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Modelling of topography and sedimentation along syn-sedimentary faults: WinGeol/SedTec

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Abstract

WinGeol/SedTec is a software package which simulates erosion and deposition in dependency of topography, fault movements, lithological properties and sea level. Sediment transport such as mass and suspension flows are induced by elevation or concentration differences between neighbouring cells. Grain size reduction during sediment transport is included into the model. The spatial distribution of different rock types in the source area is used to model sediment composition. Rock types are characterized by their resistance to erosion and grain size reduction during sediment transport. Input data for simulation include elevation, lithology, fault data and tabular data from various data sets such as sea level curves and control points. Faults are defined by their geometry, geographic position, time interval of activity, and a displacement vector. Examples simulated with WinGeol/SedTec include landscape deformations due to translation and rotations of several fault blocks, erosion and deposition along a steep scarp and sediment transport and grain size distributions in sedimentary basins such as the Pleistocene Mitterndorf basin in Austria.

Das Softwarepaket WinGeol/SedTec simuliert Erosion und Sedimentation in Abhängigkeit von Topographie, Störungsbewegungen, Lithologie und Meeresspiegel. Sedimenttransport wie etwa Massenströme und Suspensionsströme werden dabei durch Höhen- oder Konzentrationsunterschiede zwischen benachbarten Zellen ausgelöst. Die Reduktion von Korngrößen während des Transports wird genauso berücksichtigt wie die räumliche Verteilung verschiedener Gesteinstypen im Abtragungsgebiet, die wesentlich die Sedimentzusammensetzung beeinflussen. Die verschiedenen Gesteinstypen sind im Wesentlichen durch ihre Widerstandsfähigkeit gegenüber Erosion und durch eine spezifische Korngrößenreduktion während des Transports charakterisiert. Eingangsdaten für die Simulation sind Höhenmodelle, Lithologien, Störungsdaten und Datentabellen, wie Meeresspiegelkurven und/oder Kontrollpunkte. Störungen werden durch ihre Geometrie, ihre geographische Lage, das Zeitintervall ihrer Aktivität und durch einen Verschiebungsvektor definiert. Fallbeispiele, die mit WinGeol/SedTec simuliert werden können, umfassen Landschaftsveränderungen durch Translationen und Rotationen von Störungsblöcken, Erosion und Ablagerung an Steilhängen, sowie Sedimenttransport und Korngrößenverteilungen in Sedimentbecken wie etwa die pleistozäne Mitterndorfer Senke im Wiener Becken (Österreich).

1. Introduction

Modelling of sedimentary processes has become a major research area in the last decades (e.g. Paola, 2000). Models are used to experiment on and to test geological hypothesis as well as for simulating real world cases. Theoretical modelling of sedimentary systems is vastly used, especially in the oil industry and in aquifer sedimentology and hydrogeology (e.g. Harbaugh et al., 1999; Paola, 2000; Sheets et al, 2002; Bridge and Hyndman, 2004). Numerical models for simulating sedimentation use varying approaches, e.g. differential equations or fuzzy logic (e.g. Hardy and Gawthorpe, 1998; Bowman and Vail, 1999; Nordlund, 1999).

The simulation of syntectonic sedimentation, i.e. sediments deposited under the influence of active faulting or folding, comprises a complex geological phenomenon, and modelling of syntectonic sedimentary systems requires the incorporation of both sedimentological and tectonic parameters and corresponding algorithms (e.g. Clevis et al., 2003). Several published stratigraphic simulators offer only passive tectonic displacement of layers but not contemporaneous processes of sedimentation and deformation along active faults (e.g. Bowman and Vail, 1999). The presented software package WinGeol/SedTec has been designed for 3D forward simulation of sedimentation in syntectonic basins (Faber and Wagreich, 2002). The software simulates erosion and deposition under the influence of synsedimentary tectonic movements.

