Plate Deformation - Rift Basins

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Aim

The aim of this tutorial is to illustrate how to define intracontinental rift basins within deforming plate models. We will as an example the Cretaceous rifting within South America and Africa during opening of the South Atlantic region.

Included files

Click here to download the data bundle for this tutorial.

The tutorial dataset (8.3-RiftBasinTutorialData.zip) includes the following files:

Seton_etal_ESR2012_Coastlines_2012.1.gpmlz

Seton_etal_ESR2012_StaticPolygons_2012.1.gpmlz

Seton_etal_ESR2012_PP_2012.1.gpmlz

Seton_etal_ESR2012_2012.1.rot

crust1_SedimentThickness_15m.gpml

See www.earthbyte.org/Resources/earthbyte_gplates.html for additional EarthByte data sets.

This tutorial dataset is compatible with GPlates 2.0.

Background

It has long been recognised that the fit of the African and South American continents prior to South Atlantic rifting is not satisfactory without invoking some internal deformation within one or both of these continents. The prime candidates for the location of this deformation are rift basins within Central Africa and Southern South America.

Many previous reconstructions have incorporated this motion, but the way the 'deforming' aspect is represented within the kinematic models is a simple extension of rigid plates - we can divide each continent up into several rigid blocks (represented as rigid polygons in the plate model), and allow them to move relative to one another. The relative motions are defined such that relatively small overlaps exist for reconstruction times prior to the timing of extension within the rift basins. The amount of overlap is used as a proxy for the amount of extension implied by the model within each region. This simple approach is similar to that often used for reconstructing conjugate passive margins - see the 'Exporting Reconstructions to ArcGIS' tutorial for an example.

Within a topological model, a more nuanced approach is required. Without deforming regions, these rift zones can only be represented as a linear plate boundary that is no different from a mid ocean ridge. Any point on one side of the boundary will be considered part of one plate, and a point just the other side of the boundary will be considered part of the other plate. The implication for geodynamic models is that the plate velocities imposed will define a very narrow region of high extension, whereas the deformation within these regions is likely more distributed and diffuse (and the details may change through time).

Using GPlates deformation tools, we can define a more detailed and informative representation of deformation in areas of rifting. We can use available geological and geophysical observations to define the extent of rift basins (differentiated from undeformed regions adjacent to them), which can then be incorporated into the global topological plate polygons as deforming regions (analogous to 'diffuse' plate boundaries between rigid plate polygons either side). In this tutorial, we will go through the process of creating these regions.

The discussion here is based on a model of South Atlantic opening by Torsvik et al (2009), since the kinematics from this reconstruction are implemented within the Seton et al (2012) global compilation. Please refer to these papers for further geological background.

Exercise 1 - Cretaceous Rift Basins in Africa

Part 1: Understanding the deformation inherent within existing reconstruction models

Firstly, we will load the files from the Seton et al. (2012) plate motion model, and look at how deformation is represented within a rigid, topological plate model. Within this global model, the poles of rotation that describe South Atlantic rifting are taken from the studies of Nürnberg and Müller (1991) and Torsvik et al (2009).

1. From the tutorial data, load the Coastline, Static Plate Polygons, Dynamic Plate Polygons and rotation file for the Seton et al (2012) model.
    - Seton_etal_ESR2012_Coastlines_2012.1_Polyline.gpmlz
    - Seton_etal_ESR2012_StaticPolygons_2012.gpmlz
    - Seton_etal_ESR2012_PP_2012.1.gpmlz

- Seton_etal_ESR2012_2012.1.rot

2. Set the reconstruction time to 132 Ma, and focus on the region of Africa and South America.

3. Turn off the resolved topology layer temporarily (Seton_etal_ESR2012_PP_2012.1.gpmlz), so we can focus on the static polygons (Figure 1).

Note the overlap between the static polygons that represent NW Africa, NE Africa, Southern Africa, South America, and the two subplates in Southern South America (labelled Colorado and Parana subplates) (Figure 1). The overlap represents the fact that these plates will move away from each other at some point between this reconstruction time and present day (you can compare what you're looking at with Figure 10 of Torsvik et al., 2009).

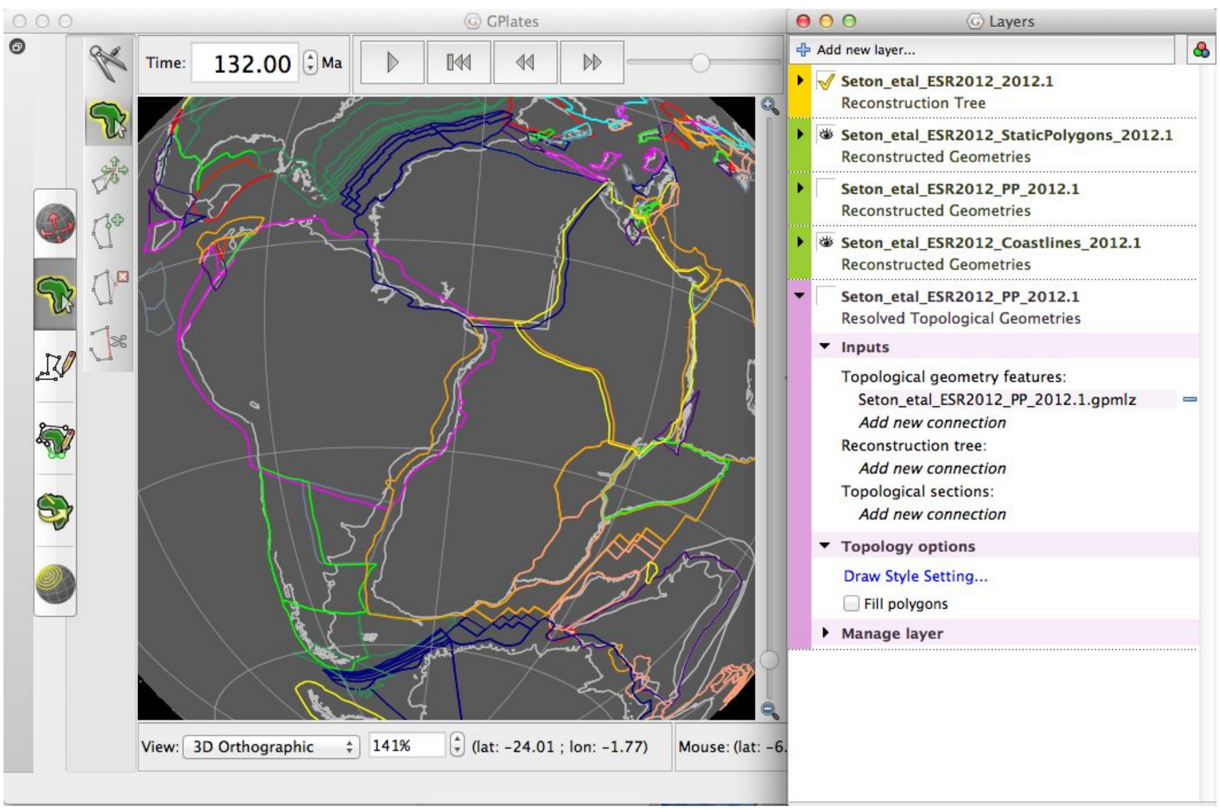

Figure 1: Overlap between static polygons (Step 3)

4. Play the reconstruction forward to see how this extension develops. This extension is finished earlier in South America than Central Africa, where the relative motion continues until 83.5 Ma in this reconstruction.

5. Turn off the static polygon layer and turn on the Resolved Topology layer

(Figure 2).

