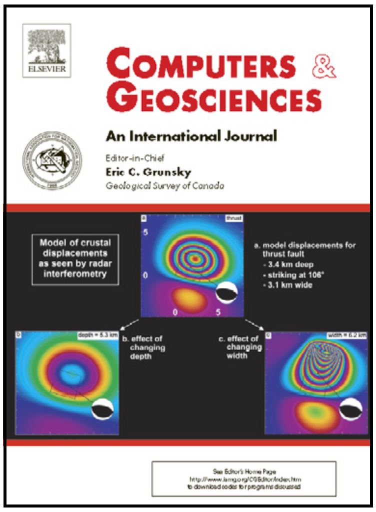

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PII: S0098-3004(12)00103-3
DOI: doi:10.1016/j.cageo.2012.03.015
Reference: CAGEO2861

To appear in: *Computers & Geosciences*

Received date: 6 June 2011
Revised date: 16 February 2012
Accepted date: 18 March 2012

Cite this article as: Stuart R. Clark, Are Magnus Bruaset, Mark A. Smethurst, Christian Tarrou, Trond Vidar Stensby, Jakob Skogseid and Allison K. Thurmond, 4DPlates: On the fly visualization of multilayer geoscientific datasets in a plate tectonic environment, *Computers & Geosciences,* doi:10.1016/j.cageo.2012.03.015

4DPlates: On the fly visualization of multilayer geoscientific datasets in a plate tectonic environment

Stuart R. Clark, Are Magnus Bruaset, Mark A. Smethurst[1]

Computational Geoscience Department
Simula Research Laboratory
Fornebu 1364, Norway

Christian Tarrou, Trond Vidar Stensby

Kalkulo AS, Fornebu 1364, Norway

Jakob Skogseid, Allison K. Thurmond

Statoil AS, Forusbeen 50, Stavanger 4035, Norway

Abstract

This paper presents the 4DPlates, an application designed to display high resolution data and reconstruct their positions in the geologic past. 4DPlates makes use of level of detail (LoD) grids with a 4-8 tree structure to store the data so only the require resolution for a particular viewpoint is used. This facility means that the user can interact with large data sets on the fly, achieving between 30 and 50 frames per second with a large test data set. The article presents the design and functionality of the application, from view-dependent visualization to the ability to reconstruct data in the distant past. Finally, we apply the application in two geoscientific settings. In the first, we calculate the tectonic subsidence from sediment loading and test the variation of the sediment density to the resulting subsidence grid. Secondly, we examine two South Atlantic reconstructions and highlight minor

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[1] also at Avalonia Geophysics, University of Exeter, Penryn, TR10 9EZ, UK

Preprint submitted to Elsevier *March 22, 2012*

differences between them visible in the closeness of the fit of the topographic grids. The application excels at providing an interactive manipulation of high resolution data, whether it be reconstructing the data, setting the lighting angle or vertical exaggeration, or modifying parameters in the underlying formulas.

Keywords: Geospatial visualization, GPU computing, plate reconstructions, level of detail, tectonic subsidence, geological reconstructions

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1. Introduction

Making use of computers to calculate plate positions based on Euler rotations has been around for many years. One of the first software packages to display and interactively update them was the PLATES software developed at the University of Texas Institute for Geophysics (Gahagan, 1998). This software allowed for the reconstruction of coastal outlines, magnetic isochrons and other data based on geographical points. In an attempt to provide an open source solution equivalent to the PLATES software as well as a basic set of open data for making reconstructions, GPlates has been developed over the last decade (Boyden et al., 2011). In addition to the features of PLATES, GPlates added the ability to display raster images on the globe. If a time-series is available, these can be displayed as the reconstruction is done (Boyden et al., 2011). Another program, SPlates (Torsvik et al., 2006), provides features particular to developing paleomagnetic reconstructions, such as investigating the effects of True Polar Wander or constraining features to latitudinal positions, but manipulating longitude. Moving beyond the idea of rigid plates, PPlates (Smith et al., 2007; White et al., 2010) allows for plate reconstructions to occur on deformable meshes: by defining a mesh over a compressed or torn piece of lithosphere, a transformation of the mesh allows for the compression or tearing to be undone. The 4DPlates application complements the previously mentioned software by supporting much larger and high precision data sets that describe the surface or interior structure of the Earth. In a variety of ways, these data sets can be interactively manipulated in 4Dplates allowing geoscientists to test scenarios and communicate their results efficiently.