2. Functional principles of WinGeol/SedTec

WinGeol/SedTec is written in C/C++ and has been compiled for Windows XP/2000. The principal idea for the development of WinGeol was to create a tool for visualization and analysis of geological or geology related datasets. Therefore, there are some similarities with GIS software:

- Layer based data organization
- Usage of vector, raster and database data
- Tools for data manipulation (geometry, geographic projections, import / export, data conversion)
- Digitizing of vector and tabular data (database & text layers)

Functions which are beyond the scope of standard GIS include:

- Viewing of data in 2D, 3D and Profile mode
- Lineament Statistics
- FaultTrace – a tool for determination of azimuth and dip of geo-

logical strata and faults from digital elevation models and optional satellite / aerial photography data
- Hydrological functions
- Tool for digitized geological profiles
- Lamination Tool – semi automatic analysis of layered materials
- Subsurface Modeller – a tool to create volume models for later numerical groundwater modelling (for example within MOD FLOW by Scientific Software Group), supports the integration of faults
- SedTec

3. WinGeol/SedTec

SedTec is one of the major modules within WinGeol. It simulates erosion and deposition in dependency on topography, tectonic movements, lithological properties and sealevel.

Sedimentation modelling is based on a cellular automata approach (Fig. 1; see also Bowman and Vail, 1999; Clevis et al., 2003). The depositional area is divided into equally spaced cells. Sediment transport is induced by elevation or concentration differences between neighbouring cells. In the case of an elevation difference a topographically driven mass transport is generated; in the case of concentration differences sediment transport due to compensation of concentration differences is calculated. This approach is planned for modelling of suspension transport in marine settings.

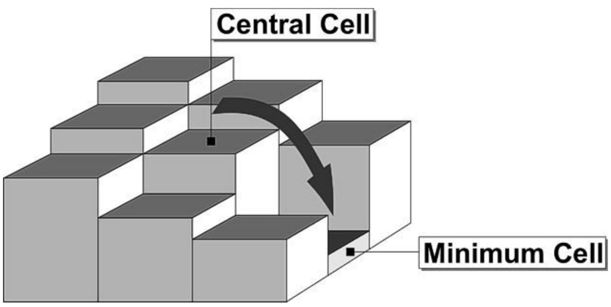


Figure 1: Example of a neighbourhood matrix used to simulate sedimentation in WinGeol/SedTec; a certain part of the elevation difference between the central cell and the lowest neighbour (light grey) will be moved from the centre to the grey cell.

3.1. Erosion and sediment transport

The main algorithm of WinGeol/SedTec is the mass transport function based on the neighbourhood matrix; all other functions which describe, what will happen to the transported sediments (e.g. grain size reduction, amount of transported sediment) are extensions of this function. Input data for simulation include digital elevation models (simple plane or real world model), fault data (optional), lithological raster map (optional), lithological parameters (e.g. resistance to erosion), sea level (single value or time dependant), sediment supply, control points (optional).

Within each time step the following parameters are computed:
- New topography: *surface = Previous Surface - Erosion + Sediments + Tectonic*
- Total mass balance (erosion & sedimentation) for each grid position
- Amount of erosion per grid cell
- Amount of sediments per grid cell
- Grain size distribution of different lithologies (any number of lithologies and grain sizes classes are possible)
- Control points: Define locations with known sediment thickness, sedimentation is stopped or a warning message is issued if this value is passed

