XRF Penetration depth

How Deep Can You Measure?

Depth of measurement varies based on two properties: the energy of the element and the density of the matrix. As each photon is emitted as a K or L shell line, the spectral peaks resulting from such fluorescence can be thought of as atom counts of sorts - though the quantity of photons is determined by both the voltage of the tube and the depth of penetration. The depth of penetration can be calculated by the following equation:

$$I/I0 = e[-(\mu/\rho)x] \quad (1)$$

where I is the quantity of photons returning from the sample, I_0 is the quantity of photons entering the sample, μ/ρ represents the mass attenuation coefficient of a given element for a particular matrix, and x represents the density of the object. You can find mass attenuation coefficients at NIST.gov. Assuming a limit of 1% returning photons from a silicate matrix, the depths of analysis can be approximated by the following formula:

$$d(cm) = 4.36/(-\mu/\rho)\rho \quad (2)$$

where d(cm) is the depth in centimeters. Thus, you only need two variables to calculate the depth of a given photon’s energy in a given matrix. You can obtain mass attenuation coefficients ($-\mu/\rho$) from the NIST website. Just click the link, put in the chemical formula, select ‘Mass Attenuation Coefficient (cm^2/g) vs E (keV) Graph’ as the Type of Data, and choose an appropriate energy range Sub-Range - I usually just do 1 - 40 keV but you can choose whatever range you like. You will then receive the mass attenuation coefficients in a small table to the lower right of the page. Then you need a density estimate for the sample. For water this would be 1 $g\text{-}cm^{-3}$, for a silicate it would be 2.648 $g\text{-}cm^{-3}$. Copy these data and use equation (2) to obtain a list of estimated measurement depth for each element:

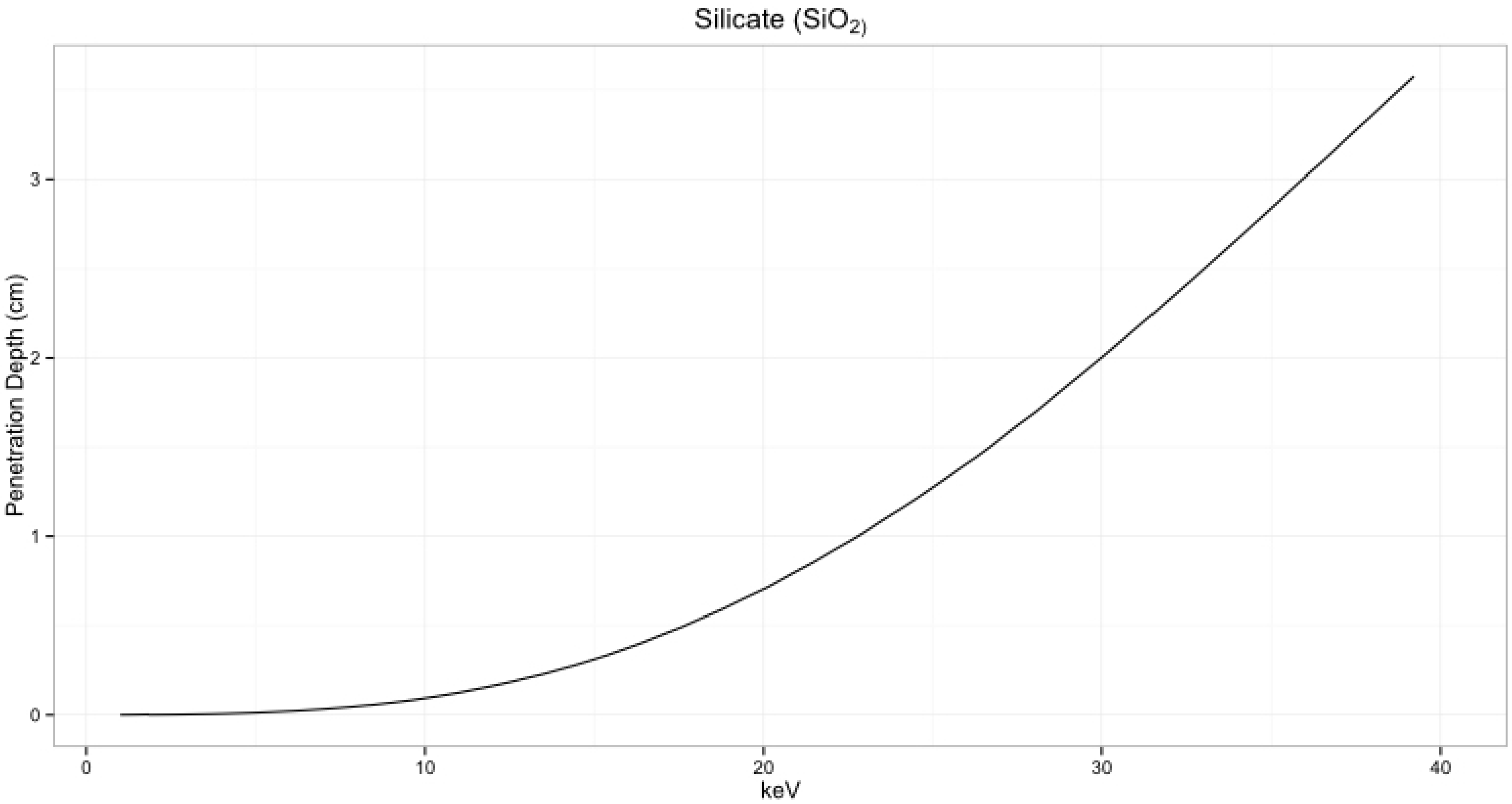
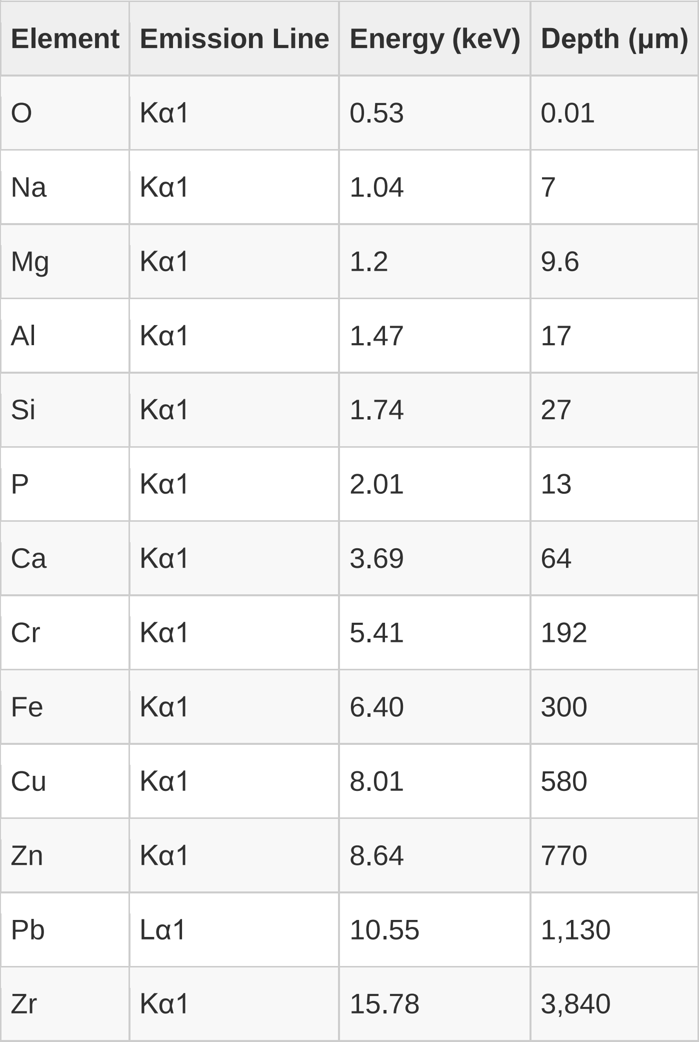


Figure 1: Depth of measurement in a pure silicate

Elements that fluoresce with low energy, such as silica at 1.7 keV, will only return photons from 20 µm deep into a SiO_2 matrix, while elements that fluoresce at higher energies, such as Zirconium at 15.77 keV, will return photons from as deep as 3.4 mm. As a consequence, elements with higher energies of fluorescence will be more easily identified in smaller concentrations. As energy in x ray tubes is non evenly distributed, there is a further discrimination against the fluorescence of elements on the extreme ends of an energy spectrum (near 1 and 40 keV). Furthermore, the fluorescence of one element can influence that of another. A high concentration of Zinc, with a K-alpha fluorescence of 8.78 keV, sits on the absorption edge of Copper, with a K-alpha fluorescence of 8.01 keV. A high concentration of Zinc will distort the quantity of Copper present in the spectra.

It may be more intuitive to think about this in terms of a table:



Element	Emission Line	Energy (keV)	Depth (μm)
O	Kα1	0.53	0.01
Na	Kα1	1.04	7
Mg	Kα1	1.2	9.6
Al	Kα1	1.47	17
Si	Kα1	1.74	27
P	Kα1	2.01	13
Ca	Kα1	3.69	64
Cr	Kα1	5.41	192
Fe	Kα1	6.40	300
Cu	Kα1	8.01	580
Zn	Kα1	8.64	770
Pb	Lα1	10.55	1,130
Zr	Kα1	15.78	3,840

Table 1: Depth of select elements in a silicate

However, density is important too. The same physical relationship is present between elements in a denser matrix, however the total depth is considerably shorter:

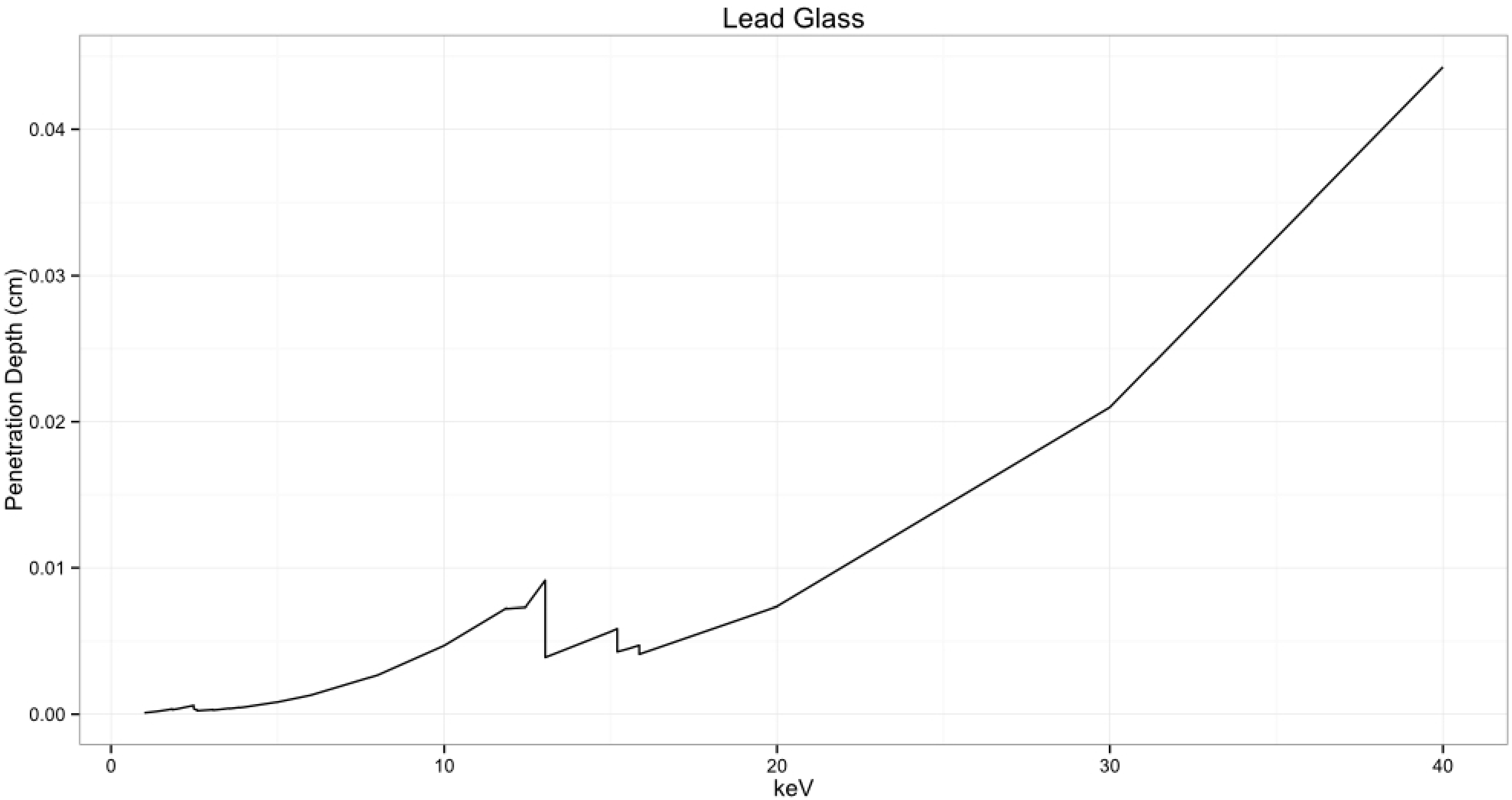
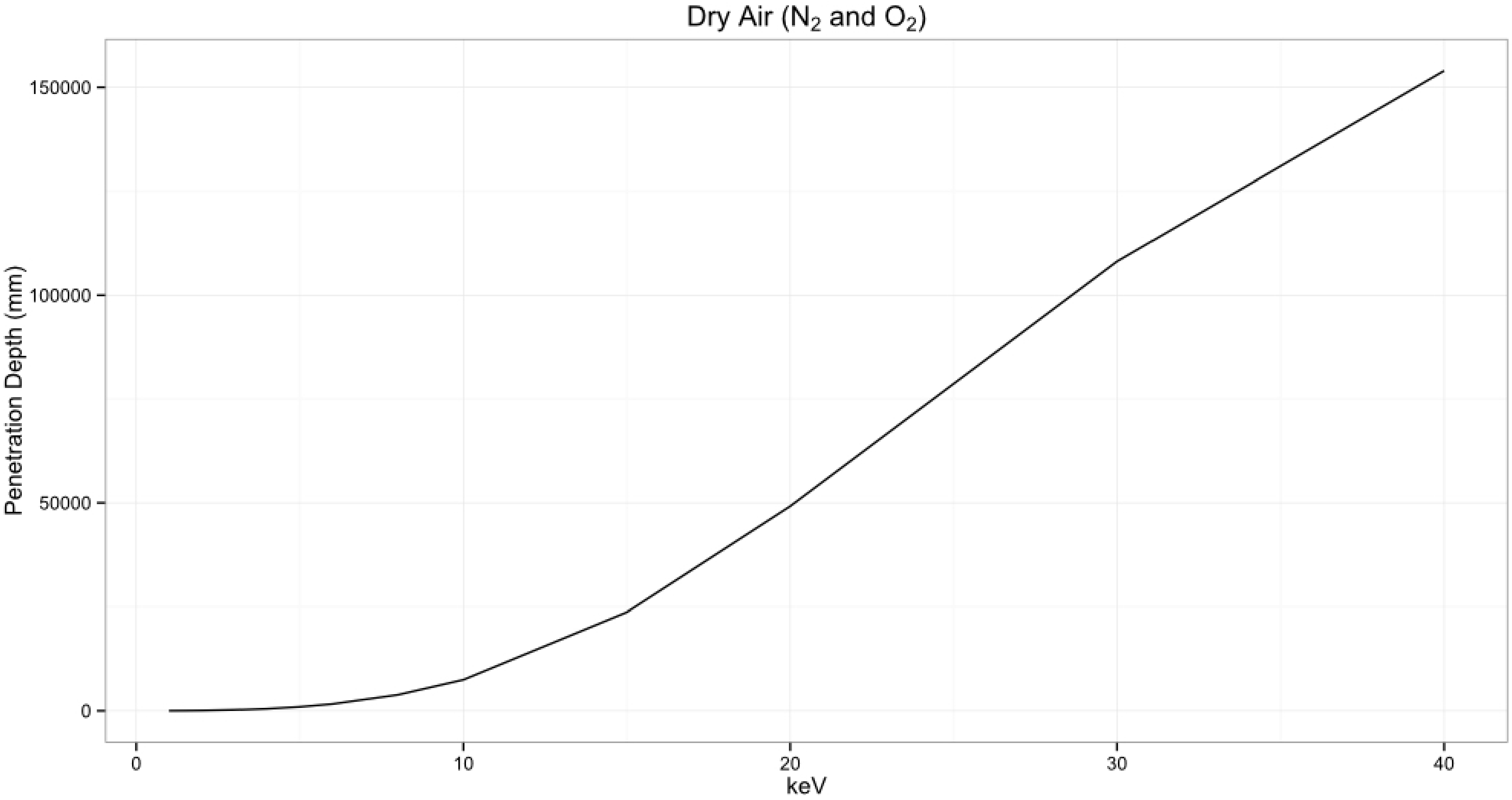
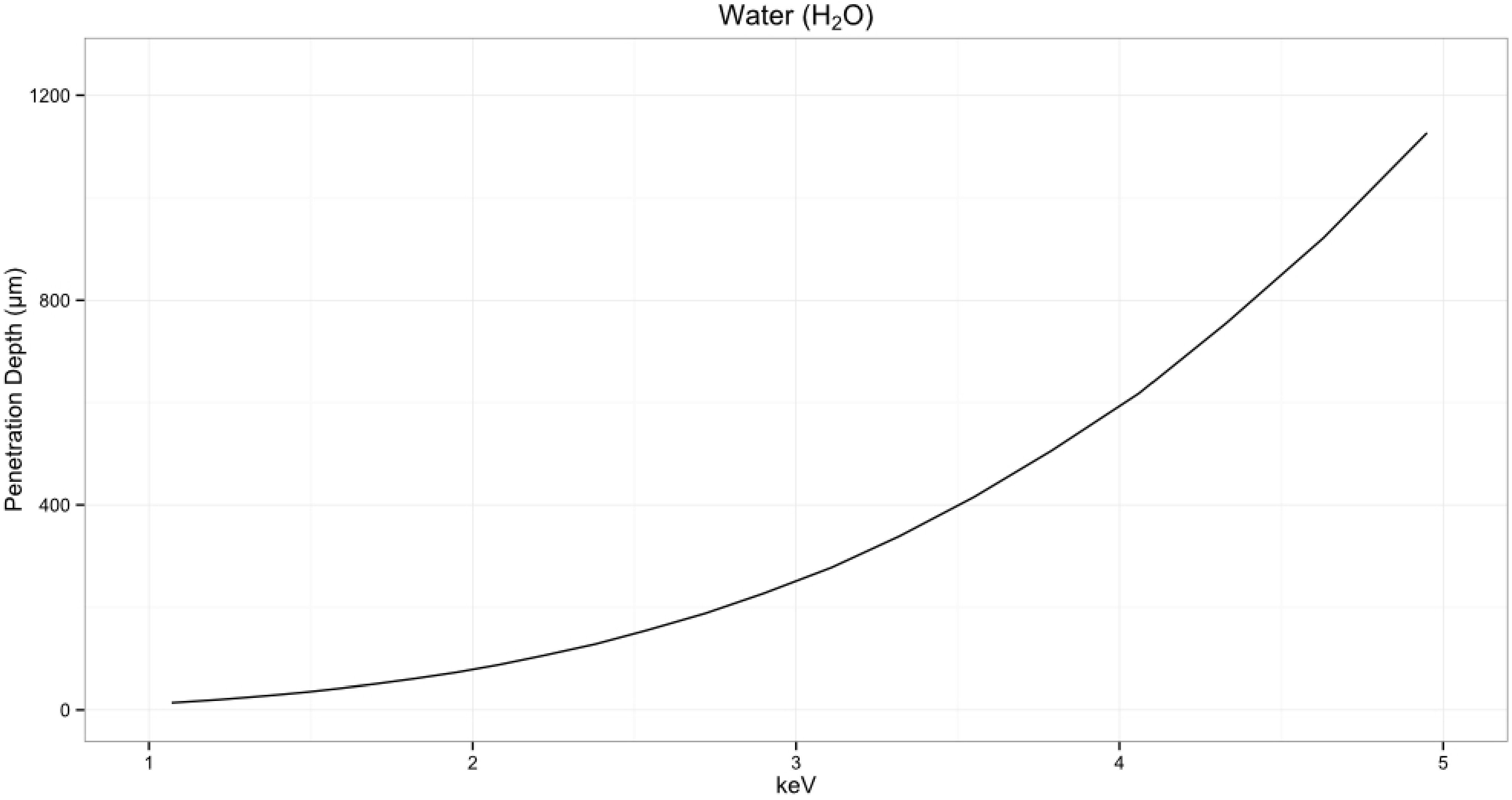


