Beryllium-10 in magmas

Identifying chemical inputs and outputs in subduction zones

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1 Learning objectives

This exercise is designed to introduce students to a workflow for interpreting geochemical datasets. Students will practice:

- → Making first-order calculations of chemical fluxes
- → Querying large online open-source data repositories
- → Retrieving raw geochemical data from primary peer-reviewed sources
- → Visualizing geochemical data using open-source software
- → Supporting interpretations with empirical observations

2 Guidelines

A basic knowledge of igneous rock types (ultramafic to felsic), igneous rock forming minerals (olivine, pyroxenes, feldspars, and quartz), magma genesis (flux melting), and magmatic differentiation are essential for this lab. **Review these concepts** and ask the instructor to define terms for you.

The necessary geochemical data are gathered by you from real published datasets, so they will be imperfect and lacking metadata. Ask the instructor for help if you get stuck on technical issues with the online databases or software. Trouble shooting is an intentional part of this exercise because problem solving is a fundamental skill for all Geoscience research activities. Follow the procedure, save often, and do not be afraid to tinker (and even break things!). Good luck and have fun.

3 Background

Geoscientists have sampled and analyzed thousands of igneous rocks from near plate boundaries to investigate melt sources and melt-forming processes within different tectonic environments (e.g. mid-ocean ridges and subduction zones). This lab focuses on a subset of samples collected near *volcanic arcs*, which are derived from flux melting of the upper mantle above subduction zones (Figure 3.1).

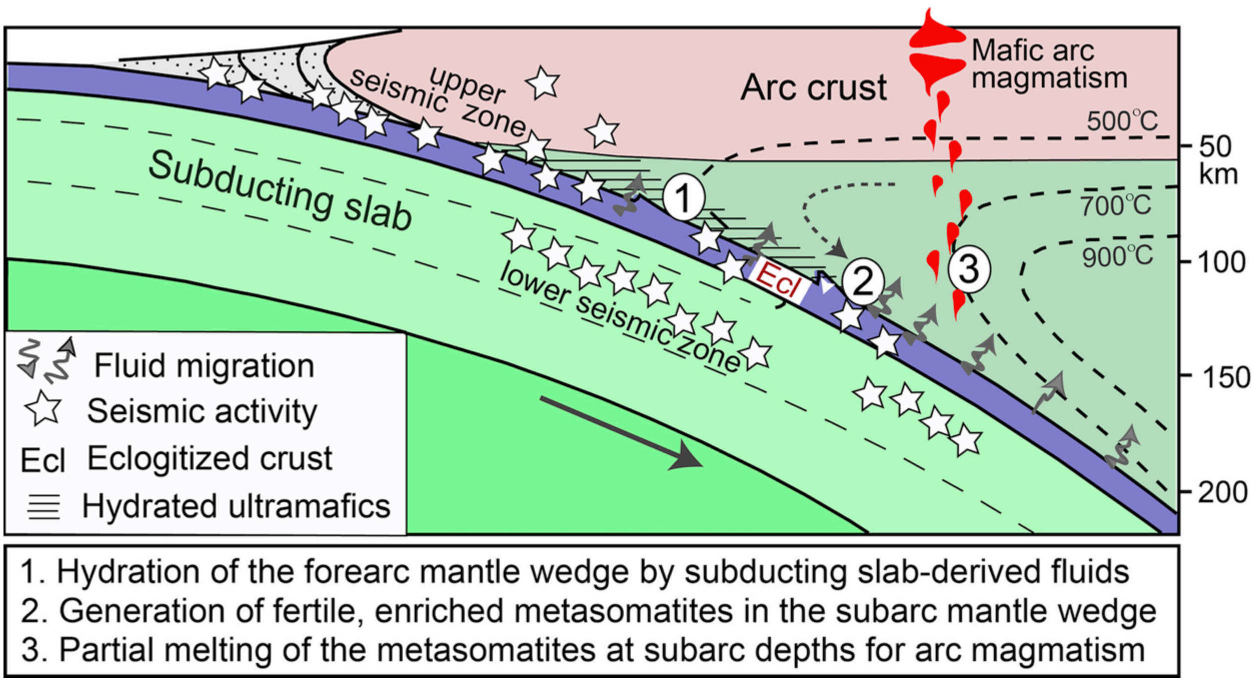

Figure 3.1: Schematic cross-section of a subduction zone showing the distribution of seismic events and fluid transfer from the subducting plate to the upper plate mantle wedge. Fluids fluxing from the lower-plate cause three major changes in the upper plate mantle (points 1-3), including magmagenesis (point 3). From Zheng (2019), after Angiboust et al. (2012).

Samples of igneous rocks from subduction zone settings generally have distinct trace element profiles compared to equivalent rocks from mid-ocean ridge settings (e.g. comparing basalts to basalts with similar SiO_2 and Mg#; Figures 3.2 & 3.3). In addition to magma differentiation by partial melting and fractional crystallization, two important factors influence magma compositions in subduction zone settings:

1. The fluid-mobility of trace elements (solubility)
2. Fluid-mediated mass transfer among chemically distinct rock types