4DPlates can display, reconstruct and manipulate high resolution geographic data sets, dividing them by tectonic plate and allowing these layers to move independently. In Figure 1, two laters of regional high-resolution data of the Santos Basin bathymetry and depth-to-basement are shown respectively. These grids are displayed on top of the global topography grid ETOPO1 (Amante and Eakins, 2009). In addition, a number of seismic transects criss-cross the high resolution data showing the raw data that went into generating the high-resolution regional grids. The Santos Basin, located off the coast of Brazil, and the South Atlantic in general will feature in a number of the figures in this article. While this figure is a static image, the video demonstration included below shows the variety of technology described below as well as illustrates the rendering speed and 4DPlates' usefulness for communicating scientific ideas.

As well as being an ideal tool for visualizing, comparing and communicating reconstruction models, 4DPlates allows geophysical calculations, such as tectonic subsidence, to be calculated from gridded data sets, scalars and geological age. The results of such algorithms are quickly rendered and can be reconstructed or scalar parameters changed and the effect seen in real time. This is made possible by a hierarchical data representation of the raster data and by performing the calculations on the graphics processing unit (GPU) of the computer. This paper begins by outlining the particular technologies used by 4DPlates and then demonstrates the scientific utility of the software.

2. Technology: a look under the hood of 4DPlates

2.1. View-dependent visualization

To enable rapid display of textures, an existing description of adaptive texture hierarchies (Hwa et al., 2005) served as the starting point for the implementation of 4DPlates. This description proposed a tile-based data structure defined on a planar domain that allowed the resulting surfaces to be textured, using, for example, images of a terrain. However, the concept we had of 4DPlates visualizing geological data sets from the small to global scale, from the surface to the deep interior of the Earth, required a spherical data representation. Hwa et al. (2005) offered a technique that replaces the planar domain with a regular icosahedron. This platonic solid can be seen as a polyhedral approximation of the sphere using 20 equilateral triangles as faces. From this geometrical base, more accurate approximations of the sphere are achievable through successive refinement of the faces.

As in the original algorithm of Hwa et al. (2005), the 4DPlates implementation uses the 4-8 grid hierarchy. The geometry is represented by a structure of diamond-shaped tiles, each of which comprises a regular grid with a fixed number of grid nodes in each direction. Each tile is linked to one or more parent (larger) and child (smaller) tiles. Given the fixed grid size per tile, the parents represent coarser information and the children account for finer details. Between each generation, the tiles are rotated 45 degrees. Traversing to a parent tile, the information for the new tile is the result of a low-pass filtering, while the traversal to a child tile calls for data interpolation. For the purposes of 4DPlates, each node also carries a geo-reference that provides a link between the data representation and the geodetic coordinate system.

Given a viewpoint and camera angle in three-dimensional space, 4DPlates determines the subset tiles necessary for the scene rendering. This subset is defined to be the smallest number of tiles that are sufficient to visualize the area of interest without introducing graphical anomalies (Bruaset et al., 2008). Consequently, the closer the scene to the viewing perspective, the higher the resolution of the tiles that are used. The application also makes use of memory cache to store tiles that have previously been displayed.

2.2. Displaying multi-resolution data and transects

4DPlates is plate tectonic aware, and as such can reconstruct data sets into their locations in the geological past just as the software packages outlined in section 1. However, 4DPlates provides the ability to cut gridded data by the outline of tectonic plates and assign them to the corresponding plate. Finally, the data fragments can be completely or partially masked according to their individual times of appearance and disappearance. A variety of data sets can be imported into 4DPlates and assigned to move with a particular plate. Examples of such data sets are global or regional grid-based data such as satellite imagery, magnetic field anomalies or depth-to-basement maps.