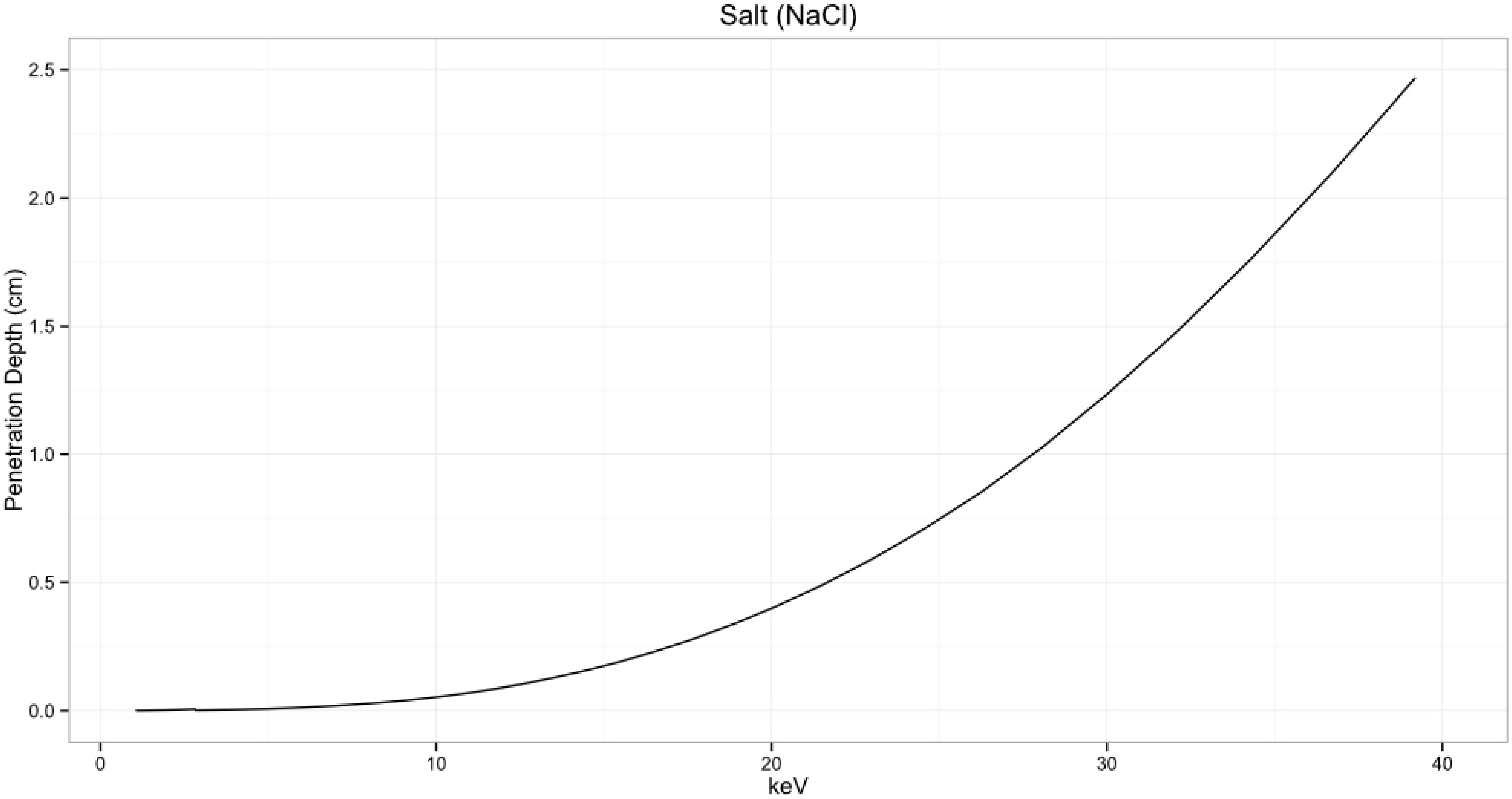
Figure 2: Depth of measurement in a lead glass.

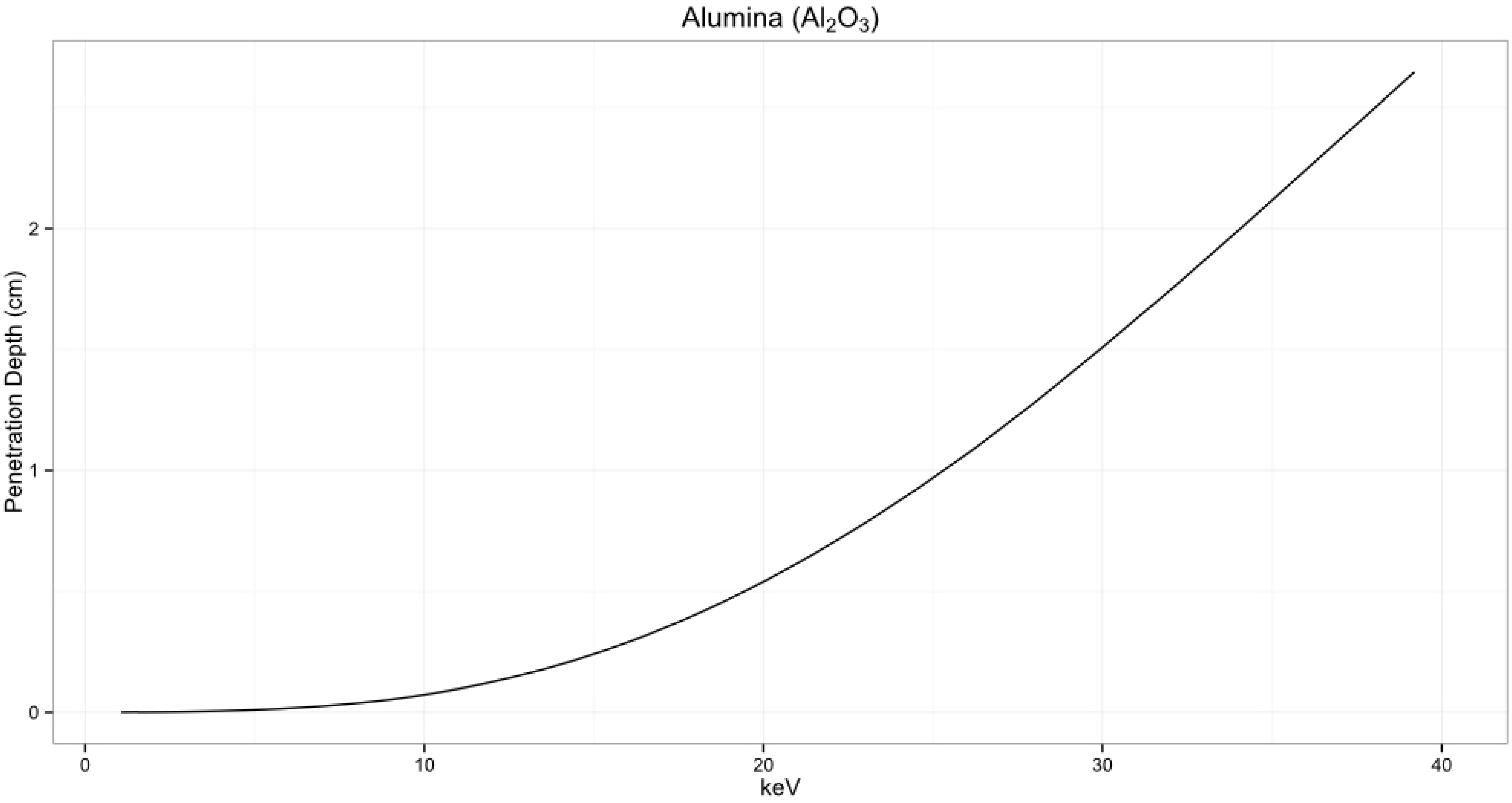
You can see how this can vary by matrix to matrix. I am including a number of examples of measurement depth in different matrices below. The first section will be for common substrates, biological materials, historical pigments, metals, and plastics.

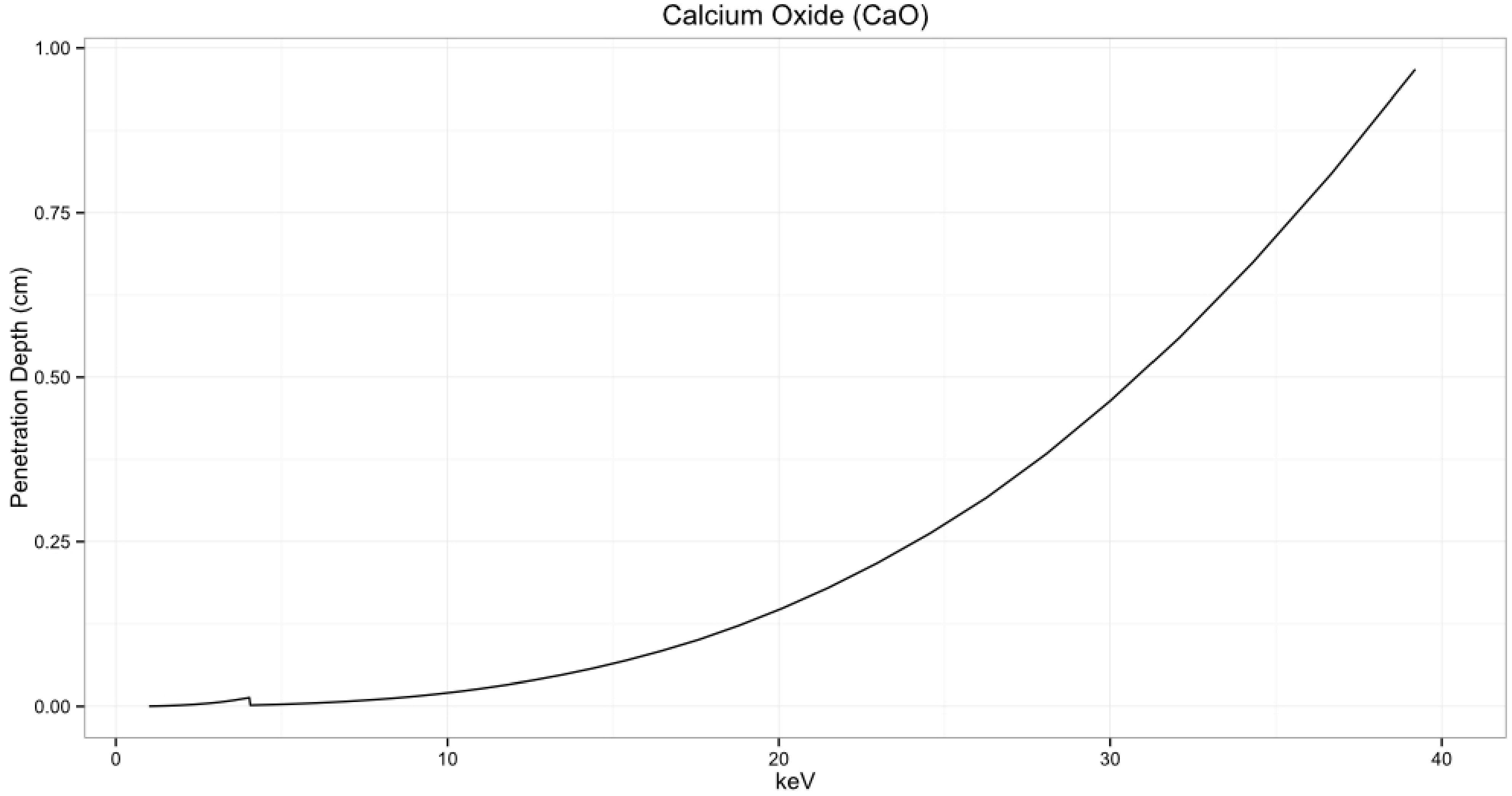
Common Substrates

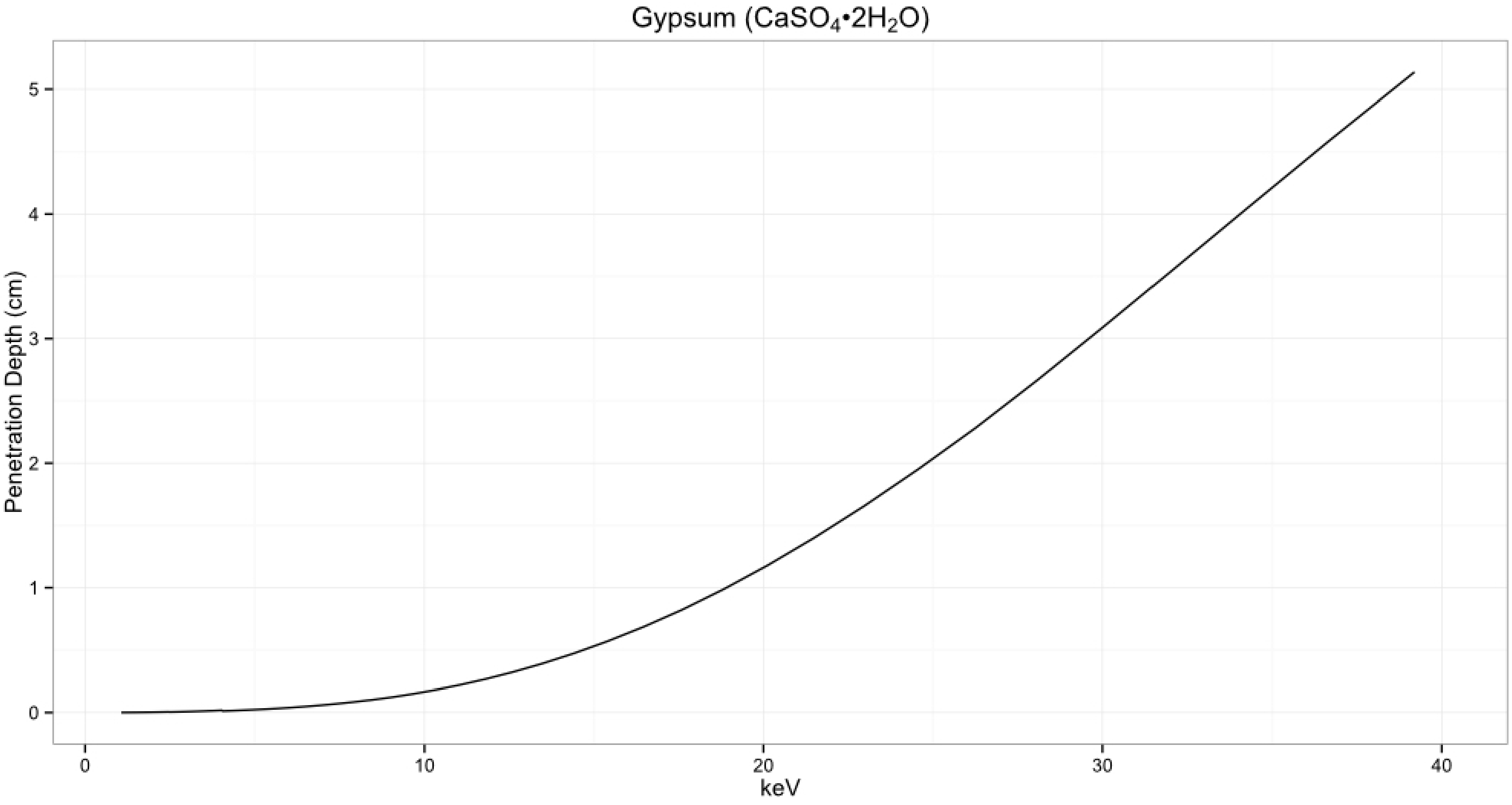



Water (H_2O)
Penetration Depth (µm)
1200
800
400
0
1
2
3
4
5
keV


Salt (NaCl)
Penetration Depth (cm)
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
keV

