Measuring Plate Motion with GPS: Iceland

Student worksheet

Situated 1817 km from London, England in the Northern Atlantic Ocean, Iceland is a lively country increasingly popular with tourists from around the world that are traveling, in part, to see its ever-changing tectonic landscapes. The volcanoes and geothermal features which dot the island though are not random and are active parts of the terrain. In 2010, Eyjafjallajökull (left), located on the southern portion of Iceland roared to life and for three months caused havoc with European air travel due to the large amount of glass-rich ash and debris ejected up to 8km into the atmosphere.

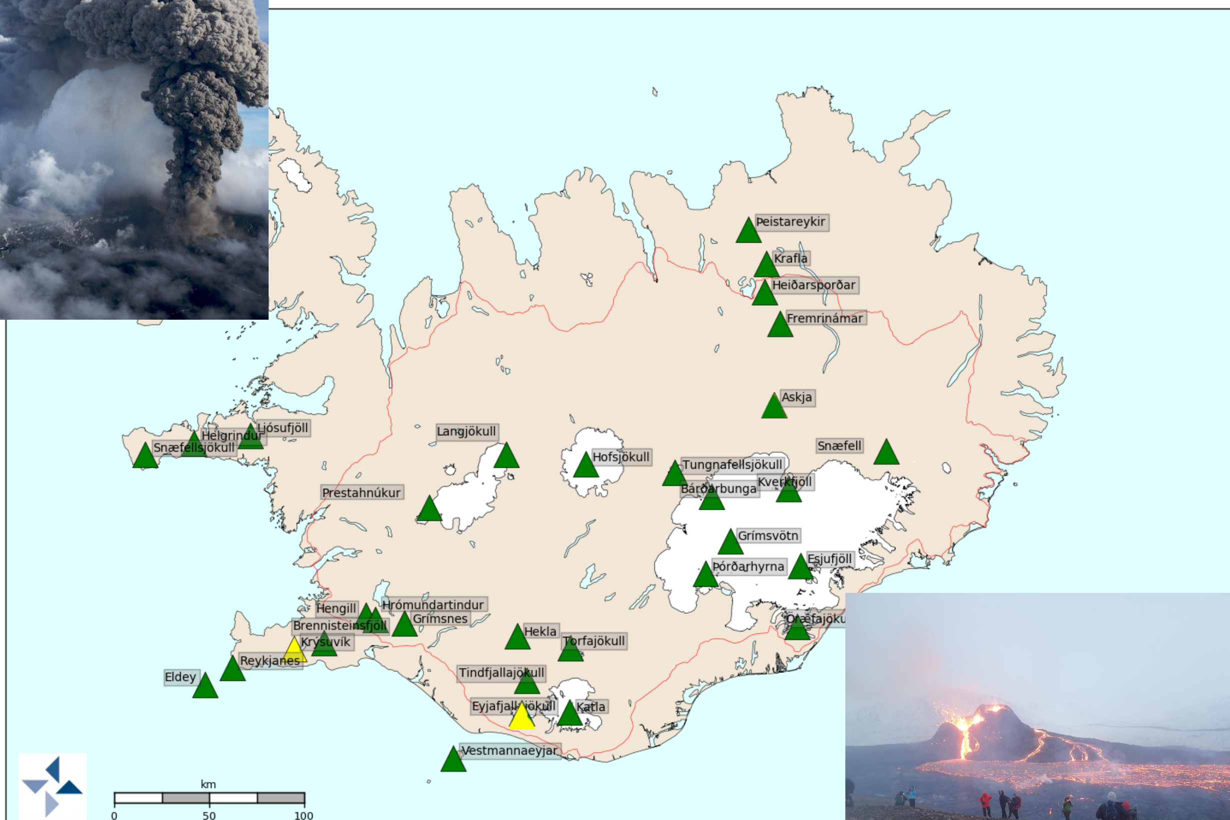


Image 2; Berserkur - CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=102361635

In March 2021, after lying dormant for 800 years, Geldingadalir (right) on the Reykjanes peninsula, erupted effusively with a large amount of magma being produced and eventually partially filling three different valleys. Two defensive barriers were built in early May 2021 in an attempt to divert flows away from telecommunication lines and the southern coastal road but by late May those barriers had already been overrun. After 8 months of spectacular eruptions, Geldingadalir ceased activity.

These volcanic eruptions are a result of plate boundary tectonics and are a highly visual aspect of the terrain. In both cases, earthquake swarms predated the eruptions and told researchers that something was happening beneath the surface.

Student version. May 1 2022. Roger Groom, Cate Fox-Lent, and Shelley Olds, UNAVCO. Revised (2015) by Nancy West and Kathleen Alexander; additional revisions (2022) David Thesenga

Under our feet is a dynamic, ever-changing Earth. Pressure builds. Time passes. Earth's outer shell is rearranged. Sooner or later – a sudden shift releases the pent-up pressure. Earthquake!

Scientists monitor Earth's movement in advance of an earthquake so we can be more prepared. Global Positioning System (GPS) is used to study how Earth's tectonic plates move and deform. GPS monuments are cemented into the ground to measure how the underlying plate moves in three directions (north-south, east-west, and up-down). While GPS units in a car measure movement in miles per hour, high-precision GPS units used for scientific studies measure tectonic plate movement as slow as **a few millimeters in a year**. Even those few millimeters can be important—slowly moving crust can build up energy, leading to an earthquake.

Part 1: How does GPS work to pinpoint a location on Earth?

Pinpointing location with GPS:

1. What can we do with geodesy?
2. What do the pieces of bubblegum represent? How far above the Earth would they actually be?
3. What does each length of string represent?
4. How many satellites are needed to pinpoint the location of a spot on Earth? Why?

5. Sketch a diagram of the locating position demonstration, labeling the components: satellites (and the number needed to pinpoint a location), distance (time), and GPS/Earth.

