

Ice Sheet influence exercise

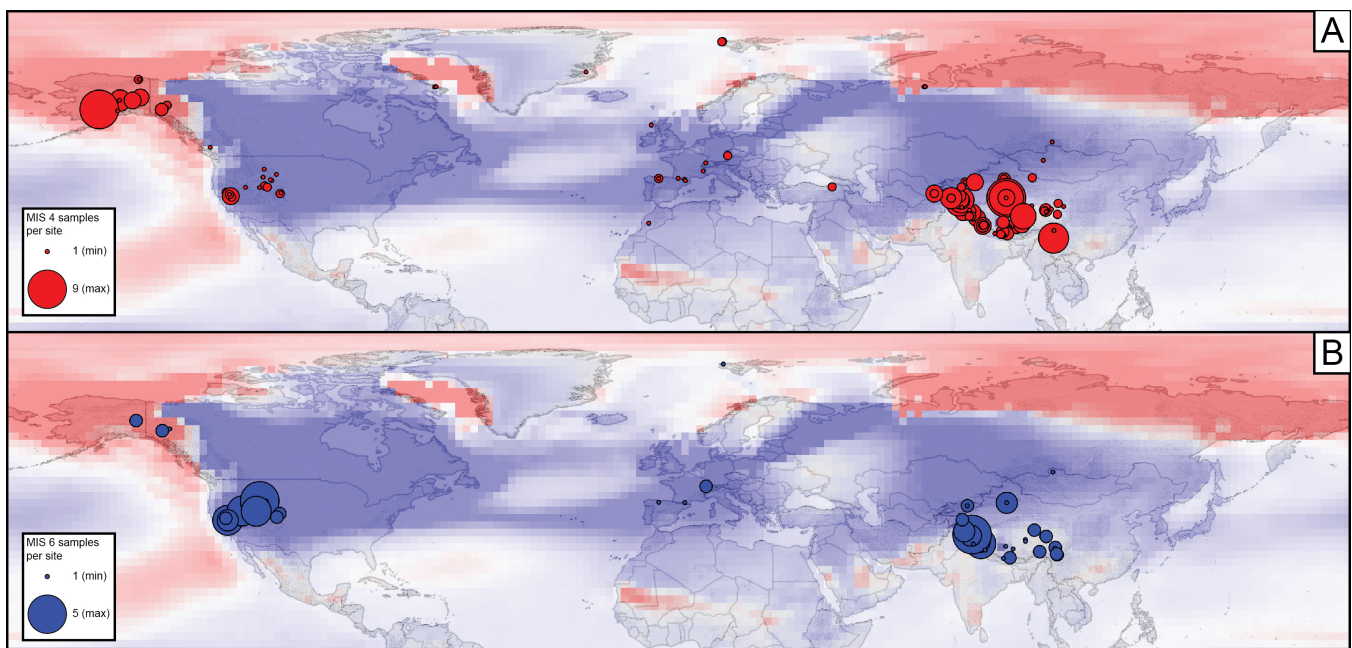
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ICE-D workshop exercise 1

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In this example exercise, we will be exploring and extending the hypothesis set forward in Tulenko et al. (2020) - and others cited in the paper - that large ice sheets existing during the LGM interrupted upper atmospheric circulation patterns and altered regional climate in such a way that led to the relatively unique patterns of alpine glacier chronologies in North America. Briefly, the ice sheet influence led to relatively warmer climate in Beringia and relatively cooler climate in the Western US during the LGM which allowed for the preservation of MIS 4 moraines in Beringia and obliteration of any MIS 4 moraines that may have existed in the Western US.

The point of this exercise is to 1) test if the data from North America support this hypothesis, and 2) further test if ice sheet influence extends to the entire Northern Hemisphere by extracting all MIS 4 and MIS 6 ages from ICE-D Alpine and comparing the spatial distribution to climate model output. Our if/then statement would be: if Ice Sheet influence on atmospheric circulation was a major control on alpine glacier fluctuations during the LGM, then we would expect to find a majority of MIS 4 ages in regions that were relatively warmed during the LGM and a majority of MIS 6 ages (ie the culmination of the last major glaciation prior to the last glacial cycle) in regions that were relatively cooled during the LGM.

