Introduction to Rasters and Time-Dependent Rasters

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WARNING:

The first time you import an age-coded raster, GPlates will take time to create some cache files (this can take 5 or more minutes).

The cache files that GPlates creates in the same folder are quite large (up to 100 Mb each), meaning that you need to have enough storage space.

Aim

The aim of this tutorial is to teach the user to import and visualise raster data in GPlates.

Included Files

Click here to download the data bundle for this tutorial.

For this tutorial we will be using a few different sets of files. These include:

- Time-dependent raster sequences of reconstructed ocean floor age as published by Seton et al. (2012) from the EarthByte group.
- Sample raster images of time-dependent dynamic topography created by Bernhard Steinberger, based on a dynamic topography model published by Müller, Steinberger et al. (2008)
- The MIT-P08 tomography model of the P-wave velocities published by Li et al. (2008)
- A detailed colour image of the global topography and bathymetry published by the US National Oceanic and Atmosphere Administration: color_etopo1_ice_low.jpg
- A coastline file: Seton_etal_ESR2012_Coastlines_2012.1_Polygon.gpmlz

- A rotation file: Seton_etal_ESR2012_2012.1.rot

This tutorial dataset is compatible with GPlates 1.5.

Background

GPlates gives us the functionality to do age-based masking of raster data,and this means any age-grid can be used to mask underlying rasters which in turn can be cookie-cut by polygons and rotated to their position in the past. It is also possible to specify a surface extent of any longitude and latitude range for the raster, enabling rasters of a smaller size to be correctly sized and positioned on the globe.

In this tutorial we will be working on importing and visualising raster data in GPlates and rotating and masking raster data back through time. For all those computer illiterate folk out there, a raster is simply a file which is made of 2-dimensional grid of pixels and is stored as JPEGs or grid files like netCDF. This is different to vector data we have used in previous tutorials, that are composed of points, lines and polygons.

Exercise 1 – Loading and visualising raster data

This first exercise is going to walk you through the steps of importing a a raster into GPlates.

File → Import → Import Raster → Raster_Tutorial_Data → **color_etopo1_ice_low.jpg** (Figure 1)

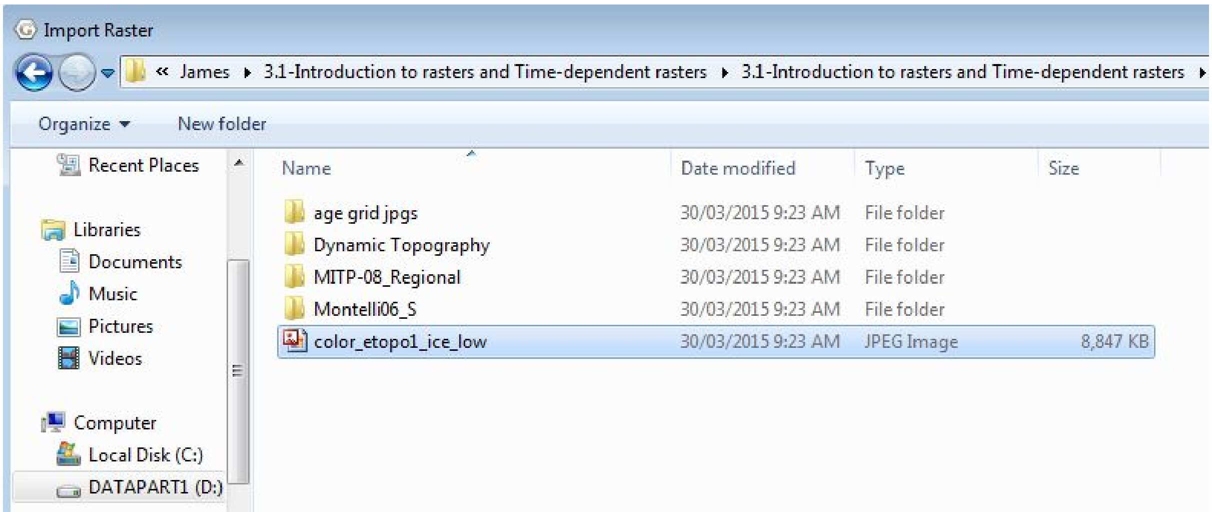

Figure 1. Selecting the raster (color_etopo1_ice_low) from the Import Raster window

The dialogue then will ask you to assign a certain band to the raster image (Figure 2). You can choose between the “band 1” when loading a normal raster (as you are now) or “age” depending on whether it is a Time-dependent raster. Chose “band 1”. Select “Next”.

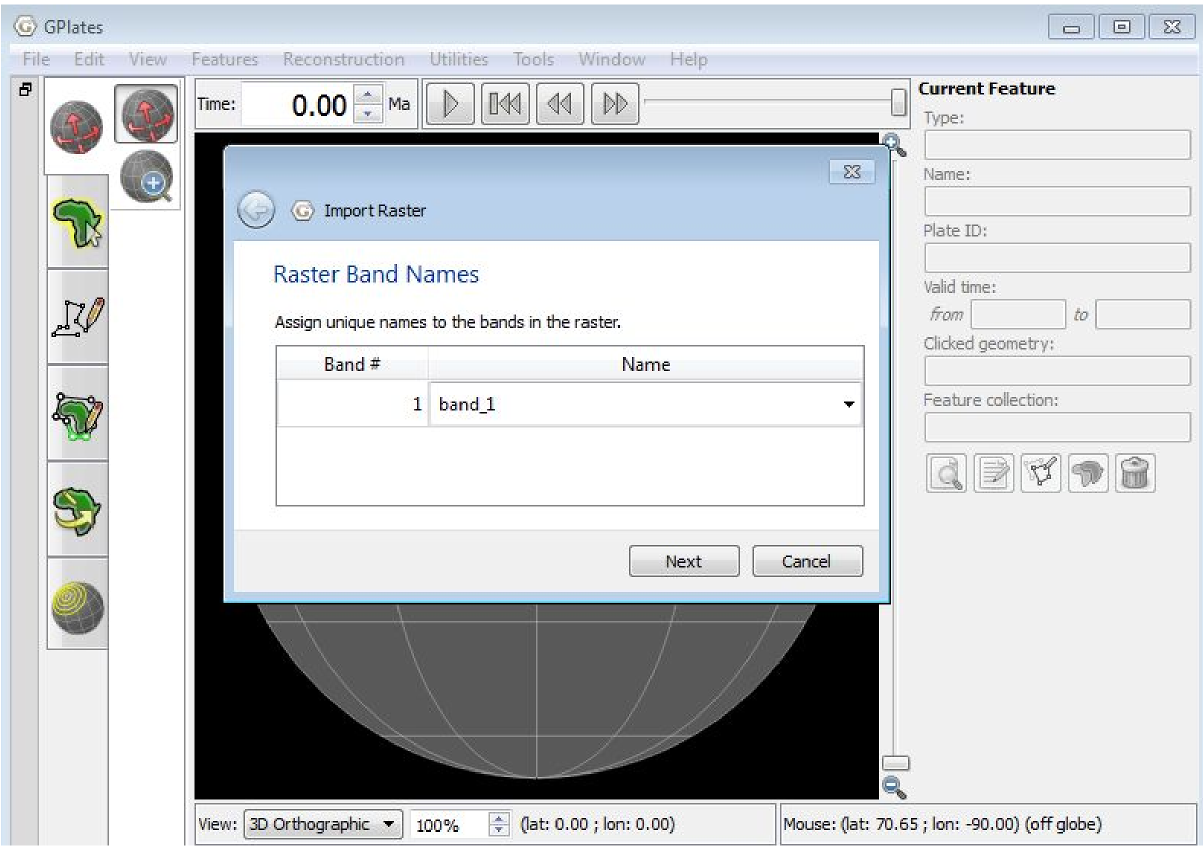

Figure 2. Assigning raster band names

A Georeferencing Box will open (Figure 3). This dialogue box enables you to set the geographic extent of the raster. The default is set to a global extent. As we want the raster to cover the globe check the extents are set to top and bottom as 90.000° and -90.000° respectively, and left and right as -180.000 and 180.000 respectively. Later on in this tutorial we will go through an example of using a regional raster. Select “Next”.

