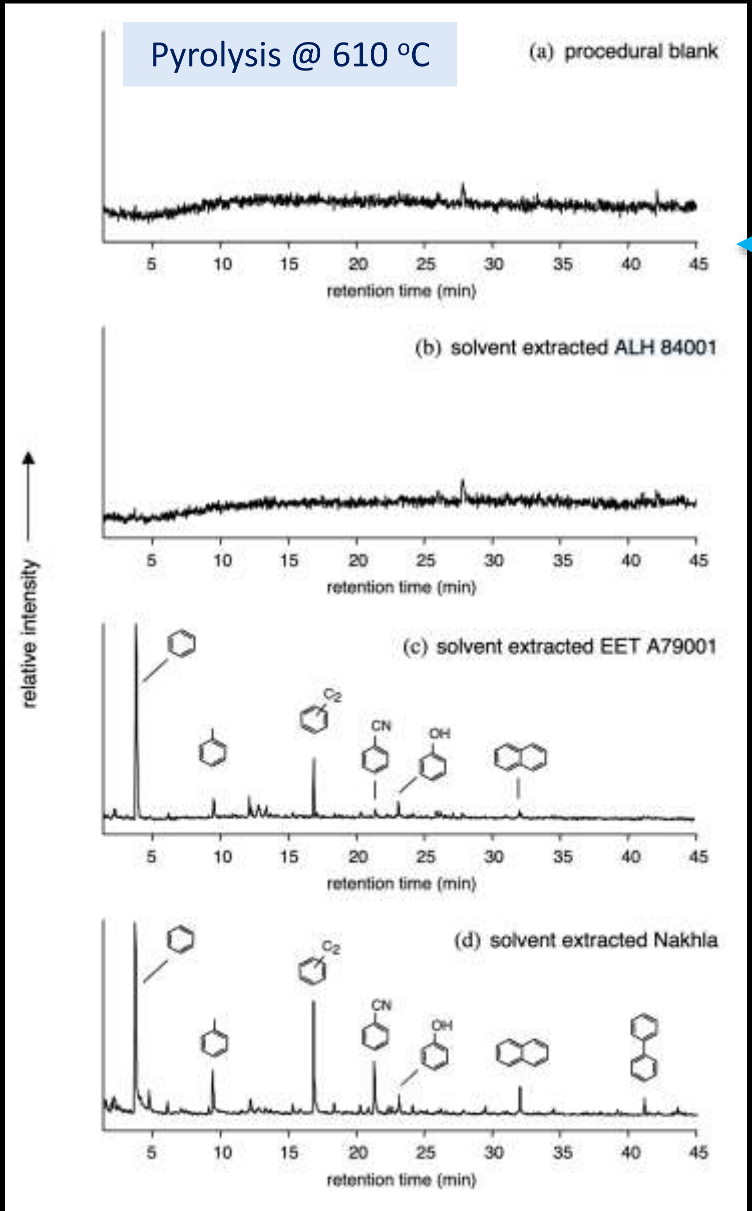
The Martian Meteorite Record

- Shergottites (basalts), Nakhlites (clinopyroxenite), Chassignites (dunite) plus ALH 84001 (orthopyroxenite) and NWA 7034 (breccia) - SNC meteorites.
- Martian origin of SNC meteorites determined by comparison of trapped gas composition to Viking atmospheric measurements and oxygen isotopes.
- Delivered by impacts without geological context and terrestrial residence time increases contamination risk.
- Most SNCs are relatively young (< 2.4 Ga) igneous rocks from volcanic activity.

Image credit: NASA JSC

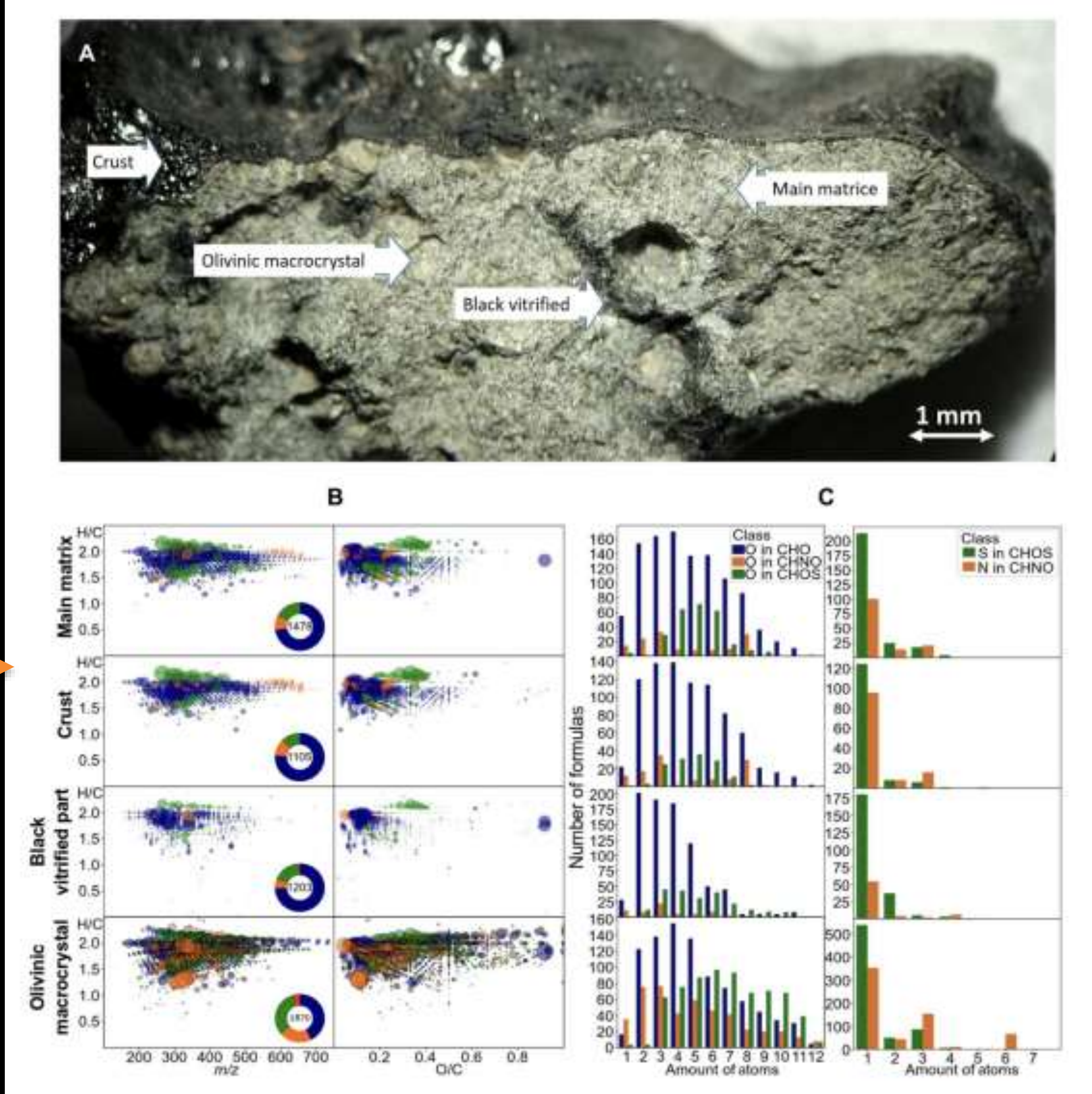
Electron microscopy revealed chain structures resembling living organisms in meteorite fragment ALH84001.