In this exercise, we will be querying ICE-D Alpine to extract MIS 4 and MIS 6 ages, and then grouping and displaying sample sites that contain the ages extracted from ICE-D Alpine using QGIS. The sample sites are then overlain onto model output from Lofverstrom et al. (2014) that is publicly available on the NOAA Paleoclimate Database. An example of the final result is shown below.



Step 1. Begin the exercise by extracting a list of all ages stored in ICE-D Alpine - with two separate queries - that are in the Northern Hemisphere and fall within approximately within the MIS 4 age window (50,000 - 80,000 years ago; allow for some sample age error) and approximately within the MIS 6 age window (115,000 - 150,000 ka). In the query, ask the database to list the following attributes:

- sample name
- sample latitude
- sample longitude
- sample site
- calculated age (using LSDn scaling)

Note: these instructions will change when we incorporate a WFS link into the webpage that continually updates as we add more data into the database. Once that happens we will be able to make these queries straight in QGIS.

The SQL query is structured as follows:

```
select
CONCAT_WS(" ",
iced.base_sample.name,
iced.base_sample.lat_DD,
iced.base_sample.lon_DD,
iced.base_site.short_name,
iced.base_calculatedages.t_LSDn
)
from iced.base_sample, iced.base_calculatedages, iced.base_site,
iced.base_application_sites
where iced.base_sample.site_id = iced.base_site.id
and iced.base_sample.id = iced.base_calculatedages.sample_unique_id
and iced.base_site.id = iced.base_application_sites.site_id
and iced.base_calculatedages.t_LSDn > 50000
and iced.base_calculatedages.t_LSDn < 80000
and iced.base_sample.lat_DD > 0
and iced.base_application_sites.application_id = 2
```

Note: in this query, *select CONCAT_WS* has the database extract entries (based on what you specify after the command) and format the entries with the attributes that you define in the parentheses. The *from* and *where* commands define which tables in the database you are extracting from (in this case, the *base_sample* table, the *base_site* table and the *base_calculatedages* table) and how those tables are specifically linked (ie which attribute ties entries from one table to their respective entry in a separate table). In the case of ICE-D, entries are linked by a unique ID, which is an industry standard.

Furthermore, for those who interacted with the old database, you will note not only the changes to the table names and the introduction of unique IDs as table links, but we added another few lines of code to specify which application we want to extract data from. All ICE-D applications (ie ICE-D Greenland, ICE-D Alpine, ICE-D Antarctica, etc.) are all in one database now, and each sample is assigned to