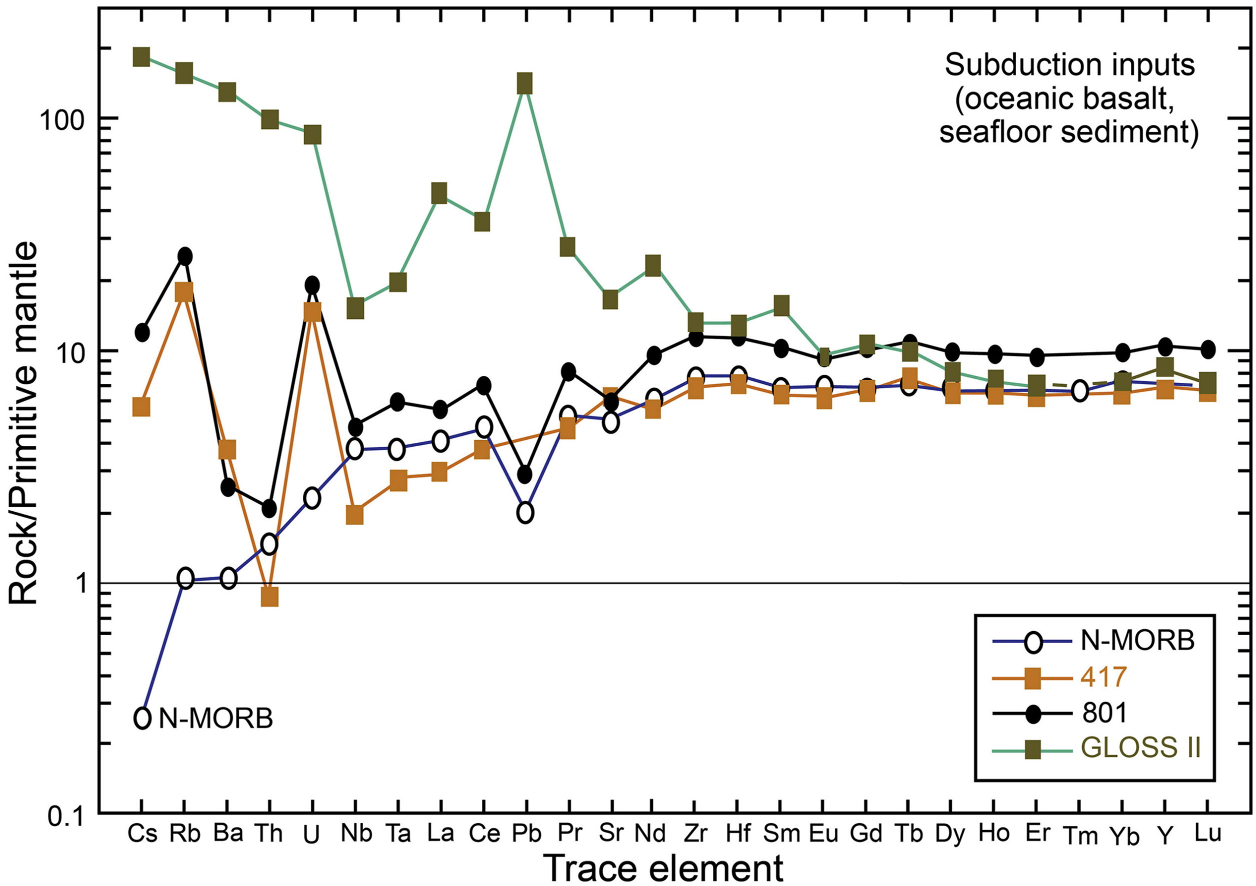

Figure 3.2: Primitive mantle normalized spider diagrams showing the inputs into subduction zones. Note the relative enrichment of fluid-mobile elements (LILEs; Cs^{+}, Rb^{+}, K^{+}, Ba^{2+}, Sr^{2+} and Pb^{2+}) and relative depletion of fluid-immobile elements (HFSEs; Y^{3+}, REE^{3+}, Th^{4+}, Zr^{4+}, Hf^{4+}, Nb $^{5+}$, and Ta^{5+}) in seafloor sediments (GLOSS II) and altered mid-ocean ridge basalts (417 & 801) compared to normal mid-ocean ridge basalts (N-MORBS). From Zheng (2019). Data sources: altered oceanic basalt (ODP sites 417 and 801, Kelley et al., 2003; Staudigel et al., 1996), globally subducting sediment (GLOSS II, Plank, 2014).

3.1 Beryllium-10: the smoking gun

While the trace element patterns of volcanic outputs from subduction zones (i.e. island arc basalts; Figures 3.2 & 3.3) suggest seafloor sediments are somehow mixing their chemical signature with the upper mantle during flux melting, the process is not well-understood because direct observations are not possible. So how do we know that sediments are in fact being deeply subducted?