In contrast to virtual globes, 4DPlates can simultaneously visualize both global and regional data sets, organized as a stack of spherical shells. Data sets of different resolutions can be stitched together or viewed as separate layers. Vector data and raster images can also be imported and displayed as well as vertical transects. By positioning the two ends of transect in latitude, longitudinal and vertical coordinates, the transect is scaled to sit in the image. Figure 1 illustrates several of these data types combined in one image. Deviations of the transect from a vertical plain can be added by specifying a discrete number of doglegs. Just as the grid layers can be masked according to the underlying age-grid, sections of the transect can also be removed when the reconstruction age is older than the corresponding sea-floor age underlying the transect.

2.3. Scientific Calculations

4DPlates can perform user-defined calculations with input from multiple gridded data sets. The output calculations can be added to the project as a new grid data set, displayed, and even used as one of the inputs to a subsequent algebraic operation. Geological time can be used as a variable. As the reconstruction time changes in 4DPlates, calculations based on geological time will also change, and the resulting calculated grids are rapidly re-rendered on the globe to reflect the changes. This ease of manipulation is due to the fact that the formulas are translated into GPU-shaders that are quick to update. When displaying a calculated grid layer, a slider is displayed for each user-defined scalar variable. Changing the slider updates the displayed grid in real time.

2.4. Compatibility

Using the Geospatial Data Abstraction Library (www.gdal.org), 4DPlates can read most industry-standard data formats. Newly introduced gridded data are pre-processed to construct the tile-based data structure required for an efficient level-of-detail rendering. The data sets can later be exported in a variety of standard file formats. The current version of 4DPlates is designed to work with other programs by sharing raster and vector data formats with ArcGIS, ENVI, ERDAS, GMT, Plates, GPlates and SPlates. The text file containing the plate motion model is also used by PLATES, GPlates, SPlates and many other reconstruction softwares. 4DPlates has behind-the-scenes communication with GPlates and SPlates so that the applications can be run simultaneously, sharing data files and offering the the user their collective computational strengths in a strongly synergistic manner. 4DPlates also detects modifications made to its data files by other applications, further strengthening its functional links to other software.

2.5. Visual elements

4DPlates is able to display multiple layers of data, each visualized on top of the other. Transparency can be set for each layer by adjusting a slider, from completely opaque to completely transparent. For example, in Figure 2, a global magnetic anomaly grid, EMAG2 (Maus et al., 2009), is displayed with transparency over the global topography grid ETOPO1 (Amante and Eakins, 2009). Other visual elements can be adjusted on the fly as well, such as the lighting direction or colour palette. Settings can be adjusted for one layer or a set of layers simultaneously. The setting of transparency is particularly important when 4DPlates is required to display data on multiple concentric shells representing different depth horizons in Earth.

2.6. Movie generation

Movies can be generated from a series of key frames. Each frame is associated with the current viewpoint and geologic age, captured from user-defined viewpoints. Movie frames are rendered as the globe is smoothly rotated between the viewpoints simultaneously with the grids moving according to their geological positions. Grids based on time-dependent formulas will also evolve during the rendering process. Windows Media Video© or MPEG© format movies can be generated as a result.

2.7. User interactivity

While all of the above features are useful in themselves, the main benefit 4DPlates offers is on the fly visualization of the grid-based data sets. Data sets can be selected to use the graphics processing unit (GPU) for calculations, data-masking and spherical rotations. The GPU algorithms are implemented as special code fragments called GPU-shaders. The processing power of the GPU also is used to implement fine-grained and completely interactive raster colour mapping, surface scaling and lighting. Interactive manipulation of these visualization parameters can reveal details in the geological data that are not visible in a single rendering and saves time preparing several images with different lighting via the use of scripts, for example.

In this section, we present a brief analysis of the frame rate per second of the display given three different complexities of display. In each of the models, 51 plates for a South Atlantic project are loaded, each plate consisting of a piece of ETOPO1 (Amante and Eakins, 2009) cut-out by the PLATES (Gahagan, 1998) polygons. These plates are then assigned reconstructions according to PLATES (Gahagan, 1998) and an animation of 720

Table 1: Frame rate results, N = 10

Model	Average Time (s)	Increase	Mean FPS frames/s	Standard-Deviation FPS frames/s
A	15.4	-	46.7	0.11
B	16.44	10%	43.8	0.12
C	22.8	40%	31.6	0.06

frames is generated as the model is reconstructed from the present to 114Ma. The reference model, A, reconstructs the present-day topography while the second model, B, adds the complexity of masking younger seafloor than the reconstructed time according to the global age grid of Müller et al. (2008). The third model, C, adds to B by also calculating adjusted bathymetry of Stein and Stein (1992). The average and standard deviation of the frame rate for each of the models run on a NVidia Quadro^{TM} 2000M is presented in Table 1. This is comparable to 44.56 tested on a standard OpenGL scene in a product review test (Murray, 2011).