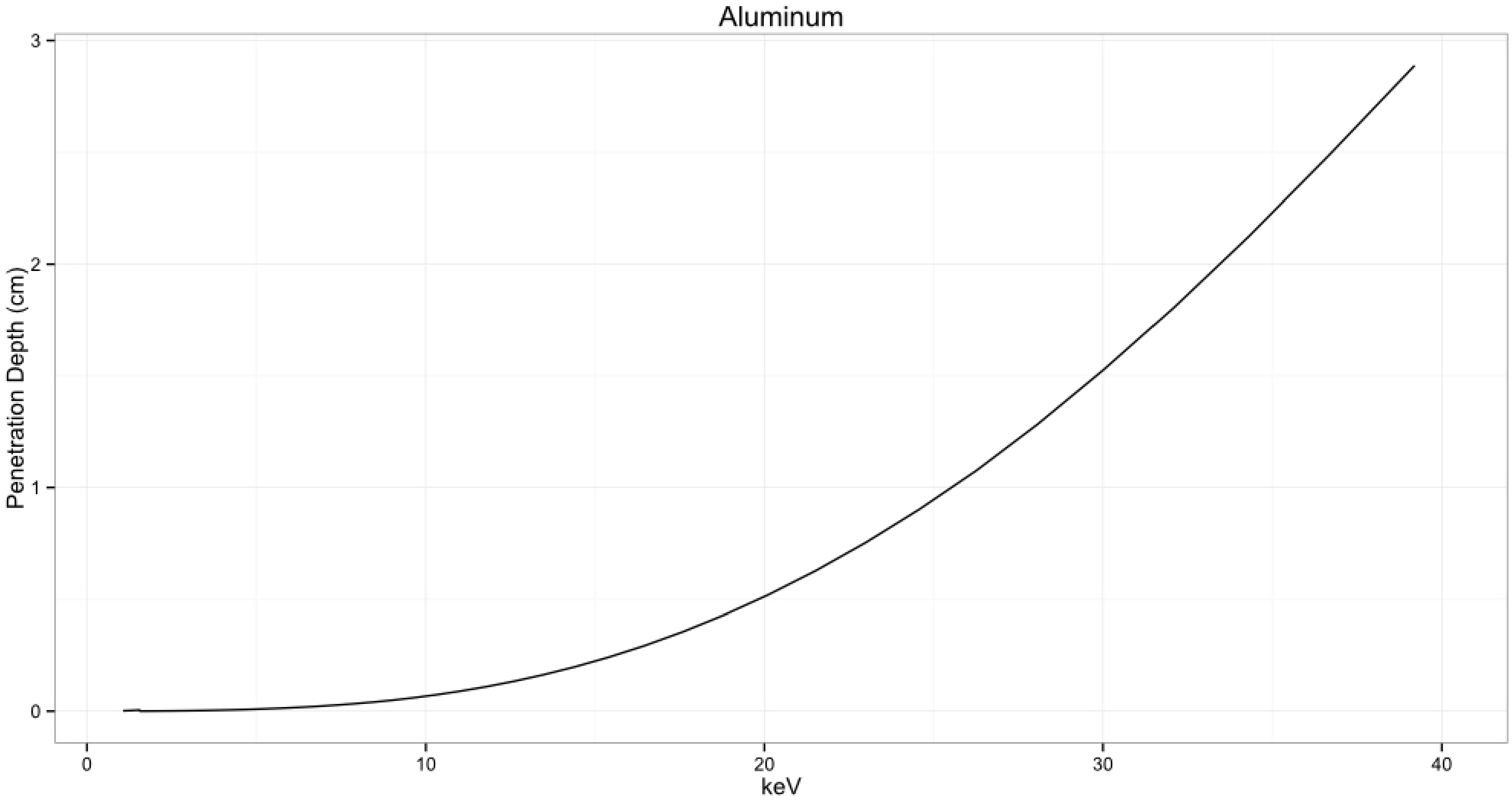

Alumina (Al_2O_3)
Penetration Depth (cm)
0
1
2
keV
0
10
20
30
40

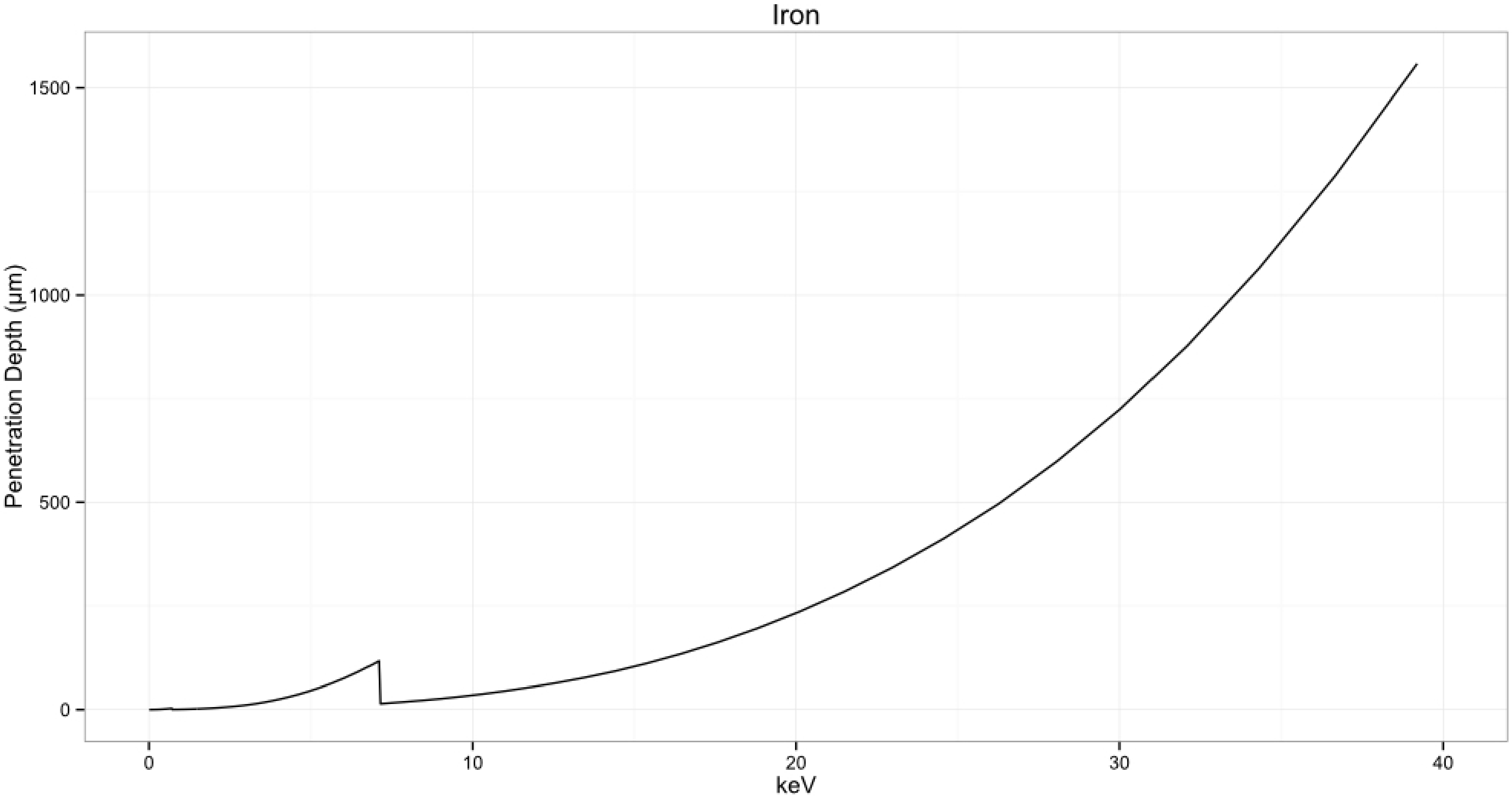

Calcium Oxide (CaO)
Penetration Depth (cm)
1.00
0.75
0.50
0.25
0.00
0
10
20
30
40
keV

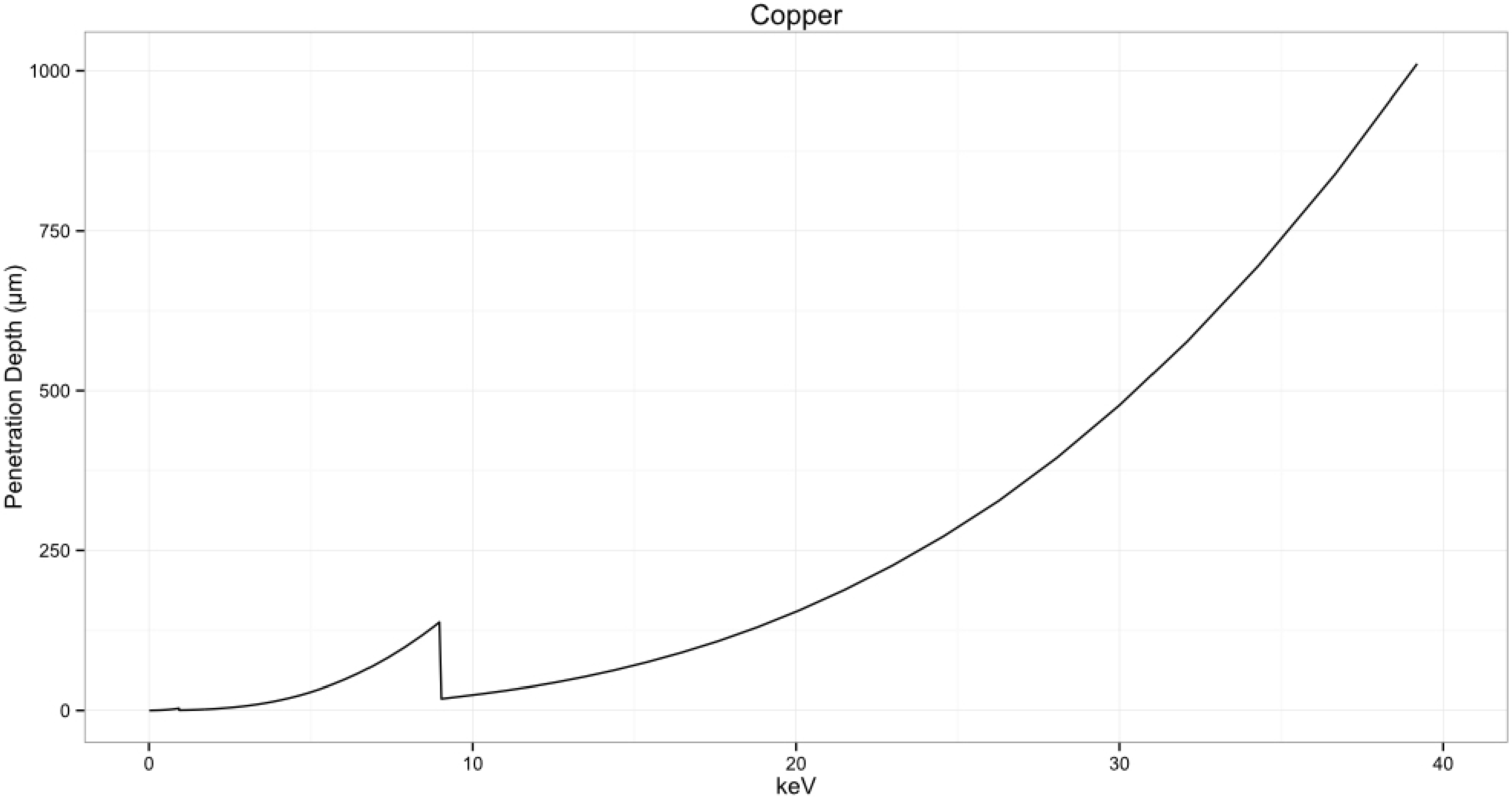


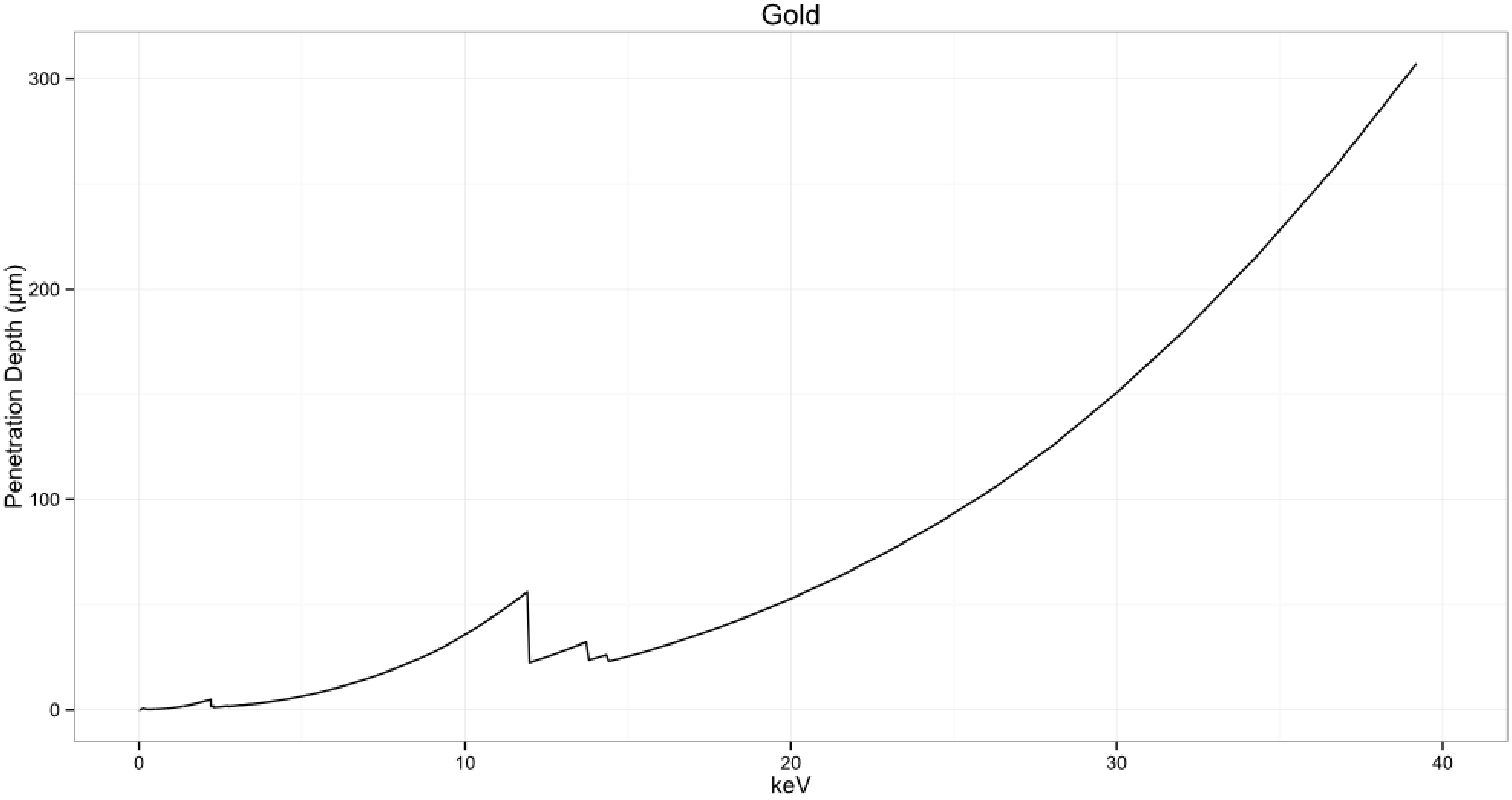
Gypsum ($CaSO_4 \cdot 2H_2O$)
Penetration Depth (cm)
0
1
2
3
4
5
keV
0
10
20
30
40