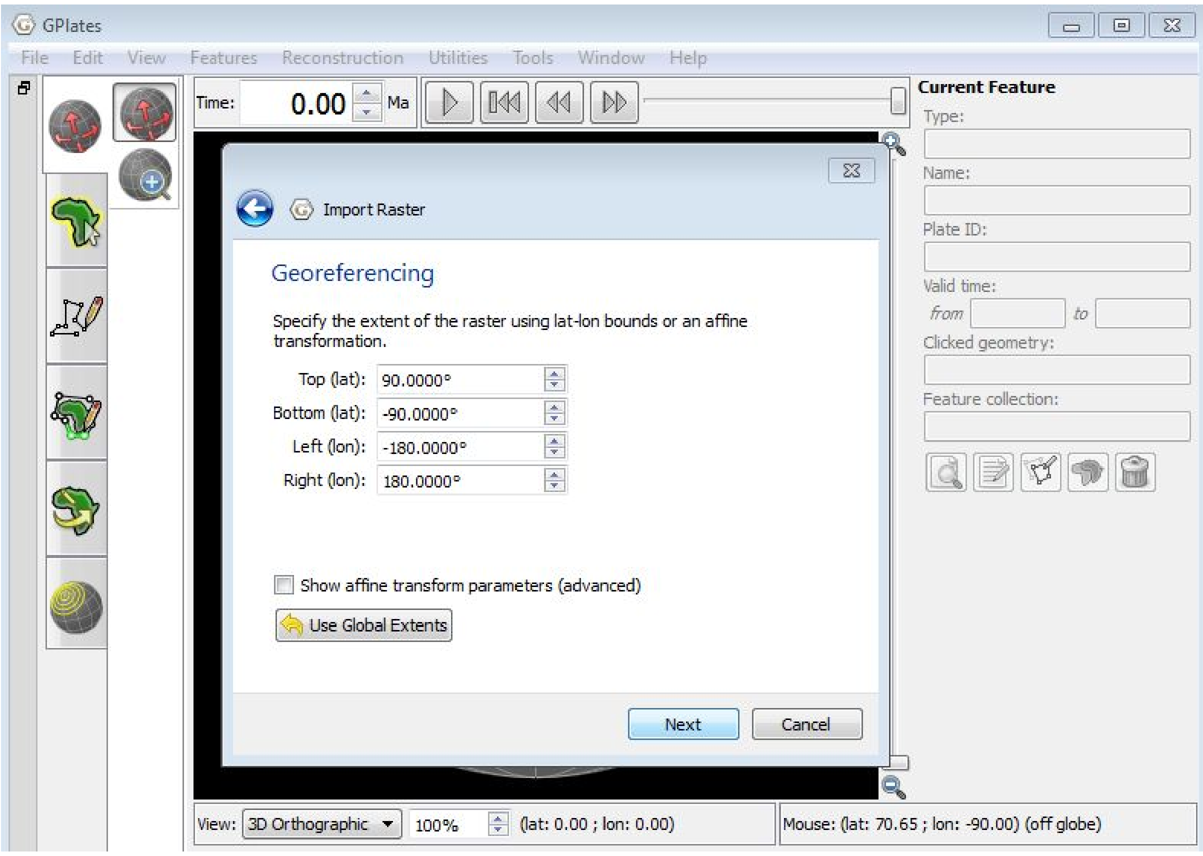

Figure 3. Assigning Latitudinal and longitudinal extent to raster

The final step is to create a feature collection. Select "Create new feature collection" and select finish (Figure 4).

Note in the bottom of this box there is a message informing you that the raster metadata (metadata is loosely defined as data about data) will be saved in a GPML file in the same directory. Instead of importing the raster again, you can simply go to File → Open Feature Collection

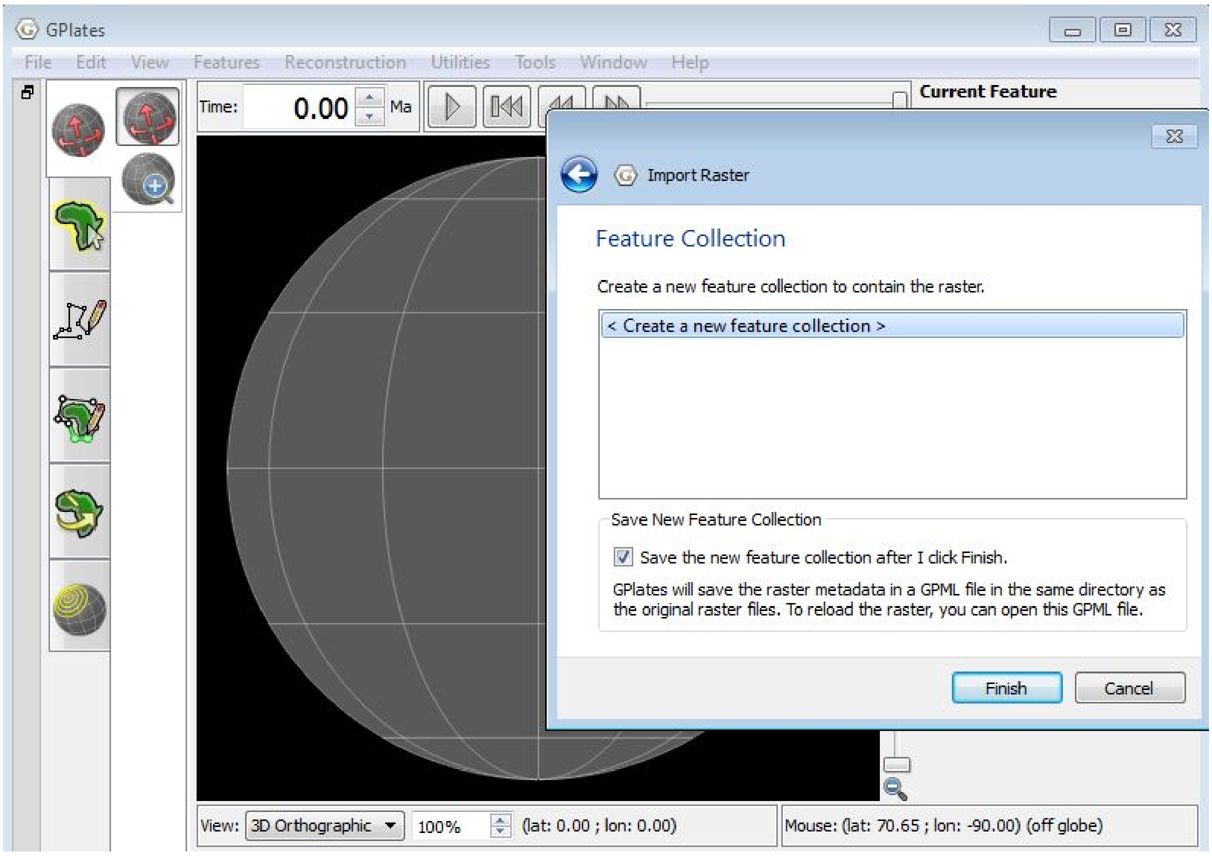

Figure 4. Creating a feature collection for raster

The raster color_etopo1_ice_low should now be displayed on the globe (Figure 5).

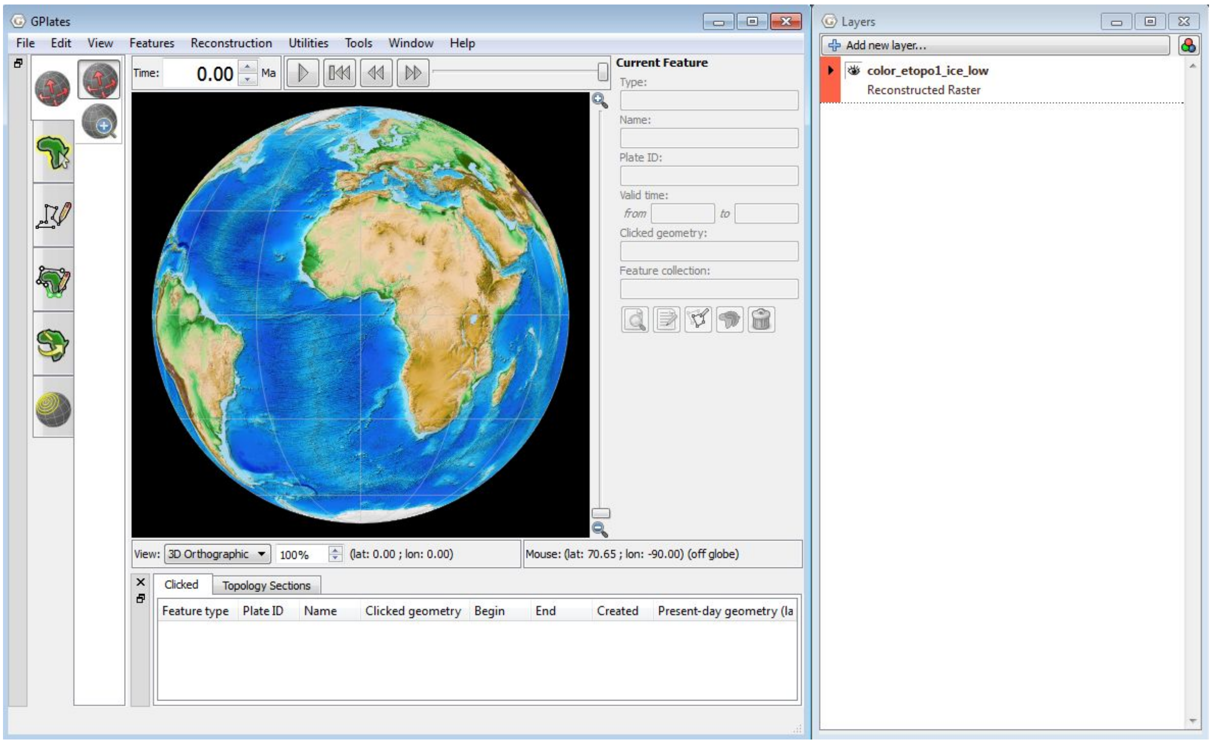

Figure 5. color_etopo1_ice_low raster imported into Gplates successfully.

Exercise 2 – Time dependent rasters: Global dynamic topography

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Now we will visualise time-dependent rasters in GPlates. Time depednent rasters are a series of rasters that have been age-coded so we can observe the evolution of a dataset through time. In the following exercises we will be observing snapshots of geodynamic models of dynamic topography (Appendix. A) and depth slices from seismic tomography models which are coded to geological age.

Dynamic topography is vertical motion of the Earths surface attributed to mantle processes. For example, dense, sinking material, such as subducting slabs, drag down over-lying crust, whereas buoyant upwellings push up overlying crust. For an informative overview of dynamic topography, the 2001 Scientific America article “Sculpting the Earth from Inside Out by Professor” by Mike Gurnis is a good place to start.

In this exercise we will be importing a sequence of time-dependent raster images showing geodynamic model results of dynamic topography since the Mid-Cretaceous (0–100 Ma), provided by Bernhard Steinberger (GFZ Potsdam). These images have been generated at 1 Myr intervals.

1. Load the time-dependent rasters using the following sequence of commands: File→ Import Time-Dependent Raster (Figure 5).