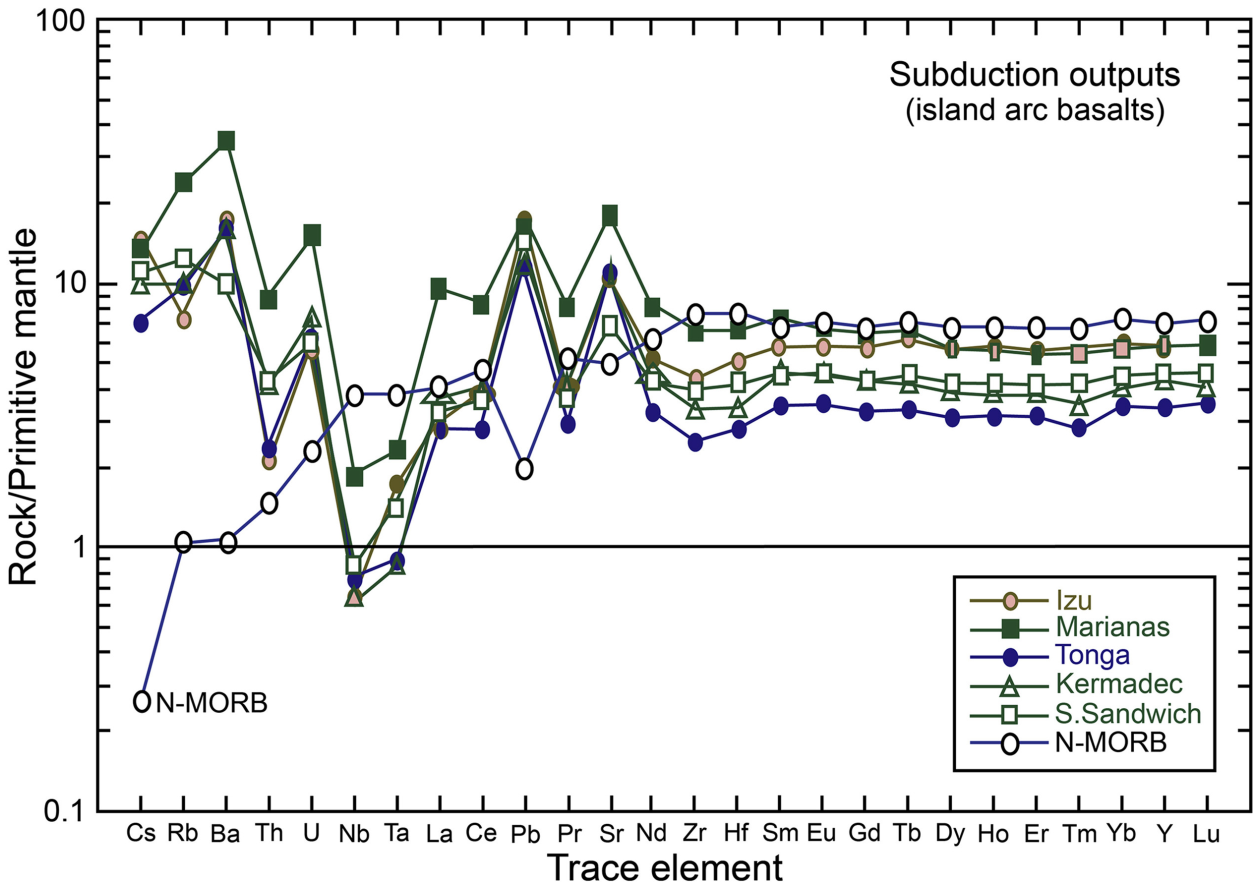

Figure 3.3: Primitive mantle normalized spider diagrams showing the outputs from subduction zones. Note the relative enrichment of fluid-mobile elements (LILEs; Cs^{+}, Rb^{+}, K^{+}, Ba^{2+}, Sr^{2+}, and Pb^{2+}) and relative depletion of fluid-immobile elements (HFSEs; Y^{3+}, REE^{3+}, Th^{4+}, Zr^{4+}, Hf^{4+}, Nb $^{5+}$, and Ta^{5+}) in island arc basalts compared to normal mid-ocean ridge basalts (N-MORBS). Note the similarities and differences of LILEs, Th, and Pb between subduction zone inputs and outputs. From Zheng (2019). Data source: island arc basalts (Elliott, 2003).

The short-lived radioactive isotope Beryllium-10 (^{10}Be) might provide definitive evidence. ^{10}Be is created in Earth's atmosphere in a process called spallation and decays rather quickly with a half-life of 1.39 Ma. ^{10}Be can fall out of the atmosphere and into Earth's oceans within raindrops, where it ultimately gets incorporated into clay minerals on the seafloor (pelagic sediments). Since ^{10}Be has such a short half-life, the only way it could possibly be detected in island arc basalts is if it gets quickly subducted with seafloor sediments, transfers via fluids into the upper mantle wedge, and erupts as lava back onto Earth's surface before it decays away beyond detection limits of analytical instruments (Blake et al., 2008).

Modern mass spectrometers can measure ^{10}Be at concentrations as low as 10^6 atoms per gram, so in principle even tiny amounts of ^{10}Be in seafloor sediments should be detectable in island arc basalts if the sediments are subducted quickly enough.

4 Test your knowledge (25pts)

If a plate is subducted at 5.3 cm/yr and carries sediments with trace amounts of ^{10}Be into the mantle, how long would it take the sediments to reach a depth of 90 km? Assume the sediments enter the trench at t=0 and that the subduction dip angle is 48°. Hint: this problem involves solving for sides of a right triangle with trigonometric functions. **Sketch the problem on paper, or digitally, and show your work**. See Figure 4.1 to get started.