6. What is the ground station's purpose?

7. Sketch a diagram to show the parts of the gumdrop GPS and components of a GPS station:

Procedure for using gumdrops to model a GPS monument:

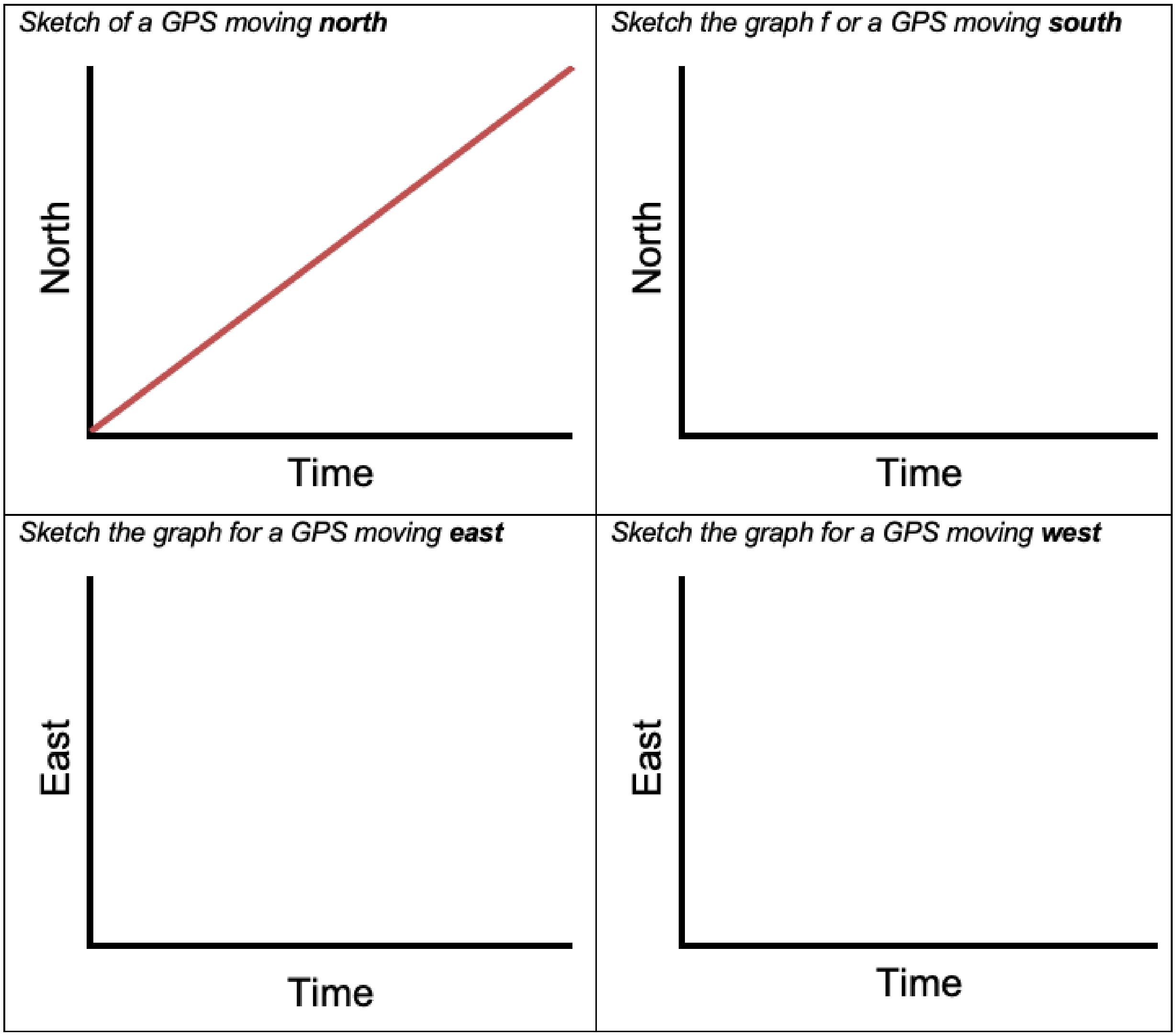
1. Insert three toothpicks diagonally into the gumdrop (the GPS antenna). The toothpicks will act as the legs or braces to hold the monument steady.
2. Insert a slightly shorter toothpick sticking straight down from the middle of the gumdrop. The tip of this toothpick should be just barely above the surface. This will be the *"place marker."*
3. Put very small pieces of clay on the bottom of the legs (not the place marker) and affix the GPS to the transparency. The clay acts as cement to hold the GPS monument in place. In reality, the legs are concreted deep into the ground. When the ground moves, the GPS also moves.
4. Set aside this model for now. Answer questions 6-7 above in the right-hand column.

Part 2: What can GPS tell us about Iceland?

Introduction: Measuring GPS Movement with Time Series Plots:

Time series plots show the position of a monument as time passes. There are three directional components: north-south, east-west, and up-down movement (You will not be using the vertical motion in this exercise).

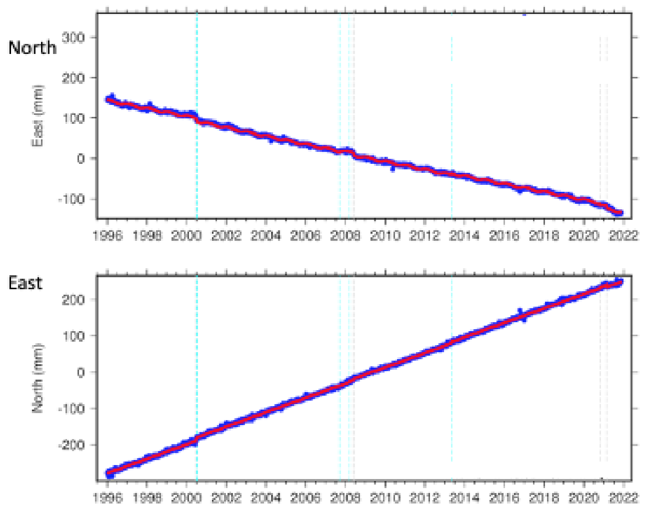
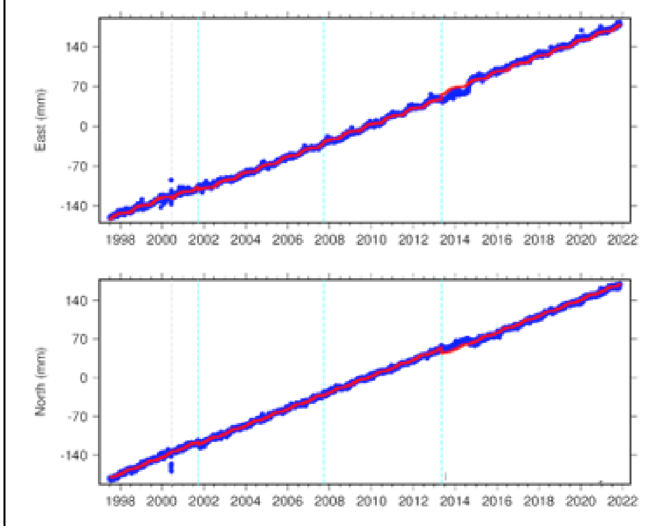
As a reference to help read time series plots, **sketch what graphs look like for each direction vs. time in the box below**. Use your model to envision a monument moving purely north through time. What would its graph look like? (See below for this example.)



