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**You should know something
if you want to learn something new –
a story of stable isotopes**

Seminar of the Institute of Physics

Jan Kochanowski University

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Stable isotopes – definition

- Atoms containing the same number of protons but a different number of neutrons in their nuclei
- The term “stable” is relative, depending on the detection limits of radioactive decay times. A stable isotope is defined as an isotope for which no radioactive decay has been experimentally detected
- The results of stable isotope measurements can be given as δ values or as isotope ratios

$$\delta_{(\text{‰ or ppt})} = \frac{R_{(\text{sample})} - R_{(\text{standard})}}{R_{(\text{standard})}} \times 1000$$

$$R = {}^{13}\text{C}/{}^{12}\text{C}, {}^{18}\text{O}/{}^{16}\text{O}, {}^{34}\text{S}/{}^{32}\text{S}, {}^2\text{H}/{}^1\text{H} (\text{D}/\text{H})$$

Selected stable isotopes

δ value	R value	Standard
$\delta^2\text{H}$	$^2\text{H}/^1\text{H}$	V-SMOW
$\delta^3\text{He}$	$^3\text{He}/^4\text{He}$	Atmospheric He
$\delta^6\text{Li}$	$^6\text{Li}/^7\text{Li}$	L-SVEC
$\delta^{11}\text{B}$	$^{11}\text{B}/^{10}\text{B}$	NBS 951
$\delta^{13}\text{C}$	$^{13}\text{C}/^{12}\text{C}$	V-PDB
$\delta^{15}\text{N}$	$^{15}\text{N}/^{14}\text{N}$	Atmospheric N_2
$\delta^{18}\text{O}$	$^{18}\text{O}/^{16}\text{O}$	V-SMOV
$\delta^{34}\text{S}$	$^{34}\text{S}/^{32}\text{S}$	CDT
$\delta^{37}\text{Cl}$	$^{37}\text{Cl}/^{35}\text{Cl}$	SMOC

V-SMOW – Standard Mean Ocean Water (artificially prepared in the International Atomic Energy Agency in Vienna)

SMOC – Standard Mean Ocean Chloride

V-PDB – Pee Dee Belemnite (artificially prepared in the International Atomic Energy Agency in Vienna)

V-CDT – Canyon Diablo Troilite (artificially prepared in the International Atomic Energy Agency in Vienna)

IUPAC Periodic Table of the Elements and Isotopes

Element Background Color Key

Standard atomic weights are the best estimates by IUPAC of atomic weights that are found in normal materials, which are terrestrial materials that are reasonably possible sources for elements and their compounds in commerce, industry, or science. They are determined using all stable isotopes and selected radioactive isotopes (having relatively long half-lives and characteristic terrestrial isotopic compositions). Isotopes are considered stable (non-radioactive) if evidence for radioactive decay has not been detected experimentally.

- Element has two or more isotopes that are used to determine its standard atomic weight. The isotopic abundances and atomic weights vary in normal materials. These variations are well known, and the standard atomic weight is given as lower and upper bounds within square brackets, []. Conventional atomic weight, such as for trade and commerce, is shown in white.
- Element has two or more isotopes that are used to determine its standard atomic weight. The isotopic abundances and atomic weights vary in normal materials, but upper and lower bounds of the standard atomic weight have not been assigned by IUPAC or the variations may be too small to affect the standard atomic weight value significantly. Thus, the standard atomic weight is given as a single value with an IUPAC assigned uncertainty that includes both measurement uncertainty and uncertainty due to isotopic abundance variations.
- Element has only one isotope that is used to determine its standard atomic weight. Thus, the standard atomic weight is invariant and is given as a single value with an IUPAC evaluated uncertainty.
- Element has no standard atomic weight because all of its isotopes are radioactive and, in normal materials, no isotope occurs with a characteristic isotopic abundance from which a standard atomic weight can be determined.

element name: **cadmium** isotope mass number (number of protons + neutrons): **114**; black number indicates the isotope is stable

element symbol: **Cd** **116**; red number indicates the isotope is radioactive

atomic number (number of protons): **48**

conventional atomic weight for elements with pink background: **112.414(4)**

standard atomic weight: **112.414 ± 0.004** uncertainty in last digit

1 hydrogen H 1 1.008 [1.007 84, 1.009 11]	2 lithium Li 3 6.94 [6.938, 6.997]	3 beryllium Be 4 9.012 1831(6)	4 boron B 5 10.81 [10.806, 10.821]	5 carbon C 6 12.011 [12.0096, 12.0116]	6 nitrogen N 7 14.007 [14.006 43, 14.007 28]	7 oxygen O 8 15.999 [15.999 03, 15.999 77]	8 fluorine F 9 18.998 403 163(6)	9 neon Ne 10 20.1797(6)	10 sodium Na 11 22.989 769 28(2)	11 magnesium Mg 12 24.304 [24.304, 24.307]	12 aluminum (aluminium) Al 13 26.981 5384(3)	13 silicon Si 14 28.085 [28.086, 28.086]	14 phosphorus P 15 30.973 761 998(6)	15 sulfur S 16 32.06 [32.059, 32.075]	16 chlorine Cl 17 35.45 [35.446, 35.457]	17 argon Ar 18 39.948 [39.942, 39.963]	18 potassium K 19 39.0983(1)	19 calcium Ca 20 40.078(4)	20 scandium Sc 21 44.956 908(6)	21 titanium Ti 22 47.867(1)	22 vanadium V 23 50.9415(1)	23 chromium Cr 24 51.9961(6)	24 manganese Mn 25 54.938 043(2)	25 iron Fe 26 55.845(2)	26 cobalt Co 27 58.933 194(3)	27 nickel Ni 28 58.6934(4)	28 copper Cu 29 63.546(3)	29 zinc Zn 30 65.38(2)	30 gallium Ga 31 69.723(1)	31 germanium Ge 32 72.630(8)	32 arsenic As 33 74.921 595(6)	33 selenium Se 34 78.971(6)	34 bromine Br 35 79.904 [79.901, 79.907]	35 krypton Kr 36 83.799(2)	36 rubidium Rb 37 85.4678(3)	37 strontium Sr 38 87.62(1)	38 yttrium Y 39 88.906 84(1)	39 zirconium Zr 40 91.224(2)	40 niobium Nb 41 92.906 37(1)	41 molybdenum Mo 42 95.96(1)	42 technetium Tc 43 [97.906 254]	43 ruthenium Ru 44 101.07(2)	44 rhodium Rh 45 102.905 48(2)	45 palladium Pd 46 106.42(1)	46 silver Ag 47 107.8682(2)	47 cadmium Cd 48 112.414(4)	48 indium In 49 114.818(1)	49 tin Sn 50 118.710(7)	50 antimony Sb 51 121.760(1)	51 tellurium Te 52 127.60(3)	52 iodine I 53 126.904 47(3)	53 xenon Xe 54 131.293(6)	54 caesium (cesium) Cs 55 132.905 451 96(6)	55 barium Ba 56 137.327(7)	56-71 lanthanoids	57-71 actinoids	72 hafnium Hf 72 178.49(2)	73 tantalum Ta 73 180.947 88(2)	74 tungsten W 74 183.84(1)	75 rhenium Re 75 186.207(1)	76 osmium Os 76 190.23(3)	77 iridium Ir 77 192.217(2)	78 platinum Pt 78 195.084(1)	79 gold Au 79 196.966 570(4)	80 mercury Hg 80 200.592(3)	81 thallium Tl 81 [204.382, 204.385]	82 lead Pb 82 207.2(1)	83 bismuth Bi 83 208.980 40(1)	84 polonium Po 84 [209]	85 astatine At 85 [210]	86 radon Rn 86 [222]	87 francium Fr 87 [223]	88 radium Ra 88 [226]	89-103 actinoids	104 rutherfordium Rf 104 [261]	105 dubnium Db 105 [262]	106 seaborgium Sg 106 [266]	107 bohrium Bh 107 [264]	108 hassium Hs 108 [277]	109 meitnerium Mt 109 [268]	110 darmstadtium Ds 110 [285]	111 roentgenium Rg 111 [282]	112 copernicium Cn 112 [285]	113 nihonium Nh 113 [284]	114 flerovium Fl 114 [289]	115 moscovium Mc 115 [288]	116 livermorium Lv 116 [293]	117 tennessine Ts 117 [294]	118 oganesson Og 118 [294]
																		57 lanthanum La 57 138.905 47(7)	58 cerium Ce 58 140.116(1)	59 praseodymium Pr 59 140.907 66(1)	60 neodymium Nd 60 144.242(3)	61 promethium Pm 61 [145]	62 samarium Sm 62 150.36(2)	63 europium Eu 63 151.964(1)	64 gadolinium Gd 64 157.25(3)	65 terbium Tb 65 158.925 354(8)	66 dysprosium Dy 66 162.500(1)	67 holmium Ho 67 164.930 328(7)	68 erbium Er 68 167.259(3)	69 thulium Tm 69 168.934 218(6)	70 ytterbium Yb 70 173.045(10)	71 lutetium Lu 71 174.9668(1)	89 actinium Ac 89 [227]	90 thorium Th 90 232.0377(4)	91 protactinium Pa 91 231.036 89(1)	92 uranium U 92 238.028 91(3)	93 neptunium Np 93 [237]	94 plutonium Pu 94 [244]	95 americium Am 95 [243]	96 curium Cm 96 [247]	97 berkelium Bk 97 [247]	98 californium Cf 98 [251]	99 einsteinium Es 99 [252]	100 fermium Fm 100 [257]	101 mendelevium Md 101 [258]	102 nobelium No 102 [259]	103 lawrencium Lr 103 [260]																																										

Number of stable isotopes

Number of elements in the periodic table

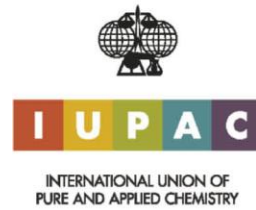
118

Number of stable isotopes

~300

Number of radioisotopes

~3000 (~3000-6000 unknown radionuclides)

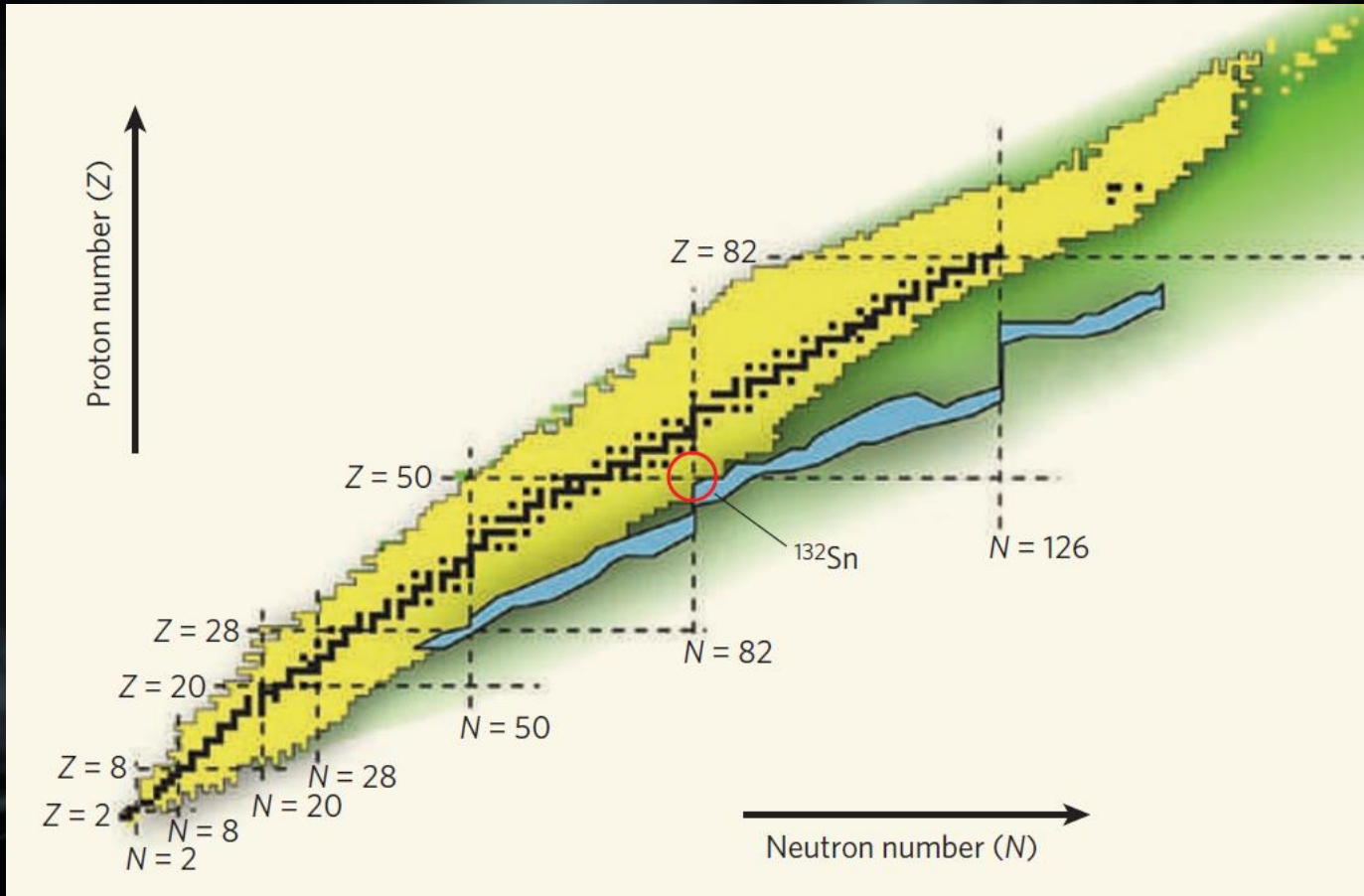


www.tableofisotopes.com

Values are the latest IUPAC values as of October 2018

The Periodic Table of the Elements and Isotopes: Copyright Sara Glidewell 2016-2018

Stability of nuclei



Nuclides of even atomic numbers are more abundant (>3) than those with odd numbers (1-2), except for He, Be and C

The doubly magic stable isotopes:

^4He : 2 protons + 2 neutrons

^{16}O : 8 protons + 8 neutrons

^{40}Ca : 20 protons + 20 neutrons

^{48}Ca : 20 protons + 28 neutrons

^{208}Pb : 82 protons + 126 neutrons

The number of protons (Z) against the number of neutrons (N) for stable isotopes (black), radioactive isotopes that have been produced (yellow), radioactive isotopes that may exist but have not yet been observed (green), and isotopes that are thought to be produced in a succession of nucleosynthesis reactions called the r-process (blue)

Fractionation process

Isotope fractionation is the partitioning of isotopes between two substances /two phases of the same substance with different isotope ratios

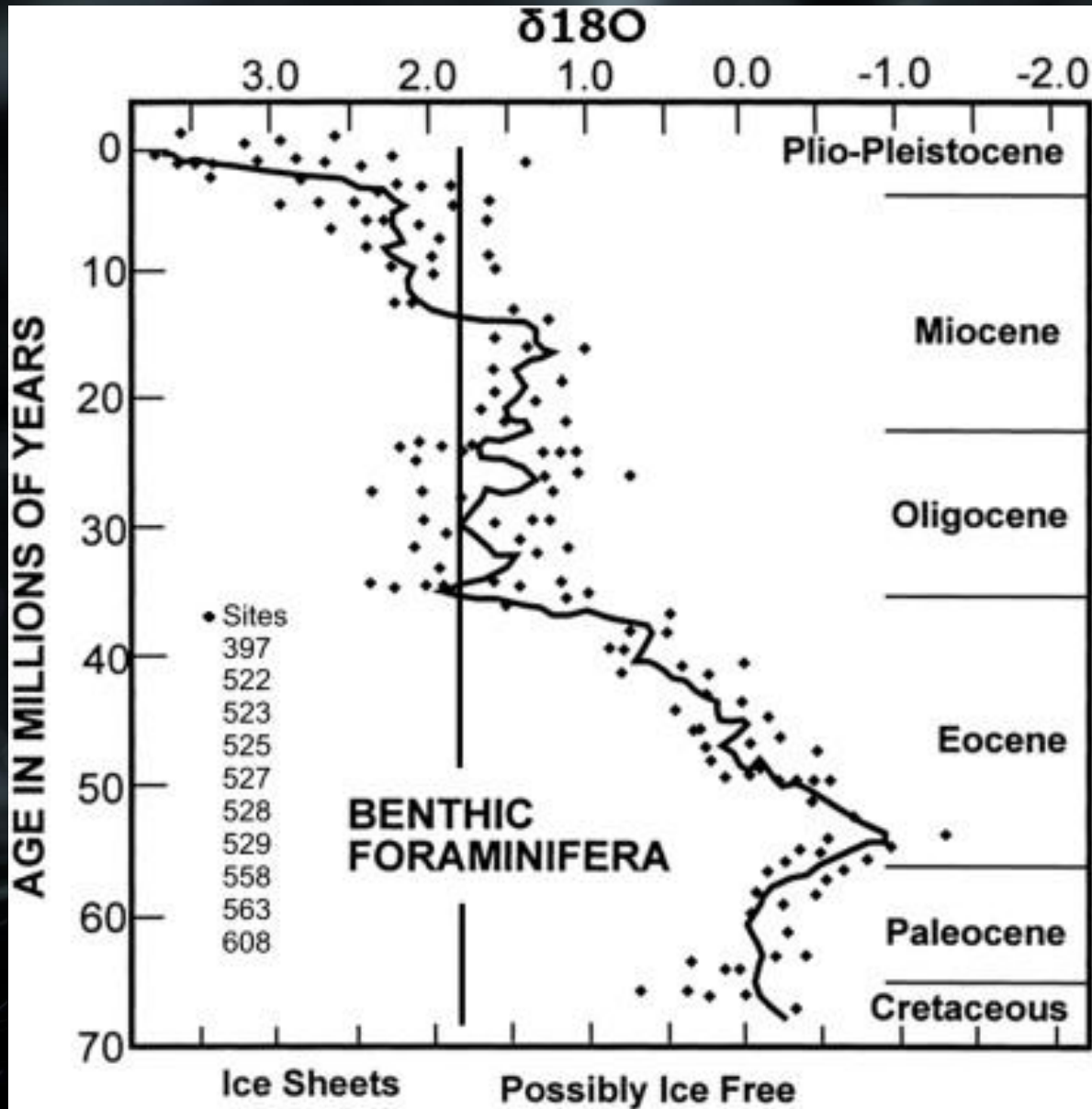
This process occurs as:

1. **Isotope exchange reactions** (equilibrium isotope distribution) e.g. evaporation-condensation processes
2. **Kinetic processes**, which depend primarily on differences in reaction rates of isotopic molecules (incomplete and unidirectional processes like evaporation, dissociation reactions, biologically mediated reactions, and diffusion)

Application of stable isotopes in geology

- Thanks to the study of the isotopic composition of rocks, it is possible to determine their origin (genesis)
- The isotopes He, Hf, Ne, Pb and O are used to study the source of magma in the Earth's mantle
- Isotopic composition of H, C, O, S can be helpful in reconstructing the crystallization of minerals occurring in paragenesis and their crystallization temperatures
- Reconstruction of paleotemperatures – during glacials the values of $\delta^{18}\text{O}$ are lower than during periods with higher temperature (e.g. interglacials)
- Studies $\delta^{11}\text{B}$ in marine carbonates were used to reconstruct the pH of sedimentary basins, as the fractionation of $^{11}\text{B}/^{10}\text{B}$ depends on pH

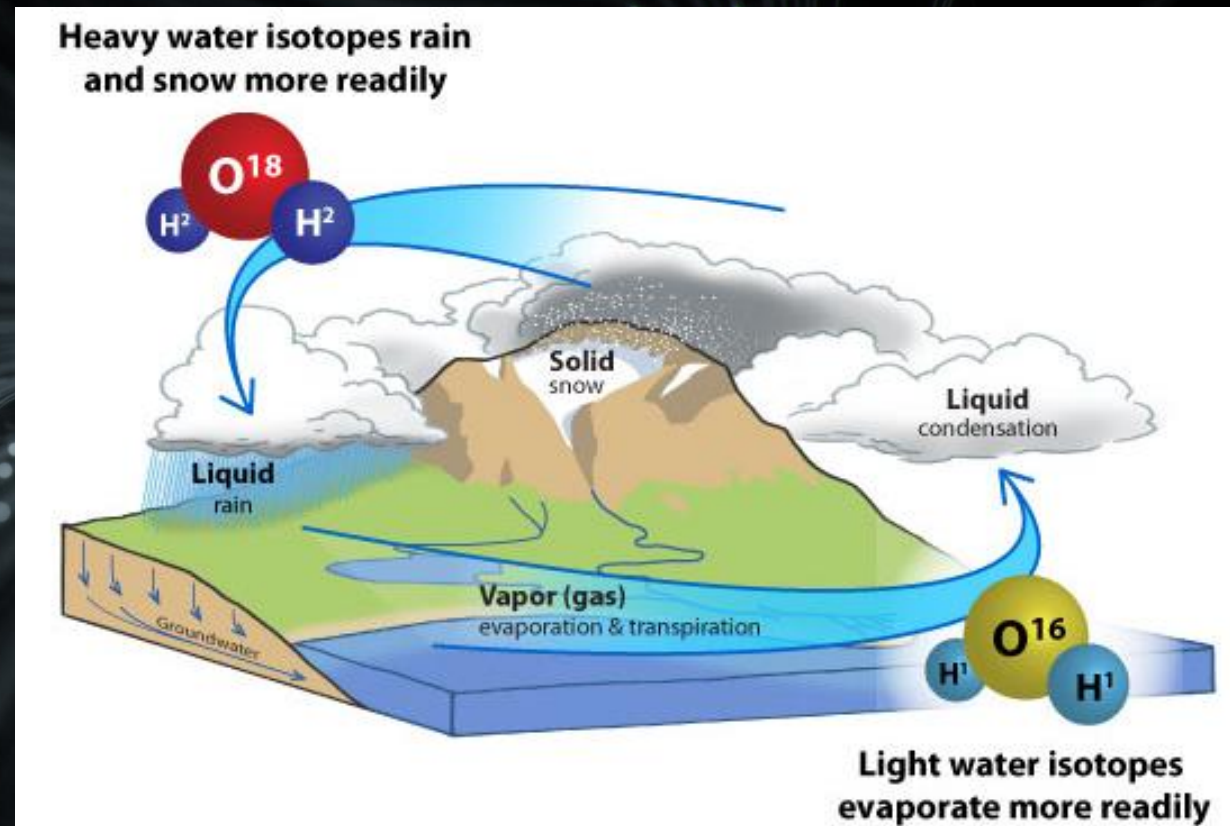
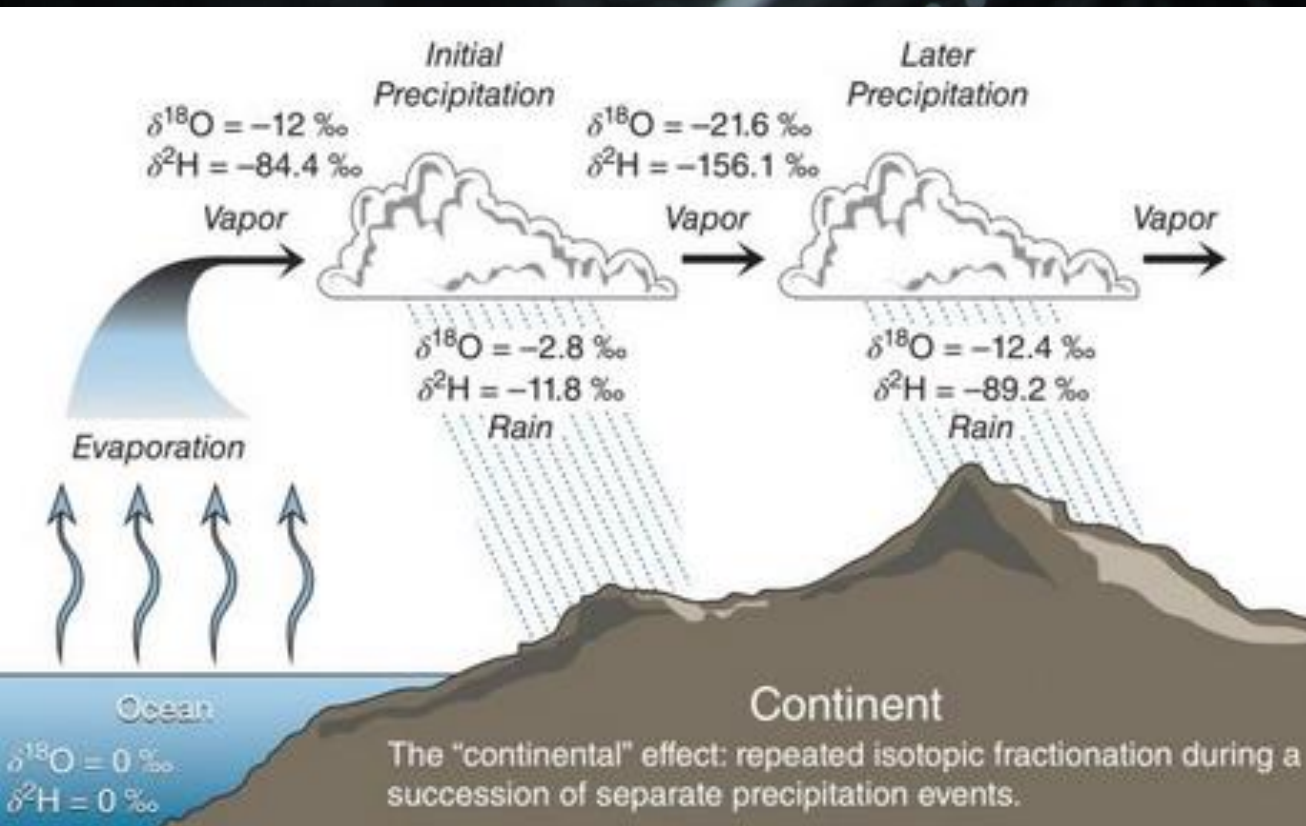
Trends in the Cenozoic oxygen isotopic record



Ishman, S. E., Karlsen, A. W., Cronin, T. M., Cronin, T. M., Wagner, R. S., & Slattery, M. (1999). Chesapeake Bay benthic foraminifera. *Microfossils from Chesapeake Bay sediments: illustrations and species database*, 10(25), 99-45.

During glacial interval ^{18}O is enriched in ocean waters and depleted in glacial ice. The foraminifera calcifying their test in isotopic equilibrium with sea water during glacial times are thus enriched in ^{18}O as compared to those calcifying during interglacial intervals

Changing hydrogen and oxygen isotope composition of meteoric water

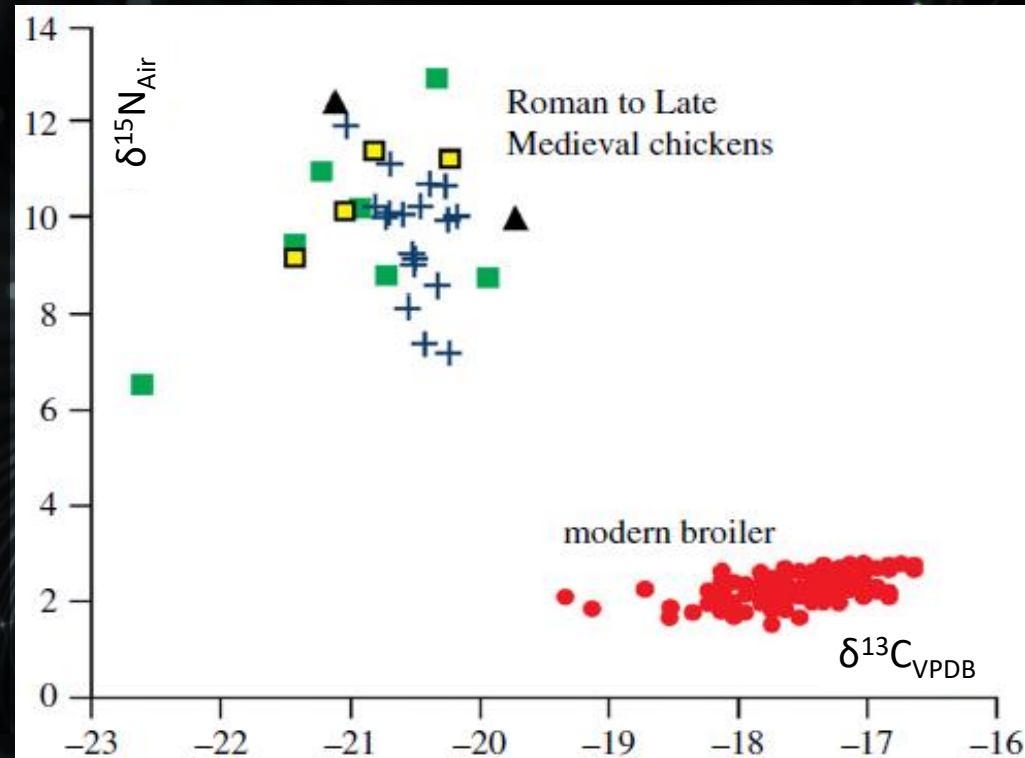


Meier-Augenstein, W. and Kemp, H. F. 2012. Stable Isotope Analysis: General Principles and Limitations. Wiley Encyclopedia of Forensic Science

<https://www.usgs.gov/media/images/water-cycle-and-water-isotopes>

The broiler chicken as a biostratigraphic marker of the Anthropocene

“Modern broiler chickens are morphologically, genetically and isotopically distinct from domestic chickens prior to the mid-twentieth century. The global range of modern broilers and biomass dominance over all other bird species is a product of human intervention”



Carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope values of chicken bone collagen

Bennett, C. E., Thomas, R., Williams, M., Zalasiewicz, J., Edgeworth, M., Miller, H., ... & Marume, U. (2018). The broiler chicken as a signal of a human reconfigured biosphere. *Royal Society Open Science*, 5(12), 180325.

Stable isotopes in hydrology

$\delta^{13}\text{C}$, $\delta^2\text{H}$, $\delta^{18}\text{O}$,
 $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{34}\text{S}$, Pb

▪ Origin of groundwater

$\delta^{34}\text{S}$, $\delta^{11}\text{B}$,
 $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{37}\text{Cl}$

▪ Origin of salinity

$\delta^2\text{H}$, $\delta^{18}\text{O}$

▪ Source of groundwater

Stable isotopes in ecology

- Stable isotopes H, C, N and O are used to study trophic relationships in ecosystems, mainly marine ecosystems
- The isotopic ratios of carbon in the diet of herbivores are used to study what plants animals feed on
- Nitrogen isotopes are used to study the trophic level of animals
- Isotopes of hydrogen and oxygen are used to study the migration routes and origin of animals (the isotopic composition of hydrogen and oxygen tissues depends on the isotopic composition of the environment during their formation)

Stable isotopes in ecology

$\delta^{13}\text{C}$, $\delta^{15}\text{N}$

- Fish migrations

$\delta^2\text{H}$, $\delta^{13}\text{C}$,
 $\delta^{15}\text{N}$, $\delta^{18}\text{O}$

- Bird migrations

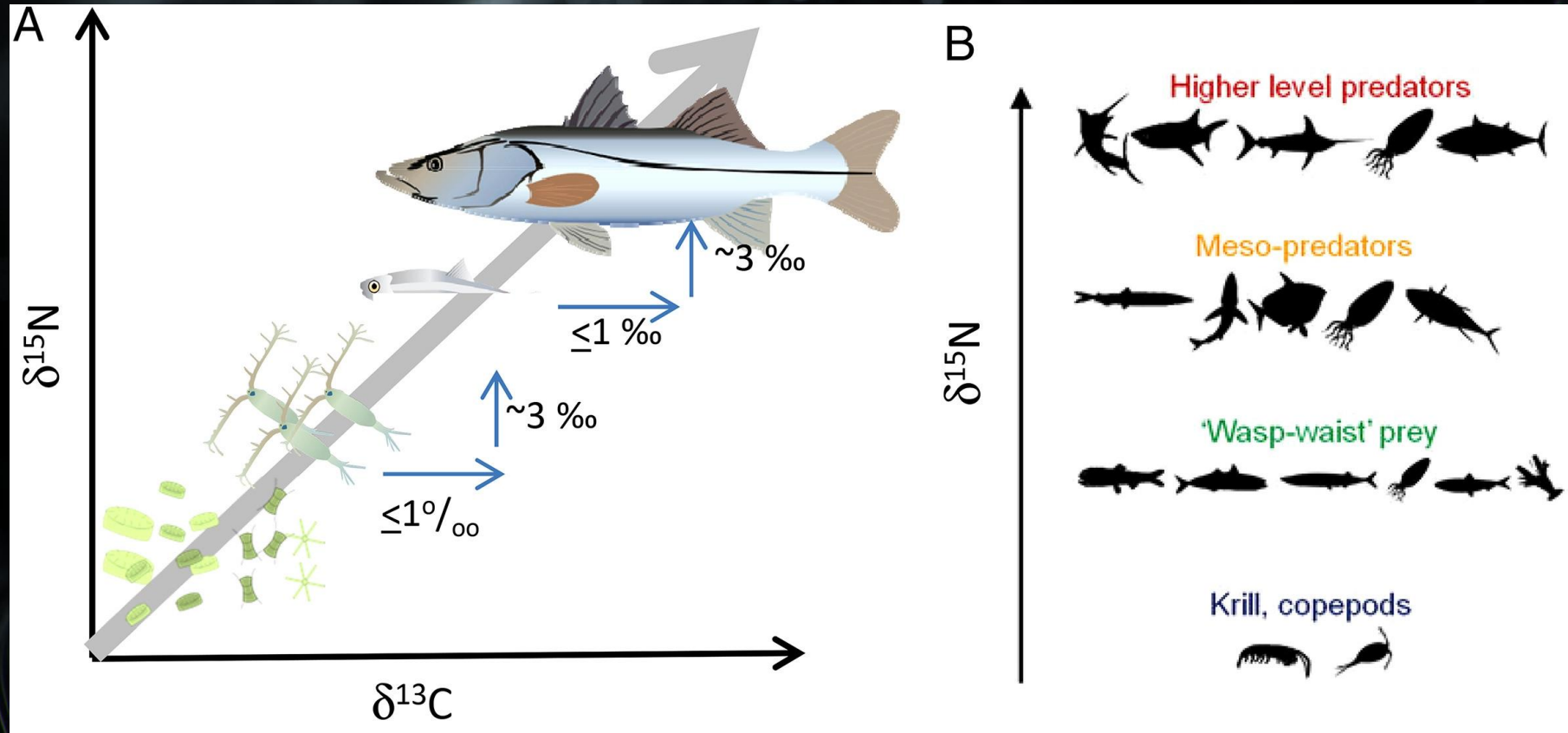
$\delta^{13}\text{C}$, $\delta^2\text{H}$

- Origin of pest insects

$\delta^{13}\text{C}$, $\delta^{15}\text{N}$

- Position in a food chain

Changes in stable nitrogen isotope at trophic levels of the ecosystem



Food web relationships based on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$

Glibert, P. M., Middelburg, J. J., McClelland, J. W., & Jake Vander Zanden, M. (2019). Stable isotope tracers: Enriching our perspectives and questions on sources, fates, rates, and pathways of major elements in aquatic systems. *Limnology and Oceanography*, 64(3), 950-981.