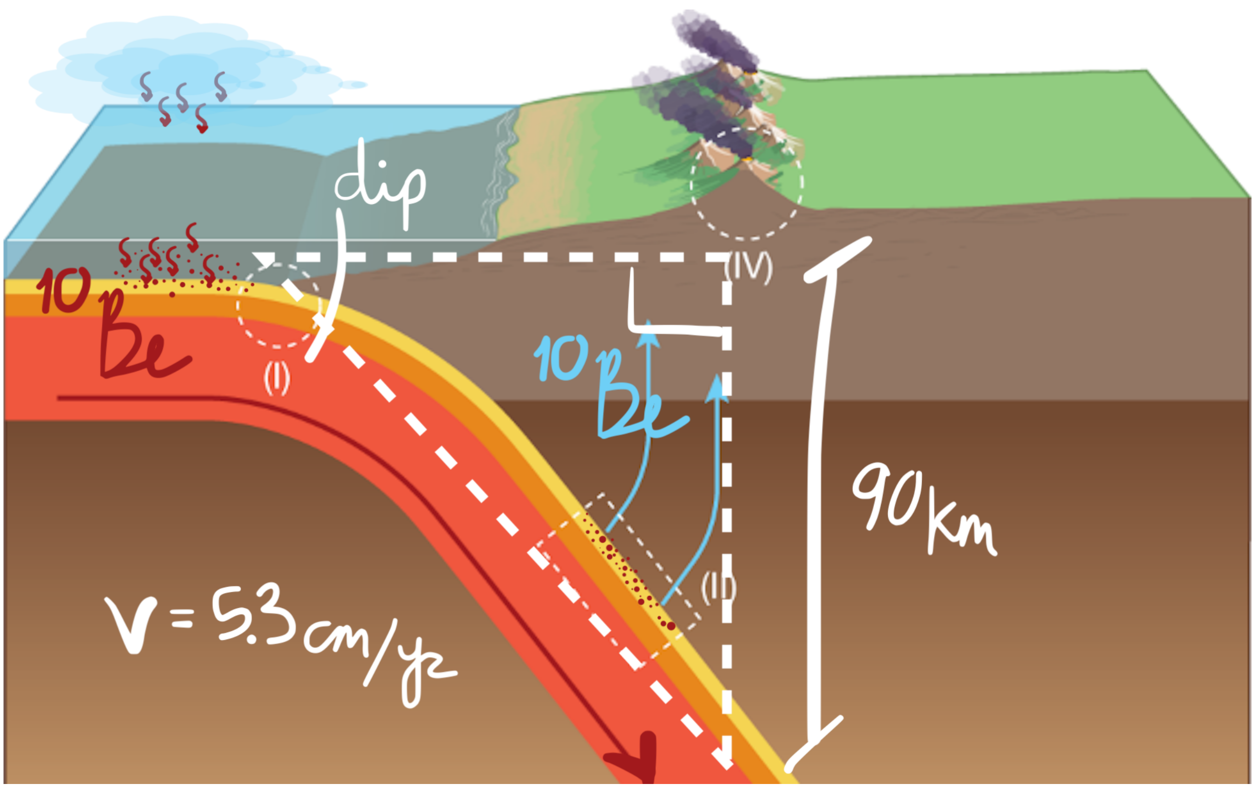

Figure 4.1: Problem setup. Hint: you will need to use the trig functions (sine, cosine, and/or tangent) to solve for the vertical subduction rate. After Plank & Manning (2019).

4.1 Follow-up question

How long would it take the sediments to reach a depth of 90 km if the plate is subducted at 9.5 cm/yr? Given that ^{10}Be has a half-life of 1.39 Ma, how many half-lives of ^{10}Be will elapse by the time sediments are delivered to 90 km depth? **Record these calculations in a table** and answer the following: **what does subduction rate imply about our ability to detect ^{10}Be in island arc basalts**?

5 Laboratory procedure

5.1 Get data from EarthChem (5pts)

We are downloading data that originated from Tera et al. (1986), which compiled ^{10}Be isotopic measurements from 109 volcanic rocks from subduction zones and 33 basalts from mid-ocean ridges. The original study is posted on our course Canvas page.

1. Open a web browser and search for EarthChem
2. Click "Search data"
3. Click "EarthChem portal"
4. Query the EarthChem portal by referencing Tera et al. (1986)
   → Click "Set" under "Reference" in the "Create a search query" box
   → Enter "tera" and "1986" into the author and year fields
   → Include only GEOROC samples and click "Continue to data selection"
5. Click "Get chemical data"
6. Select "text file" and "one row per sample" options
7. Click "Go to data" to download

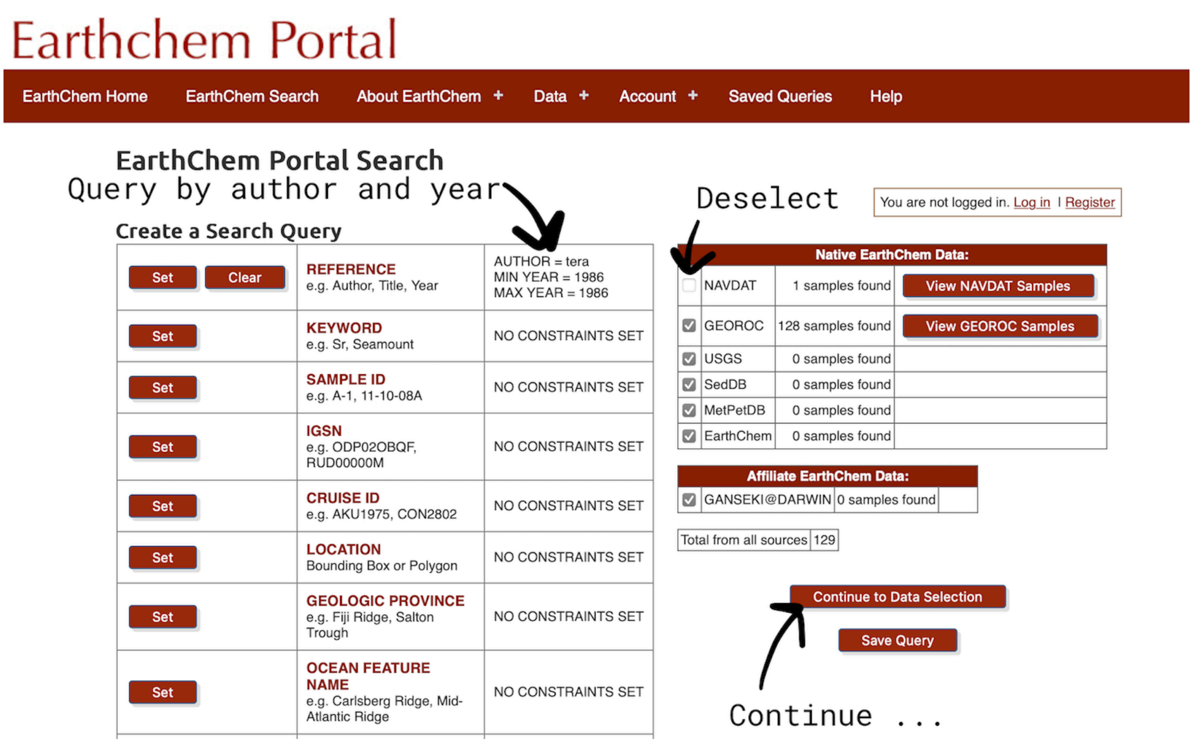

Figure 5.1: Query EarthChem by author and year of the reference study Tera et al. (1986).