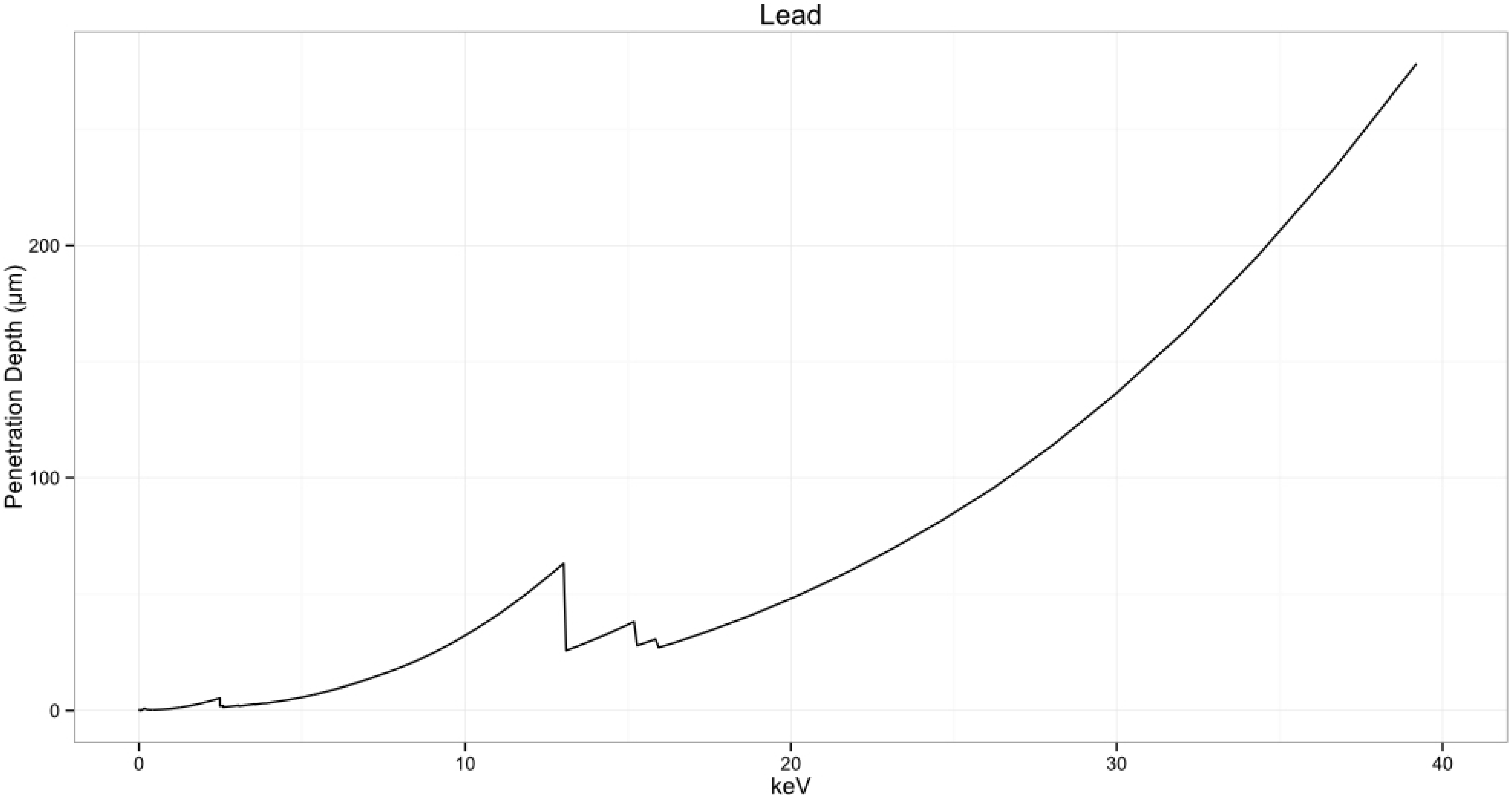
Metals

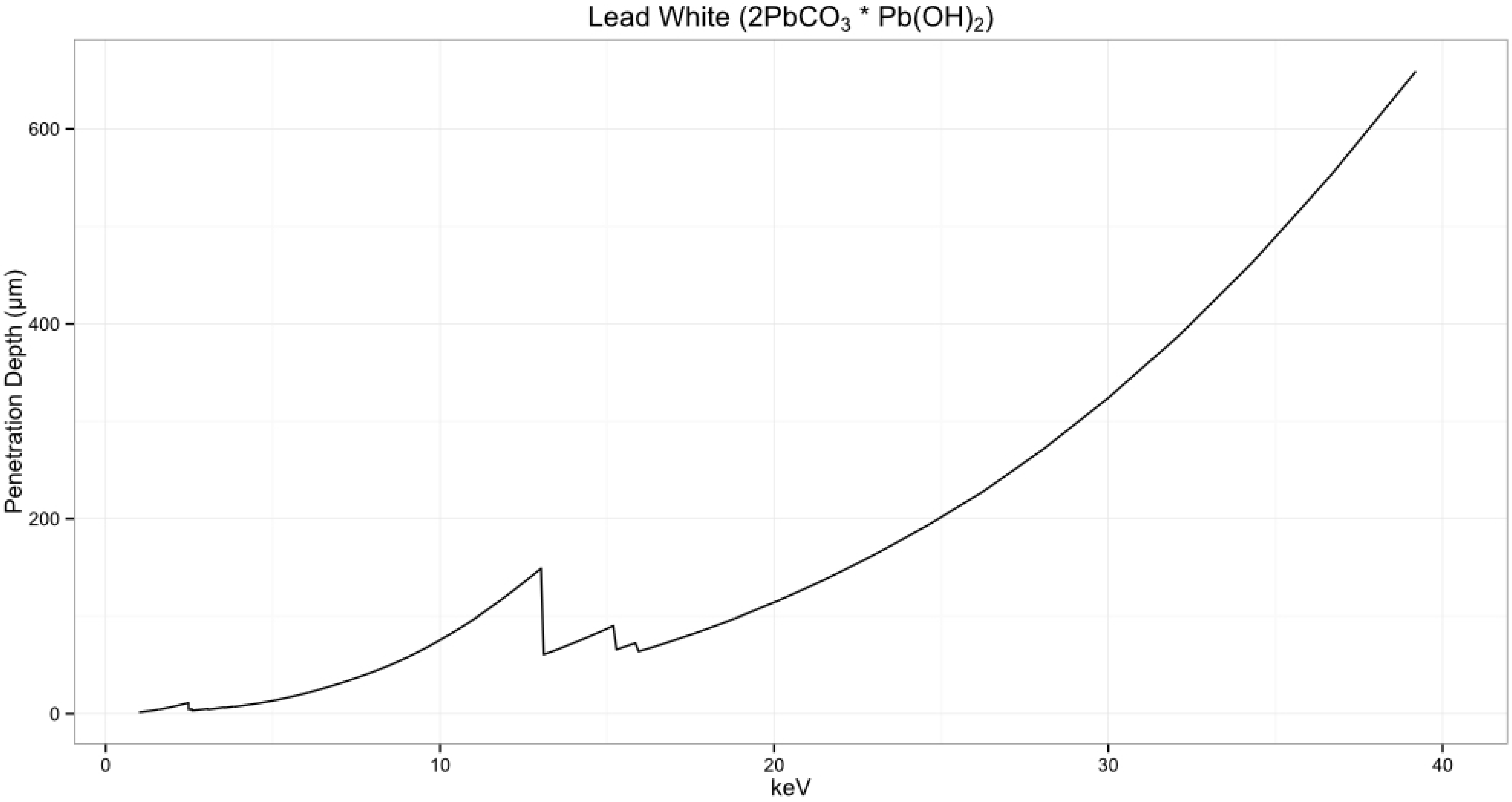


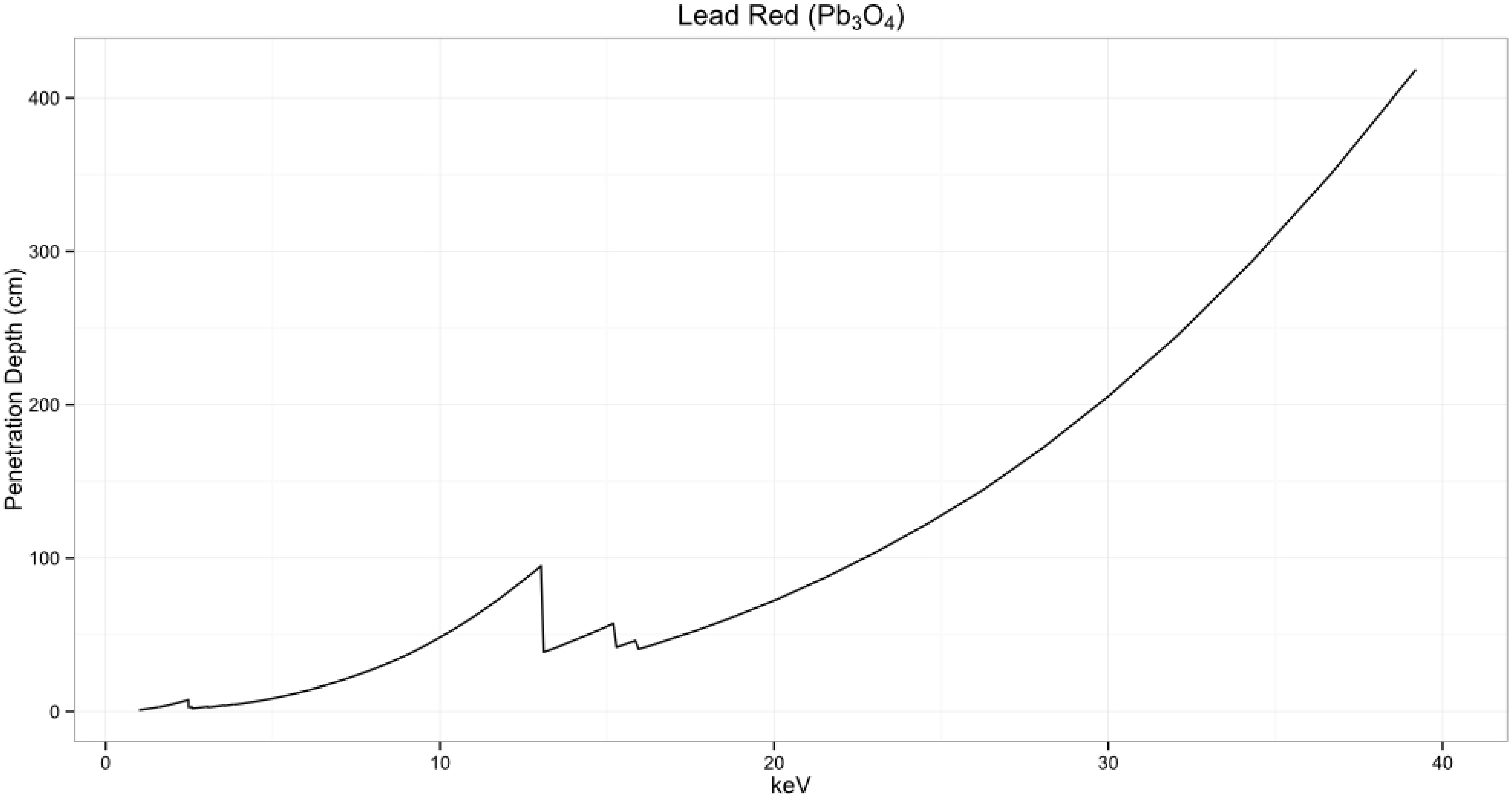

Iron
Penetration Depth (µm)
1500
1000
500
0
0
10
20
30
40
keV


Copper
Penetration Depth (μm)
1000
750
500
250
0
0
10
20
30
40
keV

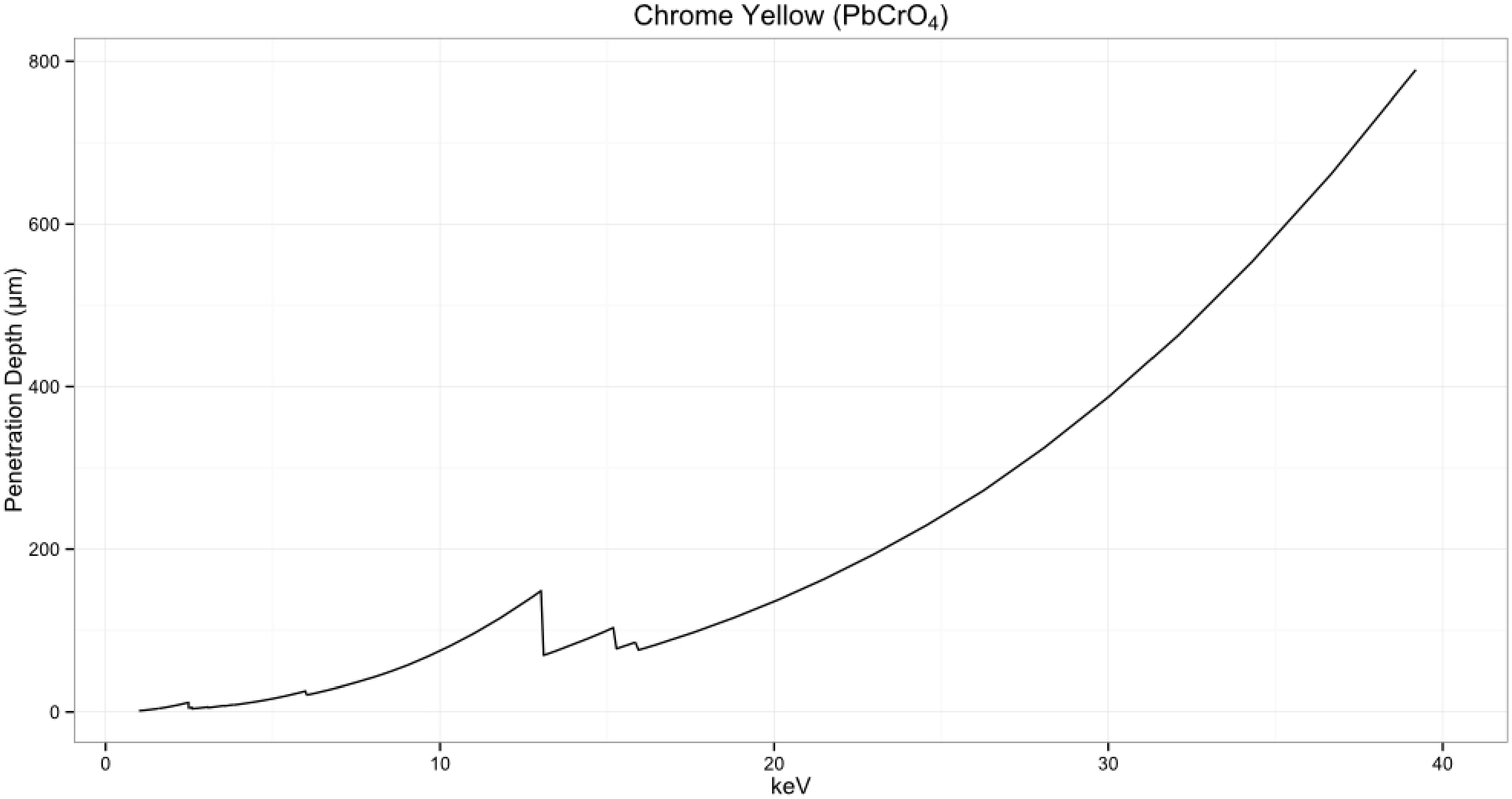

Gold
Penetration Depth (µm)
300
200
100
0
0
10
20
30
40
keV

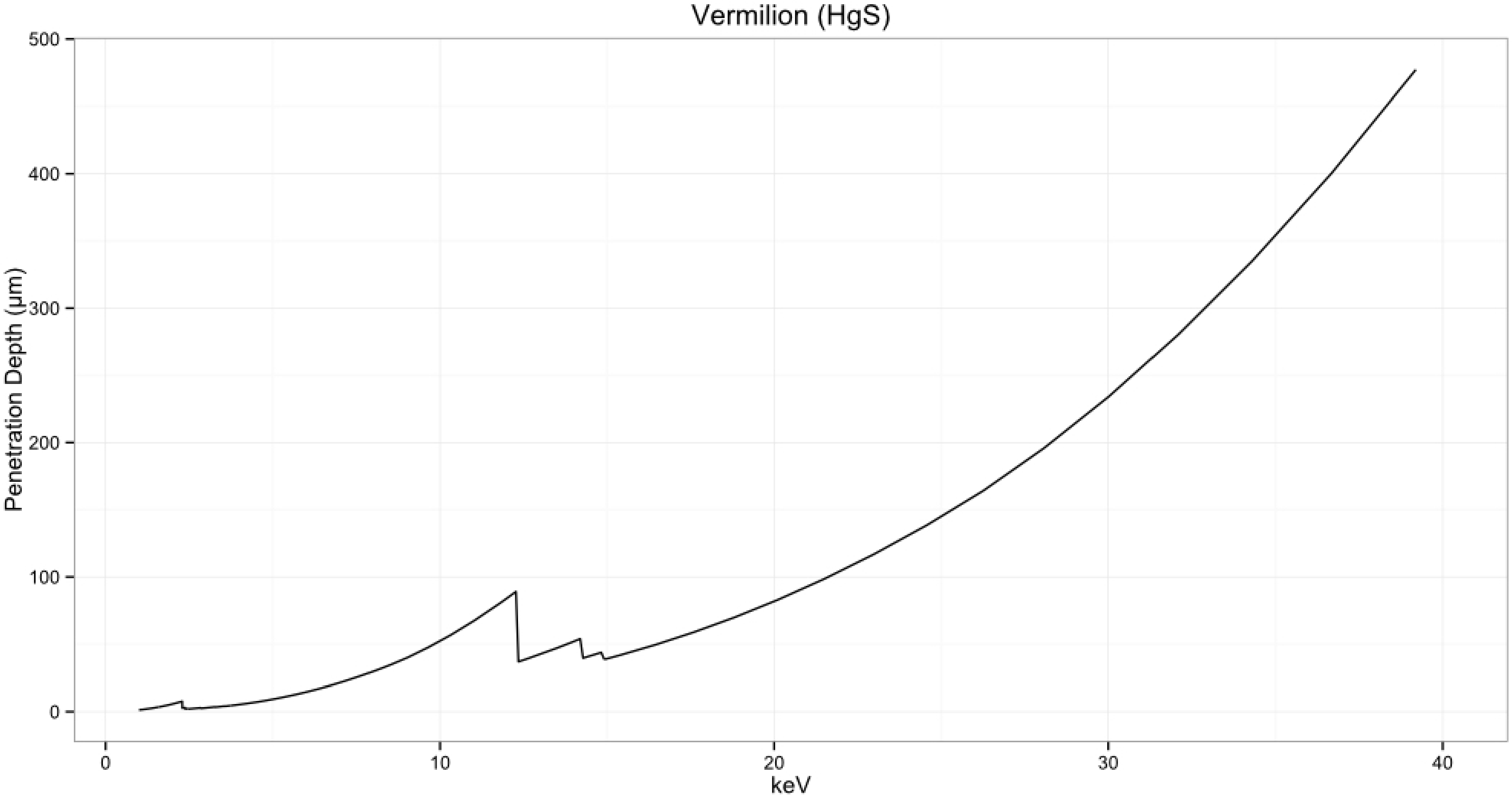

Lead