Stable isotope research in forensic sciences: the authenticity of food products

- For the first time, stable isotopes were used to establish the authenticity of wine in the European Union (origin and year of production)
- Currently, this method is used to check the authenticity of other products: milk, honey, juices, spices
- Carbon stable isotopes allow to determine the origin of plant products (isotope composition reflects the type of photosynthesis)

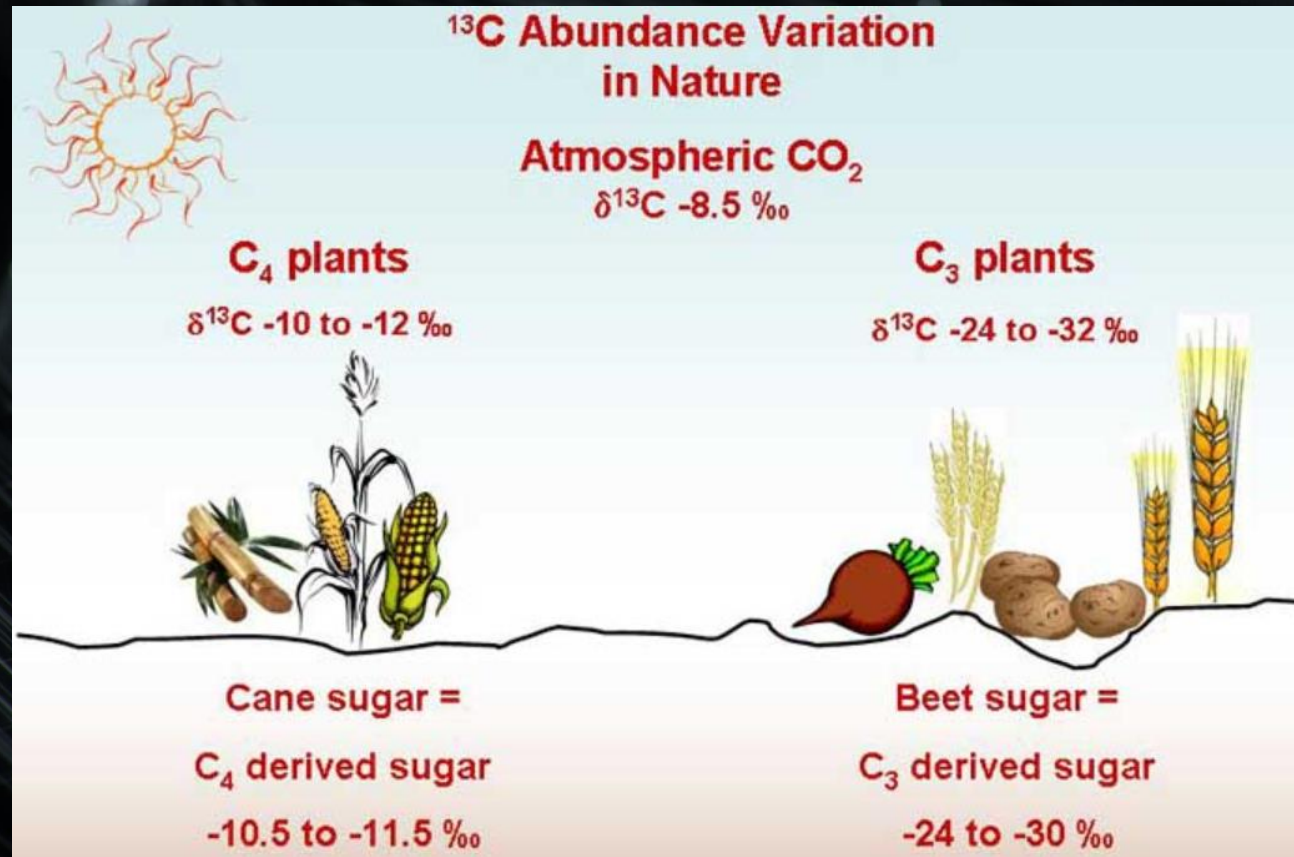
Stable isotope research in forensic sciences: the origin of food products

- Stable oxygen isotopes in food containing water indicate the place of origin (isotopic composition of food reflects the isotopic composition of local rainwater)
- Nitrogen and sulfur isotopes can be used to determine the place of origin of the product ($\delta^{34}\text{S}$ values indicate distance from the sea, $\delta^{15}\text{N}$ inform about cultivation practices, which vary from country to country)
- Stable strontium isotopes can be used as an indicator of place of origin because they reflect the isotopic composition of the bedrock

$\delta^{13}\text{C}$ values in C3 and C4 plants

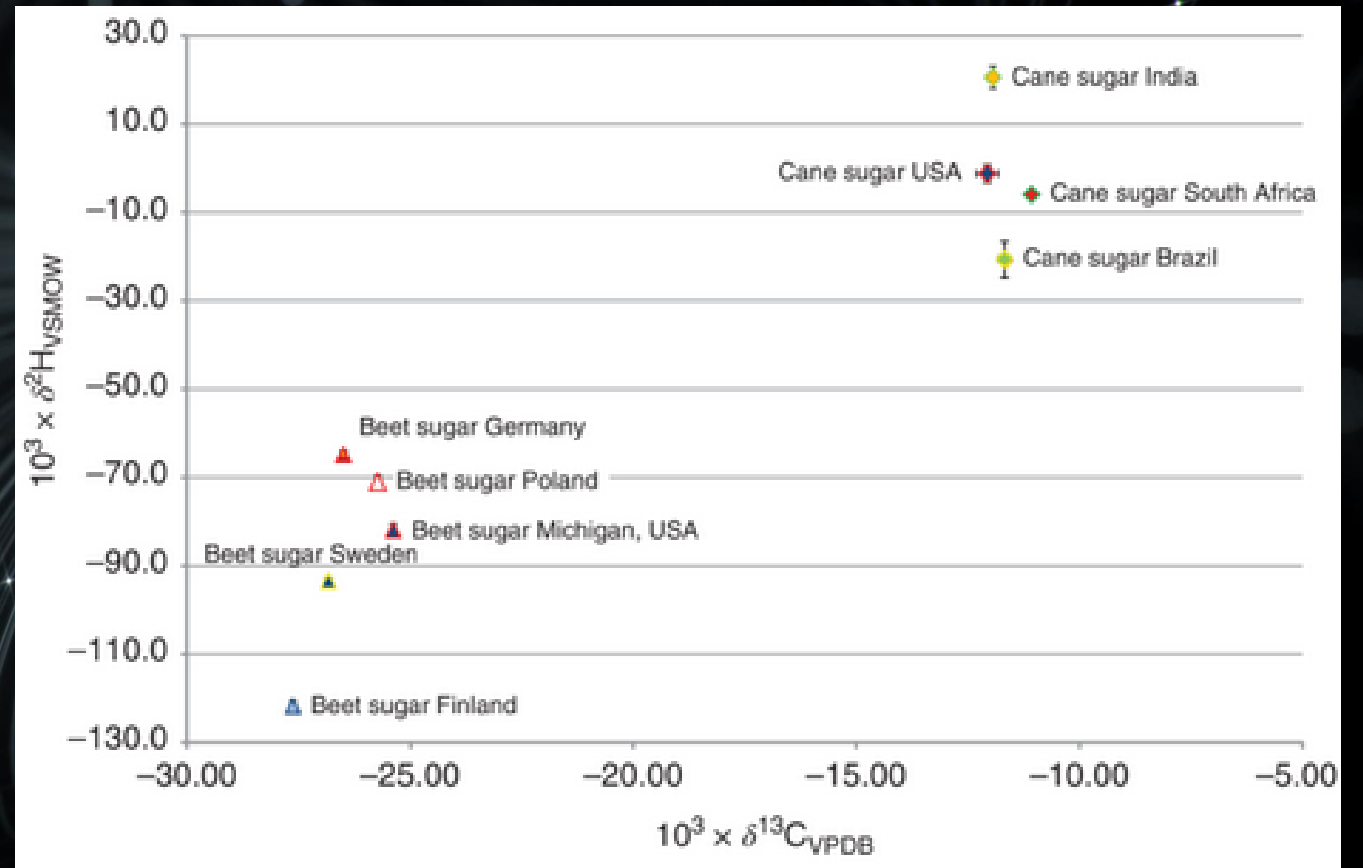
C3 plants – the first product of CO_2 assimilation is 3-phosphoglyceric acid (three-carbon compound)

C4 plants – the first stable product of CO_2 assimilation is a compound with four carbon atoms – oxaloacetate (e.g. corn, sugar cane, millet)

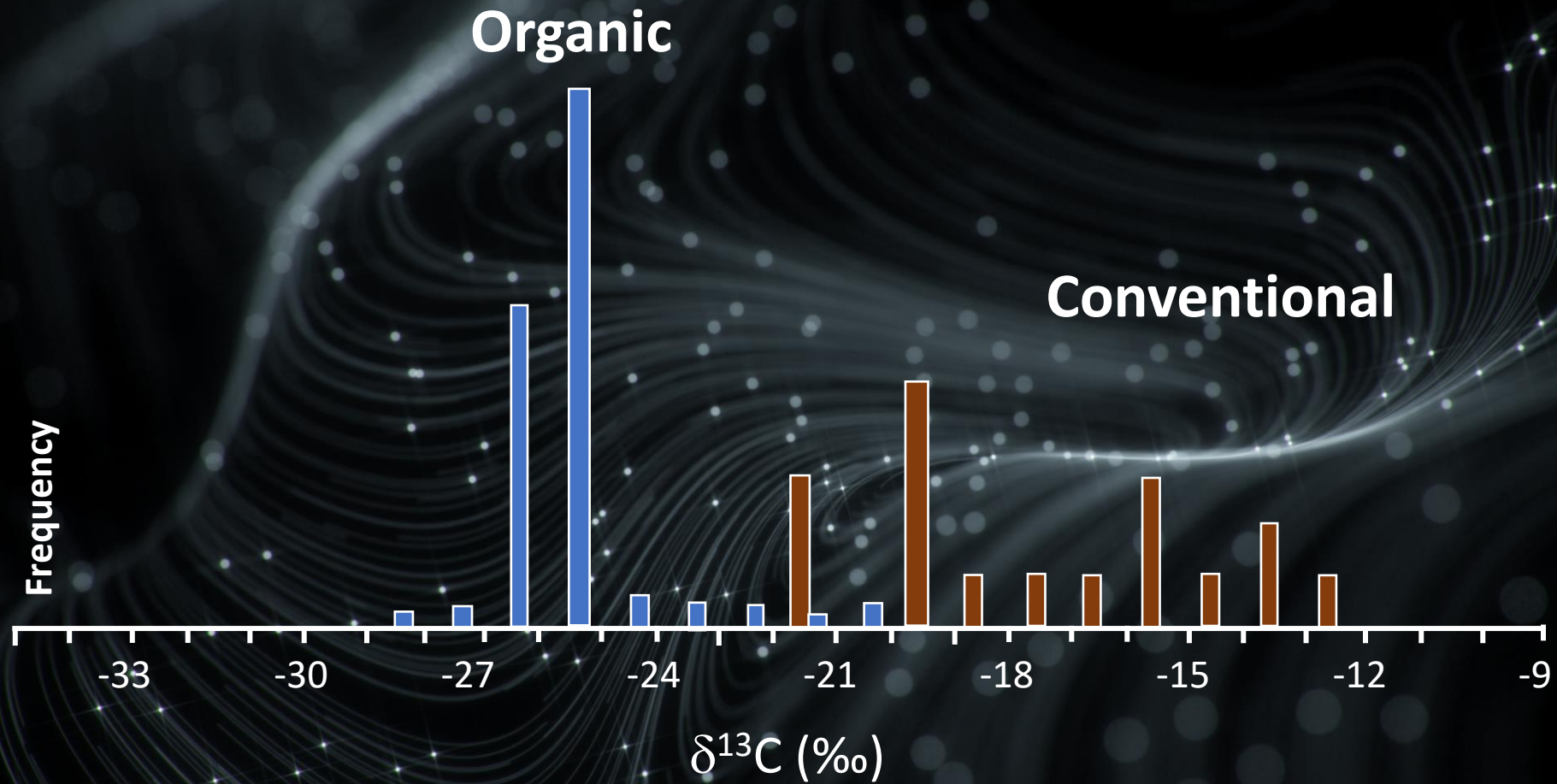


Carbon and hydrogen isotopes in sugar from different regions of the world

SUGAR TYPE	$\delta^{13}\text{C}_{\text{VPDB}}$ (‰)	$\delta^2\text{H}_{\text{VSMOW}}$ (‰)
Beet sugar, Poland	-25.42	-71.0
Beet sugar, Sweden	-26.84	-93.4
Cane sugar, Brazil	-11.76	-21.4
Cane sugar, S Africa	-11.10	-6.7

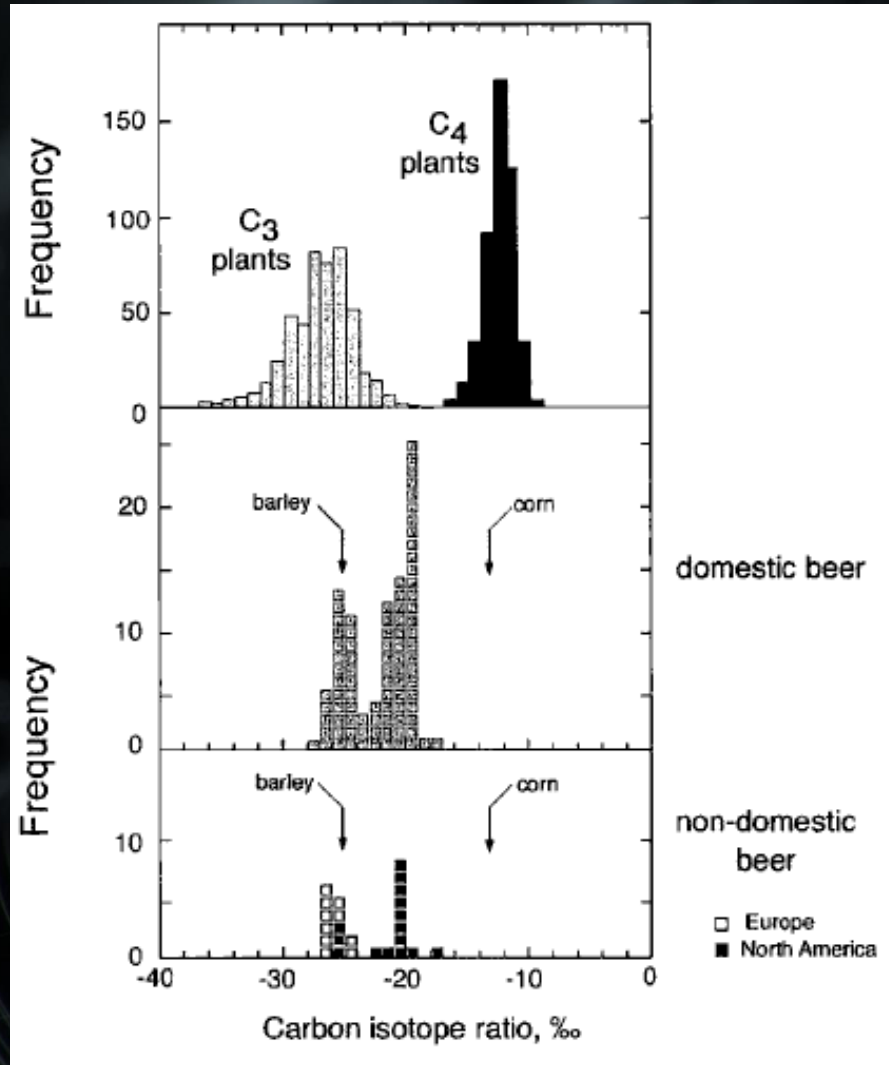


$\delta^{13}\text{C}$ in conventional and organic beef



Boner M, H Förstel. 2004. Stable isotope variation as a tool to trace the authenticity of beef. *Analytical and Bioanalytical Chemistry* 378: 301-310