Exploring Iceland's GPS data and maps

By analyzing multiple GPS time series plots you can determine the directions and rates of regional deformation. As the ground moves, these GPS stations move with it. Look at the data from GPS monuments REYK and HOFN, from Iceland on the next page.

Use the data from GPS Monuments REYK and HOFN to answer the questions below.

GPS Monument REYK	GPS Monument HOFN
	

24 Hour Positions Using Final Orbits (blue) and Rapid Orbits (magenta).
Processed by the Nevada Geodetic Laboratory.
Plotted on 2021-Dec-28. Last data on 2021-Nov-20.

1. Think, simulate the movement of each GPS using the data and the map with your gumdrop GPS models, then discuss with your neighbor: what general directions are monuments REYK and HOFN moving? How did you determine this?

   REYK is moving __________ HOFN is moving ______________

2. Are the two monuments moving towards each other, away from each other, or in the same direction?

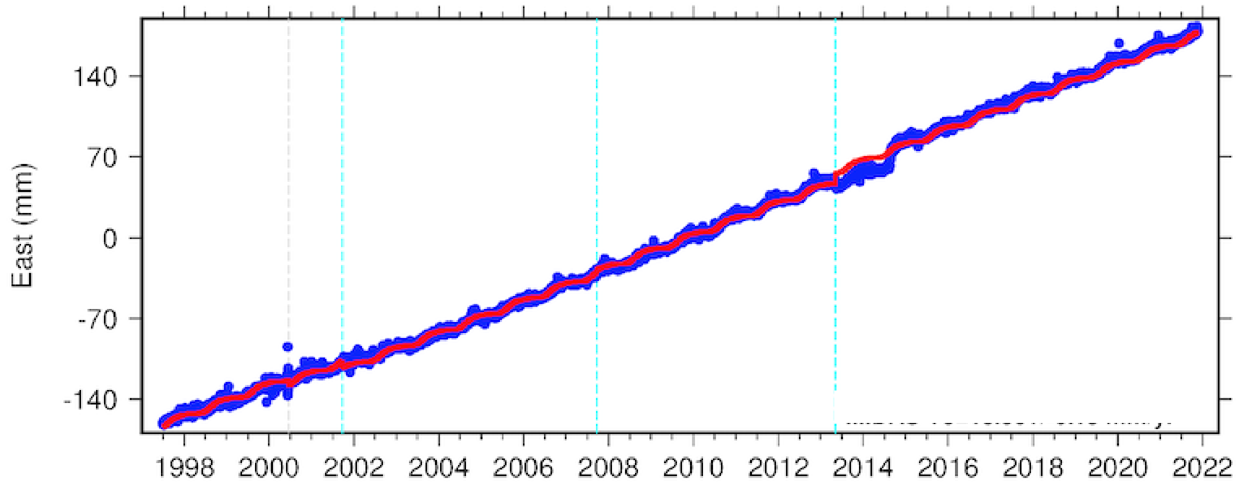
3. On these time series plots, the trend lines have already been drawn for you. What are the units of measurement for these time series?

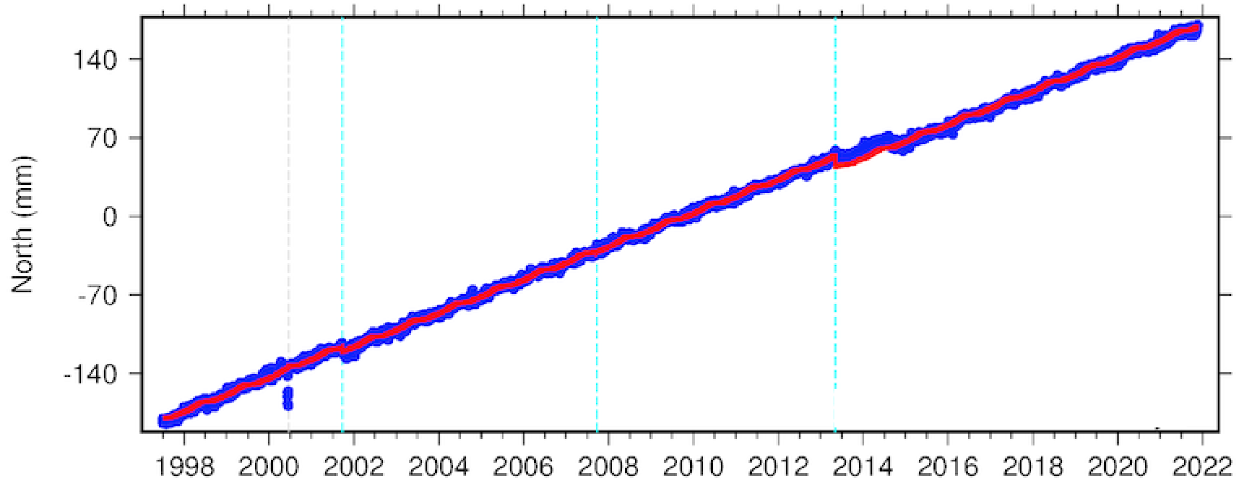
   X-axis uses _______________ and y-axis uses _______________________

<u>Calculating velocities of the GPS stations:</u>

On the next two pages are larger copies of the time series plots for HOFN and REYK. Complete the tables under the data to calculate annual motions in north-south and east-west directions for REYK and HOFN.

HOFN time series plot 1997 – 2021 (North and East plots)





(Movements to the south and east are written as negative numbers).