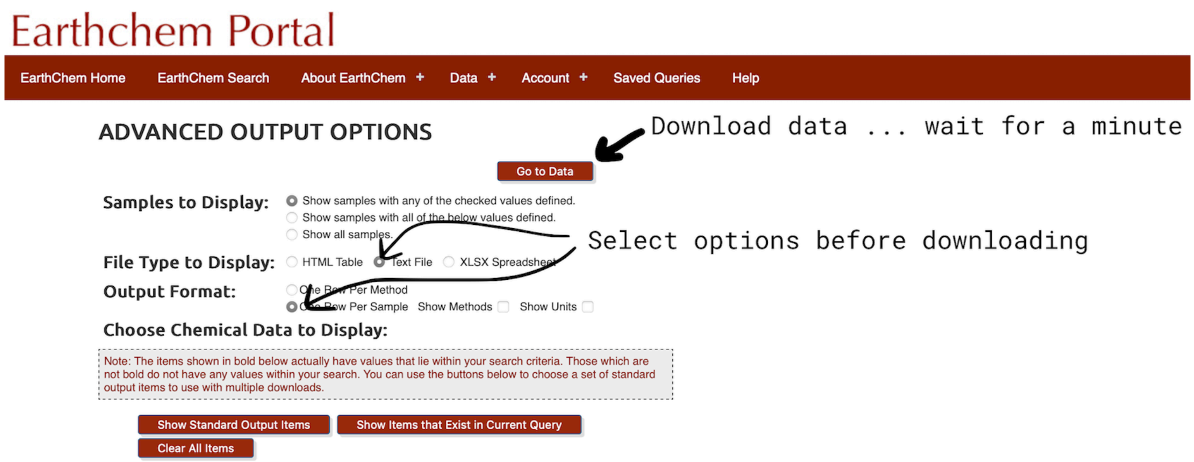

Figure 5.2: Download the raw geochemical data as a text file with one row per sample.

5.2 The more you know (5pts)

Who maintains and funds EarthChem? **Write this down down in your notes**.

5.3 Explore the data (15pts)

Use excel, a text editor, or another program of your choice to **open the data file**. Most geochemical data comes in a rectangular shape, with each column representing a variable and each row representing a single observation or sample.

Look at the data structure and ask yourself:

- → Can I make sense of all of the variables?
- → Are there missing variables that I would like to have?
- → Are some of the variables redundant or useless?
- → Is the format consistent for each observation?
- → How many observations are there?
- → Do I know what the values are?
- → Do I know what the units are?
- → Are there blank cells? Why?

In a few sentences, **write down three observations about the data structure that stand out to you**.

5.4 Quality assurance (15pts)

Compare the data you downloaded from EarthChem to the table published in the original article (Figure 5.3). **Write down which variables from the original table did not make it into the EarthChem repository**. If I were to ask you to add the missing variables back into your data file and carefully check the accuracy of all 128 observations, **give me a first-order estimate of how much time that might take you to complete** (in hours and minutes).

TABLE 1: Flood, Rift, Oceanic Island and Mid-ocean Ridge Basalts Analyzed for ^{10}Be

Location	Lat.	Long.	Vol. No.[1]	Rock Type	Age[2]	Donor/ I.D.[3]	Alt.[4]	^{10}Be[5]
OCEANIC ISLANDS AND RIFT VOLCANOES								
Pribilofs	57.17	-170.25	1104-07	Basalt	?	Marsh/SG 7	V	0.1
Pribilofs	57.17	-170.25	1104-07	Basalt	?	/SG 11	V	0.2
Kilauea	19.43	-155.29	1302-01	Basalt	1960	Philpotts/HHP-66-1	II	0.6
Kilauea	19.43	-155.29	1302-01	Basalt	1921	Marsh/KIL-4		0.7
Kilauea	19.43	-155.29	1302-01	Basalt	1921	Marsh/KIL-4		0.4
Duplicate								0.1
Kilauea	19.43	-155.29	1302-01	Basalt	1959	USNM/113500		0.1
Kilauea	19.43	-155.29	1302-01	Basalt	1983F	Zoller		0.1
Mauna Loa	19.48	-155.61	1302-02	Basalt	1950	USNM/113502-8		0.2
Krafla	65.73	-16.68	1703-11	Basalt	1977	USNM/115380-5		0.2
Krafla	65.73	-16.68	1703-11	Basalt	1984F	Rubin		<0.2
Krafla	65.73	-16.68	1703-11	Basalt	1984F	Rubin		<0.2
Azores	38.60	-28.73	1802-01	Basalt	1958	USNM/109363	I	0.0
Nyamuragira	-1.38	29.20	0203-02	Basalt	1981F	Katsui	II	0.2
Duplicate								0.3
Erebus	-77.58	167.17	1900-02	Basalt	1979F	Zoller		0.7
Duplicate								0.2
MORB								
Juan de Fuca	44.67	-139.33		Basalt		USNM/111240-225		0.1
E. Pacific	-3.40	-102.60		Basalt		USNM/113673-11		0.2
Galapagos	4.23	-85.30		Basalt		USNM/113152		0.3
Carlsberg	3.42	63.54		Basalt		USNM/115294-12		0.9
Indian O.	-34.98	69.99		Basalt		USNM/113716-7		0.1
FLOOD BASALTS								
Watchung	?	?		Basalt	~200 My	Geigengack	VI	0.3
Grande Ronde	45.30	118.33		Basalt	15 My	Carlson/W-3		0.7
Umatilla	46.15	119.15		Basalt	13.5 My	Carlson/WU-2		0.2
Abert Rim	42.40	120.15		Basalt	15.5 My	Carlson/OR-3		0.3
ALTERED SAMPLES								
Kilauea	19.43	-155.29	1302-01	Basalt	1955	Marsh/KIL6		16.3
Duplicate								2.7
Steens Mt.	42.40	118.33		Basalt	15.5 My	Carlson/50-1		10.3
Steens Mt.	42.40	118.33		Basalt	15.5 My	Carlson/50-2		7.7
Steens Mt.	42.40	118.33		Basalt	15.5 My	Carlson/50-6		2.4
Steens Mt.	42.40	118.33		Basalt	15.5 My	Carlson/50-4		0.6
Steens Mt.	42.40	118.33		Basalt	15.5 My	Carlson/50-5		0.3

