

Plate Deformation - the Andes

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Updated for GPlates 2.2 and the reconstruction of Müller et al. (2019) by Christopher Alfonso and Behnam Sadeghi

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[Plate Deformation - the Andes](#)

[Aim](#)

[Included files](#)

[Background](#)

[Exercise 1 - Deformation of the Andean margin](#)

[Part 1: Defining motions of points along a deforming margin](#)

[Part 2: Building a deforming line feature](#)

[Part 3: Combine deforming margin into global topological model](#)

[Exercise 2 - More detailed Andean Deformation](#)

[Part 1: Load the deformation raster sequence](#)

[Part 2: Create deformation tracker points](#)

[Part 3: Create a Topological Mesh over the Deformation Region](#)

[Additional Exercises](#)

[References](#)

Aim

This tutorial provides the first steps towards modelling plate deformation in GPlates. Traditional plate reconstructions typically consider the Andean margin as a single, rigid boundary through time. However, several studies

have shown how the morphology of the Andean margin of South America is likely to have changed significantly during Cenozoic oroclinal bending. The aim of this tutorial is to show how the details of this process can be incorporated into a (global) topological plate model using GPlates.

Exercise 2 allows users to build the deforming network visualised in tutorial 8.1.

Included files

Click [here](#) to download the data bundle for this tutorial.

The tutorial dataset (8.2-Plate_Deformation_Andes.zip) includes the following files:

- Rotations: Muller_etal_2019_CombinedRotations.rot
- Coastlines: Muller_etal_2019_Global_Coastlines.gpmlz
- Plate boundaries:
Muller_etal_2019_PlateBoundaries_DeformingNetworks.gpmlz
- Georeferenced image of Andean margin deformation (Fig. 1), after McQuarrie et al. (2002):
McQuarrie_Geology2002_fig3_rectify_clip.gpml
McQuarrie_Geology2002_fig3_rectify_clip.jpg
- Georeferenced time-dependent images of Andean deformation, after Arriagada et al. (2008): Arriagada_Images.gpml
- GPlates project file for Exercise 2: 8.2_P2.gproj

See <https://www.earthbyte.org/category/resources/> for additional EarthByte data sets.

This tutorial dataset is compatible with GPlates 2.2.

Background

There are various different ways to build a deforming topological network and this tutorial will guide the user through one way of doing so.

Exercise 1 - Deformation of the Andean margin

In the first example, we'll consider how the morphology of the Andean margin has evolved through the last 70 Ma based on reconstructions presented by McQuarrie (2002). This study used balanced cross-sections to estimate shortening within the Andes and how the magnitude of shortening varied along strike. The results are summarized in a map-view figure that illustrates evolution of the Bolivian orocline (Figure 1).

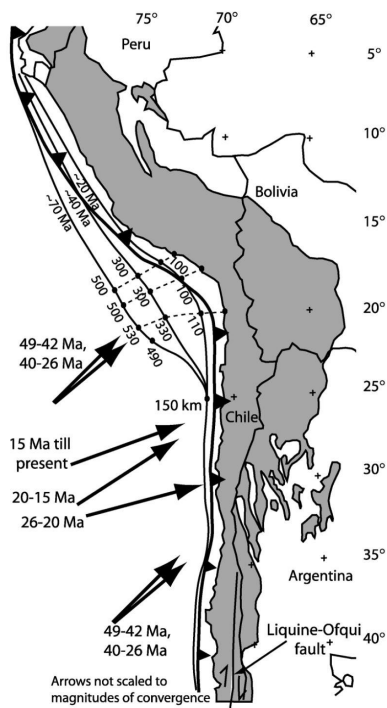


Figure 1: from McQuarrie (2002), 'Initial plate geometry, shortening variations, and

evolution of the Bolivian orocline’.

1. Using the File → Open Feature Collection menu load the following files:
 - Muller_etal_2019_CombinedRotations.rot
 - Muller_etal_2019_Global_Coastlines.gpmlz
 - Muller_etal_2019_PlateBoundaries_DeformingNetworks.gpmlz
 - McQuarrie_Geology2002_fig3_rectify_clip.gpml

To make visualisation easier, it is recommended to hide layers you are not using, such as the gold Resolved Topological Networks layer and the purple Resolved Topological Geometries layer.

A georeferenced version of Figure 1 is provided in the tutorial data set. To make the global plate model geometries move consistently with the raster, we need to make South America (Plate ID 201) the fixed plate.

2. Go to Reconstruction → Specify Anchored Plate ID... and set the value to 201.

(to see what difference this makes, try reconstructing the geometries and raster sequence with the Anchored plate as 000. You’ll see an increasing mismatch between the South America coastlines and rasters as the reconstruction age increases).

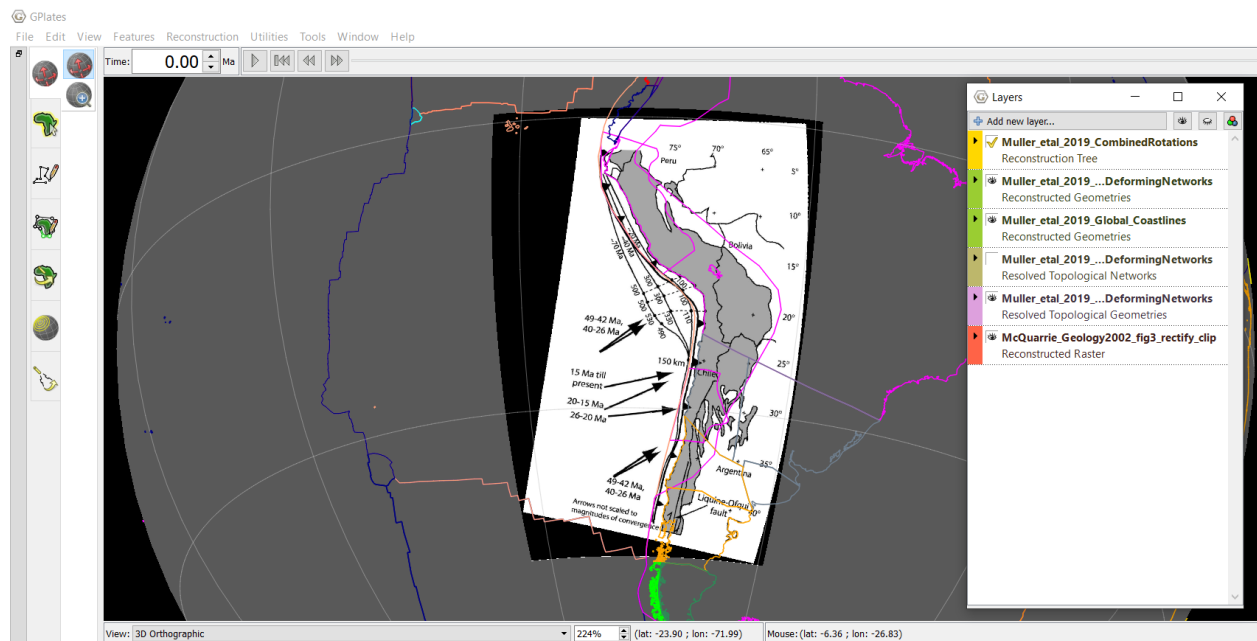


Figure 2: Estimated location of the Andean margin at 70 Ma, 40 Ma and 20 Ma with Plate

201 fixed.

In the area of what is now the Bolivian orocline, the margin moves >500 km west due to crustal shortening. Compare this with the rigid topologies in traditional plate models, where the margin is defined as a rigid line.

Part 1: Defining motions of points along a deforming margin

Before we start worrying about topologies, we will first create a series of points along the Andean margin, each with an individual motion history, that represent this change in morphology through time.

To do this, we will have to create a series of points with unique plate IDs, so that we can define them with a motion independent from that of one of the 'major' plates like South America. In GPlates, all relative motions are defined by assigning plate IDs and rotation poles, whether this be for a major plate or a single point within a deforming mesh.

To create these points for the Andes, first set the reconstruction time to 0 Ma. Then go to the Digitization menu on the left of the GPlates window, and select 'Digitize new multi-point geometry'. Since each point will end up with a unique plate ID, we will have to create each point separately and define the attributes accordingly. An example of the process for one point would be as follows:

3. Digitise 1 point at a desired location along the present-day Andean margin line (digitise the points along the subduction zone trench location, not the coastline).
4. Select 'Create Feature...'
5. Leave Feature Type as 'Unclassified Feature' (the default), and click 'Next'.
6. Set 'averageSampleSitePosition' as the geometry's purpose. Set the Plate ID to a unique value. In this case, to avoid conflict with existing

Plate ID in use, we will use multiple-digit numbers. The numbering system is up to you, in this case we'll start at 2010001 (where the 201 is taken from the Plate ID for South America) and increment upwards from there. Also make sure to set the begin and end time of the point to 'Distant Past' and 'Distant Future' (Figure 3).

7. Click Next, and Next again, then select the <Create a New Feature Collection> option to save these new points into a new file. Save all subsequent points into this same feature collection.

Geometry Property

Which property best indicates the geometry's purpose?

- averageSampleSitePosition
- Centre line
- centre
- domainSet
- Error boundary
- meshPoints
- Outline

Common Properties

Reconstruction Method: By Plate ID

Plate ID: 2010001 Conjugate ID: None

Begin (time of appearance): 0.00 Ma ☒ Distant Past

End (time of disappearance): 0.00 Ma ☒ Distant Future

Name: Andes_1

☐ Create conjugate feature

Previous Next Create and Save Cancel Create

Figure 3: Assigning properties to a feature (Step 3).

8. Repeat this sequence for a series of points along the (present-day) Andean margin (Figure 4) - the position and number of points you

decide to digitise is up to you. Make the Plate ID different for each point (e.g., 2010002, 2010003, etc.).

