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Kinematic subsidence modelling of the Lower Rhine Basin

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Abstract

Kinematic geological models can greatly enhance our understanding of the interaction and timing of processes involved in the formation of sedimentary basins. The prototype tool for the calculation and visualisation of such models presented here is aimed at studying subsidence rates and patterns at basin scale: A backstripping algorithm is applied to a geometrical 3D-model consisting of prismatic volumes, constructed from an initial set of stacked triangulated surfaces. As a result, we obtain a collection of palinspastically restored volumes for each timestep of basin evolution. The backstripped volumes of each layer are then arranged within a timescene, and the set of timescenes collected as a hierarchical timetree. By interpolating between succeeding key-frames, the subsidence history of the basin can be viewed as an interactive, continuous animation. The approach is illustrated using a high-resolution dataset from the German part of the Cenozoic Lower Rhine Basin.

Keywords: 3D-backstripping, animation, key-frame interpolation, subsidence modelling

Introduction

The geologist's world is in fact a four dimensional one, consisting of geological bodies developing in time, which we handle in selected aspects based on 2D and 3D projections – either as conceptual models in our minds, as traditional maps and sections, or on the computer. When supported by an appropriate database and management system, it is possible to interactively select and combine different up-to-date data sources and to provide a synoptic view, which makes such models superior to conventional printed maps, cross-sections, and block drawings. Since geologists are not satisfied with static 3D-models, they look for animated '4D-models', true to scale in space and time, to test and communicate ideas about sedimentary and structural developments in earth history. The term *palinspastic reconstruction* has been coined for a 'restoration of stratigraphic layers to their initial pre-tectonic disposition' (Ramsey & Huber, 1987: 558). Various techniques have been proposed to calculate such backward reconstructions, all based on a careful, process-oriented investigation of the present geological situation (Siehl, 1993). Normally the supporting data are sparse, compared to the complexity of the geological objects they stand for. The observed patterns can only be interpreted, if the geologist experiments with alternative models in mind and with process-oriented hypotheses how the structures could have developed.

The objective of current research in interactive modelling of geological surfaces and bodies is the opening up of the third and fourth dimension by a balanced kinematic backward reconstruction of volumes.

Instead of presenting the result of palinspastic reconstructions as a series of snapshots, it would be much more instructive to use a continuous anima-

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tion. We have therefore investigated the potential of applying *key-frame interpolation* to animate geological models. The next chapter gives an overview of this technique and provides a geological example. In addition, it introduces the concept of *timetrees* as a hierarchical collection of time-dependent geometries.

Since we are interested in explaining facies distributions and sedimentation processes as a response to tectonics, we start with subsidence analysis as the least complicated way of determining temporal constraints and boundary conditions for subsequent dynamic lithospheric basin models. The following chapters deal with: the application of *3D-backstripping* in a model of stratigraphic surfaces in order to supply the necessary key-frames, some implementation details and the explanation of the steps taken to construct a kinematic model of the Central Lower Rhine Basin (Fig. 1).

Kinematic modelling based on key-frame interpolation

Key-frame interpolation is a common animation technique, by which a geometrical object is stored at a finite number of timesteps, so that its shape at in-between times can be calculated by interpolation. Since two geometric objects are interpolated point by point, this method requires them to possess the same number of points as well as an identical connectivity.

In order to avoid abrupt changes in velocity, which are not desired in most animations, splines have been

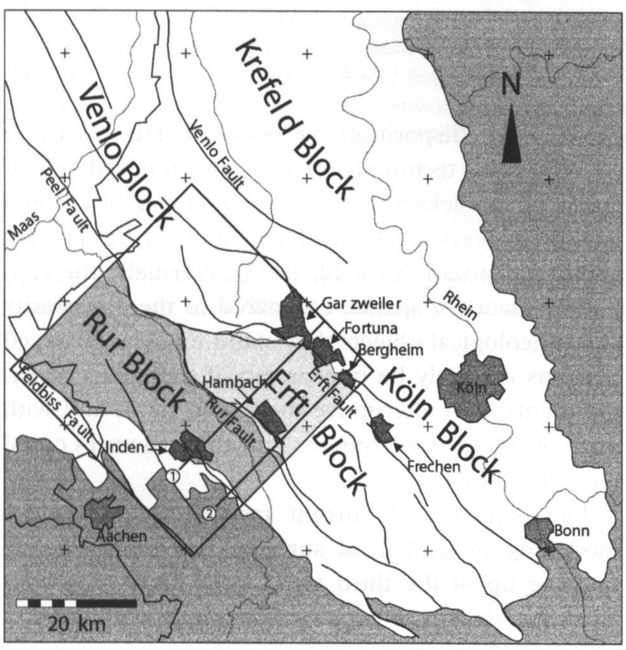

Fig. 1. Map of the Lower Rhine Basin: The outlined study area covers the southern part of the Rur-Block and the north-western part of the Erft-Block (compare Fig. 5). Lines (1) and (2) mark the location of two cross-sections (Fig. 9); scale approx. 1: 1 000 000.

used to obtain smoother motions. However, since geological processes rarely run smooth, this is not necessary in most geological applications. Instead, it is more adequate to apply a simple linear interpolation, and to add more timesteps, as additional data become available.

For most geometric operations like scale, move, rotate and simple deformations, it is sufficient to store only one key-frame for each timestep. Polthier & Rumpf (1995) extended this concept to handle adaptive geometries. By providing two key-frames for each timestep, objects can also appear and disappear, be separated and joined, or be refined and generalised.