Penetration Depth (µm)
200
100
0
0
10
20
30
40
keV

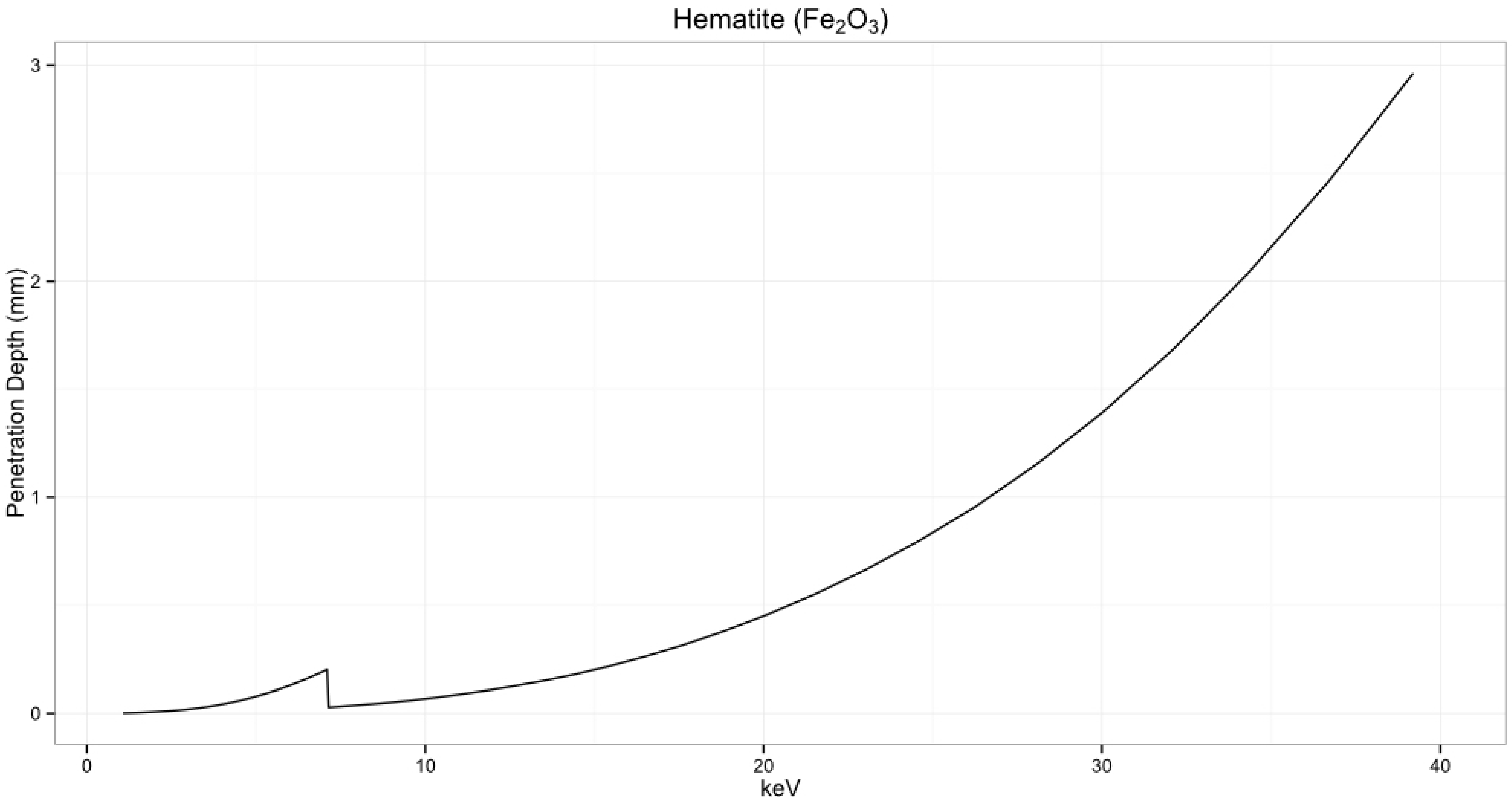

Lead White ($2PbCO_3 * Pb(OH)_2$)
Penetration Depth (µm)
600
400
200
0
0
10
20
30
40
keV



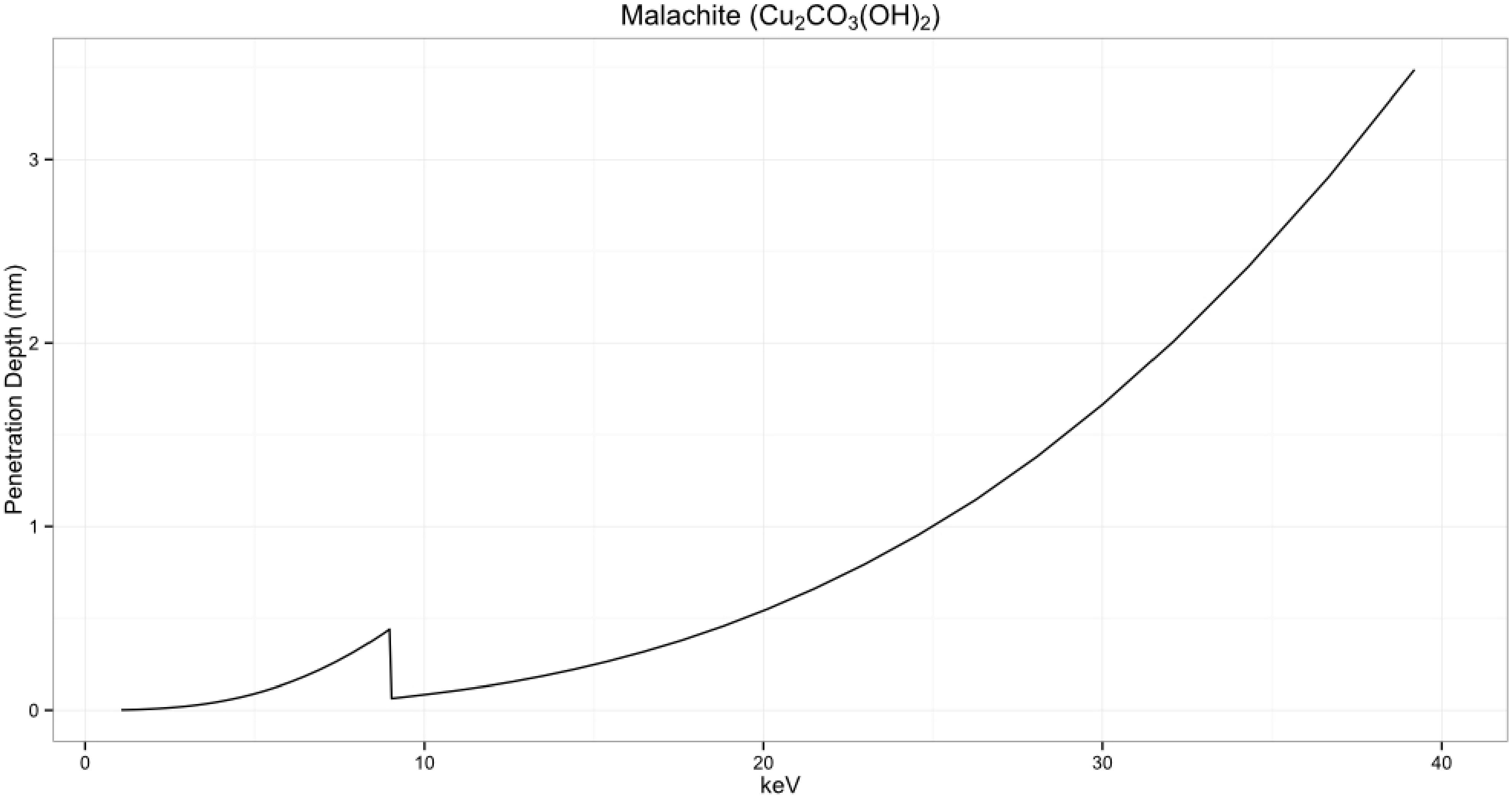
Lead Red (Pb_3O_4)
Penetration Depth (cm)
400
300
200
100
0
0
10
20
30
40
keV

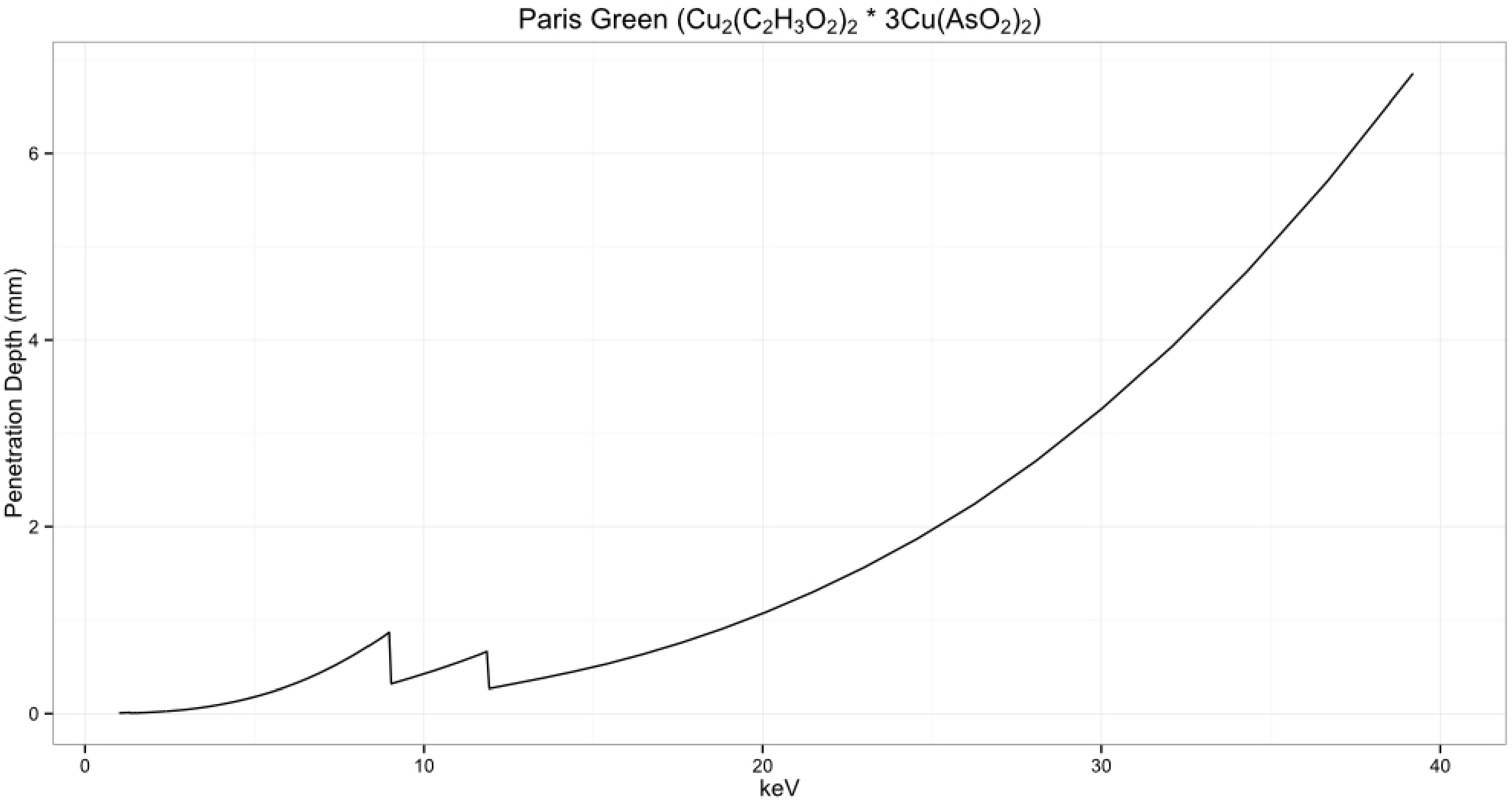

Chrome Yellow ($PbCrO_4$)
Penetration Depth (µm)
800
600
400
200
0
0
10
20
30
40
keV