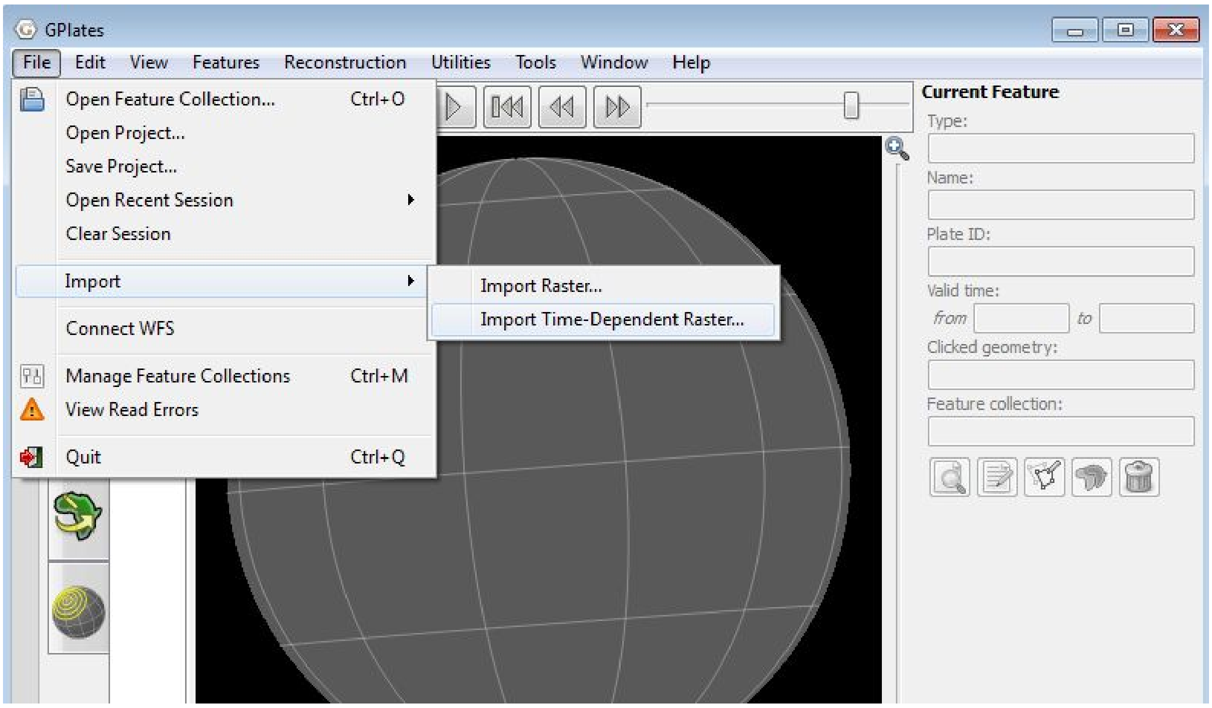

Figure 5. Navigating the menu bar to import time-dependent raster sequences.

Select the 'Add directory...' button and locate and select folder called “Dynamic Topography” → “jpg” in the tutorial data bundle (Figure 6). Press ‘Select Folder’ (you cannot select an individual JPEG when loading a Raster Sequence), press ‘Next”, and leave the band name as “band 1”. Press ‘Next’ and as our rasters are global, ensure that the lat-lon bounds are 90◦ to -90◦ and -180◦ to 180◦. Press ’Next’ again and create a new feature collection by selecting Done. You can also tick the checkbox in the last dialogue to save a *.gpml file storing your settings.

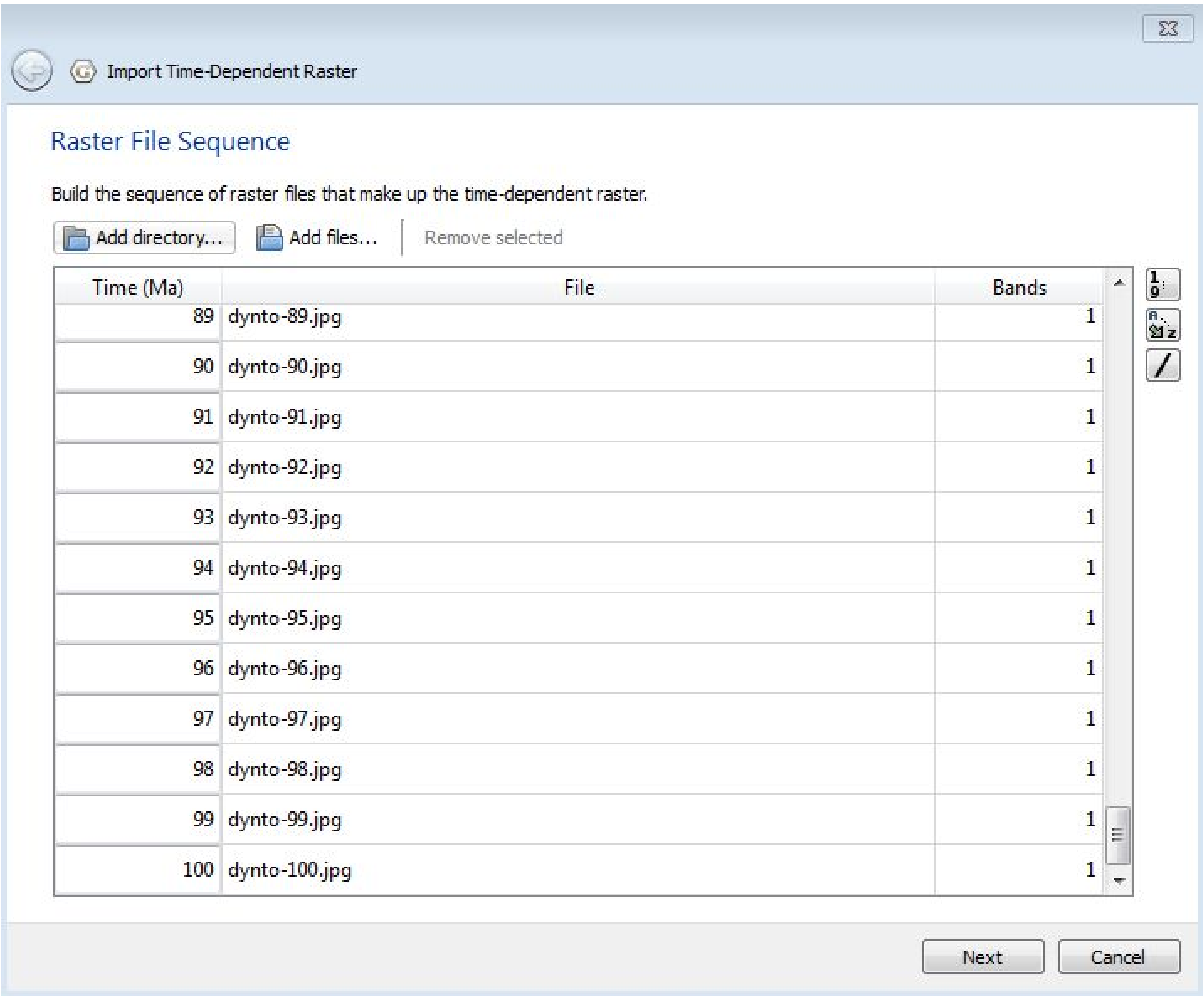

Figure 6. Once a directory has been selected, the series of jpegs contained within that directory will be displayed next their corresponding age.

2. To make these rasters more geographically meaningful, let’s open a coastline file and add this to the GPlates main window: Go to File → Open Feature Collection and locate Seton_etal_ESR2012_Coastlines_2012.1_Polygon.gpmlz in the tutorial data bundle. Click Open to add the file.

3. What are we missing? Unless we load a rotation file the coastlines (and any other datasets we want to visualise) will remain fixed in present-day coordinates. Go to File → Open Feature Collection and load in the rotation file Seton_etal_ESR2012_2012.1.rot

4. Now use the Animation Controls and/or Time Controls in the Main Window above the globe (Figure 7) to reconstruct the image sequence back through time. Blues indicate faster seismic waves travelling through colder, denser material which pulls the lithosphere down resulting in negative dynamic topography, whereas reds indicate waves travelling through hotter less dense material which pushes the lithosphere up

resulting in positive dynamic topography. To watch the evolution of the dynamic evolution of the Earth's surface since 100 Ma, set the time to 100.00 and then press the play button. See the Reconstructions section in the GPlates manual for more details about manipulating animations.

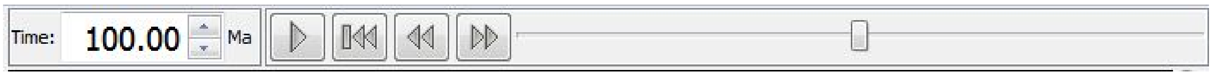

Figure 7. Time and Animation controls in the main window. You may use these controls to manually enter a time, move the slider to reconstruct the globe or animate from a selected time to the present.

Exercise 3 – Time dependent rasters: Dynamic topography and tectonics in Australasia

Time-dependent raster sequences can be combined with other reconstructable datasets in order to analyse and investigate features in the geological record. We will now exploit this functionality in order to see why dynamic topography is reflected in the geological record of several Australian basins and oceanic plateaus. Evidence for negative dynamic topography can be expressed as anomalous tectonic subsidence. By analysing stratigraphic data (obtained from exploration wells) we can calculate how a region has subsided over time. Anomalous subsidence is the long term lithospheric sinking that can not be explained by the usual reasons. That is subsidence expected from thermal cooling resulting from lithospheric stretching, or flexure due to the emplacement of a heavy load. Knowledge of the tectonic history of the region in question will further help determine if dynamic topography(the lithospheric topography changing due to mantle convection) is a potential cause of the anomalous subsidence.

Cenozoic anomalous tectonic subsidence, induced by mantle convection processes, is recorded in wells north and northeast of Australia [e.g. DiCaprio et al., 2009, Heine et al., 2010, DiCaprio et al., 2010]. If subsidence has occurred, a basin will form and sedimentation will increase.Thus if the rate of sedimentation in your well core is greater than the sediment contribution from lithospheric stretching then you can attribute it to dynamic subsidence,and would check this suspicion against mantle convection models. In our example the dynamic topography, including a 300 m downward tilt of the continent to the north- east, is due to the Australian Plate migrating towards the subduction zones of Southeast Asia [DiCaprio et al., 2009]. We will now load into GPlates the outlines of the Carpentaria Basin (N of Australia), Queensland Plateau (NE of Australia) and Marion Plateau (NE of Australia); focus regions of the above authors.