The resulting kinematic model is an hierarchical collection of independent *timescenes* called a *timetree*. Each timescene contains the key-frames of one object. Timescenes can be modified independently, added to or deleted from the model. Fig. 2 demonstrates this concept using the simple geological example of a fault cutting a stratigraphic surface:

Timescene *Surface* contains key-frame *Surface 1* as the post-object of timestep t = *-5.0*. The cartoon on the right hand side illustrates the respective connectivity. Pre-object *Surface 2* of the following timestep t = *-3.0* exhibits the same connectivity, but a different shape. By pointwise interpolation, the shape and position of the *Surface* object can be calculated for any time value between *-5.0* and *-3.0*.

At timestep t = *-3.0* the connectivity of *Surface* changes. The new object *Fault* cuts *Surface* into two parts. The pre- and post-objects *Surface 2* and *Surface 3* retain the same shape, but a different connectivity. The pre-object of timescene *Fault* has been set to NULL, since *Fault* did not exist prior to t = *-3.0*.

At timestep t = *-2.0* the down-thrown fault block has further subsided. *Surface 4* displays the same connectivity as *Surface 3* of the previous timestep, thus shape and position can again be interpolated for each time value between *-3.0* and *-2.0*. By interactively adjusting the system time of the model, the change in geometry of all objects can be viewed as a continuous animation.

Modelling basin subsidence

Geohistory analysis (Van Hinte, 1978) aims at constructing and comparing quantitative subsidence curves for specific locations (usually wells) within a sediment basin. Before plotting depth vs. time, some corrections have to be applied, for the decompaction of present day compacted thicknesses, to account for the loss of porosity during burial, as well as for fluctuations in relative water depth and absolute sea level. A detailed description of this method, including a sam-

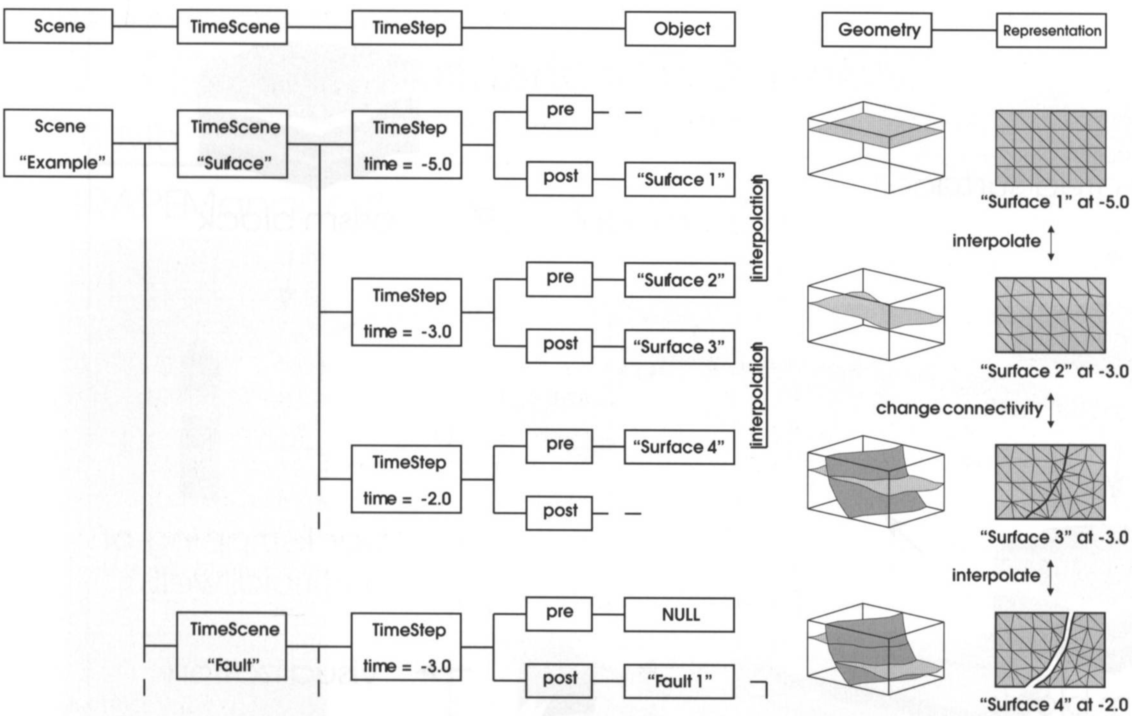

Fig. 2. Timetree representation of a simple animated geological model. For explanation see text.

ple implementation (BASIC), is given by Allen & Allen (1990).

In order to apply backstripping to a whole sediment basin, we need to provide the present day geometry and material parameters (lithology) of the basin fill, as well as its chronostratigraphic framework. The number of timesteps of a subsidence model depends on the number of layers, with added timesteps to account for times of non-deposition (paraconformities) and erosion (disconformities).

Construction of prismatic volumes and calculation of keyframes

The integrated earth modelling software GOCAD (ASGA, 1996) has been successfully used to create structural geological models and to provide initial geometries for subsequent palinspastic reconstructions (Alms et al., 1998). A short description of the steps necessary to construct such a model will be given in the last chapter.

A model of GOCAD TSurfs (triangulated surfaces) can be used to define present day basin geometry (Fig. 3). During interactive construction of the model, GOCAD's *OnStraightLine* constraint provides a way to ensure equal triangulation of the TSurfs within each fault block (see last chapter). As a consequence, it is easily possible to construct prismatic volumes from these stacked TSurfs. A corresponding method exists to build vertical cross-sections from a list of GOCAD PLines (polylines). The resulting prism model acts as container for a collection of prism blocks and sections. Lithological parameters and the chronostratigraphic framework of the model are then added from an external script file.