Beer adulteration

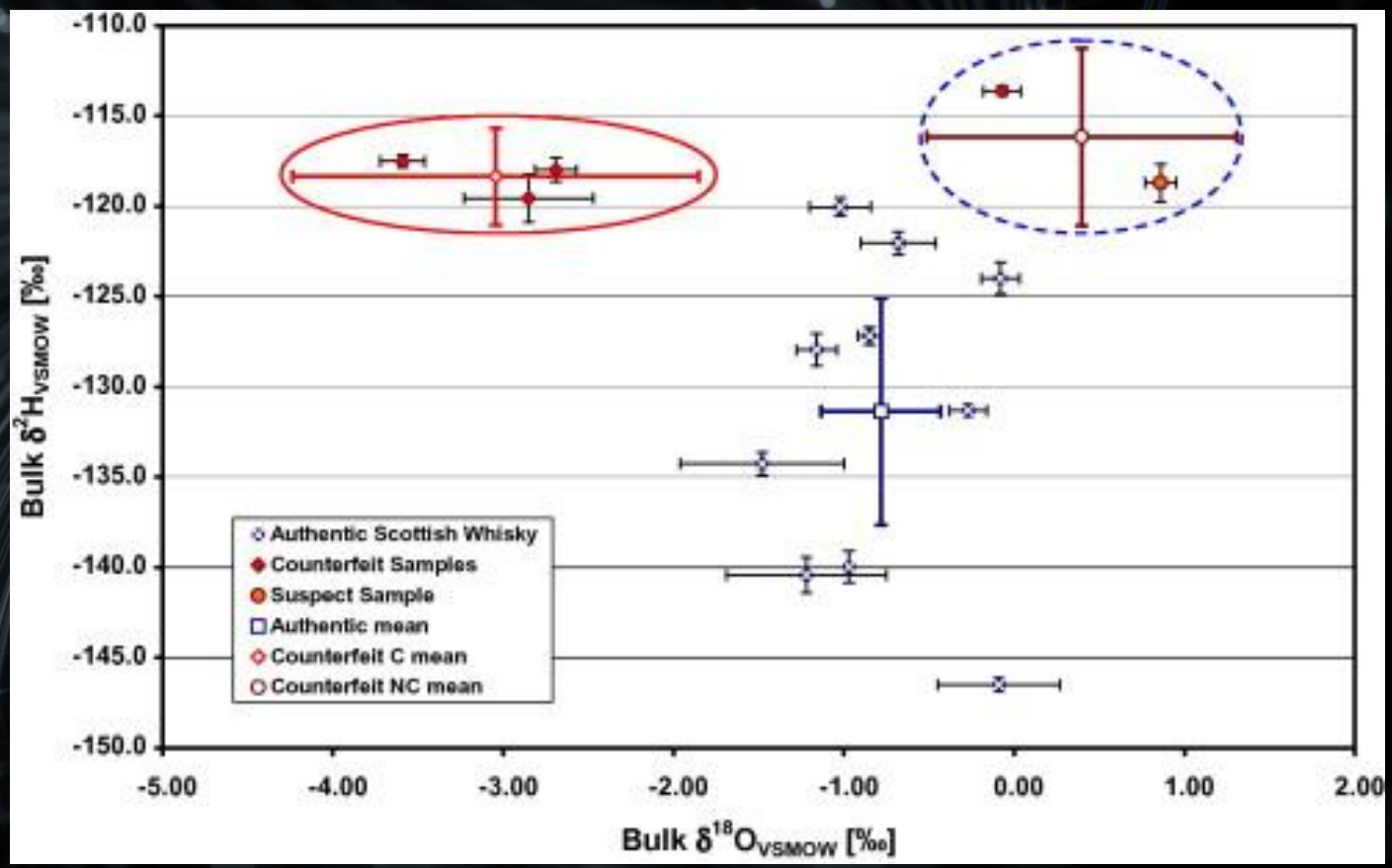


Beer = barley or wheat grain + hops + water

Barley is a C₃ plant and corn is a C₄ plant. Some samples of American beer have higher values of $\delta^{13}\text{C}$ (addition of 50% corn+50% barley) than European beer (addition of 100% barley)

Application of ^2H and ^{18}O stable isotopes for detection of counterfeit scotch whisky

Bulk $\delta^2\text{H}$ and corresponding bulk $\delta^{18}\text{O}$ values from genuine whiskies, counterfeit whiskies and a whisky suspected to be counterfeit



Meier-Augenstein, W., Kemp, H. F., & Hardie, S. M. L. (2012). Detection of counterfeit scotch whisky by ^2H and ^{18}O stable isotope analysis. *Food Chemistry*, 133(3), 1070-1074.

Wine authentication with stable isotopes

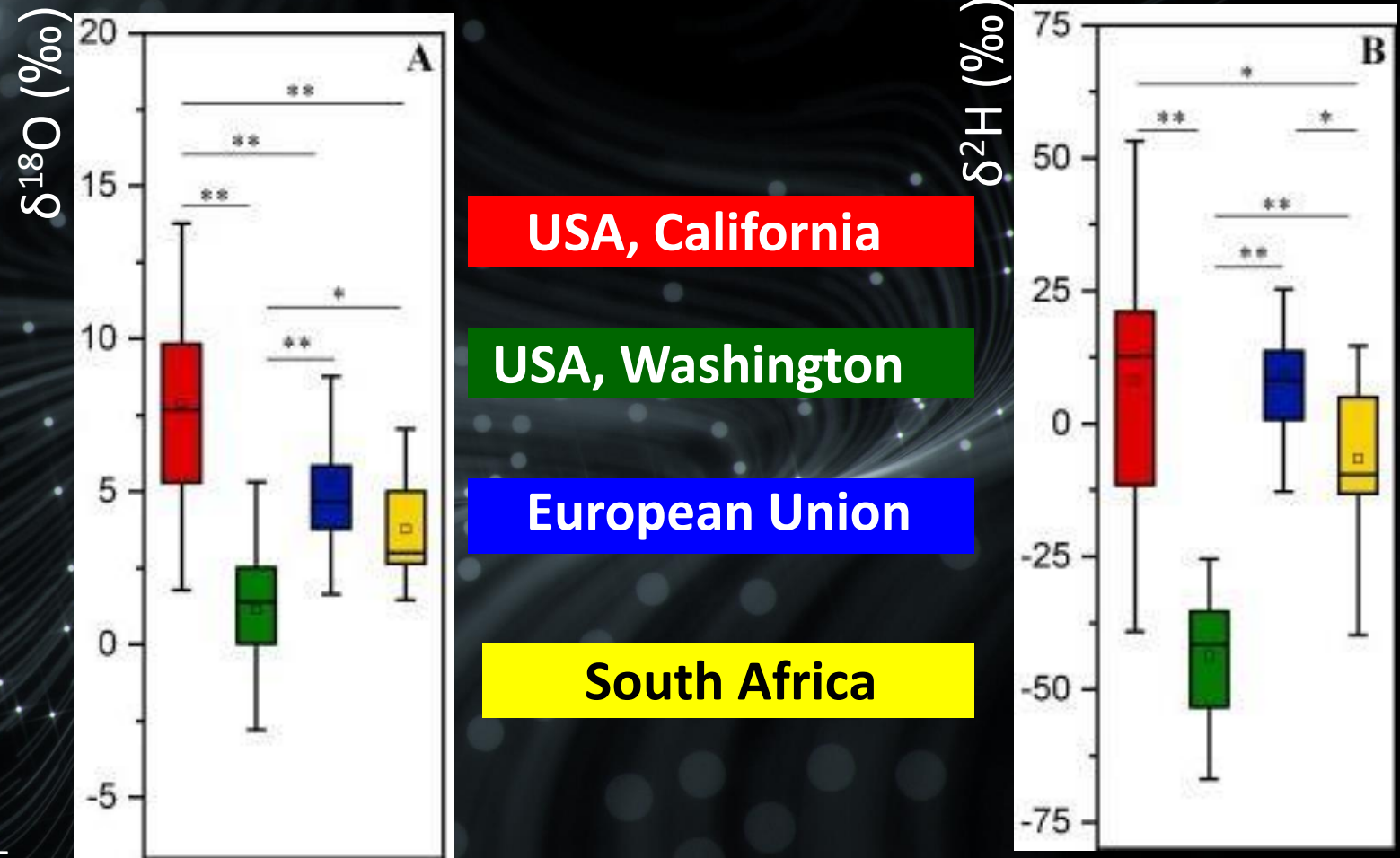
Biotic fractionation

$^2\text{H}/^1\text{H}$

$^{18}\text{O}/^{16}\text{O}$

$^{13}\text{C}/^{12}\text{C}$

Abiotic fractionation



Christoph, N., Hermann, A., & Wachter, H. (2015). 25 Years authentication of wine with stable isotope analysis in the European Union—Review and outlook. In *BIO Web of Conferences* (Vol. 5, p. 02020). EDP Sciences.

Orellana, S., Johansen, A. M., & Gazis, C. (2019). Geographic classification of US Washington State wines using elemental and water isotope composition. *Food Chemistry: X*, 1, 100007.

Isotopes in determining food authenticity

$\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$ ▪ Mineral water

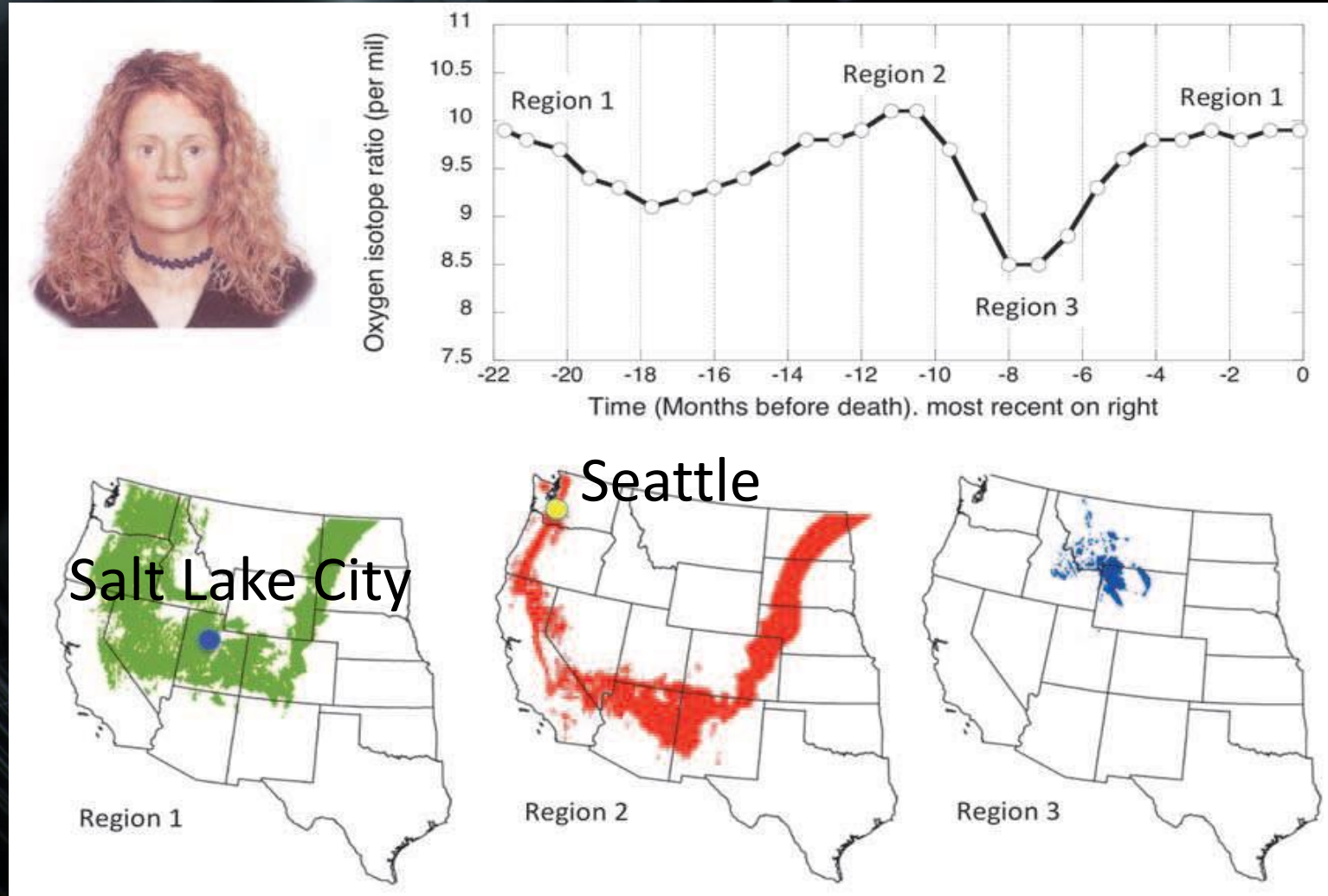
$\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{18}\text{O}$,
 $\delta^{34}\text{S}$, $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^2\text{H}$ ▪ Milk
▪ Meat

$\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{16}\text{O}$ ▪ Rice

$\delta^2\text{H}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ ▪ Tea

$\delta^2\text{H}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$,
 $\delta^{34}\text{S}$, $^{87}\text{Sr}/^{86}\text{Sr}$ ▪ Orange juice

Stable isotope research in forensic sciences: identification of unknown murder victims



Ehleringer, J. R., Chesson, L. A., Valenzuela, L. O., Tipple, B. J., & Martinelli, L. A. (2015). Stable isotopes trace the truth: from adulterated foods to crime scenes. *Elements*, 11(4), 259-264.