3. Scientific analysis with 4DPlates

3.1. Applying scientific formula to gridded data

Custom grid data sets can be created by applying user-defined algebraic functions to one or more existing grid data sets. In most other applications, assessing the effect of varying one or more of the parameters in the function is an iterative process involving changing the function, running the function on the data sets, and generating a new visualization of the result. In 4DPlates, the function is applied to the data and the result displayed in a manner similar to popular commercial spreadsheet programs, allowing sum, multiply and host of other mathematical formulas using C-style syntax. Changing any part of the function results in an immediate change in the output grid and its graphical representation on the globe. Variables can be adjusted using a slider and the effect of the change in value is immediately apparent on the map. If geological time is included in the function then adjustment of the time slider results in a change in the calculated grid data set.

For example, to calculate the tectonic subsidence due to sediment loading,s, the following formula applies (ignoring load-induced flexure):

$$s = \frac{h_s(\rho_m - \rho_s)}{\rho_w - \rho_m}, \tag{1}$$

(Fowler, 2005) for which h_s and ρ_s are the thickness of and density of the sediments while ρ_m and ρ_w are the densities of the mantle and water respectfully. If we take the crustal thickness to be the difference between the sea-bottom, A, and basement horizons, B (both positive upwards) and converting the subsidence to a horizon, S relative to present-day sea-level rather than the sea-bottom, we arrive at the following equation:

$$S = (-B - (-A))\frac{\rho_m - \rho_s}{\rho_w - \rho_m} - (-A) \tag{2}$$

In Figure 3, the regional topography of southeastern Brazil is shown along with the bathymetry of the adjoining seafloor in two windows of 4DPlates, both from ETOPO1 (Amante and Eakins, 2009). In addition, two other local geometrical surfaces in the Santos Basin represent the basement (lower layer) and a high-resolution seafloor bathymetry (upper layer). Using these two layers for input as B and A respectively, a colour overlay of the tectonic subsidence from the sediment is displayed on the upper layer. ρ_m and ρ_w are taken to be 3.3g/cm^3 and 1.03g/cm^3 respectively (Fowler, 2005, see p. 557). In the left pane, the sediment density, ρ_s, is fixed at 2.3g/cm^3 while in the right pane when ρ_s is varied to 2.951g/cm^3; the change of the colours in the overlay is visible. As a result of the sedimentary density increasing there is an commensurate decrease in the magnitude of the calculated subsidence.

3.2. Verifying and Refining Plate Reconstructions

One of the main applications of 4DPlates is for the communication and verification of plate reconstructions. Two different models can be compared side-by-side, or the implications of a single model on the alignment at a certain time of geophysical and geological features can be checked. In Figure 4, two different reconstruction models are shown side-by-side at two different times. Only a small amount of oceanic crust is visible because crust younger than the age of the reconstruction is masked out. The remaining crust is depth-corrected according to its younger age following the formula of Stein and Stein (1992). Paleo-ocean water depth grids can be generated by applying a sea-level curve to the ocean age grid. It follows from this that 4DPlates can quickly provide critical input for paleo-ocean current modelling and climate modelling. While the difference between the reconstructions in Figure 4 is not discernible in the lower figures at 100Ma, slight differences are visible in the top most frames at 120Ma. With views in all four windows linked, the user can zoom in on the areas of difference. Where there is an overlap or gap at the time of opening, other data sets, such as initial subsidence that can be calculated from once the sediment loading is removed Fowler (2005, see p. 571 for details) or the global magnetic anomaly used in Figure 2 can help determine which reconstruction is more accurate.