In order to calculate decompacted thicknesses for each timestep, all prism blocks and sections have to be decomposed into a collection of artificial 'wells'. After applying the general decompaction equation (Allen & Allen, 1990: 270), we obtain a matrix of decompacted depths which can then be re-assigned to a copy of the respective block or section. In addition to the geometries, the timetree description of the kinematic model is calculated, which then holds all information needed to define the animation.

Assumptions and simplifications

Geohistory analysis assumes a nonlinear decrease of thickness and porosity with depth solely by compaction. In addition, the sedimentary record must be largely preserved. The method given in the previous chapter implies, that all faults are modelled as vertical contacts of neighbouring blocks or sections. This can only be assumed for *basin scale subsidence models*, where the horizontal extension of the model is much larger than its vertical thickness. As a further simplification, lithology is currently treated as homogeneous within each layer and relative water depths are kept at a constant value for each time step.

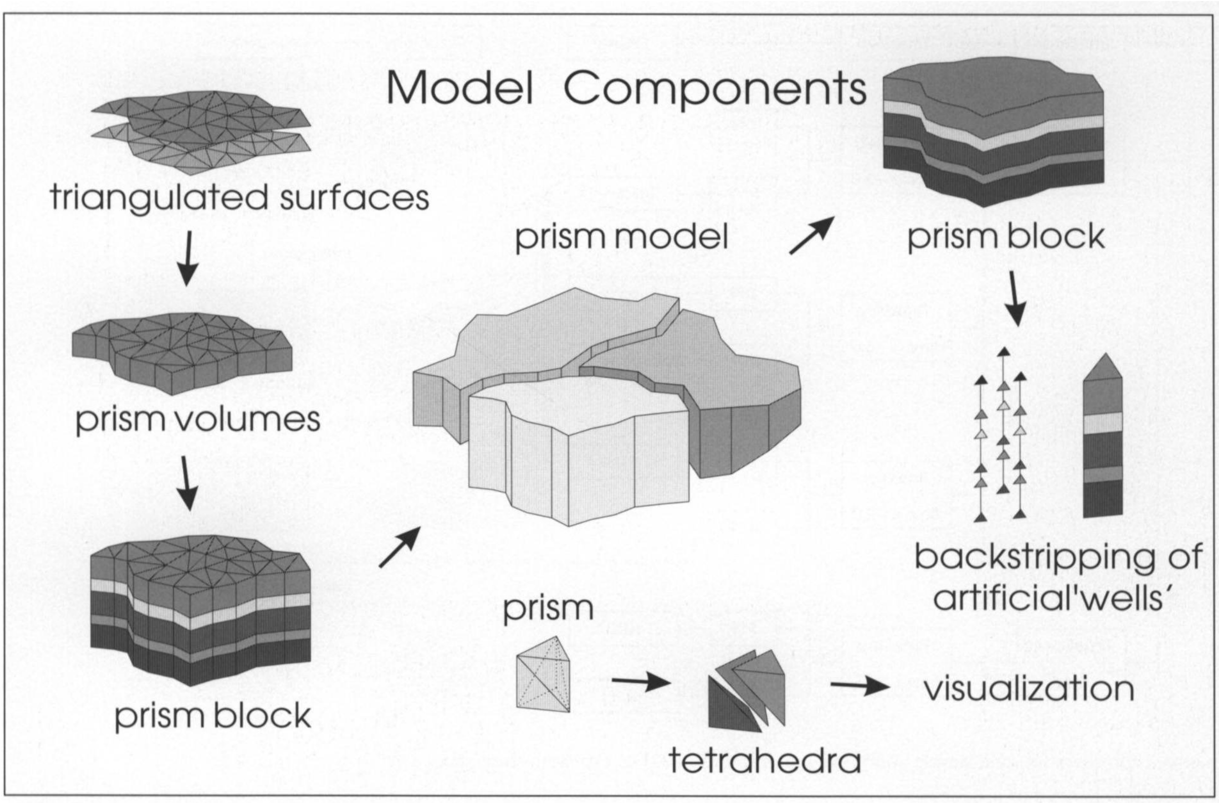

Fig. 3. Construction of a prism model composed of prismatic volumes. These volumes are decomposed into artificial 'wells' to calculate backstripped thicknesses.

Implementation

Our modelling tool consists of two modules for 3D-backstripping and visualization, implemented on SGI workstations and Linux PCs using the GRAPE (GRAphics Programming Environment) graphics library version 5.4 (SFB 256, 1997). GRAPE has been developed for the purpose of scientific visualization at the Institute for Applied Mathematics (IAM) at Bonn University and is freely available for non-commercial organisations. It provides an object-oriented class library (ANSI-C) as well as a programmable user interface and can easily be included in other applications. Our tool utilises GRAPE's geometry classes (Fe2d, Fe3d) and classes supervising time-dependent geometries (Scene, TimeScene, TimeStep).

Fig. 4 demonstrates the output of the visualization module. The GRAPE Manager holds menus to control lighting, surface properties, and camera movement, and also a timetree browser. A ruler can be used to interactively adjust model time. Alternatively, a movie player provides a convenient method to run the animation displayed in the camera window.

The Lower Rhine Basin example

The Cenozoic Lower Rhine Basin forms the continuation of the Rur Valley Graben from the Central Netherlands to North-western Germany. It is the northern branch of the much larger Central European Rift System (Ziegler, 1994). Subsidence commenced during the Early Oligocene, whereas differential subsidence can be recognised from Late Oligocene to Present. The sedimentary fill is predominantly made up of marine sands, intercalating with continental to deltaic deposits towards the south-east. The basin contains the largest economic lignite deposits in Europe, worked by the mining company Rheinbraun AG in huge open cast mines.

