

Visualization of the continental drift in real-time

Lorenz Rogge
TU Braunschweig
rogge@cg.tu-bs.de

Christian Lipski
TU Braunschweig
lipski@cg.tu-bs.de

Marcus Magnor
TU Braunschweig
magnor@cg.tu-bs.de

Abstract

We present an approach to simulate and visualize the paleontological change of the terrestrial globe through time. As input, maps of the Earth at different points in time, each showing a specific stage in the Earth's development, are used. To display the continuous change of Earth through time, smooth transitions between consecutive input maps are computed by manual correspondence matching. Our system makes it possible to display the Earth's paleogeographic development as an interactive globe in real-time.

Keywords: plate tectonics, paleogeography, interactive real-time visualization, 3D modelling, morphing

1 INTRODUCTION

Paleogeography is an important as well as popular topic in geography education, especially when considering the high interest in the fields of climate change and fossil fuels. Historical views of the Earth's configuration have been printed in geological atlases for decades, but still a simple and interactive technique to display the changing appearance of Earth is missing. While there are scientific simulations that create highly correct data in order to support research in geology and geophysics, they are not suitable for a interactive real-time display of the tectonic movement through time. Looking at the *PLATES Project* of the University of Texas [6], the data generated in simulations is used to create animated video sequences. These, however, are not interactive and only allow to watch the continents movements from a fixed point of view. Alternatively, Artistic animations of the continents' movement must be produced in a very labor-intensive manner. Our goal is thus to create a system to display the change of the Earth's surface as correct as possible and interactively in real-time. It is designed to be an educational tool that offers a much richer experience than static maps or globes.

A set of texture maps, each representing the Earth's surface at a specific point in time, is used as initial input data and processed by manual correspondence matching to create geometrical data for each continent. The shape and movement of the continents are then interpolated in real-time. (see Fig.1). We explicitly allow for a manual processing of the data. In order to keep human labor at a minimum, we employ a tectonic morphing model that enables the user to create these transitions

swiftly. The presented system consists of two parts. The first part is an editor, which allows the user to process the initial textures and export the data into a designated format. This data consists of several meshes representing the continents and their movement and transformation over time. The second part is the interactive viewer, which gives the user the opportunity to view the continental drift at any time from any viewing angle at any point in time.

In Section 2, related work of paleogeographic visualization system and also of morphing techniques are presented. Section 3 gives a brief introduction to plate tectonics in general. Our tectonic morphing model is introduced and discussed in Section 4. The manual creation of meshes and their transformations with our editor application is described in Section 5. Finally, we present results in Section 6 before we conclude in Section 7.

2 RELATED WORK

2.1 Tectonics simulation and animation

Various systems exist that produce animations of the Earth's lithosphere through time. These can be categorized into two major groups of tectonic animation systems.

The first group is directly connected to tectonic simulations. An example for this software is the *PLATES Project* [6]. Animations of continental drift are a by-product of actual tectonic simulations. These reconstructions are of high precision, however, each visualization output requires a remarkable amount of pre-processing that inhibits real-time computation. Furthermore, only raw geographic information is displayed.

The second group focuses on the visual aspects. Taking the raw geological data of actual simulations as a basis, they enrich the data by taking information about vegetation and climate into account. The resulting data sets usually consist of hand-painted texture maps at discrete time steps, e.g. [4], [13]. Thus, content creation is usually labor-intensive and is only feasible for a few

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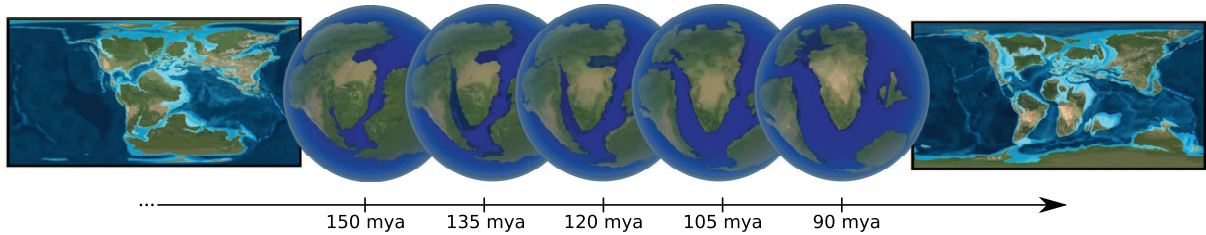


Figure 1: Morphing of continental structures between two time slices. The two texture maps (left and right) serve as input. A three-dimensional depiction of intermediate points in time is obtained by morphing.

dozen time steps. Animations are created by morphing between these images. Again, artists have to create transitions manually. Two prominent examples are [5] and [11], where pre-rendered animations are projected onto a spherical display.

