Changing Rotations, Equivalent Finite Rotations, and Cross-Overs

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Aim

This tutorial is designed to teach the basics of implementing and manipulating rotations in GPlates. You will employ and build on the skills you acquired in the Plate Reconstructions tutorial.

Background

Plate reconstructions in *GPlates* require a set of instructions, stored in the rotation file (*.rot), that allow the software to rotate and move geometries through time. Each motion is defined by a finite rotation; each line in the rotation file containing a Plate ID, an assigned time, Euler rotation and relative Plate ID. Such a framework allows plate motion models to be hierarchically structured, with relative plate motions embedded in an absolute reference frame – where Africa tends to be the trunk of the hierarchy. The resulting absolute plate motions are a cumulative motion of all plates higher up in the rotation hierarchy. The complicating factor is a scenario where one tectonic element changes from moving relative to one plate to moving with another. This is particularly the case when continental fragments collide and accrete, and their motion “crosses-over” to move relative to another plate. In such situations, the rotation file must contain two entries for a single time. Both entries are equivalent finite rotations with different Relative Plate IDs. We will cover a number of hypothetical scenarios of Borneo’s (Plate ID 614) motion to cover the most common examples of calculating equivalent finite rotations and cross-overs. You need to download *GPlates 1.5* and use the Sample Data that is provided.

Basics of a rotation file

The entries below (in bold) are an example of a rotation file for Borneo (Plate ID is the first column) at three times (present-day, 10 and 25 Ma). In

this case, Borneo is moving relative to Plate 673 (6^{th} column), which is Sumatra in the EarthByte rotations. The ages (2^{nd} column) are in million years, and are followed by the finite Euler rotation (3^{rd} to 5^{th} column). The columns are space or tab-delimited. GPlates treats anything following the exclamation mark ("!") as a comment, and ignores any lines that have a Plate ID of 999. This is a legacy code from the PLATES rotation scheme where lines beginning with 999 are ignored. This will become useful later, as it will be necessary to "comment out" particular lines in the rotation file. Note that GPlates can deal with Plate IDs exceeding three digits unlike the PLATES format, as long as they are integers.
The extracted portion of the rotation file from the GPlates 1.5 Sample Data indicates that there is no relative motion between Borneo and Sumatra during the 0 to 10 Ma time interval, while there is some motion between 10 and 25 Ma. If consecutive lines in a rotation file have the same Euler rotation (i.e. columns 3 to 5), it means that there has been no relative motion between the plate pairs during that time interval. Remember, in GPlates we deal with finite rotations, and not stage rotations. However, stage rotations can be exported from GPlates.

614 0.0 0.0 0.0 0.0 673 !KLM-NSM Kalimantan(Borneo)-North Sumatra
614 10.0 0.0 0.0 0.0 673 !KLM-NSM
614 25.0 3.03 101.54 -10.0 673 !KLM-NSM small ccw rot according to pmag, Muller et. al. 2008

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7+
Plate ID (Integer)	Age (Float/Integer in Ma)	Lat	Lon	Angle of rotation	Relative (conjugate) Plate ID (Integer)	Comment

Table 1. Summary table showing the basic layout of entries required in a rotation file. In practice, each entry is separated by a space or tab in order to differentiate between each type of entry.

Included Files

Click here to download the data bundle for this tutorial.

The tutorial dataset
(2.2-Changing_Rotations_Equivalent_finite_Rotations_Cross_Overs.zip)
includes the following files:

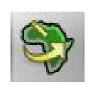
Australia-Antarctic rotation model file: AusAnt_ExampleRotation.rot
Global rotation model file:
Global_EarthByte_GPlates_Rotation_AusAnt_Example.rot

Coastline file: Seton_etal_ESR2012_Coastlines_2012.1_Polygon.gpmlz

Fracture zone fiile: AusAnt_FZs.gpml

This tutorial dataset is compatible with GPlates 1.5.

Exercise 1 – Applying a rotation

In the Plate Reconstructions tutorial you learnt how to move features around on the globe using the Modify Reconstruction Pole tool , we used the example of moving South America to fit together with Africa like a jig-saw. It is more likely for tectonic reconstructions that you will want to change or apply a rotation to a feature back in time, rather than changing anything at the present-day. Using a simple example, we will learn how to apply a rotation.

Australia started to move away from Antarctica ~83 Ma. According to Tikku and Cande (1999), Australia moved in a northward direction relative to a fixed Antarctica. You will implement this rotation in the provided rotation file, AusAnt_ExampleRotation.rot. For simplicity, this file contains rotations for Australia and Antarctica only.

1. Open AusAnt_ExampleRotation.rot in a text editor so you can see what it looks like (Figure 1):

a. Plate ID 000 = Spin axis

b. Plate ID 001 = Atlantic hotspots

c. Plate ID 701 = Africa

d. Plate ID 801 = Australia

e. PlateID 850 = Tasmania

f. Plate ID 802 = Antarctica

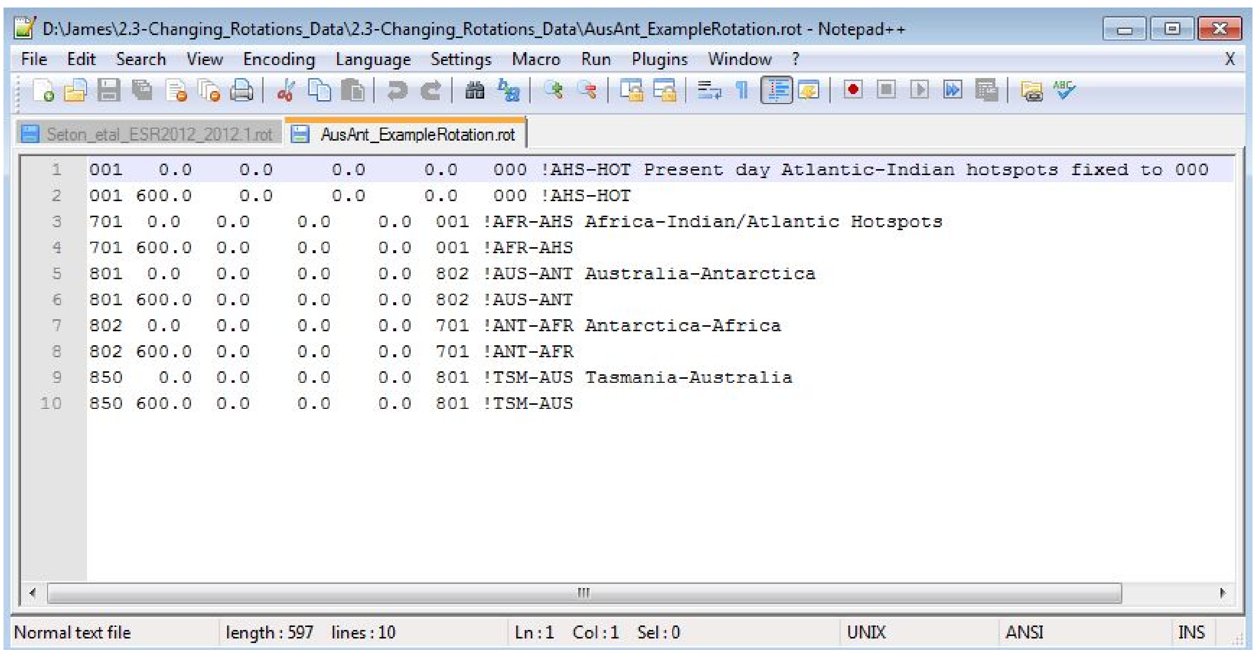


Figure 1. The contents of our example rotation file.

You will notice that Australia moves relative to Antarctica, Antarctica moves relative to Africa, Africa moves relative to the hotspot reference frame which is fixed to the spin axis.

2. Open GPlates

3. File > Open Feature Collection… (Figure 2) > select AusAnt_ExampleRotation.rot and the EarthByte coastline file from the sample data bundle for this tutorial > Open

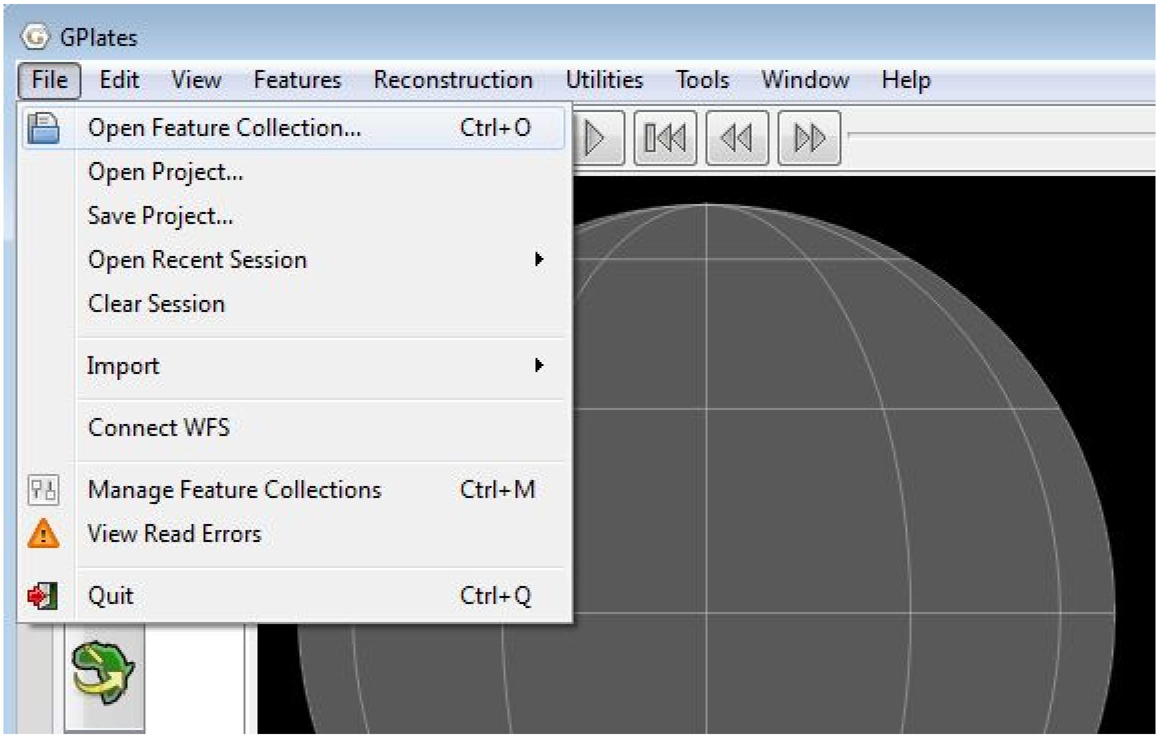


Figure 2. Loading feature collections into GPlates

4. Rotate the globe so that it is centred on Australia. Now reconstruct backwards through time. You will notice that the feature data stay fixed in their present-day locations (this is because they have no relative rotations). The only thing that changes is that features will disappear if you reconstruct to before their 'appear time'.

It is generally believed that Australia moved northwards, relative to a fixed Antarctica, between ~83 Ma and the present (Tikku and Cande, 1999). We will implement this rotation.