Data preparation

The data used to build the initial static model, were taken from a series of 20 structural contour maps (scale 1: 25 000) constructed by Rheinbraun mining engineers for the purpose of hydrological simulations. The dataset includes top and base of the main lithological units (lignite seams, major clay layers) from the base of the Oligocene to the Pliocene Reuver clay. The original maps contained fault polygons, isohypse and outcrop lines, and model boundaries. All data were provided as DXF files and had to be converted to the appropriate GOCAD formats.

A study area of 42 by 42 km was chosen, covering the main tectonic units (Rur and Erft Blocks) as well as the major fault zones (Erft and Rur fault systems,

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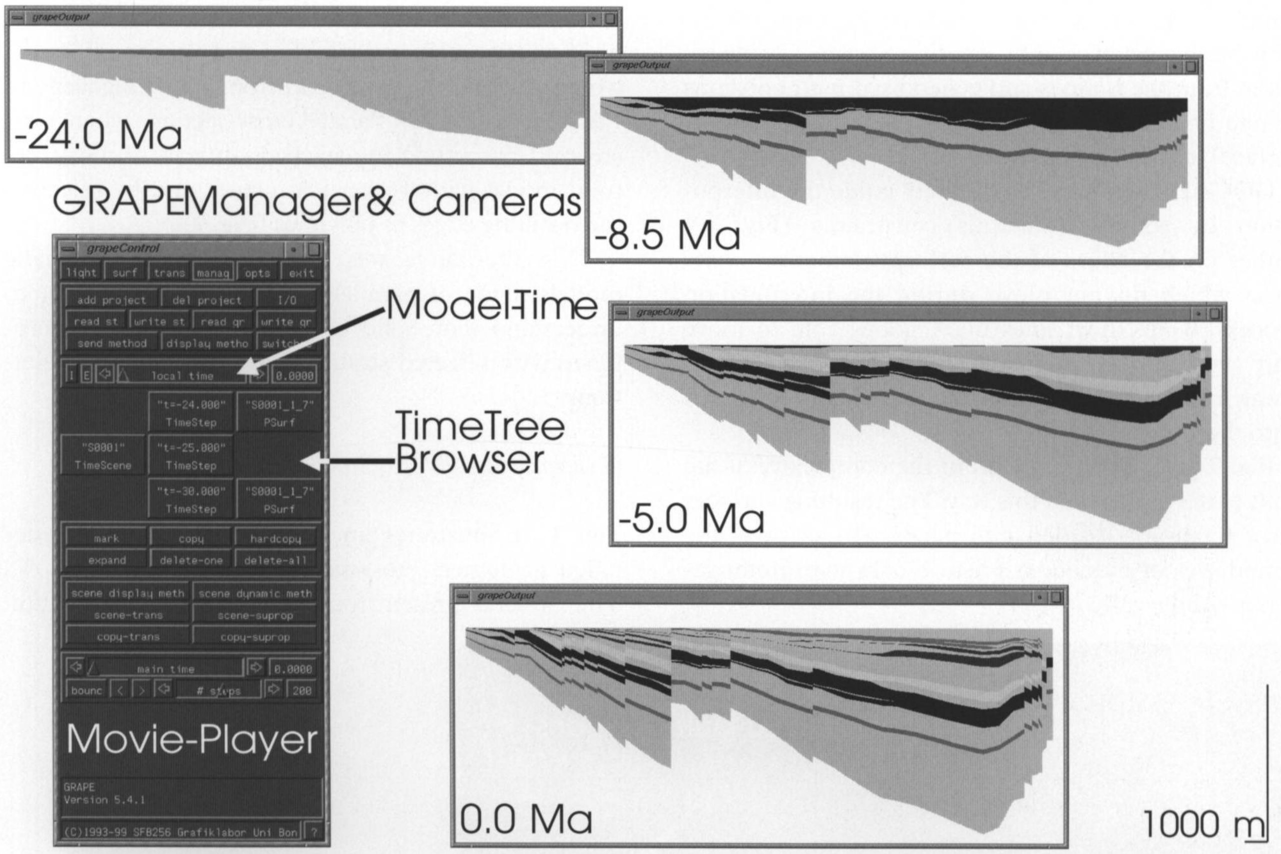
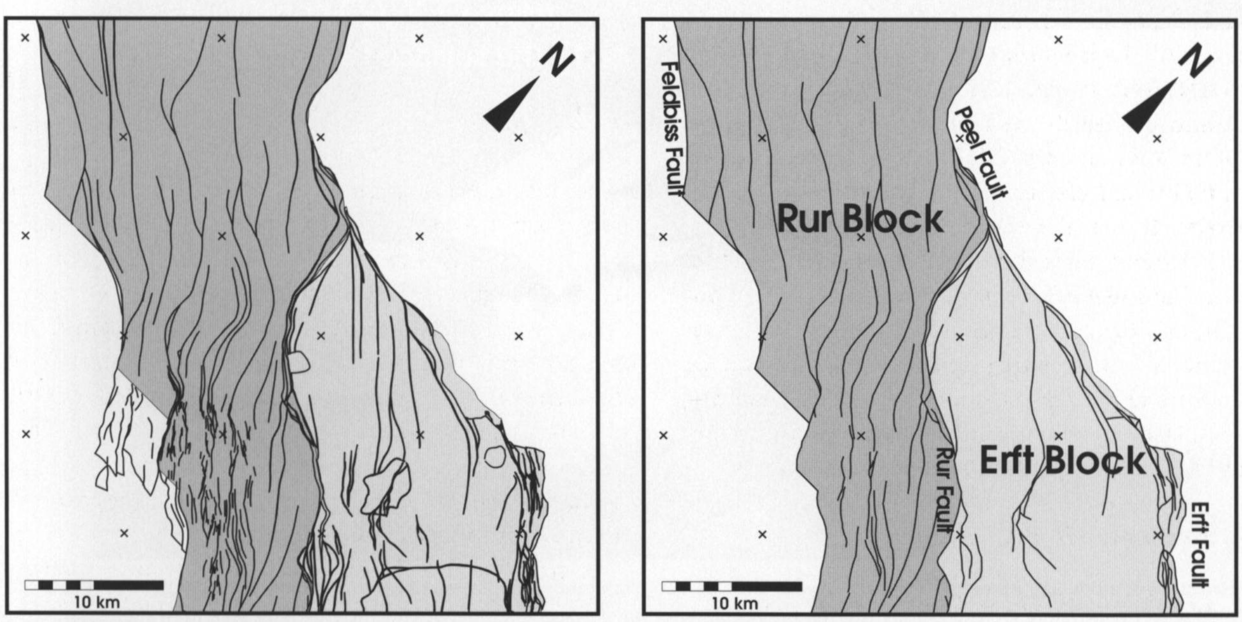