Stable isotopes in environmental studies

Lead stable isotopes:
 ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb

$\delta^{15}\text{N}$, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$,

Lead stable isotopes, $\delta^{34}\text{S}$

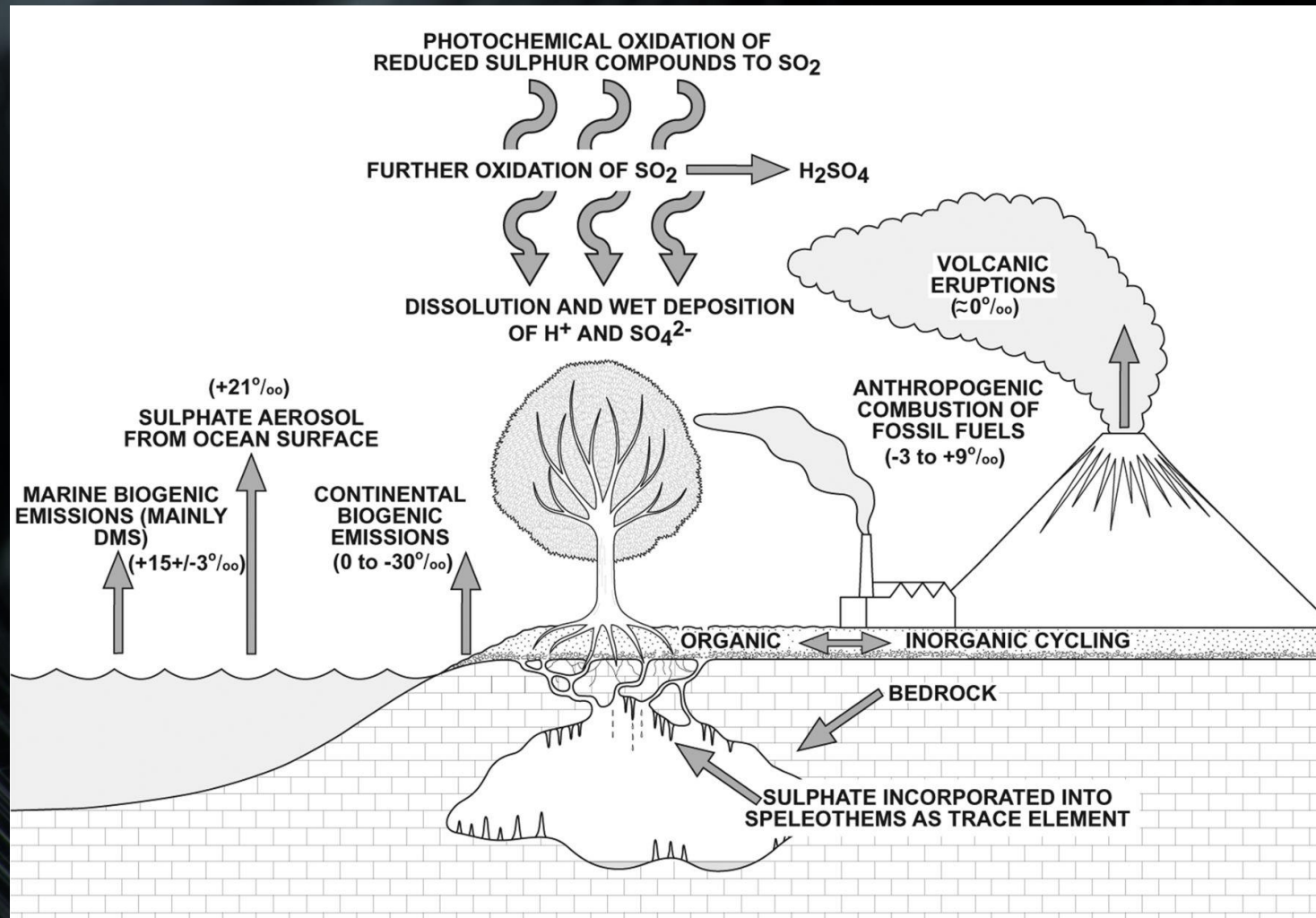
Lead stable isotopes,
 $^{87}\text{Sr}/^{86}\text{Sr}$

$\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{37}\text{Cl}$

$\delta^{18}\text{O}$, $\delta^{34}\text{S}$

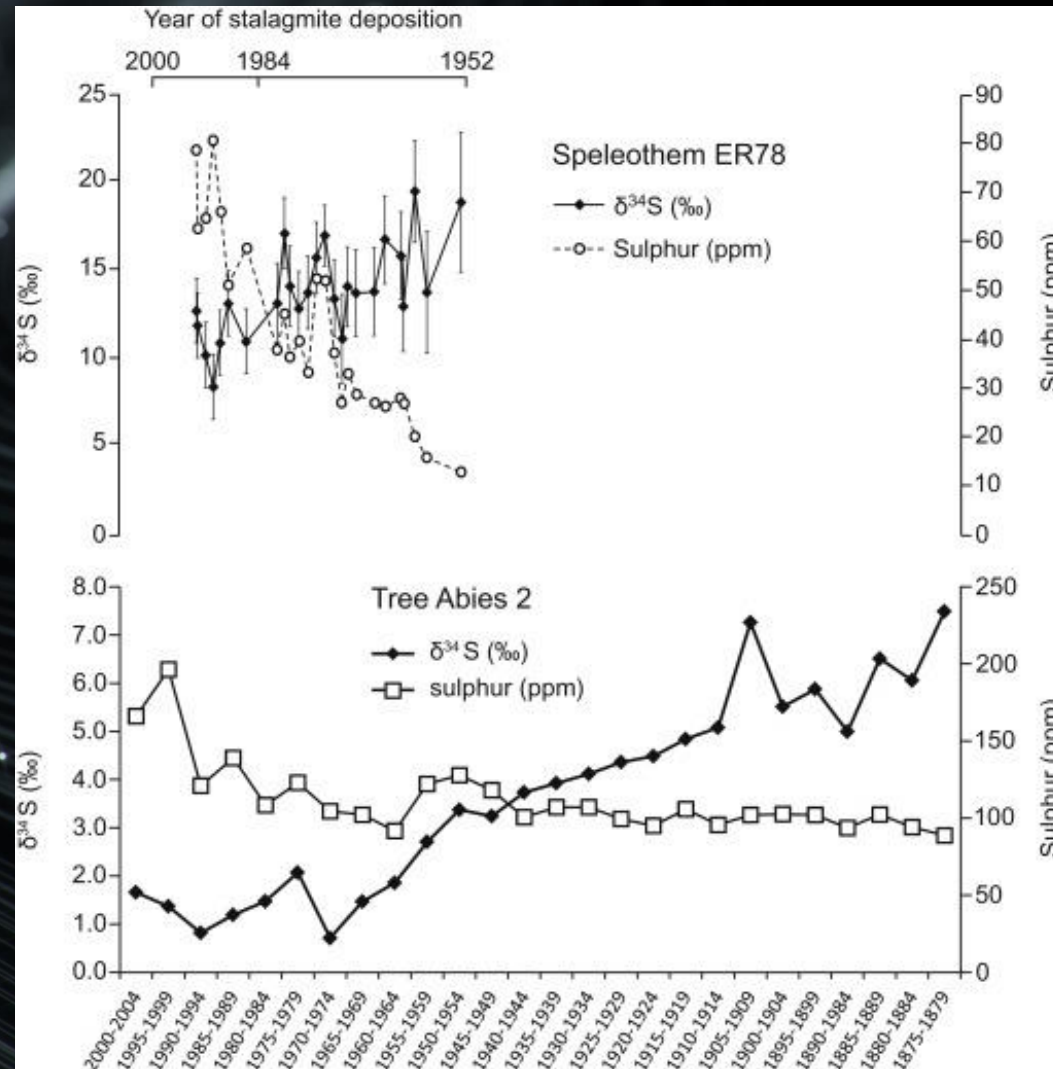
- Pollution with Pb compounds
- Pollution with nitrates
- Coal combustion emissions
- Particulate pollution
- Pollution with organic compounds
- Pollution with sulfur compounds

Environmental paleoreconstruction

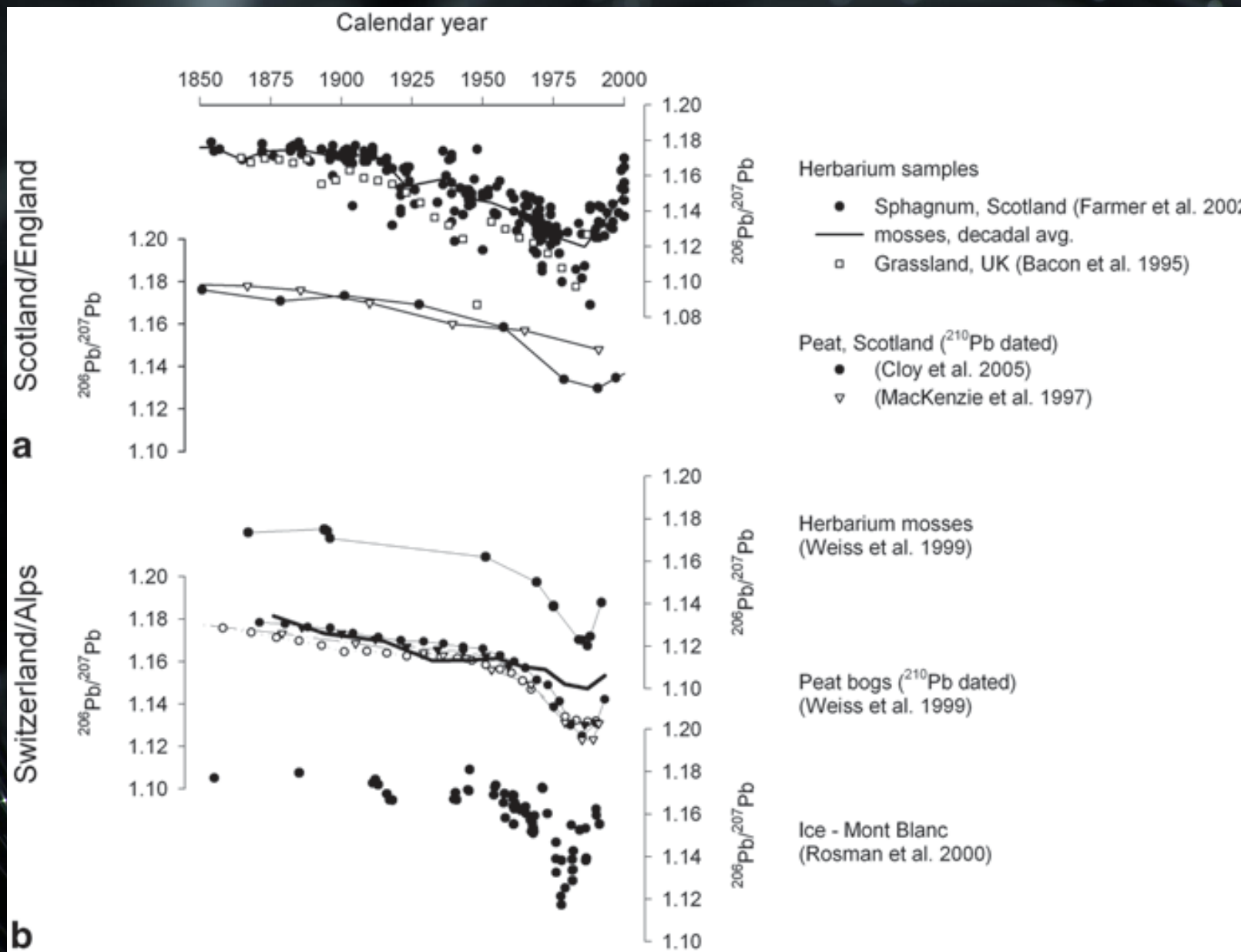


Wynn, P. M., Fairchild, I. J., Baker, A., Baldini, J. U., McDermott, F. (2008). Isotopic archives of sulphate in speleothems. *Geochimica et Cosmochimica Acta*, 72(10), 2465-2477.

Records of sulfur loading to speleothem ER78 and tree ring archives (fir) of environmental change collected from Ernesto cave in NE Italy

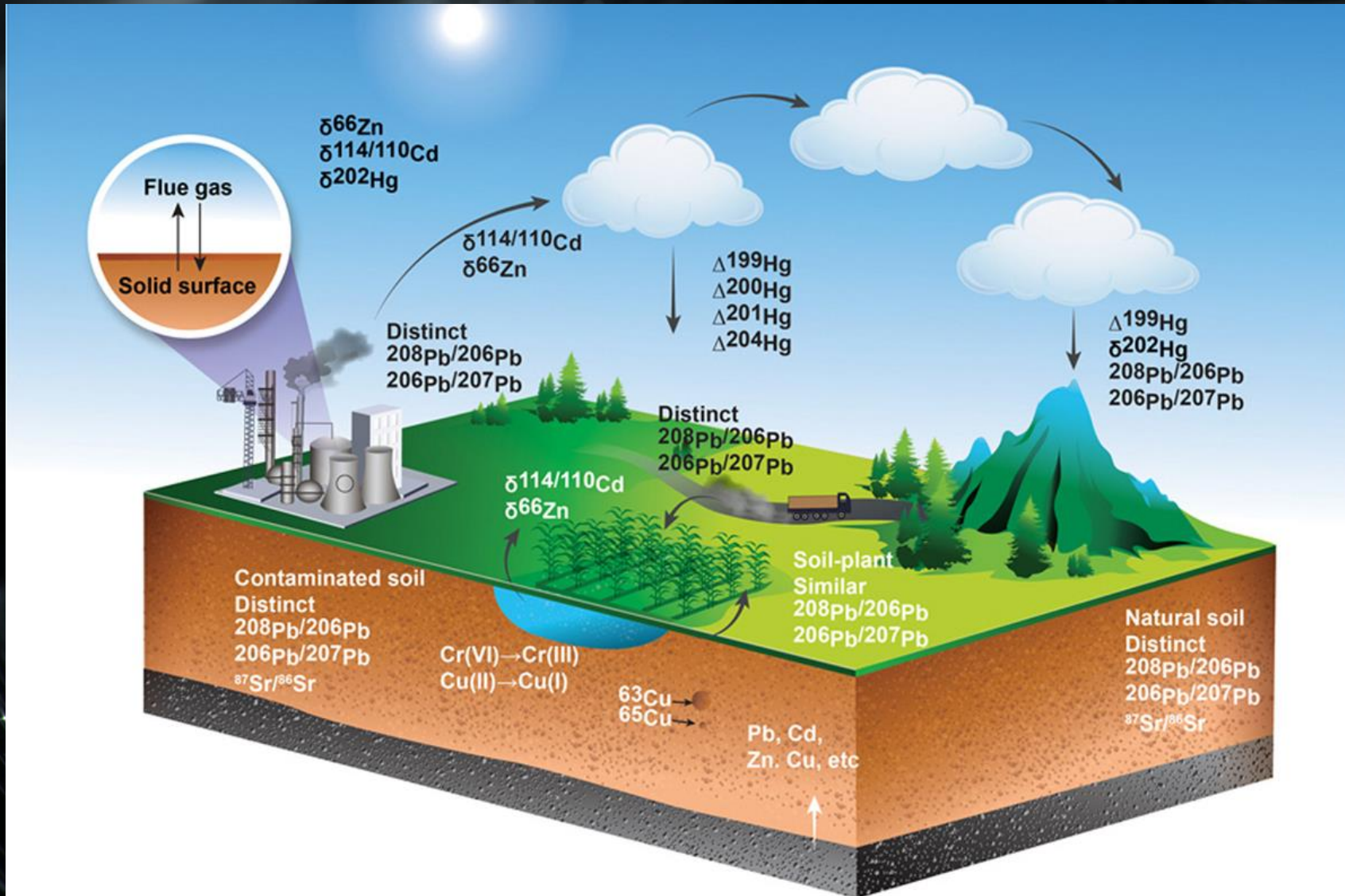


Wynn, P. M., Loader, N. J., Fairchild, I. J. (2014). Interrogating trees for isotopic archives of atmospheric sulphur deposition and comparison to speleothem records. *Environmental Pollution*, 187, 98-105.



Hansson, S. V., Bindler, R., De Vleeschouwer, F. (2015). Using peat records as natural archives of past atmospheric metal deposition. In *Environmental Contaminants* (pp. 323-354). Springer, Dordrecht.

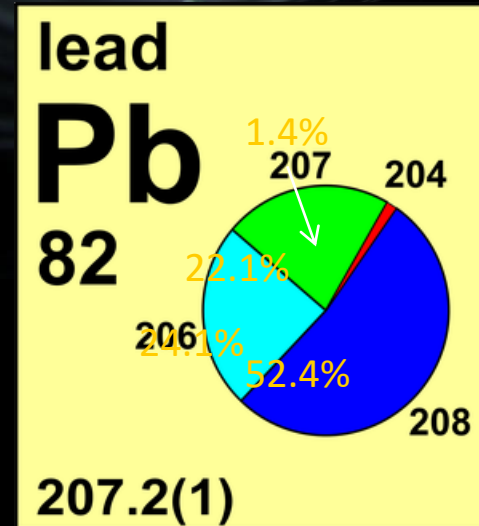
Identification of metal sources in soils



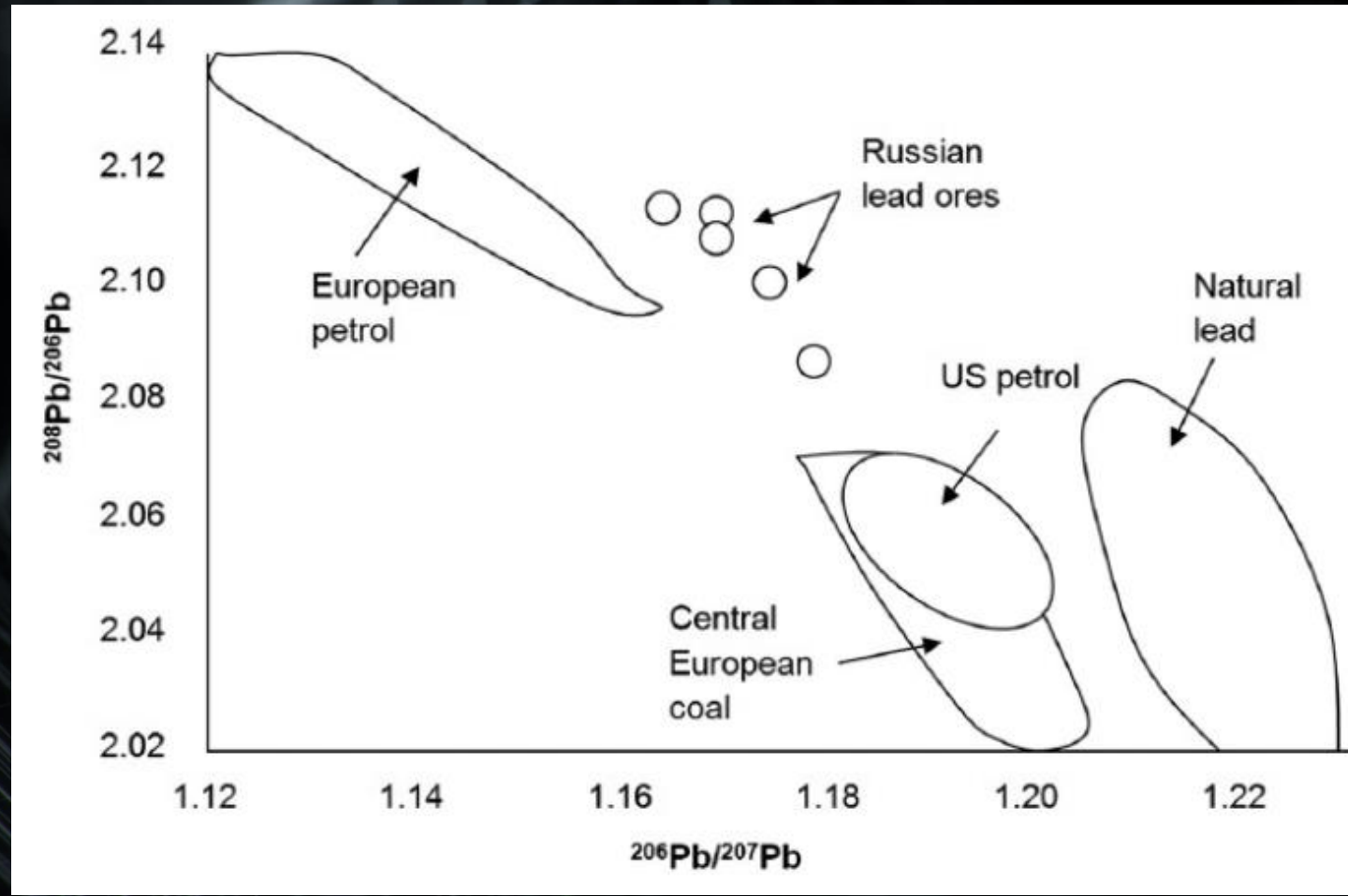
Wang, L., Jin, Y., Weiss, D. J., Schleicher, N. J., Wilcke, W., Wu, L., ... & Hou, D. (2021). Possible application of stable isotope compositions for the identification of metal sources in soil. *Journal of Hazardous Materials*, 407, 124812.