[1]Volcano number taken from Simkin et al. 1981.
[2]"A" denotes a flow from an active volcano, "H" an historic flow, "F" a flow taken immediately after eruption.
[3]Donor/I.D. lists names of sample donor and donor's sample identification. USNM samples were made available by W. Melson.
[4]Alteration class. See Table 3.
[5]^{10}Be concentrations, 10^6 atoms/gram.

Figure 5.3: Original data table published in Tera et al. (1986). Data like these have been painstakingly digitized into online repositories like EarthChem. However, the information is often transferred inaccurately and/or incompletely.

In light of this estimated time commitment, in 1-3 sentences, **write down anything that comes to mind about how your views have changed towards quality assurance with respect to data collection, transfer, and storage**.

5.5 Data cleaning and visualization (35pts)

Raw EarthChem data at a glance

```
Rows: 128
Columns: 17
$ `SAMPLE ID` <chr> "2", "2", "KIL-4", "KIL-4", "KIL-4", "RUBIN1", "RUBIN2", "
$ IGSN        <lgl> NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA
$ SOURCE      <chr> "GEOROC", "GEOROC", "GEOROC", "GEOROC", "GEOROC", "GEOROC"
$ REFERENCE   <chr> "TERA, F.; BROWN, L.; MORRIS, J. D.; SACKS, I. S.; KLEIN,
$ `CRUISE ID` <lgl> NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA
$ LATITUDE    <dbl> 38.000, 38.000, 19.430, 19.430, 19.430, 65.730, 65.730, 19
$ LONGITUDE   <dbl> 141.00, 141.00, -155.29, -155.29, -155.29, -16.68, -16.68,
$ `LOC PREC`  <dbl> 0.100, 0.100, 0.010, 0.010, 0.010, 0.010, 0.010, 0.010, 0.
$ `MIN AGE`   <dbl> NA, NA, NA, NA, NA, NA, NA, NA, NA, 15.5, 15.5, NA, NA, 15
$ AGE         <dbl> NA, NA, NA, NA, NA, NA, NA, NA, NA, 15.5, 15.5, NA, NA, 15
$ `MAX AGE`   <dbl> NA, NA, NA, NA, NA, NA, NA, NA, NA, 15.5, 15.5, NA, NA, 15
$ MATERIAL    <chr> "igneous", "igneous", "igneous", "igneous", "igneous", "ig
$ TYPE        <chr> "volcanic", "volcanic", "volcanic", "volcanic", "volcanic"
$ COMPOSITION <chr> NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA
$ `ROCK NAME` <chr> "andesite", "andesite", "tholeiite", "tholeiite", "tholeii
$ MINERAL     <lgl> NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA, NA
$ BE10        <dbl> 0.6, 0.8, 0.7, 0.4, 0.1, 0.0, 0.0, 16.3, 2.7, 10.3, 7.7, 0
```

Cleaned data at a glance

```
Rows: 133
Columns: 8
$ id        <chr> "mm77-102", "kan5-8", "adag-81dr", "k81-7a", "at112", "at129
$ region    <chr> "alaska", "alaska", "alaska", "alaska", "alaska", "alaska",
$ location  <chr> "adak", "kanaga", "adak", "kastochi", "atka", "atka", "atka"
$ type      <chr> "iav", "iav", "iav", "iav", "iav", "iav", "iav", "iav", "iav
$ latitude  <dbl> 51.92, 51.93, 52.00, 52.18, 52.38, 52.38, 52.38, 52.38, 52.3
$ longitude <dbl> -176.75, -177.15, -176.58, -175.50, -174.15, -174.15, -174.1
$ rock      <chr> "xenolith", "basalt", "xenolith", "andesite", "basalt", "bas
$ be10      <dbl> 3.30, 5.80, 0.70, 4.08, 2.50, 2.00, 3.30, 3.00, 2.60, 2.70,
```

Download the "cleaned" dataset posted on our Canvas course page. In excel, a text editor, or program of your choice, explore these data and try to notice any differences compared to the EarthChem version. In a sentence or two, **write down any of your thoughts on the presentation of this updated dataset compared to the raw EarthChem dataset**.

Using excel or program of your choice, **reproduce your own version of the histograms shown in Figures 5.4 & 5.5**. There are three goals: 1) compare the ^{10}Be concentrations of various rock types, 2) compare the ^{10}Be concentrations of island arc volcanic rocks (type = "iav") among various regions, and 3) do this carefully such that our figures are compelling, informative, and useful for making interpretations.