Fig. 4. GRAPE tool for the visualization of kinematic models. For the stratigraphy of the depicted cross-section compare Fig. 9, section (2).

Peel boundary fault). In order to keep data volumes to a minimum, the maps had to be generalised (Fig. 5). This included a careful inspection of all features, manual elimination of minor faults, simplification of detailed boundary and fault polygons, and aggregation of complicated fault zones to single faults. This process resulted in a simplified dataset of major structures only, corresponding to a scale of approx. 1: 250 000.

Constructing the initial geometrical model

As explained earlier, key-frame interpolation requires the geometric objects to possess the same



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number of points, as well as an identical connectivity. This has been achieved by creating a primary triangulation from the isolines and generalised fault polygons of one horizon and by fitting copies of this 'master surface' to the points of each dataset.

GOCAD users can interactively guide the interpolation by setting numerous constraints (Fig. 6): Cubes on the edges of the surface symbolise *control nodes* which do not move during the interpolation process, while short lines mark nodes able to move only vertically (*OnStraightLine*). Tree-like arrows point from the controlling data points up and down onto the surface.

Fig. 7 gives an impression of the complexity of the fault pattern modelled this way. The resulting surfaces must finally be divided into patches to serve as the boundaries of individual prism blocks with homogeneous stratigraphy.

The complete kinematic subsidence model consists of 20 stratigraphic layers within their structural framework, covering the time span from Late Oligocene to Pleistocene (Fig. 8). Parallel cross-sections where constructed by cutting the stacked surfaces of the structural model with 16 vertical planes and by selecting the resulting edges as polylines (Fig. 9).

This alternative was chosen, because kinematic models made of parallel cross-sections are easier to understand than solid blocks, especially when combined with selected stratigraphic surfaces for orientation.

Geological Results

Fig. 4 demonstrates an animated example of a detailed geological cross-section (section 2 of Fig. 9). The cameras present four timesteps in the evolution