Organic Compounds in SNCs



High molecular weight organic matter in Martian meteorites revealed by pyGC-MS

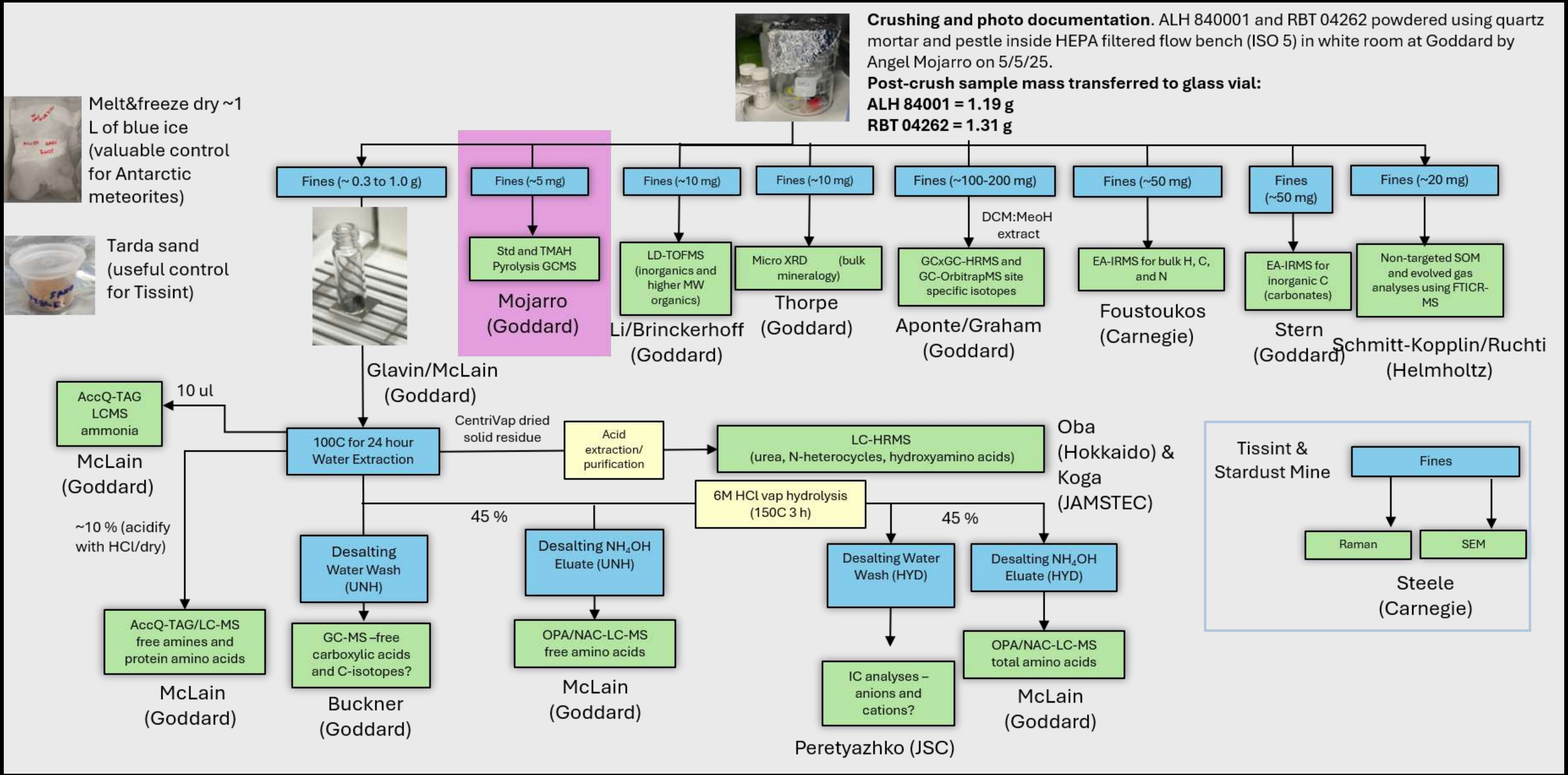
Sephton et al., 2002



Complex soluble organic matter in Tissint Martian meteorite samples including carboxylic acids from $C_3 - C_7$