5. Centre your globe so that Australia and the coastline of Antarctica nearest Australia are in view (Figure 3).

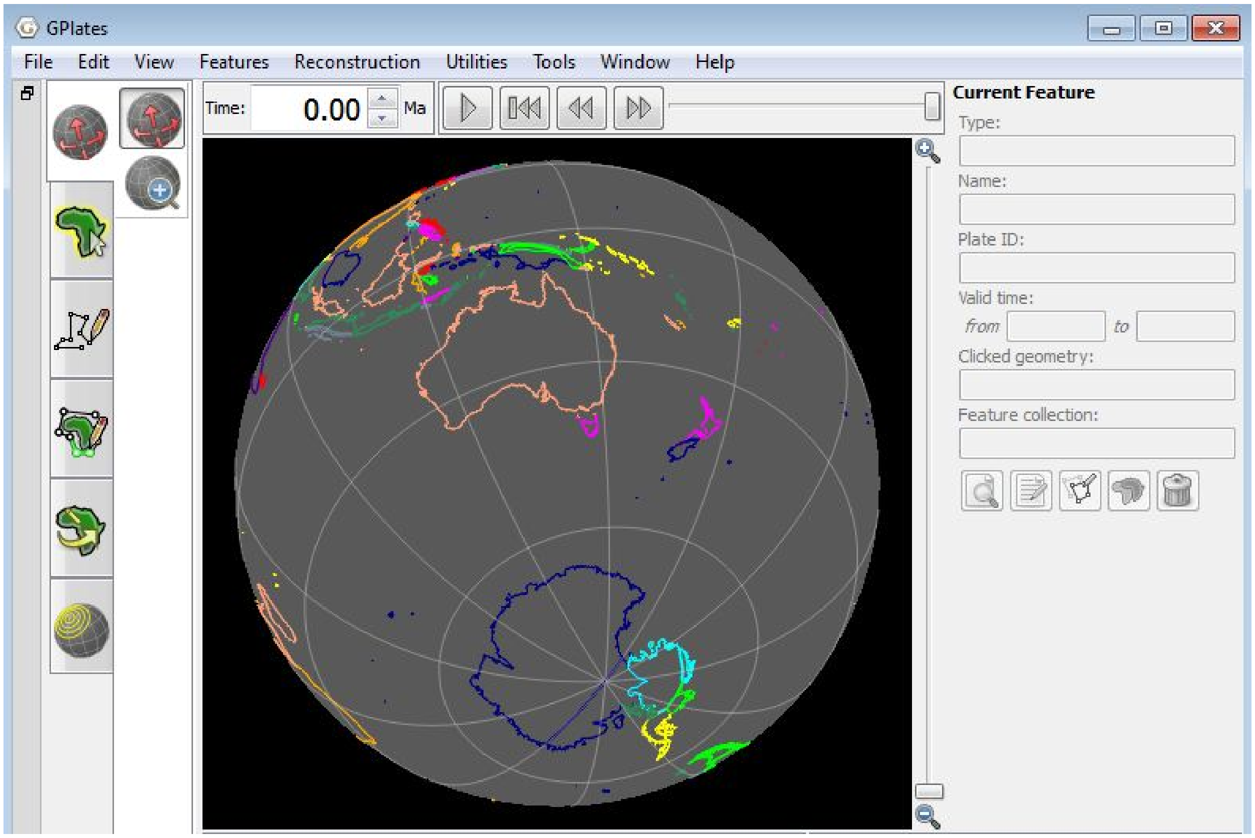


Figure 3. View of Australia and Antarctica.

6. As we want to implement a rotation at 83 Ma, jump to this time using the Time controls.

7. Use the Choose Feature tool  to select Australia and then click Modify Reconstruction Pole .

8. Drag Australia in a southward direction so that it approximately lines up with Antarctica (Figure 4). Once the feature attains the desired position and orientation, clicking Apply (right of the globe), this will open up Apply Reconstruction Pole Adjustment window, where you can review the details of your implemented rotation (Figure 5).

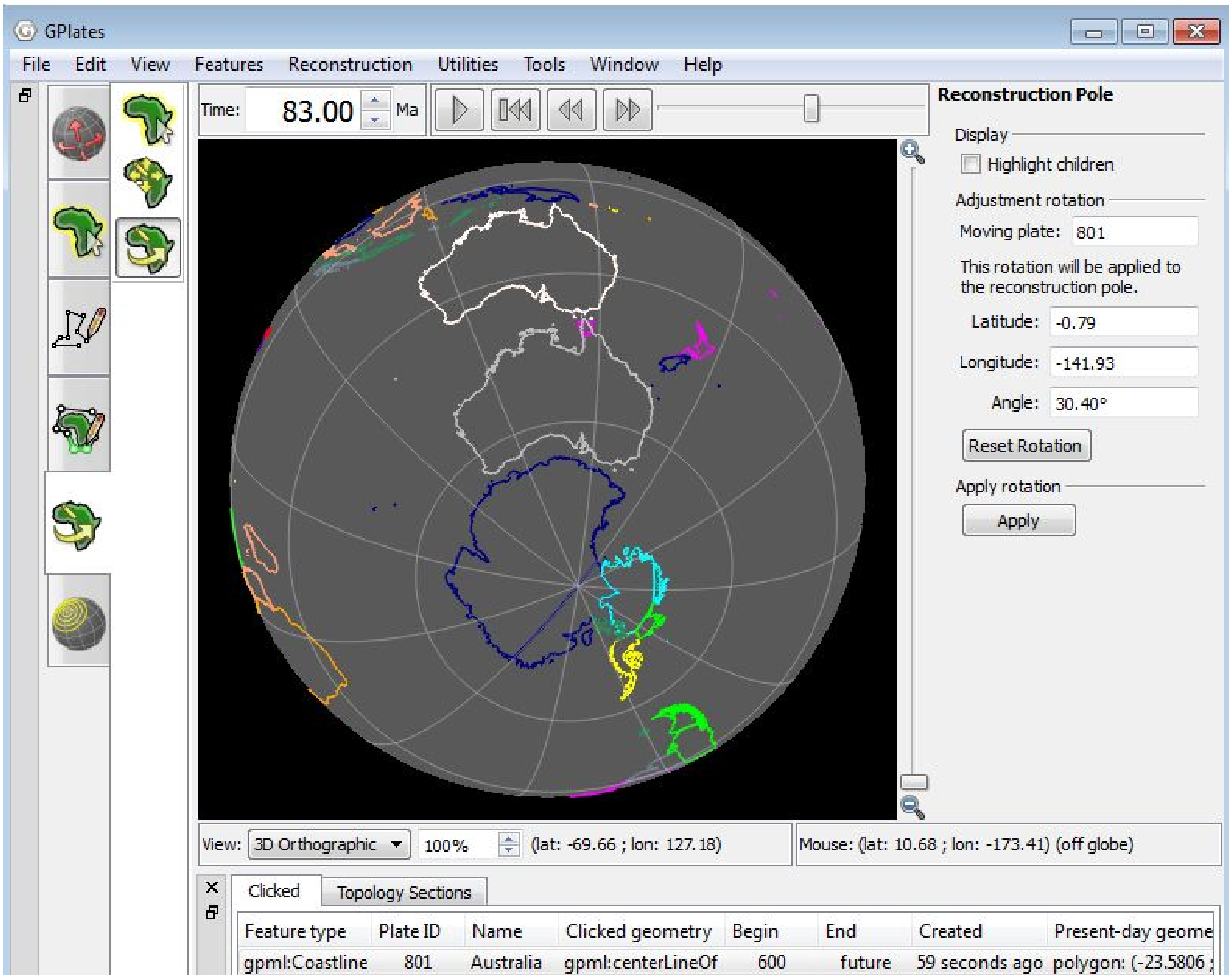


Figure 4. Australia has been dragged southward at 83 Ma to line up with Antarctica.

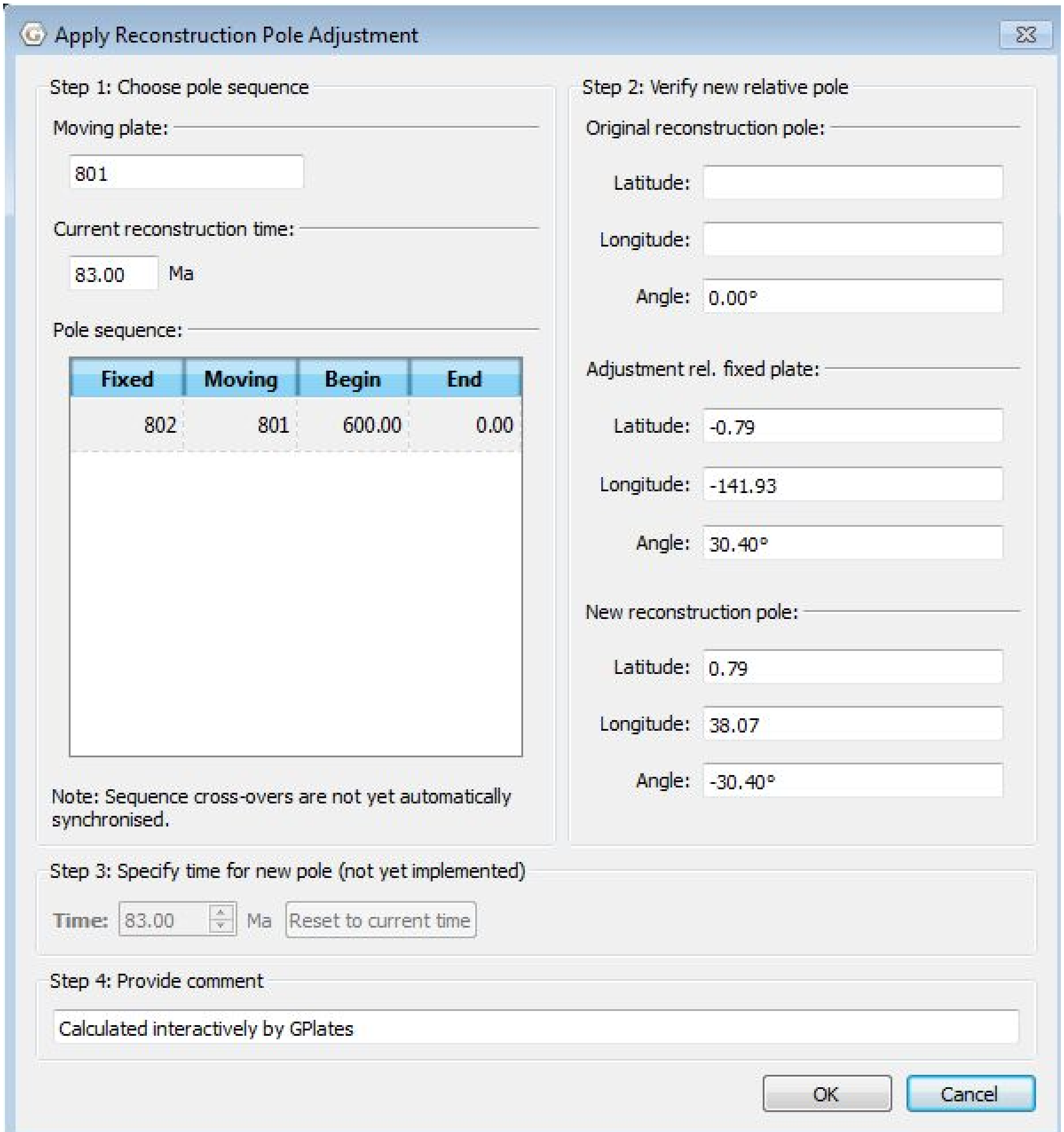


Figure 5. Apply Reconstruction Pole Adjustment window, where you can review the details of your rotation implementation.