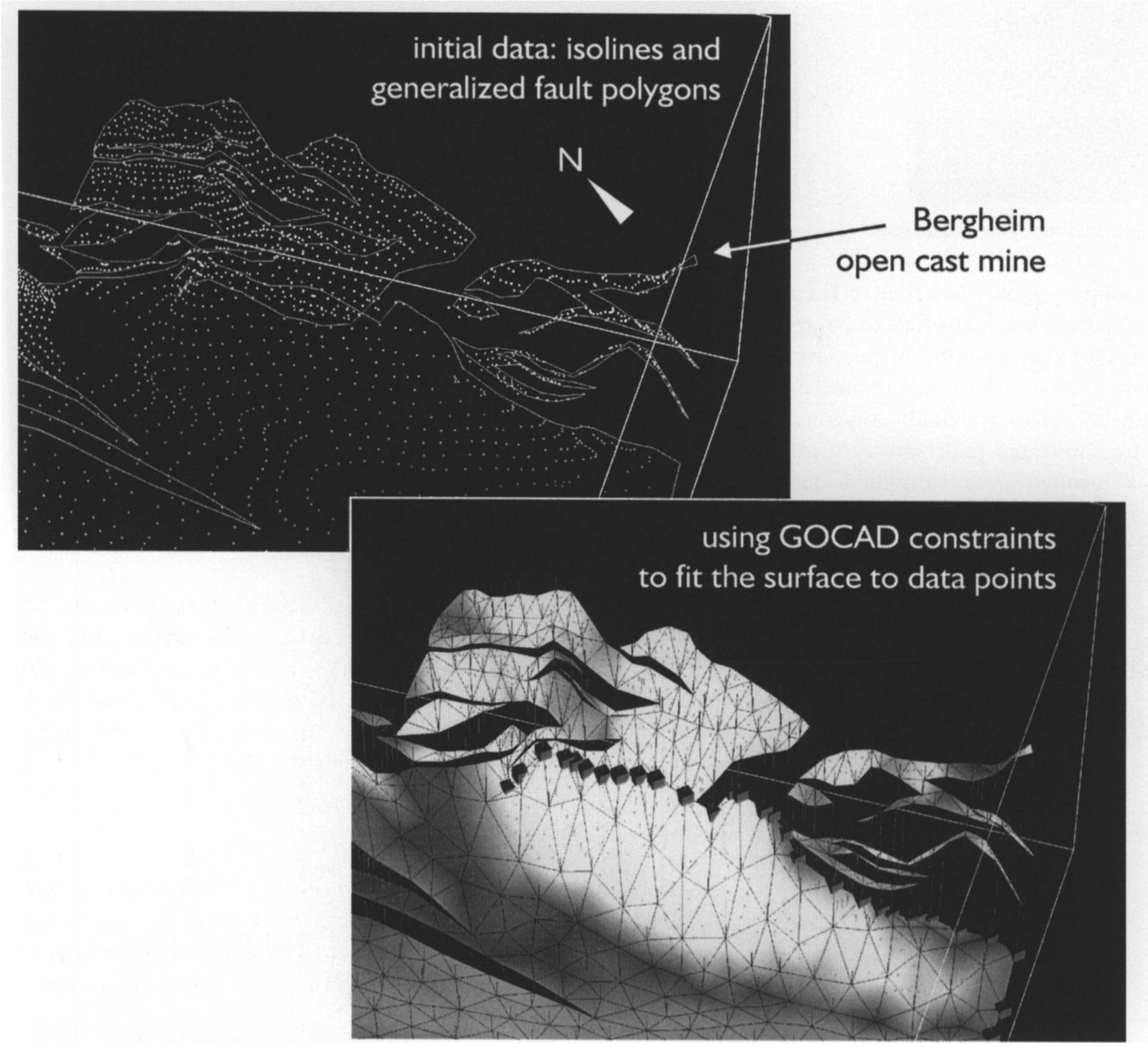

Fig. 6. Two steps in modelling a stratigraphic surface with GOCAD. Top: fault polygons (lines) and control points (dots) of the initial data set. Bottom: GOCAD constraints are used to control the interpolation of the surface. Oblique view of the Erft fault system in the easternmost part of the study area; vertical exaggeration 10:1.

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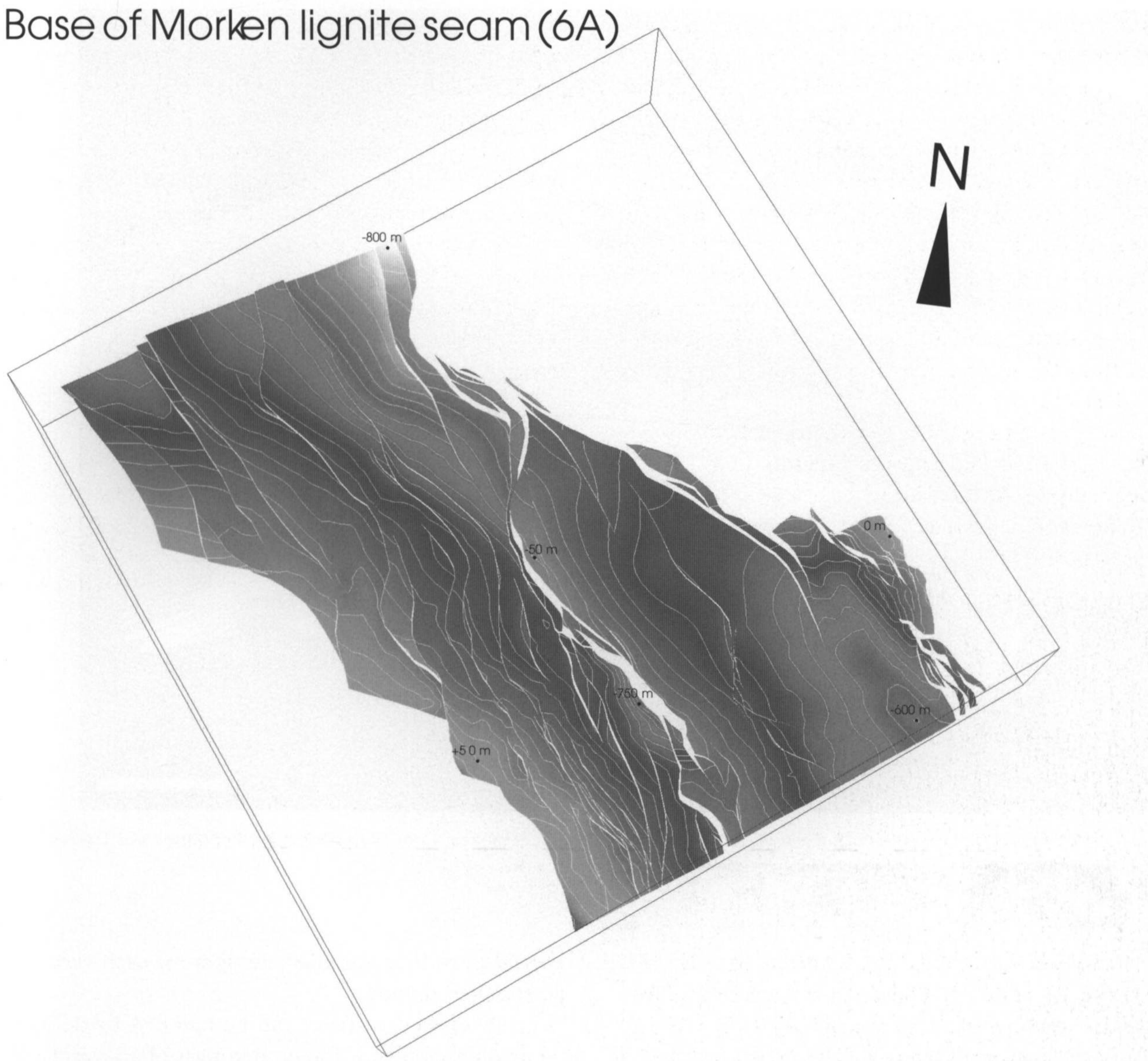