HOFN North plot:
Over 10 years, how far did HOFN move? ________ millimeters (mm) in 10 yrs

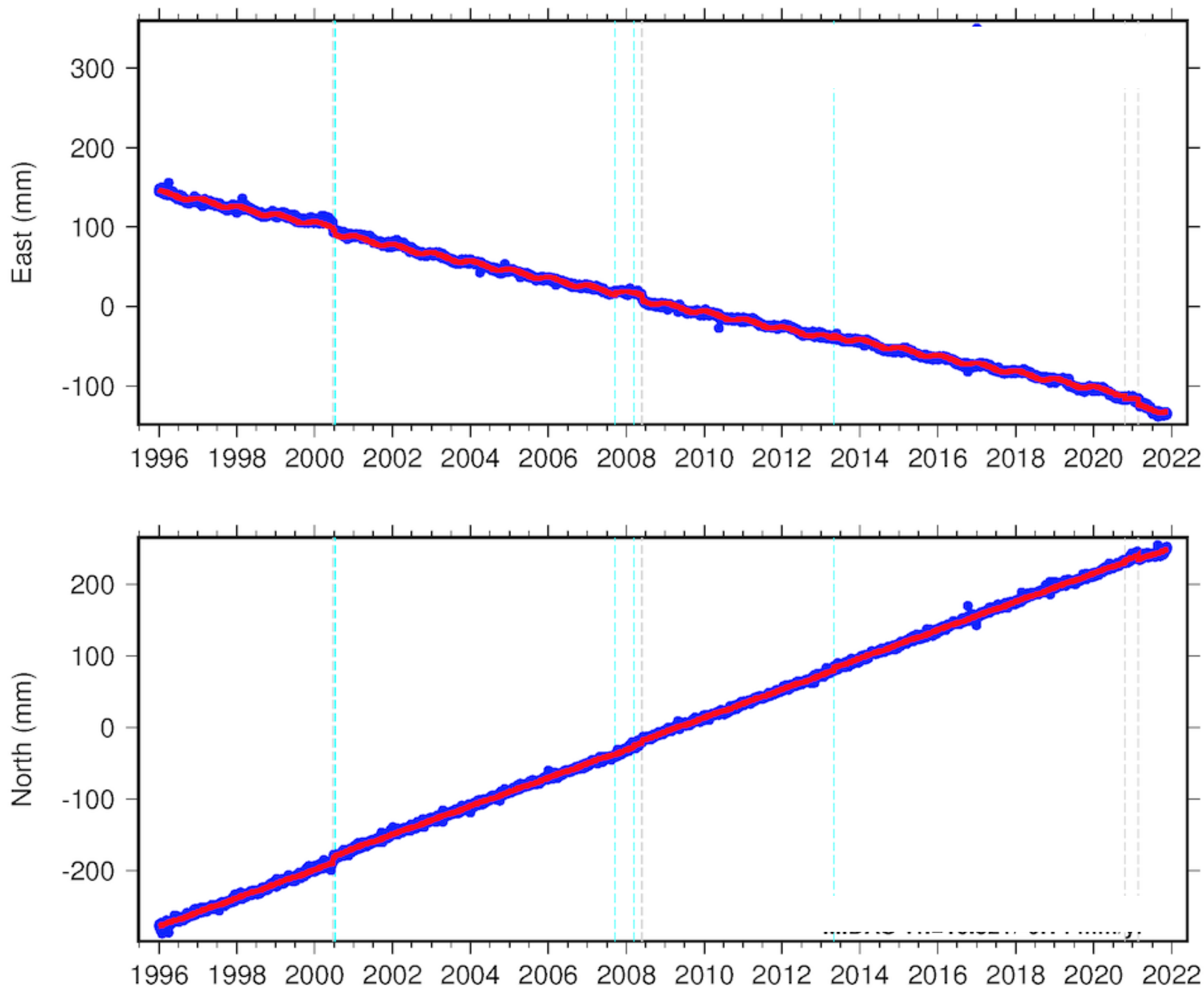
Each year, this station is moving: _________ mm/year to the (north or south) (circle one).

HOFN East plot:
Over 10 years, how far did HOFN move? __________ mm over 10 years.

Each year, this station is moving ________ mm/year to the (east or west). (circle one)

HOFN: Do you findings agree with your previous answer about the general motion of HOFN?

REYK time series plot 1997 – 2021 (North and East plots)



(Movements to the south and east are written as negative numbers).

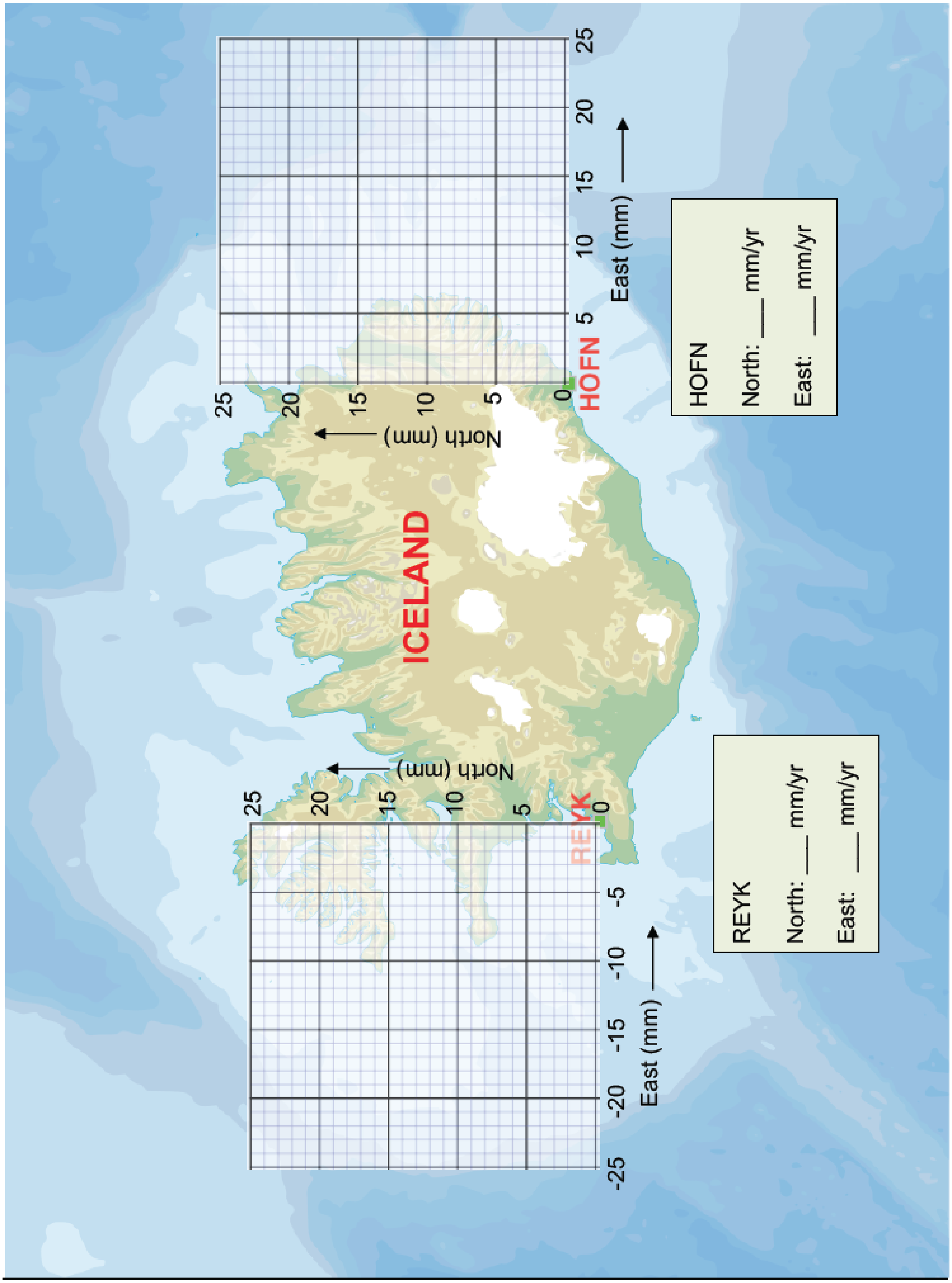
REYK North plot:
Over 10 years, how far did REYK move? _______ millimeters (mm) in 10 years