As our system is also designed to give a visually pleasing experience, we designed our system to work with artistically enhanced texture maps. Compared to existing approaches, we contribute two major advantages. First, we keep the creation of transitions as simple and fast as possible by using a manual correspondence matching technique specifically tailored for paleogeographic data sets. Second, we do not need to pre-render the animation, so that the Earth’s surface can be rendered on-the-fly for any viewpoint at a given point in time.

2.2 Morphing Techniques

In order to investigate the possibility of creating transitions between time instants automatically, we evaluate state-of-the-art morphing techniques. At first thought, two dimensional morphing techniques seem adequate to solve the problem. The principle of image morphing in 2D space is very common in computer graphics. Many approaches and solutions have been developed to automatically transform one image into another. This is often done by computing the optical flow between a pair of images, a well-established technique [2]. A survey of recent approaches can be found at [3]. Image based morphing is able to smoothly transform both shapes and colors of objects in these images. The problem remains that an adequate 2D parametrization of the surface has to be found. Cylindrical, azimuthal or conical projections are commonly used for this task. All these projections encounter the one common problem of mapping singularities of the poles. Conformal mapping [10] allows to choose the locations of the poles on the globe’s surface. However, there are no two opposite locations on Earth that are covered by sea at all paleogeographic stages. In addition, distortions appear in all regions that are not in the equatorial zone.

Therefore, morphing 3D geometry is a more appropriate approach to generate interpolated views of the terrestrial globe. In fact, transforming two meshes to an intermediate spherical representation is a common approach to the general problem of polyhedral morphing [9], a thorough survey can be found at [1]. Avoiding the pitfalls of 2D morphing, the remaining problem with 3D mesh morphing is to find correspondences between two such meshes. Since the differences in shape and appearance between two states of the Earth can be quite large and may often be ambiguous, an automatic feature extraction and matching is not feasible in our case. Whole islands or even continents disappear between two consecutive depictions of the Earth (see Fig.12). Two continents with distinctive shorelines may also form a continuous super-continent (e.g., Pangea or Gondwana) in another time slice (see Fig.1). To summarize, automatic 2D or 3D morphing techniques are neither robust nor accurate enough to cope with the available and coarse data sets. Instead, we rely on a manual approach that is closely linked to the general plate tectonics model and produces visually convincing results with only little user input.

3 BACKGROUND

At the beginning of the 20th century geologists and physicists developed a new theory of the physical behavior of the Earth’s composition and its development over time. Prior to this new theory the Earth was assumed to be rigid. The new theory assumed a dynamical system of continental plates drifting over the Earth’s liquid interior, the almost matching coastlines on either side of the Atlantic Ocean initiated the development of this theory of continental drift. Alfred Wegener pointed out, that the congruency of the coastlines of South America and Africa never could have been caused by rising water levels or sinking landmass [14]. Thus, the theory of diverging landmasses, which were touching at these coastlines in the past, was more likely. J. Tuzo Wilson also proved the fact of diverging and moving continental plates using the example of the Hawaiian Islands forming a nearly straight line of

volcanic islands [15]. Observations in submarine geology, change in magnetism and volcanic activities triggered further research in this field. Since then, geologists have evaluated data from geological structures distributed over the present continents to generate historical maps, which display the configuration of the Earth's surface in the past. The cause for the drift is assumed to be convection of magma within the mantle of the Earth. Upwards flowing magma pushes onto the planet's crust and pushes it to either side. New crust is being created at the region where the continental plates drift away from each other by the uprising magma which hardens as it reaches the surface. According to [13], evidence of the continents' past position is given by paleomagnetism, linear magnetic anomalies, paleobiogeography, paleoclimatology, and geologic history. Due to the individual motion of the continental plates, three basic zones can be found when two continents are adjacent: divergence zone, convergence zone and transform zone (see Fig.2).