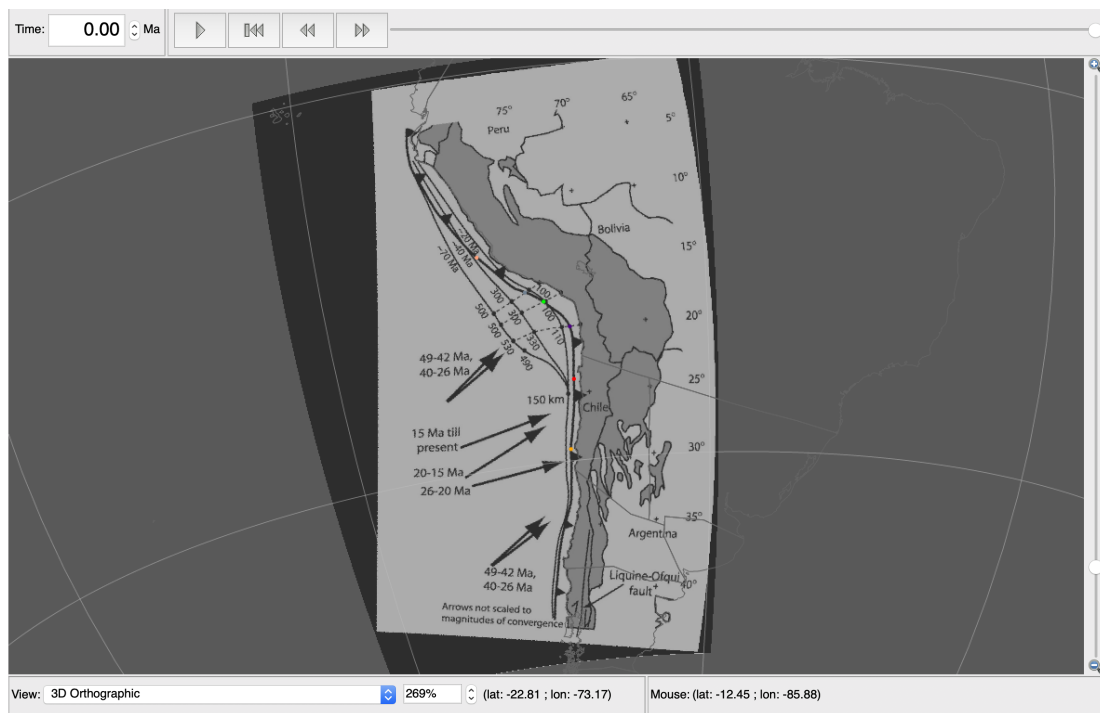


Figure 4: Example of digitised points along the margin (Step 6). Note that the colour of each point is different, denoting their different plate IDs.

Next, we need to implement the motion history of each point. The details of how any feature moves within GPlates is stored within a rotation file, and these points are no different. So first, we need to create a 'blank' set of rotations for each plate. See the '2.2: Changing Rotations, Equivalent Finite Rotations, and Cross-Overs' and '2.1: Plate Reconstructions' tutorials for a more detailed description.

One additional point to mention here is that rotation tables in GPlates need not all be stored in one file. Instead, we can have motion histories for different rotation files and link them together within GPlates. This has the advantage of keeping motion histories for deforming regions separate from the main global rotation files, rather than creating one large, unwieldy rotation file.

9. Use a text editor (e.g., Notepad, Textmate) to create a blank rotation file with entries for each of the Plate IDs assigned to the newly digitized points (Figure 5).

1	2010001	0.0	90.0	0.0	0.0	201	!	Andes tutorial
2	2010001	250.0	90.0	0.0	0.0	201	!	Andes tutorial
3	2010002	0.0	90.0	0.0	0.0	201	!	Andes tutorial
4	2010002	250.0	90.0	0.0	0.0	201	!	Andes tutorial
5	2010003	0.0	90.0	0.0	0.0	201	!	Andes tutorial
6	2010003	250.0	90.0	0.0	0.0	201	!	Andes tutorial
7	2010004	0.0	90.0	0.0	0.0	201	!	Andes tutorial
8	2010004	250.0	90.0	0.0	0.0	201	!	Andes tutorial
9	2010005	0.0	90.0	0.0	0.0	201	!	Andes tutorial
10	2010005	250.0	90.0	0.0	0.0	201	!	Andes tutorial
11	2010006	0.0	90.0	0.0	0.0	201	!	Andes tutorial
12	2010006	250.0	90.0	0.0	0.0	201	!	Andes tutorial

Figure 5: An example of the blank rotation file for the points along the Andean margin (Step 7).

In this example, the motions of each point will be defined relative to South America (201).

[Note that as discussed in the '2.2: Changing Rotations, Equivalent Finite Rotations, and Cross-Overs' tutorial, we have to add zero rotations both at present day and at some point in the distant past to begin with. We'll then modify them later].

10. Load this rotation file into GPlates. Make the 'Muller_etal_2019_CombinedRotations' global rotation file the default reconstruction tree by ticking the tickbox, but also expand this layer in the layer manager and click on 'Add a new connection'. Select the Andes rotation file you have just loaded (Figure 6). This layer now treats the contents of both these files as if they were one big table of rotations, combined from the contents of the two individual files.

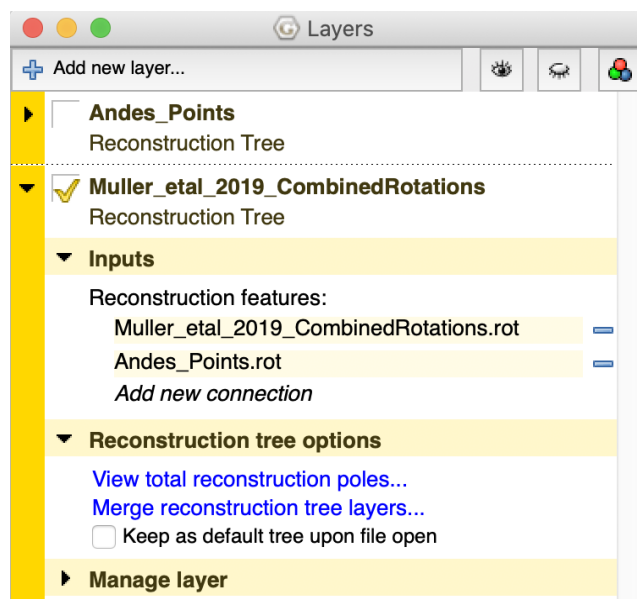


Figure 6: Creating the connection between the global rotation file and the Andes rotation file (Step 8)

For Mac users, if there is an error when loading the rotation file, or the poles of the digitised points are unable to be moved, this may be due to the usage of the wrong line endings by the text editor. To fix this, the line endings must be converted to Windows line endings using a text editor (e.g., Fig. 7) in order to allow GPlates to understand where the line breaks are in the text file and differentiate between the different rows.

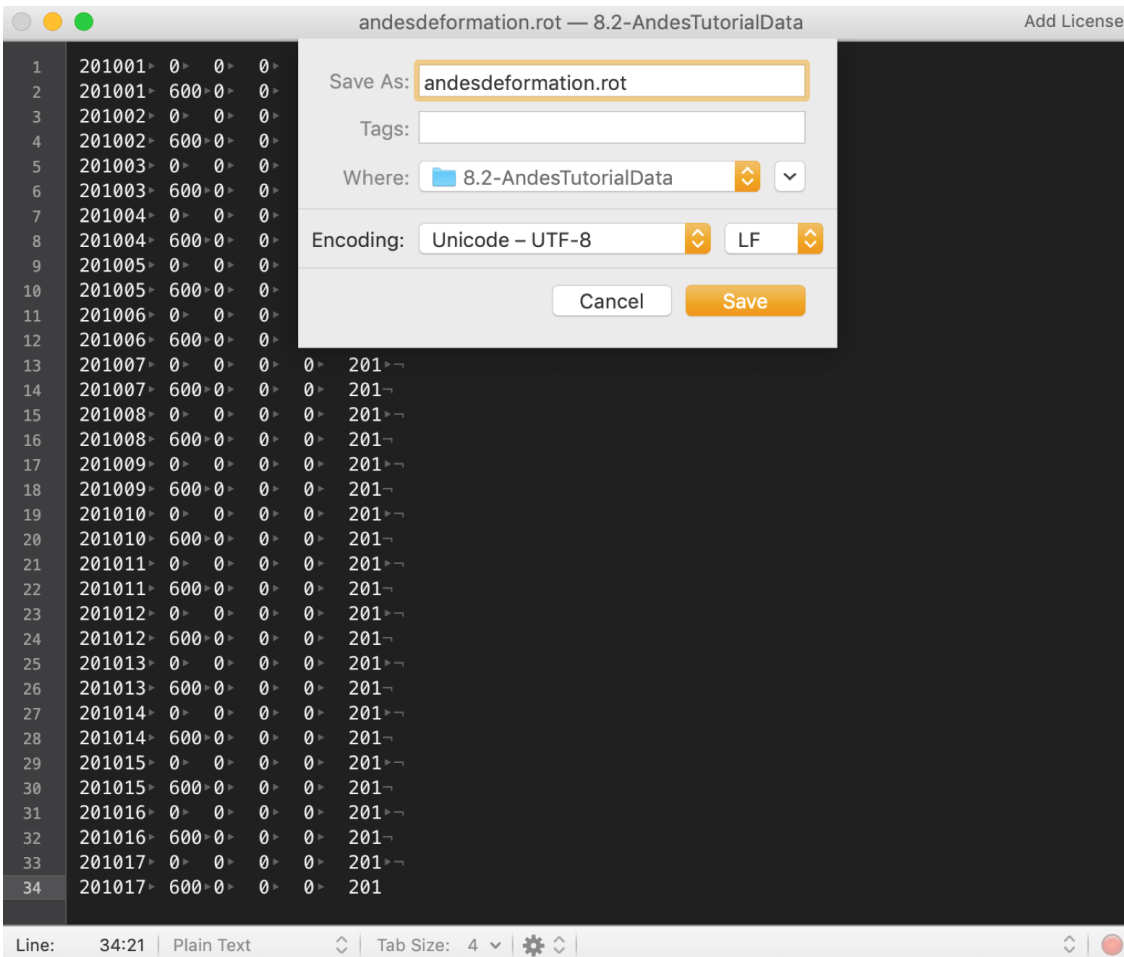


Figure 7: Saving the rotation file with “LF” line endings in TextMate

Now we are ready to define the motion histories for each of the new points on the Andean margin. This will require the use of the ‘Pole Manipulation’ tool, which was described in ‘2.2: Changing Rotations, Equivalent Finite Rotations, and Cross-Overs’ tutorial.

11. Set the reconstruction time to 20 Ma (this is the youngest time for which the McQuarrie study defines a morphology for the margin).
12. Select one of the points, then select the ‘Pole Manipulation’ tool.
13. Drag the point from its location at present day to a point that would

approximate the location of the equivalent point on the plate boundary at 20 Ma.

Note that this will require some amount of 'eyeballing', because the lines shown on the georeferenced image illustrate the migration of the coastline whereas we are trying to model the migration of the subduction zone trench which lies ~100 km oceanward. In general we can use the shortening estimates (Figure 1) to check that the magnitudes of motion we impose are consistent. (We can use the dashed lines as a guide to the direction of motion that the points should follow).