1. Locate and open the files **CarpentariaBasin.gpml**, **QueenslandPlateau.gpml** and **MarionTerrane.gpml** from the tutorial data bundle.

2. We will also load in the locations of several wells that have recorded anomalous tectonic subsidence in the Cenozoic. We will do this using the option to load files also from the Feature Manager: File → Manage Feature Collections. Click on the Open File button and load the file **Wells_Australia.gpml**.

3. We will now adjust the colouring of the line and polygon data to make it easier to see: go to Features → Manage Colouring (Figure 8) and from the Feature collection drop down menu select All → Single colour and select "Black" Figure 9). Now we can clearly see the coastlines, wells and basin/plateau outlines.

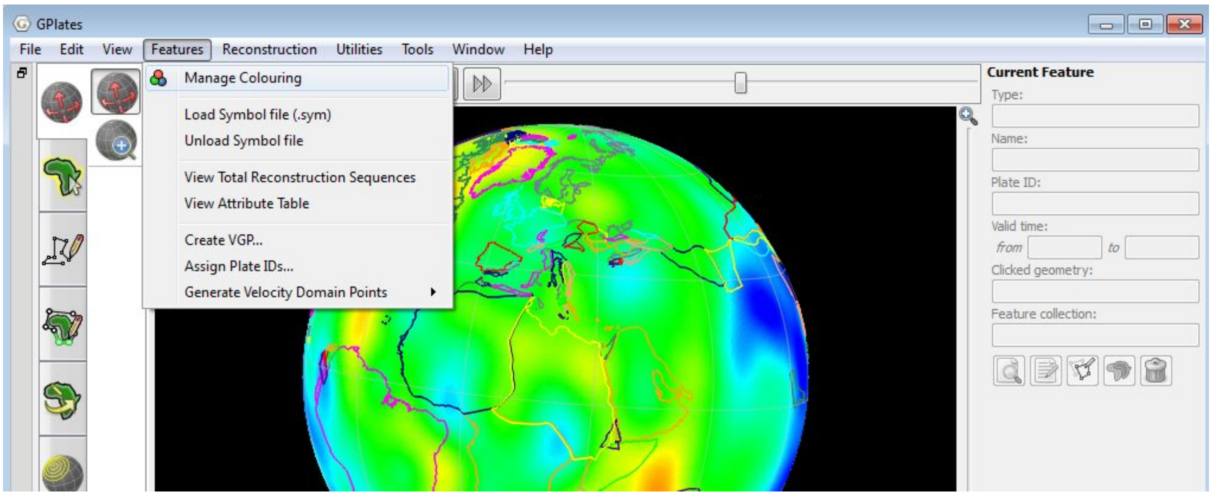

Figure 8. Navigating the menu bar to open the Manage Colouring window.

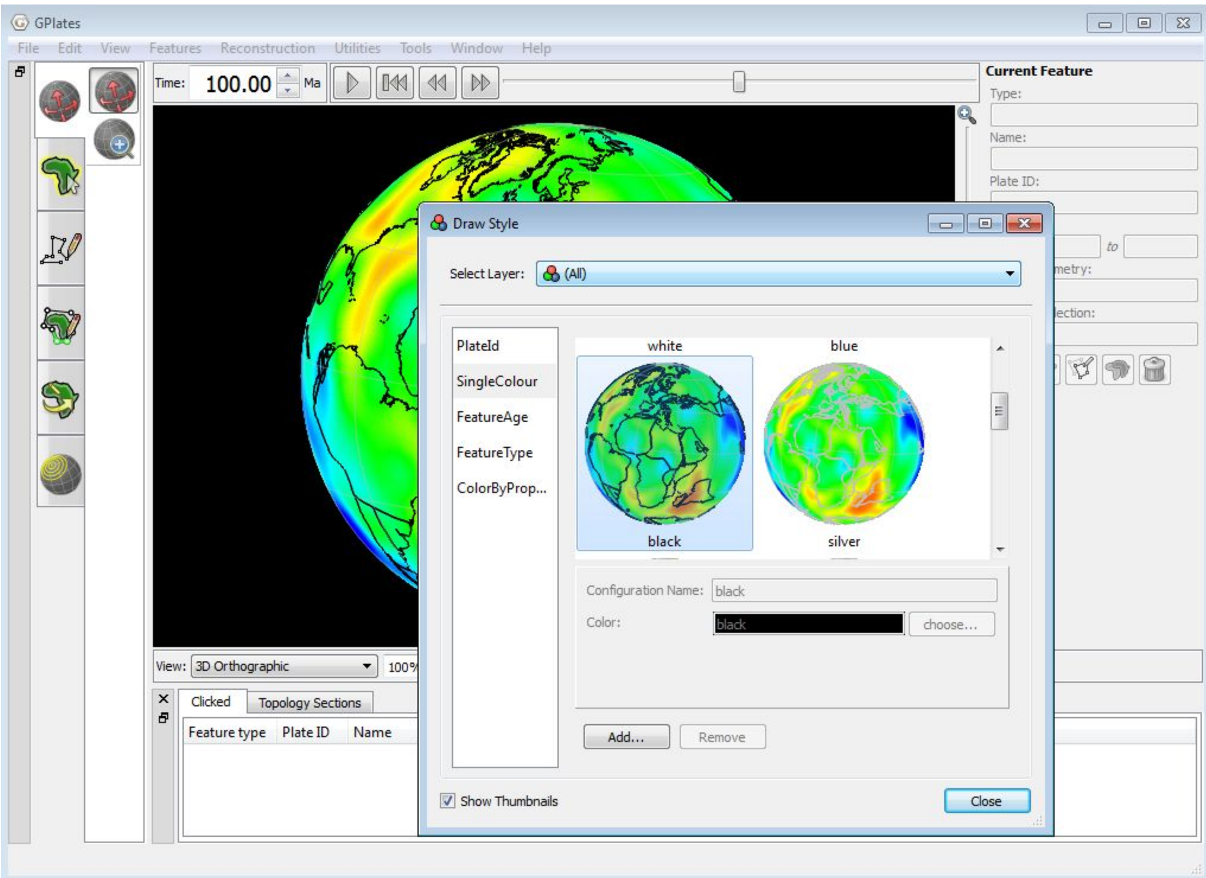

Figure 9. Changing the colour of all feature data to black.

4. Now play the animation through from 100–0 Ma.

How does the dynamic topography signal evolve in the focus areas we have loaded?

You will notice that the negative signal strengthens as Australia migrates in a north-northeasterly direction (Figure 10).

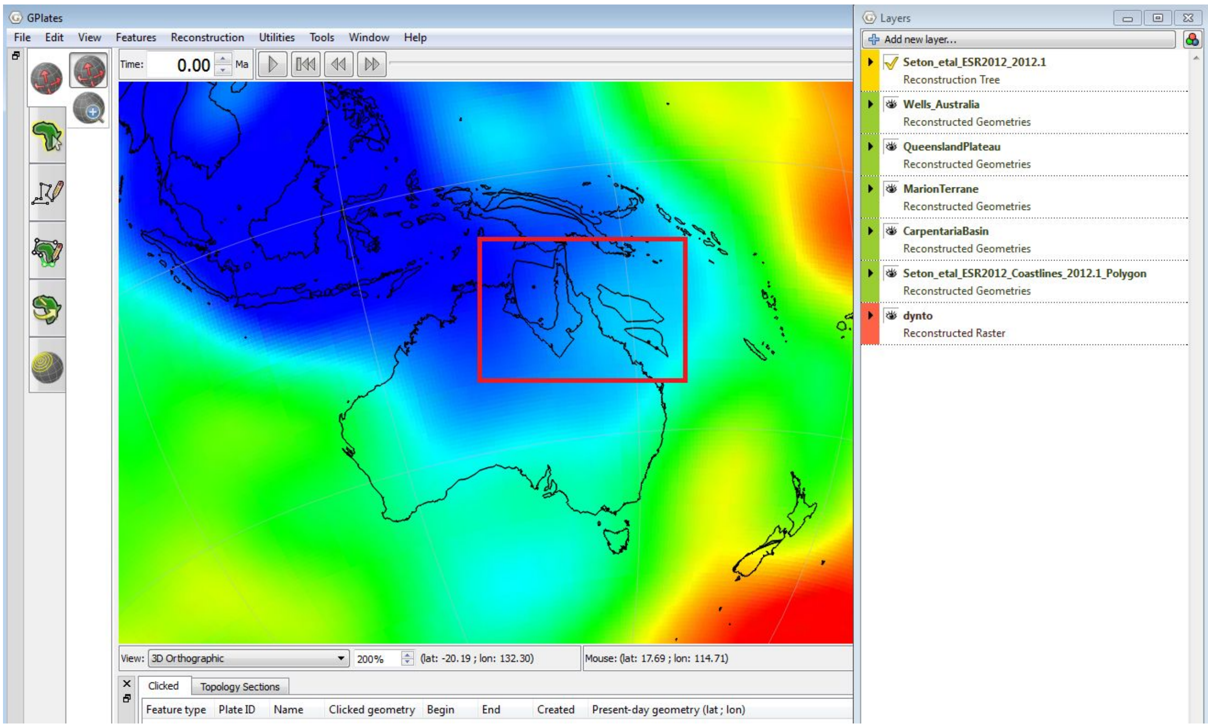

Figure 10. View of the Australian region with Gulf of Carpentaria basin outline and the Duyken-1 well (black dot) as well as the Marion and Queensland Plateau polygons and other well data. Background are time-dependent dynamic topography images.