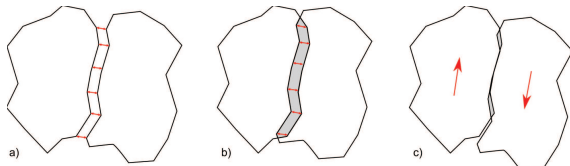


Figure 2: Three typical zones of continental drift: a) divergence zone, b) convergence zone and c) transform zone

The motion of each plate can be described as a motion along circles on the spherical surface. Every point of a plate moves along its own circle around the sphere. The center point of these concentric circles is called the *Euler pole* [8]. Every point of a plate is rotated by the same angle around this Euler pole as the plate moves over the surface. In order to describe a motion for a single continental plate only three values, the longitude and latitude of the Euler pole and the angle of rotation around it, have to be defined. For introductions into paleogeography, we refer to [7], [12].

4 A TECTONIC MORPHING MODEL

As stated in section 2.2, using an image based morphing technique causes problems near the poles. E.g., a continent that covers the south pole at one point of time and moves away towards the equator at another point of time changes its projected shape significantly, even if its actual shape remains unchanged (see Fig.3).

As far as we know, there is no parametrization of a spherical surface that does assign only a single and unique set of parameters to a sphere's pole. These singularities in 2D parametrization seem to be inevitable. Therefore, morphing in the projected texture space given by the parametrization of the sphere can be very hard for some configurations. Another problem is that

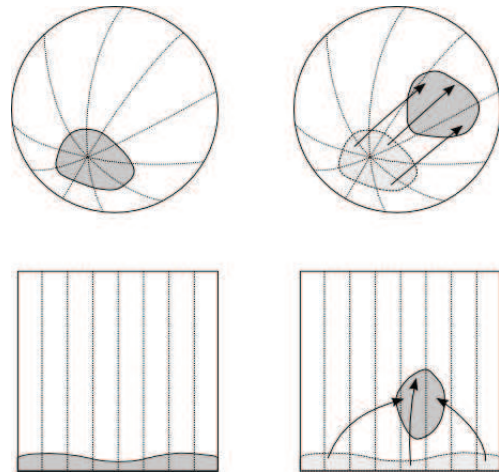


Figure 3: Morphing of a continent situated around the polar region in spherical space (top) and in texture space (bottom). A simple linear translation of the continent in spherical space with no change in shape (upper right) results in a complex distortion in its shape in texture space (lower right).

automated morphing in texture space using optical flow requires to identify and match corresponding features in a pair of texture maps. When having two converging continental plates, that merge from one time slice to another, features in the merged region cannot be identified properly and thus, no plausible flow in that region can be computed. Also, the maps available are often not very similar, since the time difference between two maps may be several million years. In this period of time the face of the Earth may change dramatically and it is hard to identify corresponding regions even for the human eye. The solution to this problem is to choose another morphing approach for this application. Instead of morphing textures it is more appropriate to morph the geometry itself. Continents may be modeled as single patches of geometry emphfloating on the globe's surface. Using the Euler pole notation a continuous motion of a continent can be described by interpolating the given values between time slices. Given a geometry patch as a polygonal mesh, every vertex can be moved separately by interpolating the vertices' positions between consecutive time slices. Thus, the shape of a geometry patch can be altered locally as well in addition to the basic movement. Together this yields a technique of moving and morphing continents on the globe's surface. Neglecting tectonic movement below sea levels and elevation change in general, this model still bears much resemblance to the original plate tectonics model. Changes in shape and elevation can both be taken care of by applying local deformation, which leads to the same visual effect. The problem of merging and separating continents is also solved, since

a new set of geometry can be used for each time slice. In the case of two merging continents one can use two geometry patches for each continent while they are still separate. Upon aggregation of the two continents, a single geometry patch is used to represent this new continent in the future.

4.1 Continental Meshes

We developed an appropriate model called *Continental Mesh* which is capable of transforming a patch of geometry belonging to one point in time to how the patch would look like in the succeeding point in time. Ideally, one continental mesh corresponds to a single continental plate or a coherently moving group of islands.

A mesh may consist of several faces which are stored in a designated list. The faces' vertices are stored separately and referenced by the faces for memory optimization. Each vertex has an assigned transformation vector which allows to alter the mesh's shape during transformation. Furthermore, angles and rotational axes are defined for each Continental Mesh on the globe's surface. In order to morph and render the continents over time, it is necessary to blend texture colors smoothly. This may happen when a region changes its vegetation or a mountain emerges at a region of two colliding continents. For this purpose, a Continental Mesh contains two lists of static texture coordinates - one for the texture map of the first of two succeeding time slices and another one for the second. While morphing between two time slices, the color values of both textures can be blended linearly by the ratio of transformation.