Each year, this station is moving: _______ mm/year to the (north or south). (circle one)

REYK East plot:
Over 10 years, how far did REYK move? _________ mm over 10 years.

Each year, this station is moving… ________ mm/year to the (east or west). (circle one)

REYK: Do your findings agree with your previous answer about the general motion of HOFN?


ICELAND
HOFN
North (mm)
East (mm)
0 5 10 15 20 25
HOFN
North: ___ mm/yr
East: ___ mm/yr
REYK
North (mm)
East (mm)
0 -5 -10 -15 -20 -25
0 5 10 15 20 25
REYK
North: ___ mm/yr
East: ___ mm/yr

Displaying Horizontal Velocities on a Map

We know the velocity each monument is moving in the north-south direction and in the east-west direction. Now we are going to add these together to show the total horizontal motion.

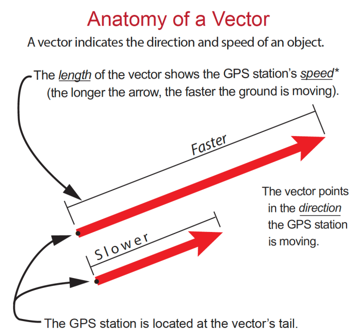
1. Copy your answers from the previous pages for REYK and HOFN onto the blanks at the bottom of the map of Iceland on the previous page. Remember that directions to the south and west are written as negative values. REYK is on the west side of Iceland; HOFN is on the east side of Iceland.

Drawing vectors to show velocity

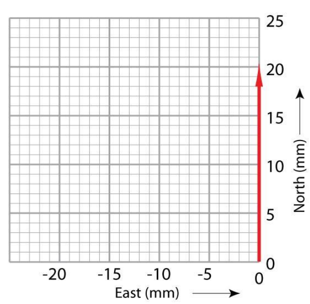
What is a vector?

A vector is a special type of arrow that shows velocity and the direction of motion. We can draw a vector to show the north motion and another vector to show the east (or west) motion. By adding them together we can show the total horizontal motion!

The **vector's tail** is the location of the GPS monument.
The **direction the vector points** is the direction the GPS station is moving.
The **length of the vector** represents the velocity the GPS monument and the land beneath it is moving.

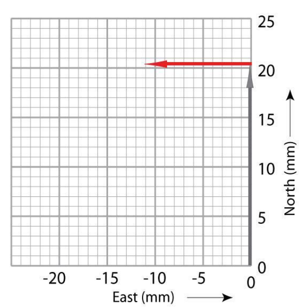


Adding vectors: Step 1.



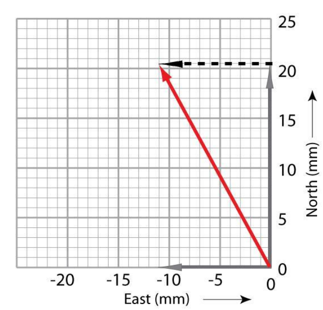
Start at the origin (0,0) draw a light arrow along the north axis the length equal to the north velocity (e.g. one block is 1 mm/yr.)

Step 2.



Draw the east vector from the end of the north vector's arrowhead.
(A vector moving west is drawn to the west.)

Step 3.

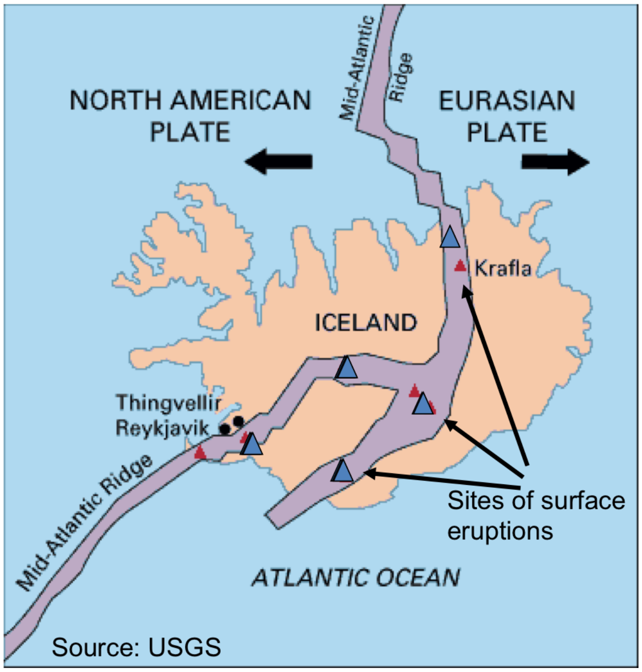


Draw a diagonal arrow from (0,0) to the arrowhead of the east vector. This new vector is the sum of the north and east vectors.