9. In this window you can verify the new relative pole and details (Figure 5). Click OK, this will implement your rotation.

You will notice that Australia is now positioned adjacent to Antarctica at 83

Ma (Figure 6).

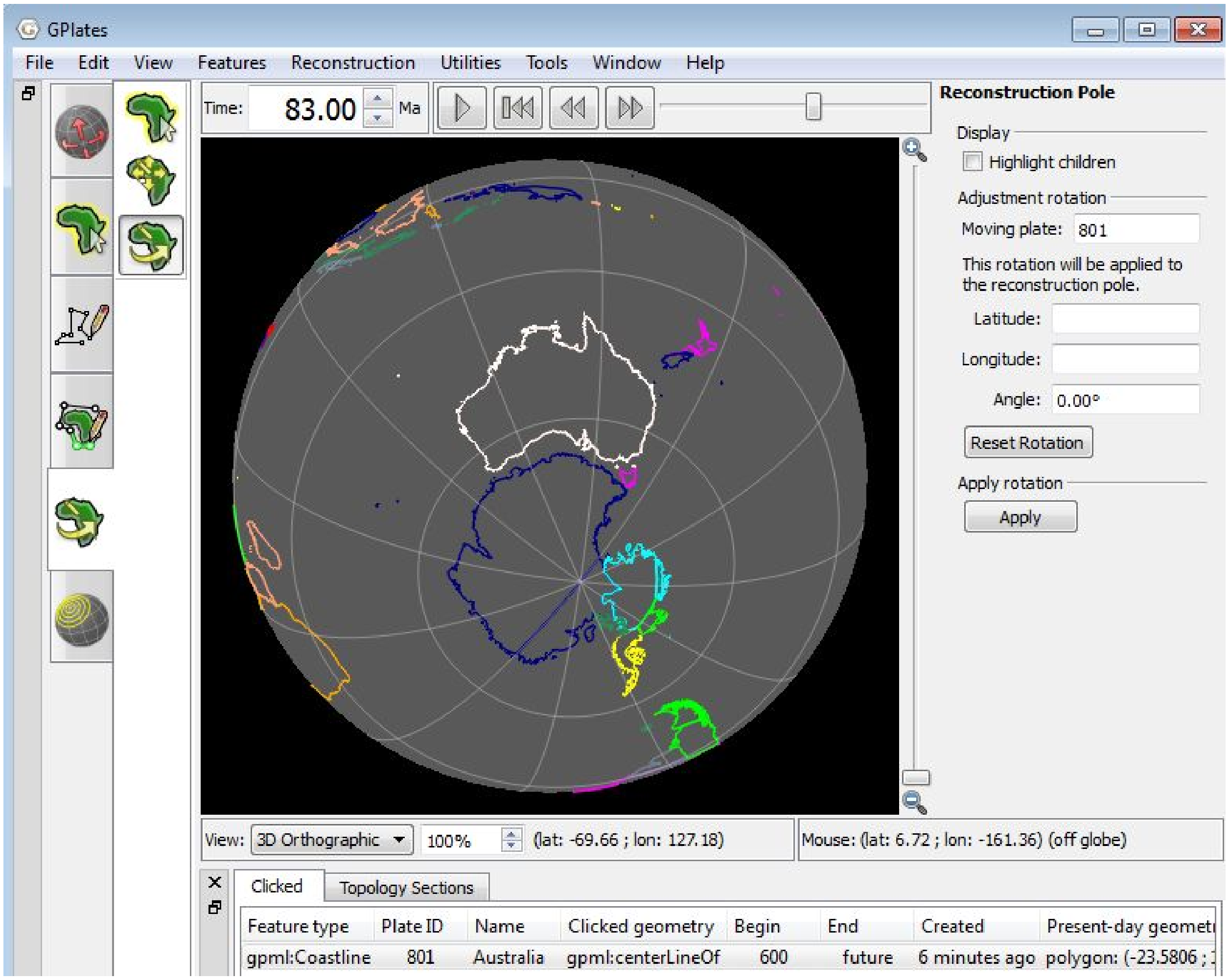


Figure 6. Australia is now positioned adjacent to Antarctica at 83 Ma. It is south of it's present-day position.

10. Now you need to save your rotation file. File > Manage Feature Collections > save a copy of the rotation file with a new name (this is so you can compare it to the old rotation file) > now load this new rotation file by clicking Open File and navigating to the directory where it is saved > Open.

11. Use the Animation slider to reconstruct from 83 Ma to the present. You will see Australia move in a northward direction relative to Antarctica!

12. However there is one more thing we need to do. If you jump to 600 Ma for example and animate back to 0 Ma, you will notice that Australia starts in

its present day coordinates, moves southward to its 83 Ma position and then moves northwards again. This is because the location of Australia at 600 Ma is the same as present-day in our rotation file (Figure 7). We need to alter the rotation file so that there are not rotations between 600 Ma and 83 Ma.

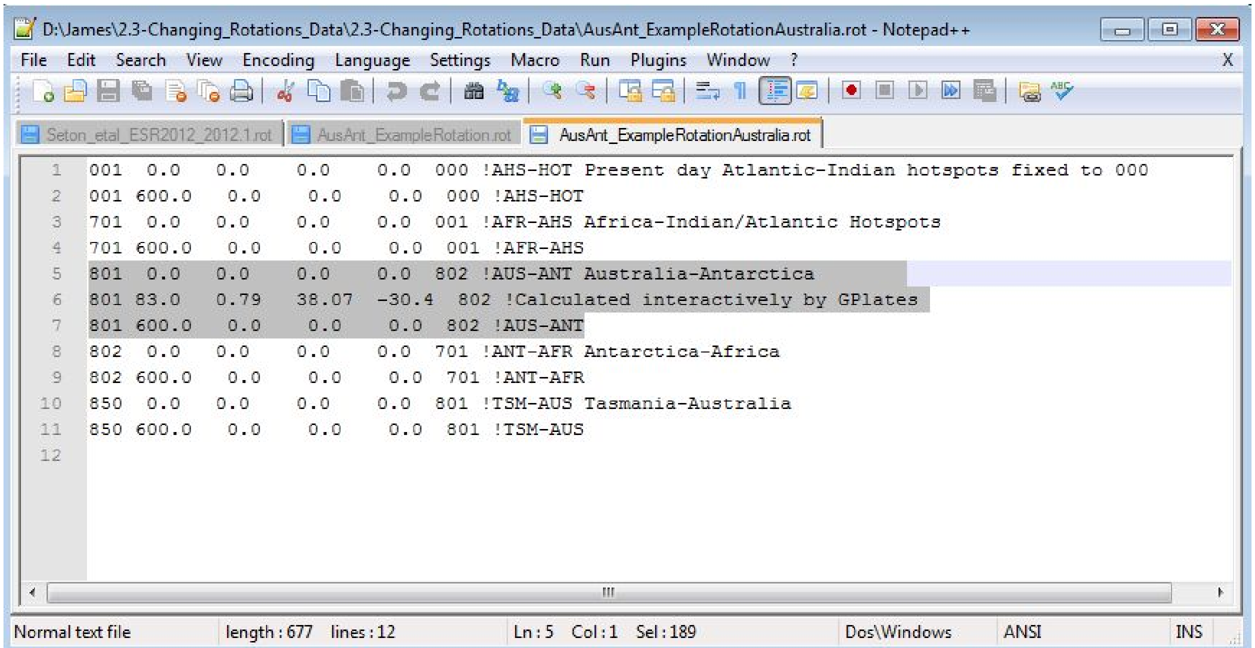


Figure 7. A rotation has been added for Australia at 83 Ma. However notice that the latitude and longitude of Australia at 600 Ma is the same as present-day.

13. Open the new rotation file in a text editor. And make the 600 Ma rotation data (lat., long., rotation angle) for Plate ID 801 the same as the 83 Ma rotation (ie duplicate the data) (Figure 8). This will result in no rotation between Australia and Antarctica until the period 83 Ma – 0 Ma.

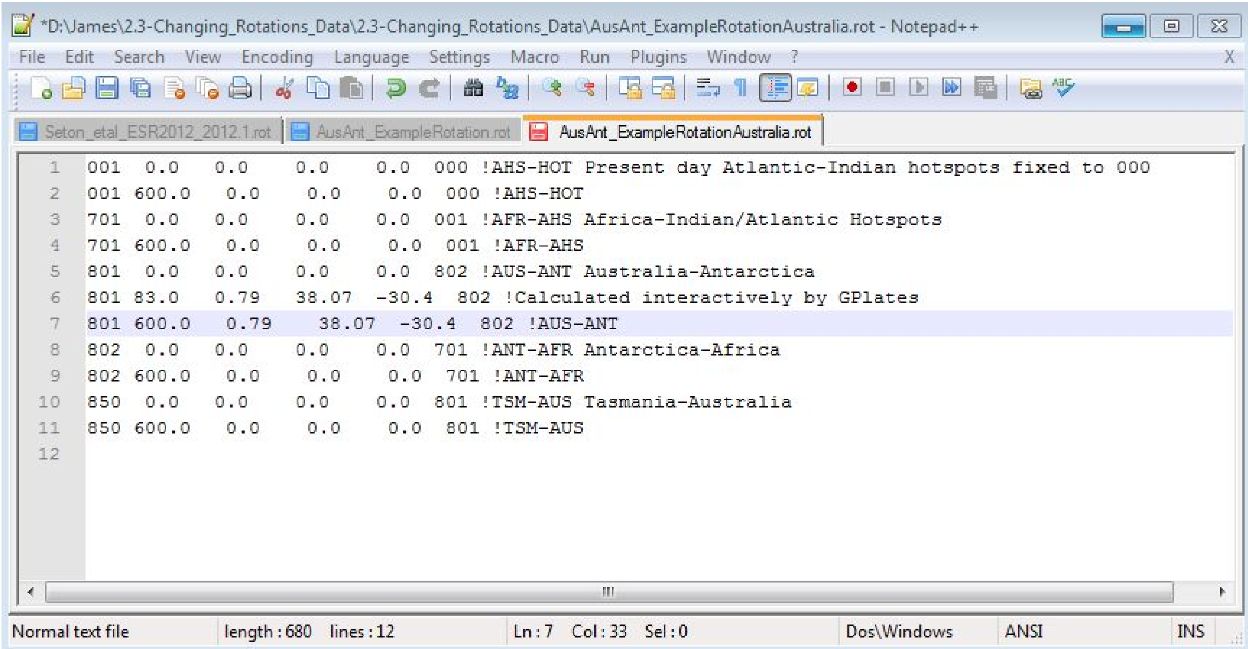


Figure 8. Modified rotation file, note that the 600 Ma and 83 Ma rotations for Plate ID 801 are the same.

14. Load your modified rotation file into GPlates and animate forward in time from say 150 Ma. You will notice that Australia stays attached to Antarctica until 83 Ma.