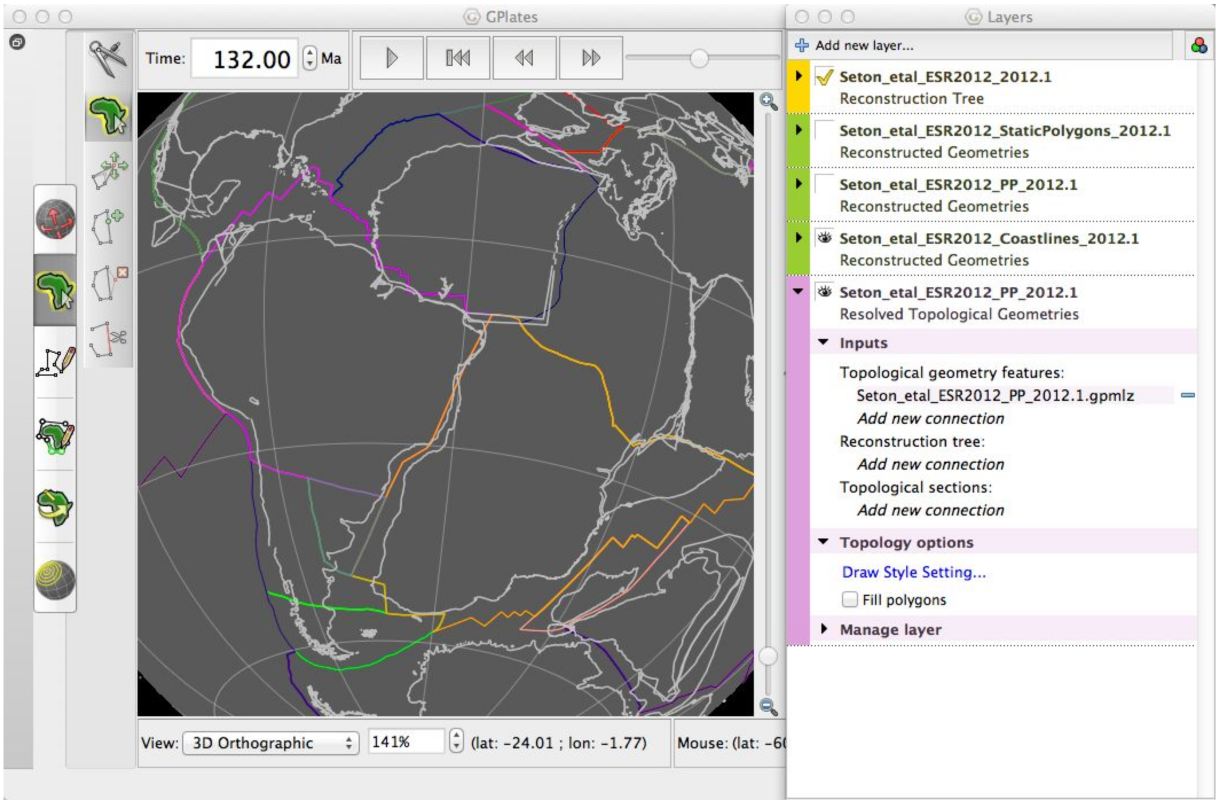

Figure 2: Extensional boundaries within Africa and South America at 132 Ma (Step 5)

Within the Seton et al (2012) topologies, the extensional boundaries within Africa and South America are represented as lines. Our aim will be to modify these boundaries to be more analogous to more diffuse zones of continental rifting. Note that in this tutorial we will only deal with the intracontinental rifts.

Part 2: Deciding where the deformation should be distributed

Before we modify the topologies to include deforming regions, we first need some basis for where the deformation is distributed. For the purposes of this tutorial we will focus on one such example, sediment thickness. We will use the global, 1 degree resolution sediment thickness included in the recently revised CRUST1.0 model of global crustal structure.

A global sediment thickness grid file (and associated gpml file) has been included in the tutorial data (resampled to 15 minute resolution).

1. Load this gpml file into GPlates (“crust1_SedimentThickness_15m.gpml”), then connect the raster layer to the Static Polygons (Figure 3, see Tutorial 3.2 for a full description).

2. Change the display limits of the raster to between 0-4 (Figure 3).

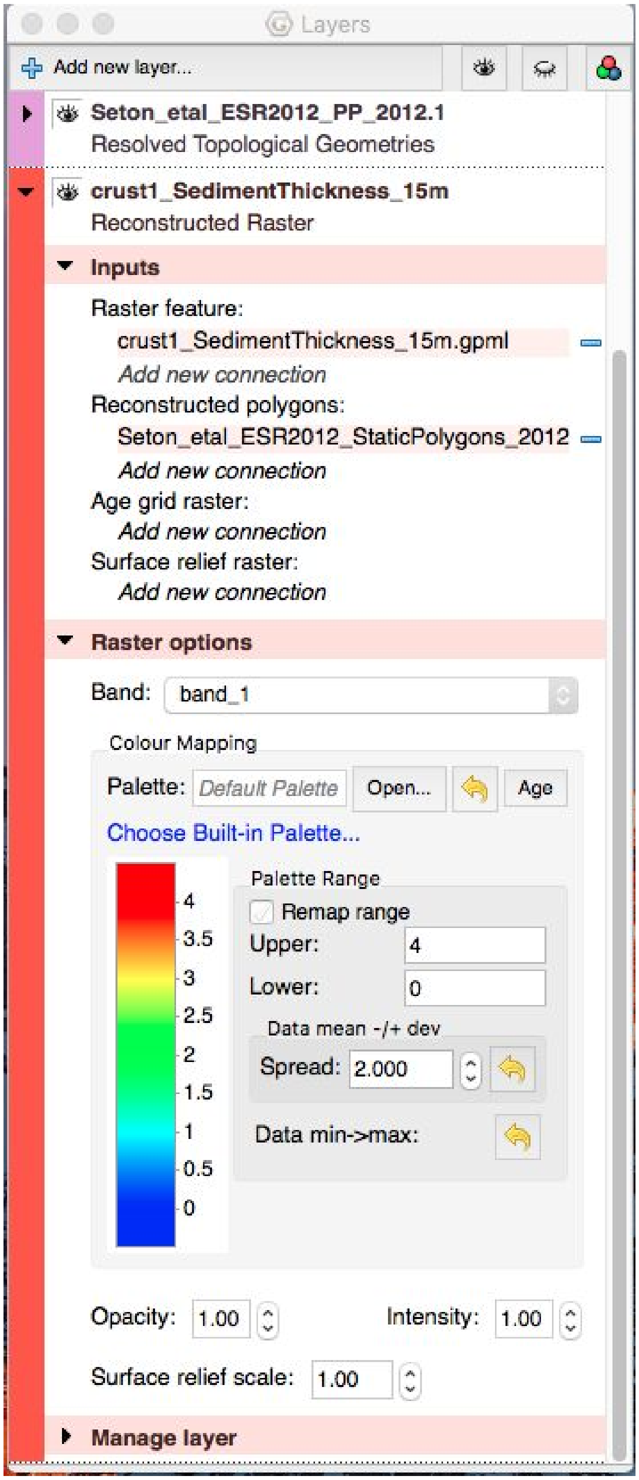

Figure 3: Adding the connection to the static polygons layer for the sediment thickness raster (Step 1) and changing the colour display limits for the sediment thickness grid (Step 2)

3. Change the reconstruction time to 84 Ma, and concentrate on central

Africa (Figure 4).