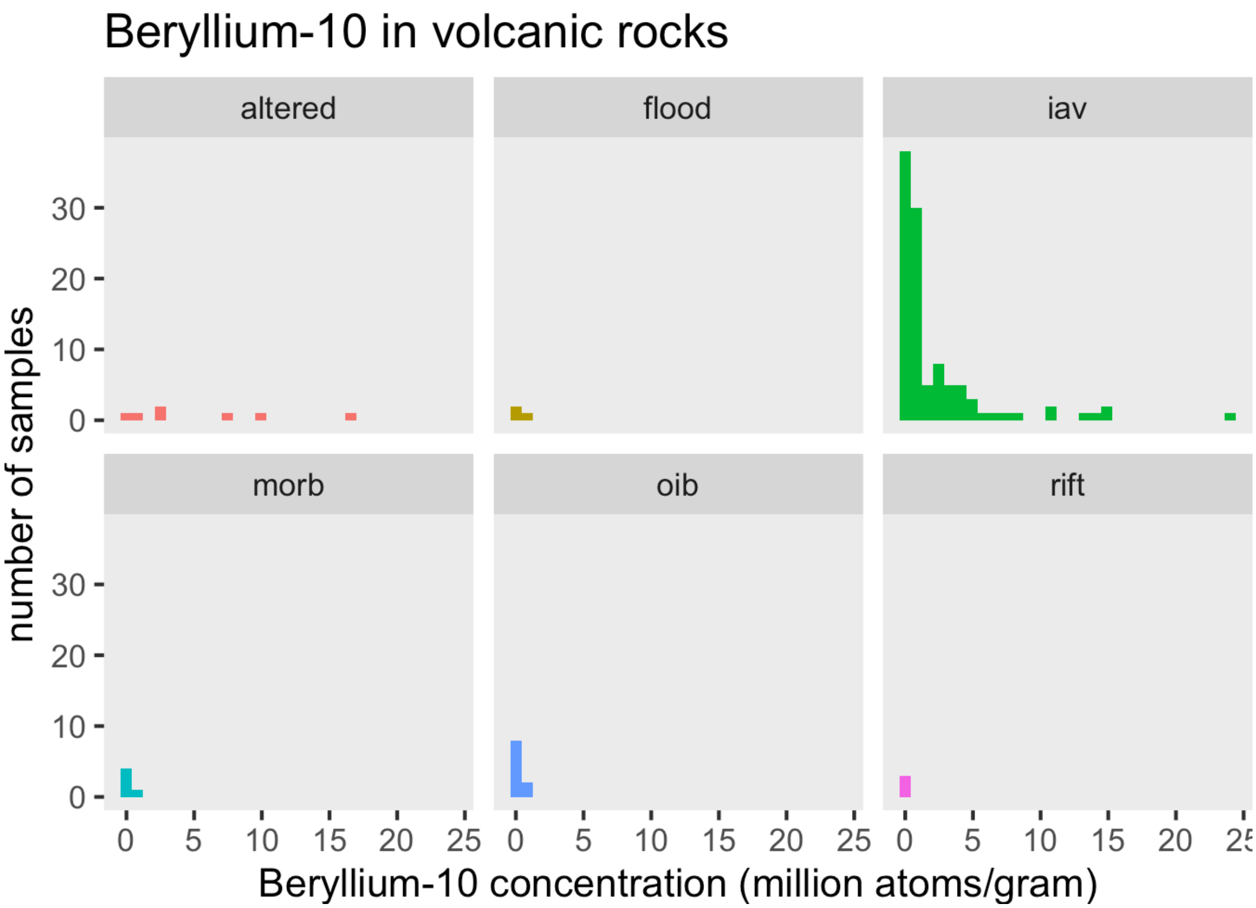

Figure 5.4: Beryllium-10 concentrations in various volcanic rock types. Types = altered: hydrothermally-altered samples, flood: continental flood basalt, morb: mid-ocean ridge basalt, oib: ocean-island (hotspot) basalt, rift: continental rift basalt. Data from Tera et al. (1986).

Please be creative and think carefully about the best ways to represent these data. To get full points the figures must include the following elements:

→ An informative title
→ Both axes labels with units (if any)
→ A legend (if using symbols or colors)
→ A caption to help the reader understand the figure