Exercise 2 – Modifying an existing rotation

In this second exercise we will learn how to modify an existing rotation file. Keeping with the theme of Australia and Antarctica we will implement a new rotation for Australia at 83 Ma. Whittaker et al. (2007) proposed that 83 Ma Australia was located further eastwards with respect to Antarctica than previously thought (e.g. Tikku and Cande, 1999). They suggest that from ~83 Ma to 50 Ma Australia moved northwest relative to a fixed Antarctica, before then commencing northward motion between 50 Ma and the present. The timing of their proposed change in plate motion at ~50 Ma coincides with the Hawaiian-Emperor bend and subduction of the Izanagi-Pacific ridge.

1. Eject all existing rotation files from GPlates but keep the Seton_etal_ESR2012_Coastlines_2012.1_Polygon.gpmlz file loaded. File > Manage Feature Collections > click the eject symbol  corresponding to

all loaded rotation files. Keep the Manage Feature Collections window open.

2. Open File > select the rotation file for this exercise Global_EarthByte_GPlates_Rotation_AusAnt_Example.rot > Open

The rotation file we have just loaded is significantly more complicated than that of the last exercise. Reconstruct the globe back through time and you will see that all the plates move. If you open this rotation file in a text editor you can see how much longer and more detailed it is compared to the last exercise.

3. Use the Time Controls to jump to 83 Ma.

We will use the fracture zones to help us constrain the position of Australia 83 Ma.

4. File > Manage Feature Collections > Open File > select AusAnt_FZs.gpml from the data bundle > Open

Following Whittaker et al. (2007) we will align the Antarctic fracture zone with the most westerly Australian fracture zone, whereby shifting Australia east relative to a fixed Antarctica.

5. Use the Choose Feature button  to select the Australian fracture zone> click Modify Reconstruction Pole  > drag the fracture zone eastward so that it is connected to the Antarctic fracture zone(Figure 9) > click Apply (right of globe) > you can then click OK in the Apply Reconstruction Pole Adjustment window once you have reviewed the details of your new reconstruction and are satisfied.

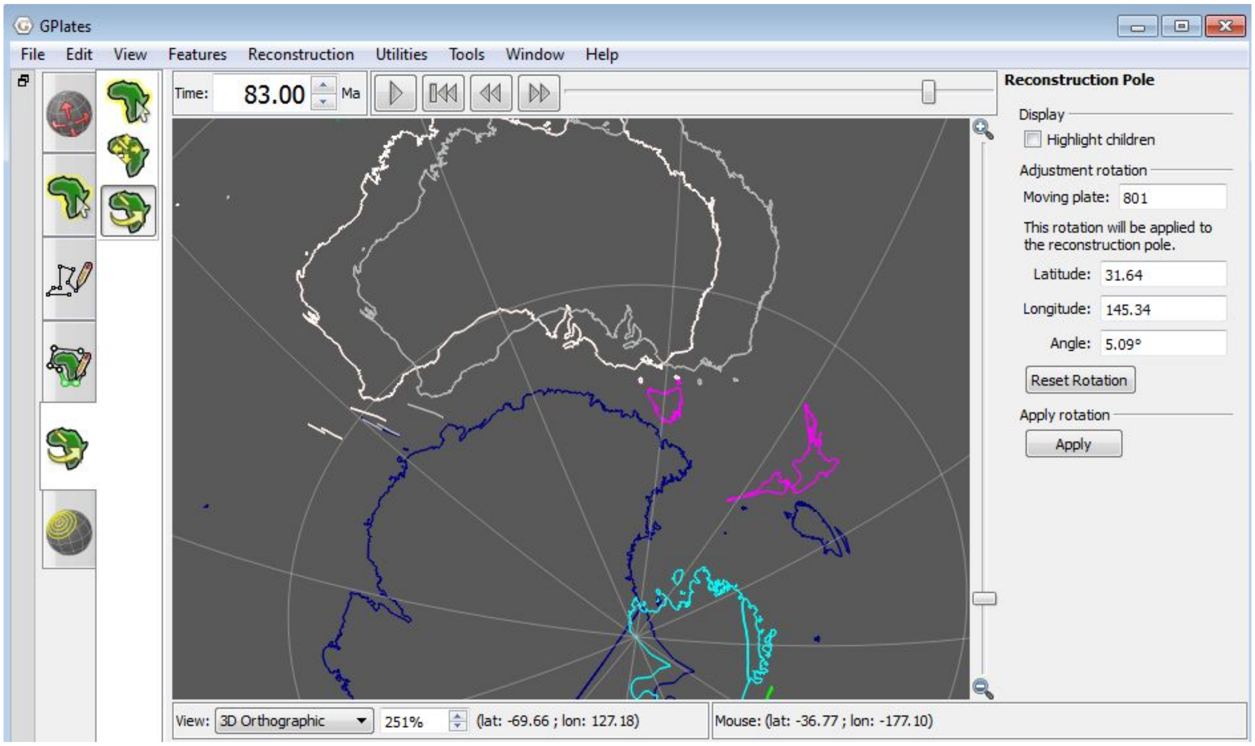


Figure 9. Australia shifted east using the Modify Reconstruction Pole tool.

When you return to the globe you will notice that Australia is located further east than when you started (Figure 10). We now need to save this data.

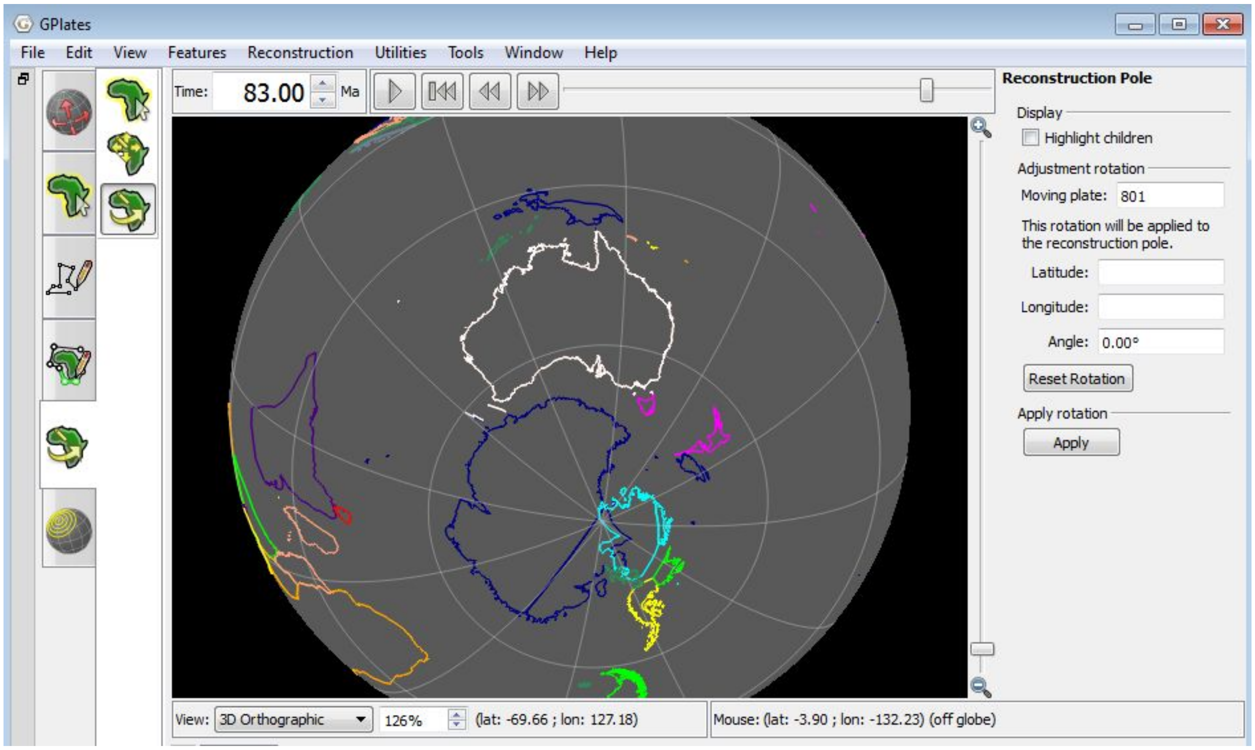


Figure 10. Australia shifted further east 83 Ma.

6. File > Manage Feature Collections > save your Global_EarthByte_GPlates_Rotations_AusAnt_Example.rot file with a new name  so that you preserve the old rotation file.

Now use the Time controls to watch Australia's motion from 83 Ma to present-day and you will see that there is northwest motion of Australia relative to a fixed Antarctica between 83 Ma and ~50 Ma. Then Australia commences northward motion.

7. Open your modified rotation file and the original rotation file using a text editor and scroll down to the entries for Plate ID 801, compare the two rotation files, you will see that they have different entries now for 83 Ma (Figure 11).

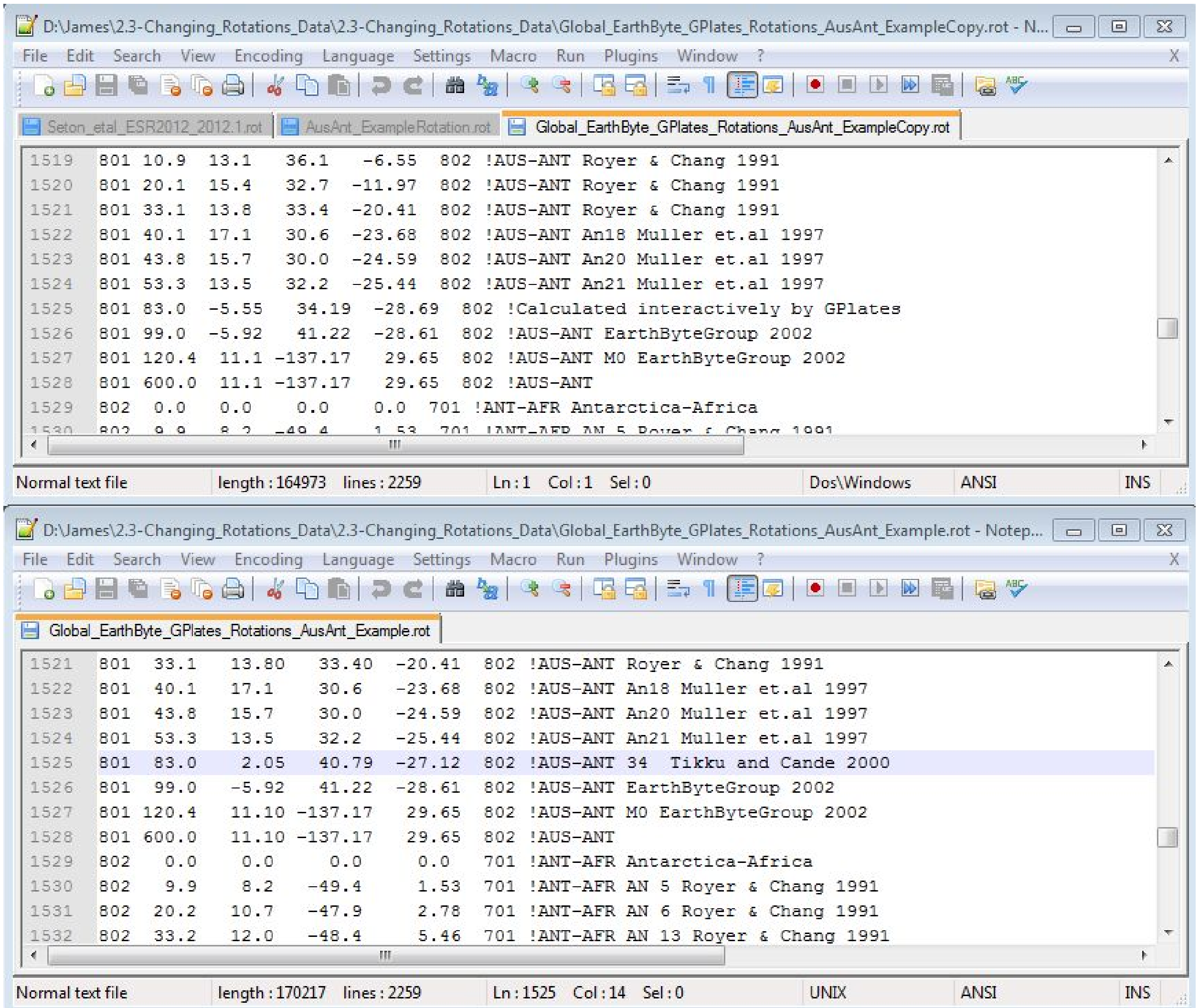


Figure 11. New (top) and old (bottom) rotation files showing entries for Plate ID 801. Entries for 83 Ma have changed.