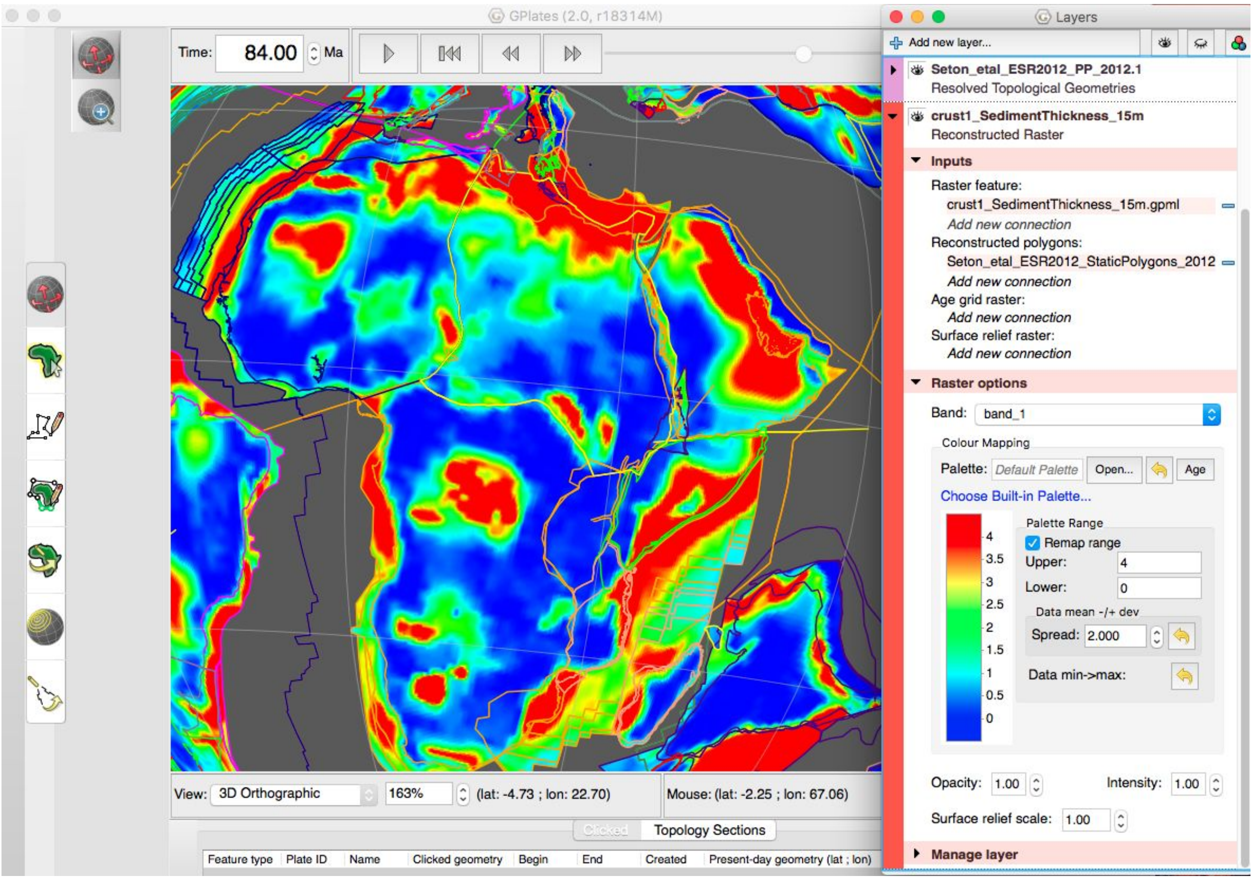

Figure 4: Sediment thickness reconstructed to 84 Ma (the raster layer is connected to the Static Polygons layer)

The rationale for using a map of sediment thickness to guide our definition of deforming regions is fairly simple - if the deforming regions are extensional basins, then we might expect the zones of high extension and crustal thinning to correlate with thick sediment accumulations. The sediment thickness map alone provides no indication of the timing that these sediment accumulated, or whether the accumulations correspond to rift basins or some other mechanism. For the thick sediments along the boundaries separating NW, NE and Southern Africa, we can check against the locations of rift basins defined in different literature (Figures 5 & 6).

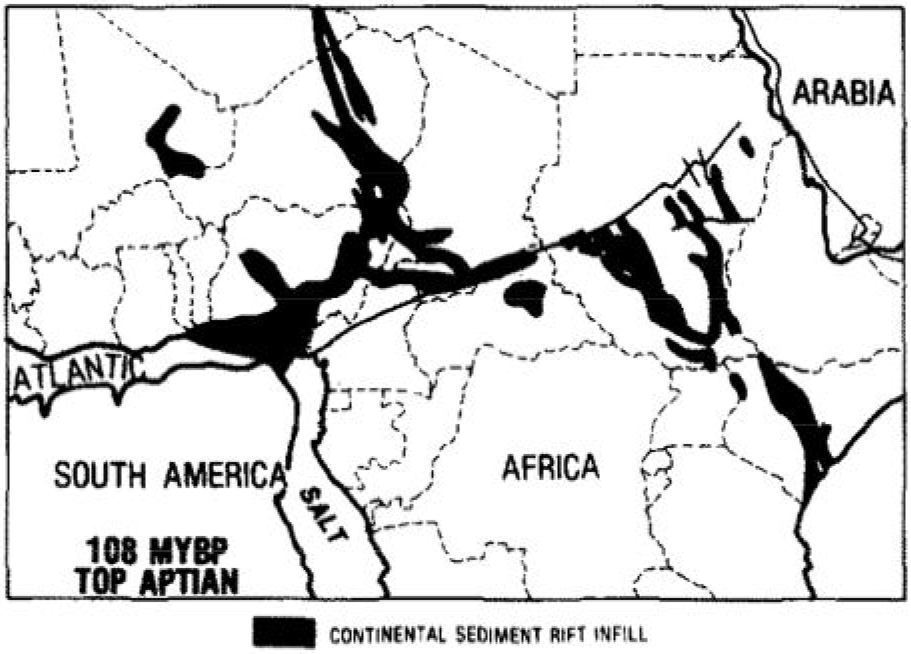

Figure 5: Development of major rift basins at 108 Ma (Genik et al, 1992)

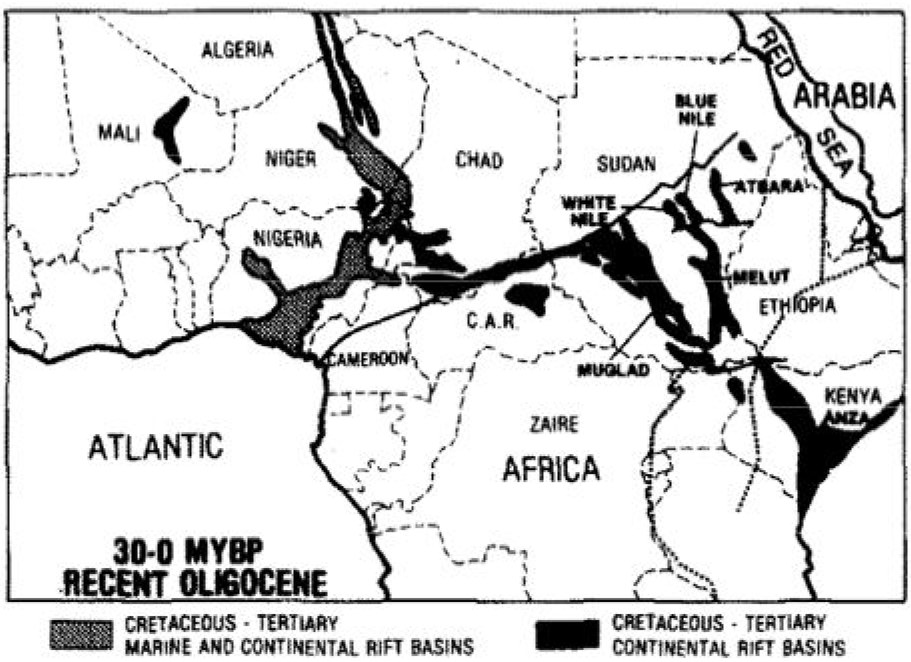

Figure 6: Rift configuration at 30 Ma (Genik et al, 1992)

If we compare the distribution of Cretaceous basins in this interpretation (Figure 5) to the sediment thickness grid and the plate boundaries in the topological model (Figure 4), we can see that there is a pretty good correlation between all three for the basins of the Central African Rift

System. The sediment thickness grid also includes additional significant accumulations in other areas (e.g. the Congo Basin within southern Africa, or the Taoudeni Basin within NW Africa), which is not thought to be related to South Atlantic rifting and is not represented in the topological plate boundaries.