14. Click on Apply, and a window will pop up showing the new rotation calculated based on how you moved the point. Click on OK, and this rotation will be added to the sequence of rotations in the Andes Deformation table of rotations.

Note that the change won't be saved to file until you manually save your changes in the 'Manage Feature Collections' dialogue. Note also that we are only modifying the Andes rotation file, because this is the file that contains rotations for the plate ID 2010001 (or similar) - the global rotation file will not be modified.

15. Repeat this step for the other points, so that all the points are repositioned onto the 20 Ma plate boundary (Figure 8).

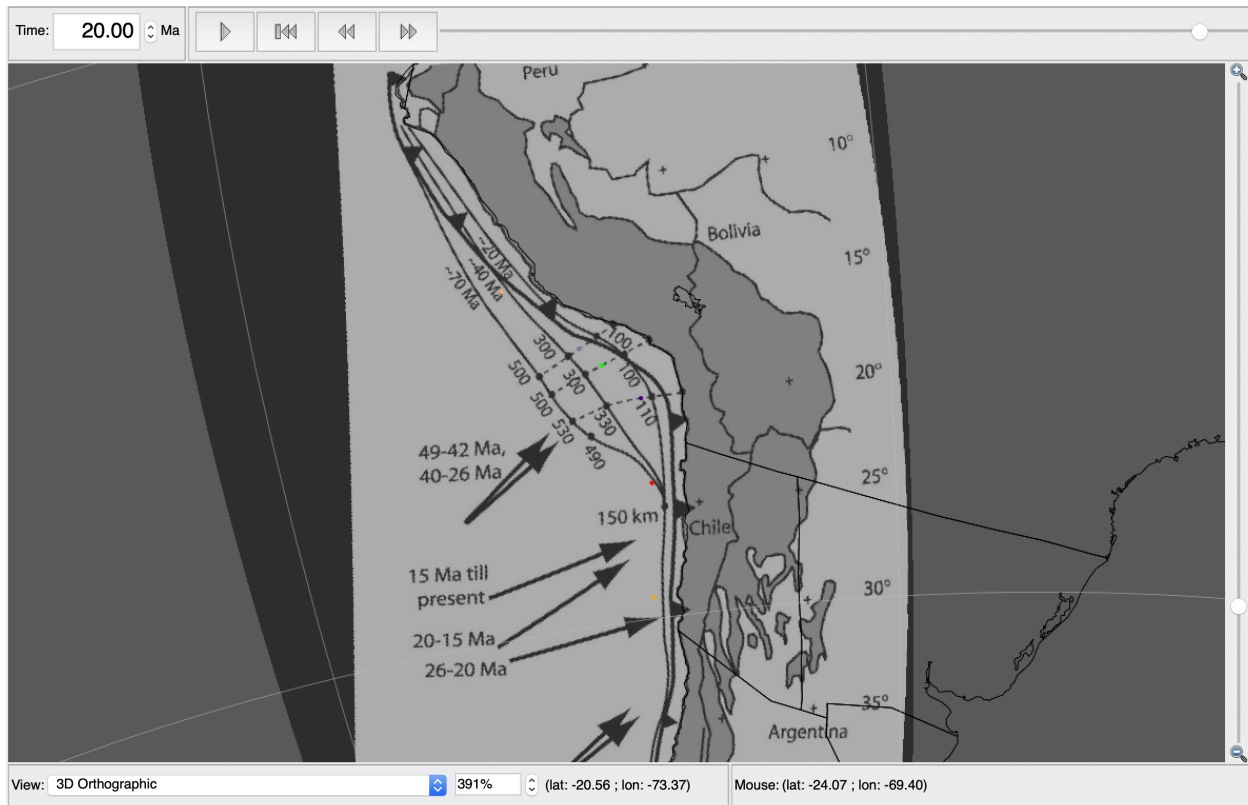


Figure 8: Location of points along Andean margin at 20 Ma (Step 15).

16. Repeat this process (Steps 12–15) for 40 Ma and 70 Ma.

Note that you don't need to modify the rotation if the point hasn't moved relative to the previous time step (e.g., the southernmost point in Fig. 8 doesn't need to move from 70-20 Ma.)

17. Play back the rotation sequence from 70 Ma to present. The points should move progressively eastwards, providing a dynamic representation of the evolution defined by the four timeslices represented in the original image, but with locations interpolated for all times in between.
18. At this point, save changes to unsaved files.
19. Also at this point, it is worth returning to the rotation file in the text

editor (make sure to reload the file after you've saved the changes you made in GPlates).

20. Take the rotations for each point at 70 Ma (or the oldest time for which you defined a new rotation), and cut and paste this over the zero rotations at 250 Ma (Figure 9)

This essentially says 'the points should not move relative to 201 between 250–70 Ma'. See the '2.2: Changing Rotations, Equivalent Finite Rotations, and Cross-Overs' tutorial for more details.

```
1 2010001 0.0 90.0 0.0 0.0 201 ! Andes tutorial
2 2010001 20.0 57.9452 -134.4602 -0.6037 201 !
3 2010001 40.0 57.9775 -134.4505 -2.0739 201 !
4 2010001 70.0 58.2489 -134.119 -3.8555 201 !
5 2010001 250.0 58.2489 -134.119 -3.8555 201 !
6 2010002 0.0 90.0 0.0 0.0 201 ! Andes tutorial
7 2010002 20.0 63.3214 -122.4297 -0.9543 201 !
8 2010002 40.0 64.549 -119.3224 -3.0651 201 !
9 2010002 70.0 61.5089 -126.2156 -4.8945 201 !
10 2010002 250.0 61.5089 -126.2156 -4.8945 201 !
11 2010003 0.0 90.0 0.0 0.0 201 ! Andes tutorial
12 2010003 20.0 69.9713 -71.9681 -1.2844 201 !
13 2010003 40.0 69.8562 -78.6968 -3.3242 201 !
14 2010003 70.0 67.2224 -102.5015 -5.2375 201 !
15 2010003 250.0 67.2224 -102.5015 -5.2375 201 !
16 2010004 0.0 90.0 0.0 0.0 201 ! Andes tutorial
17 2010004 20.0 65.7982 -62.7489 -0.9737 201 !
18 2010004 40.0 66.0414 -70.6456 -1.2796 201 !
19 2010004 70.0 65.6775 -82.3557 -1.4465 201 !
20 2010004 250.0 65.6775 -82.3557 -1.4465 201 !
21 2010005 0.0 90.0 0.0 0.0 201 ! Andes tutorial
22 2010005 20.0 60.2893 -59.6975 -0.7596 201 !
23 2010005 250.0 60.2893 -59.6975 -0.7596 201 !
24 2010006 0.0 90.0 0.0 0.0 201 ! Andes tutorial
25 2010006 20.0 55.0291 -146.2996 -0.4769 201 !
26 2010006 40.0 57.906 -143.6842 -1.1605 201 !
27 2010006 70.0 57.6033 -144.0769 -2.4159 201 !
28 2010006 250.0 57.6033 -144.0769 -2.4159 201 !
```

Figure 9: Andes rotation file after implementing zero relative motion at 250–70 Ma (Step 20).

Part 2: Building a deforming line feature

A topological line feature can be constructed from a series of points or lines, each with individual plate IDs (and therefore independent motion histories). This enables us to construct lines whose geometry evolves through time, but to also use these line features as boundaries within a topological polygon in the same way as rigid lines. See the Topology tutorials for more detailed instructions on how to build topological features.

1. To do this, go to the 'Topology' menu, then select 'Build New Line Topology'.
2. Click on one of the points for which we've just defined rotations, starting at one end of the sequence of points. Then click on 'Add' on the right-hand menu. Repeat this for each point in order (e.g., from north to south) (Figure 10).

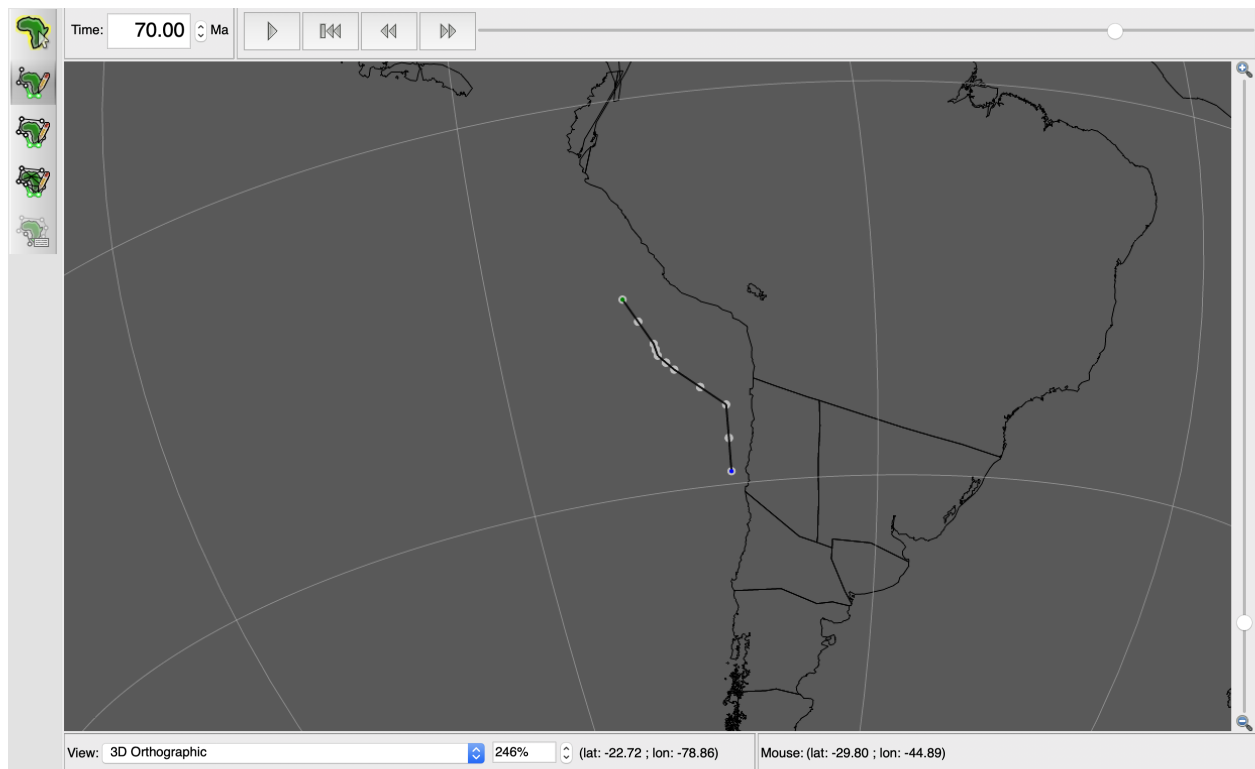


Figure 10: New line topology after all points have been added (Step 2).