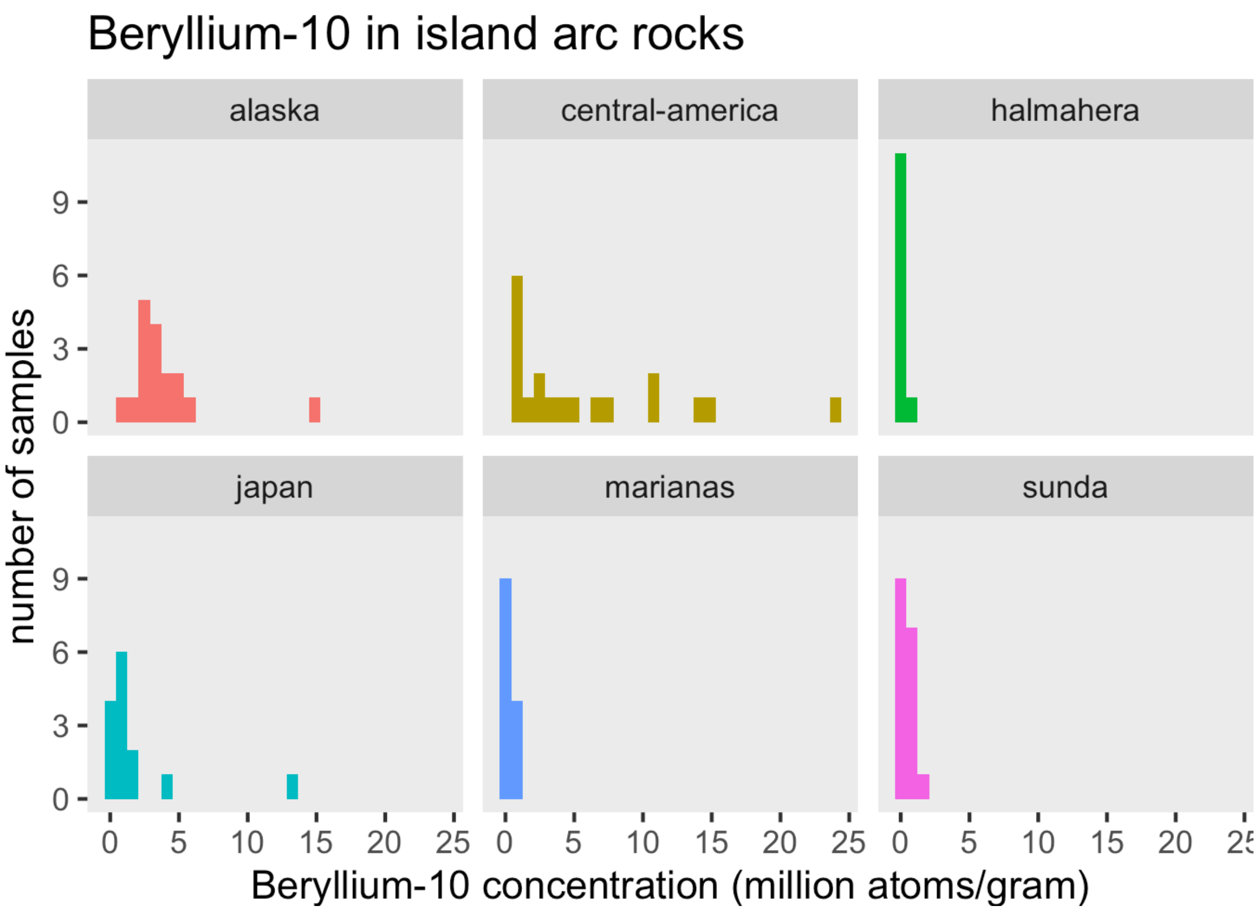

Figure 5.5: Beryllium-10 concentrations in island arc rocks from various regions. Data from Tera et al. (1986).

5.6 Interpreting the data

Recall that ^{10}Be is not found in the mantle, but is concentrated to some degree in Earth's atmosphere, oceans, and seafloor sediments. So how does ^{10}Be show up in some volcanic rocks that were sourced from the mantle? Which rock types are they? And what does a measurable concentration of ^{10}Be imply about sediment cycling in subduction zones? **In a paragraph, answer the three questions above.** Use your plots as supporting evidence for your claims.

Further reading for the curious

Read more about the challenging nature of sharing geochemical data in this article written by members of the international geochemical community (including the current project director of EarthChem, Kerstin Lehnert).

R code

The following code was used to make the figures in this lab exercise.

```
# Load libraries
library(magrittr)
library(readr)
library(ggplot2)
```

```
# Read data and look at its structure
data <- read_tsv('data/earthchem_download_93232.txt')
glimpse(data)
data <- read_csv('data/tera-1986-geochemica-be10-clean.csv')
glimpse(data)
```

```
# Visualize samples by rock type
data %>%
  ggplot() +
  geom_histogram(aes(be10, fill = type, group = type)) +
  facet_wrap(~type, ncol = 3) +
  labs(
    title = 'Beryllium-10 in volcanic rocks',
    y = 'number of samples',
    x = 'Beryllium-10 concentration (million atoms/gram)',
    fill = 'rock type'
  ) +
  guides(fill = 'none') +
  theme_gray(base_size = 16) +
  theme(plot.margin = margin(), panel.grid = element_blank())
```

```
# Visualize island arc samples by region (with sample sizes >= 10)
data %>%
  filter(type == 'iav') %>%
  group_by(region) %>%
  filter(n() >= 10) %>%
  ggplot() +
  geom_histogram(aes(be10, fill = region, group = region)) +
  facet_wrap(~region, ncol = 3) +
  labs(
    title = 'Beryllium-10 in island arc rocks',
    y = 'number of samples',
    x = 'Beryllium-10 concentration (million atoms/gram)',
    fill = 'region'
  ) +
  guides(fill = 'none') +
  theme_gray(base_size = 16) +
  theme(plot.margin = margin(), panel.grid = element_blank())
```

References

Angiboust, S., Wolf, S., Burov, E., Agard, P., & Yamato, P. (2012). Effect of fluid circulation on subduction interface tectonic processes: Insights from thermo-mechanical numerical modelling. *Earth and Planetary Science Letters*, *357*, 238–248.

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Kelley, K., Plank, T., Ludden, J., & Staudigel, H. (2003). Composition of altered oceanic crust at ODP sites 801 and 1149. *Geochemistry, Geophysics, Geosystems*, *4*(6).

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Plank, T., & Manning, C. (2019). Subducting carbon. *Nature*, *574*(7778), 343–352.

Staudigel, H., Plank, T., White, B., & Schmincke, H. (1996). Geochemical fluxes during seafloor alteration of the basaltic upper oceanic crust: DSDP sites 417 and 418. *Washington DC American Geophysical Union Geophysical Monograph Series*, *96*, 19–38.

Tera, F., Brown, L., Morris, J., Sacks, I., Klein, J., & Middleton, R. (1986). Sediment incorporation in island-arc magmas: Inferences from 10Be. *Geochimica Et Cosmochimica Acta*, *50*(4), 535–550.

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