In 4DPlates, the small circle relative motions of plates are illustrated by flow-lines: graphical constructs that trace the paths followed by reference points placed along the divergent boundaries between conjugate plates. In 4DPlates, the user can decide where, along a divergent plate margin, flow lines will be generated and what time interval each increment of motion in the flow-lines will represent. These flow-lines illustrate the motion histories of plates over a wide time interval in a single image. In addition, flow-lines are updated on the fly as the user changes the reconstruction age. Two sequences of flow-lines can be plotted, those for the sea-floor spreading stage and another for the rifting phase in the continental crust. Asymmetries in the rifting phase can be accounted for by specifying the degree of asymmetry: the amount of material left on one or other margin when sea-floor spreading starts. Figure 5 illustrates flow-lines showing the lines of motion between a large number of tectonic blocks in the North Atlantic based on the reconstruction of Skogseid (2010).

Flow-lines simulate the gradual growth of oceanic crust encoded in a rotation file and can be used to generate age grids of the oceanic lithosphere consistent with the motion model in the rotation file. This may be necessary where this is little or no magnetic anomaly picks or to improve the gridding at fracture zones. In such cases, the flow-lines will not conform to the assumptions of the global age-grid of Müller et al. (2008); 4DPlates can use the flow-lines to create a regional age-grid that that can then supersede a global age-grid in the region of interest.

4. Discussion

Level of detail visualization has become popular with the advent of Google Earth^{TM}. 4DPlates extends the idea by being the first such application that delves into the world of plate tectonics. In addition, it enables multiple layered large gridded data sets to be interactively manipulated by applying scientific formulas or just manipulating colour palettes and lighting. Also, plate tectonic reconstructions can be compared using gridded data throughout geologic time.

In this paper, we have given an overview of the capabilities of the code, demonstrated its ability to be truly interactive and shown its usefulness in several examples. The code is currently under development and its capabilities are being extended. The authors hope that with increased exposure, ideas of how the application can benefit geoscientists and how it can be refined will be forthcoming.

Acknowledgement

The presented work was funded by a research grant from Statoil AS. The authors thank Statoil AS and Kalkulo AS for the provision and support of 4DPlates as well as Dr. Badr Ghorbal and an anonymous reviewer for their suggestions.

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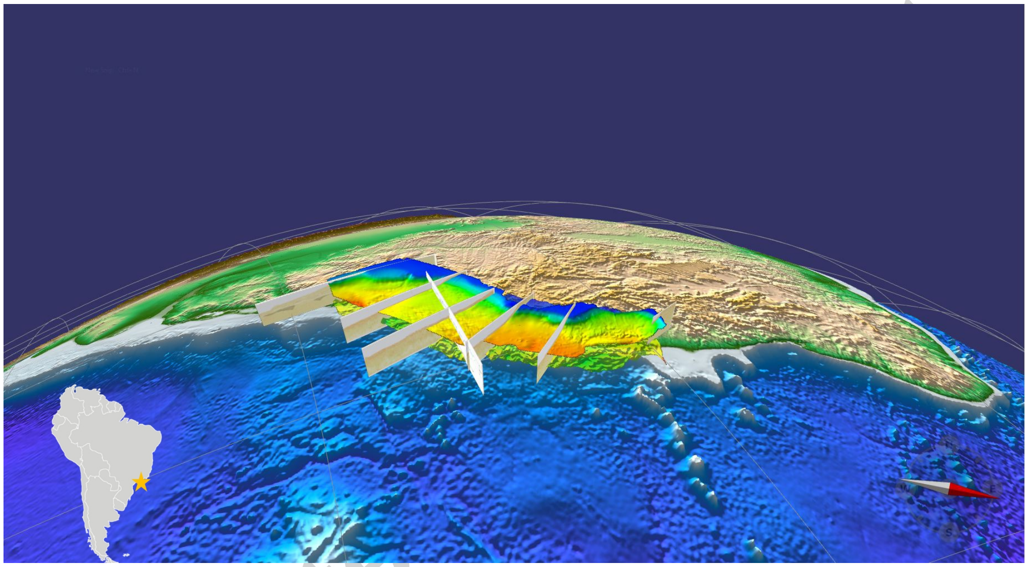


Figure 1: Multilayer global and higher resolution regional data sets (with vertical exaggeration) are shown in the region of the Santos Basin, offshore Brazil, viewed from the east. The location of the Santos Basin is shown as a star on the inset political map. The topmost regional layer is a high resolution grid of the sea-floor bathymetry while the layer below that is the depth-to-basement. Both of these are partially derived from interpretations of the seismic transects placed, to scale, across the basin. Finally global topography from ETOPO1(Amante and Eakins, 2009) covers the rest of the visible globe.