3. Once all the points have been added, click 'Create' and specify all the

attributes as required (make sure to change the Begin and End time, for example to 'Distant Past' and 'Distant Future'). Save this new feature to a new feature collection.

Once created, you should be able to see a line feature, with 6 vertices, where each vertex moves independently based on the previously defined motion history (Figure 11)

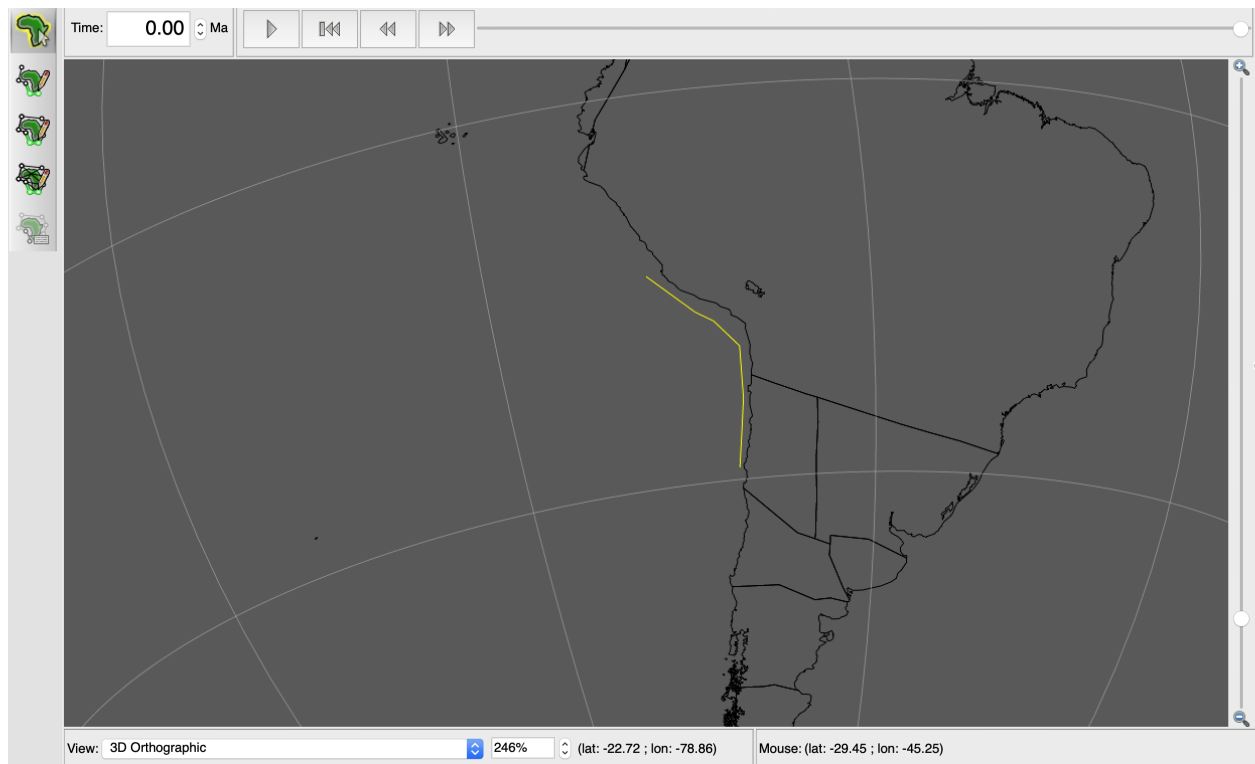


Figure 11: New line feature with 6 vertices

This line feature can now be treated like any other line in GPlates - we can add subduction zone properties, and use it as one of the boundaries within a topological plate boundary polygon.

Part 3: Combine deforming margin into global topological model

To use this boundary as part of the topological polygons for the Nazca plate, we first need to remove the section which is already used in the model.

1. With the reconstruction time set to 0 Ma, start by selecting the 'Andes Subduction Topology' line feature from the 'Muller_etal_2019_PlateBoundaries_DeformingNetworks' Resolved

Topological Geometries layer.

- If you cannot find this feature, try going to View → Geometry Visibility and make sure 'Show Topological Sections' is checked.

2. Delete this feature.

You'll notice that straight away the topologies 'break', as evidenced by the long, straight lines going annoyingly across the display (Figure 12).

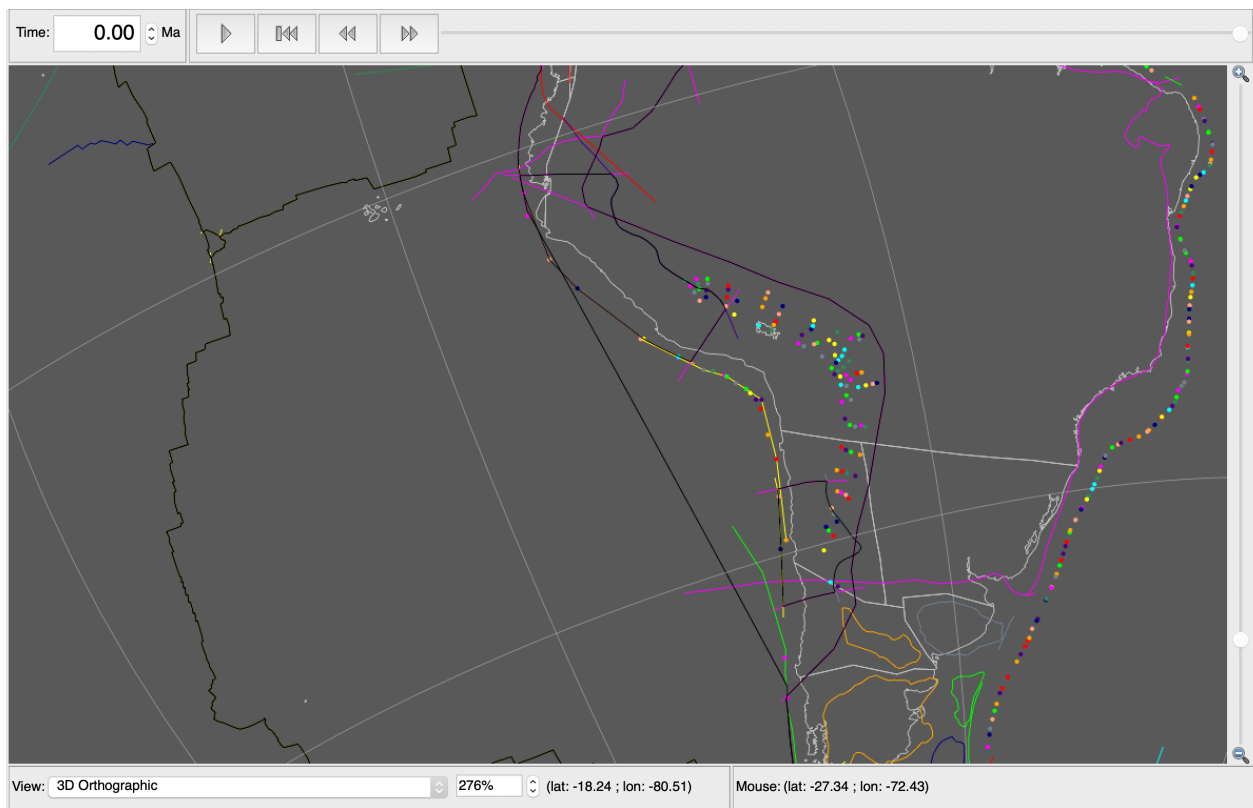


Figure 12: Broken topologies when the South American Trench is 'split' (Step 2).

Since we have deleted a portion of the plate boundary topologies, the topological polygons now need to be rebuilt to incorporate our newly-created topological line.

To do this, we will merge the pre-existing northern and southern sections of the Andean margin that we want to keep with the topological line we just created, to create a topological line that extends along the whole Andean margin. We will then rebuild the plate boundary polygon, replacing the

previous Andean line section with the new, deforming version.

3. Select the topological line we already created. Go to the 'Edit Topology Sections' tool, then add the rigid features defining the northern and southern parts of the Andean margin, adding one at the beginning of the Topology Sections list and the other at the end (Figure 13). You may also need to edit the pre-existing rigid features, or create some additional ones of your own, to ensure that the ends of your topological line intersect with the pre-existing plate boundary features (this process is similar to that described in the Appendix to Tutorial 5.2 – Working with Mid-Ocean Ridge Features).