Schmitt-Kopplin et al., 2023

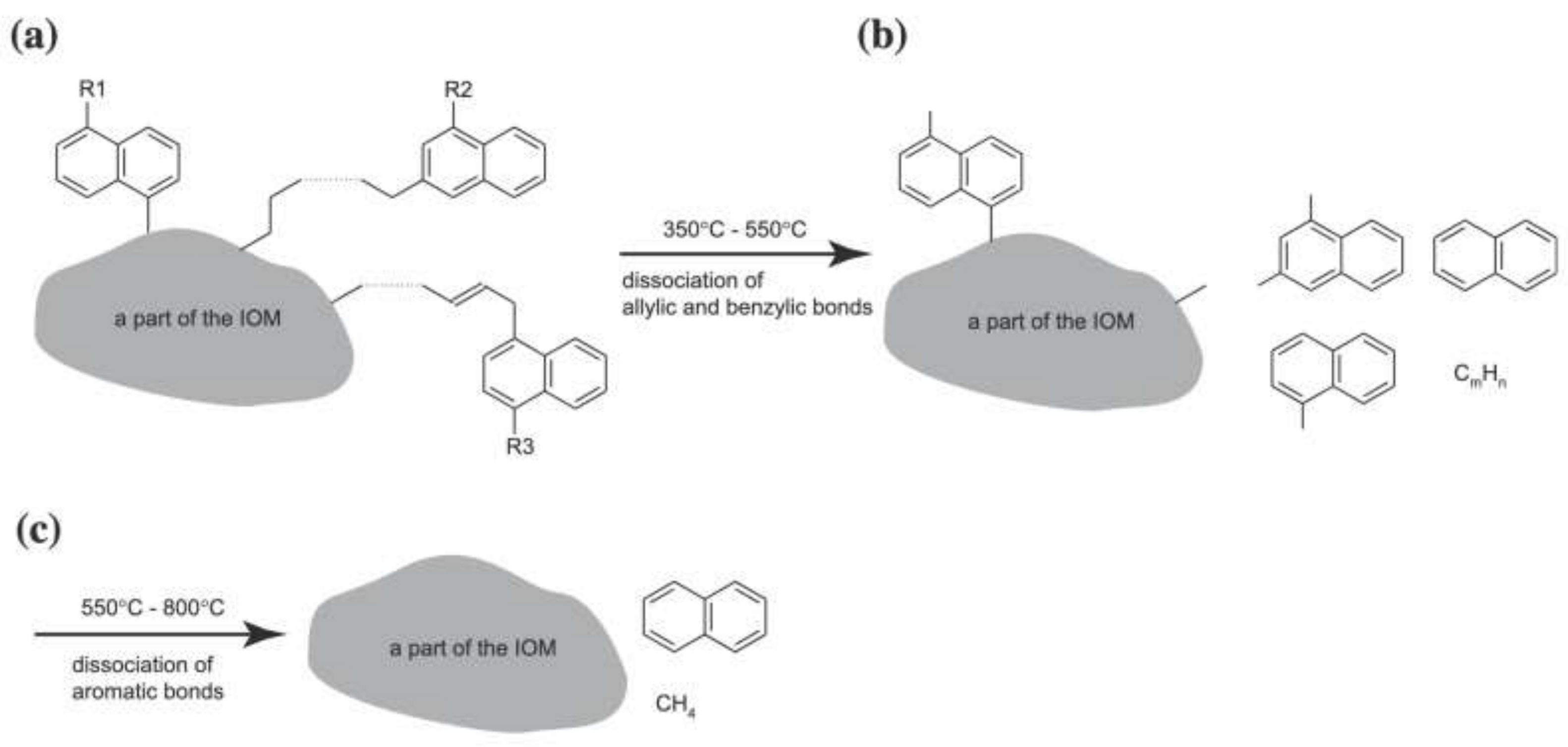
SNC Coordinated Analysis



Stepwise Pyrolysis of SNC Meteorites

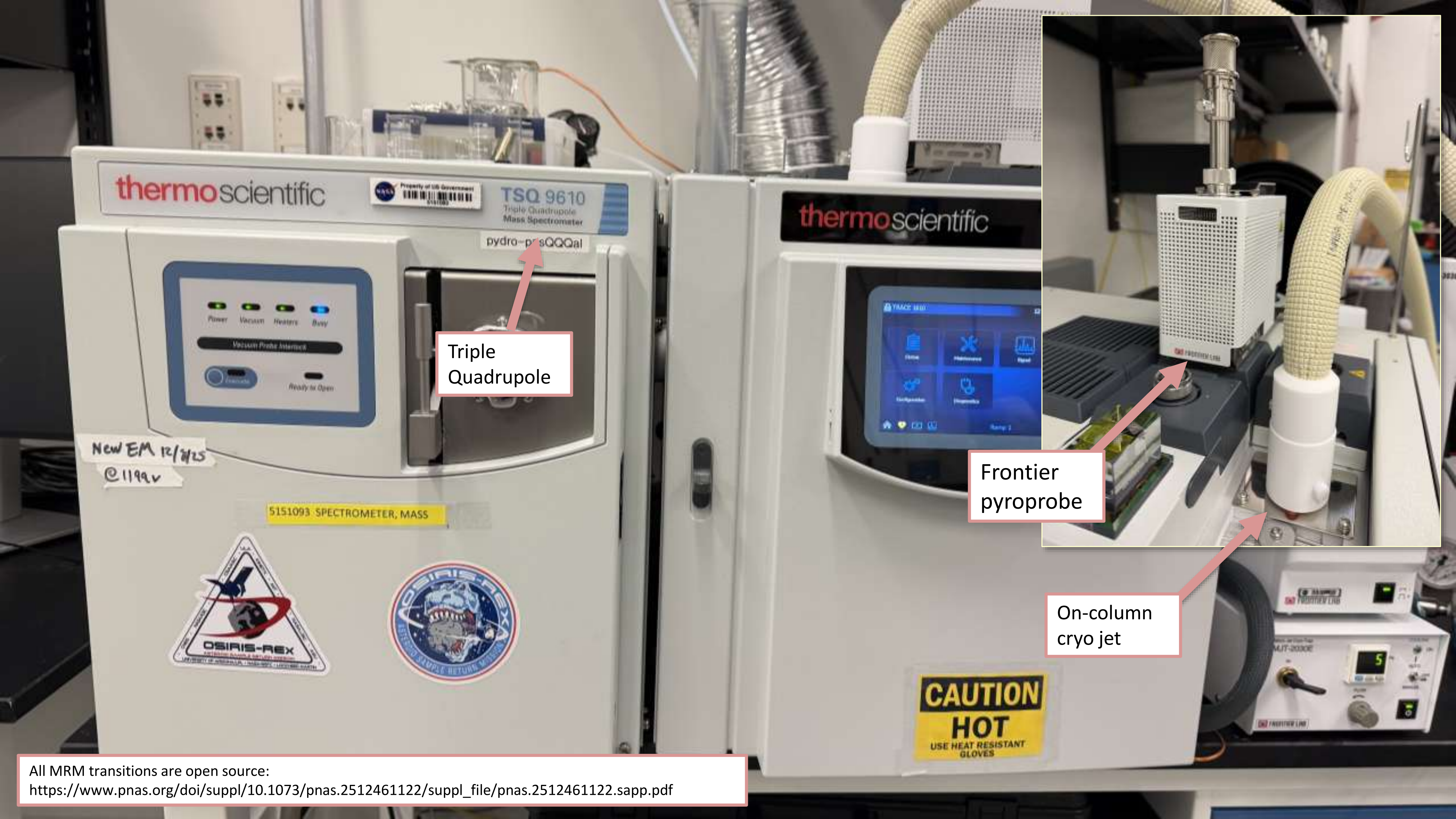
Characterize different carbon reservoirs SOM/bitumen and IOM/Kerogen.

I. 50 – 300 °C: Thermal desorption
    I. Free and adsorbed compounds
    II. Terrestrial contamination
II. 600 °C: Pyrolysis
    I. Macromolecular organic matter
    II. Terrestrial contamination
III. 800 °C
    I. Refractory organics
IV. 1000 °C
    I. Graphitic carbon



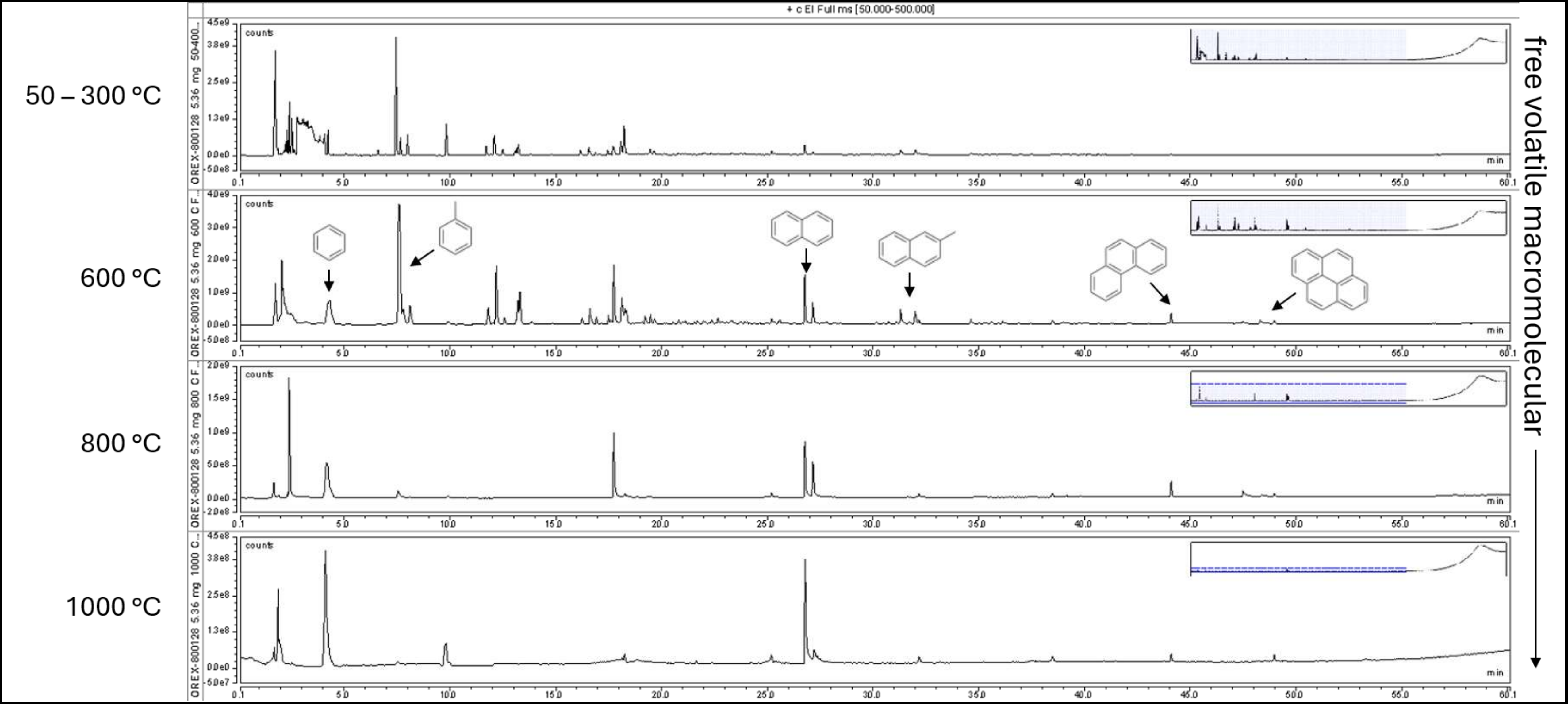
Gradual and stepwise pyrolysis of insoluble organic matter from the Murchison meteorite reveals structural and isotopic heterogeneity.

Okumura & Mimura 2011

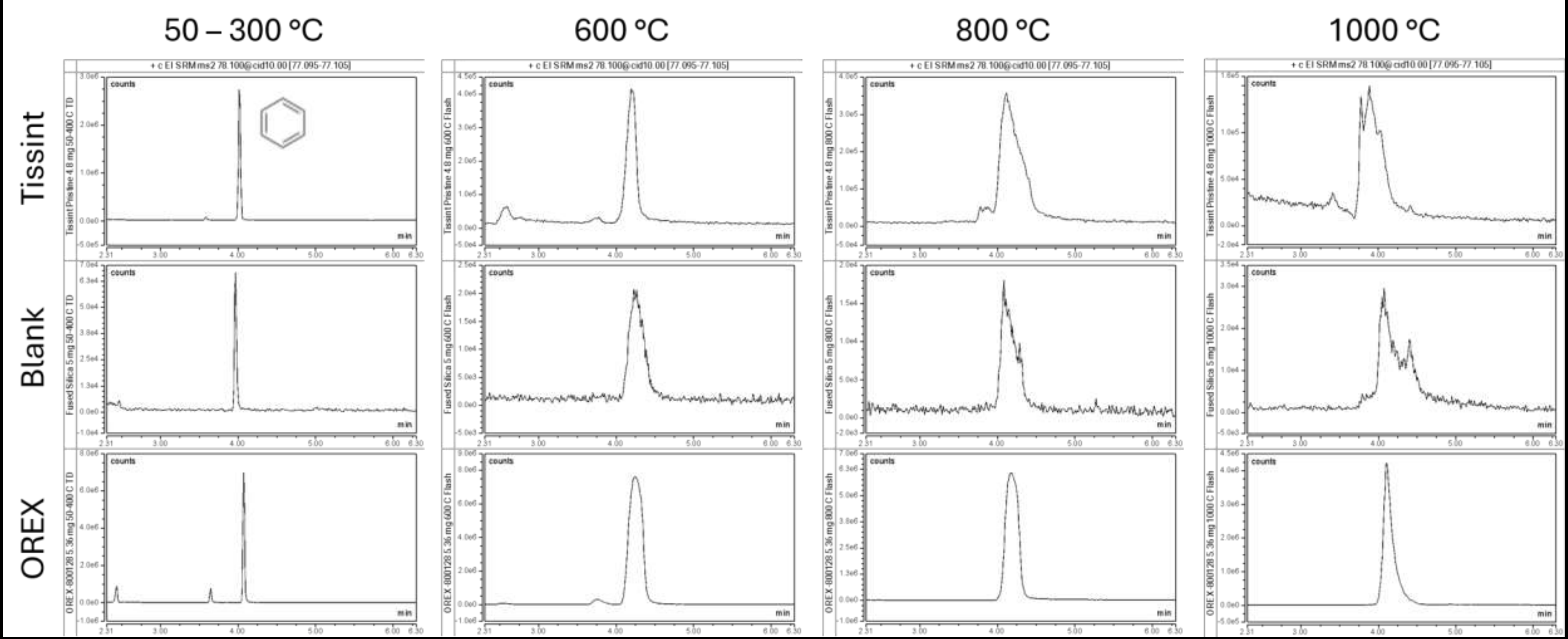


All MRM transitions are open source:
https://www.pnas.org/doi/suppl/10.1073/pnas.2512461122/suppl_file/pnas.2512461122.sapp.pdf