Exercise 4 – Time dependent rasters: Seismic tomography and slab windows

For the next exercise you will require the following two regional raster bundles included in the tutorial dataset:

Montelli06_S (Regional dataset)

MITP0-08 (Regional dataset)

We will now be using a combination of regional time-dependent rasters and reconstructable data sets to reveal an assumed Late Cretaceous-Early Tertiary 'slab window' beneath Sundaland (Whittaker et al., 2007) – a region of Southeast Asia comprising the Malay Peninsula, Borneo, Java, Sumatra and the surrounding islands.

Slab windows

Slab windows form as a result of spreading ridges intersecting subduction zones. When ridges are subducted the down-going plates continue to diverge, yet due to an absence of ocean water to cool the upwelling asthenosphere and form new oceanic crust, the plates no longer continue to grow and a gap develops and widens. Seismic tomography enables us to visualise slab windows from present-day and past subduction.

Seismic tomography

Seismic tomography is a method of imaging the Earth's interior to reveal regions of past and present subduction, and hot mantle upwellings. It involves establishing how fast seismic waves (elastic waves) travel through the mantle, for example seismic waves generated by earthquakes. This information is then used to infer regions of anomalously hot or cold material; 'anomalous' is judged as deviating from a global reference model. As the speed of seismic waves travelling through the mantle is influenced by temperature, velocity can be used as a proxy for temperature (fast velocities = cold material, slow velocities = hot material). However, mantle composition also affects the speed of wave propagation, and therefore establishing correlations between velocities and mantle structures is not simple.

The included data bundle includes 2 sequences of regional time-dependent raster images, and one global time-dependent raster sequence, showing seismic tomography. These images were generated from the seismic tomography model PRI-S05 (Montelli et al., 2006) and model MIT-P08 (Li et al., 2008). Although seismic tomography is a method for imaging the structure of the present-day mantle, by establishing a relationship between slab depth and slab age (i.e. when the slab was being subducted at the surface, NOT the age of the oceanic crust) we can use tomography data to learn about past subduction zones. By examining the relationship between subducted materials sinking velocity and its current depth, we can make estimates about the age of subducted material. Table 1 displays the corresponding depth of the age coded tomography slices.

Table 1. Age – depth relationship for tomography slices based on Lithgow-Bertelloni and Richards (1998).

Depth Slice $[km]$	Age $[Ma]$
0	0
240	5
480	10
684	15
744	20
804	25
864	30
924	35
984	40
1044	45
1104	50
1164	55
1224	60
1284	65
1344	70
1404	75
1464	80
1524	85
1584	90
1644	95
1704	100
1764	105
1824	110
1884	115
1944	120
2004	125
2064	130
2124	135
2184	140
2244	145
2304	150
2364	155

You can load Time-dependent Raster Sequences, which are raster images whose pixels change according to the reconstruction time.

Presently, GPlates can open RGBA images (which have a Red, Green, Blue and optional Alpha value for each pixel in the image) including common file formats such as JPEG (JPG), PNG, TIFF and GIF.

If you want to load your own time-dependent raster set, make sure:
- Each image is a jpg file
- All files are named: name-time.jpg
- The time-numbers are integers (time in Ma)

Example:
Montelli06_P-3.jpg
Montelli06_P-4.jpg
Montelli06_P-5.jpg
etc.

For our region of interest time-dependent raster sets already exists. The seismic tomography data shows the mantle structure at different depths, which are assumed to represent certain ages in the past.

To load the Time-dependent Raster Sequence, select Import Time-dependent Raster from the File Menu (Figure 11). This will open the first 'Import Time-Dependent Raster' window.

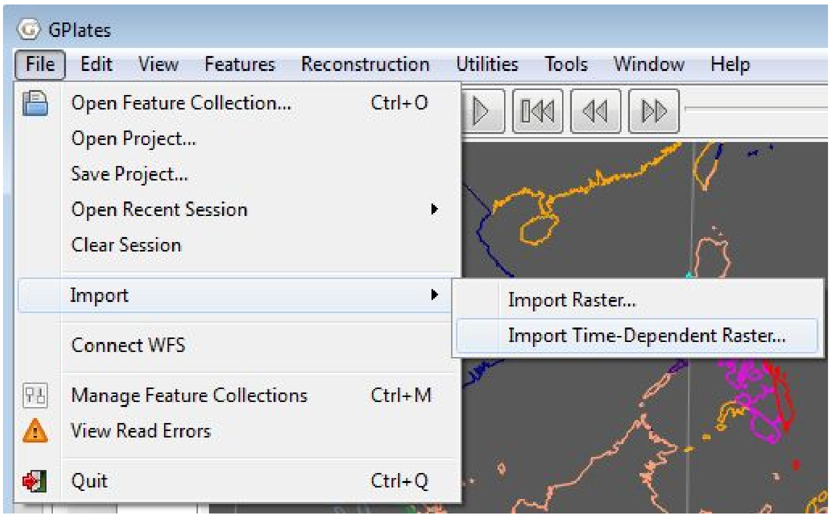

Figure 11. Under the File tab, select ‘Import’, ‘Time-dependent Raster’.

To add raster images, we have two options.

1. If we are using multiple files which are saved in a single folder, we can use the ‘Add directory…’ button and select the entire folder in which the images are saved.

2. Alternatively, if we are using multiple files which are saved alongside other files we do not want to load, or use the ‘Add files...’ button and select them all individually.

In this example, we will load the entire folder and use the Montelli tomography model. The importing Rasters data bundle also contains the MITP08 model, so feel free to try it out also. Keep in mind that for this SE Asia example, only the regional MITP08 model (MITP-08_Regional) is applicable.

Click the ‘Add directory’ button. Navigate to the folder in which your Montelli06_S folder is saved, select it and then click ‘Select Folder’ (Figure 12). GPlates will take some time to add the raster file sequence. Don’t close the window!

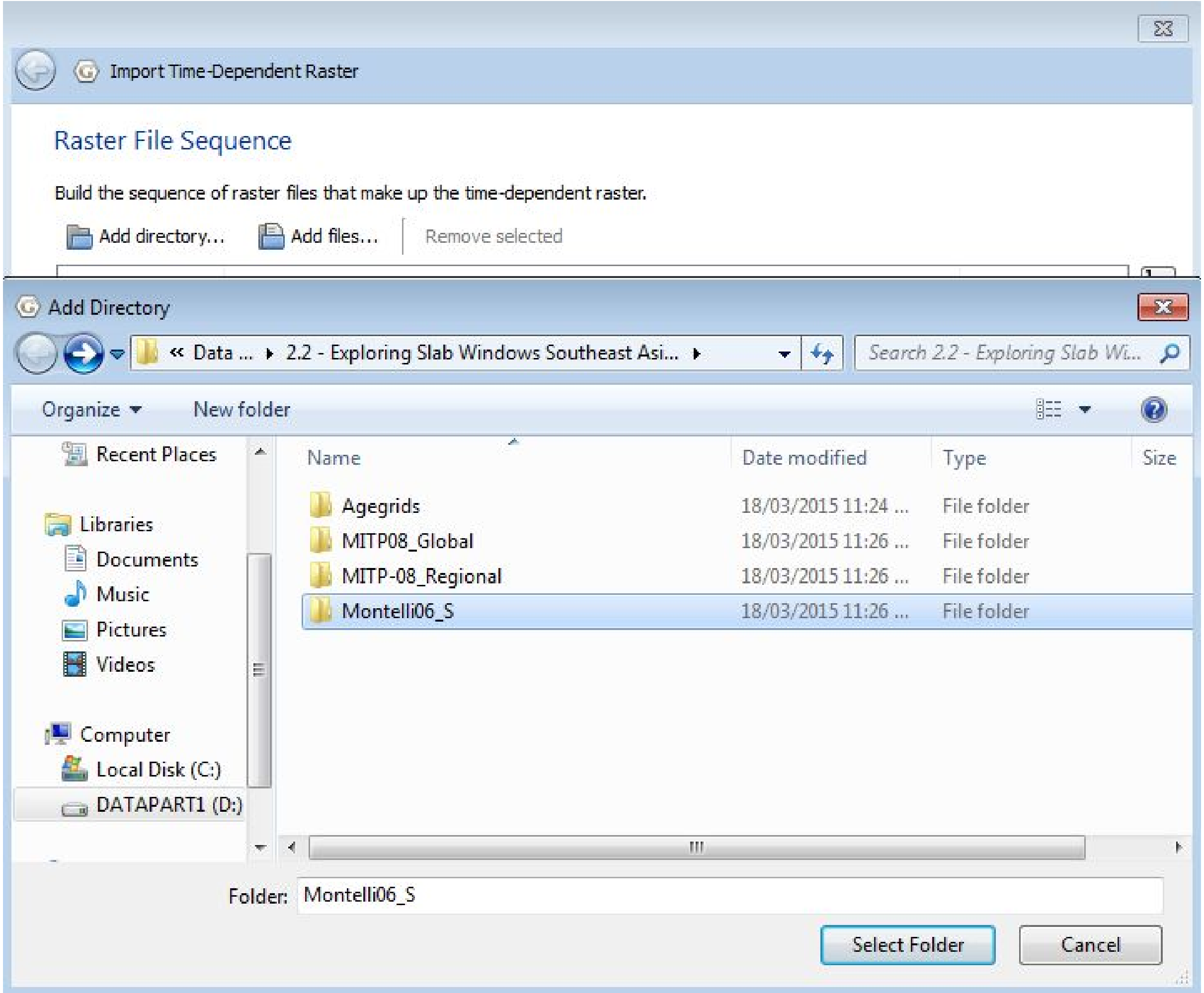

Figure 12. Use the 'Add directory' button to select the folder in which your raster images are saved. In this example, this is the folder 'Montelli06_S' included in the tutorial dataset.

You will see all the individual raster files loaded (Figure 13). Click Next.