Fig. 7. Top view of the faulted stratigraphic surface 'Base of Morken lignite seam'. The depth below mean sea level is indicated at several locations; vertical exaggeration 5:1.

of the Lower Rhine Basin, each several millions of years apart. At -24,0 Ma the so called 'Clay 1' has been deposited in a tectonically quiet period, following a time-span of differential movements in the Late Oligocene. At -8,5 Ma the 'Main Lignite' seam of the Lower Rhine Basin has been deposited during a phase of slow subsidence during the Middle Miocene. Towards the south-east, the lower part of the seam ('Morken' seam) is split off by an intercalation of marine sands ('Frimmersdorf' sand). Between -8,0 and -5,0 Ma the area of the greatest peat thickness experiences the maximum subsidence, which in turn leads to the highest thickness of Pliocene 'Rotton' clay being deposited in that area. Strongly enhanced rates of tectonic movements can be observed during the Pliocene and Pleistocene.

Further examination of the animated geologic history of the Lower Rhine Basin will facilitate the detailed analysis of differential facies distribution and paleogeographical change in the context of synsedimentary structural development, and reveal additional insight into the mechanisms of basin evolution.

Modelling Results

Kinematic models can only be adequately observed and presented in front of a computer screen. Nevertheless we would like to summarise the experience and results gained from working with our prototype modelling tool:

The *key-frame interpolation* technique is well suited to animate geological processes. Still, a fundamental problem exists, to provide geometrical objects, which

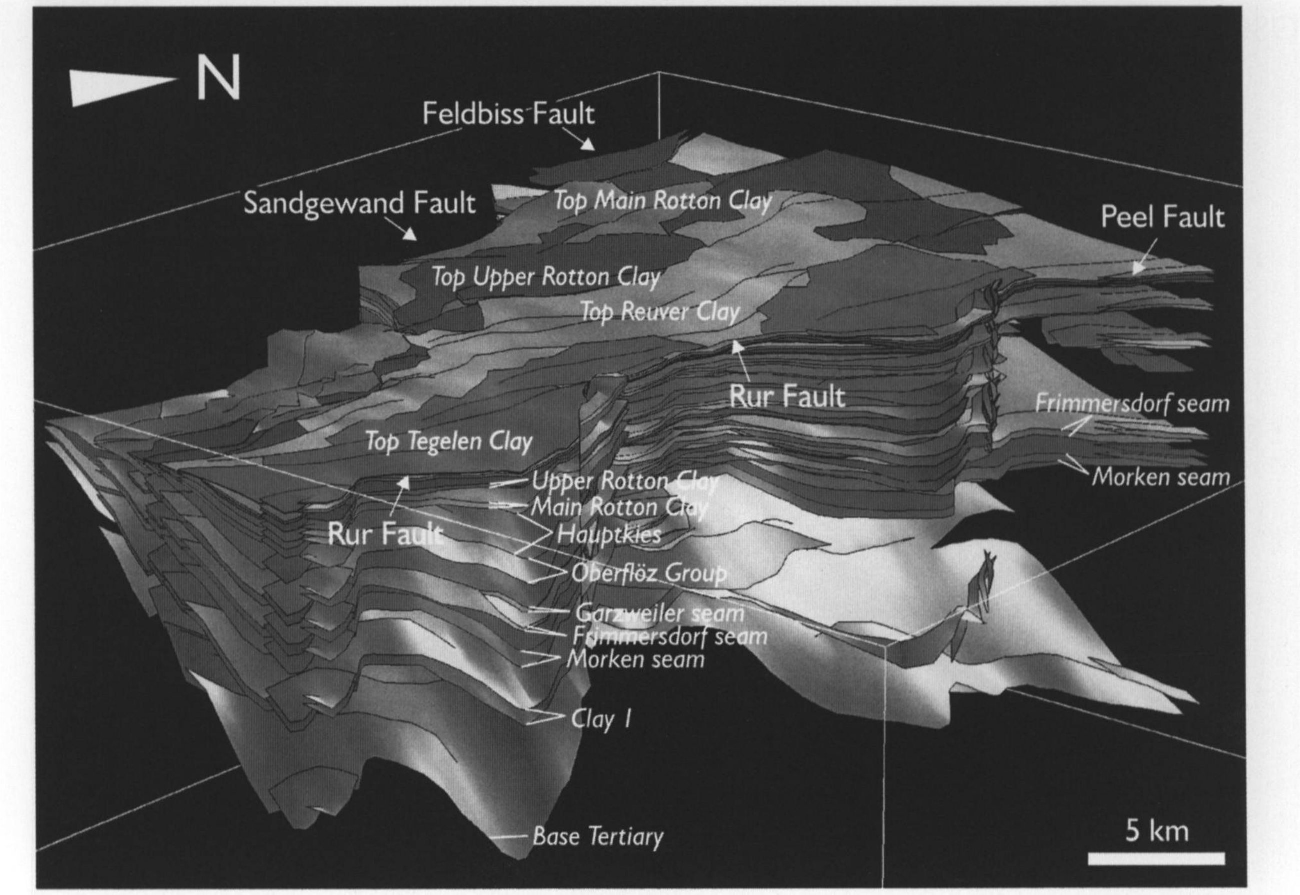

Fig. 8. GOCAD model of the Rur-Block made up of 20 stratigraphic surfaces ranging from Base Tertiary to the Reuver and Tegelen clays (Hager, 1981). Oblique view from East to West; vertical exaggeration 10:1.

are triangulated with an equal connectivity. The 3D-backstripping approach chosen in our example allows to create such geometries by taking only vertical movements into consideration. The error introduced this way can be neglected for studies at basin-scale.