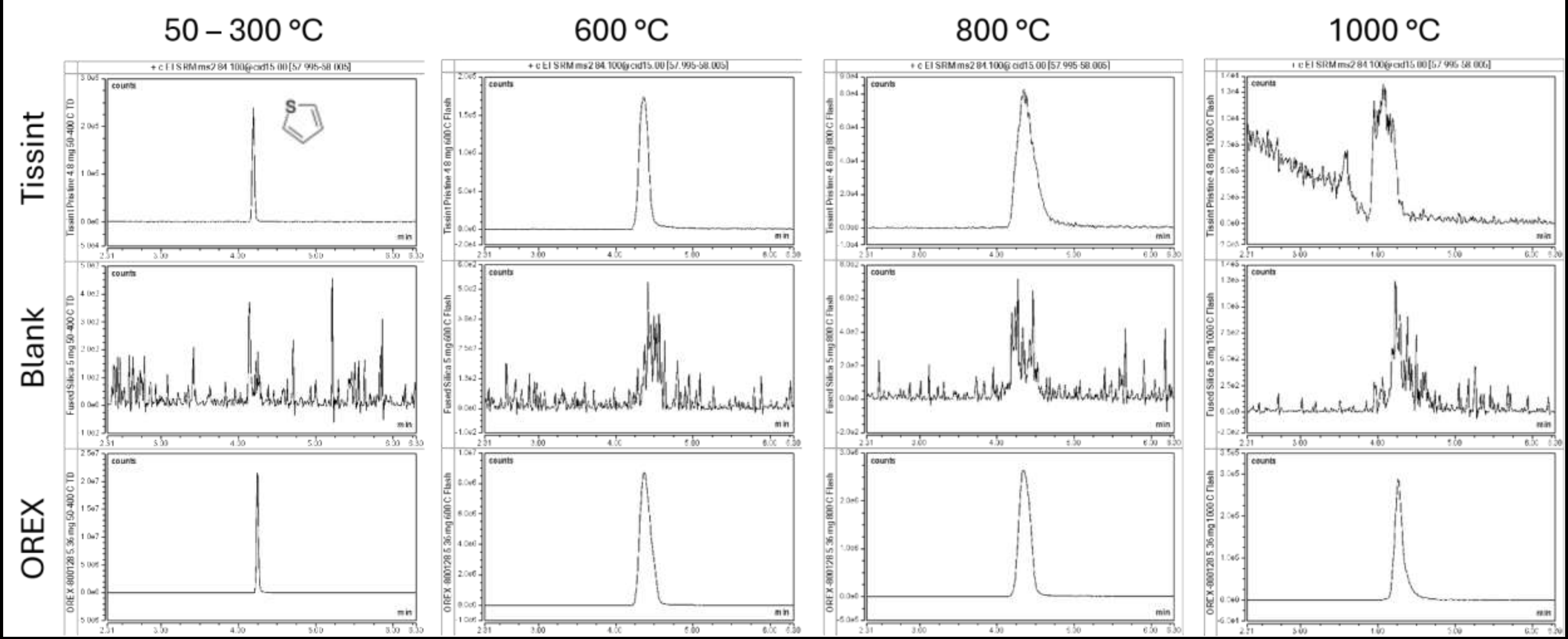
SNC: Tissint (pristine)



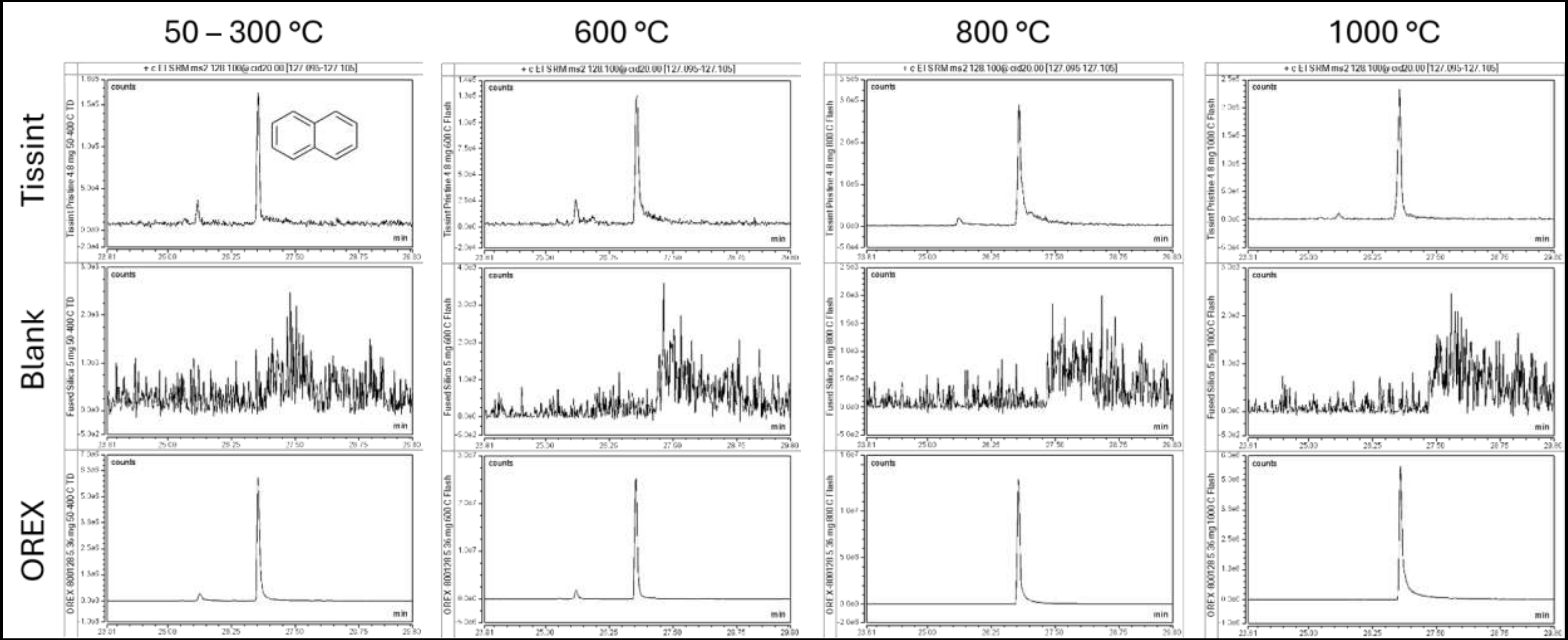
Benzene (m/z 78.1 → 77.1)



Thiophene (m/z 84.1 → 58)