4.2 Mesh transformation

To move a Continental Mesh on the spherical surface, the common representation of *Euler poles* [8] can be realized by quaternion rotation. An Euler Pole depicts a point on the globe's surface, defining a rotational axis through this point and the center of the globe. Every vertex of a mesh may be moved on a spherical surface by rotating it around an axis defined by a given Euler Pole. Having the sphere originate at $(0, 0, 0)^T$ in space the coordinates of an Euler Pole already represent the vector of the rotational axis. Furthermore, a mesh may also rotate around its central point while simultaneously moving along a trajectory on the spherical surface. A rotational axis through a central point is used to rotate all vertices and achieves a circular rotation of the complete mesh. The set of per-vertex-transformation vectors is precomputed by storing the euclidean distance of every pair of corresponding vertices. Because a rotational technique is used for moving whole meshes over the globe's surface for longer distances, it is negligible that the transformed vertices do not move on an arc-like trajectory but on straight lines through space, since these transformations remain quite small. Given the vertex set V , the transformation vectors $\vec{t}_i \in T \subset \mathbf{R}^3$, the global

rotation axis $\vec{r} \in \mathbf{R}^3$ and the corresponding angle $\phi \in \mathbf{R}$, the circular rotation axis $\vec{r}_c \in \mathbf{R}^3$ and the corresponding angle $\theta \in \mathbf{R}$, a transformation ratio $r \in \mathbf{R}$ and a rotation-function $rotate : \mathbf{R}^3 \times \mathbf{R}^3 \times \mathbf{R} \rightarrow \mathbf{R}^3$ using quaternion rotation, the following steps have to be computed consecutively:

1. Rotate every vertex around the global rotational axis \vec{r} about the ratio r of the rotation-angle ϕ (see Fig.4)

$$\forall \vec{v}_i \in V \quad \vec{v}_i' = rotate(\vec{v}_i, \vec{r}, r \cdot \phi) \quad (1)$$

2. Rotate every vertex around the central rotational axis \vec{r}_c about the ratio r of the rotation-angle θ

$$\forall \vec{v}_i' \in V' \quad \vec{v}_i'' = rotate(\vec{v}_i', \vec{r}_c, r \cdot \theta) \quad (2)$$

3. For every vertex \vec{v}_i'' add the ratio r of the corresponding transformation-vector \vec{t}_i (see Fig.5)

$$\forall \vec{v}_i'' \in V'' \quad \vec{v}_i''' = \vec{v}_i'' + r \cdot \vec{t}_i \quad (3)$$

The vector \vec{v}_i''' is the final rotated vertex, which can be now rendered to the screen.

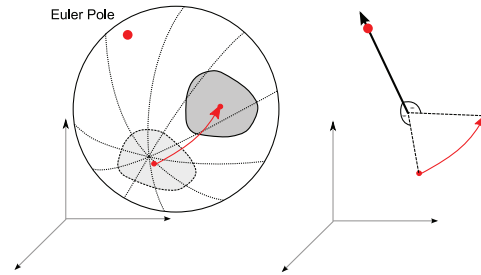


Figure 4: Rotation of mesh around a global axis. After defining an Euler pole for a continental plate, it can be rotated around the axis through this point.

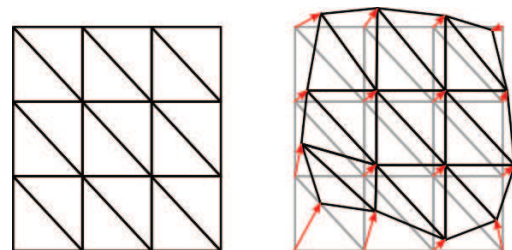


Figure 5: Every vertex has its individual 3d transformation vector, allowing smooth transformations of the mesh's shape.

The texture coordinates are constant for all times and only the ratio of blending two texture layers together changes over time.

5 MANUAL CORRESPONDENCE MATCHING

By using the Continental Mesh model as a representation of the continental drift, it is necessary to preprocess the texture data first. The texture maps of the continents are a basis for the selection and manual correspondence matching of continents. Creating a simulation of the Earth's tectonic movement consists of these three succeeding steps.

- Loading and pre-processing of input data (texture maps)
- Using texture data to create morphable continental meshes
- Morphing and display of meshes

The second step involves manual work, since for every time slice a set of meshes has to be created and adapted to the following time slice.