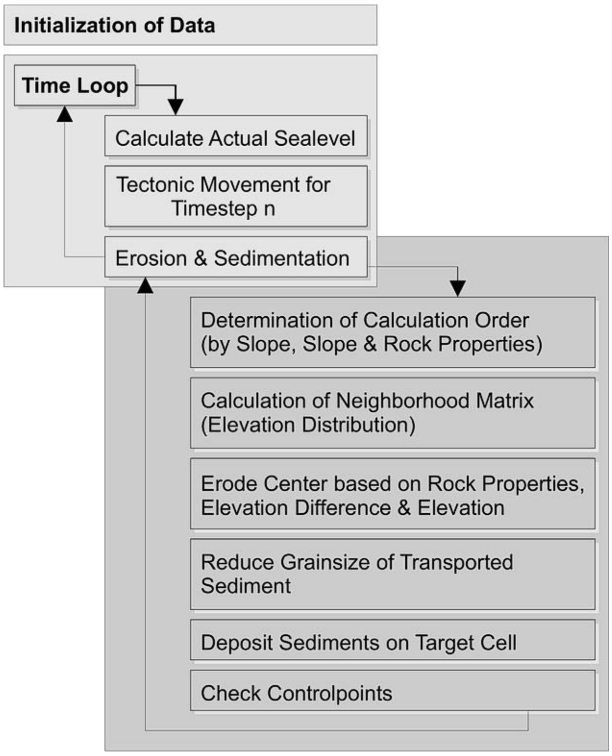


Figure 2: Simplified workflow of WinGeol/SedTec.

3.1.1. Erosion Factor

The erosion factor is defined as the amount of material which is moved from a higher location to a lower location during a time step. The erosion value may be determined from field observations or from a series of model runs to get a realistic value. Using a "lithological" base map different erosion factors may be assigned to different rocks.

$$erosion = dh \times erosion\_factor \times cf \times shoreline$$

l$erosion_factor$: dimensionless number between 0 and 0.5

0 no material transport

0.5 elevation difference between center and target cell will be completely equalized (WinGeol/SedTec Version 1 uses the reciprocal)

h_0 elevation of center cell

h_1 elevation of target cell

$dh = h_0 - h_1$

cf correction factor to consider weight of overburden and age (see below) *shoreline* if the elevation of the processed cell is between sea level and wavebase, erosion might be increased using this correction factor

3.1.2. Correction factor

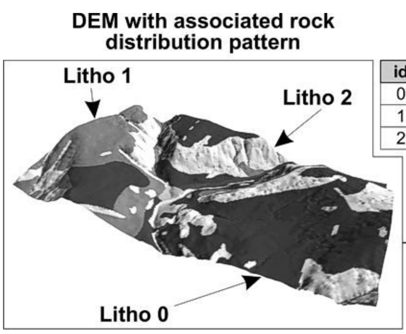
The resistance to erosion is assumed to increase with age and the weight of the overlying material. Young sediments which have not been covered will be eroded very easily in contrast to sediments which have been significantly buried below younger strata. This correction factor will be calculated at the end of each time step and increases the value which has been calculated at the end of the previous time step.

$$cf = \frac{1}{(0.5 + n) \times dt \times w \times rcf}$$

w weight of overlying material +0.5 × weight of actual processed cell
dt duration of time step
n number of all time steps – number of actual time step
rcf correction factor assigned for each different rock type
cf resistance correction factor

3.1.3. Spatial variations of lithological properties

Rock types are characterized by several properties like their resistance to erosion, weathering and grain size reduction during transport. The spatial distribution of different rock types are extracted automatically from a lithological raster map at the beginning of the simulation (Fig. 3).



Rock property table

id	litho	relief	grainsizered.	unconsolid.	density	weathering
0	Litho 0	20	0.03	5	2.7	1
1	Litho 1	50	0.005	5	2.7	1
2	Litho 2	100	0.02	5	2.7	1

Linkage created automatically at simulation start, the id value corresponds with the color value of the associated rock distribution map.

Figure 3: Extraction of spatial distribution of bedrocks from raster maps and linking of associated properties (relief factor, grain size reduction during transport, erodability of unconsolidated sediment, density, weathering factor).

3.1.4. Grain size reduction due to transport

The reduction of grain sizes during transport depends primarily on the distances grains are transported, on the material of the grains and on the transport mechanisms involved. The grain size reduction factor describes how much of a certain grain size fraction is reduced to the next smaller grain size per unit distance (one kilometre); this factor is material depend.

Because of memory and calculation time limitations it is not possible to trace every particle within the simulation, therefore the program works with transport distance / grain size classes (assumption that grain size reduction is proportional to the transport distance). This means that after a certain distance of transport a certain amount of material is moved from one to the next transport distance class. The number of classes is not fixed and not limited. Dependent on the material the rate of material moved between two classes is variable.

3.1.5. Grain size dependent transport

Another assumption made during the transport simulation is that the finer the material is, the easier it can be transported. If a volume element contains finer and coarser material the fine material will be transported first. If more than one material type is used in the simulation, materials which are easier to move (lower density) will be processed first.