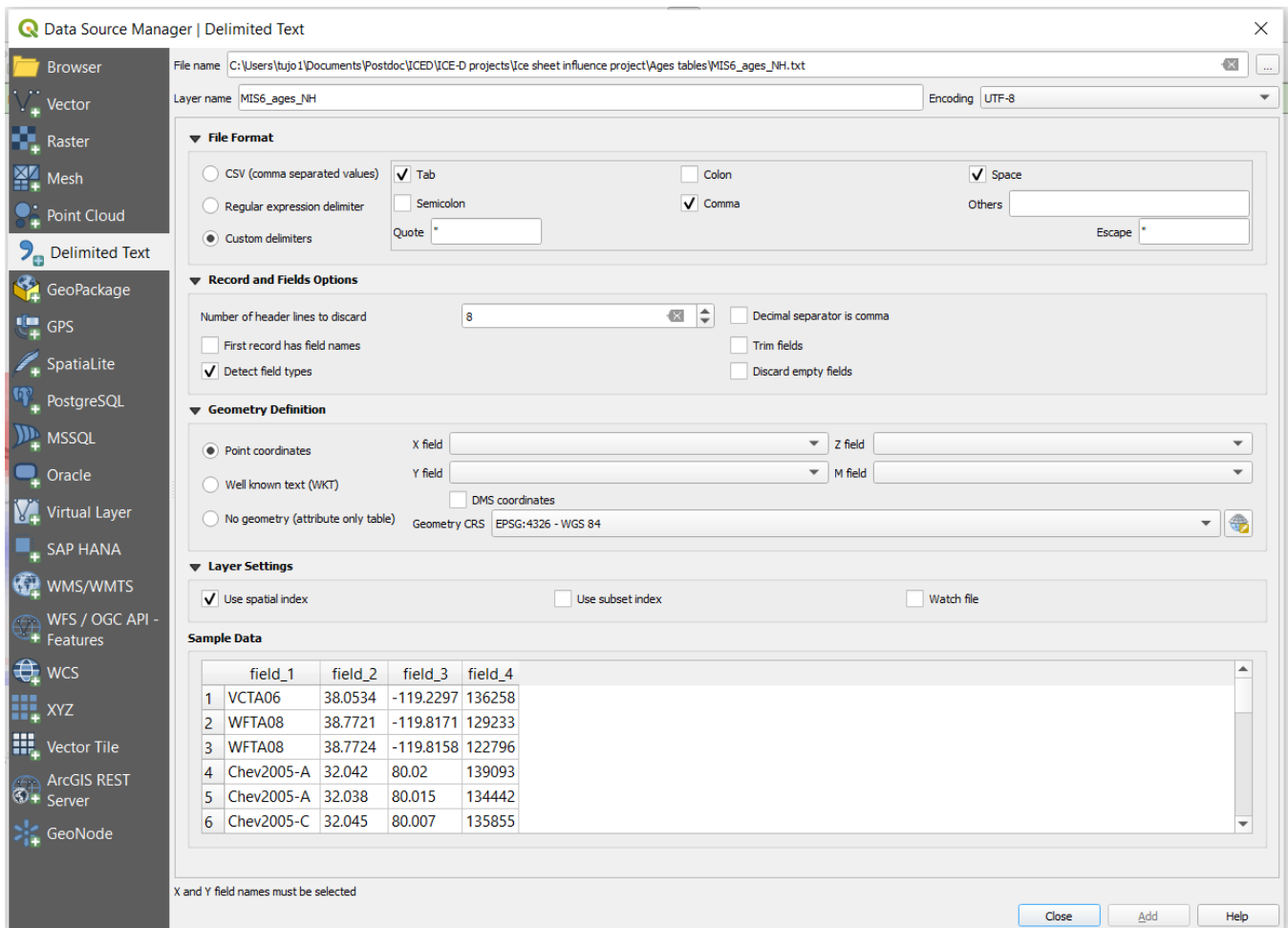
one/more application through the `base_application_sites` table. In this case, the `application_site_id` of 2 refers to ICE-D Alpine.

Anyway, moving on. For now, I simply copied these entries into a delimited text file. Delimited text files are easily read and opened in GIS software like ArcGIS and QGIS. As previously stated, this step will be consolidated into GIS software once we are able to provide a continuously updated WFS link on the webpage to the samples database.

Step 2. Now we want to display the data on a map in a meaningful way to highlight where we might confidently argue MIS 4 moraines exist and where they do not. To do this, I used the DISSOLVE tool in QGIS (the tool also exists in ArcGIS and works much the same way as I've outlined here) to group each sample into its respective *site*, and then display each *site* with a marker whose size is determined by the number of samples in that site that contain MIS 4 ages. The steps listed here should also be done for sites with MIS 6 ages.

The sites with a large number of MIS 4 ages would give high confidence in an MIS 4 age assignment and the sites with 1-2 samples might either indicate 1) these samples are outliers in a site dating a non-MIS 4 landform or 2) the site does not have enough samples measured to confidently assign any age to the landform.