5.1 Input data

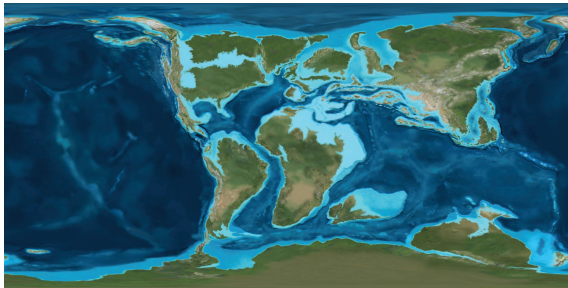


Figure 6: This is a sample map of the Earth's appearance 105 million years ago (from [4]), which is used as an input texture map for this time slice. The input texture maps include information on both vegetation (e.g., desert regions in the subtropics) and climate (e.g., no ice caps on poles).

Altogether, we used 26 texture maps of rectangular shape distributed between 600 million years ago and the present day (see Fig.6). This data set was provided by the Northern Arizona University [4]. Each texture map has a resolution of 3000 px x 1500 px. Time differences between two consecutive textures range from 15 million years to 40 million years. In addition to geographic information, differences in vegetation and climate are visible.

After loading each texture from disk, pixels belonging to oceans are tried to be identified, using their colorhue value to distinguish if a given pixel represents water or landmass. So far this is not an adaptive process and some regions might be labeled false. However, using the texture set provided by [4] oceans are identified very well using this technique. During all succeeding

stages, only pixels depicting continents, islands and ice masses, such as polar caps, are considered.

5.2 Editor Workflow

The editor is used for creating smooth transitions between each pair of consecutive time slices. It is loaded with a certain configuration defining which time slices are available and which texture files to load from disk (see Fig.7). This initial data provides a textured spher-

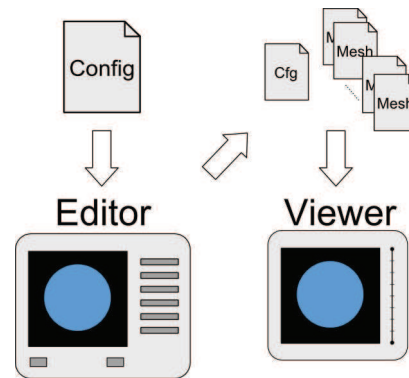


Figure 7: Processing and propagation of data throughout the program. The editor uses a config file containing information about available time slices and file paths to their texture maps. After manual correspondence matching of the input data, a configuration file for the viewer and a set of meshes is created and finally displayed by the viewer.

ical, static mesh for each time step. The user is able to move back and forth between these time steps and may also rotate the globe in any preferred way. Having a single globe for each time slice, the user selects several disjoint regions, each corresponding to a single continental plate (see Fig.9). These highlighted regions are converted into separate, disjoint Continental Meshes. Please note that these selections do not actually have to correspond to the actual continental plates. Any selection of a region that moves more or less uniformly is valid. For each Continental Mesh, a global transformation as well as several local transformations are defined by the user. The texture coordinates of the transformed vertices according to the next time slice's texture are computed automatically. This process has to be done for each continental plate in each time step. Creating and editing Continental Meshes from a textured globe follows a certain workflow (see Fig.8).

1. Selection of faces
2. Creation of a mesh from this selection
3. Adjusting the mesh to the next time slice
4. Saving the mesh to disk

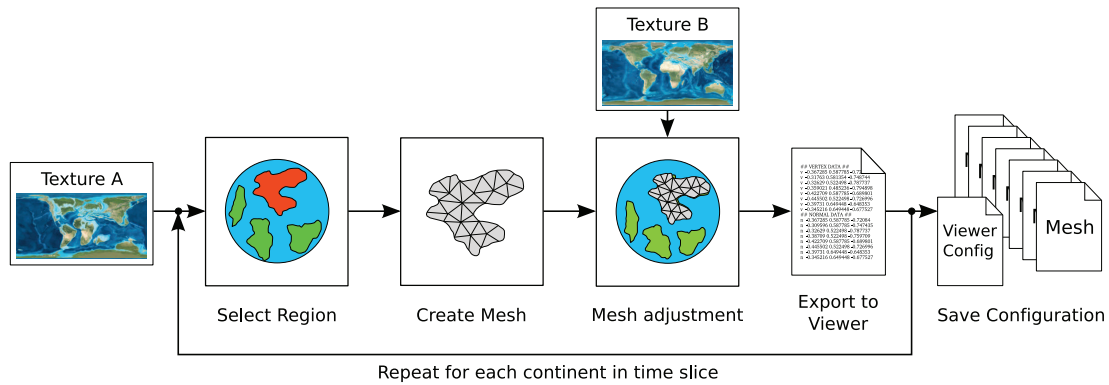


Figure 8: Editor Workflow. The user selects a continental plate from the first time slice (Texture A) and provides correspondences to the second key frame. This must be done for every continental plate. The meshes and their transformations are saved to disk.