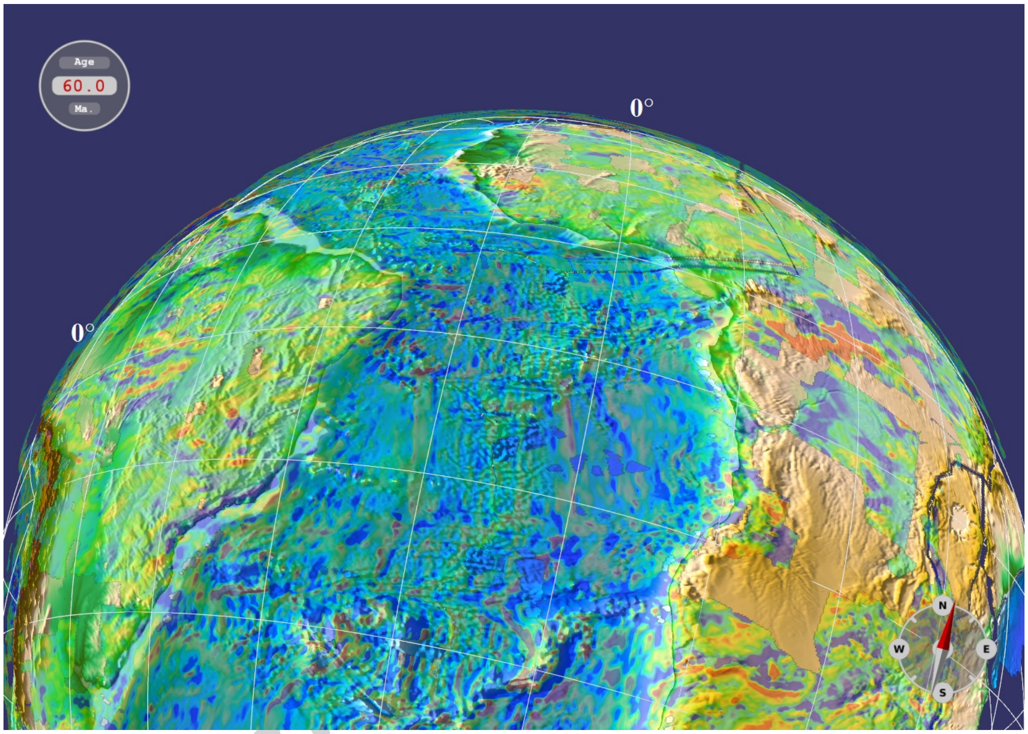
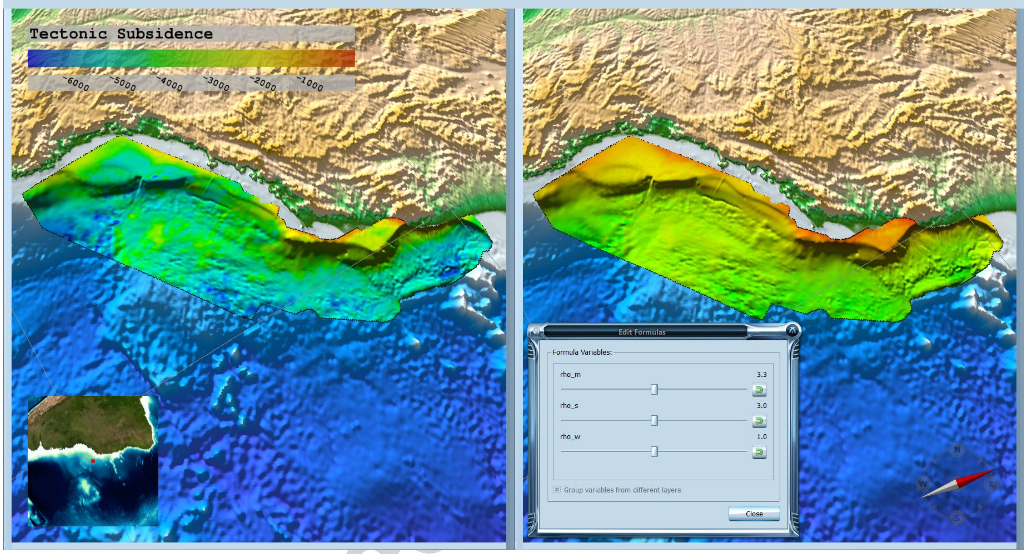