2. Following the steps above, use the graph paper on the map near REYK to add the North and East velocities together to find the total horizontal velocity for REYK on the previous page.

3. Using the same procedure, draw the total horizontal motion vector for HOFN.

4. Use your gumdrop models to simulate this motion by moving your model along each vector, starting at the tail and moving the model toward the head. Does this match the movements you had simulated at the beginning of Part 2?



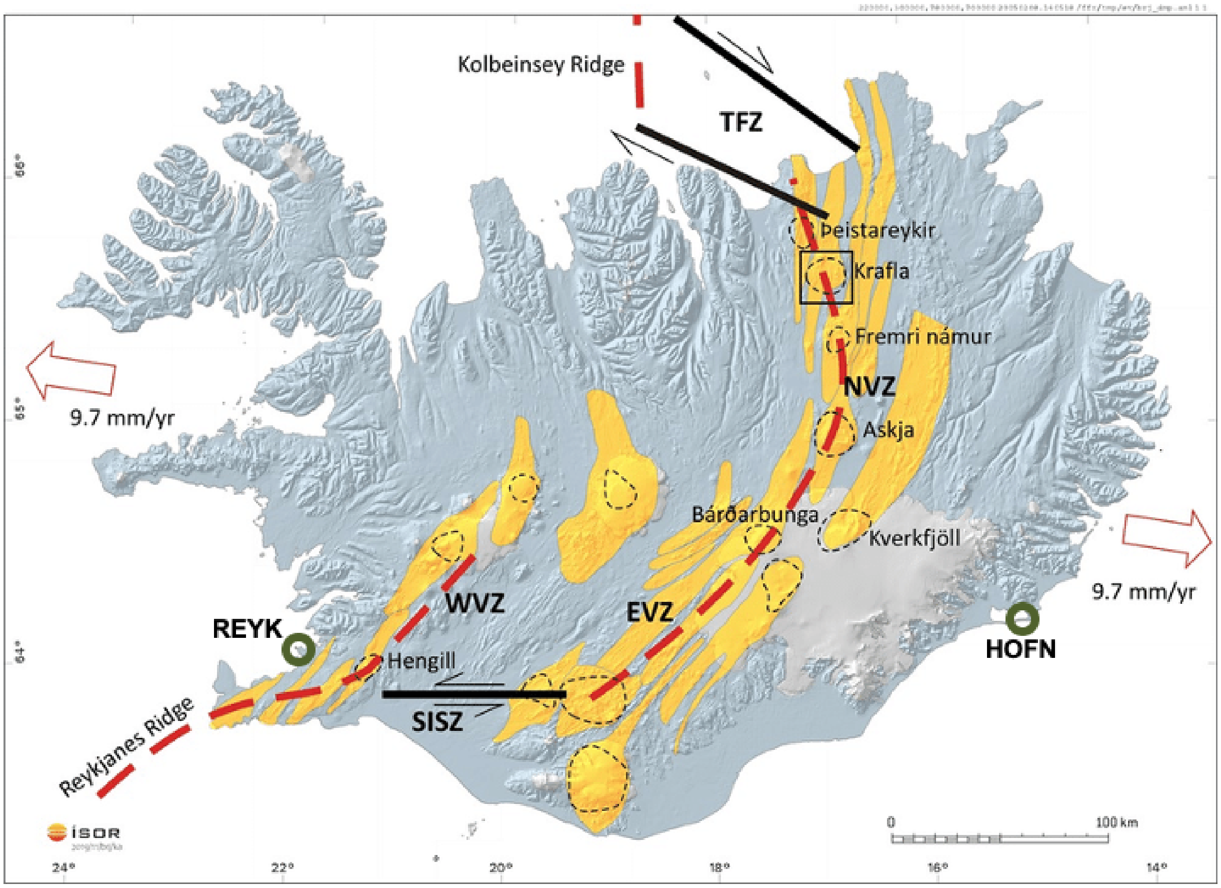
Interpreting the Data and Maps

Work with a partner to answer these questions.

To the left is a very simplified version of the tectonics in Iceland, below is a more detailed version which also shows the GPS monuments REYK and HOFN.

1. Describe how the resulting vectors of the two GPS monuments REYK and HOFN are different and how they are similar.

2. Remember that the monuments are fastened to the ground. If they are moving, then the ground must be moving. If you flew in a plane over Iceland, 1000 years from now, how far apart will the monuments be in the east – west direction? (Hint, go back to the East graphs)



A simplified tectonic map of Iceland showing the location of Krafla (black square). Red broken lines represent spreading zones. WVZ is the Western Volcanic Zone, EVZ is the Eastern Volcanic Zone, NVZ is the Northern Volcanic Zone. SISZ is the South Iceland Seismic/Transform Zone and TFZ is the Tjörnes Fracture/Transform Zone. Thin black broken lines show central volcanoes and yellow-colored areas fissure swarms.

3. Give one possible explanation for the way the ground is moving in Iceland. What's filling in the gap that is forming?

4. All three of the maps show the location of recent lava eruptions in Iceland. On your map with vectors, sketch in the Mid-Atlantic Ridge. In what way does this support or conflict with your explanation?

5. What kind of tectonic boundary is this?

Bonus: Where else in the world do we see seafloor spreading? Where in the past have we seen seafloor spreading? If your teacher directs you to use computers, use the UNAVCO Velocity Viewer to explore the world to find this answer.

Calculate the magnitude of the annual motion vectors for REYK and HOFN. You can use a ruler and the graph paper to create a scale or you can use the Pythagorean theorem. (That is, take the square root of [(north velocity)^2 + (east velocity)^2].)

There are a few gaps in the data for some of the stations. Given what you know now about how GPS data is collected and their location in Iceland, give two possible causes for the gaps.

Exploring Plate Motions Using GPS Data on the UNAVCO Velocity Map Tool

Now that you have the skills necessary, let's look at scientific GPS time series plots and figure out the direction our Earth's tectonic plates are moving! Go explore using the UNAVCO GPS Velocity Viewer: (Click the link below or use a search engine to search for "UNAVCO GPS Velocity Viewer")

http://www.unavco.org/software/visualization/GPS-Velocity-Viewer/GPS-Velocity-Viewer.html

Key features of the Velocity Viewer are:

- High precision GPS from the Network of the Americas (NOTA) and other networks;
- Web-based free platform;
- Data-sets: near-real time (NOTA); historical (GSRM);
- Plate motion is relative to a reference frame; and
- Changing the reference frame changes the perspective of plate motion.