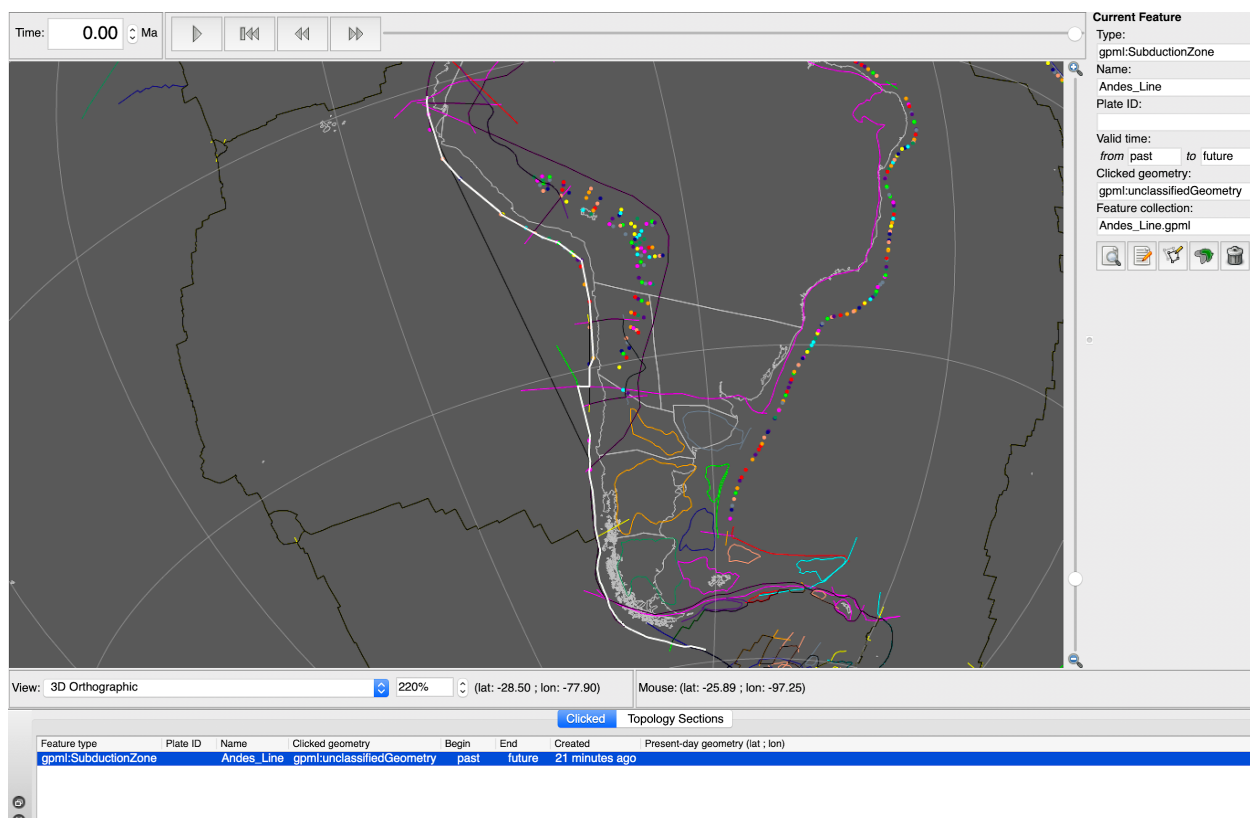


Figure 13: The topological line defining the western boundary of the South American continent (Step 3).

The process of (re)building polygons is similar, and is described in detail in Tutorial 5.1 – Topological Closed Plate Polygons. This is done by selecting the topological polygon we want to update, then clicking on 'Edit Topology Sections'

4. Remove the deleted 'Andes Subduction Topology' segments from the topology list, and add the new topological line in its place. Then click 'Apply...' (Figure 14)

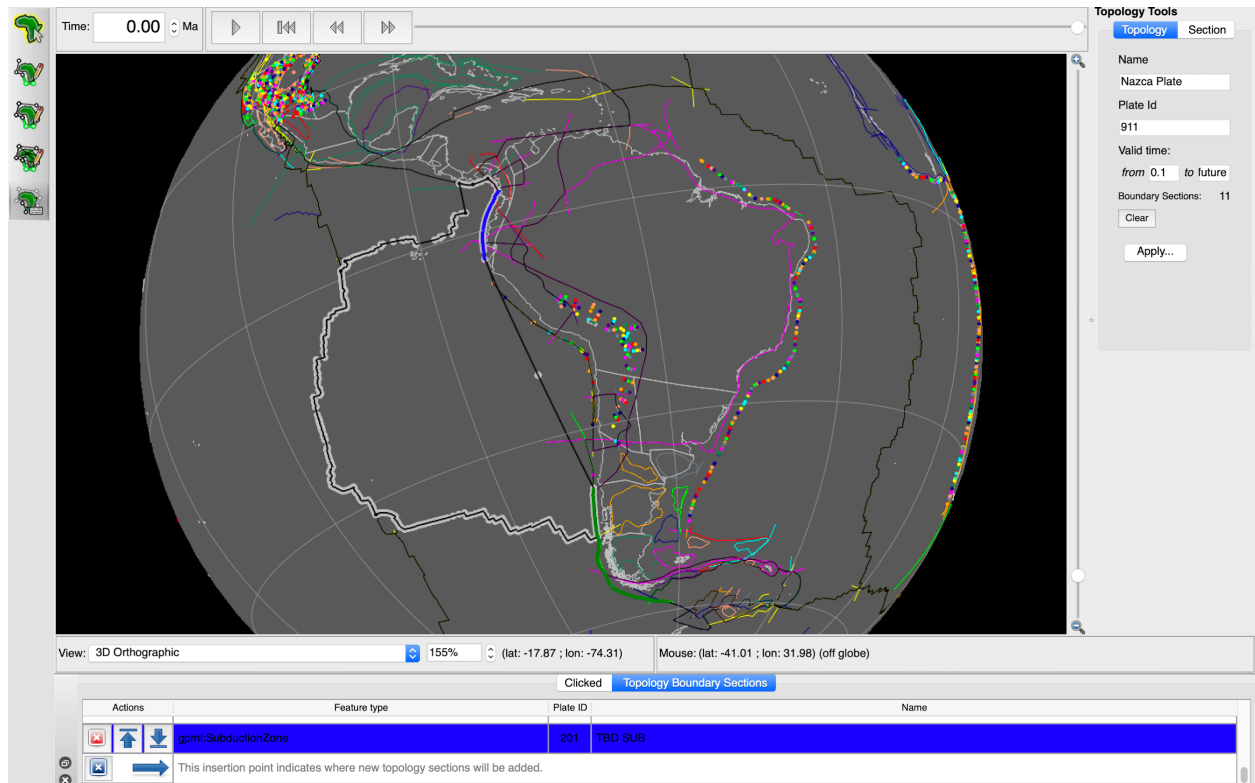


Figure 14: Rebuilding the Nazca Plate topology (Step 4).

5. The plate boundaries should be back to normal, but now incorporating the deforming margin (Fig. 15).

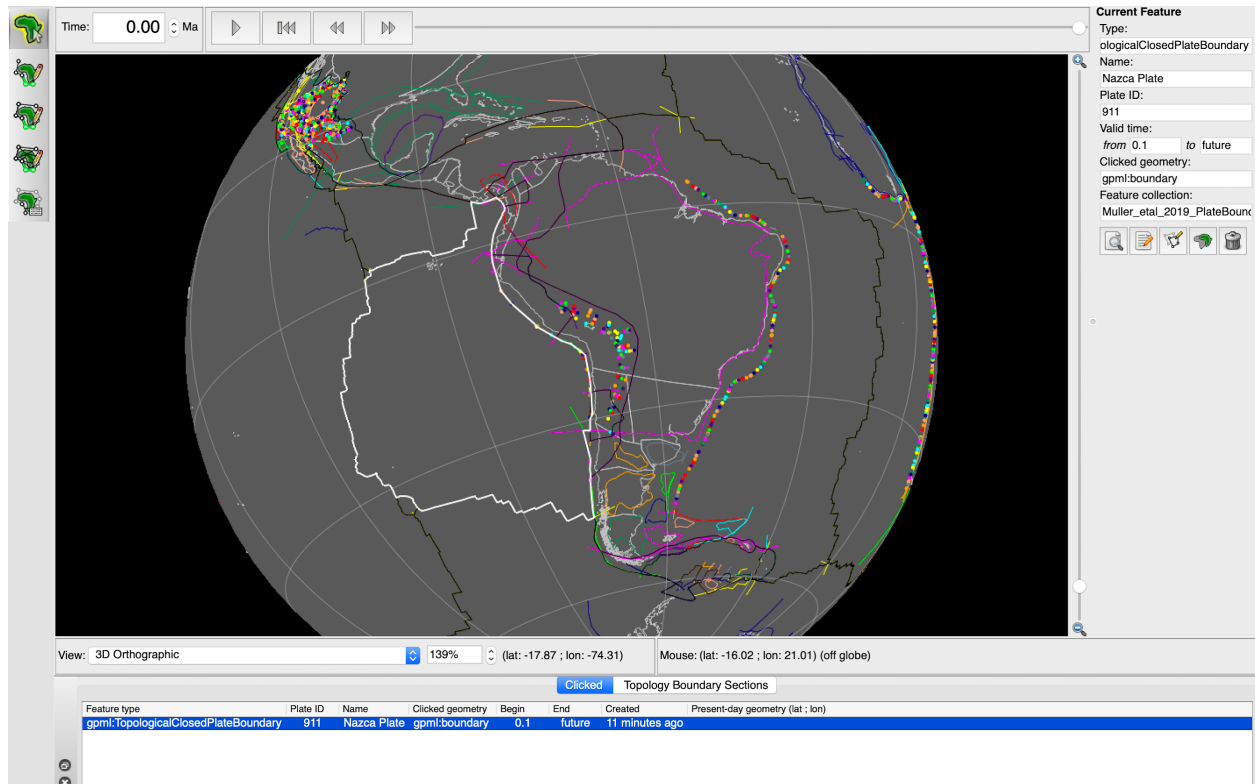


Figure 15: The updated Nazca Plate boundary (Step 5).

As is often the case when working with topological polygons, you will likely need to repeat the rebuilding process for many different time steps due to the limited lifespan of each polygon.

Exercise 2 - More detailed Andean Deformation

In this second exercise we will go through the process of capturing the more detailed model of Andean evolution contained within the study of Arriagada et al (2008). This study generated a series of map-view restorations of deformation within the central Andes from 45 Ma to present day using available information on the magnitude and age of tectonic shortening, combined with paleomagnetic data to constrain local block rotations. The restorations are presented in a series of intuitive figures and animations that we can capture as a time dependent raster sequence, georeference and load into GPlates. From there, we can generate a set of points with individual motion histories that represent the same deformation histories. Then, we

combine the motion histories for each point into a single topological deforming region that describes the overall kinematics consistent with the original study.

Part 1: Load the deformation raster sequence

The first step is to capture the deformation model from the original study of Arriagada et al (2008).

[We are not going to go through that in detail here - however, bear in mind that if you wanted to do this, the steps involve georeferencing a series of images (the georeferencing would be done in ArcGIS) corresponding to different reconstruction times, then loading the series of georeferenced images files into GPlates using the 'Import time-dependent raster' option. See the '2.2: Changing Rotations, Equivalent Finite Rotations, and Cross-Overs' and '3.1: Introduction to Rasters and Time-Dependent Rasters' tutorials for further details]

As a short-cut for this tutorial, the tutorial data set includes a time-dependent raster sequence derived from the animation made available as supplementary material as part of the Arriagada et al (2008) study. The movie file was converted to a series of images, then loaded into GPlates (the original movie contains images at 0.5 Ma intervals, but in the interests of file size we only include 5 Ma intervals here).

1. To load this raster sequence, either load the GPlates project file "8.2_p2.gproj" or load the associated gpml file from the tutorial data folder ("Arriagada_Images.gpml"), along with the following feature files:
 - Muller_etal_2019_CombinedRotations.rot
 - Muller_etal_Global_Coastlines.gpmlz
 - Muller_etal_2019_PlateBoundaries_DeformingNetworks.gpmlz

You should see the present day image appear within South America (Figure 16).