Note: to better appreciate the change in motion of Australia relative to a fixed Antarctica you can specify Antarctica as the ‘anchored plate’ rather than the spin axis (default). Reconstruction > Specify Anchored Plate ID > enter 802. Now when you reconstruct the globe you can really notice that Australia moves in a northwest direction between 83 Ma and ~50 Ma.

Things to consider:

The cursor provides longitude and latitude locations to help with re-orienting. This is particularly useful when trying to replicate work from other literature.

Check the existing rotation file for the time increments for the plates. By reconstructing at these times will avoid jumps between two time steps. For example if the existing rotation file has rotations at 10 Ma and 20 Ma, by creating a new rotation at 16 Ma will only change the rotation between 10 Ma and 16 Ma. Between 16 Ma and 20 Ma the plate may jump erratically according to the old pole of rotation, unless you change it or an older timestep.

Exercise 3 – Re-calculating equivalent rotations and inserting a cross-over

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If we use Borneo as an example, we know that in the Seton et al. (2012) model that is included in the GPlates 1.5 Sample Data, Borneo (614) moves relative to Sumatra (673) from 0 to 100 Ma. Say that we want to change the rotation model in a way that Borneo moves relative to Sumatra only between 0 and 10 Ma, and then crosses-over to Indochina, we need to calculate the equivalent rotation at 10 Ma between Borneo and Indochina using GPlates.

1. Make sure the rotation file ('Seton_etal_ESR2012_2012.1') is **loaded** in GPlates.

2. Reconstruction > Specify Anchored Plate ID > Enter 604 and click OK. Here we are setting a new relative plate. The new relative Plate ID for this example will be 604 (Indochina). If you reconstruct through time, you will notice that Indochina remains fixed.

Note: Plate IDs can be queried interactively in GPlates by clicking the 'Feature Inspection' tool and then clicking a geometry feature, such as those contained in the coastline file.

3. Reconstruct to the time of the cross-over, here being 10 Ma.

4. To view the equivalent rotation at 10 Ma between 614 and 604, go to Reconstruction > View Total Reconstruction Poles (Figure 12). Go to the 'Equivalent Rotations rel. Anchored Plate' and scroll down to 614. The entry

for Borneo (614) displays the Euler rotation that will need to be entered into the rotation file: -16.8497 -76.8497 -0.593467. Copy these numbers to a text file, or write them down somewhere.

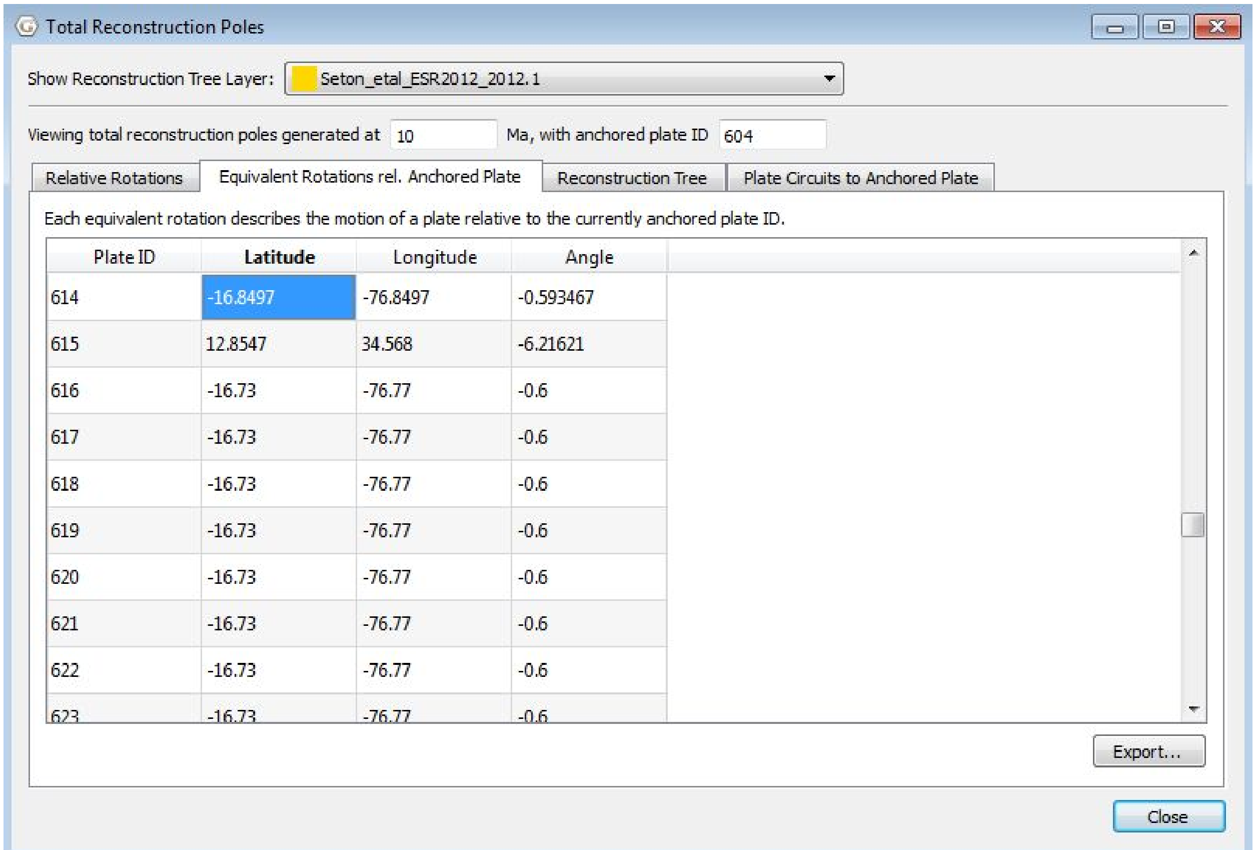

Figure 12. The 'Equivalent Rotations rel. Anchored Plate' tab in the Total Reconstruction Poles window, showing the equivalent rotation between plates 614 and 604 at 10 Ma.

5. We can now insert this rotation into the rotation file, and create a new model for Borneo's rotation – such as assuming that Borneo did not move relative to Indochina before 10 Ma. Alternatively, we can insert new published rotations for Borneo, or build them interactively in *GPlates*. For the sake of this part of the exercise, we assume Borneo has had no motion relative to Indochina before 10 Ma. To create the cross-over, open the rotation file in a text editor. You may want to work on a copy of your file. Keep the rotations at 10 Ma and younger, since we only want to alter the rotation for earlier times. Create a new entry at 10 Ma, remembering that cross-overs have two Euler rotations at that reconstruction time – one with the existing relative motion, and one for the new plate pair. Below is the original rotation file entry for Borneo:

614 0.0 0.0 0.0 0.0000 673 !KLM-NSM Kalimantan(Borneo)-North Sumatra
614 10.0 0.0 0.0 0.0 673 !KLM-NSM
614 25.0 3.030 101.54 -10.0 673 !KLM-NSM small ccw rot according to pmag, Muller et. al. 2008
614 40.0 3.030 101.54 -10.4 673 !KLM-NSM Muller et. al. 2008
614 50.0 3.030 101.54 -15.4 673 !KLM-NSM Muller et. al. 2008
614 70.0 3.030 101.54 -15.4 673 !KLM-NSM Muller et. al. 2008
614 100.0 27.39 141.79 -20.28 673 !KLM-NSM Muller et. al. 2008
614 100.0 26.74 133.02 -21.75 604 !KLM-ICH Kalimantan-Indochina cross-over Muller et. al. 2008
614 200.0 26.74 133.02 -21.75 604 !KLM-ICH Muller et. al. 2008

The new entries will look something like this:

614 0.0 0.0 0.0 0.0000 673 !KLM-NSM Kalimantan(Borneo)-North Sumatra
614 10.0 0.0 0.0 0.0 673 !KLM-NSM
614 10.0 -16.8497 -76.8497 -0.593467 604 !KLM-ICH Kalimantan-Indochina cross-over, Tutorial 2015
614 200.0 -16.8497 -76.8497 -0.593467 604 !KLM-ICH Assuming no motion between KLM and ICH

You will notice that there are now two entries for 10 Ma, and that the second entry (belonging to the older set of rotations from 10 to 200 Ma) contains the Euler rotation calculated in the previous step and that the relative Plate ID is 604 (Indochina). Note that the Euler rotation at 10 and 200 Ma are the same, which implies that there has been no motion Borneo-Indochina motion during this time interval.

6. Say we wanted to incorporate the position of Borneo at 40 Ma from the original file, but with the new plate pair, then we simply reconstruct to 40 Ma and repeat Step 4 using our original rotation file. The equivalent finite rotation relative to Indochina (604) is 2.97531 (lat), 103.633 (lon) with an angle of -23.7881. You can now create an entry in the new rotation file at 40 Ma with these numbers, and copy them to the 200 Ma time to ensure no relative motion occurs between 40 and 200 Ma. Make use of the comment fields to help you remember what you did. Remember, anything following the "!" is treated as a comment. Make sure the columns are space or tab-delimited, including a space or tab between the Relative Plate ID and the comment field symbol ("!"). With the new entries, the rotation file should now contain something like this:

614 0.0 0.0 0.0 0.0000 673 !KLM-NSM Kalimantan(Borneo)-North Sumatra
614 10.0 0.0 0.0 0.0 673 !KLM-NSM
614 10.0 -16.8497 -76.8497 -0.593467 604 !KLM-ICH Kalimantan-Indochina cross-over, Tutorial 2015
614 40.0 2.97531 103.633 -23.7881 604 !KLM-ICH Equivalent rotation from original 614-604 plate pair
614 200.0 2.97531 103.633 -23.7881 604 !KLM-ICH Muller et. al. 2008
614 300.0 26.74 133.02 -21.75 604 ! KLM-ICH

At this stage, make sure these entries are pasted into your new rotation file. Make sure to overwrite the existing rotations. If you keep the old rotations and insert new ones, *GPlates* will not know which ones to use and you will end up with velocity artefacts and bizarre motions of your plates. Once you have entered your new rotations, save the rotation file (make sure it has a .rot file extension) and (re-) load it in *GPlates* (File > Manage Feature Collections).