It is also worth considering the timing of the motion between the different blocks. The three plate polygons in question have plates IDs of 714 (NW Africa), 715 (NE Africa) and 701 (Southern Africa).

4. Open the rotation file ("Seton_etal_ESR2012_2012.1.rot") in a text editor, and then navigate to the section that contains the rotations for these plates.

701 moves relative to the absolute reference frame, and the relative motion between the different African blocks is described by the relative motions of 714 and 715 (as the moving plates, column 1) relative to 701 (as the fixed plate, column 6).

```
Seton_etal_ESR2012_2012.1.rot
710 600.0  15.0   37.2  -18.21  701 !  DAN-AFR
712  0.0   0.0    0.0    0.0  701 !  LVB-AFR Lake Victoria Block-Africa
712 600.0   0.0    0.0    0.0  701 !  LVB-AFR
713  0.0   0.0    0.0    0.0  701 !  NMZ-AFR North Mozambique-Africa
713 600.0   0.0    0.0    0.0  701 !  NMZ-AFR
714  0.0   0.0    0.0    0.0  701 !  NWA-AFR Northwest Africa-Africa
714 120.4   0.0    0.0    0.0  701 !  NWA-AFR Torsvik et. al. (2009)
714 131.7  33.65   26.02    2.34  701 !  NWA-AFR Torsvik et. al. (2009)
714 600.0  33.65   26.02    2.34  701 !  NWA-AFR Torsvik et. al. (2009)
715  0.0   0.0    0.0    0.0  701 !  NEA-AFR Northeast Africa-Africa
715 83.5   0.0    0.0    0.0  701 !  NEA-AFR Torsvik et al. (2009)
715 120.4  40.5  -61.4   -0.7  701 !  NEA-AFR Torsvik et al. (2009)
715 600.0  40.5  -61.4   -0.7  701 !  NEA-AFR Torsvik et al. (2009)
718  0.0   0.0    0.0    0.0  707 !  TEL-MOR Tellian-Morocco
718 300.0   0.0    0.0    0.0  707 !  TEL-MOR EarthByte 2009
718 750.0   0.0    0.0    0.0  707 !  TEL-MOR EarthByte 2009
Line: 1666  Column: 10   Plain Text   Tab Size: 4
```

Figure 7: Rotation data for different African blocks (Step 3)

We can determine that NW Africa (714) moves relative to Southern Africa (701) from 131.7 Ma to 120.4 Ma in this model, while NE Africa (715) moves relative to Southern Africa from 120.4 Ma to 83.5 Ma (Figure 7). Note that, by implication, there is also relative motion between NW Africa and NE Africa during the 131.7 to 83.5 Ma time period.

Part 3: Build the Topological Boundaries and Network Topology

The first step to building a deforming networks over the deformation regions is to define line geometries that will define the boundaries of the deformation zone.

1. Select the ‘Digitization’ menu from the toolbar on the left of the GPlates window, then select the ‘Digitize New Polyline Geometry’. Digitize three new lines, which encompass the regions of the Central African Rift System basins as indicated by the sediment thickness map (Figure 8).

When constructing these lines, keep in mind the following:

- Each line should be digitized so that it intersects with other (existing) lines such that we will be able to resolve the combination of lines into a single topological network polygon that encompasses the deforming region (and that can be added into the global set of topological polygons).
- Assign each line the Feature Type ‘TopologicalClosedPlateBoundary’
- Each line should be assigned an appropriate Plate ID - for example, the boundary that marks the southern edge of the rift zone adjacent to Southern Africa should be assigned the Plate ID 701. The other appropriate Plate IDs are shown in Figure 8.
- For each line created, you’ll also have to modify the Begin and End times - based on Genik et al., (1992) set this to 132 Ma and 0 Ma.

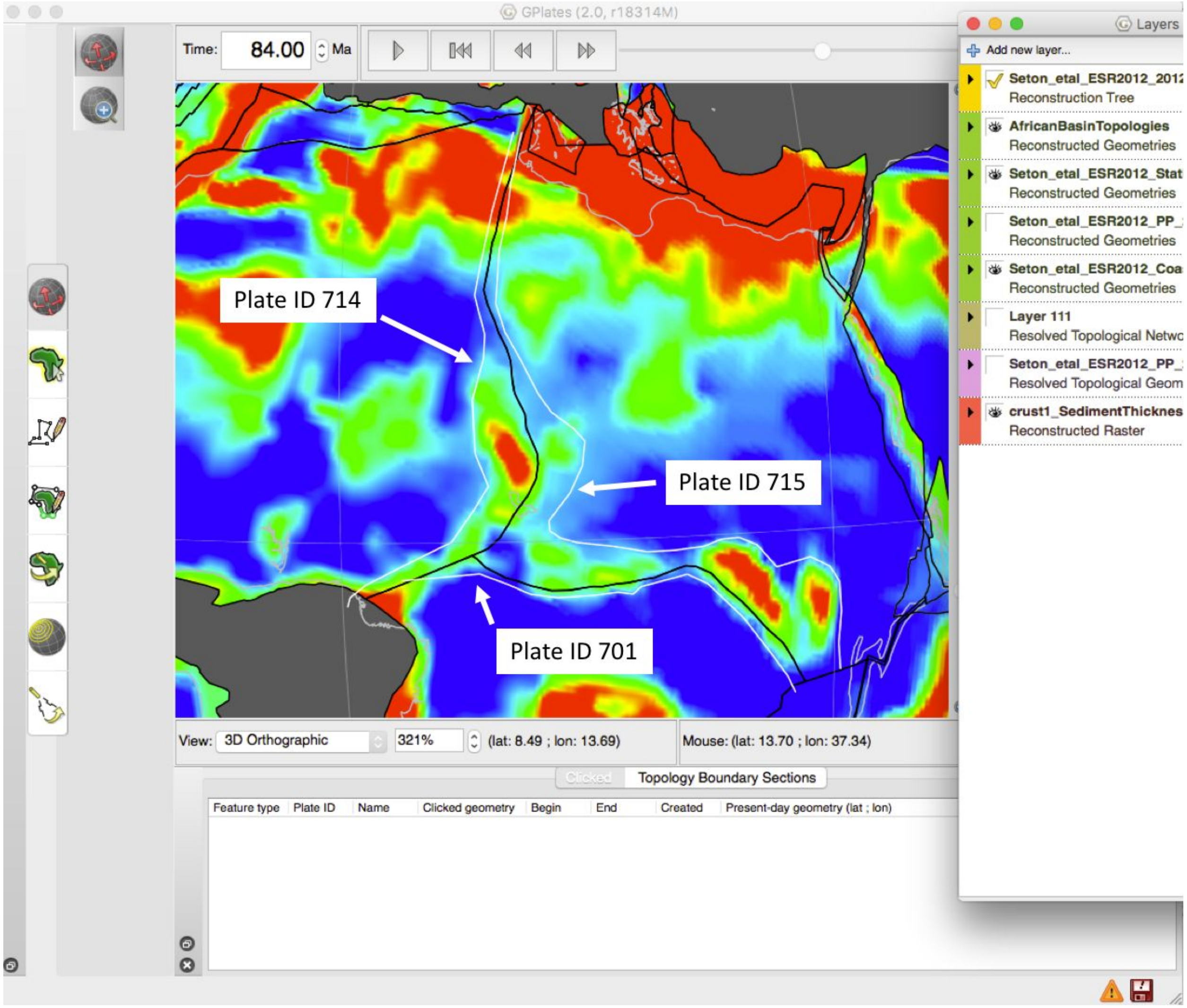

Figure 8: Example of the three new boundaries (white lines) which encompass the regions of the Central African Rift System Basins. The appropriate Plate IDs that they should be assigned are also shown. Static polygons are coloured black to avoid confusion with new lines, Coastlines are in silver.