As with the previous example, it is important to set the Anchored Plate ID to 201 (South America).

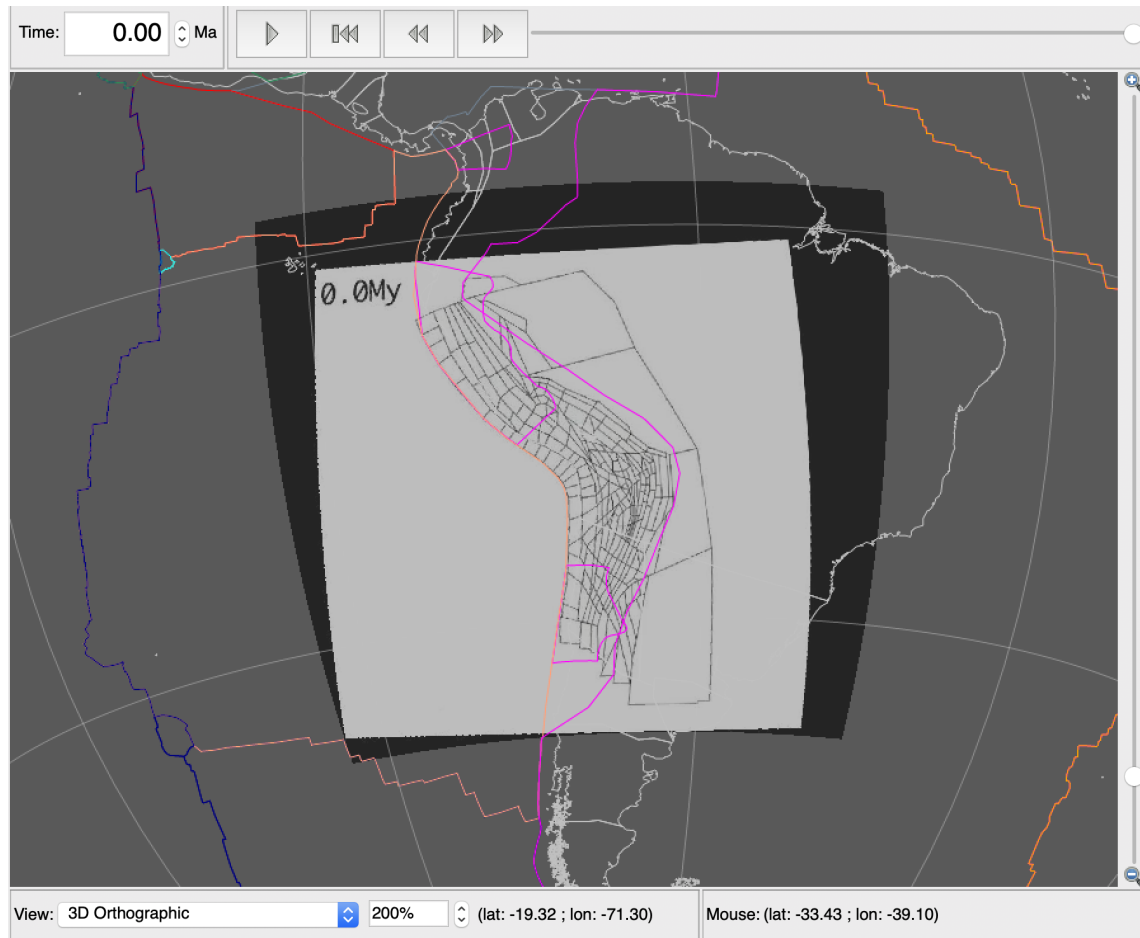


Figure 16: Present day reconstruction image over South America

2. Zoom in on South America, then change the reconstruction time to 45 Ma. You should see the Andean margin based on the Arriagada et al (2008) time dependent raster sequence, corresponding approximately with the plate boundary defined in the plate boundaries .gpmlz file (Figure 17).

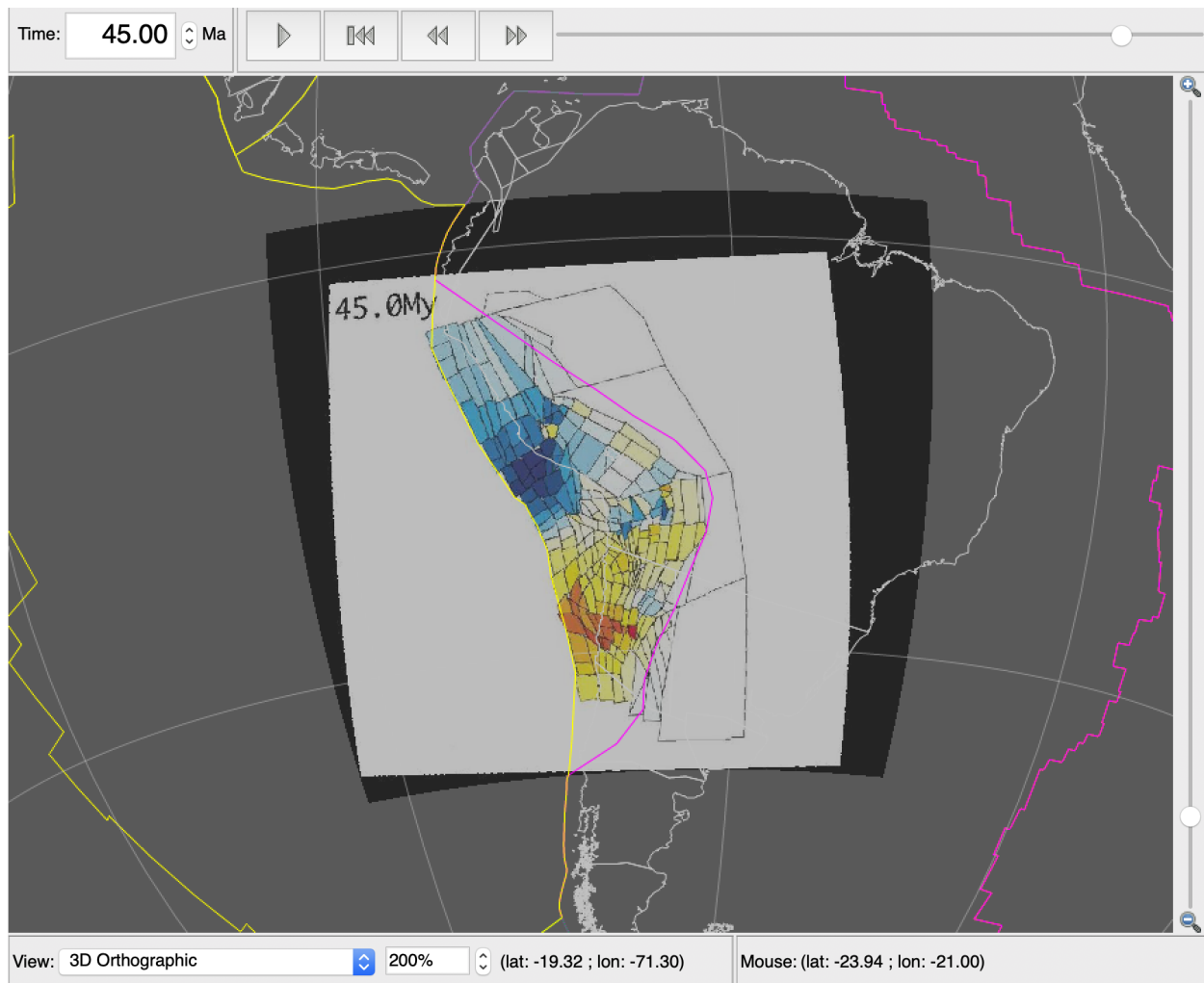


Figure 17: Andean margin at 45 Ma based on the Arriagada et al (2008) raster sequence (Step 3).

Part 2: Create deformation tracker points

Deformation tracker points are points with their own Plate IDs, whose motion can be defined independently from that of the 'major' plates like South America. In GPlates, all relative motions are defined by assigning plate IDs and rotation poles, whether this be for a major plate or a single point within a deforming mesh.

1. To create these points for the Andes, first set the reconstruction time to 0 Ma.

Next, you need to decide what level of detail you want to incorporate into your model. The level of detail you employ is entirely up to you, and depends on how much time you want to spend on the task and the purpose of your model. For example, if you were only interested in how the shape of the Andean margin has evolved you could ignore the interior mesh points entirely. Alternatively, you could define mesh points at each vertex of the 257 blocks within the original model. This tutorial illustrates the process with 6 points along the Andean margin and 10 points in the interior zone of crustal deformation.

You then need to decide which points to digitize. For the purposes of this tutorial we will just do ten points (Figure 18).

2. Digitise the desired number of points and assign individual plate IDs sequentially (e.g., from 2010000 to 2010009 if you are digitising 10 points)