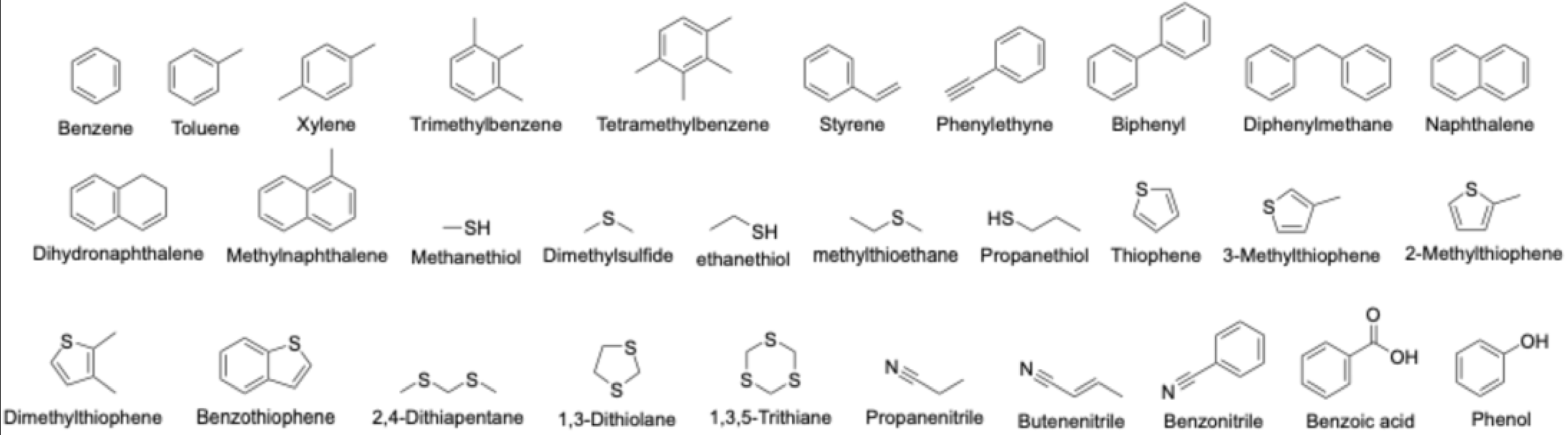


Naphthalene (m/z 128.1 → 127.1)



Work in Progress

Organic matter preserved in 3-billion-year-old mudstones at Gale crater, Mars

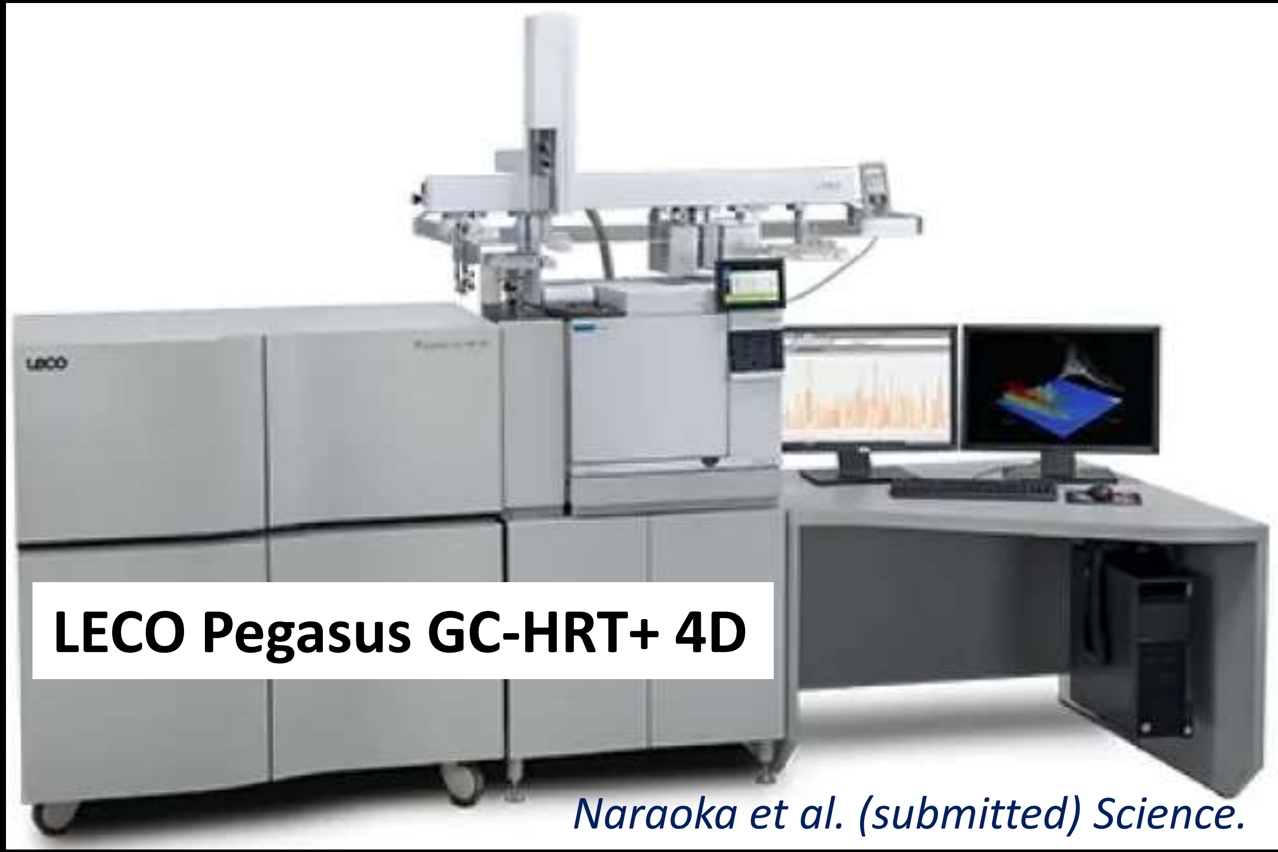


Detections across: Eigenbrode et al., 2018; Freissinet et al., 2020, 2025; Millan et al., 2022; Williams et al., 2026

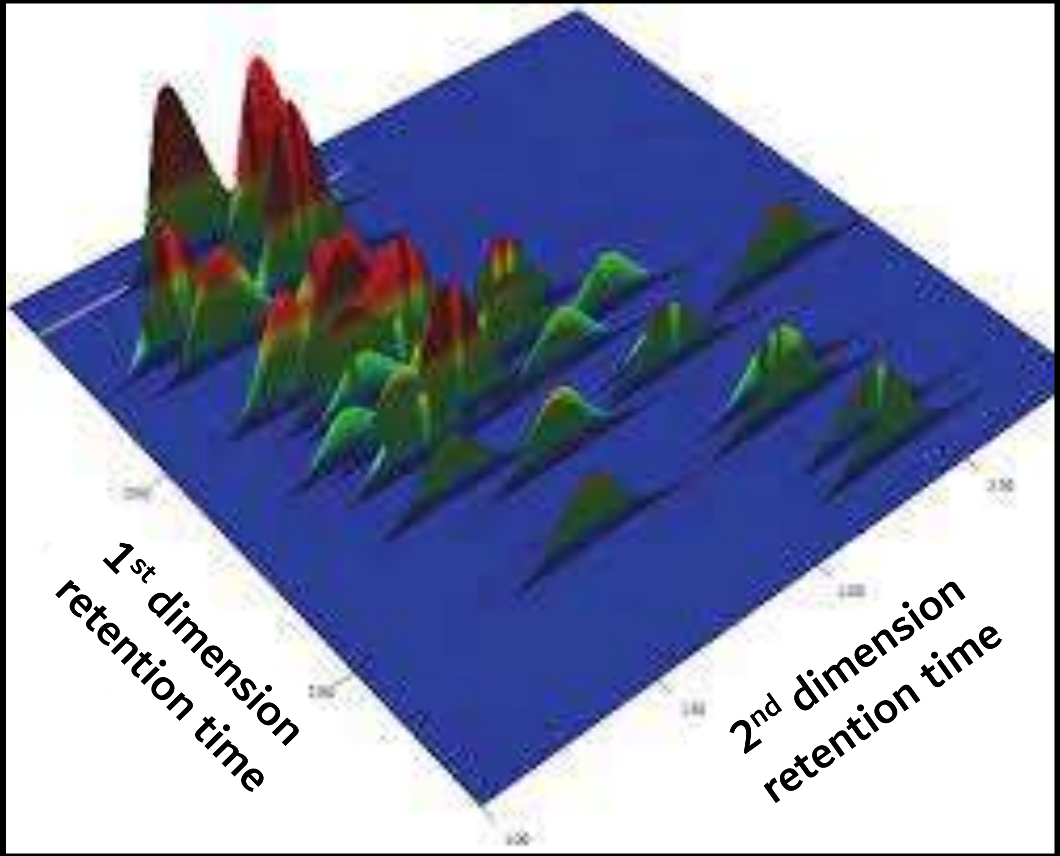
Soluble organics: GC×GC-HRMS Analyses

Two-dimensional gas chromatography allows for an untargeted search of soluble organic species belonging to compound classes of varying polarities.