Lead stable isotopes

- Lead stable isotope ratios are widely used for apportionment of pollution sources and for tracking pollution pathways in the environment because, as opposed to isotopes of copper and zinc, they do not undergo fractionation
- The values of $^{206}\text{Pb}/^{207}\text{Pb}$ ratio in lead emitted from anthropogenic sources are in the range of 1.15-1.19 whereas in lead from natural sources, the $^{206}\text{Pb}/^{207}\text{Pb}$ ratio is approximately 1.5
- Higher Pb concentrations in natural archives are accompanied by a decrease in $^{206}\text{Pb}/^{207}\text{Pb}$ ratio



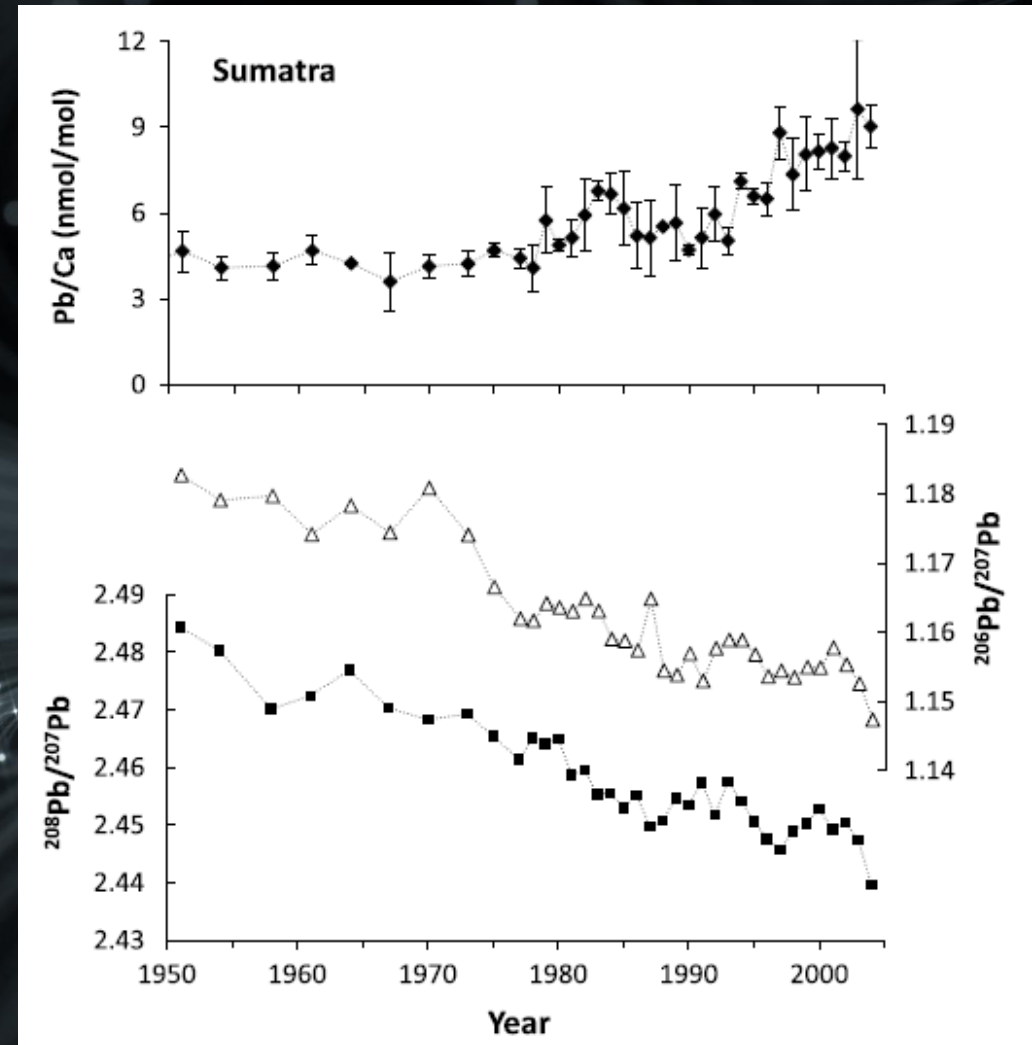
A $^{206}\text{Pb}/^{207}\text{Pb}$ versus $^{208}\text{Pb}/^{206}\text{Pb}$ plot showing the different isotopic compositions of selected lead sources



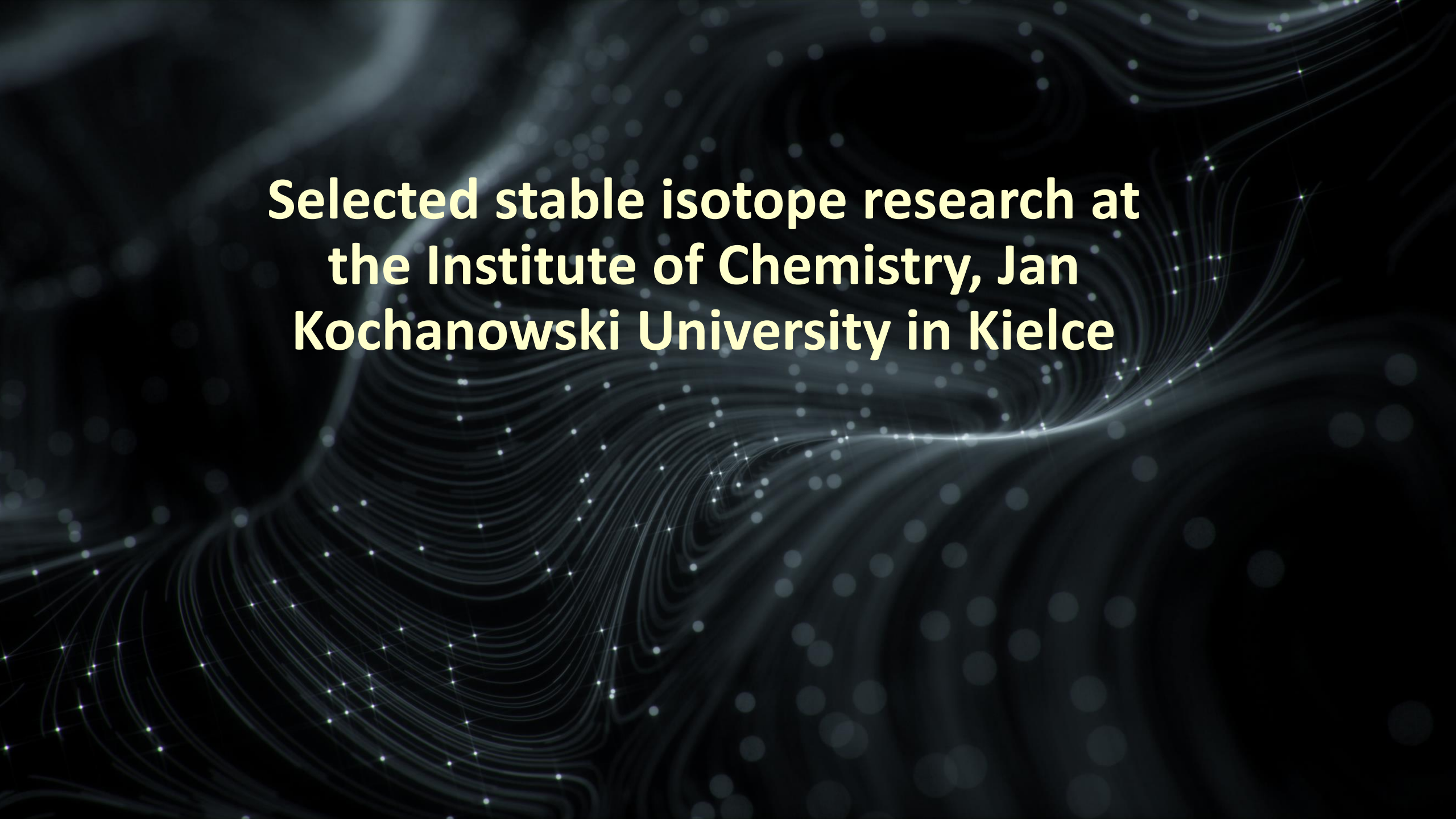
Dean, J. R., Leng, M. J., & Mackay, A. W. (2014). Is there an isotopic signature of the Anthropocene?. *The Anthropocene Review*, 1(3), 276-287.

Pb/Ca ratios and Pb stable isotopes in corals from western Sumatra

Significant Pb contamination started in the western Sumatra region around the mid-1970s given the increasing Pb/Ca ratios and decreasing $^{206}/^{207}\text{Pb}$ and $^{208}/^{207}\text{Pb}$ ratios around that time

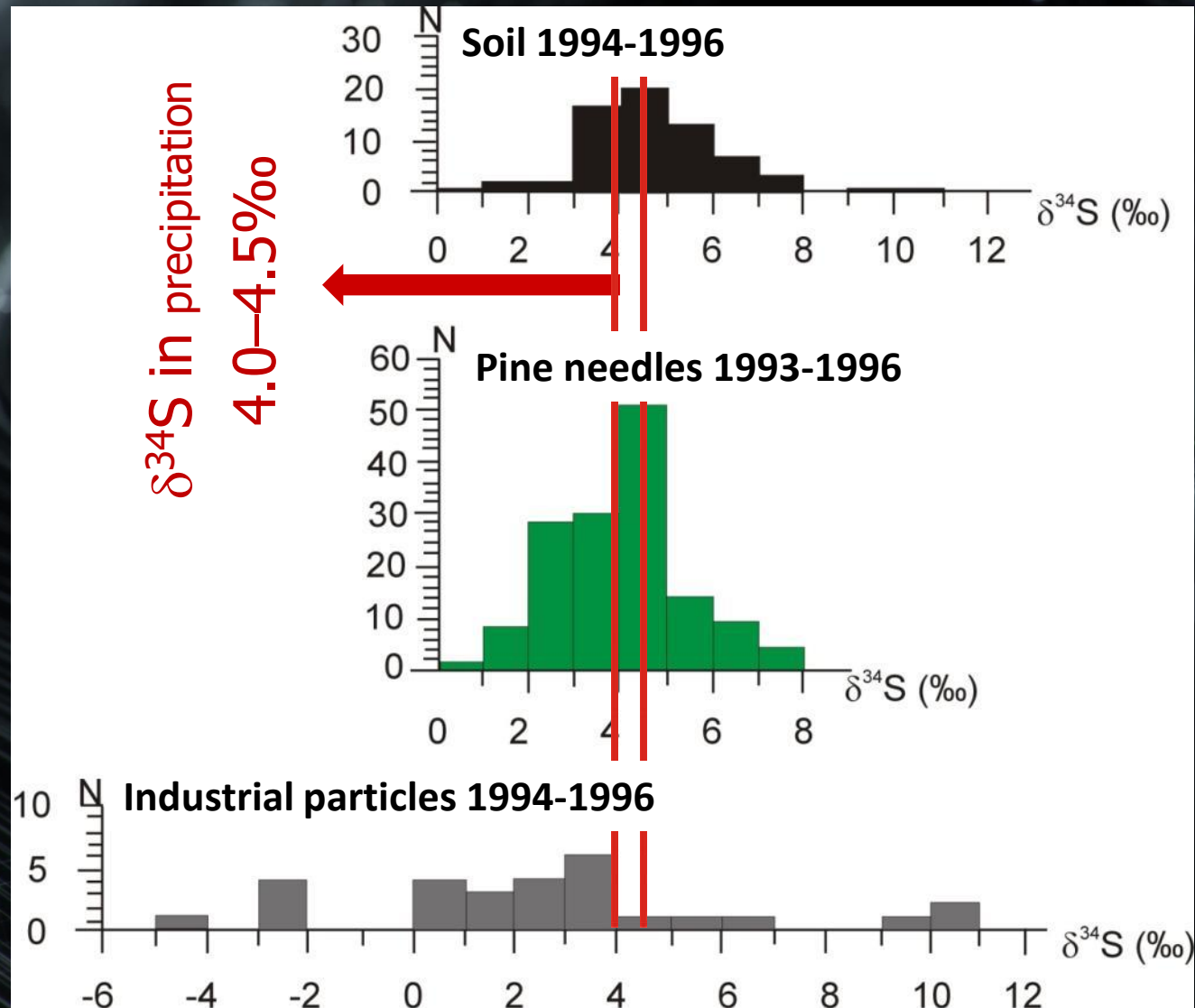


Time series of Pb/Ca (\blacklozenge), $^{206}/^{207}\text{Pb}$ (\triangle), and $^{208}/^{207}\text{Pb}$ (\blacksquare) ratios in the western Sumatra coral

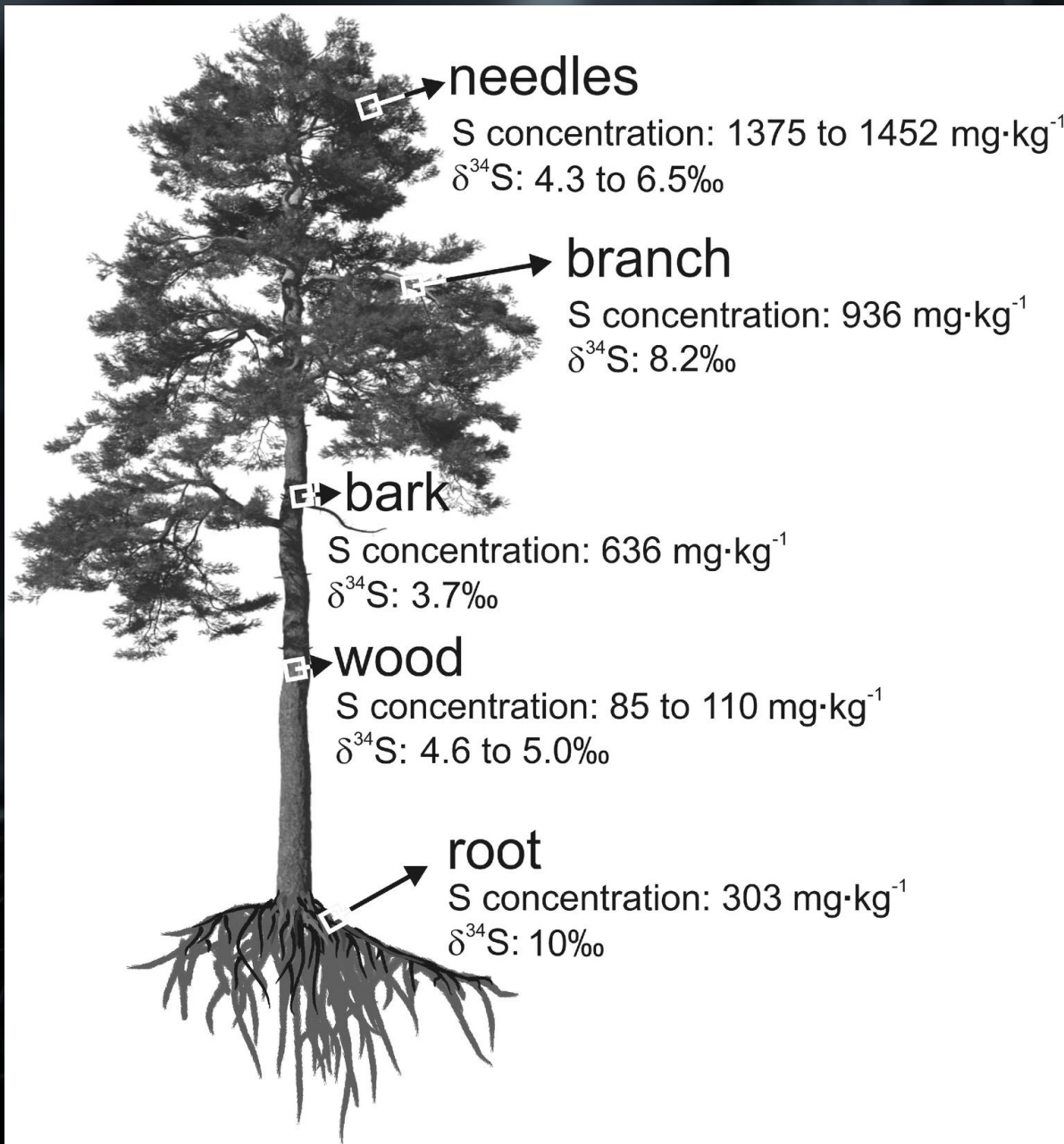


**Selected stable isotope research at
the Institute of Chemistry, Jan
Kochanowski University in Kielce**

Anthropogenic impact assessment: isotopic fingerprint



Migaszewski, Z. M., & Pałowski, P. (1996). Trace element and sulphur stable isotope ratios in soils and vegetation of the Holy Cross Mountains. *Geological Quarterly*, 40(4), 575-594.