At first the user selects faces on the globe’s surface representing a single continental plate. The user may adjust and refine the shape of the current selection, which is quite useful in regions where two continental plates are very close or touch each other. Then the selected region is exported into a new Continental Mesh. This mesh can be moved on the globe’s surface to match the corresponding region’s position in the succeeding time slice. Also its shape may be adjusted by selecting and moving single vertices. This helps to match coast-lines and important details of the moved region. To give a feedback of the current matching accuracy, the underlying globe is textured with the succeeding time slice’s texture in this editing step. In common cases and depending on the size of a given continental plate, a created mesh consist of about 100 to 300 vertices. Although this may sound very labor-intensive, this part of the workflow is actually quite efficient due to two facts. First, the alignment of continental plates is often quite good after setting a global transformation during the previous step. This transformation has to be defined only once per mesh and affects all vertices at the same time. Second, the mesh resolution is quite coarse (we place a vertex at roughly each 4 degrees of longitude or latitude), so that in most cases only a few vertices along the coastal lines have to be adjusted. Still, we observe that this resolution is sufficient to achieve the desired visual accuracy. The adjustment itself is done by a simple click-and-drag action per vertex while the moved vertices always stay on the globe’s surface during translation. After aligning everything properly, the user can save this particular mesh and continue to select and modify new continental meshes. Finally, everything is saved into a configuration file.

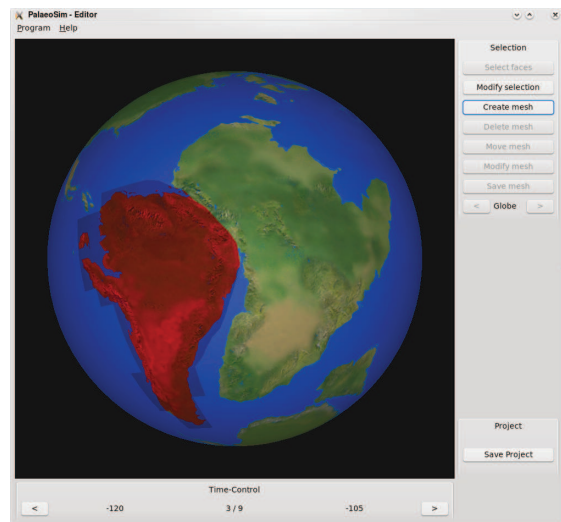


Figure 9: Editor Window. While selecting a mesh (here representing the South American continent). The user is able to select specific regions and move/adapt them to their position in the succeeding time slice. The buttons on the right allow to select and modify meshes and save this configuration. The buttons on the bottom are used to navigate through available time slices.

6 RESULTS

The task of displaying the continental drift in real-time is solved by using the Continental Mesh data structure for each continent and a datastructure to manage several time slices and their corresponding sets of Continental Meshes. We are able to display a linear interpolation of a continent’s shape and texture between two succeeding time slices. Using different sets of Continental Meshes for each time step also makes it easy to create merging or even diverging continents. Since

such events frequently occurred in Earth's history, being able to display this process in a proper way is essential. After having created appropriate data from texture maps using the editor module, the viewer application (see Fig.11) can be started with the created configuration (see Fig.10). The user is able to navigate through time using a timeline slider. Manual correspondence matching between two time slices takes approximately 30 to 60 minutes, depending on the number of continents and islands present at that time. For the whole data set of 26 time slices, two working days were spent. Using a higher resolution than this does not necessarily improve the result's quality, since continental motions usually do not change very rapidly and a higher resolution would only increase the amount of manual work. So using a larger texture set for the same time span is not necessary.