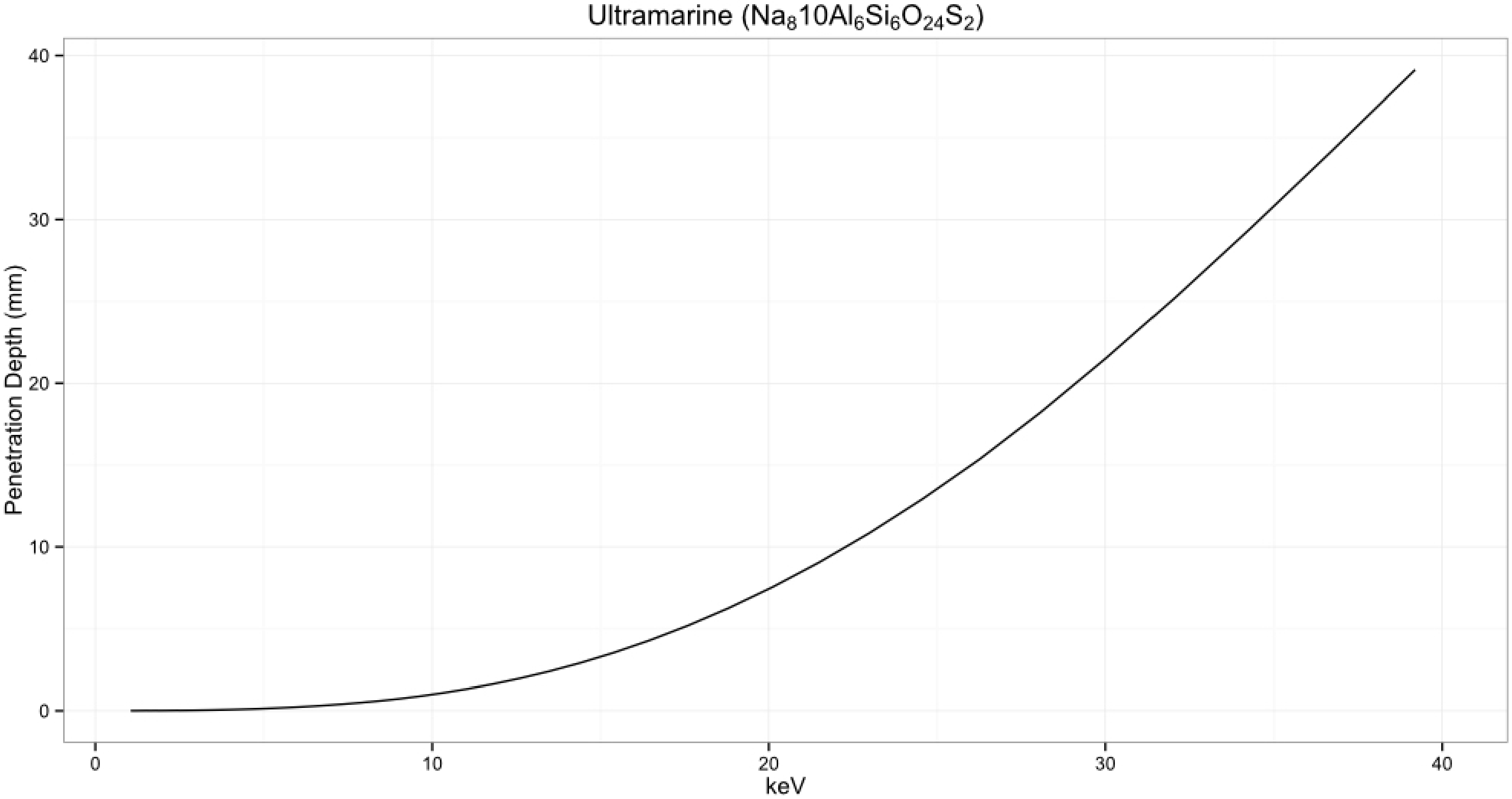

Vermilion (HgS)
Penetration Depth (μm)
500
400
300
200
100
0
0
10
20
30
40
keV

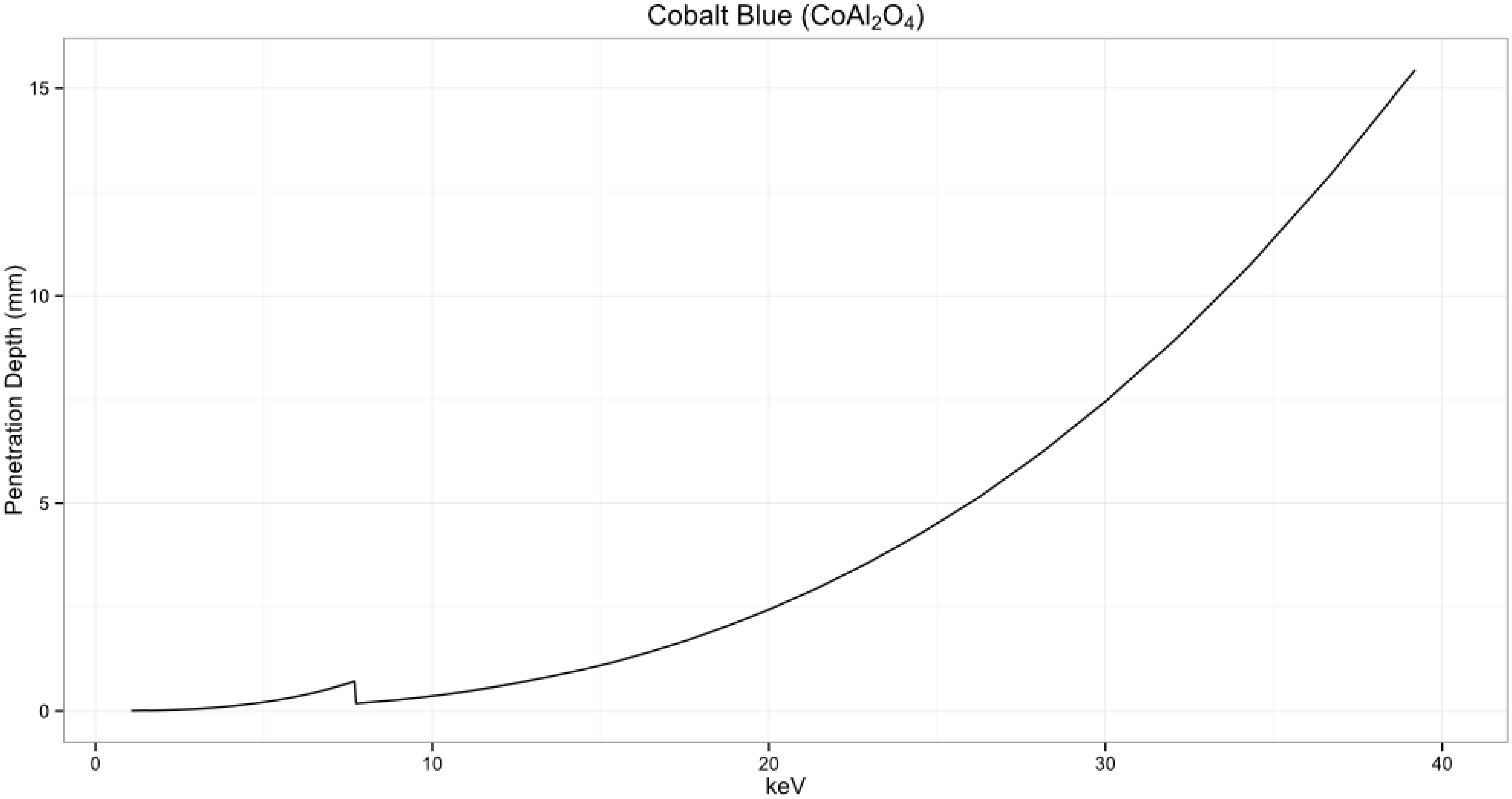


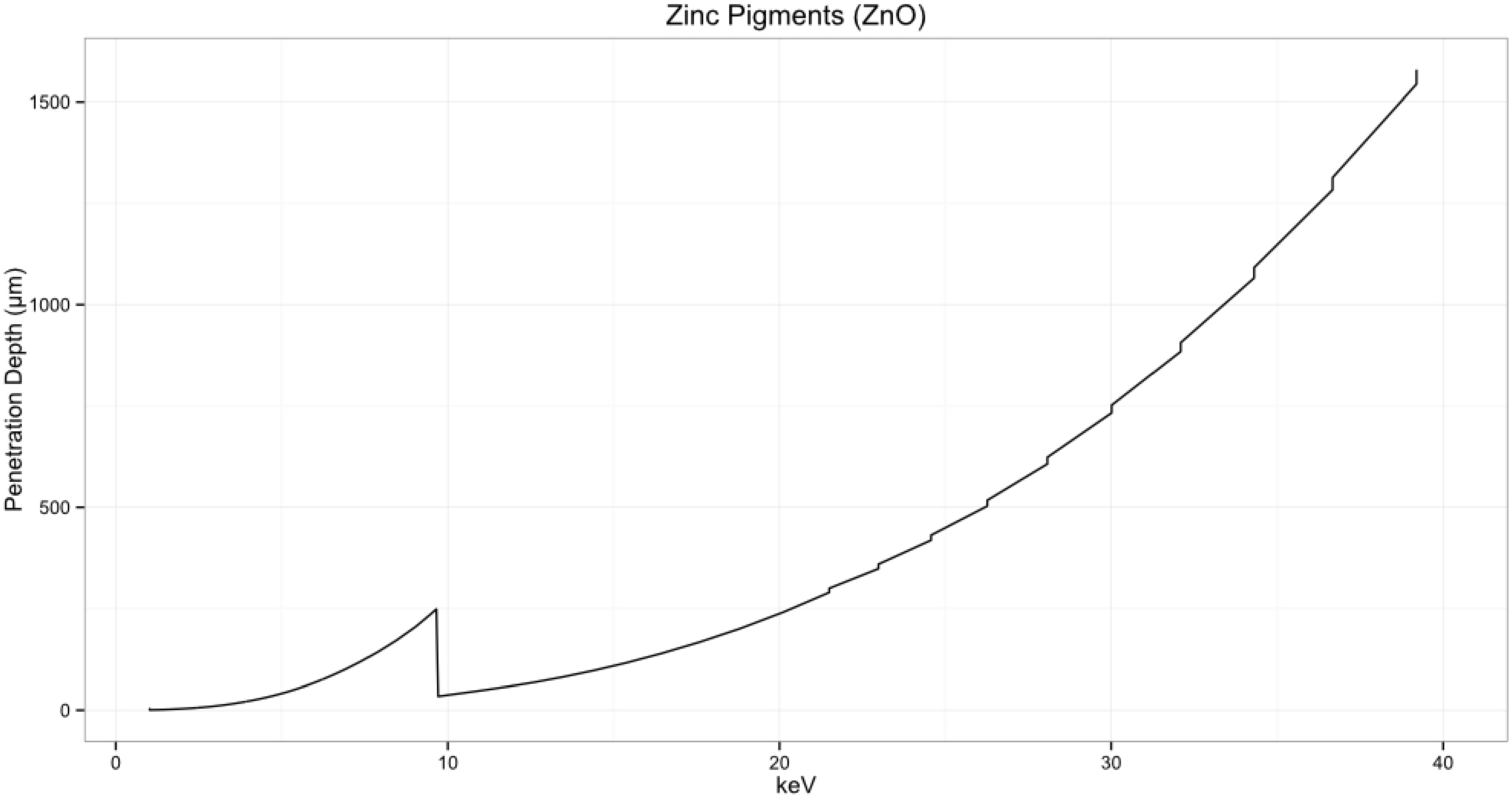
Hematite (Fe_2O_3)
Penetration Depth (mm)
3
2
1
0
0
10
20
30
40
keV

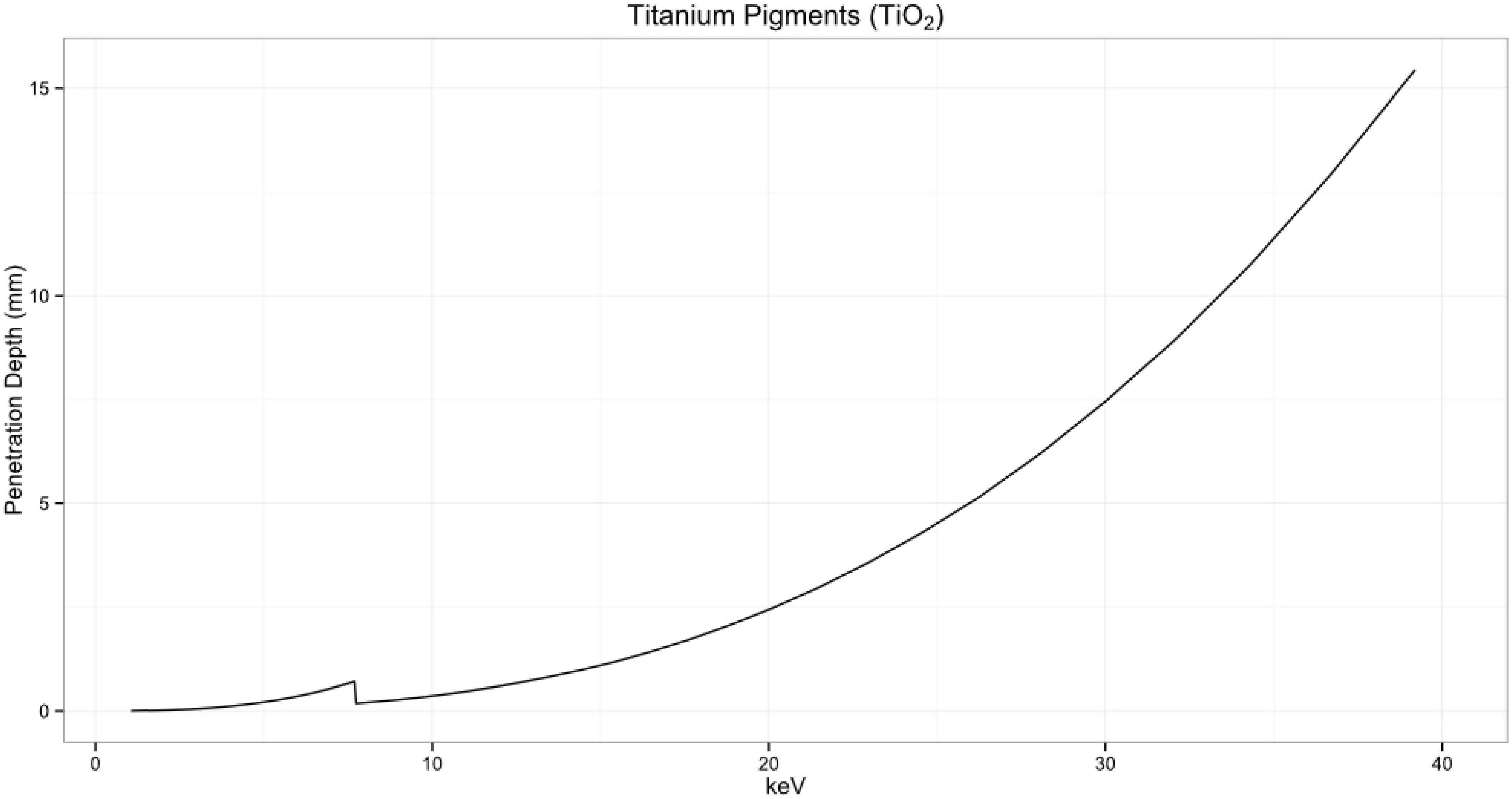

Malachite ($Cu_2CO_3(OH)_2$)
Penetration Depth (mm)
0
1
2
3
keV
0
10
20
30
40


Paris Green ($Cu_2(C_2H_3O_2)_2 * 3Cu(AsO_2)_2$)
Penetration Depth (mm)
0
2
4
6
0
10
20
30
40
keV

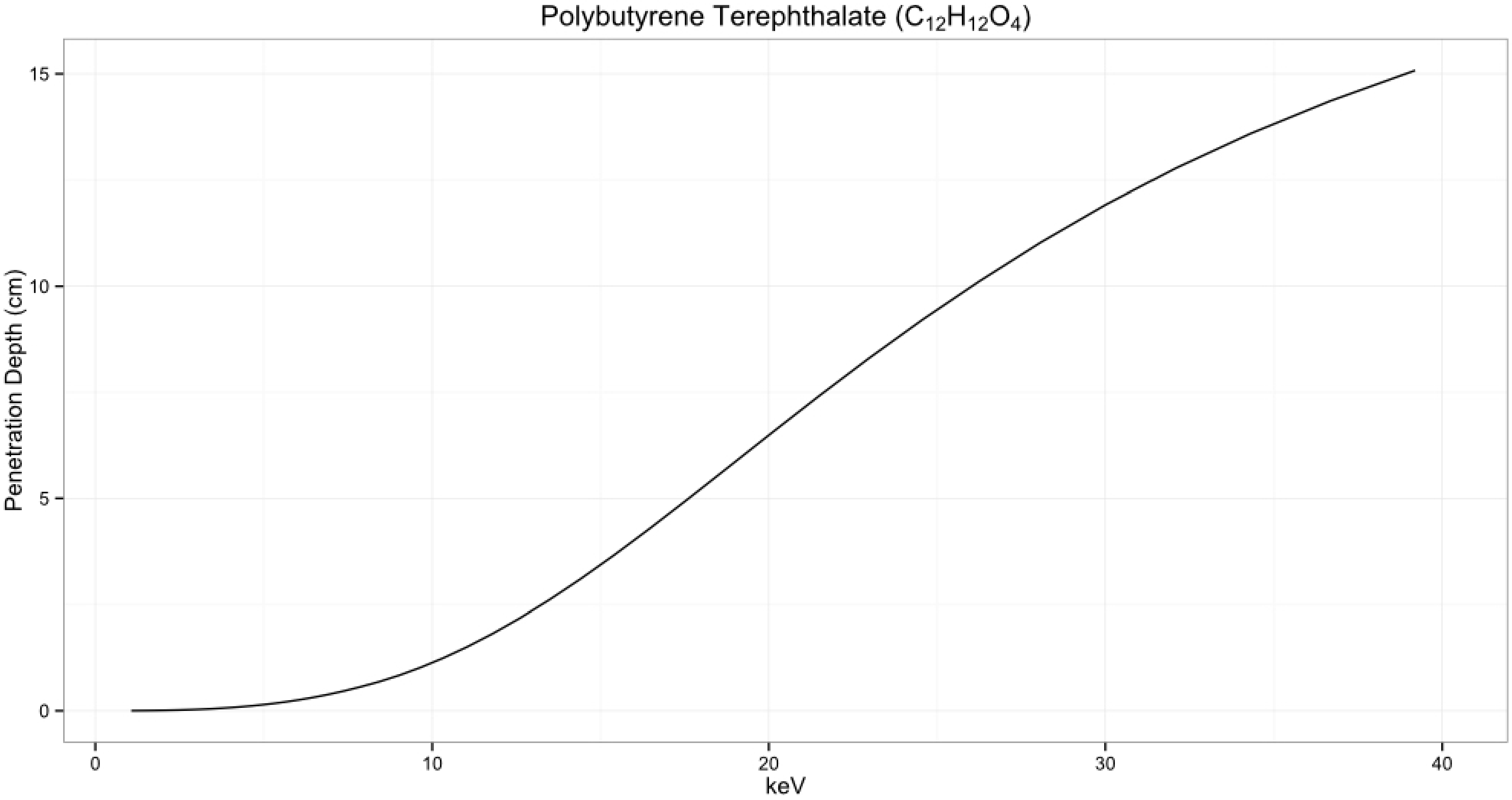

Ultramarine ($Na_810Al_6Si_6O_{24}S_2$)
Penetration Depth (mm)
0
10
20
30
40
keV
0
10
20
30
40

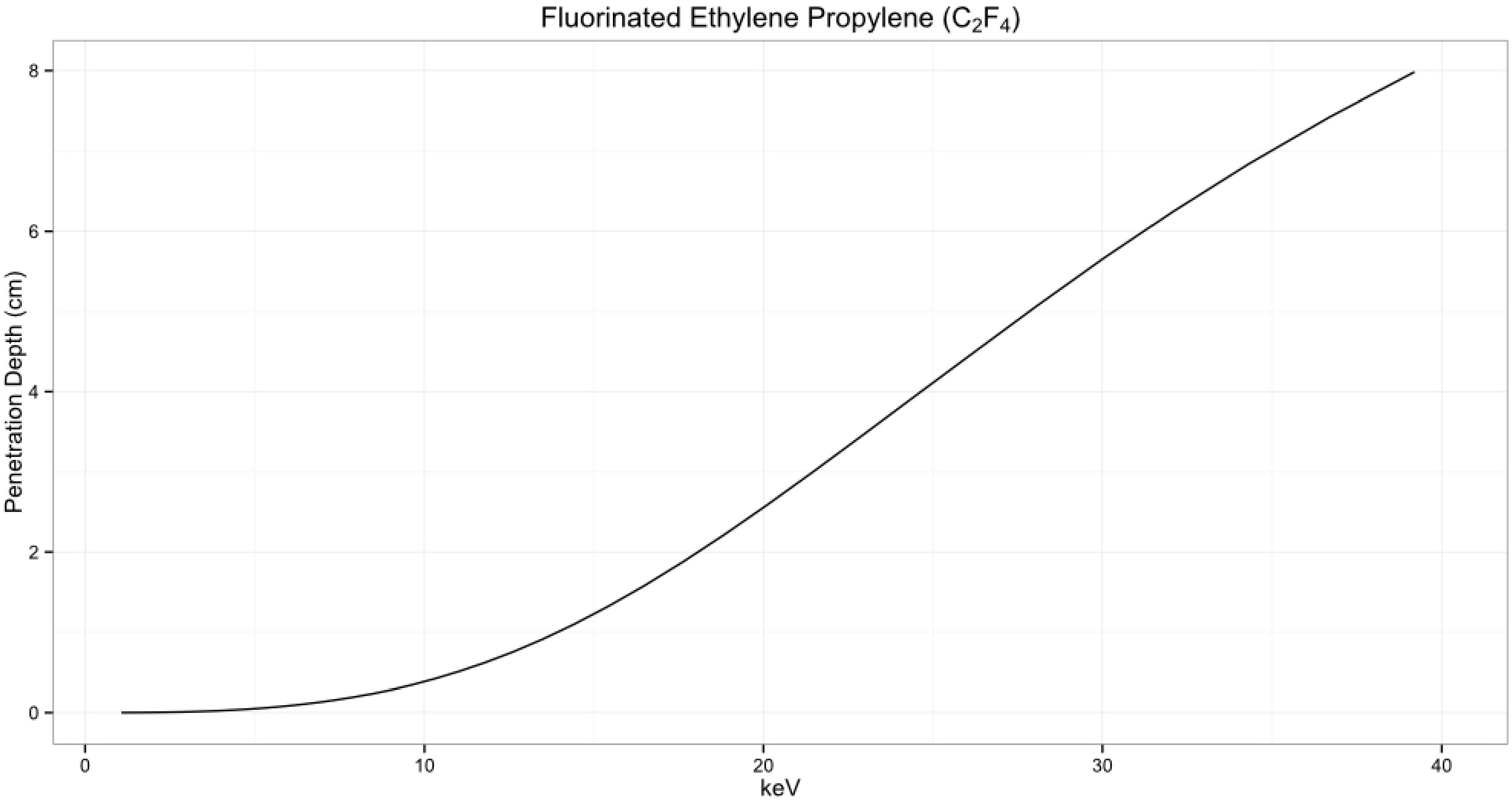

Cobalt Blue ($CoAl_2O_4$)