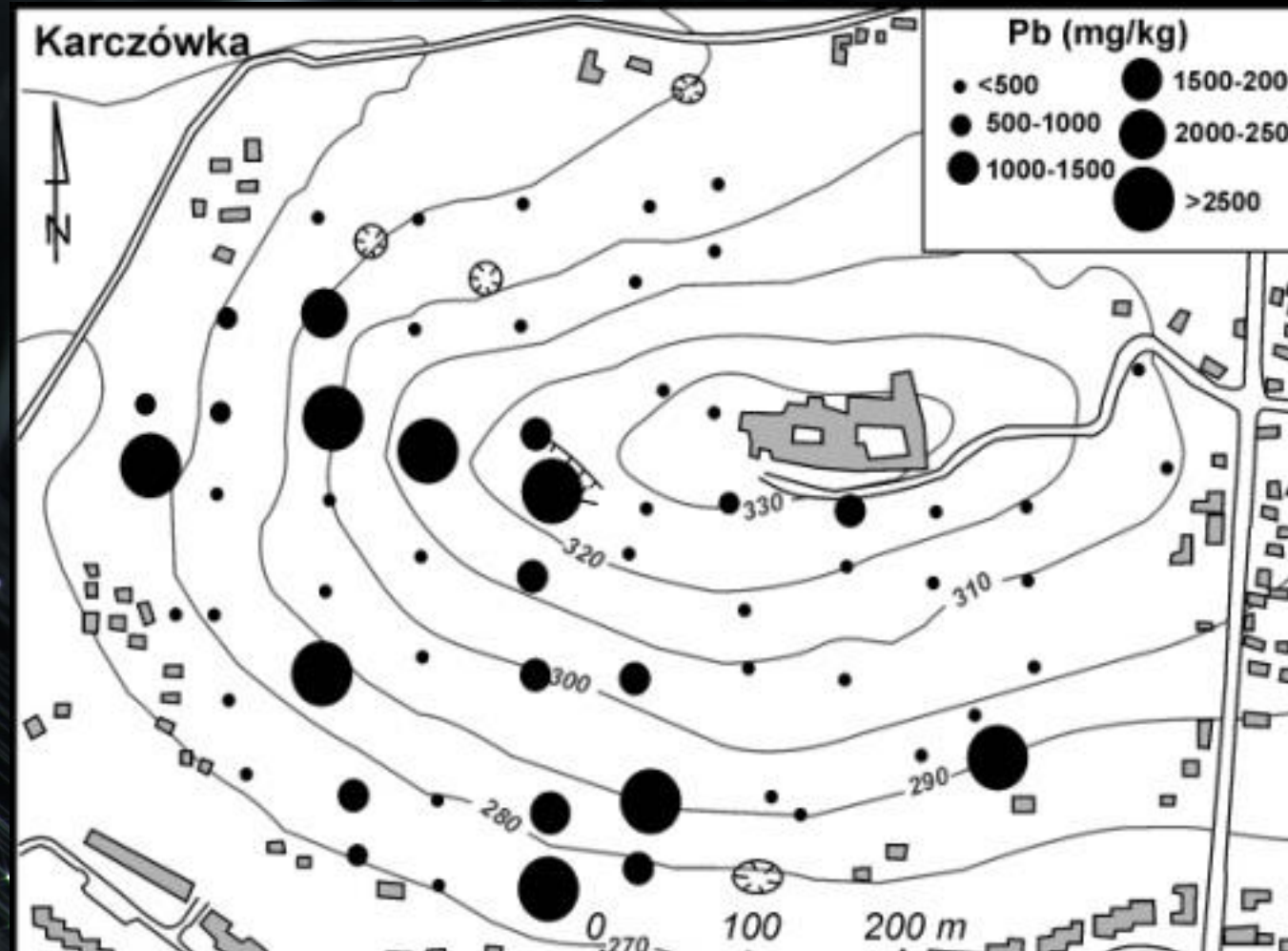
Concentrations of sulfur and $\delta^{34}\text{S}$ values in different samples from a single Scots pine (*P. sylvestris*) tree

Dołęgowska, S., Gałuszka, A., & Migaszewski, Z. M. (2021). Significance of the long-term biomonitoring studies for understanding the impact of pollutants on the environment based on a synthesis of 25-year biomonitoring in the Holy Cross Mountains, Poland. *Environmental Science and Pollution Research*, 28, 10413-10435.

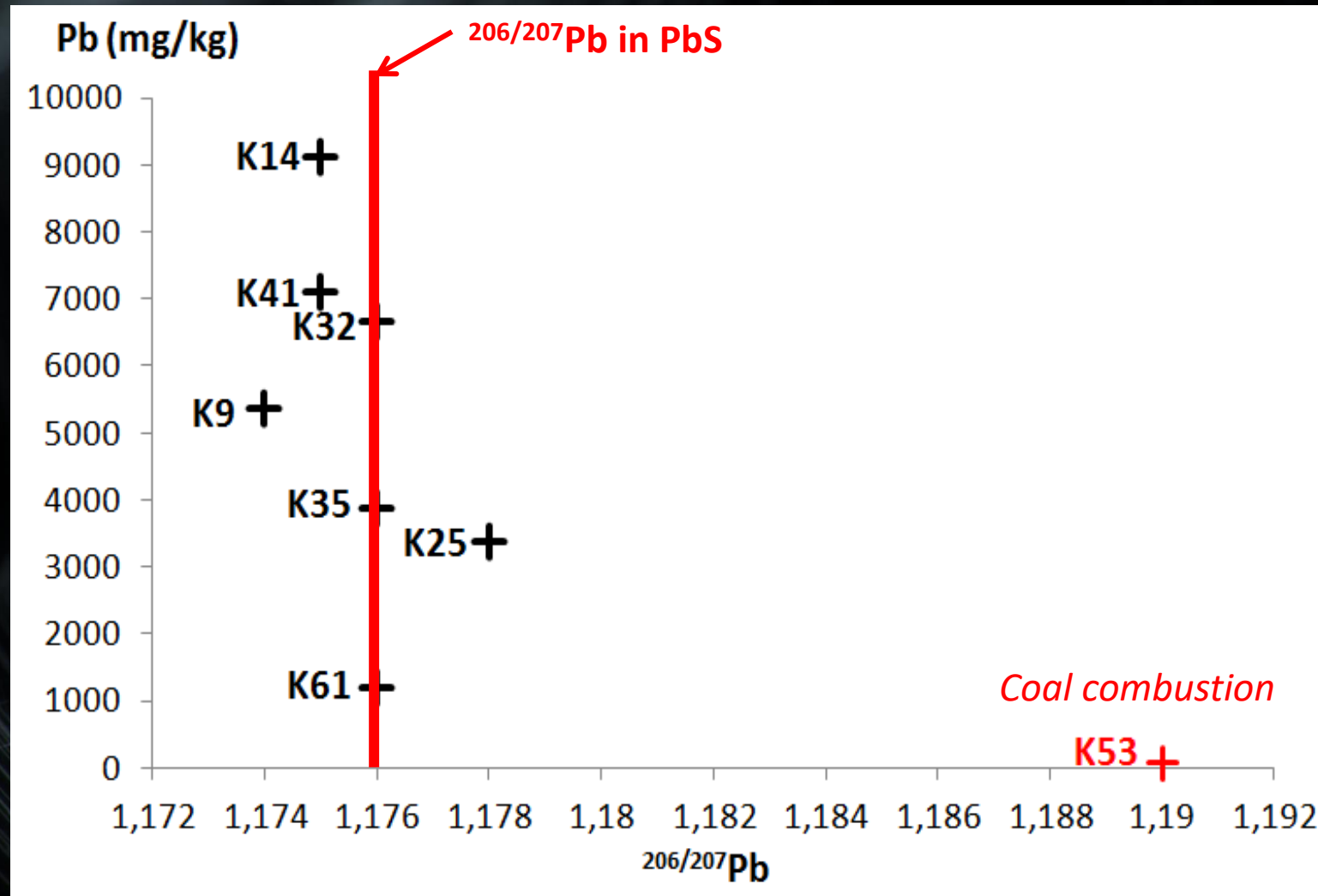
Lead isotopes of galena (PbS) in historic mining site in Kielce



Pb concentrations in soil: 41-9114 mg/kg (mean value of 1027 mg/kg)

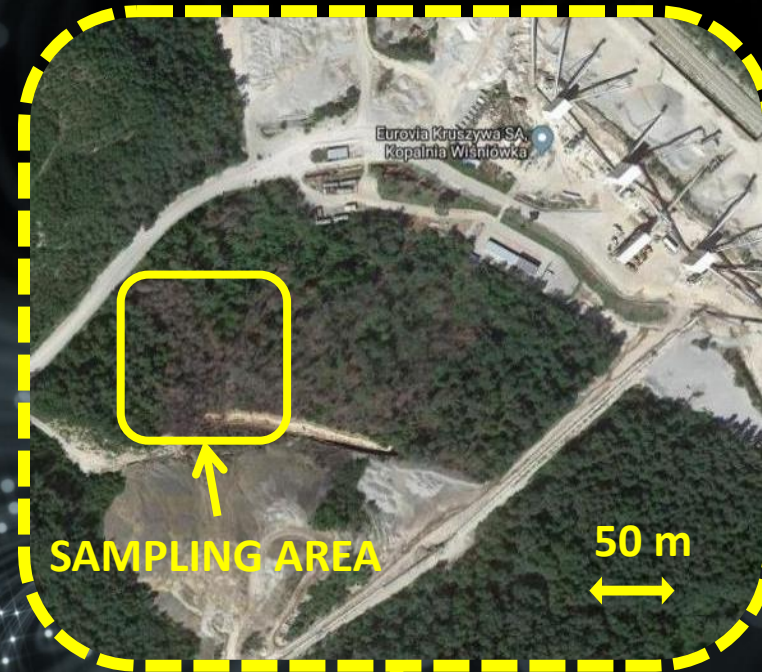


Lead concentration in soil vs. $^{206}/^{207}\text{Pb}$



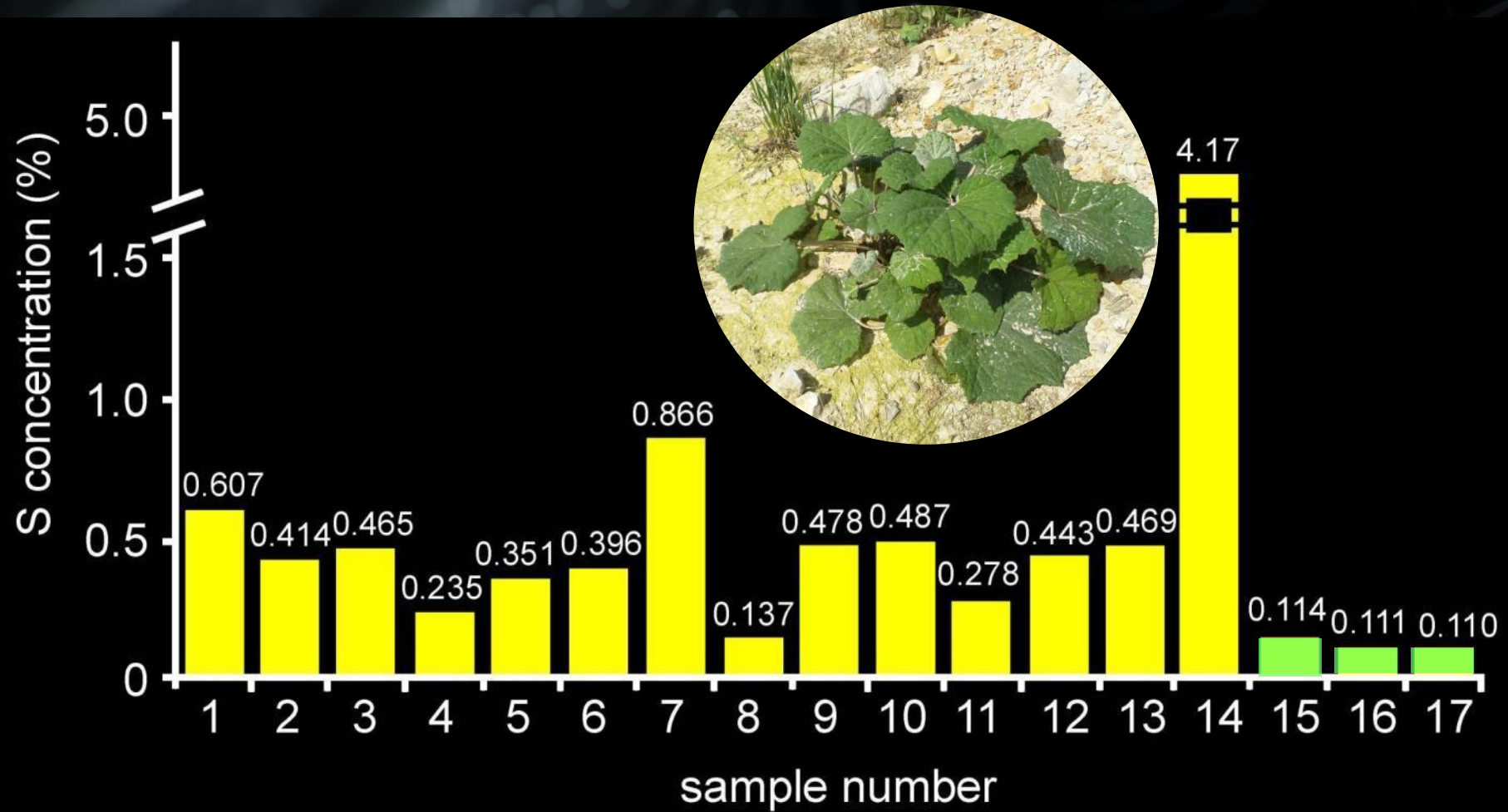
Gałaszka, A., Migaszewski, Z. M., Dołęgowska, S., & Michalik, A. (2018). Geochemical anomalies of trace elements in unremediated soils of Mt. Karczówka, a historic lead mining area in the city of Kielce, Poland. *Science of the total environment*, 639, 397-405.