Note that using this one dataset alone is somewhat approximate. In this case, we have no choice but to define boundaries that to some extent correspond to the rigid geometries in Torsvik et al (2009) model, even if the location of the implied deformation may not be immediately apparent from the sediment thickness. An example is the northern part of the boundary between NW and NE Africa. In practical cases, it is recommended to use as many alternative lines of available geological and geophysical data to refine these boundaries.

In Figure 9, the new lines are digitized to intersect an existing 'Somalia-Africa' boundary at the southern end of the Muglad-Melut Basins in Sudan. Note that this tutorial we are only dealing with the deformation between three plates - as an additional exercise, you may also want to think about relative motions between these plates and the Somali Plate (709).

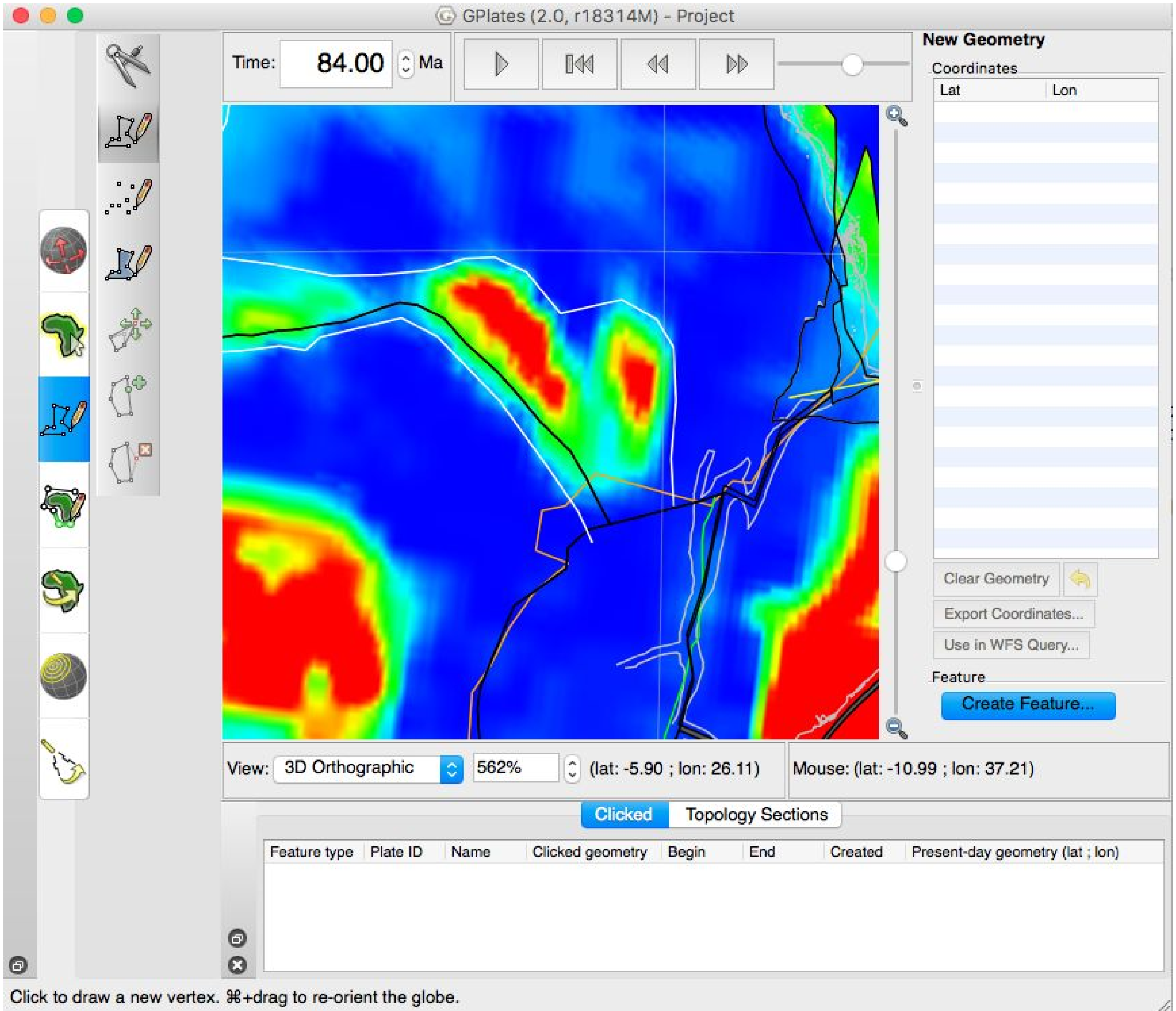

Figure 9: Newly digitised lines intersecting the 'Somalia-Africa' boundary

2. To build a network topology, select the Topology toolbar then select the 'Build New Network Topology' tool. Then, as with building any topological polygon or network, select each geometry you want to be contained in the boundary of the deforming region, in order (ie in a logical clockwise or anticlockwise progression), and then click on 'Add To Boundary' (Figure 10).