Figure 2: 4DPlates can handle transparent layers and can visualize changes in transparency, vertical exaggeration, lighting direction and colour palette on the fly. In this example, transparent magnetic field amplitudes from EMAG2 (Maus et al., 2009) elevated by 100km are overlaying topography of ETOPO1 (Amante and Eakins, 2009) with a vertical exaggeration of 10. The present-day values are reconstructed to their positions at 60Ma and the bathymetry of the sea-floor is adjusted for its age according to the formula of Stein and Stein (1992) and the age grid of Müller et al. (2008). The view is of South Atlantic and the lighting is at an elevation of 30° and from the west.



Formula Variables:

rho_m 3.3

rho_s 3.0

rho_w 1.0

☒ Group variables from different layers

Figure 3: The Santos Basin, as in Figure 1 but with two frames showing the variation of the sedimentary density on the calculated subsidence by varying a slider. In the left frame, the colour overlay on the top-most layer shows the tectonic subsidence given a sedimentary density of 2.3g/cm^3. In the right-hand frame, the sedimentary density is set at 3.0g/cm^3 causing the calculated subsidence to be much higher. Colour scale shows the amount of subsidence relative to the present-day sea-level (positive upwards). The user is able to adjust the slider shown in the figure and set any of the scalar parameters in the formula.

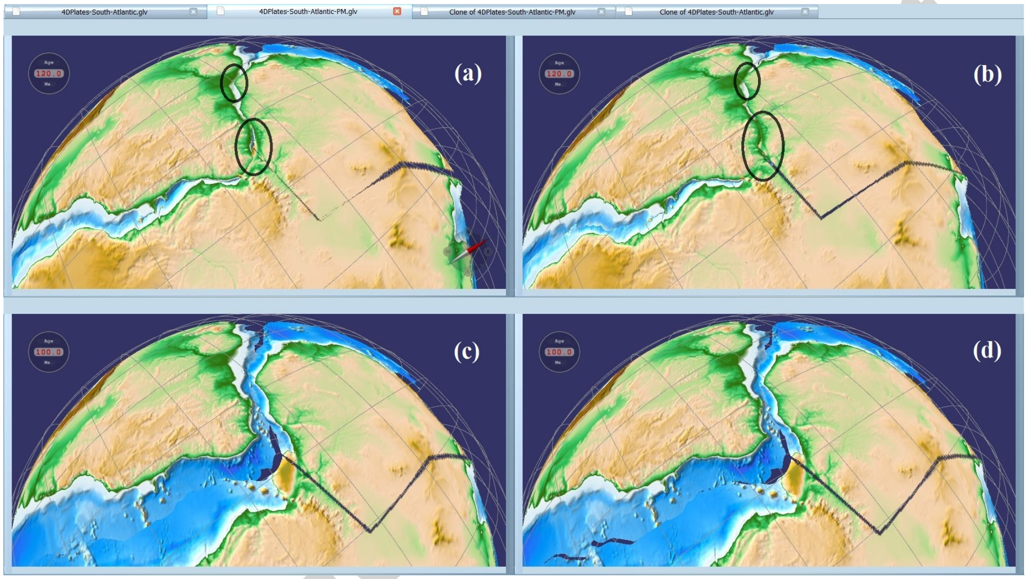


Figure 4: Comparing reconstruction models side-by-side allows geoscientists to communicate the differences in models and evaluate the impact of such differences. Reconstructions can be visualized by moving a time-slider or by tiling multiple windows of different projects. In this figure, the South Atlantic is reconstructed according to two different models: the Paleomap model (Scotese et al., 1988) at (a) 120Ma and (c) 100Ma; the GPlates model (Boyden et al., 2011) at (b) 120Ma and (d) 100Ma.