WARNING 1: *You can corrupt your rotation file if you make changes using GPlates (i.e. move a plate and save changes) and simultaneously edit the rotation file in the text editor. Therefore, if you make changes using GPlates, make sure you save the file and then re-open it in your text editor. Some text editors will automatically re-load changed files, but most will use the original stored in memory.*

Once you have successfully made the cross-over and changed to the rotation file, you can enter new rotations for Borneo with the 614-604 plate pair, or create a new rotation interactively in *GPlates*. There will be instances where you need to introduce new rotations at cross-over times, such as 10 Ma in the Borneo example. In most cases like this, you will need to comment out the rotations belonging to the older rotations (i.e. below the 10 Ma lines) because *GPlates* may not know which of the two plate pairs you want to apply the new rotation. *GPlates* will choose one of the plate pairs, most likely the entry belonging to the younger rotations.

Exercise 4 – Change and re-calculate rotations at cross-over time

1. For this scenario, we are modifying the rotations of Borneo at 10 Ma, belonging to the young plate pair (614-604). Open the rotation file in your text editor and comment out all the lines that belong to the 614-604 plate pair. Remember that lines that have a Plate ID of 999 will be ignored and will be commented out by *GPlates*. Save your changes and re-load the rotation file in *GPlates* (this is important, see Warning 1). Your entries for Borneo will now look like this:

614 0.0 0.0 0.0 0.0000 673 !KLM-NSM Kalimantan(Borneo)-North Sumatra
614 10.0 0.0 0.0 0.0 673 !KLM-NSM
999 10.0 -16.8497 -76.8497 -0.593467 604 !KLM-ICH Kalimantan-Indochina cross-over, Tutorial 2013
999 40.0 2.97531 103.633 -23.7881 604 !KLM-ICH Equivalent rotation from original 614-604 plate pair
999 200.0 2.97531 103.633 -23.7881 604 !KLM-ICH Muller et. al. 2008
999 300.0 26.74 133.02 -21.75 604 ! KLM-ICH

2. Modify rotation of Borneo interactively at 10 Ma by selecting Borneo's geometry and then altering the rotation interactively using the Modify Reconstruction Pole tool (Figure 13). See 'Tutorial 1.4 Interacting with Features' for detailed instructions on interactively rotating plates. For this example we have created a hypothetical case that implies Borneo has moved counter-clockwise between 10 and 0 Ma, thus we need to rotate Borneo's geometry in a clockwise fashion at 10 Ma. Click Apply and OK to change the rotation (Figure 14). Remember that we are modifying the younger rotations belonging to the 614-673 plate pair. Save your changes by going to File > Manage Feature Collections and clicking on the Save button.

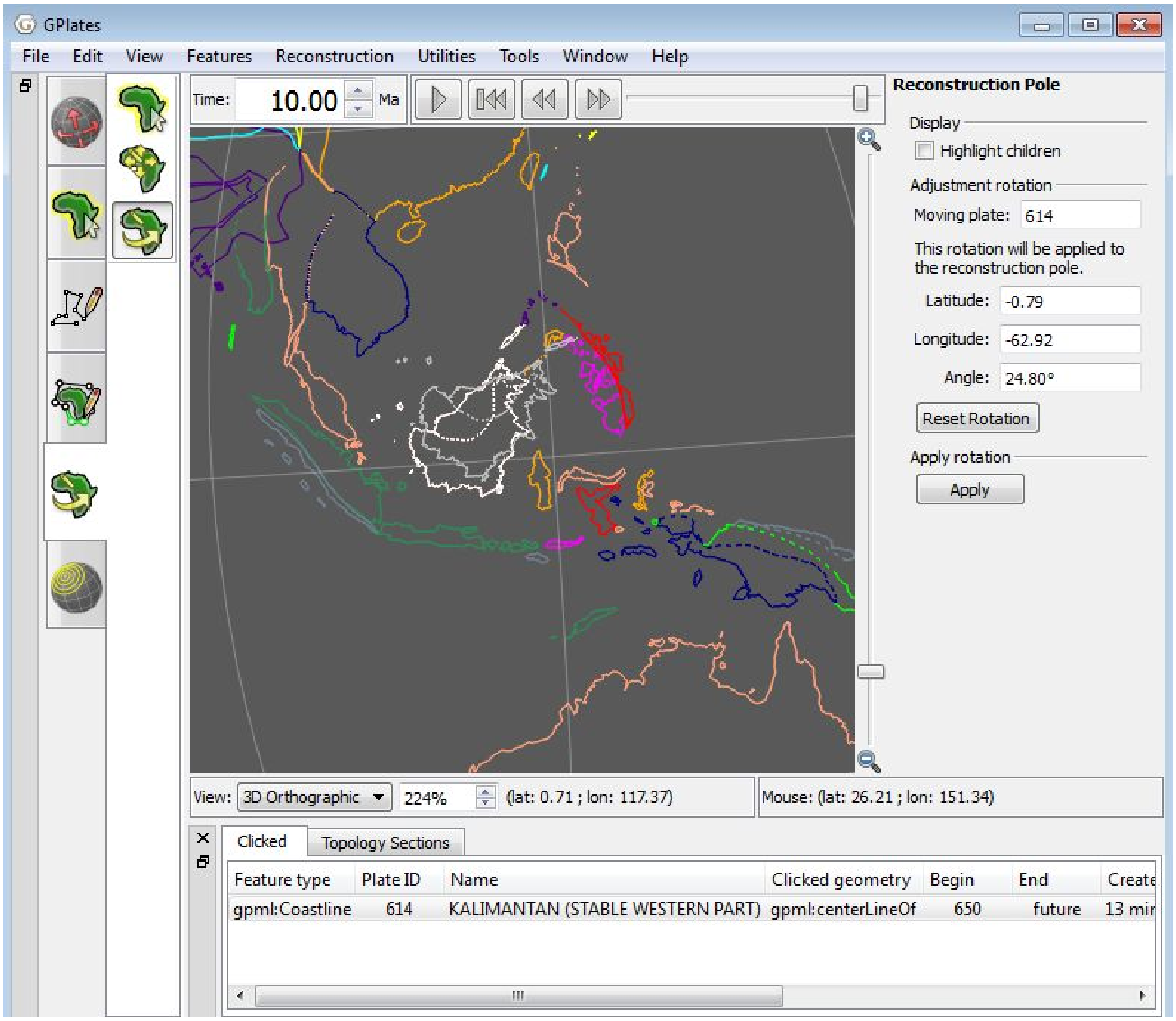

Figure 13. To modify the rotations of a plate, select the plate's geometry and then use the Modify Reconstruction Pole tool to interactively rotate it. In this example, the rotation of Borneo (614) has been interactively modified at 10 Ma.

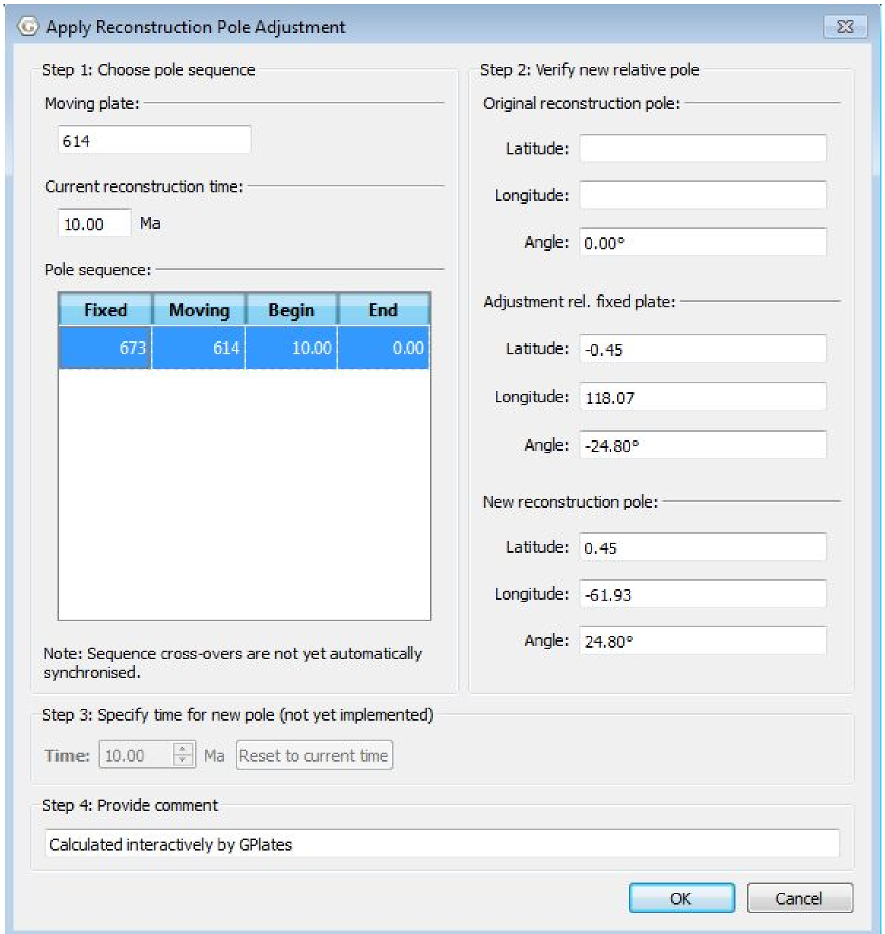

Figure 14. This summary window will appear after you interactivity modify the rotation of a plate and click Apply. To confirm your changes to the plate rotation, click OK.

3. Now we want to re-calculate the cross-over at 10 Ma. Change the Anchored Plate to be Indochina (604) by following Step 2 to 5 from Scenario 1. The Euler rotation should be -0.348348 (lat),-69.3538 (lon) and with an angle of 22.4763. Overwrite the old cross-over rotation for 614-604 at 10 Ma, and uncomment the rotations for Borneo. Save your changes in the text editor and re-load the rotation file in *GPlates*. You will notice that Borneo will no longer "jump" at 10 Ma because the new cross-over ensures a smooth transition to the new plate pair. Your entries should now look like this:

614 0.0 0.0 0.0 0.0 673 !KLM-NSM Kalimantan(Borneo)-North Sumatra
614 10.0 -0.73 -69.62 23.04 673 !Calculated interactively by GPlates
614 10.0 -0.348348 -69.3538 22.4763 604 !KLM-ICH new Kalimantan-Indochina cross-over, Tutorial 2013
614 40.0 2.97531 103.633 -23.7881 604 !KLM-ICH Equivalent rotation from original 614-604 plate pair
614 200.0 2.97531 103.633 -23.7881 604 !KLM-ICH Assuming no motion between KLM and ICH

Exercise 5 – Change cross-over rotation belonging to an older plate pair

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There will be instances where you will need to change rotations of older plate pairs (614-604), meaning that the cross-over belonging to the younger plate pair (614-673) would need to be re-calculated. Although the general steps are similar, there is a critical step that is different than in Scenario 1 or 2. In this example, we will make such changes at 10 Ma for Borneo by interactively changing the reconstruction in *GPlates*.