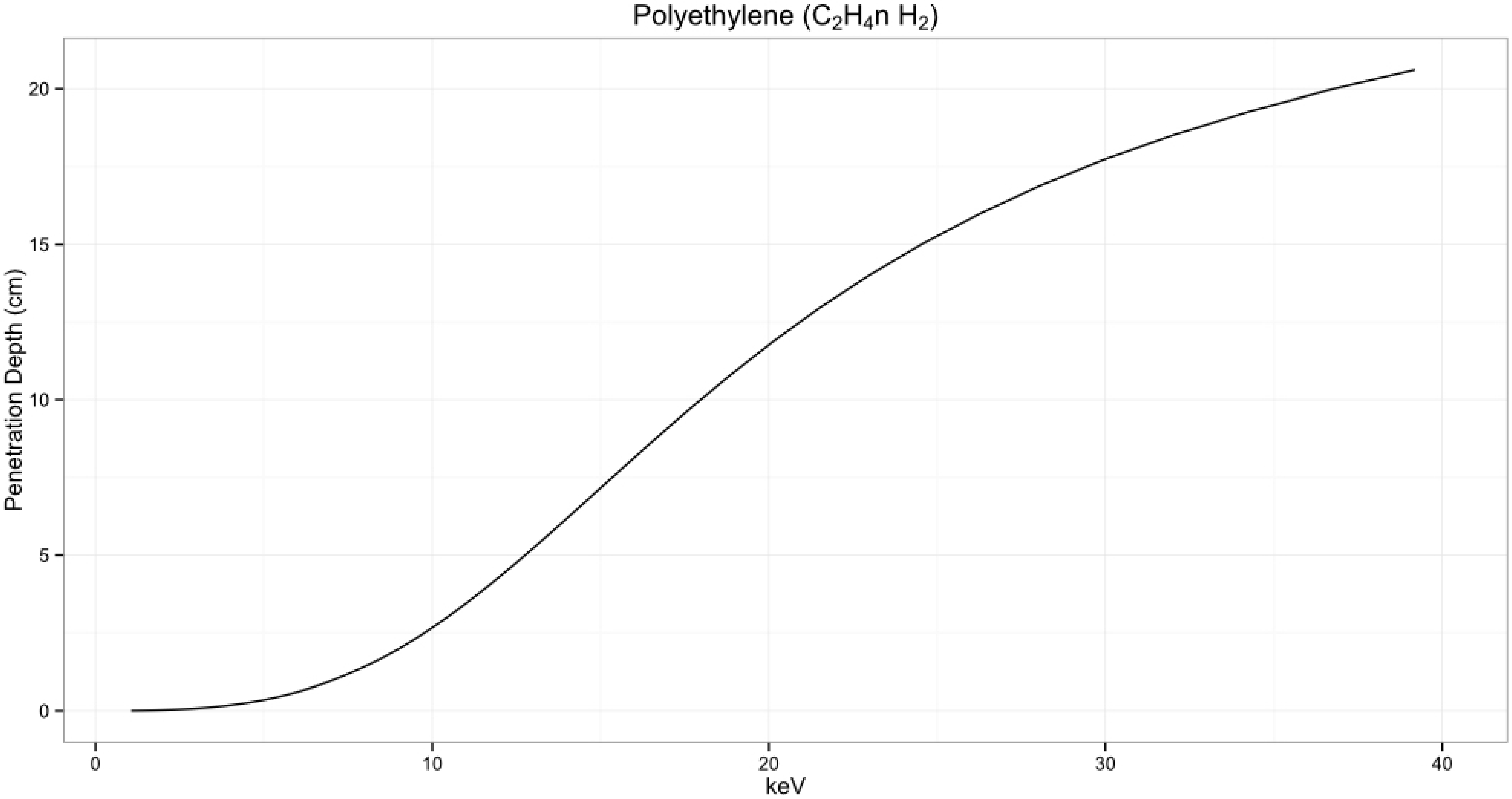

Zinc Pigments (ZnO)
Penetration Depth (µm)
1500
1000
500
0
0
10
20
30
40
keV

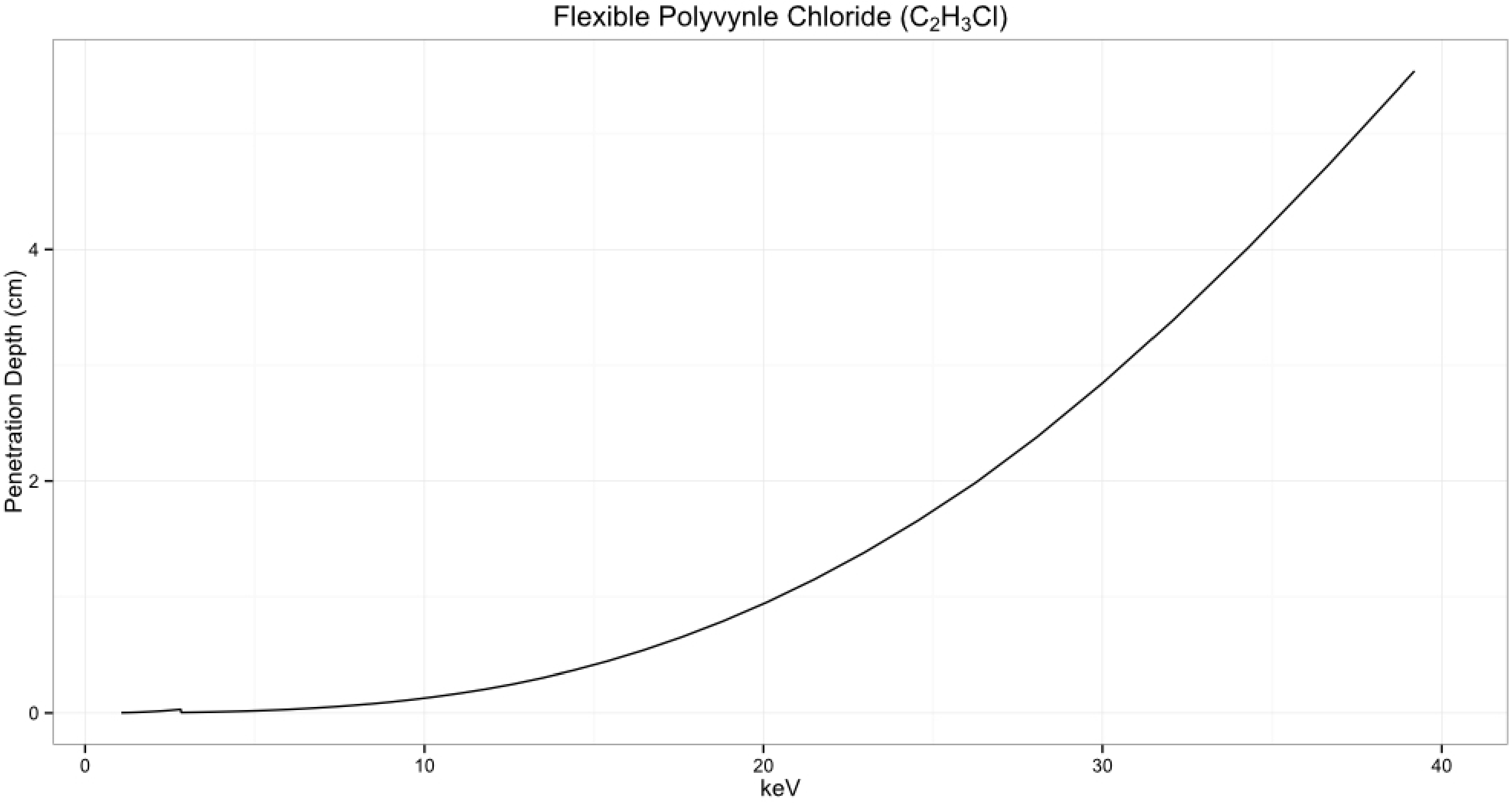

Titanium Pigments (TiO_2)
Penetration Depth (mm)
0
5
10
15
keV
0
10
20
30
40

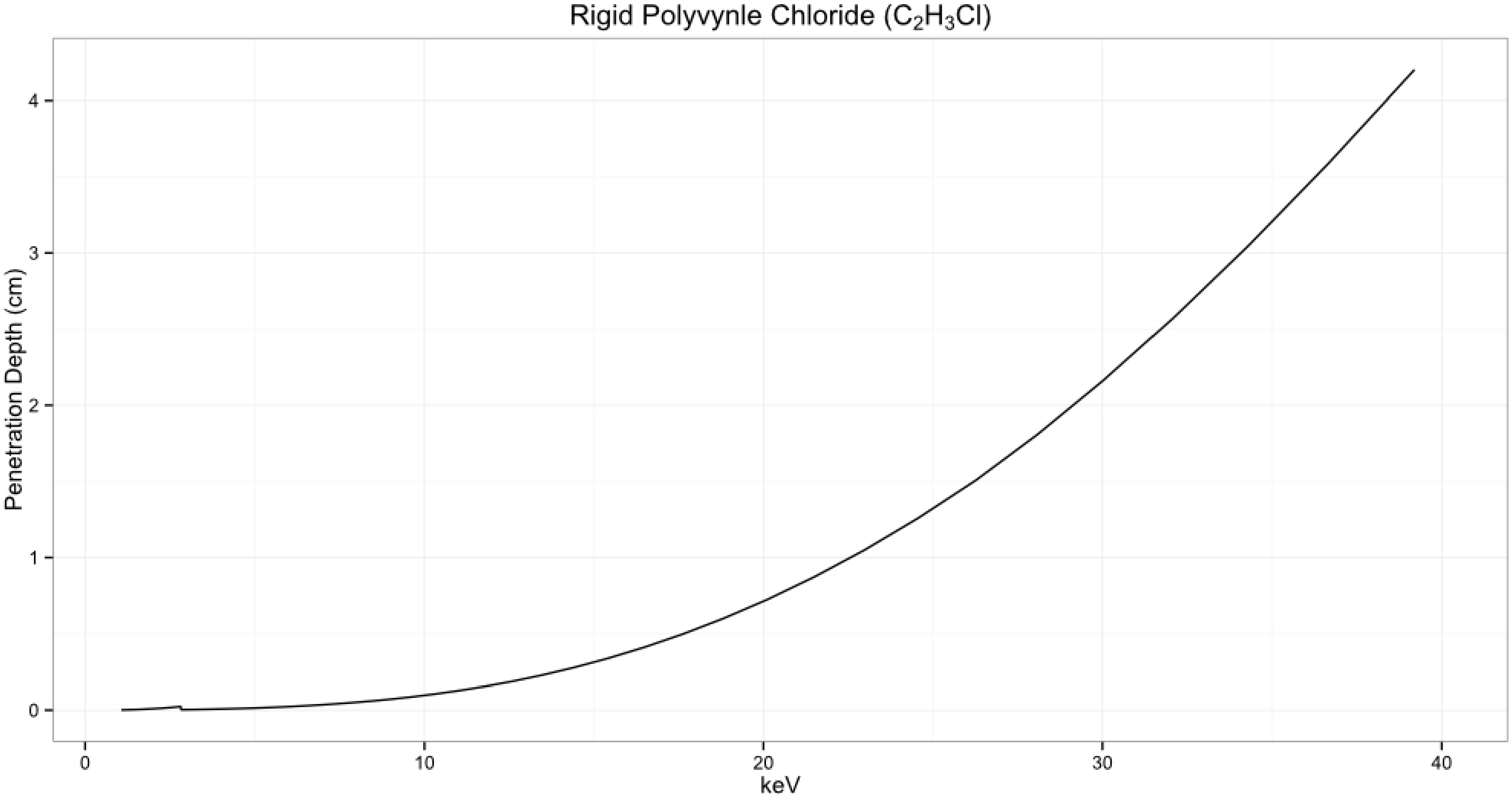
Plastics


Polybutyrene Terephthalate ($C_{12}H_{12}O_4$)
Penetration Depth (cm)
15
10
5
0
0
10
20
30
40
keV

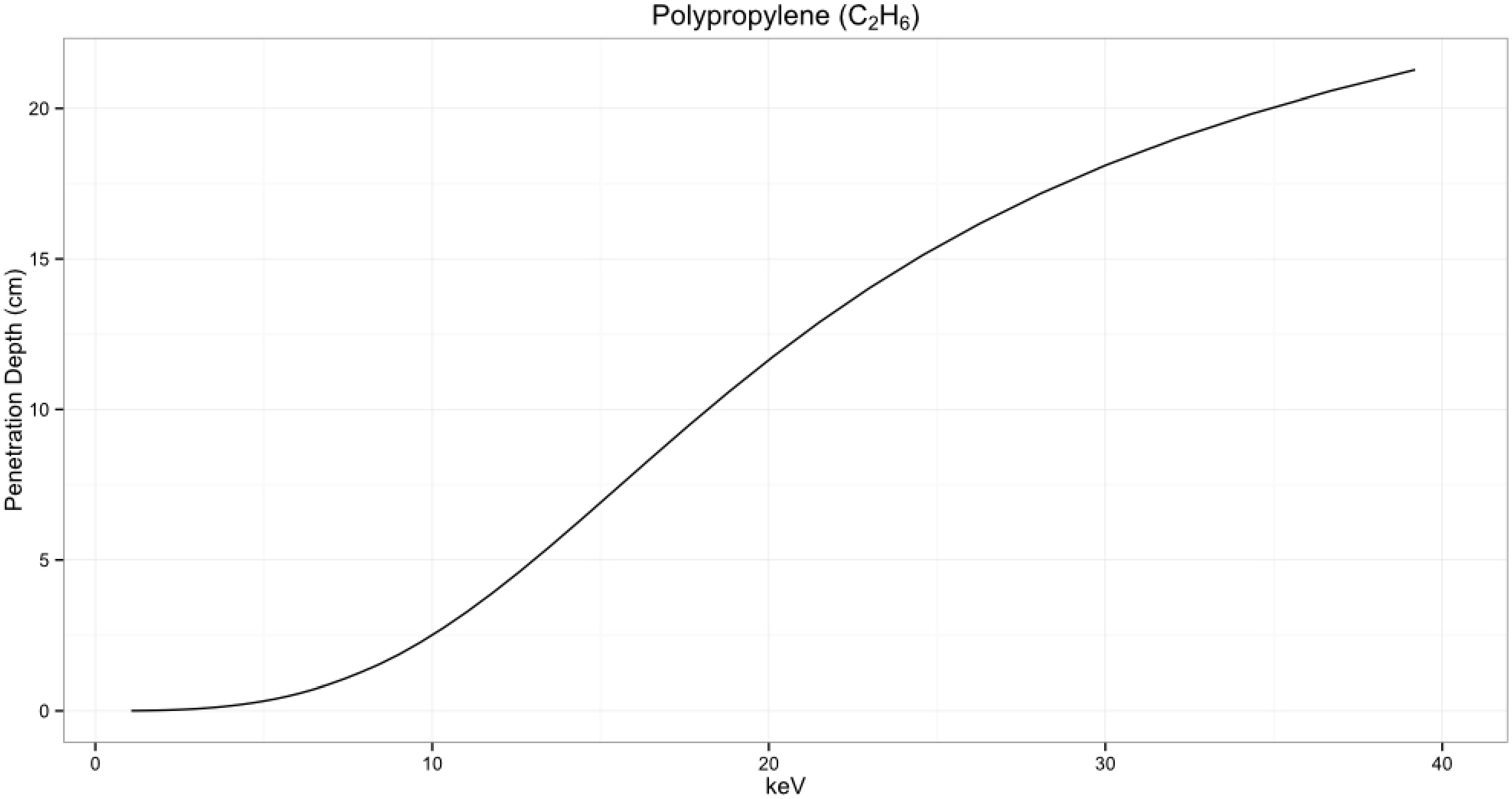

Fluorinated Ethylene Propylene (C_2F_4)
Penetration Depth (cm)
8
6
4
2
0
0
10
20
30
40
keV

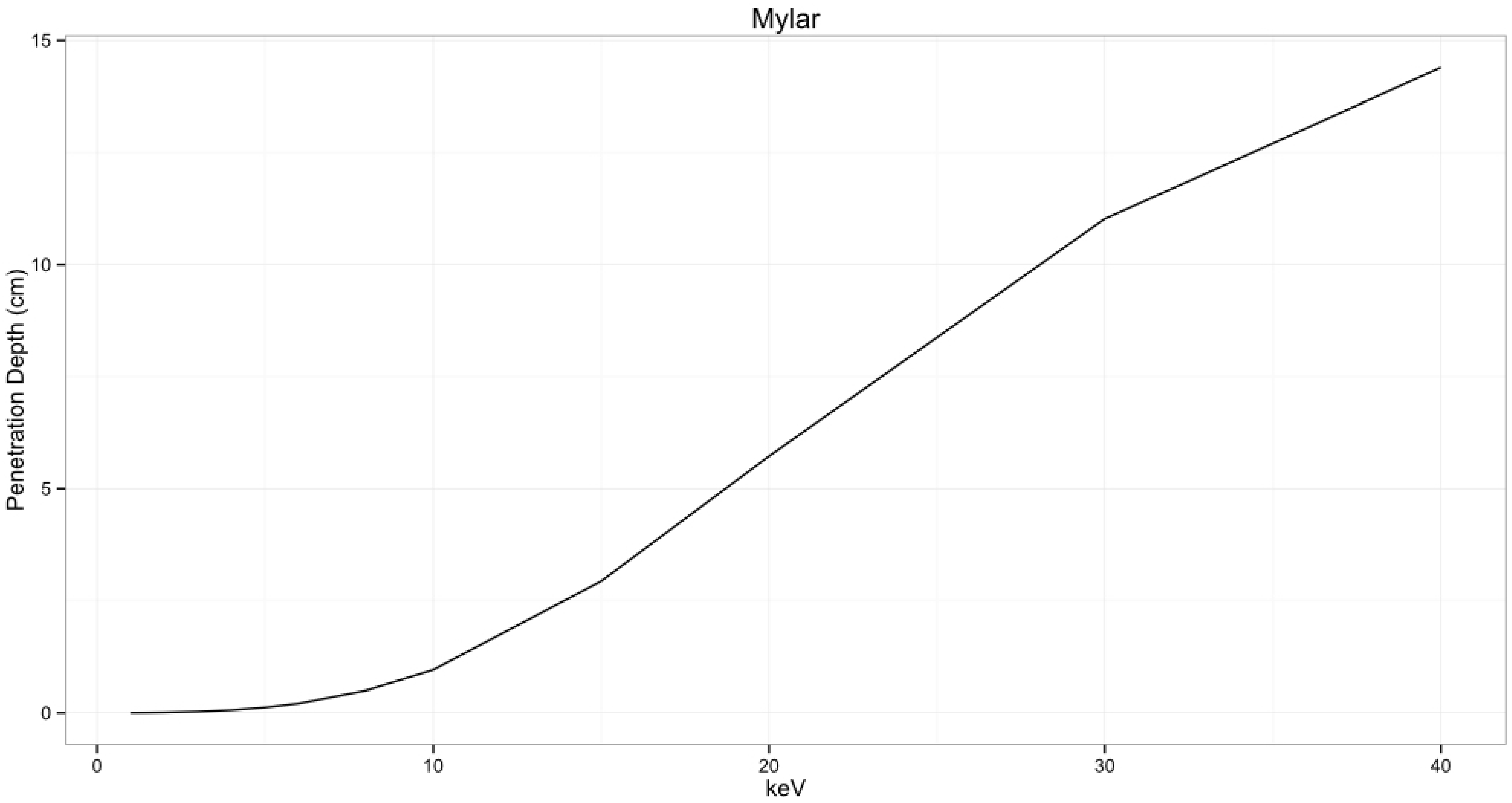

Polyethylene (C_2H_4n H_2)
Penetration Depth (cm)
0
5
10
15
20
0
10
20
30
40
keV


Flexible Polyvynle Chloride (C_2H_3Cl)
Penetration Depth (cm)
0
2
4
0
10
20
30
40
keV