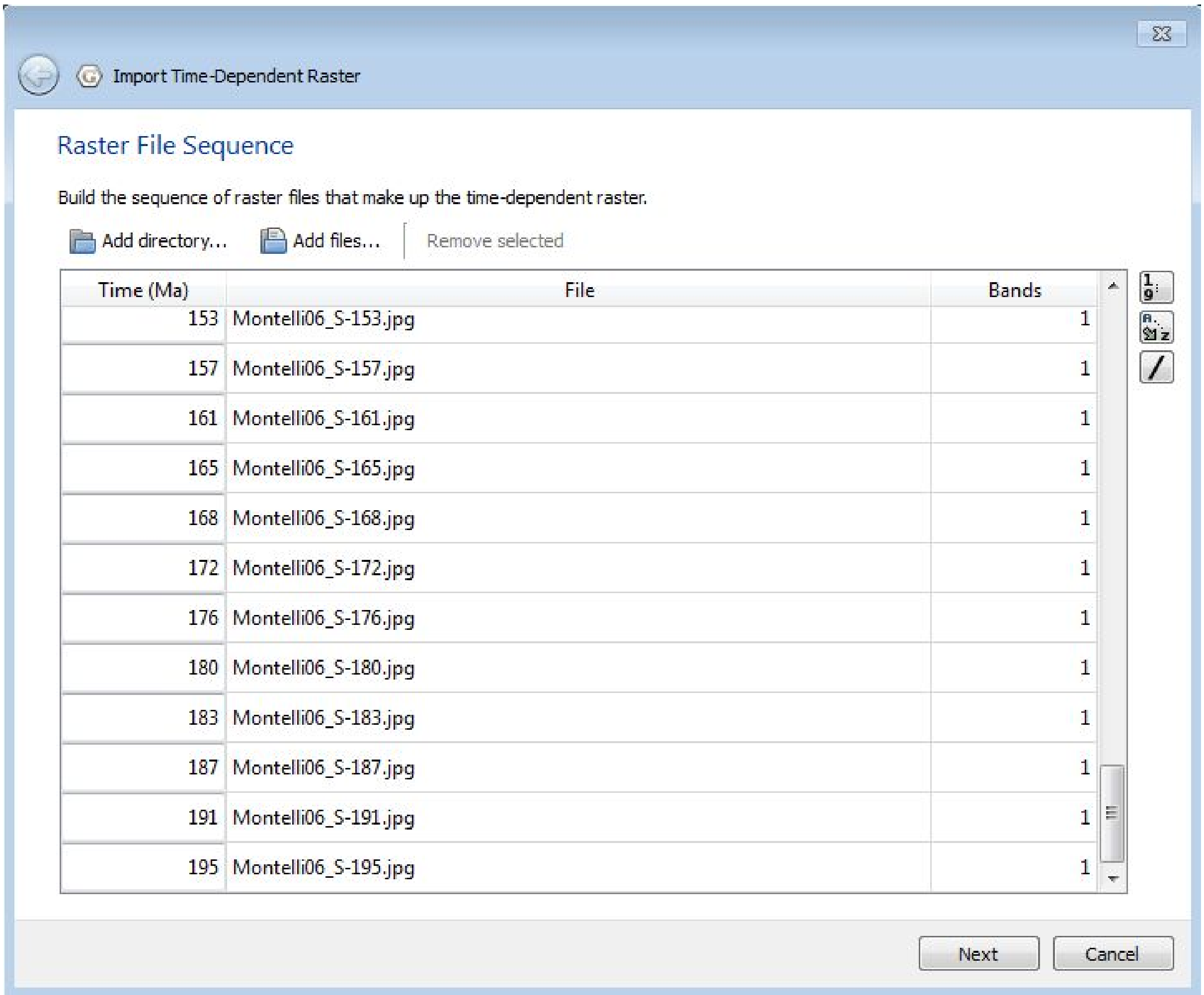

Figure 13. The first 'Import Time-Dependent Raster' window with all raster files loaded.

In the second window, you are asked to specify band names. Keep the default and click Next.

In the third window, under Georeferencing, you are asked to specify the location of raster using latitude and longitude. Since this is a regional raster, we are required to specify the position of the image to be in SE Asia. If we were instead loading a global raster, which spans the entire globe, we would keep the default location as is.

For the SE-Asia Montelli data, the coordinates are:

Top (lat): 30.0000°

Bottom (lat): -20.0000°

Left (lon): 80.0000°

Right (lon): 130.000°

Enter these coordinates in and click Next (Figure 14)
(These coordinates are also suitable for the MITP08 raster)

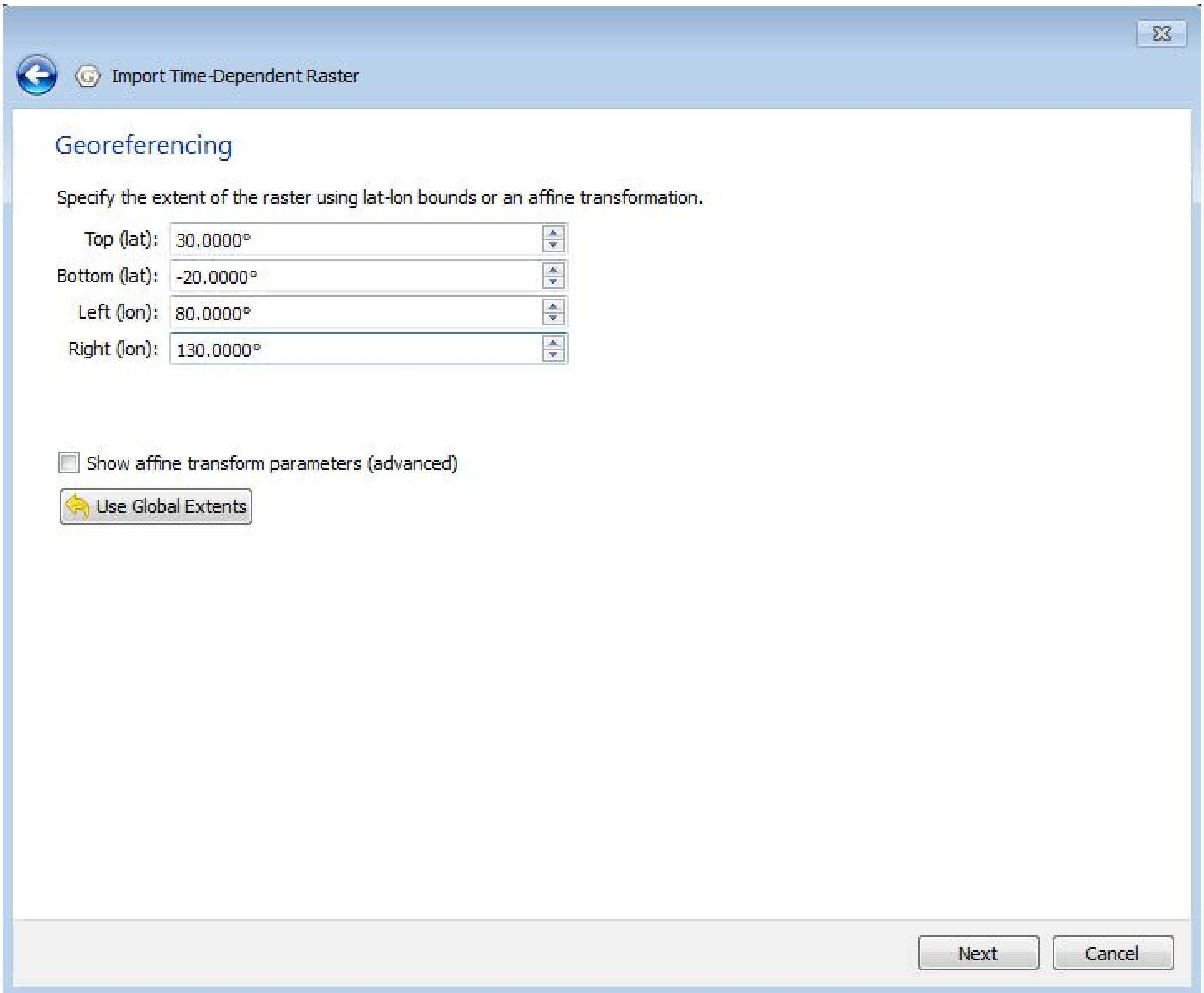

Figure 14. Enter the SE-Asia coordinates for the Montelli raster dataset (Top: 30°, Bottom: -20°, Left: 80° and Right: 130°) and click Next.

In the fourth window, you are prompted to create a new feature collection. Keep the default (< Create a new feature collection >) and press Finish.

After you have changed the Camera Position you should be able to see the seismic tomography for the SE-Asian region (Figure 15).