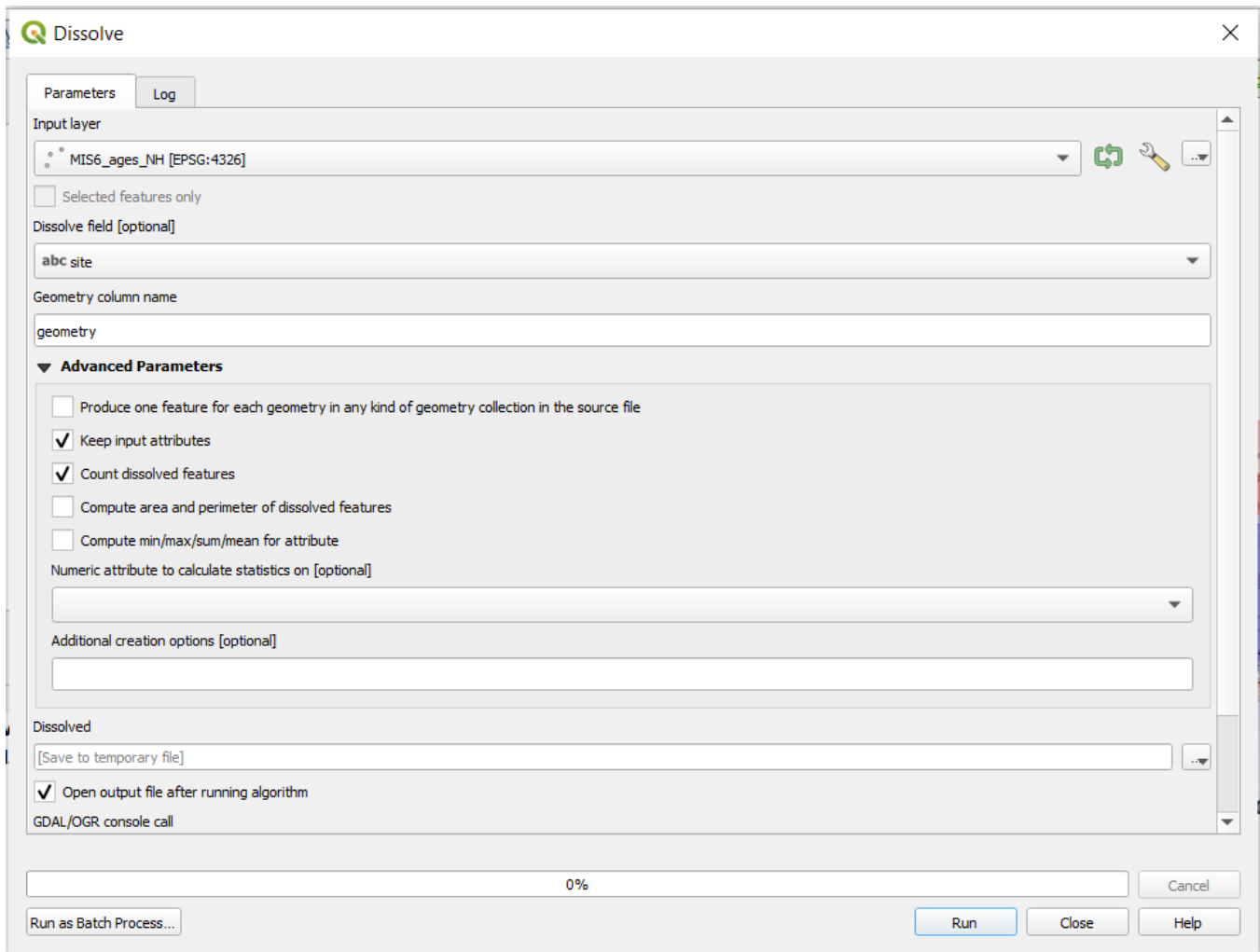
Begin by adding the delimited data to QGIS. The table can be added by selecting the "Layer" drop down menu, "add Layer", and "Add delimited text layer" and it will bring up the following window:



Specify the x and y fields as longitude values and latitude values, respectively, and make sure that the Geographic Coordinate System is set to EPSG:4326 WGS 84 (GCS_WGS_1984), which is the coordinate system GPS uses and what I must assume all samples in the database use for Latitude and Longitude. All other options in the window can remain as default.