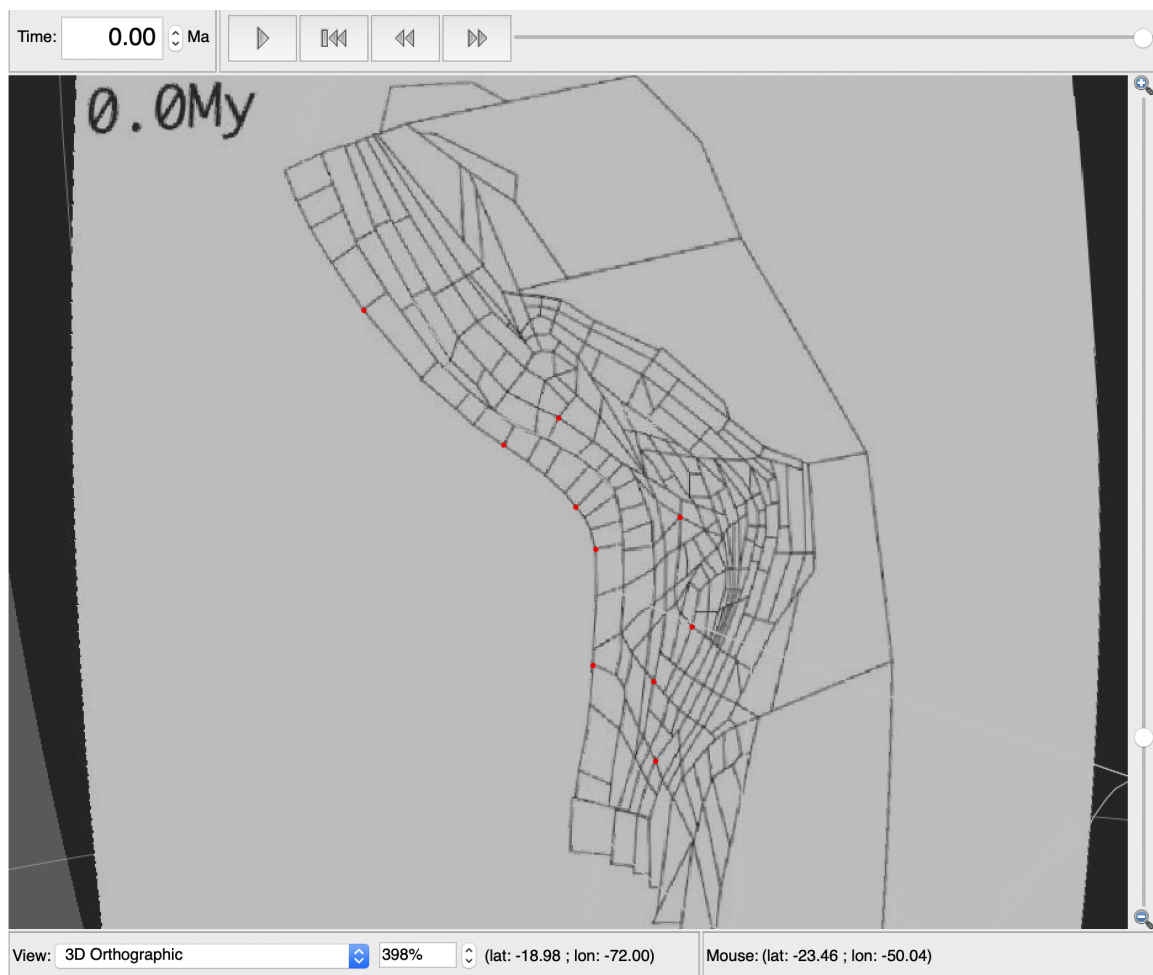


Figure 18: Digitised points in the interior zone of crustal deformation (Step 2)

One further element we need to create is a boundary line that will divide the deforming region from the stable/rigid part of South America.

3. Create this line using the line digitization tool, assigning the feature a Plate ID of 201 - we want the boundary of the deforming region to move with the existing rotations for South America (Figure 19).

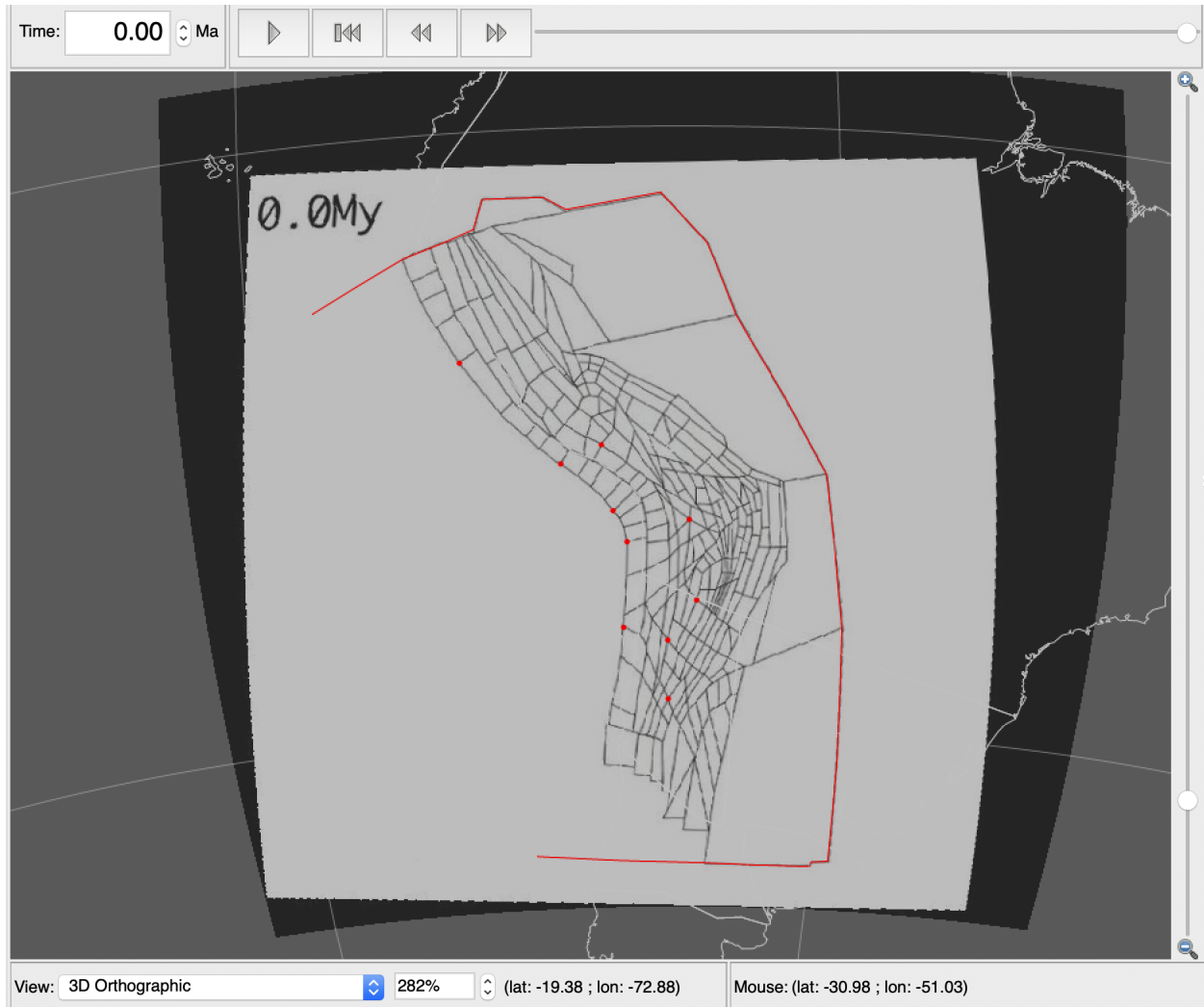


Figure 19: Digitised boundary line that divides the deforming region from the stable/rigid part of South America (Step 3)

Before we start modifying the deformation points we need to repeat the process carried out above (Exercise 1, Part 1, Step 7) to create 'blank' rotations for these points in a new rotation file.

4. In the text editor, create rotations corresponding to each point and PlateID that you have newly created. Save the edits in the text editor, then load the new rotation file into GPlates and add a connection to the main rotation file, as in Exercise 1.
5. Set the reconstruction time to some time in the past that corresponds to the most recent time in the past you want to create point displacements for, and which corresponds to a timeslice in the underlying time-dependent rasters. (in the example below we skip the 5 Ma and 10 Ma snapshots and use 15 Ma - it is up to you whether you want to capture more timeslices).
6. Using the change rotations tool, as in Exercise 1, create motion histories for each point, dragging each point to the polygon intersection in the 15 Ma image that corresponds to the same polygon intersection at 0 Ma (Figure 20), but shifted by the deformation model.

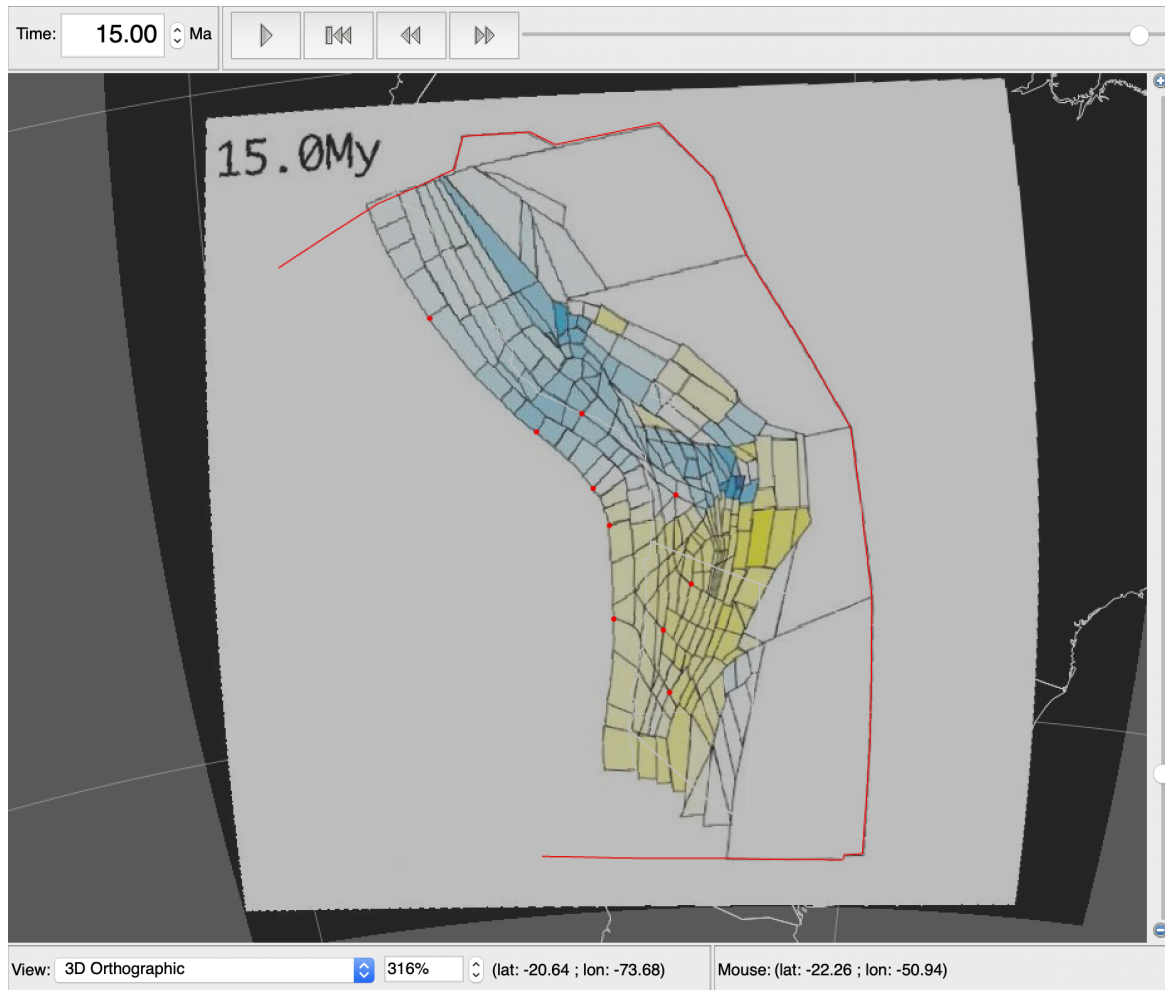


Figure 20: Modifying rotations to create motion histories for each point at 15 Ma (Step 6).