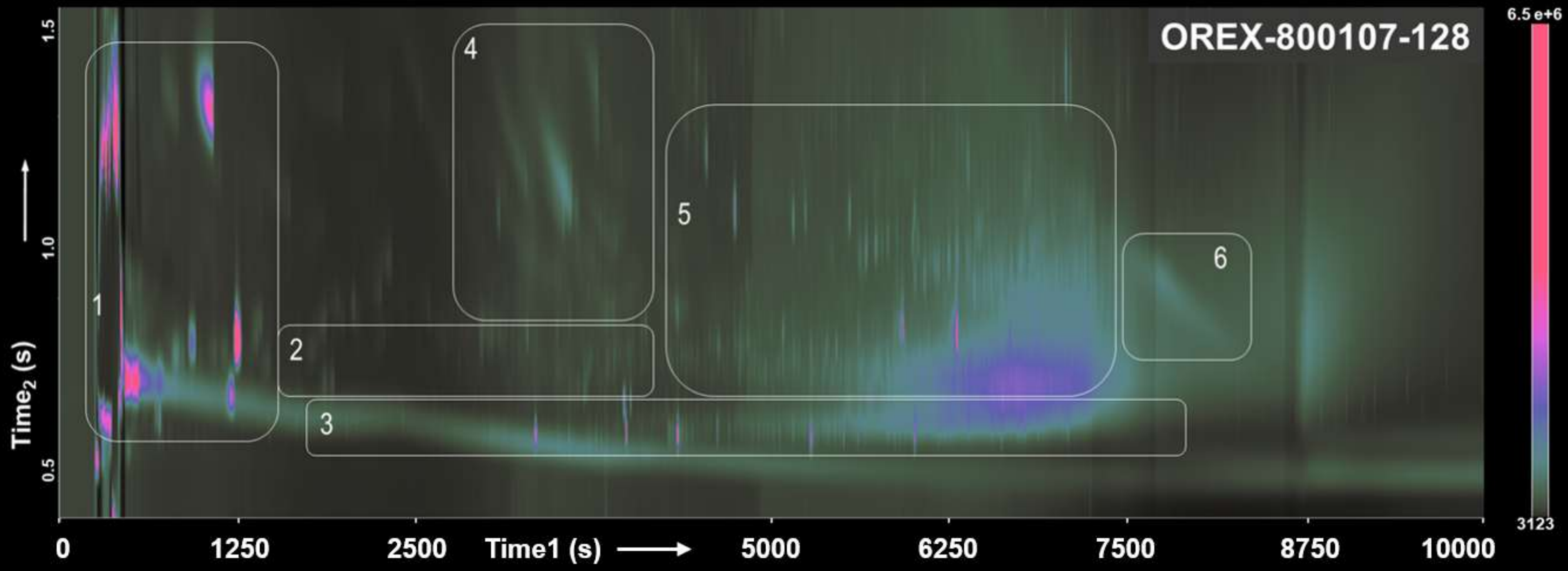
Solvent extracts were analyzed by an EI-TOF-HR-MS (25,000 m/Δm at 219 Da) to determine the accurate mass molecular formula.



Naraoka et al. (submitted) Science.



Soluble Organics in Bennu



We found 38 polycyclic aromatic hydrocarbons, and many other N-, O-, and S-containing aromatic species.

Aponte et al. (2026) *GCA 419, 165-176.*

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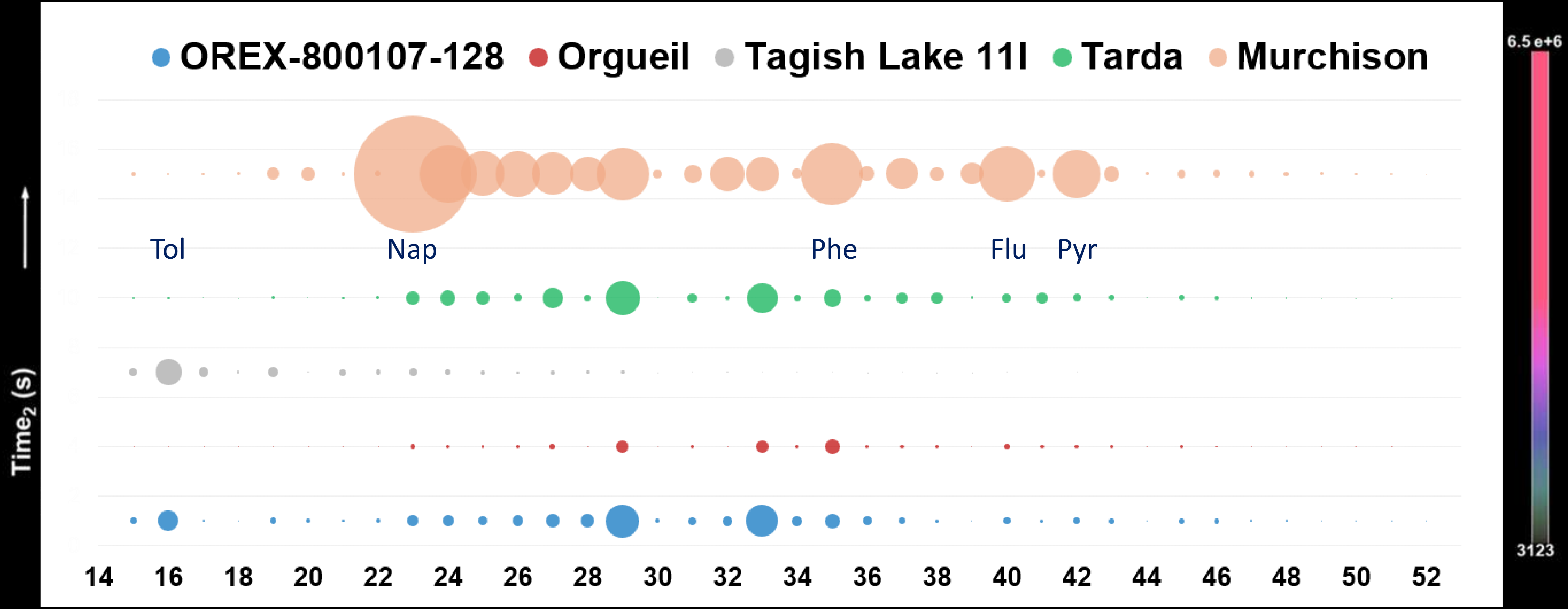