Sulfur isotopes in plants



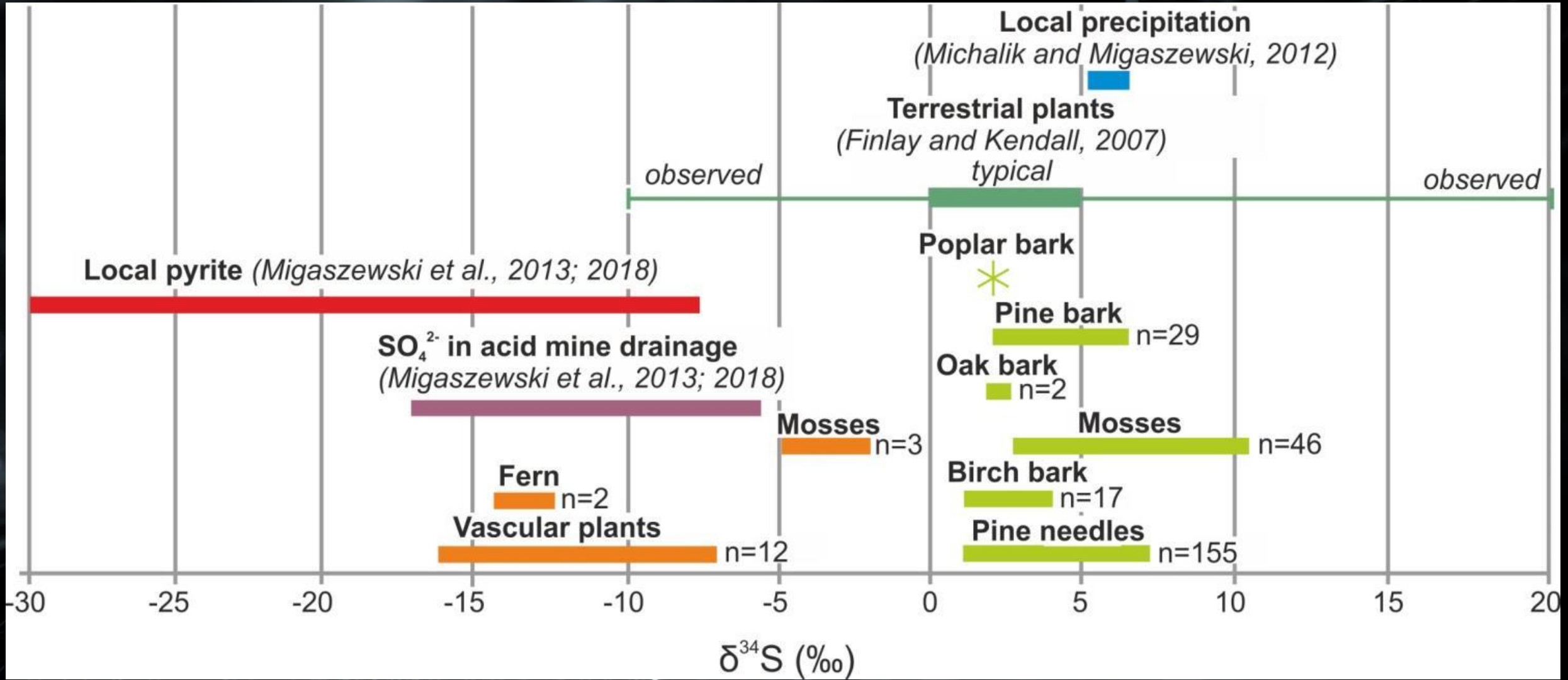
Sample no.	Plant species	Sample no.	Plant species
1	<i>Pteridium aquilinum</i> 	10	<i>Juncus effusus</i>
2	<i>Betula pendula</i>	11	<i>Quercus petraea</i>
3	<i>Salix cinerea</i>	12	<i>Chamaenerion angustifolium</i>
4	<i>Sorbus aucuparia</i>	13	<i>Oxalis acetosella</i>
5	<i>Pteridium aquilinum</i> 	14	<i>Tussilago farfara</i>
6	<i>Populus tremula</i>	15	<i>Drepanocladus aduncus</i> 
7	<i>Vaccinium myrtillus</i>	16	<i>Mnium affine</i> 
8	<i>Pinus sylvestris</i>	17	<i>Pleurozium schreberi</i> 
9	<i>Frangula alnus</i>		

Sulfur in plant samples



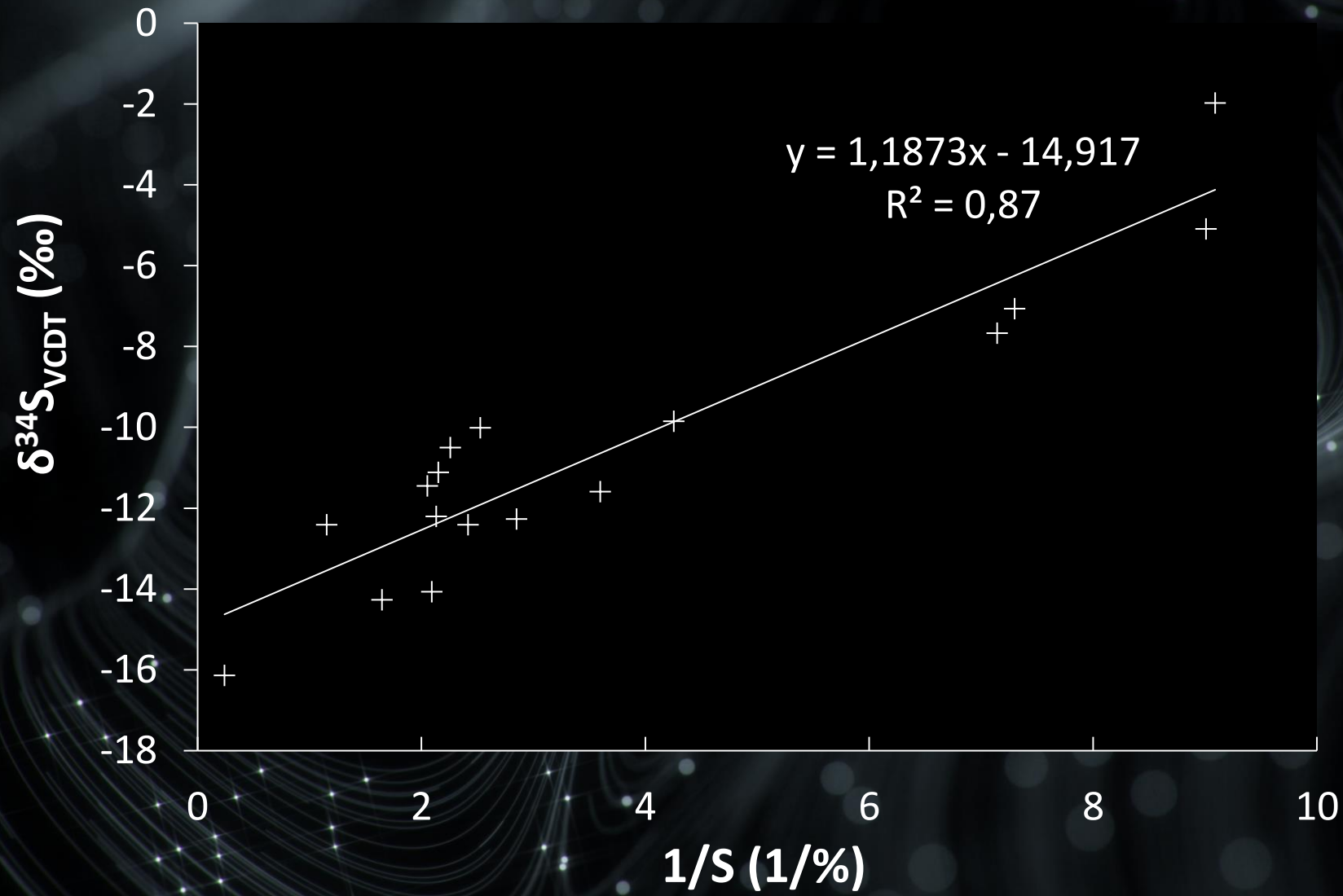
Gałaszka, A., Migaszewski, Z. M., Pelc, A., Trembaczowski, A., Dołęgowska, S., & Michalik, A. (2020). Trace elements and stable sulfur isotopes in plants of acid mine drainage area: Implications for revegetation of degraded land. *Journal of Environmental Sciences*, 94, 128-136.

Stable sulfur isotopes in the Holy Cross Mts.

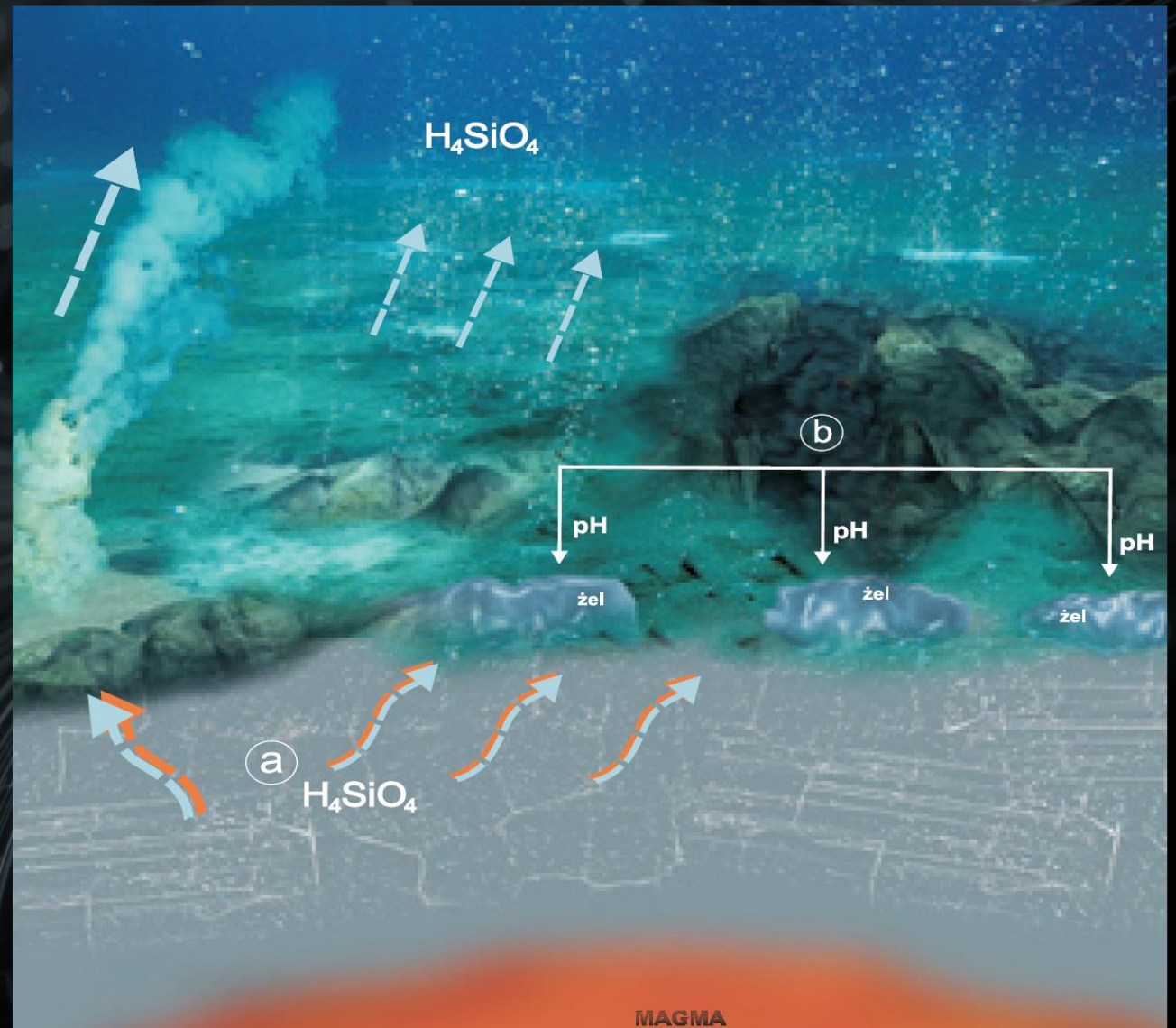


Gałaszka, A., Migaszewski, Z. M., Pelc, A., Trembaczowski, A., Dołęgowska, S., & Michalik, A. (2020). Trace elements and stable sulfur isotopes in plants of acid mine drainage area: Implications for revegetation of degraded land. *Journal of Environmental Sciences*, 94, 128-136.

Variation in $\delta^{34}\text{S}$ versus reciprocal S concentrations in plant samples



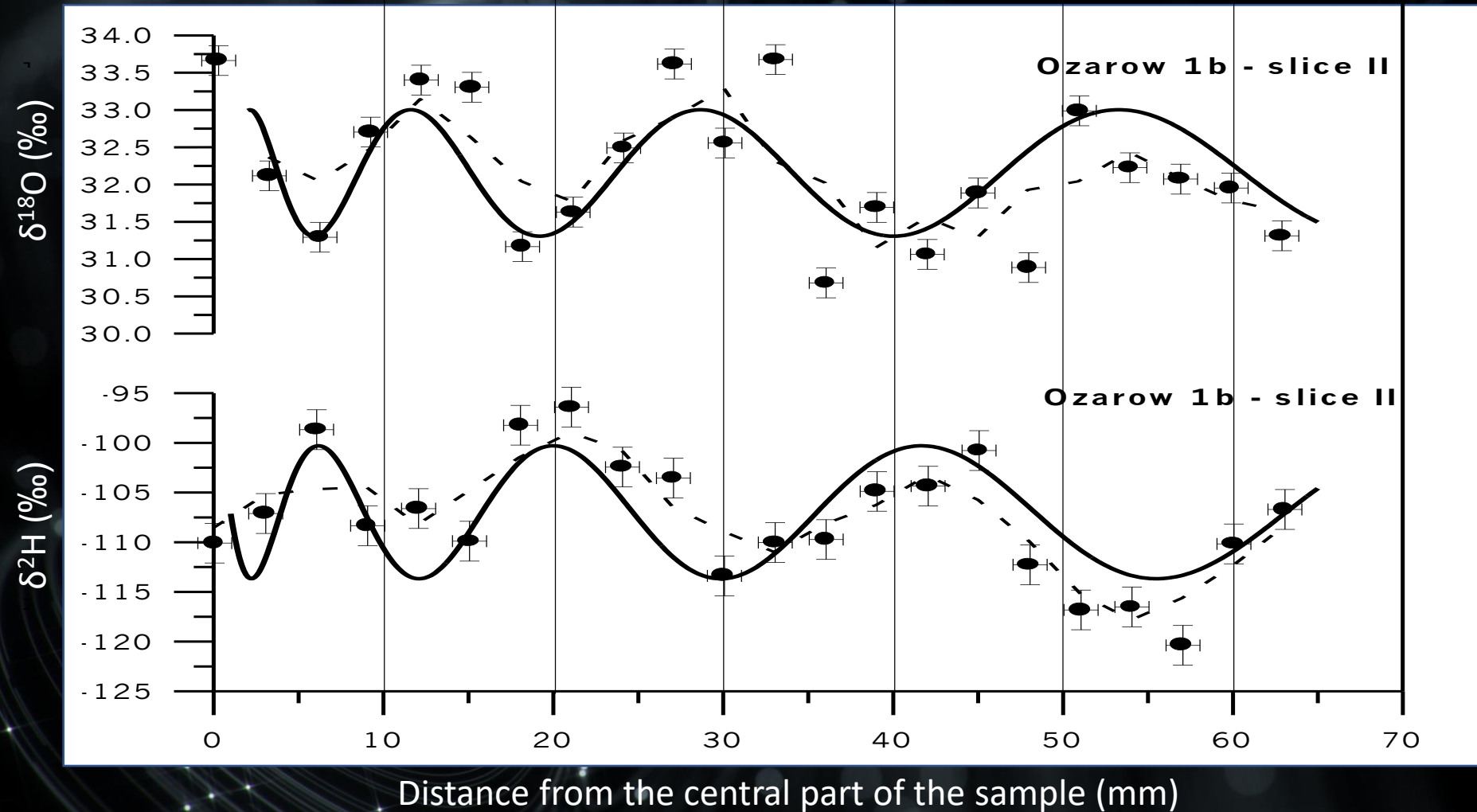
Striped chert genesis



Król, P., & Migaszewski, Z. M. (2009). Rodzaje, występowanie i geneza krzemieni. Zarys problematyki. *Historia krzemienia*, Muzeum Narodowe w Kielcach.

Migaszewski, Z. M., Gałuszka, A., Dürakiewicz, T., & Starnawska, E. (2006). Middle Oxfordian–Lower Kimmeridgian chert nodules in the Holy Cross Mountains, south-central Poland. *Sedimentary Geology*, 187(1-2), 11-28.

Results of stable oxygen and hydrogen isotope determinations in striped chert from Ożarów



Sharp, Z. D., Durakiewicz, T., Migaszewski, Z. M., & Atudorei, V. N. (2002). Antiphase hydrogen and oxygen isotope periodicity in chert nodules. *Geochimica et Cosmochimica Acta*, 66(16), 2865-2873.

In memory of late Professor Stanisław Hałas