Then you should export the data as a shapefile (this makes it easier to work with in GIS instead of the temporary file you created in the step above) by right clicking the new file in the layer panel and selecting the "export" option. Save all records in the file and select shapefile as the datatype. Once that is done QGIS should display the data in your map.

The next step will be to use the *dissolve* tool found in the GDAL toolbox -> Vector Geoprocessing -> Dissolve. The first pop up window should look like this:

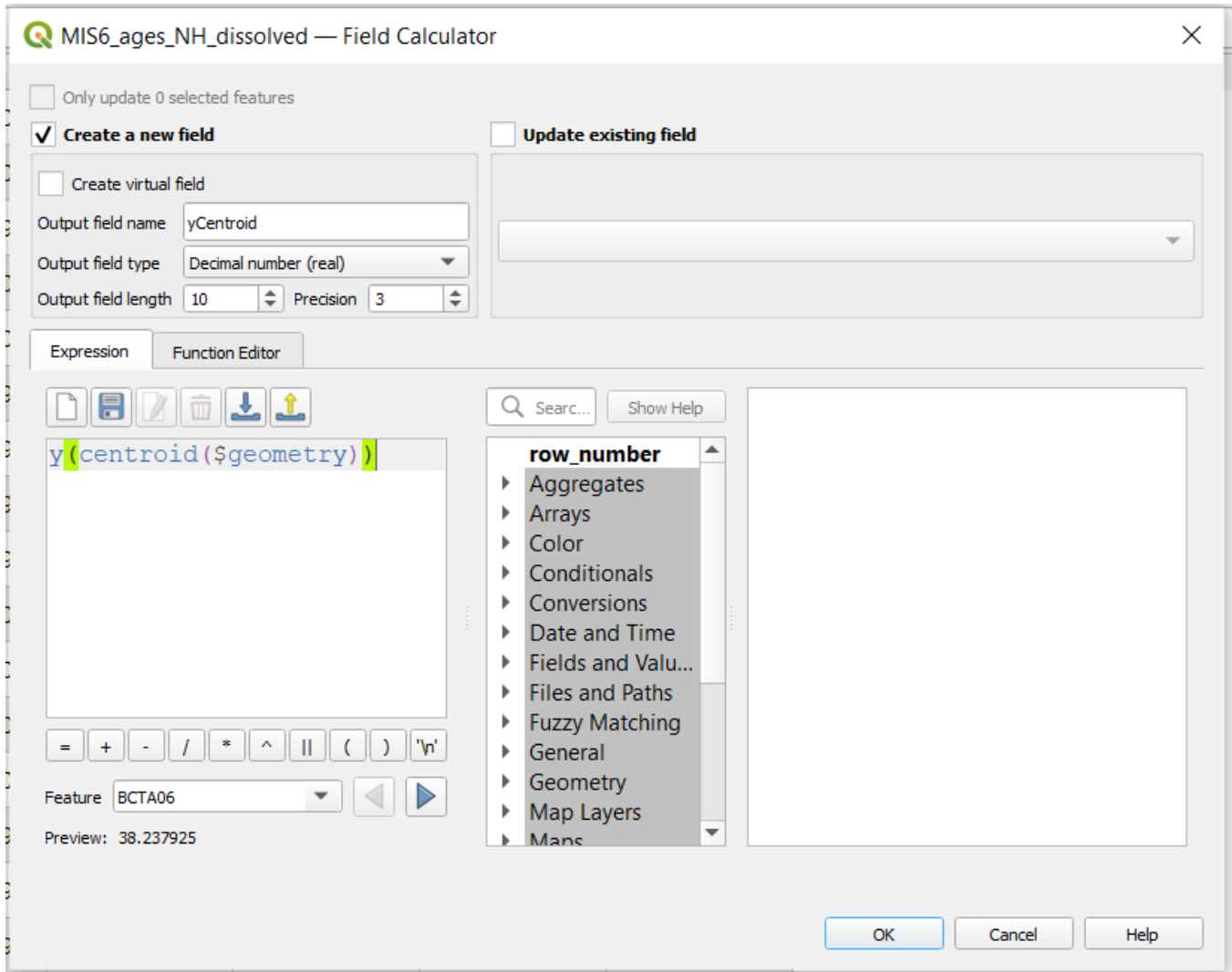


Choose the shapefile you created in the first step, specify that you want to dissolve the shapefile by the *site* attribute in the Dissolve Fields window (ie group all entries in the shapefile by their site) and then ask QGIS to compute the number of samples per site by selecting the "Count dissolved features" option in the advanced parameters window. I also select the "keep input attributes option" otherwise the new layer created will just have the site name and count of samples per site in the attribute table. Accept all other defaults and hit "Run". If it is successful, a new temporary layer will be added to your map.