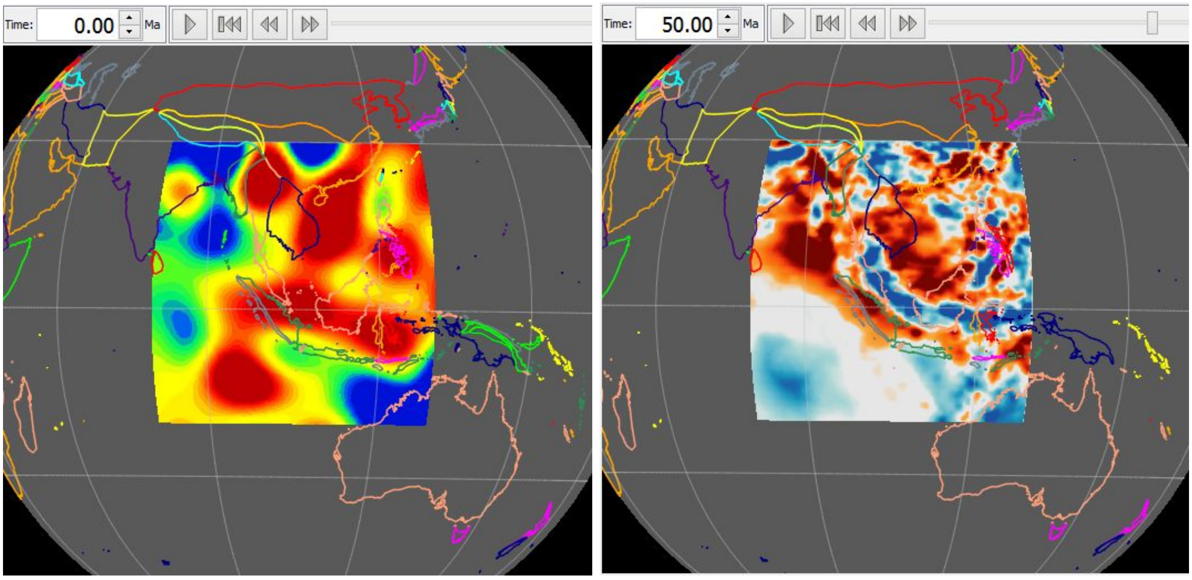

Figure 15. Seismic tomography of the SE Asian Region, with the raster surface extent set. **(a)** Tomography model is Montelli06_S at 0 Ma. **(b)** Tomography model is MITP08 at 50 Ma.

We want to use seismic tomography to find a hypothesised slab window beneath Sundaland in the late Cretaceous-Early Tertiary.

Slabs at subduction zones can be seen in seismic tomography images as regions of anomalously fast velocities (blue areas in our figures), because the slabs are colder and denser than the surrounding mantle.

A slab window can be seen as a break in the fast subducted slab.

The slab window is thought to have opened approximately between 70Ma and 43Ma and can be observed in different models at depths representative of these times.

Because the raster images are time-dependent we can animate the seismic tomography through time.

For the time-dependent raster sets that already exist for SE-Asia we can animate a period from 189 Ma to present day in 1 My time steps.

To animate the changes in seismic tomography through time we use the Animation Slider at the top of the interface. To reconstruct to a particular time, type the required age in Ma into the 'Time' text box and press Enter. As an example, reconstruct to 50 Ma using the Montelli model

(Figure 16).

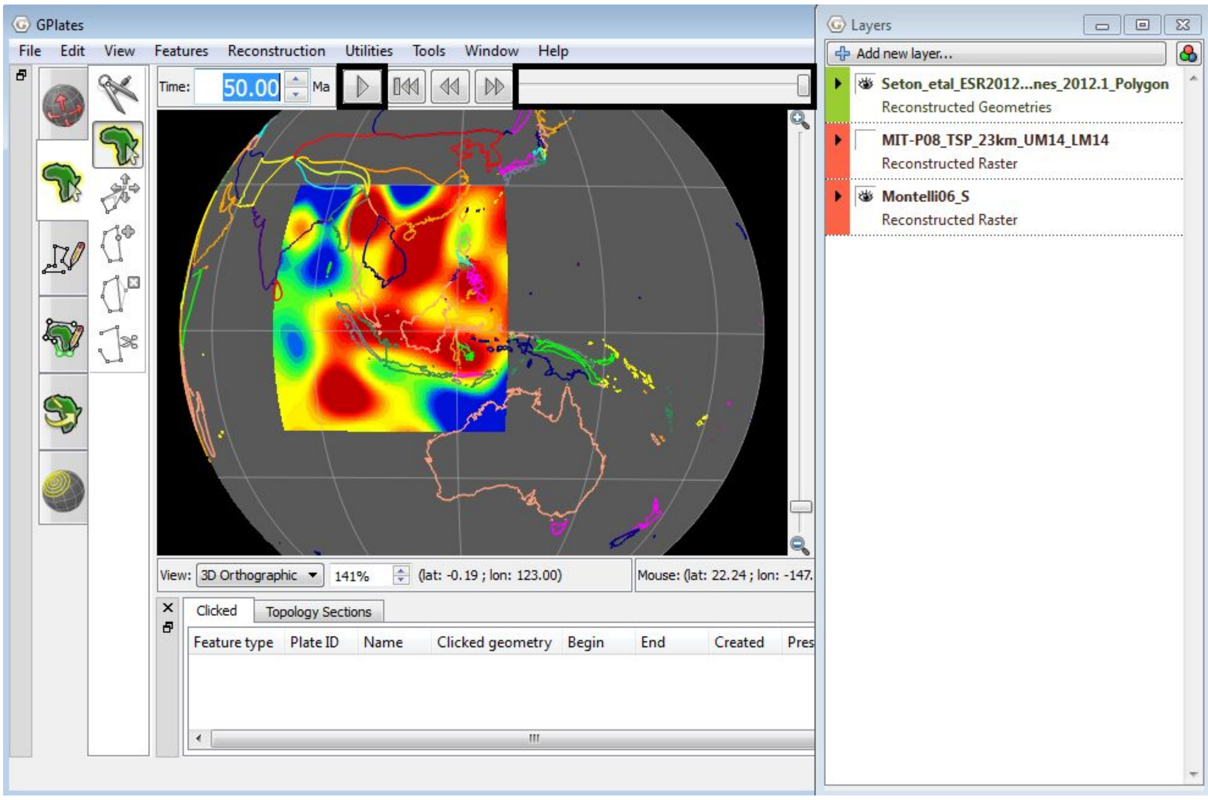

Figure 16. Reconstruct to a particular time frame by either typing the reconstruction time in Ma into the 'Time' text box (highlighted in blue, or using the Animation Slider to slide to the required reconstruction time (circled in black). Animate the changes in seismic tomography through time by pressing the Play button (circled in black)

To start the animation, press the Play button. The animation will start in the past (at the age at which you initially specified) and end at present day.

If you want to stop the animation press Pause (same button as Play).

By using the Fast Forward and the Rewind buttons you can watch the reconstruction in small steps. Press the Fast Forward/Rewind button once to adjust the current reconstruction time by one timestep forwards/backwards. The default timestep is 1 Ma.

You can also use shortcut keys:

Ctrl (CMD) + I = forwards

Ctrl (CMD) + Shift + I = backwards

By keeping the button pressed or the shortcut keys held down you can move forwards/backwards faster.

In the Animation Dialog (Figure 17) you can adjust the start and the end time for your reconstruction. To access this click Reconstruction menu and select Configure Animation

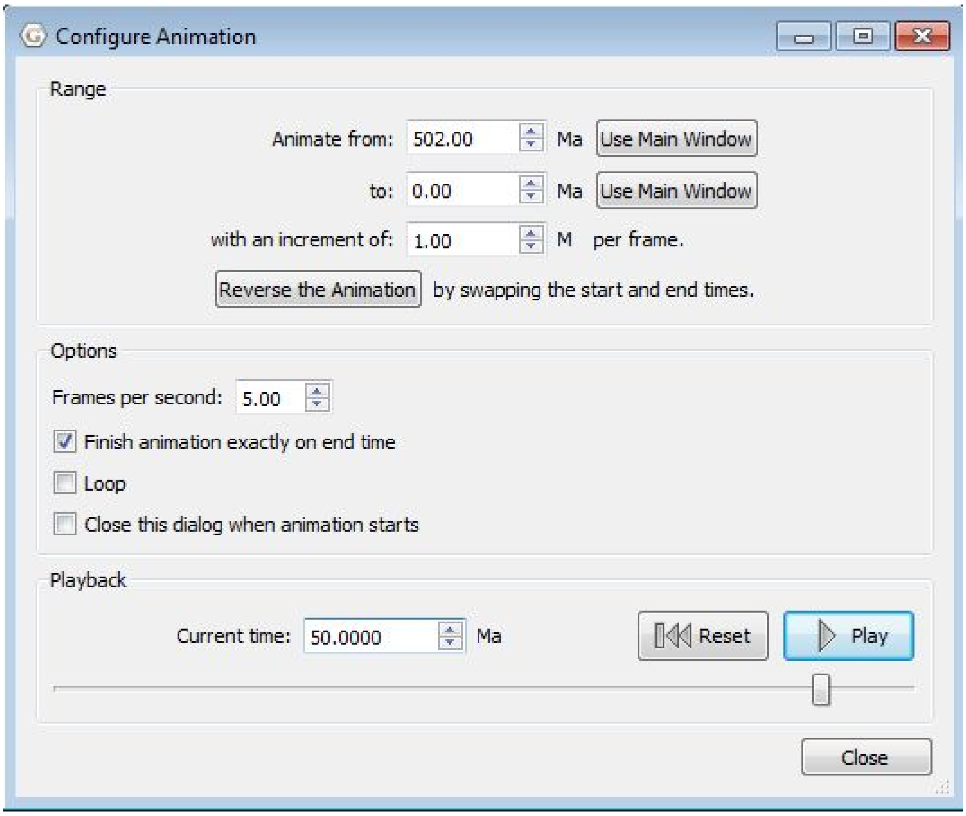

Figure 17. Animation Dialog

For our data you can choose any start time between 189 to 1 Ma.

In the Animation Dialog (Figure 17) you can also adjust the frames per second and the increment per frame.

Default settings are:

200 Ma for the start time and 0 Ma for the end time of the animation

5 frames per second

1 Ma increment per frame

If you want your animation to start at present day and go back in time you can choose Reverse the Animation from the Animation Dialog

To find our slab window we don't need our animation to start at 140 Ma. Change the start time for the animation to 80 Ma and the end time to 30 Ma.

Try to find the slab window in the different raster sequences. Look for red-yellow gaps that appear to break up a continuous blue band. The blue represents the colder oceanic slab being subducted, and the red representing the hot mantle upwelling through the gap or 'window'in the slabs.

You may find that turning off the coastlines layer by clicking the Eye in the 'Layers' window may make things less confusing (Figure 18).