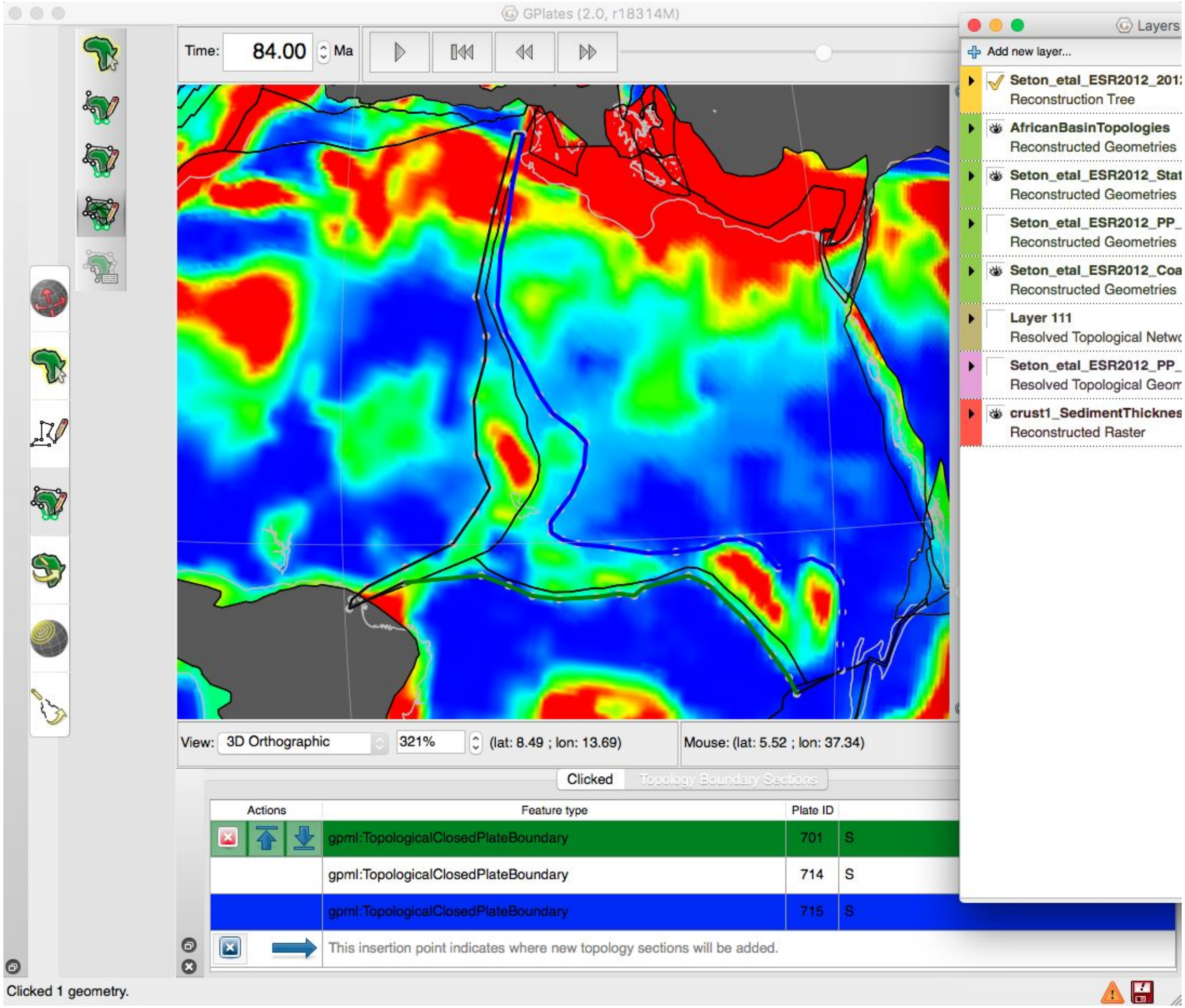

Figure 10: Building the network topology with line segments (Step 2).

3. Once we've added all the line segments (the 3 we just digitised), we click 'Create...' and go through a series of dialogues to specify properties of the new feature. Define the feature type as gpml:TopologicalNetwork, and in the next window, set an appropriate Begin and End time. The network needs to exist for the same time period as the relative motion persists between the surrounding plates so in our case this is 132 - 0 Ma. Select the option of creating a new feature collection when prompted.

4. Once you've created the Resolved Topological Network layer, it may not initially appear - firstly make the raster layer and reconstructed geometry layers invisible.

5. Expand the options under the new gold Resolved Topological Networks

layer (Figure 11).

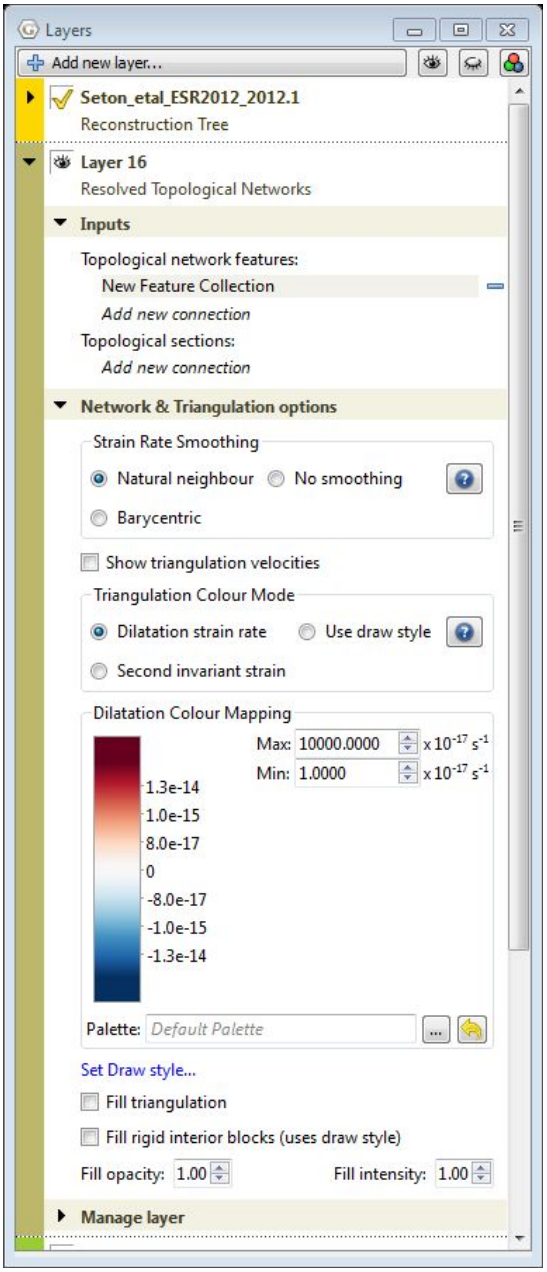

Figure 11: Layer options when Resolved Topological Networks Layer is expanded

7. Network & Triangulation options > Triangulation Colour Mode > Select Dilatation strain rate

Notice that now the African rift basin appears like a network (Figure 12) (raster turned off for clarity)