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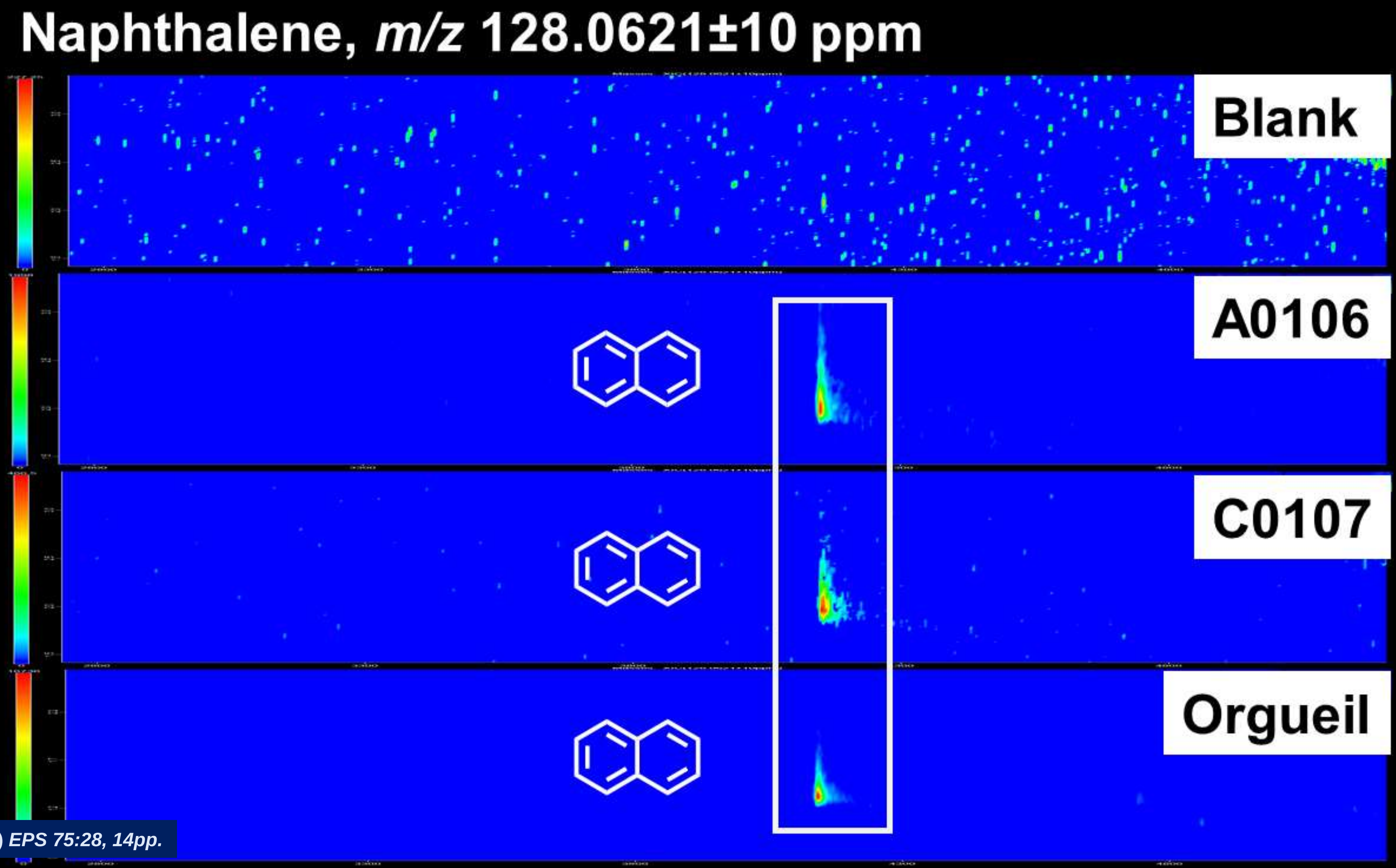
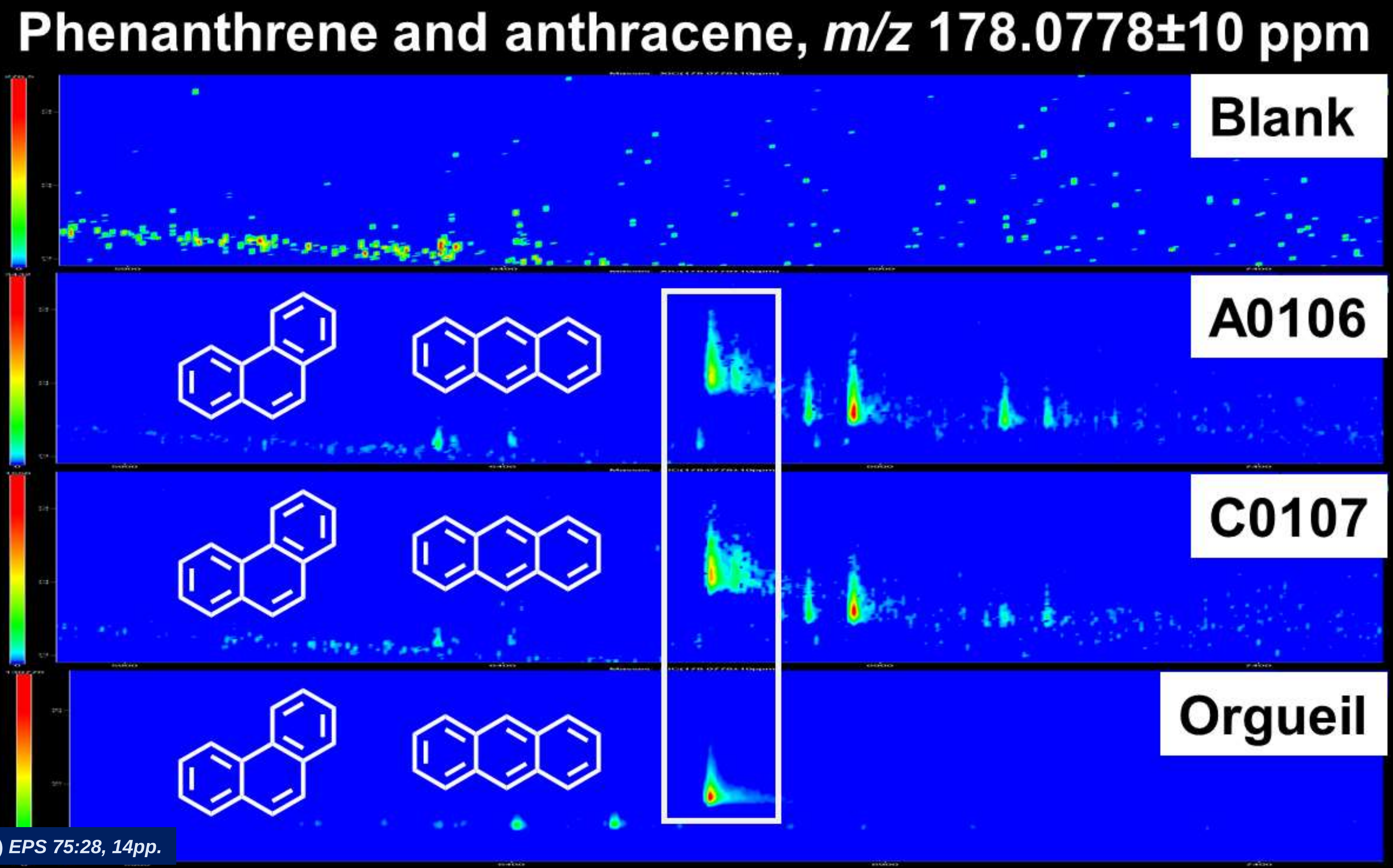
Ryugu: Naphthalene