WARNING 2: *Remember that you will no longer preserve the stage rotation of the younger pair (i.e. between 0 and 10 Ma for Borneo), as we are going to recalculate the equivalent finite rotation based on the older plate pair. This is especially important when dealing with seafloor magnetic anomalies where we have very well-defined stage rotations. In such cases it is best to work from present to past to ensure that stage rotations are preserved. A number of Generic Mapping Tools (GMT) utilities allow the calculation of stage rotations from finite rotations, and these utilities should be used to make sure that well-constrained stage rotations are preserved when re-calculating cross-overs.*

1. Open your rotation file in your text editor. Delete the 0 to 10 Ma lines belonging to the existing 614-673 (Borneo-Sumatra) plate pair. Insert a new entry at 0 Ma, with zero rotations (remember, that at present-day we should not have a non-zero finite rotation) but with the Relative Plate ID being 604 (Indochina). Save your changes and re-load your rotation file in *GPlates*. Your rotation file should look like this:

```
614  0.0   0.0       0.0        0.0  604 !KLM-ICH Kalimantan(Borneo)-Indochina
614 10.0 -0.348348 -69.3538 22.4763  604 !KLM-ICH new Kalimantan-Indochina cross-over, Tutorial 2015
614 40.0 2.97531 103.633 -23.7881 604 !KLM-ICH Equivalent rotation from original 614-604 plate pair
614 200.0 2.97531 103.633 -23.7881 604 !KLM-ICH Assuming no motion between KLM and ICH
```

2. In *GPlates*, set the Anchored Plate ID to be 673 (the target for the new cross-over rotation) and reconstruct to 10 Ma.

3. Change the rotation of Borneo interactively following Step 2 in Scenario 3 (Figure 15). Alternatively, you can introduce a new rotation (such as a published rotation) in the text editor – but make sure you save the file in the text editor and re-load it in *GPlates*. Here we have changed the rotation interactively at 10 Ma. Click Apply and OK (Figure 16), and then save your changes using the Manage Feature Collections dialog.

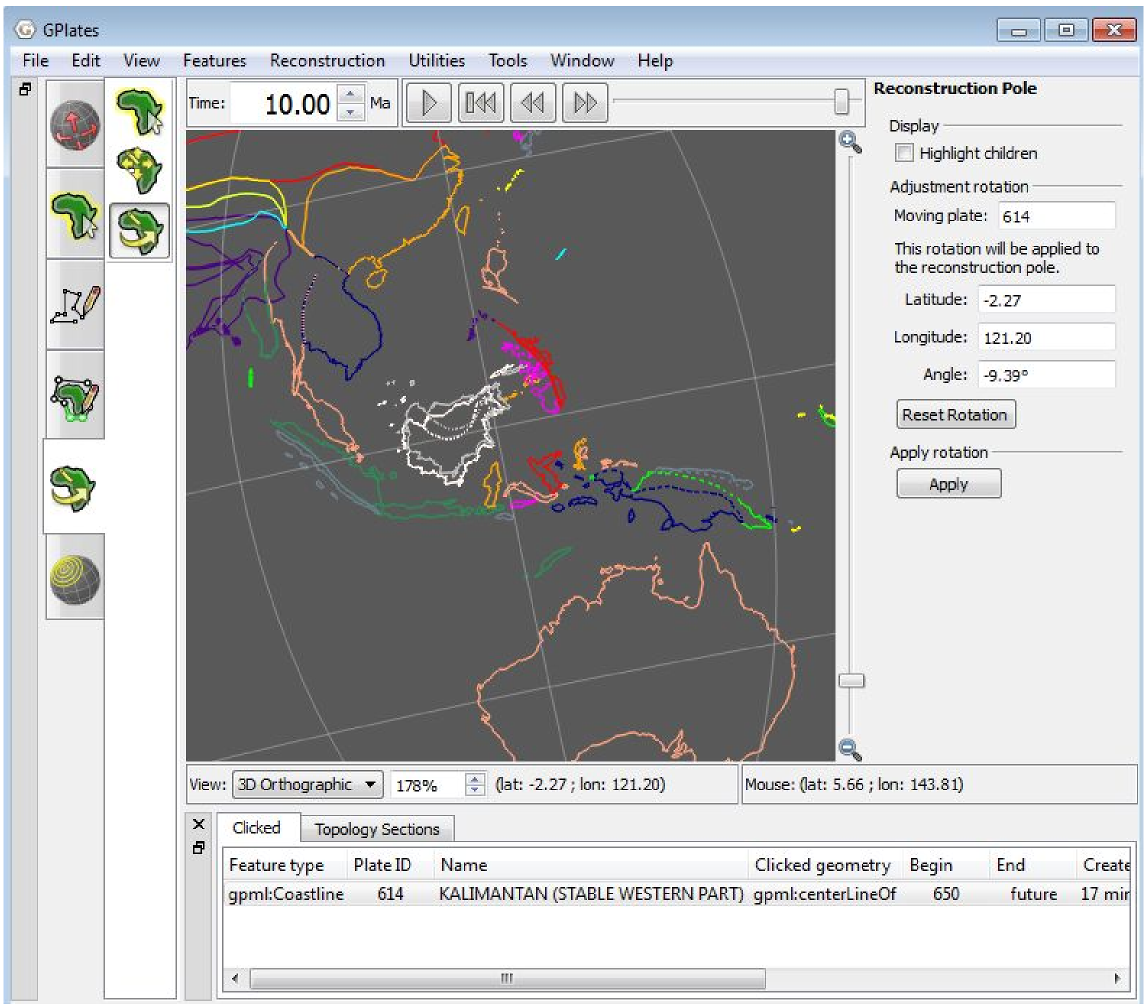

Figure 15. Again to modify the rotations of a plate, select the plate's geometry and then use the Modify Reconstruction Pole tool to interactively rotate it. In this example, the rotation of Borneo (614) has been interactively modified at 10 Ma.

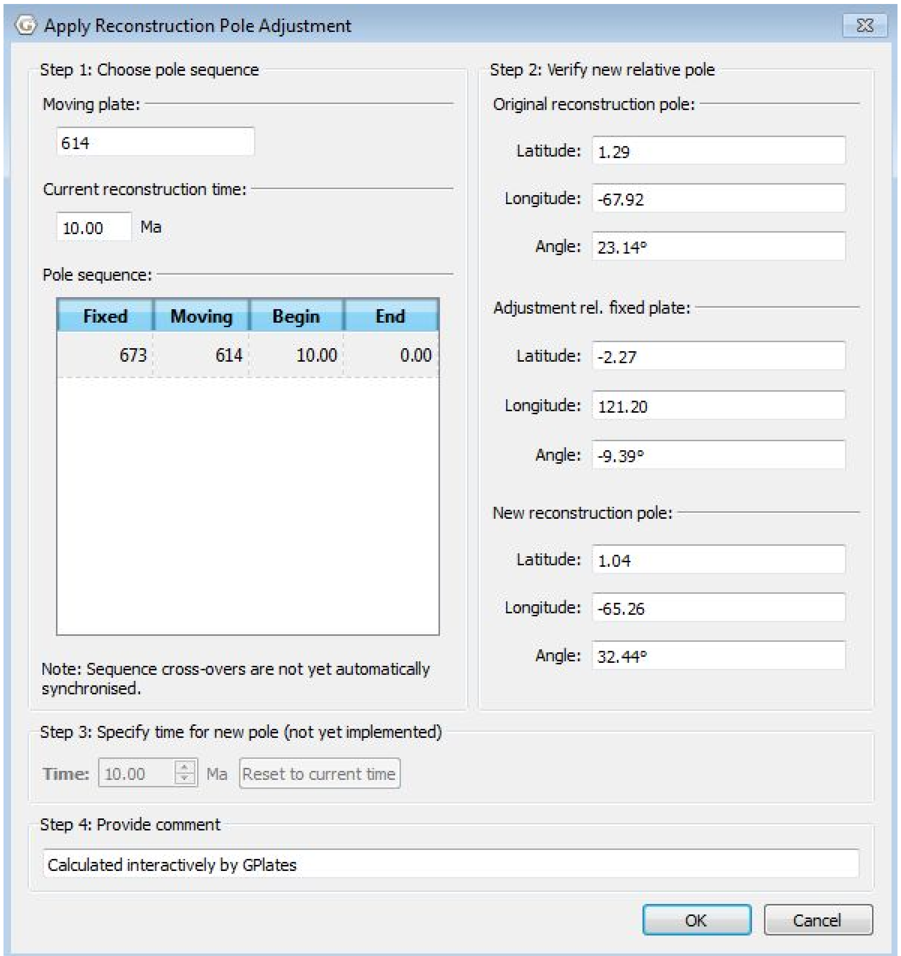

Figure 16. Again this summary window will appear after you interactivity modify the rotation of a plate and click Apply. To confirm your changes to the plate rotation, click OK.

4. Look up the equivalent finite reconstruction poles for Borneo (614) relative to Sumatra (673) at 10 Ma by going to Reconstruction > View Total Reconstruction Poles. The equivalent rotation should be -0.727708 (lat), -69.6143 (lon) with an angle of 23.0449.

5. Open your rotation file in a text editor. Change the Relative Plate ID at 0 Ma to be 673, and insert a line at 10 Ma with the results from the previous step. Save your file and re-load it in *GPlates*. You should have smooth motion of Borneo that incorporates the changes you made to the older rotation sequence. Your rotation entries for Borneo should look something like this:

614 0.0 0.0 0.0 0.0 673 !KLM-NSM Kalimantan(Borneo)-North Sumatra
614 10.0 -0.727708 -69.6143 23.0449 673 !KLM-NSM recalculated rotation from 10 Ma 614-604 plate pair

614 10.0 -0.35 -69.35 22.48 604 !KLM-ICH new Kalimantan-Indochina cross-over, Tutorial 2013
614 40.0 2.98 103.63 -23.79 604 !KLM-ICH Equivalent rotation from original 614-604 plate pair
614 200.0 2.98 103.63 -23.79 604 !KLM-ICH Assuming no motion between KLM and ICH

WARNING 3: *If you have multiple cross-overs to re-calculate, start with the youngest cross-over highest up in your plate hierarchy (i.e. closer to the absolute reference frame) and work your way to older rotations and down the hierarchy, away from the absolute reference frame.*

Additional Exercise – Rotation of Borneo (Introducing how to reverse engineer rotations from images)

In this final exercise we will move further afield to Borneo, Southeast Asia. The rotational history of Borneo (Kalimantan) is a contentious issue in the literature. Hall (2002) (Figure 17), for example, impose a 45° counter-clockwise rotation of Borneo from 26 Ma to 10 Ma, whereas Lee and Lawver (1995) prefer no rotation of this block, with only a small latitudinal change. Another extreme is Replumaz and Tapponier (2003) (Figure 18) who favour a large clockwise rotation of Borneo, which appears to be incompatible with paleomagnetic data. However, the lack of large strike-slip faults around Borneo, which would be expected under significant rotation, suggest that Borneo experienced little rotation in the Miocene. Nevertheless this remains a debated topic.