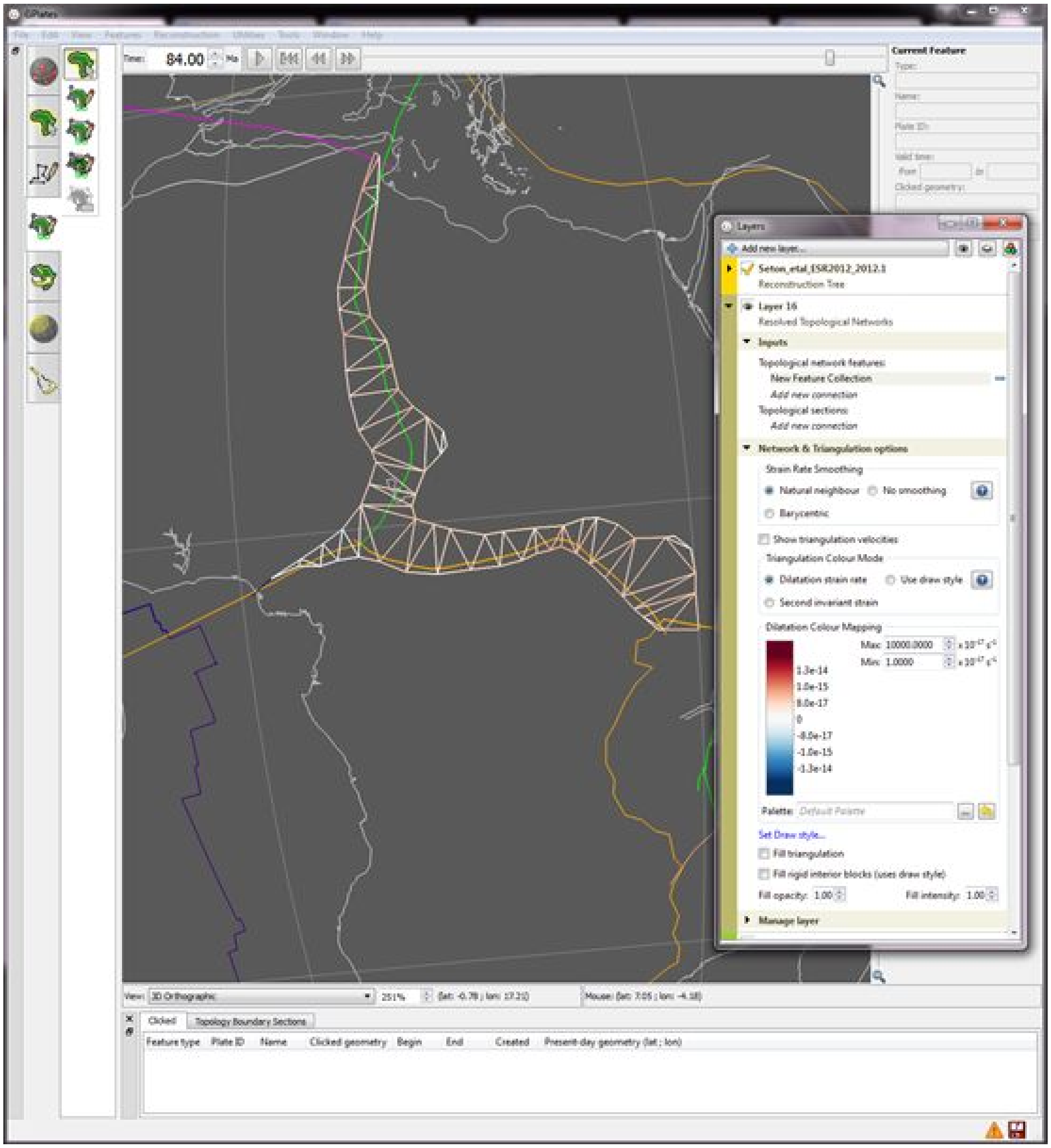

Figure 12: African Rift Basin network topologies

(Note that red = extension and blue = compression)

8. Try changing the reconstruction time to different times during the opening of the rift basins the networks represent (ie times between 132 and 84 Ma).

Another way to visualise the strain rate in a topological network is by filling the triangulations

9. In the layers window, Triangulation Draw Mode > select 'Fill triangulation'

10. Now reconstruction from 132-84 Ma and see how we can visualise the strain rate in a different way

Don’t forget to save both the new line topologies and the topological network layer!

A further task is to build this topological polygon into the global topological plate polygon set (ie. updating the plate polygons that we looked at at the very beginning, where rift zones are represented by discrete lines). This process is described in the ‘Plate Deformation - the Andes’ tutorial.

Exercise 2 - Additional Exercises

Part 1: Plate deformation within South America

Reconstructions of the opening of the South Atlantic typically include Cretaceous-age deformation within southern South America as well as Africa, and the Torsvik et al (2009) model is no exception. Thus, the next step is to repeat the exercise above for the regions of intraplate deformation between the South America, Parana and Colorado blocks.

Note that the correspondence between the rigid block boundaries inherent in the Torsvik et al (2009) reconstruction and the sediment thickness map is less clear for southern South America than for Central Africa. We can also compare the system of subplates within this reconstruction, and the kinematics of their relative motions, with those used by other authors (e.g. Nürnberg and Müller, 1991; Heine et al, 2013; Moulin et al, 2010).

Part 2: Adding more detailed kinematics

The workflow described above results in a simple representation of the deformation, where extension is evenly distributed across the deforming regions. This level of detail is appropriate for some applications (e.g. global scale geodynamic modelling), but more detail may be required for other uses. More detailed kinematic constraints can always be added within deforming regions, as illustrated in Tutorial 8.1 Plate Deformation - the Andes

As an example, look at the Muglad and Melut Basins (in Sudan) again

(Figures 11-13). The extension described by the current model is uniform across the whole model, whereas geophysical data across the area define a series of distinct rift basins separated by basement highs where deformation is negligible.

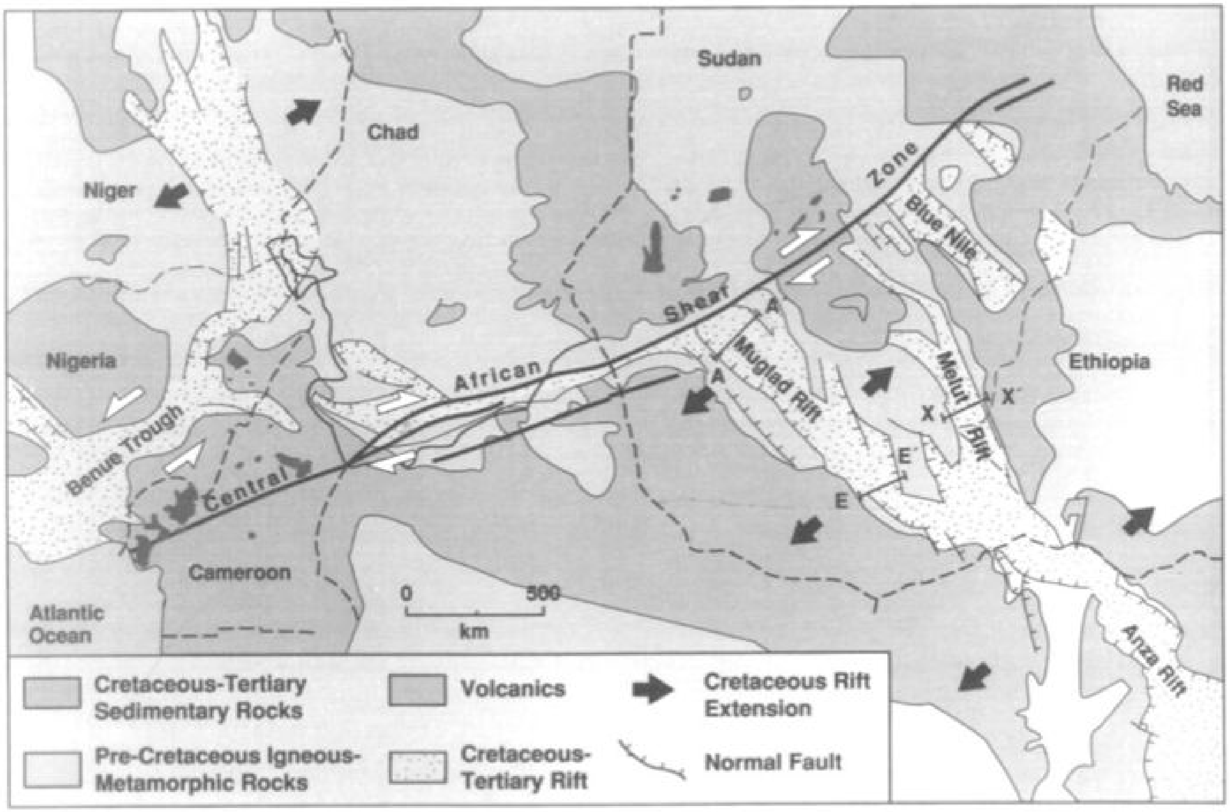

Figure 11: From McHargue et al (1992) Map of Central Africa showing components of the Central African Rift System. The rift basins of Southern Sudan are interpreted to terminate northwestward against the Central African Shear Zone. Note the locations of profile X-X' across the Melut Rift, and profile E-E' across the Muglad Rift.