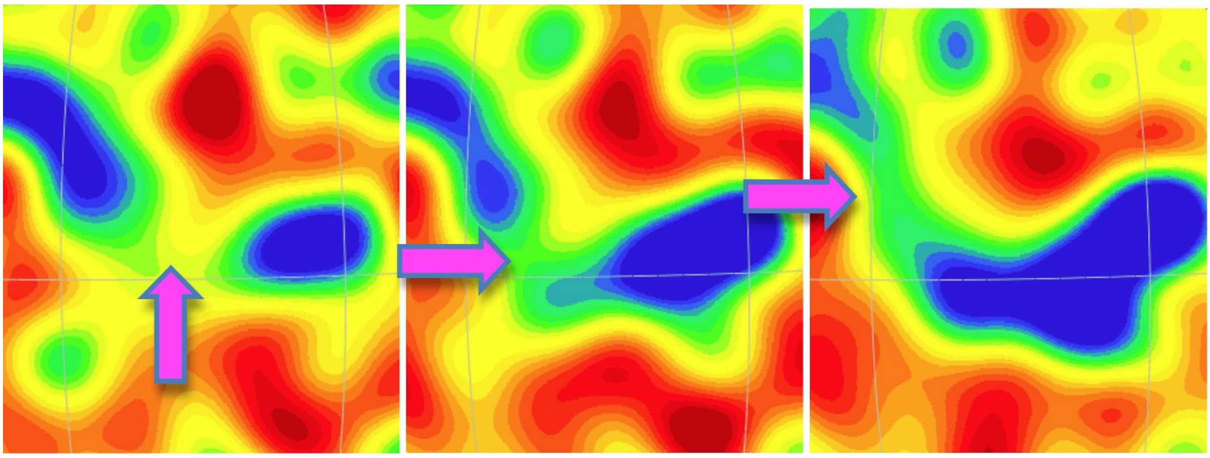

Figure 18. (a) Slab window in Sundaland using the Montelli06_S model at 70 Ma (left), 56 Ma (middle) and 43 Ma (right)

You will find that in the MITP08 model, a slab window begins to form at 63 Ma when a section of red intersects a blue band, and disappears at 38 Ma when the blue band becomes continuous once more (Figure 19).

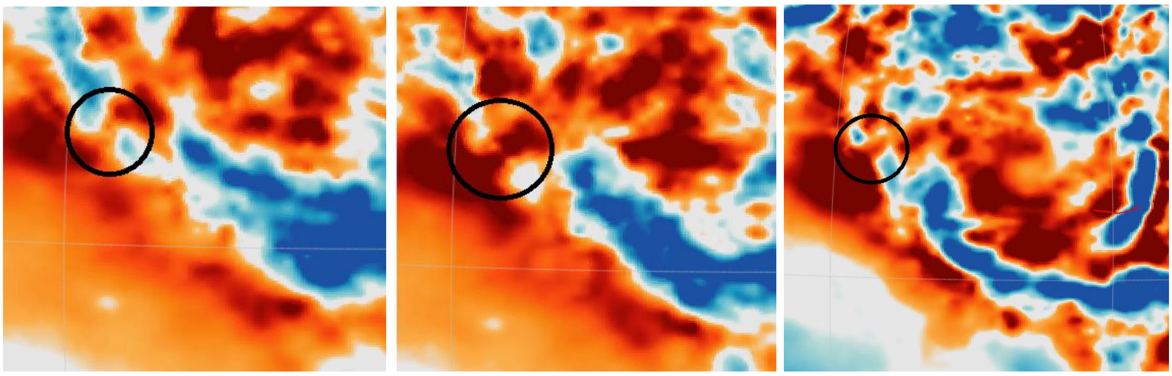

Figure 19. (a) Slab window in the MITP08 model at 63 Ma (left), 57Ma (middle) and 44Ma (right)

References

Butterworth, N., Talsma, A.S., Müller, R.D., Seton, M, Bunge, H.-P., Schuberth, B.S.A., and Shephard, G.E. (In Review), The Dynamics of Sinking Slabs, Journal of Geodynamics.

Lydia DiCaprio, Michael Gurnis, and R. Dietmar Mu ̈ller. Long-wavelength tilting of the Australian continent since the Late Cretaceous. Earth Planet. Sci. Lett., 278:175–185, 2009. doi: 10.1016/j.epsl.2008.11.030.

Lydia DiCaprio, R. Dietmar Müller , and Michael Gurnis. A dynamic process for drowning carbonate reefs on the northeastern australian margin. Geology, 38(1):11–14, 2010. doi: 10.1130/G30217.1. URL http://geology.gsapubs.org/cgi/content/abstract/38/1/11.

Theresa Fabian, Joanne M. Whittaker, and R. Dietmar Müller . Ground-truthing proposed slab window formation beneath Sundaland using Seismic Tomography. In ASEG-PESA International Geophysical Conference and Exhibition, Sydney, Australia, August 22nd-26th 2010.

Christian Heine, R. Dietmar Müller , Bernhard Steinberger, and Lydia DiCaprio. Integrating deep Earth dynamics in paleogeographic reconstructions of Australia. Tectonophysics, 438:135–150, 2010. doi: 10.1016/j.tecto.2009.08.028.

Chang Li, Robert D. van der Hilst, E. Robert Engdahl, Scott Burdick. A new global model for P wave speed variation in Earth's mantle, Geochem. Geophys. Geosyst., 9, Q05018, doi:10.1029/2007GC001806.

Carolina Lithgow-Bertelloni and Mark A. Richards. The dynamics of Cenozoic and Mesozoic plate motions. Rev. Geophys., 36(1):27–78, 1998.

Montelli, R., G. Nolet, F. A. Dahlen, and G. Masters, A catalogue of deep mantle plumes: New results from finite-frequency tomography, Geochem., Geophys., Geosyst., vol 7 (11), 2006.

Raffaella Montelli, Guust Nolet, F. A. Dahlen, and Gabi Laske. A catalogue of deep mantle plumes: New results from finite frequency tomography. Geochem. Geophys. Geosyst., 7(11):Q11007, 2006. doi: 10.1029/2006GC001248.

R. Dietmar Mu ̈ller, Maria Sdrolias, Carmen Gaina, and Walter R. Roest. Age, spreading rates, and spreading asymmetry of the world's ocean crust. Geochem. Geophys. Geosyst., 9(4):Q04006, 2008. doi: 10.1029/2007GC001743.

R. Dietmar Muller, M. Sdrolias, C. Gaina, B. Steinberger, & C. Heine, 2008. Long-term sea level fluctuations driven by ocean basin volume change, Science, 319, 1357--1362, doi:10.1126/science.1151540.

Paul Wessel and W. H. F Smith. New, improved version of Generic Mapping Tools released. EOS Trans. Am. Geophys. Union, 79(47):579, 1998.

Joanne M. Whittaker, R. Dietmar Mu ¨ller, Maria Sdrolias, and Christian Heine. Sunda-Java trench kinematics, slab window formation and overrid- ing plate deformation since the Cretaceous. Earth Planet. Sci. Lett., 255: 445–457, 2007. doi: 10.1016/j.epsl2006.12.031.

Appendix

Terminology

GPML
The GPlates Markup Language. GPML is a "dialect" of XML, in- corporating features of the Geopgraphic Markup Language. Essentially, the GPlates data model is using markup language to represent any feature (ie. geographic object).

Sample data
When you download GPlates from http://www.gplates.org, some sample data is included in your download. On Windows, this will be available after the installation in the GPlates folder at C:\Program Files\GPlates\GPlates [version]\Sample data. For the Mac, the download will leave you with a disk image (*.dmg) file. Mount the file by double-clicking, drag the GPlates application bundle into the Applications folder. The sample data is included as directory ("sample-data") in the top level of the disk image.

Raster data
Raster images comprise 2-dimensional grids of pixels, or points of colour, that are stored in image files such as JPEGS or grid files like netCDF. Note that they differ from vector images that are composed of points and line segments.

Feature
Any reconstructable object which can be loaded in GPlates. Features can be lines, points or polygons or multi-* geometries as well as raster

images.

Slab windows
Slab windows form as a result of spreading ridges intersecting subduction zones (Dickinson and Snyder, 1979). When ridges are subducted the down-going plates continue to diverge, yet due to an ab- sence of ocean water to cool the upwelling asthenosphere and form new oceanic crust, the plates no longer continue to grow and a gap develops and widens. Seismic tomography enables us to visualise slab windows from present-day and past subduction.

Seismic tomography
Seismic tomography is a method for imaging the Earth's interior; revealing regions of past and present subduction, and hot mantle upwellings. It involves establishing how fast seismic waves (elastic waves) travel through the mantle, for example seismic waves generated by earthquakes. This information is then used to infer regions of anoma- lously hot or cold material; anomalous is judged as deviating from a global reference model (e.g. PREM Dziewonski and Anderson, 1981). As the speed of seismic waves travelling through the mantle is influ- enced by temperature, velocity can be used as a proxy for temperature (fast velocities = cold material, slow velocities = hot material). How- ever, mantle composition also affects the speed of wave propagation, and therefore establishing correlations between velocities and mantle structures is not simple.

Age-depth relationship for seismic tomography

The table below show the conversion of seismic tomography depth slice to a certain age. This can then be used as time-dependent raster sequence in GPlates. Sinking Rate is approximately 1.3m/yr.

Depth(km)	Age(Ma)
0	0
100	8
200	15
300	23
400	31
500	38
600	46
700	54
800	62
900	69
1000	77
1100	85
1200	92
1300	100
1400	108
1500	115
1600	123
1700	131
1800	138
1900	146
2000	154
2100	162
2200	169
2300	177
2400	185
2500	192
2600	200
2700	208
2800	215
2900	223

Table 2. Age–depth relationship for tomography slices. Data is based on: The dynamics of sinking slabs Butterworth, N., Talsma, A.S., Müller, R.D., Seton, M, Bunge, H.-P., Schuberth, B.S.A., Shephard,G.E., in prep.