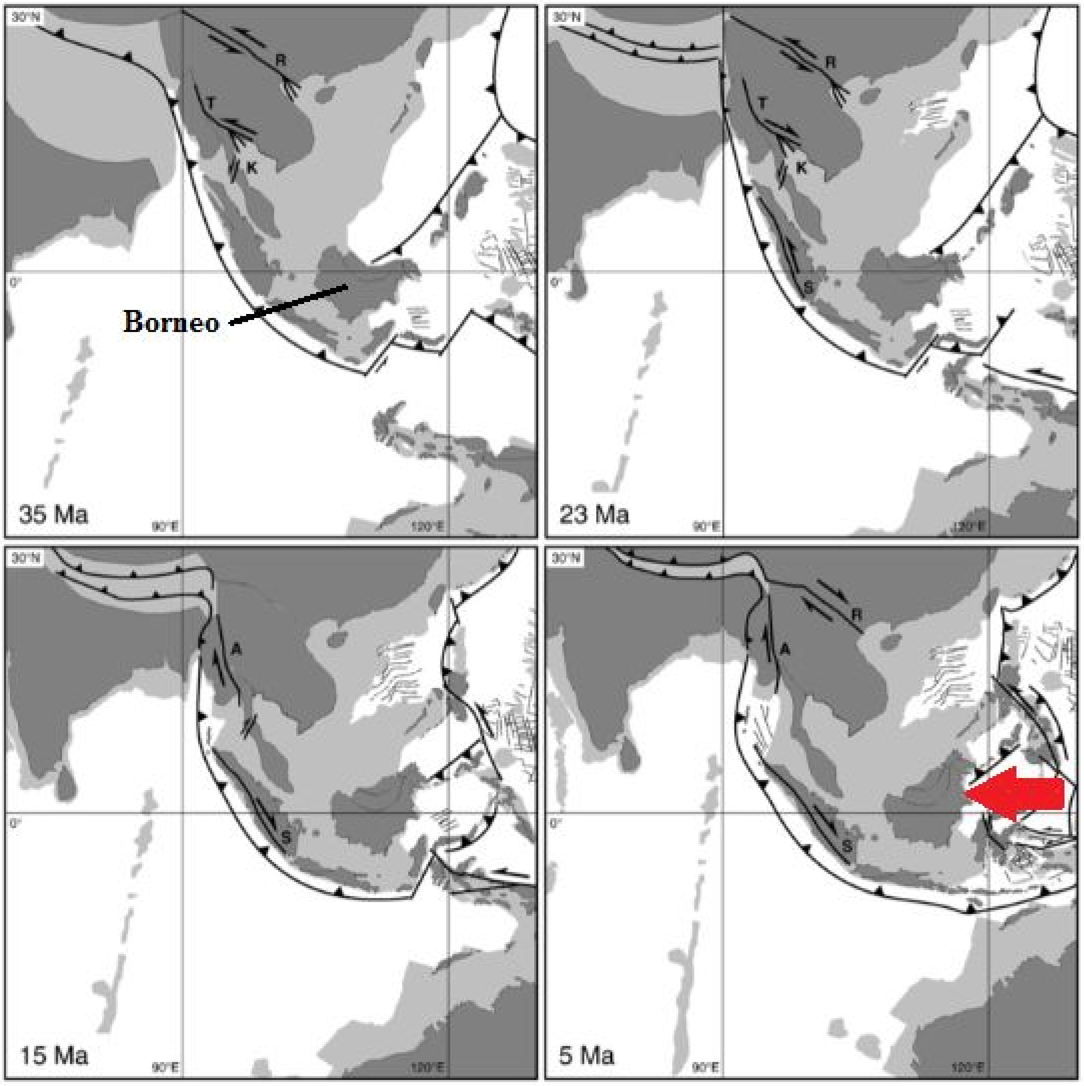

Figure 17. Reconstructions of the Sundaland region at 35 Ma, 23 Ma, 15 Ma and 5 Ma from Hall (2002). Notice the large anti-clockwise rotation of Borneo (red arrow).

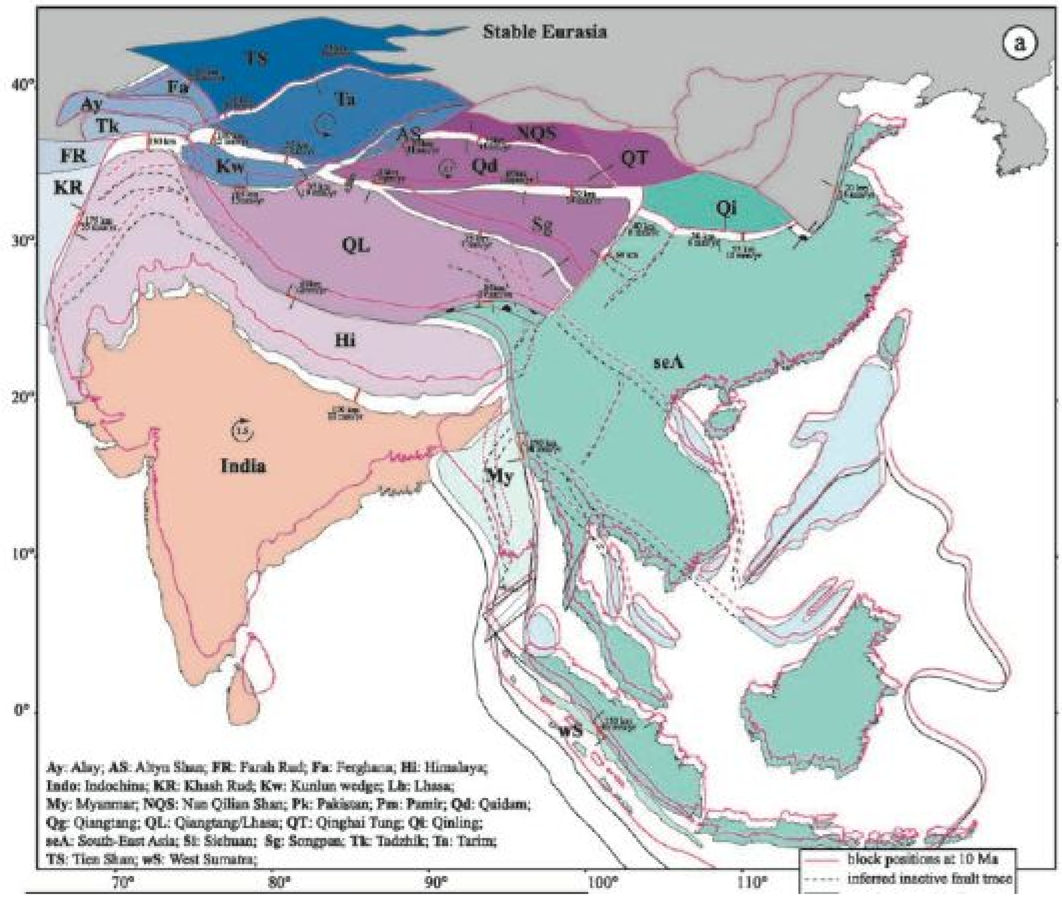

Figure 18. Replumaz and Tapponnier (2003) reconstructions of SE Asia between 10 Ma and 15 Ma.

There are a couple of approaches to reconstruct a rotation as derived from an image.

1. One way is to best discern the latitudinal and longitudinal locations of the feature manually, for example, by selecting a distinguishing part of the tectonic shape on the image (e.g. a peninsula) that is also replicated in the coastline file. The rotation should be manually changed in GPlates (See Exercise 1) until the correct coordinates and orientation are achieved. Remember to reconstruct the rotation at the correct time.

2. The second way is to load the image as a raster in GPlates (see [Tutorial 3.3 Georeferencing Images](#)), and reconstruct the rotation with the image as an underlying guide.

3. A third way is if you are provided with the three rotation pole values for a particular plate at a particular time period, with the conjugate plate specified. With this information you can manually enter it into the rotation file.

Method:

1. Rotate the window to SE Asia and select Borneo.

2. Select the relevant reconstruction time.

3. Rotate Borneo, using the skills you have developed in the previous exercise, to the desired location and orientation as determined by method of reconstruction e.g. raster loading or manual adjustment.

4. Once the feature attains the desired position and orientation, clicking Apply will transfer these changes to the rotation file.

5. To compare models you need to save the different reconstructions to different rotation files.

References

Hall, R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, models and animations. Journal of Asian Earth Sciences, 20; 353 - 431.

Lee, T.Y., and Lawver, L.A. 1995. Cenozoic plate reconstructions of Southeast Asia. Tectonophysics. 251; 85 - 138.

Replumaz, A. and Tapponnier, P. 2003. Reconstruction of the deformed collision zone between India and Asia by backward motion of lithospheric blocks. Journal of Geophysical Research. 108; 2285.

Tikku, A. A., and S. C. Cande. 1999. The oldest magnetic anomalies in the

Australian-Antarctic Basin: Are they isochrons? Journal of Geophysical Research. 104(B1); 661–677.

Whittaker, J.M., Müller, R.D., Leitchenkov, G., Stagg, H., Sdrolias, M., Gaina, C., and Goncharov, A. 2007. Major Australian- Antarctic Plate Reorganisation at Hawaiian-Emperor Bend Time. Science. 318; 83 - 86.

Appendix

Euler Rotations

The motion of any rigid body on the surface of a sphere can be described by an Euler rotation. Such a 'rotation' is defined by the axis of rotation, and an angle. The axis of rotation is defined by a single co-ordinate. The rotation angle then defines the rotation magnitude of this body around this axis. Rotation direction (clockwise or counterclockwise) is determined by the sign preceding the angle of rotation.

In the example below, Plate 501 moves relative to Plate 511 from 0 to 20.2 Ma. All the rotations in the rotation file are finite rotations (see next section). Between 0 and 9.9 Ma, Plate 501 rotates 2.75° clockwise about a pole of rotation that has a co-ordinate of 8.7°S, 76.9°E. That is, the axis of rotation is at 8.7°S, 76.9°E.

501 0.0 0.0 0.0 0.0 511 !IND-CIB India Craton-Central Indian Basin
501 9.9 -8.7 76.9 2.75 511 !IND-CIB AN5 Muller et.al. 1997
501 20.2 -5.2 74.3 5.93 511 !IND-CIB Royer & Chang 1991

Stage vs Finite rotations

A stage rotation is a rotation from one timestep to another. A finite rotation is the sum of all the stage rotations from present-day (0 Ma) to the time of interest. So for example, a stage rotation can be one from 50 to 300 Ma. To obtain the finite rotation at 300 Ma, then the stage rotation from 50 to 300

Ma needs to be added to the finite rotation from 0 to 50 Ma. The finite rotation for Plate 101 (relative to 714) from 0 to 9.7 Ma is the sum of the finite rotation between 0 and 2.7 Ma and the stage rotation from 2.7 to 9.7 Ma. Thus the finite rotation is always a cumulative sum of all stage rotations of all the rotation time intervals.

e.g.

$$ {}^{0.0Ma}_{101} finite^{9.7Ma}_{714} = {}^{0.0Ma}_{101} finite^{2.7Ma}_{714} + {}^{2.7Ma}_{101} stage^{9.7Ma}_{714} $$