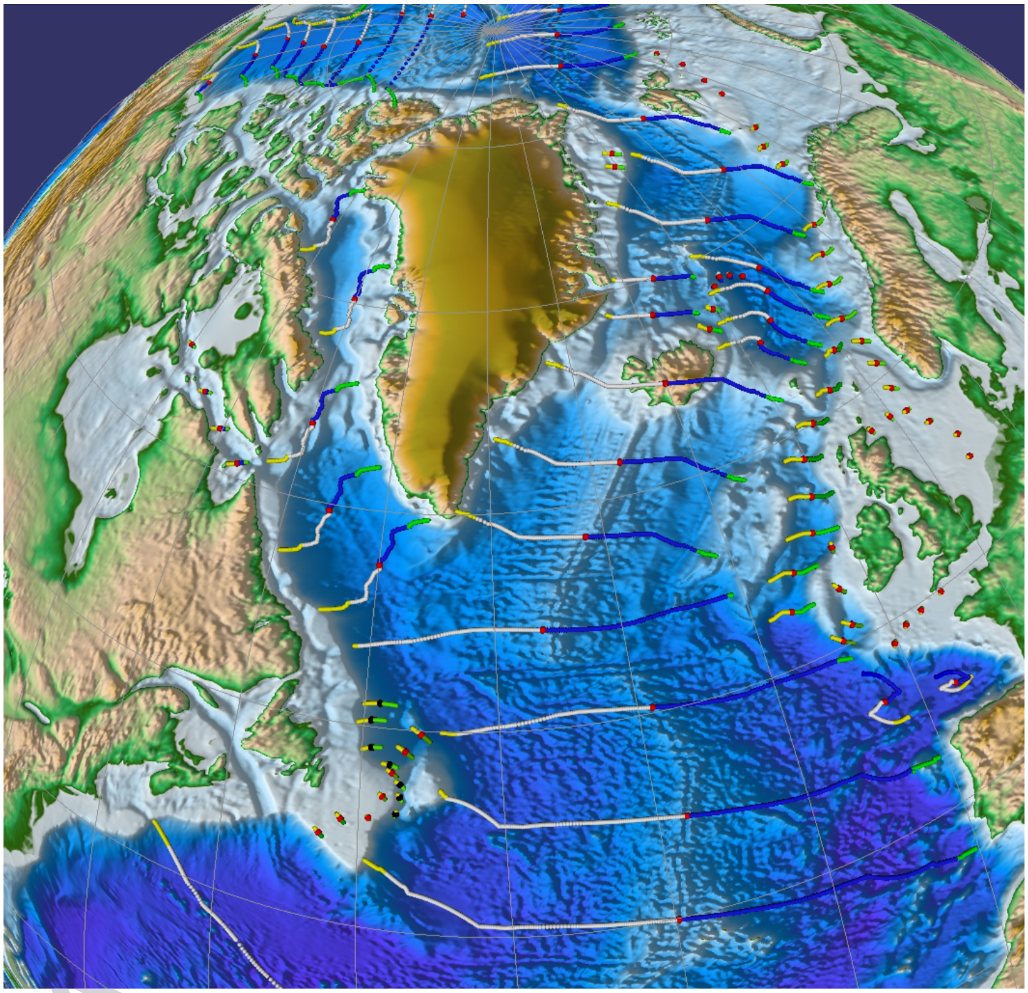


Figure 5: Flowlines showing the paths of motion between the various tectonic components that make up the North Atlantic (Skogseid, 2010). Red or dark blue dots indicate present day location of spreading or rifting centres, whether active or extinct; drift phase motion of the conjugate plates is indicated by white and blue dots. Yellow and green indicate phases of motion during the rifting phase.

> 4DPlates is a Google Earth^{TM}-like application aware of plate tectonics

> 4DPlates allows interactive plate reconstructions and grid-calculations

> GPU-calculations and 4-8 multi-layer tile hierarchy are the main technologies driving 4DPlates

> Tectonic subsidence calculations with basin data and a reconstruction of the South Atlantic are shown