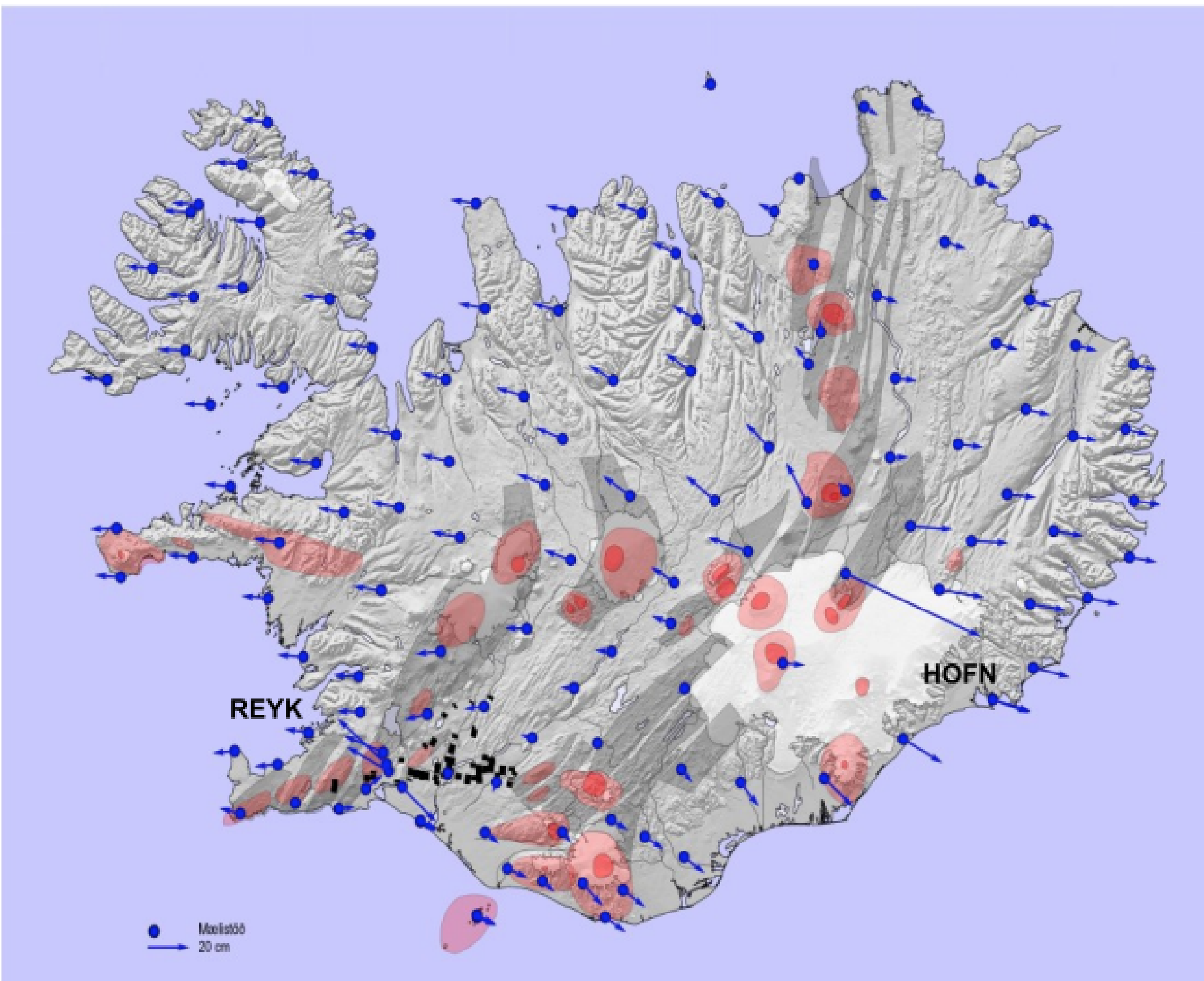


Plate motion vectors overlain onto a simplified tectonic map of Iceland. The proposed Icelandic Reference frame is used here.

1. Where else in the world do we see seafloor spreading? Sketch a few vectors that indicate plate(s) spreading (a divergent boundary).

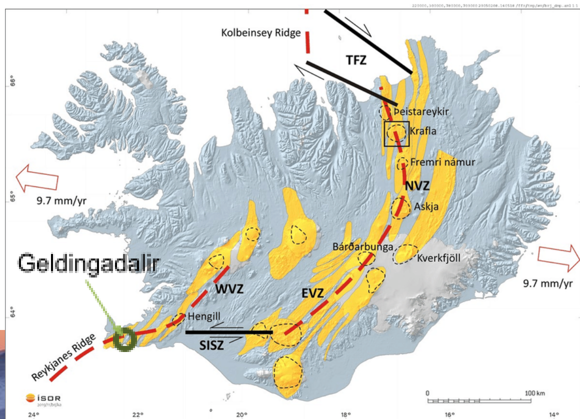
2. Find areas with high rates of motion - where are these areas? Where are areas that have high rates velocities near low velocities? What could this mean long term?

3. In regions where plate motions are relatively slow, how would you change the size of the vectors? What do you observe? How does the purple vector at the bottom of screen image (which represents 25 mm/yr in length) change?

4. Look at the same part of the world and change the data sources to show different reference frames. Recall that your reference frame will change the perspective from which you are viewing the movements. Try some of the data sources labeled modeled at the bottom of the list. What do you observe? Can you predict the types of plate boundaries in different areas of the world? Check your predictions… turn on the plate boundaries layer and other layers – how do they complement each other?