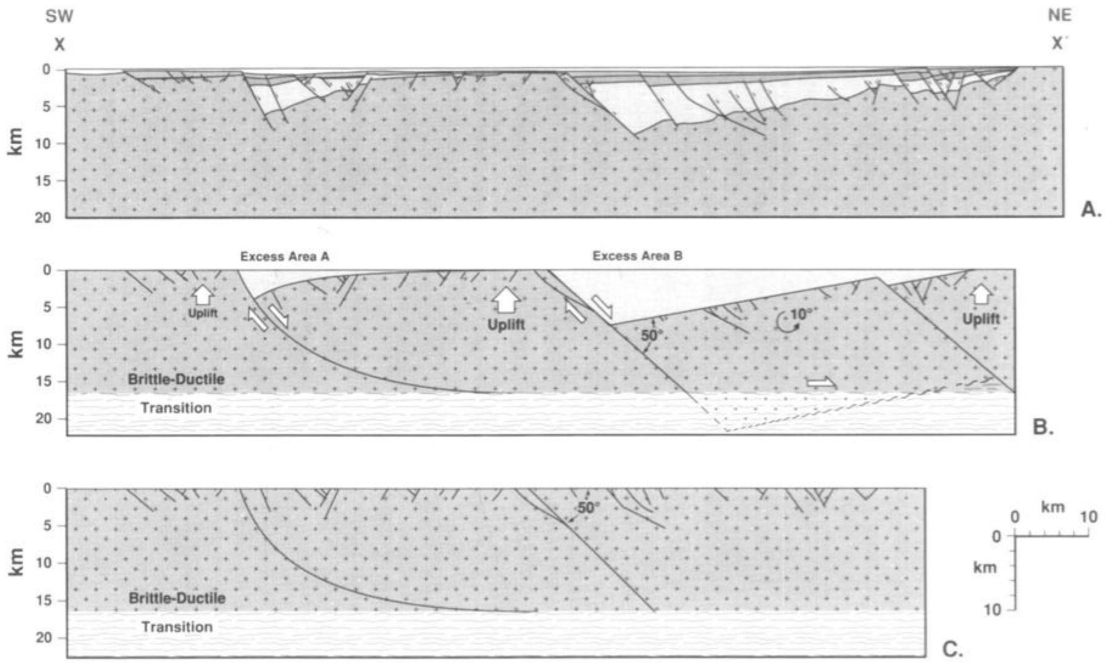

Figure 12: From McHargue et al. (1992), cross section X-X' through Melut Rift. (A) Depth section based on reflection seismic data. Basins are filled mostly with F1 sediments. (B) Generalised interpretation at end of F1 deformation. (C) Restored, undeformed, pre-rift state assuming vertical simple shear. In this interpretation, in-line combination of deformational styles includes both listric faulting and domino-type planar faulting. Total extnestion = 22.3km (21%). For location of section X-X' see Figure 11.

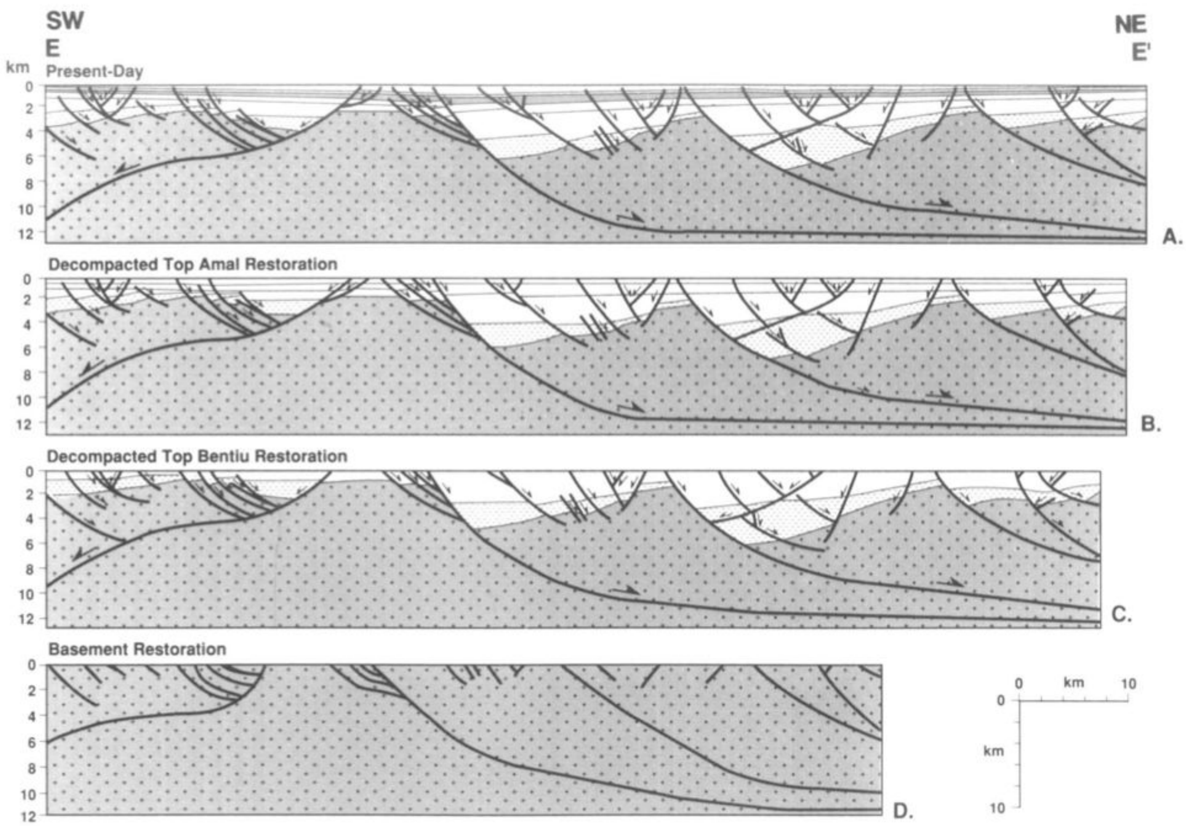

Figure 13: From McHargue et al. (1992), cross section E-E' through Muglad Rift, listric model. Depths of detachments at 12 km are calculated based on a vertical shear model of roll-over geometries. (A) Depth section of the present-day configuration of the basin derived from reflection seismic data. (B) Restoration of the basin, including decompaction approximately at the end of F2. (C) Restoration of the basin, including decompaction, approximately at the end of F1. (D) Restoration of the basin prior to deformation. This interpretation estimates that the present-day configuration of the basin represents a total strain of 32%, most of which (80%) occurred in F1. For location of E-E' see Figure 11.

Using this interpretation, a useful further exercise would be to define additional geometries within the deforming network to represent the Muglad and Melut Basins as separate rift zones, separated by an intervening (and mostly rigid) basement high.

This would require us to define a new Plate ID for this feature, add blank rotations to a rotation file, and constrain the motion based on the displacement estimates across the individual rifts given in the cross-sections above.

This also provides a check on the consistency between the amount of and timing of extension determined from the structural restoration, and the same parameters predicted by the plate kinematics.

The ‘Plate Deformation - the Andes’ tutorial provides the basis for performing these tasks - the tectonic regime here is extensional rather than compressional, but the methodology for implementing points that track the deformation is mostly the same.

References

Genik, G. J. (1992). Regional framework, structural and petroleum aspects of rift basins in Niger, Chad and the Central African Republic (CAR).Tectonophysics, 213(1), 169-185.

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McHargue, T. R., Heidrick, T. L., & Livingston, J. E. (1992). Tectonostratigraphic development of the Interior Sudan rifts , Central Africa. Tectonophysics, 213, 187–202.

Moulin, M., Aslanian, D., & Unternehr, P. (2010). A new starting point for the South and Equatorial Atlantic Ocean. Earth-Science Reviews, 98(1), 1-37.

Torsvik, T. H., Rousse, S., Labails, C., & Smethurst, M. A. (2009). A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin. Geophysical Journal International, 177(3), 1315–1333. doi:10.1111/j.1365-246X.2009.04137.x

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Seton, M., Müller, R. D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A. & Chandler, M. (2012). Global continental and ocean basin reconstructions since 200Ma. Earth-Science Reviews, 113(3), 212-270.