The amount of work necessary to construct the initial GOCAD model is rather large. A first model based on non-generalised original survey maps had to be discarded due to the great amount of manual interaction necessary. GOCAD currently does not provide any special functions to generate surfaces of equal connectivity.

The lithostratigraphical units in the Southern Lower Rhine Basin used to calculate backstripped diachronous geometries, whereas the key-frame concept assumes, that each state represents a discrete time value. Errors occur especially in areas, where clay layers and lignite seams pinch out, which have no stratigraphic equivalent within the coarser sediments deposited synchronously.

As long as only one lithology can be assigned to one lithological body, the decompacted depths calculated by the backstripping technique possess only a limited accuracy. A future version of the program should introduce a sand/shale ratio for each vertex of a geometrical body.

Partly eroded surfaces can be handled by defining an erosion factor for the eroded part of a layer. Difficulties still arise when working with completely eroded stratigraphic layers. While the former thickness of the geological bodies can sometimes be inferred from non-eroded areas, it is almost impossible to retrieve reliable information on the beginning and the end of the period of erosion. In this case, the modelling can help to test the plausibility of alternative scenarios.

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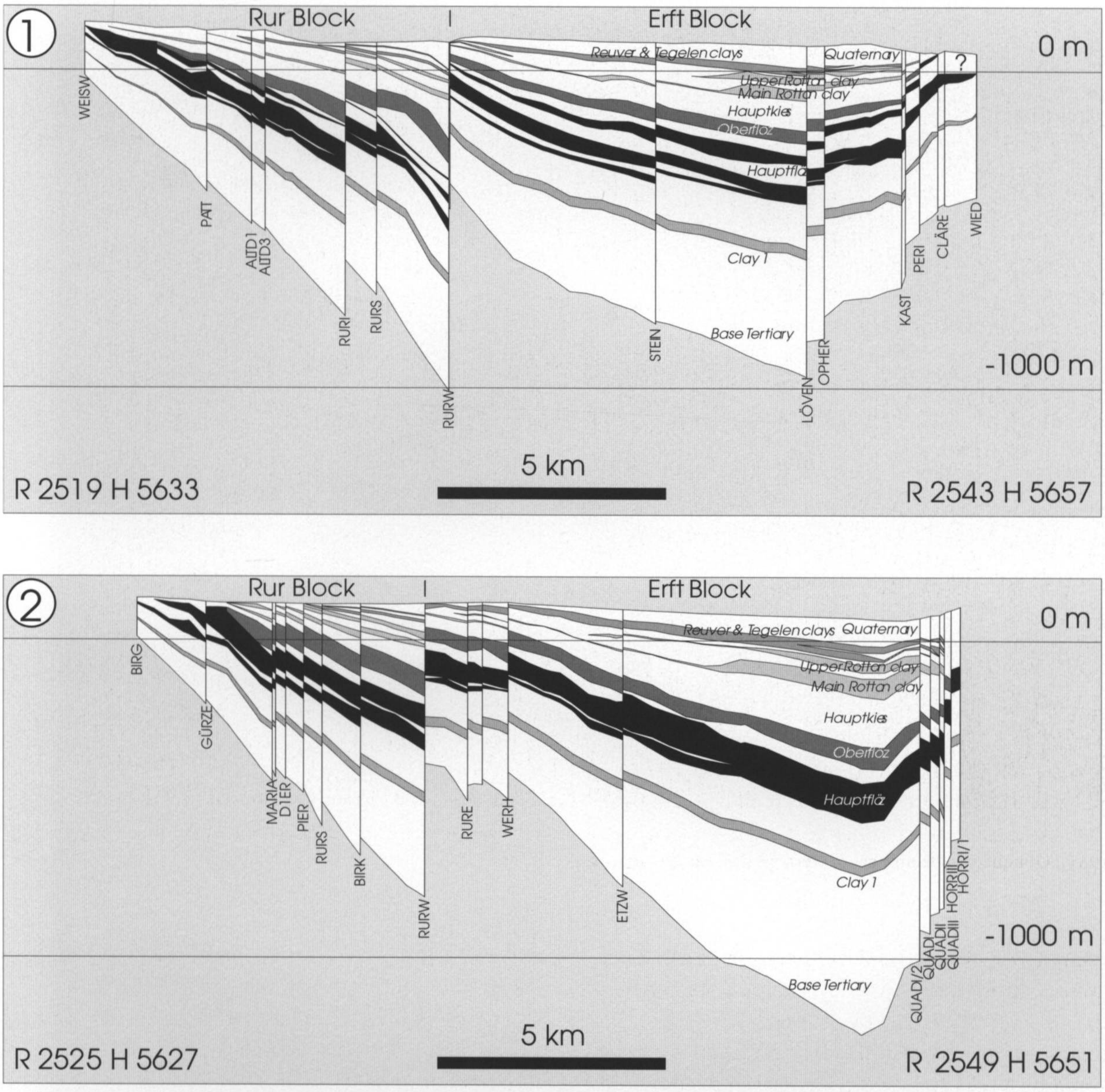

Fig. 9. Two southwest-northeast striking cross-sections through the Rur and Erft Blocks. For location of these sections refer to Fig. 1; vertical exaggeration 10:1.

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