Conclusion

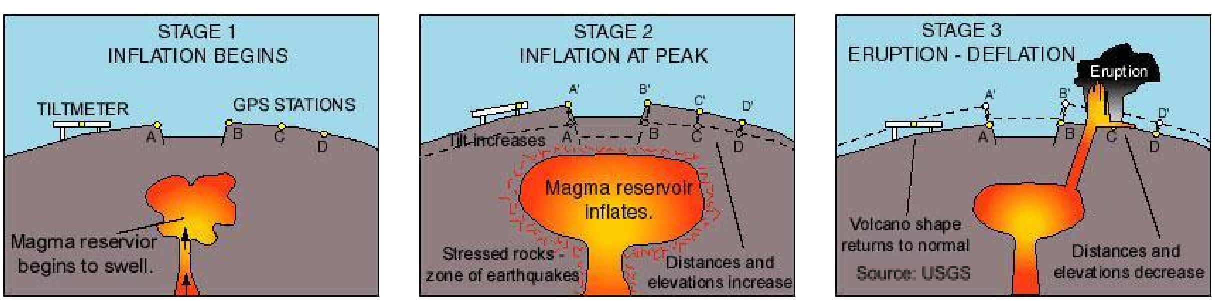
Plate boundaries and tectonic events such as volcanism and earthquakes are tightly bound together. You've been able to take a look at GPS data to see the movement of the plates in much higher resolution than can be seen with the naked eye. This data is essential to understanding what has happened in the past and helping to predict what will happen in the future.

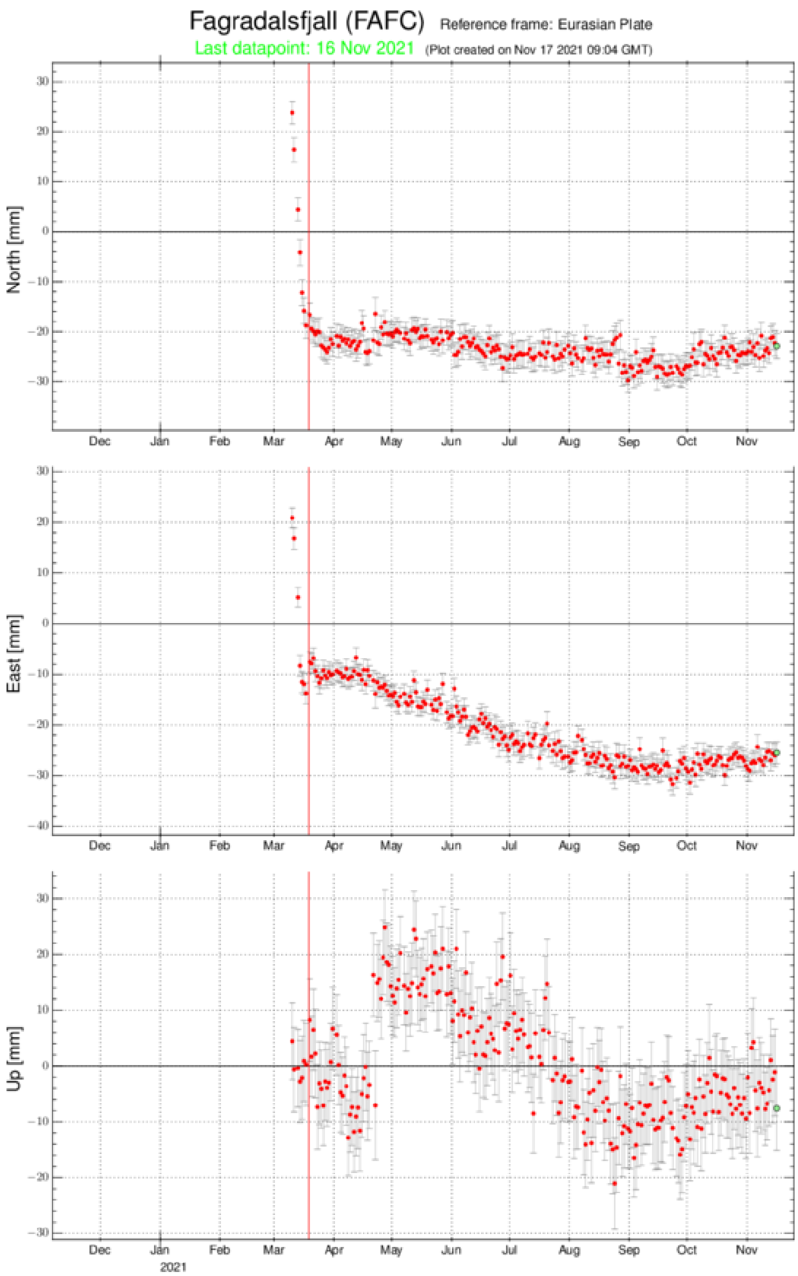


The volcanoes of Iceland will continue to erupt, some explosively and others, like Geldingadalir, more effusive and our GPS stations will be "watching". We have focused intensively in this lesson on the lateral motions of the plates but the stations are also recording VERTICAL motions. By looking at a single station, researchers (and you) can determine whether the ground surface has moved (deformed). Deformation of the surface can be a result of inflation (upward) or deflation (downward) motion – visible on the surface as swelling, sinking, or cracking. But what is causing this deformation? Deformation can be caused by magma, gas, or other fluids moving underground or by the movements of the fault zones that you previously recognized — recognizing the differences utilizes many different sources of information.

The 2021 eruption of Geldingadalir in Iceland (Source: IAVCEI)

An inflating magma chamber will cause the ground to deform and could signal that an eruption is possible. Once an eruption occurs, magma from the chamber will move to the surface, thereby decreasing the amount available in the magma chamber. This will cause deflation — once the ground has returned to its original elevation, it is likely that further eruptions will cease until the magma chamber is refilled.





The figure shows a time series plot for the GNSS station FAFC close to Fagradalsfjall (Geldingadalir). (Source: Icelandic Met Office)

Let's take a closer look at the 2021 eruption of Geldingadalir mentioned at the start.

On the left is data from the Fagradalsfjall (FAFC) station which is northwest of the main vent Geldingadalir and the closest station to the 2021 eruption.

1. What direction is the station moving? ____________

How fast is it moving? _________

Does this agree with the data from other stations that you viewed using the UNAVCO Velocity Viewer?

____

2. The last graph shows the vertical motion of the station. According to the Icelandic Met Office, the eruption of Geldingadalir began on March 19, 2021 (indicated on the graphs as a red line). Estimate the dates for the following:

Start of rapid inflation: ___________

Ending of eruption cycle: _________

3. The total amount of magma produced during the 2021 eruption is estimated to be 5.3 billion cu. feet (151 million m^3). At what rate did deflation occur?

____

4.Since the cessation of eruption activity, what has been happening at Geldingadalir based on the data provided?

5. What is the likelihood of another major eruption at Geldingadalir in the near future and how could GPS stations like FAFC be used to predict? Be prepared to defend your response.