You'll notice that there appears to be no change (all samples still show up on the map), but if you open the attribute table you will see that all that is listed are sample sites and their counts (plus the attributes you saved). Each entry is a Multipoint Shape type meaning that there can be multiple points listed in each entry.

Step 3. Now that we have a shapefile with each site listed and the number of samples per site falling within the MIS 4 age window, we should calculate the centroid of each site. Then we can export a new table that lists the site name, samples per site, and centroid of each site. This new table will be used to create the final shapefile that displays the data by site with a marker whose size we can define by the number of samples per site.

Open the attribute table of your newly created shapefile. In the top icon panel, select the icon that says "Open field calculator" and the following pop up window should open:



Name the attribute ("output field") something that makes sense (I usually just call it xCentroid for the longitude centroid and yCentroid for the latitude centroid), make sure the "output field type" is "Decimal number (real)", and accept all other defaults.

In the expression window, type the following expression:

y(centroid(\$geometry))

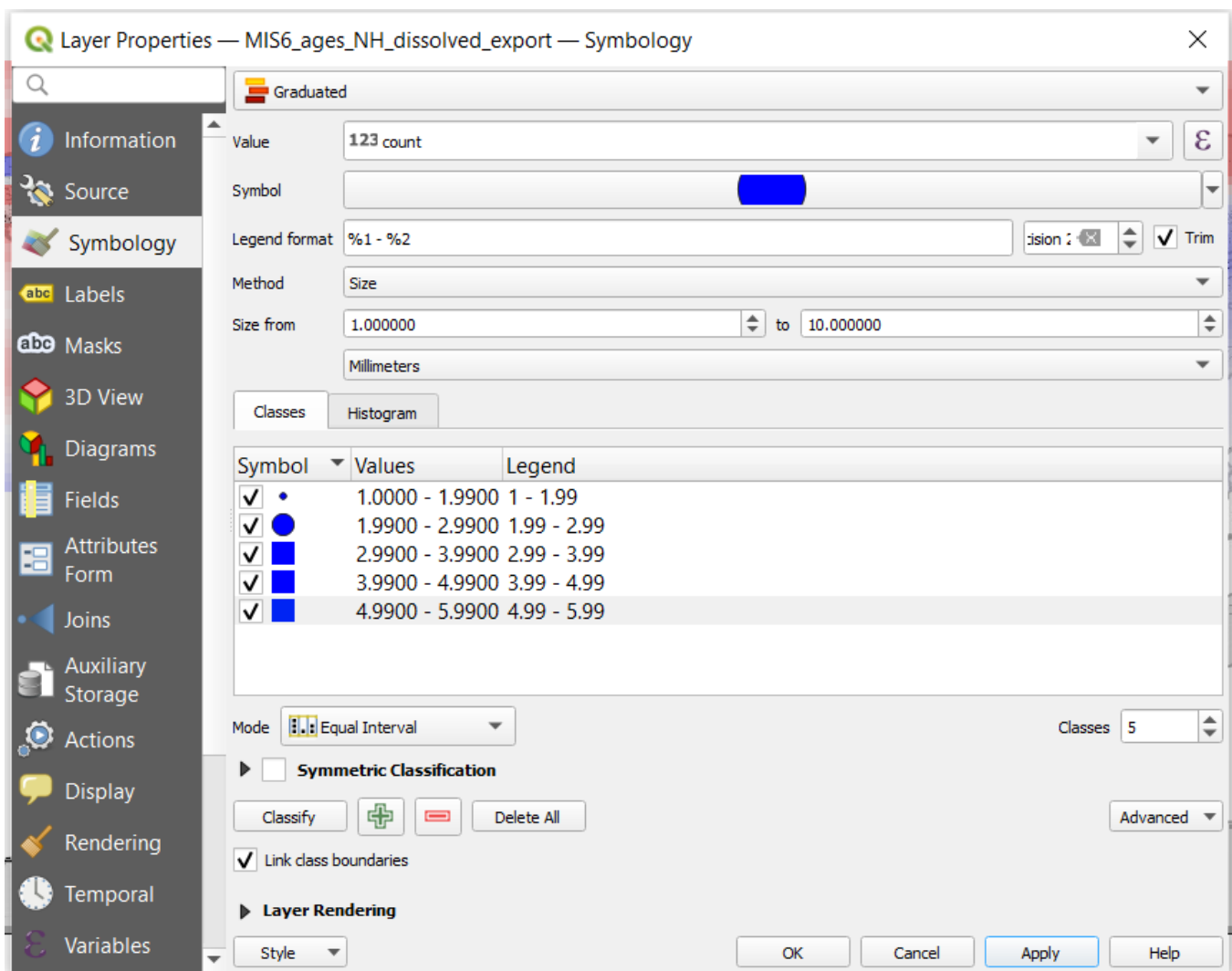
and then hit OK. You should see a new attribute field with the title you gave it and the centroid of whichever geometry you specified (in this example I specified the y geometry aka the *latitude*). Make sure you create centroid fields for both x and y!