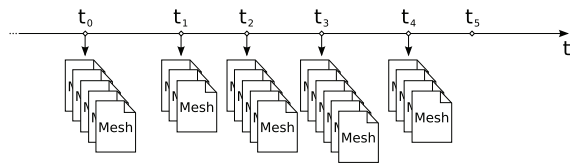


Figure 10: A basic display of the timeline used by the viewer for loading the correct set of meshes for each time slice. For every point in time the set of meshes of the preceding time slice is chosen and displayed after transformation.

The viewer loads the correct set of meshes for any given point in time and transforms these meshes by linearly interpolating their position, orientation, shape and texture. This is done in real-time using the OpenGL pipeline and taking advantage of GLSL shader programs to interpolate textures and display shaded meshes. Since every Continental Mesh is handled separately, they are accumulated during rendering into a final framebuffer, which will be displayed after all continental plates have been rendered. Since only approx. 3200 faces are rendered and only two textures have to be loaded separately, real-time frame rates can be achieved on standard hardware. Shaders, that adapt to the graphics cards capabilities, e.g. available texture units used during accumulation, are used to speed up the rendering process. When the user drags the time slider, the surface of the globe immediately alters its appearance (see Fig.12). The angle of view can be changed by dragging and rotating the rendered globe in any direction. The user might also zoom into view parts of the globe in more detail. The motion of each continental plate drift can be viewed at any speed and from any angle.

7 CONCLUSION

Using the presented approach, it is possible to display the continental drift through time in a visually pleasing

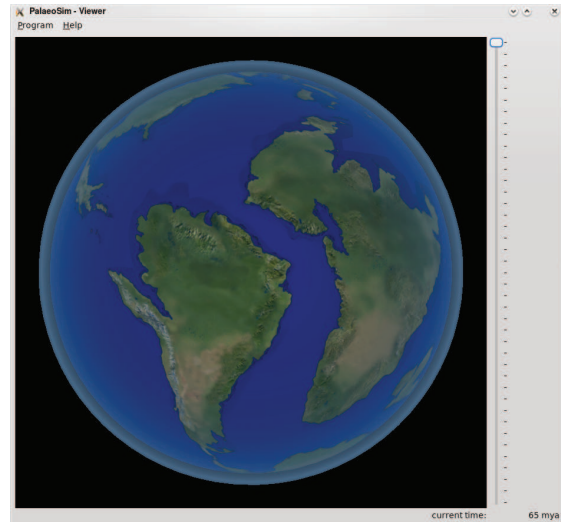


Figure 11: Viewer window displaying South America and Africa 105 mya (million years ago). By using the time slider on the right, the user is able to freely navigate through the available period of time.



Figure 12: Several interpolated views of the globe in four steps between 65 mya and 90 mya. One noteworthy event during this period is the breakup of eastern Siberia, which separated Sakhaline and the Japanese islands from the mainland. An automatic matching in this region between the two time instances can hardly be devised.

manner. The user is able to view the motion of continental plates and their transformation on a 3D globe from arbitrary perspectives. Thanks the employed morphing model, the amount of time that has to be spent on producing transitions between time slices is reasonable. The user does not need to know how to use complex modelling software such as Maya or 3dsMAX to create and texture a morphing geometry, but instead is provided a system to quickly match continental plates through consecutive time slices. The editing process is very intuitive and is easy to use even for people not familiar with commercial modelling software. The set of possible actions to deform and move geometry is pre-

defined and the user is able to quickly create the desired results. In contrast to several existing pre-computed animations, the user is able to move back and forth in time at arbitrary speed and may watch the continental drift from any preferred perspective. Being able to view the earth's surface from all possible points of view makes it easier to understand the transformation processes that have happened in the past, which was the aim of our system. There are still some issues with the current system. Selection and transformation of geometry is so far a purely manual task. In the future, user interaction should concentrate solely on resolving ambiguous cases, e.g., by defining the global transformation of continents. State-of-the-art shape matching techniques could then provide for accurate local motion estimation of coast-lines and other fine structures. Also the linear texture blending allows not to properly display the formation of lakes, rivers and other details placed within continental meshes. Erosion techniques could be used to display more transformations in these cases more realistic. Also, the current project does not yet display the ocean beds. These are of interest since many diverging zones like the Mid-Atlantic Ridge, where new crust is being created through uprising magma, are located in these regions. Another major improvement will be the inclusion of altitude into the model. Although changes in local shape can currently make up for changes in altitude, a more realistic model would explain the appearance and disappearance of islands and mountain ranges. Also slices through the Earth's mantle would be possible, enabling a visual exploration of the underlying geology and tectonic processes.

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