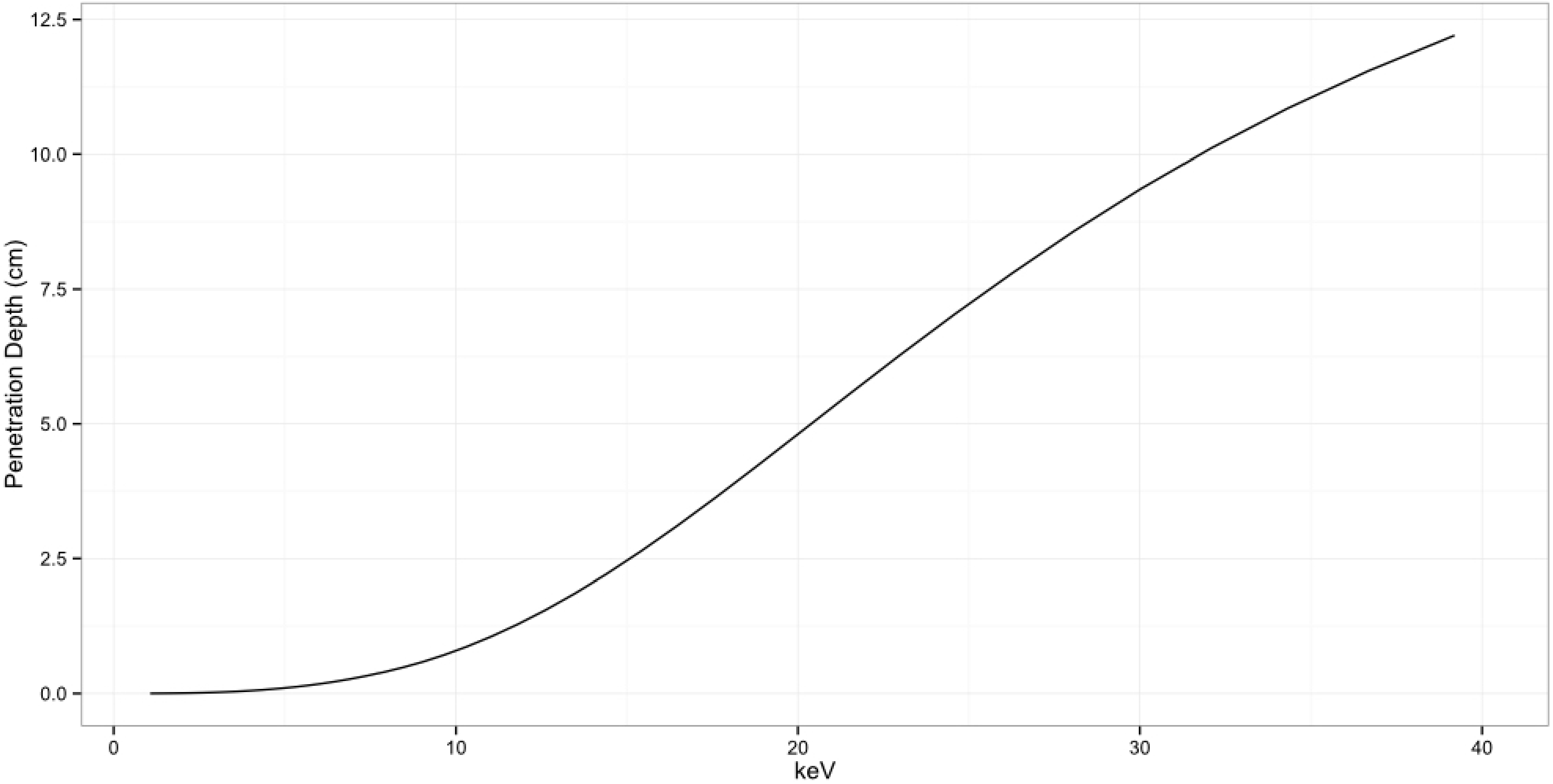
Rigid Polyvynle Chloride (C_2H_3Cl)

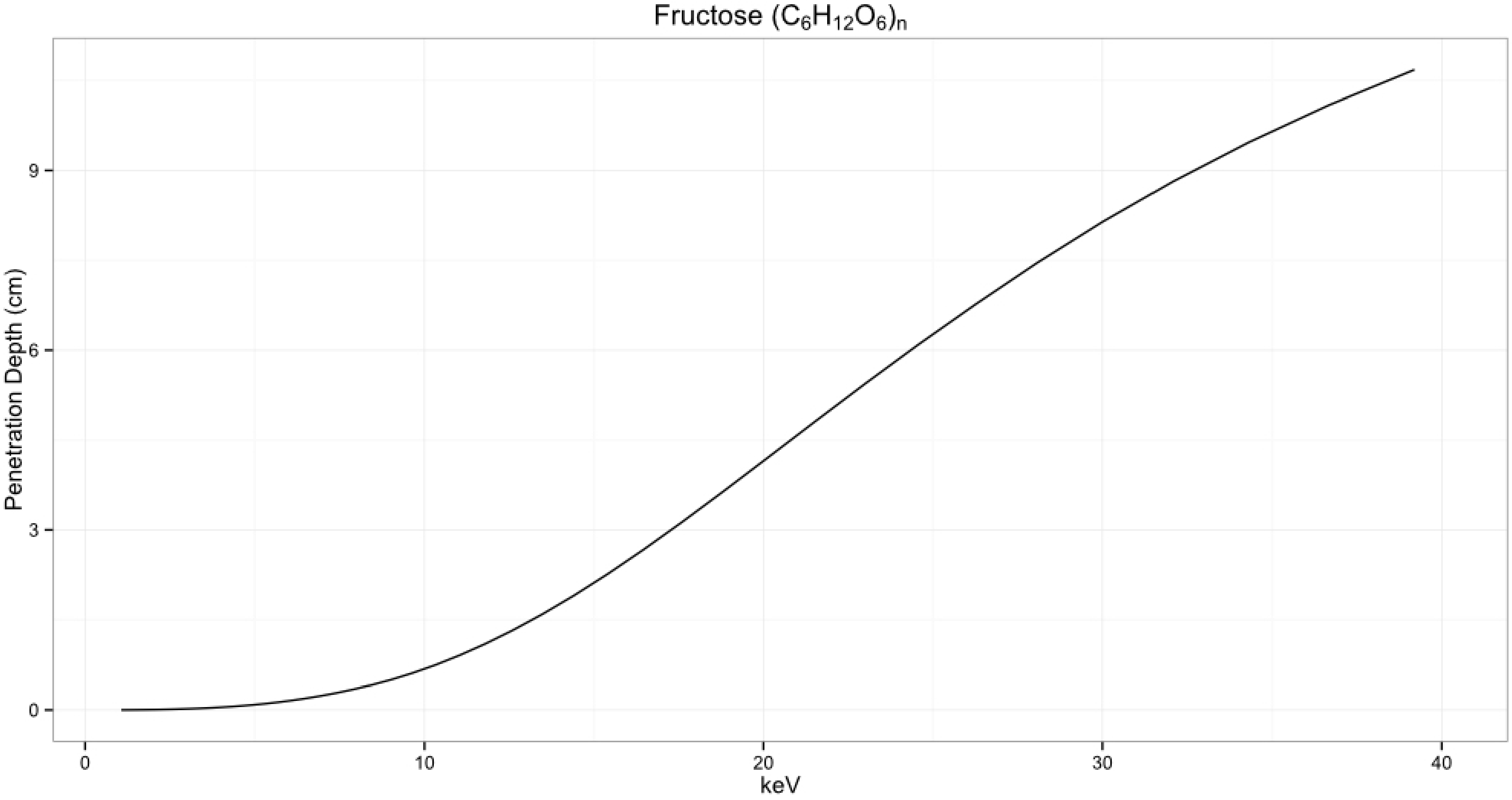

Polypropylene (C_2H_6)
Penetration Depth (cm)
20
15
10
5
0
0
10
20
30
40
keV


Mylar
Penetration Depth (cm)
15
10
5
0
0
10
20
30
40
keV

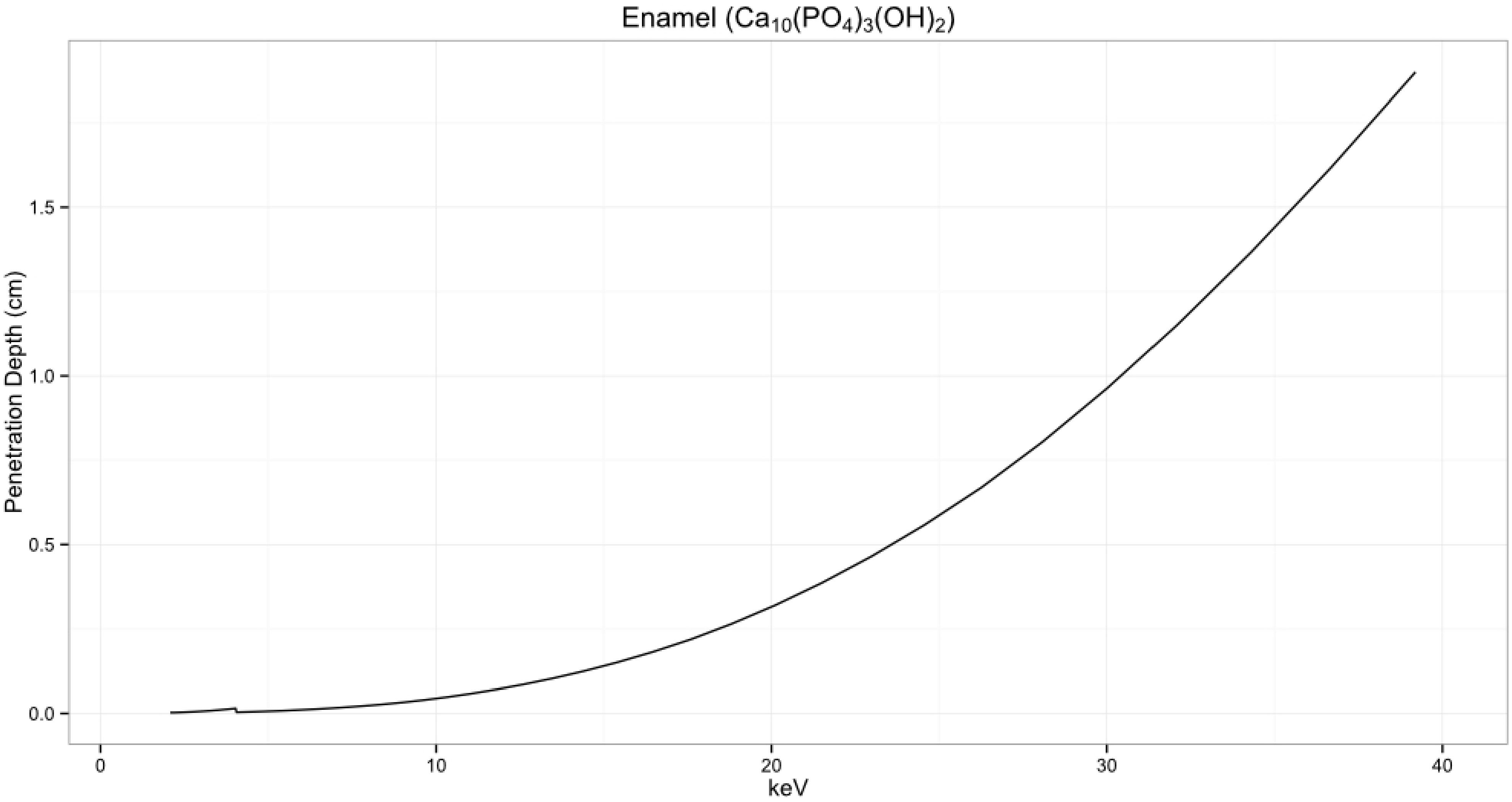
Biological Materials

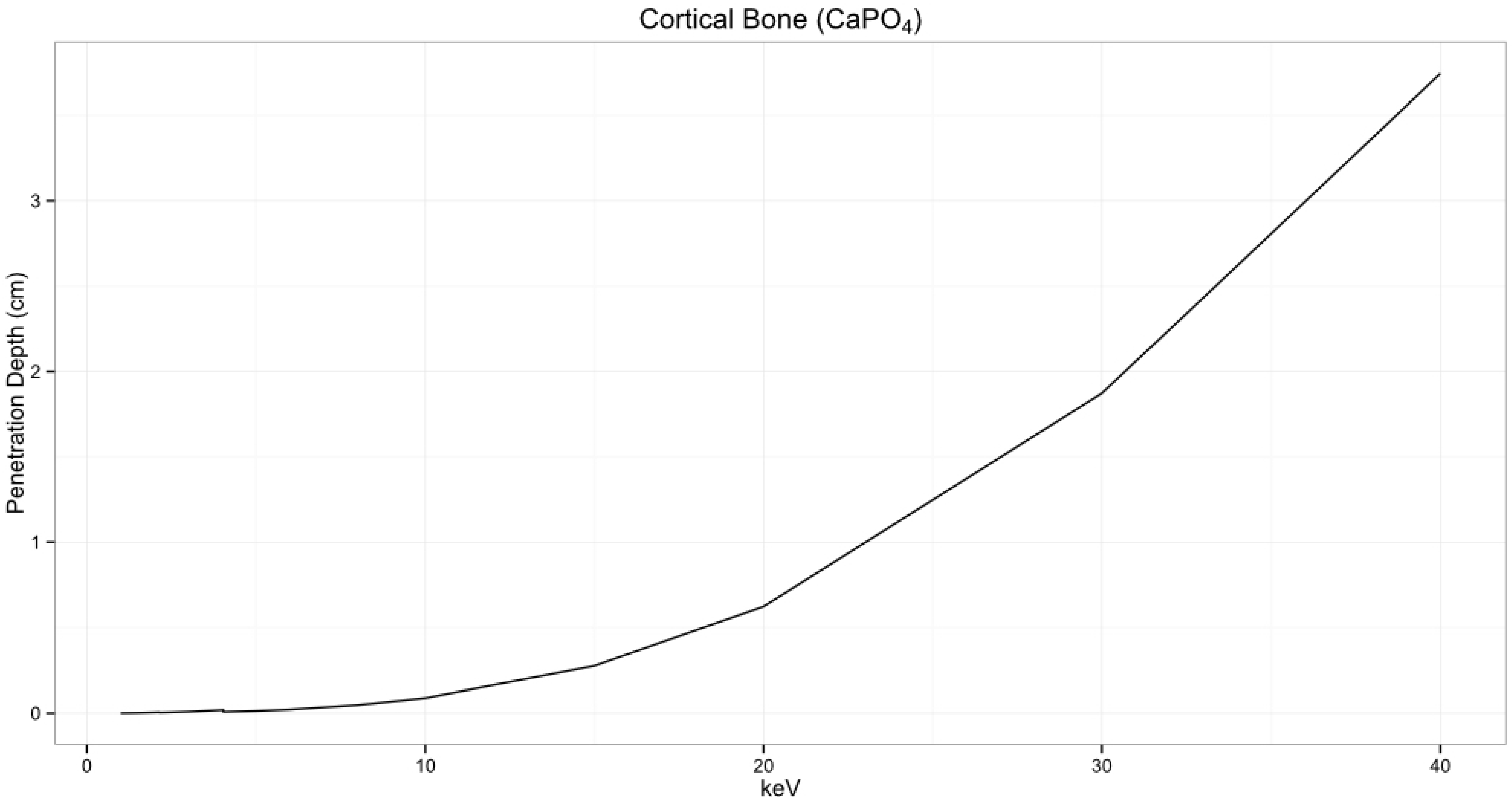
Cellulose $(C_6H_{10}O_5)_n$





Fructose $(C_6H_{12}O_6)_n$


Enamel ($Ca_{10}(PO_4)_3(OH)_2$)
Penetration Depth (cm)
0.0
0.5
1.0
1.5
0
10
20
30
40
keV


Cortical Bone ($CaPO_4$)
Penetration Depth (cm)
0
1
2
3
keV
0
10
20
30
40