Nice! Now, save your edits in the attribute window by selecting the pencil icon "Toggle editing mode". QGIS will ask if you want to save edits, select yes. And then, go back to the layer panel and export the layer as a csv file. Then, re-add that csv file to the map using the "Add delimited text layer" route (only this time use the **xCentroid** and **yCentroid** as x and y!) and save as a new shapefile.

This step is a way to manually merge all of the attribute info from the multiple points of the original SQL query into a new shapefile where each site is represented by *one* point with coordinates that correspond to the centroid of the points that make up that site. I haven't yet figured out how to automate this procedure. In the meantime, while this is an extra step, it does work.

Step 4. The final step for the samples is to display them by site and define the size of each marker by the number of samples in a given site.

To define the marker size by **site count**, right click on the sites layer in the Layers panel and select properties. Navigate to the symbology tab. From the top drop down menu select "Graduated". For Value, specify that you want to rank by the count field. See the example below that I have done for the MIS 6 moraines.



Below the Classes table, select the equal interval mode from the mode drop down menu. In the case of MIS 6 sites in the Northern Hemisphere, the largest number of samples per site was 5, so I made 5 classes in the box to the right of the mode menu. Hit the classify button, and you should see a list of symbols in the Classes table appear. The values column might be a little off, but make sure that each integer falls

within its own unique classification (ex: 1 sample per site should be classified within the smallest symbol and should be the only one in that symbol, so I define the range of that symbol to include all integers between 0.99 and 1.99. 1 is the only integer that would fall within that interval).

Under the Symbol tab, you can define the style of each symbol however you like. I made my MIS 4 sites red with a thin black outline and MIS 6 sites blue with a thin black outline. Once all of those things have been addressed, your input window should look similar to the example above. Hit Okay and you should see samples displayed similar to the first image in the exercise!

This tutorial goes over specifically how to extract and display the samples by site that fall within the MIS 4 and MIS 6 time windows. I did not spend time discussing how to display the model result from Tulenko et al. (2020), nor did I talk about how to display the hillshade and continents outlines basemap in the figure. Those could be separate tutorials on their own.

Step Observations and conclusions. What do we observe about the spatial distribution of sites with MIS 4 and MIS 6 ages?

I make four major observations:

1) The model result shows that Beringia was relatively warmed during the LGM as a result of Ice Sheet influence on atmospheric circulation. Therefore we might expect good preservation of MIS 4 moraines. Indeed, Beringia has a number of sites with multiple ages that fall in the MIS 4 window. I would argue this observation would support the hypothesis put forth in Tulenko et al. (2020). Furthermore, there appear to be fewer and more scattered ages that fall within the MIS 6 window in Beringia.