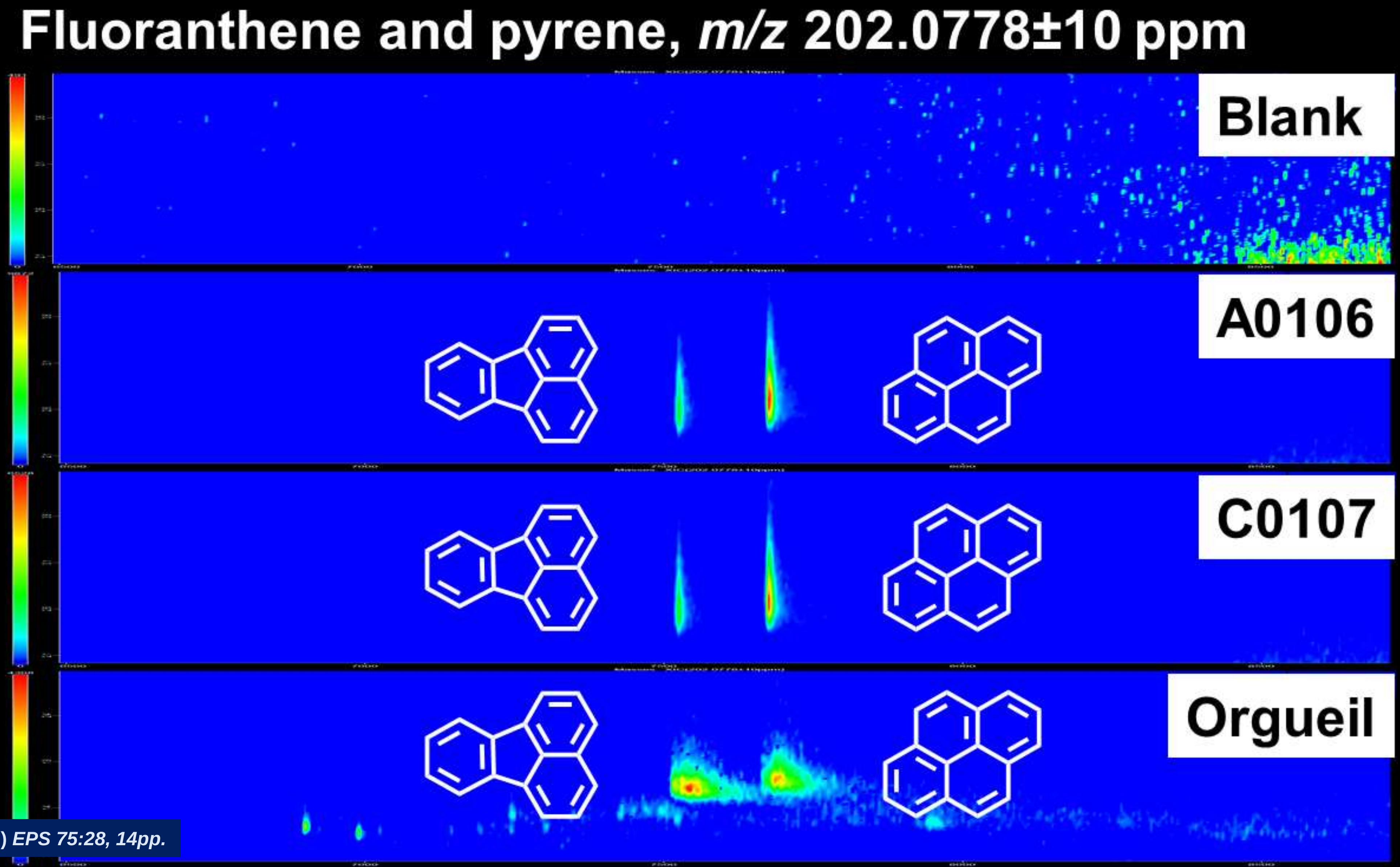
Aponte et al. (2023) *EPS 75:28, 14pp.*

Ryugu: Phenanthrene and Anthracene



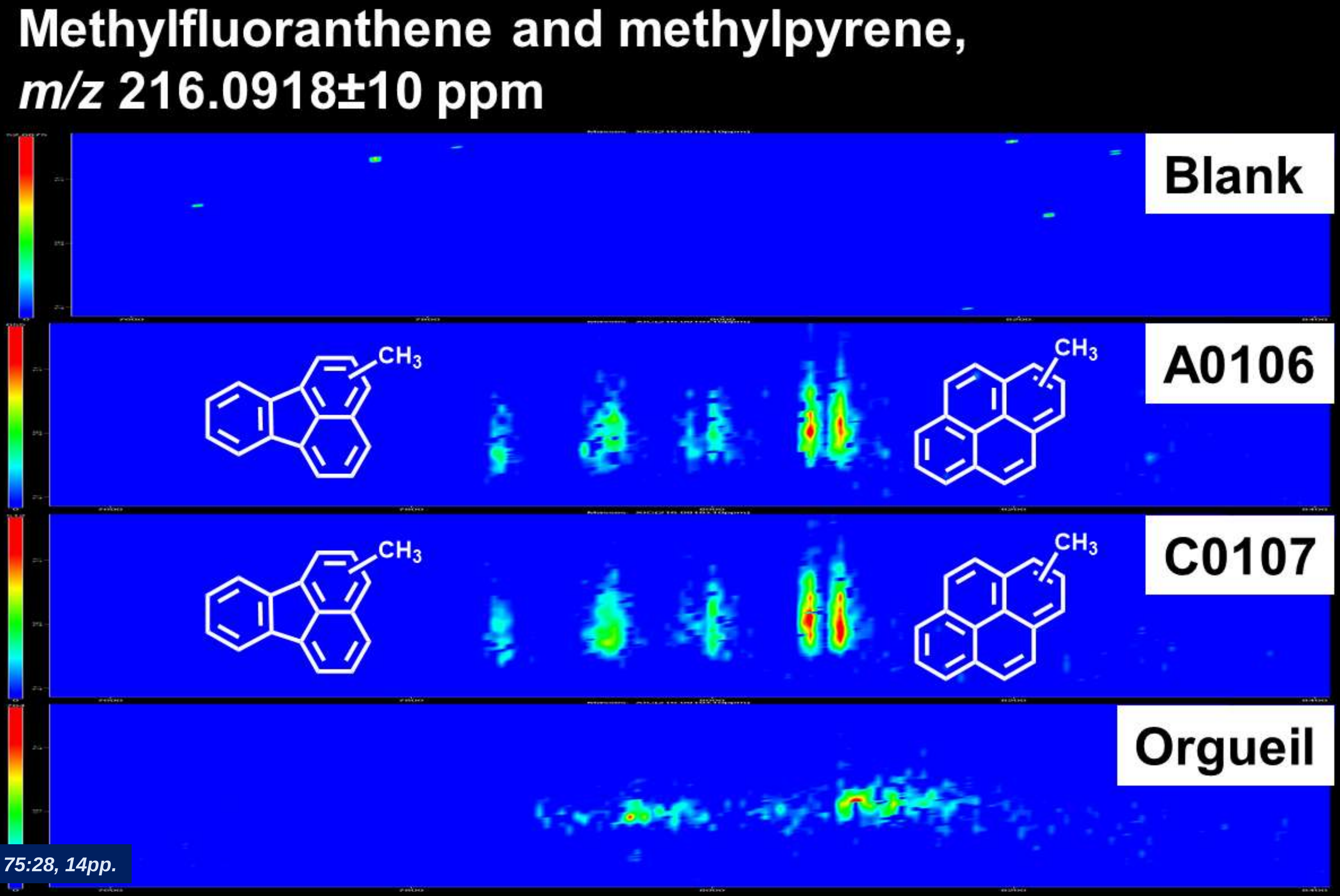
Aponte et al. (2023) *EPS 75:28, 14pp.*

Ryugu: Fluoranthene and Pyrene



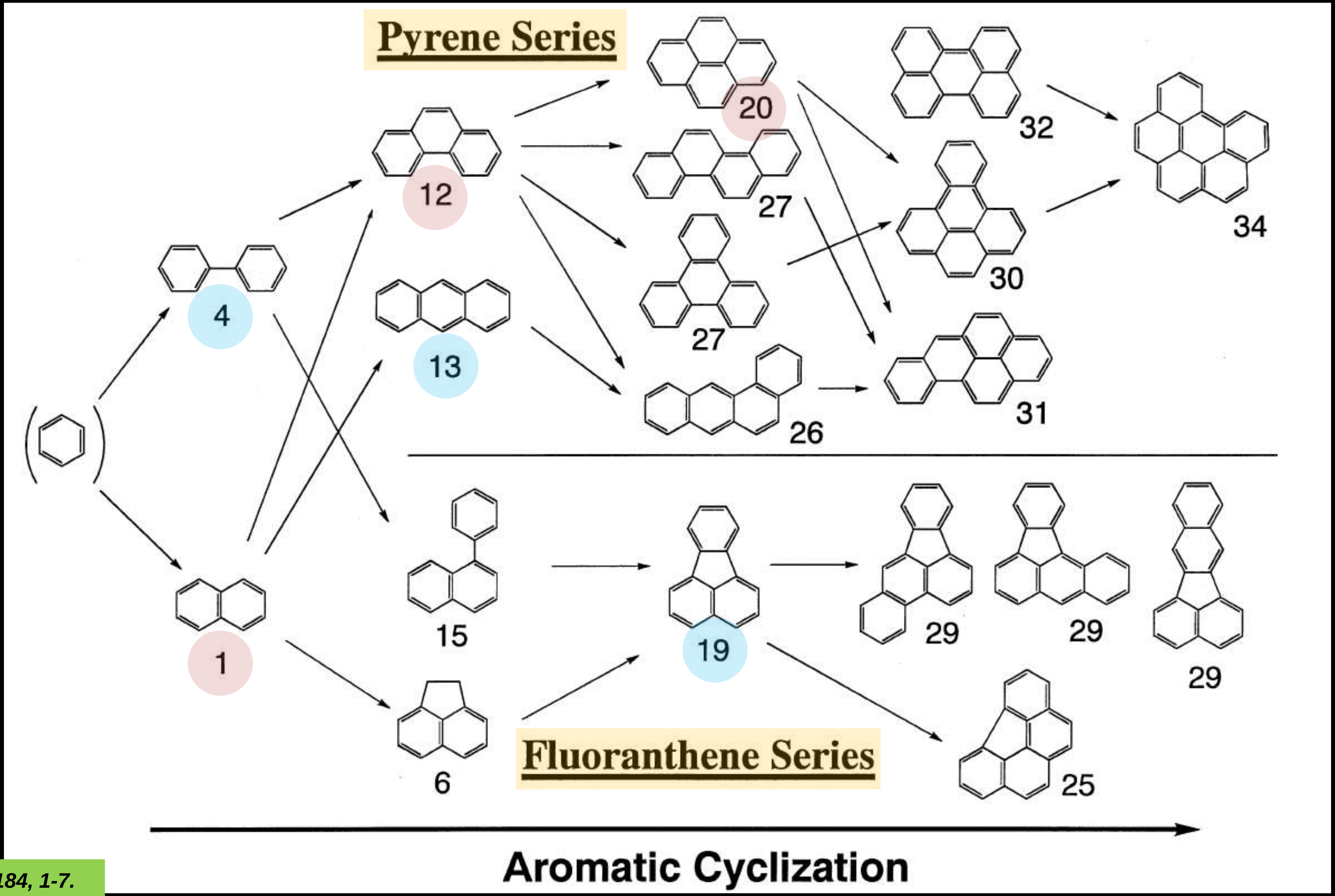
Aponte et al. (2023) *EPS 75:28, 14pp.*

Ryugu: Methylfluoranthene and Methylpyrene



Aponte et al. (2023) *EPS 75:28, 14pp.*

Reaction Pathways for PAHs



Naraoka et al. (1990) *EPSL 184, 1-7.*