7. Repeat this process (Step 6) for each of the ten points at 15 Ma.
8. Repeat Steps 5-7 for 30 Ma and 45 Ma.

Part 3: Create a Topological Mesh over the Deformation Region

1. To create a deforming network topology, select the Topology tools menu on the left, then select the 'Build New Network Topology' tool (Figure 21).

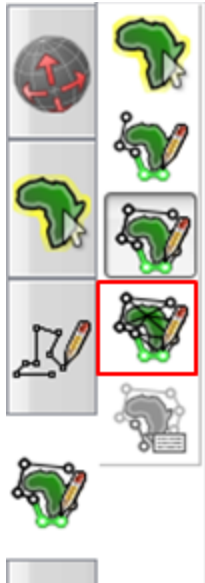


Figure 21: Build New Network Topology Tool

The process of building a topological network is largely similar to building other topological features, with one important difference - we can add points both to the interior and to the boundary. Note the two buttons 'Add To Boundary' and 'Add To Interior' (Figure 22). As we select each line or point feature to add to the topology, we have to decide whether this feature is part of the boundary or the interior.

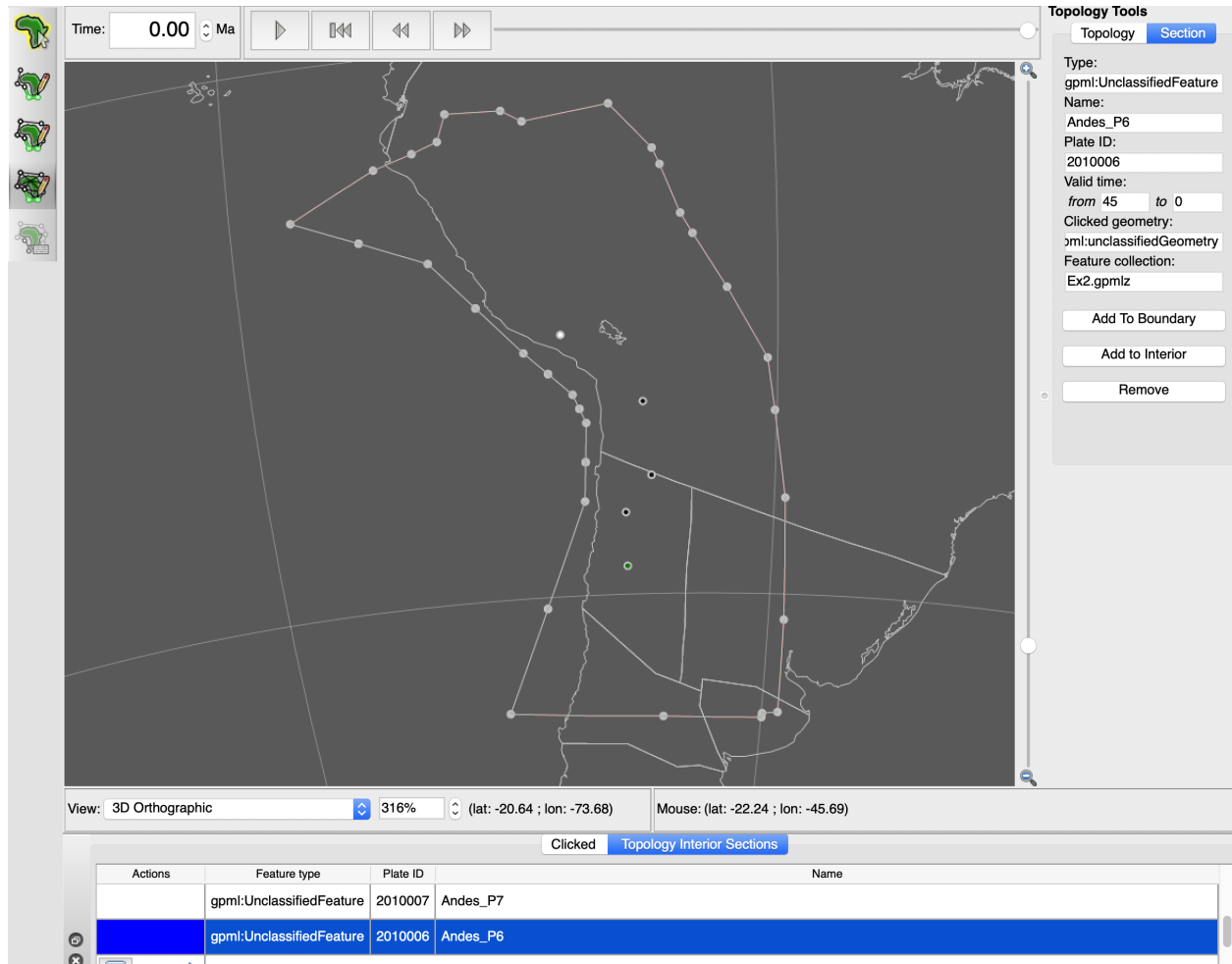


Figure 22: Adding points and lines to the boundary and interior of the topological network.

2. Add the boundary line and points to the boundary of the topological network, and add the remaining points to the interior.
3. Select 'Create', and choose the type 'TopologicalNetwork'. Give the network a name, and set its begin and end times to 45 Ma and 0 Ma respectively.

The result should look something like Figure 23.

As you reconstruct back and forward through time the mesh should evolve according to the motion of the various geometries involved in the topology.

Note that topological Network layers appear in the layer manager in gold.

4. Make sure to save your topological network feature to a file (.gpml or gpmlz).

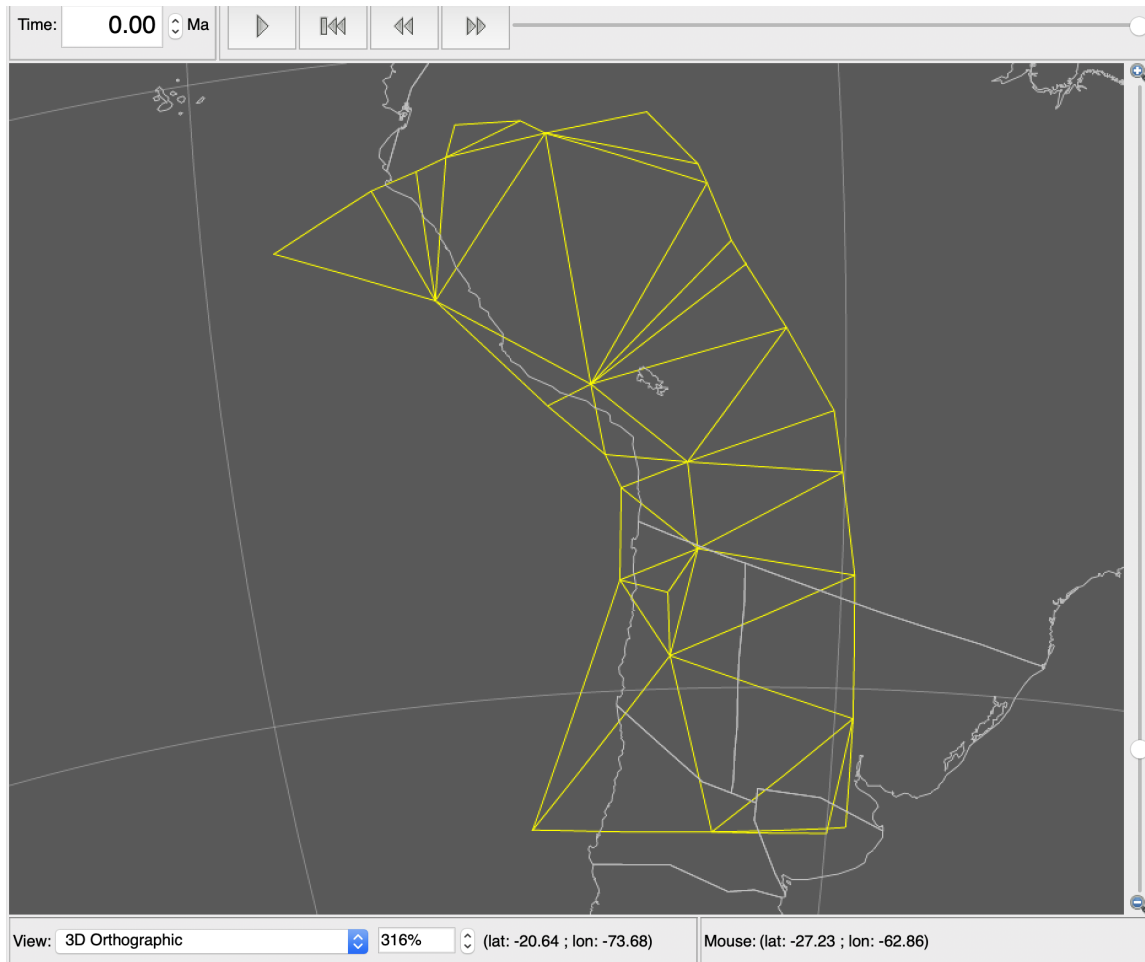


Figure 23: The newly-created topological mesh.

Additional Exercises

Firstly, note that what we just did was not completely self-consistent. We ended up with a deforming plate boundary based on the McQuarrie (2002)

shortening estimates, but the interior points based on the block reconstruction of Arriagada et al (2008). Since they are two different approaches to the same restoration, you may want to compare the two (both the end result in GPlates, and the different methodologies and observations used by reading the original papers). Other similar reconstructions have also been proposed (e.g., Kley, 1999, see the reference list).

At this point, you may want to explore some of the ways we can visualise the deformation implied by the mesh you have created. For example:

1. Loading velocity features such as mesh caps - see the 'Velocity Fields' Tutorial
2. Expand the Network layer in the Layer Manager and explore the options under 'Network and Triangulation Options'. This provides options to colour each triangular element of the mesh based on the instantaneous deformation implied.
3. Following on from Exercise 2, think about how the deforming mesh can be incorporated as a deforming region into the global plate set of topological plate polygons.

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