And the opposite appears to be true for the western US; there appear to be a number of sites in the Western US with MIS 4 ages, but there are never more than a few samples per site, suggesting these samples could either be outliers in a sample dataset dating non-MIS 4 moraines, or the sites do not provide enough samples to firmly constrain the age of the moraine. On the other hand, there are many sites in the Western US that have 4-6 samples falling within the MIS 6 age window. This pattern also seems to support the hypothesis that MIS 4 advances in the Western US were obliterated during the LGM since Ice Sheet influence led to relatively cooler conditions in the region.

2) There appears to be a lack of data in and around Europe to make any correlations. The model results would suggest that Europe should have been relatively cooled during the LGM, and thus there should not be many MIS 4 moraines in the region. Indeed, there are not many sites in and around Europe with MIS 4 ages and in all cases there are only 1-2 ages per site.

However, if there were not MIS 4 advances preserved, we might expect to find plenty of MIS 6 ages in the region, similar to what we observe in the Western US. What we actually observe though is a lack of MIS 6 ages as well. So perhaps this means either there haven't been enough pre-LGM moraines sampled in Europe, or there just aren't many that exist that can be dated using cosmogenic exposure dating. Regardless, I would argue samples from Europe do not provide any conclusive evidence that would support or refute the Ice Sheet influence hypothesis.

3) Samples collected in the Himalayas tell a very interesting story. First, model results would suggest that Ice Sheet influence was quite minimal in the Himalayas so we might not expect any correlations between sample sites and model results anyway (although if you squint you might notice that the model suggests Ice Sheets influence may have caused the western portion of the Himalayas to be cooler and the eastern portion to be somewhat warmer). And what the sample sites show is that there appears to be multiple sites that preserve large numbers of both MIS 4 and MIS 6 ages, which could suggest that LGM advances did not obliterate MIS 4 moraines, and MIS 4 advances did not obliterate MIS 6 moraines. Regardless, I would suggest that Ice Sheet influence was quite minimal and some other climatic mechanism was responsible for dictating the pattern of alpine glacier advances in the Himalayas (i.e. The strength and position of the Asian Monsoon or insolation, among other forcings.)

4) This exercise highlights opportunities for further investigation. Mainly, it makes me incredibly curious what we would find if we could target moraines in Siberia. The model suggests that there should be MIS 4 moraines there, but is that true? I am equally curious about other regions in the Northern Hemisphere like central America and Hawaii. There are moraines preserved on the Big Island of Hawaii, are any of them MIS 4?

Futhermore, the exercise only considers alpine glacier patterns for half of the planet. What about the Southern Hemisphere? Multiple sites in the Southern Alps of New Zealand and in the Andes Mountains (among other locations) provide strong evidence for significant MIS 4 advances. Why? Is there any likelihood that Ice Sheet influence on atmospheric circulation played a role, or are those sites too far removed from the Northern Hemisphere Ice Sheets? This is a problem perhaps outside the scope of my abilities, because the model result from Lofverstrom et al. (2014) only considers the Northern Hemisphere, so we would need to either have the model ran again or consider other climate models.

Finally, we are only considering alpine glacier chronologies, but there are an arsenal of other paleoclimate proxies that exist with the temporal and spatial distribution to test this hypothesis further. What do other climate proxy data suggest?

Thanks for following along!

Citations:

Lofverstrom, M., Caballero, R., Nilsson, J., Kleman, J., 2014. Evolution of the large-scale atmospheric circulation in response to changing ice sheets over the last glacial cycle. *Climate of the Past* 10, 1453–1471. <https://doi.org/10.5194/cp-10-1453-2014>

Tulenko, J.P., Lofverstrom, M., Briner, J.P., 2020. Ice sheet influence on atmospheric circulation explains the patterns of Pleistocene alpine glacier records in North America. *Earth and Planetary Science Letters* 534, 116115.