3.2. Sedimentation

Material eroded from the center cell will be completely deposited at the target cell. Future versions will use an algorithm to determine the flow rate at each location of the model and will update this data at the beginning of each subcycle. Depending on the flow rate only a part of the transported material will be deposited in the target cell.

3.2.1. Sedimentary environments

Three depositional environments are so far distinguished by WinGeol/SedTec in dependency on the topographic elevation of a cell and its position relative to the sea surface. These environments comprise subaerial, shore line, and subaquatious (see Fig. 5).

3.3. Faulting and Folding

Faulting and folding are important tectonic processes for every erosion and deposition model due to the fact that both have a strong influence on the topography. Synsedimentary faulting complicates stratigraphic modelling. Consequently, the effects of faulting have been often neglected in the modelling processes (e.g. Fuzzim software, Nordlund, 1999). Only recently models were published that account for synsedimentary faulting (e.g. Clevis et al., 2003).

Within WinGeol/SedTec a fault is defined as an element which deforms the surface. This deformation has an impact on further erosion and sedimentation. To simulate the effect of tectonic movements, areas can be defined which surface elevations will be altered. It is important to mention that tectonic deformation within WinGeol/SedTec is treated as a pure geometrical issue.

- Constant vertical movement vector
- Geometrical changes depend on the distance to the area defining element to simulate the effect of block rotation
- Effects of folding are simulated using sinus wave function

Parameters used within the tectonic module:

- Geographic position

- Start and end time of activity
- Vertical movement modes
    - constant
    - distance depend
    - sinus function – parameters: wavelength, amplitude and damping from point or line of origin

Faults are defined by digitized linear features to which the required values (to define the area which will be influenced, vertical shift) are assigned. For each time step the fault movement is calculated and the resulting new topography is the base for the next calculation step of erosion and sedimentation (Fig. 6) – the more time intervals are used the more accurate is the simulation of these two interacting processes.

3.4. Data export and comparison to real world data

The results of the simulation may be exported in different ways:

- Virtual wells (a position is specified and a log will be generated)
- Single simulation layer
- Complete model (as multilayer grid dataset)

Within the simulation cycle control points are used to check, if the maximum sediment thickness is exceeded. After completion it is possible to compare the results with well log data or existing subsurface grids. Real world well log profiles (lithological and standard geophysical logs such as SP or resistivity) can be imported into WinGeol/SedTec and directly used to check simulation results with real borehole data.

```
void ErodeGrainSizeDependent(float *insed, int subcl, int grainsizes,
    float &erosion, float *mv_sed)
{
// erosion is the amount of material which should be moved from A to B
// it is based on the erosion rate and elevation difference between
// target and center cell
// init mv_sed  will contain the moved material,
// set at the beginning to 0
for (int i=0;i<subcl*grainsizes;i++)
     mv_sed[i]=0;
// first erode smaller grainsizes  classes with small grain sizes
// have a higher number therefore reduce it after each cycle
    for (int j=grainsizes-1;j>-1;j--)
    {
        for (int i=0;i<subcl;i++)
        {
            int n = i*grainsizes+j;
                           // calculate the actual amount of material moved
            float massmove = insed[n] - erosion;
            if (massmove < 0)
            {
                // all material in this class will be transported
                mv_sed[n] += insed[n];
                erosion += -insed[n];
                insed[n] = 0;
            }
            else
            {
                // there is more material than can be transported
                // move only the fraction which can be transported
                // at set erosion to 0
                insed[n] += -erosion;
                mv_sed[n] += erosion;
                erosion = 0;
            }
        }
    }
}
```

Figure 4: Processing function of grain size dependent transport used in WinGeol/SedTec.

4. Application to a case study - the Mitterndorf basin

As a preliminary test area for the simulation software we used a strongly simplified model of the Pleistocene Mitterndorf basin south of Vienna (Fig. 7). The Mitterndorf basin ("Mitterndorfer Senke", Küpper, 1952, 1954) comprises a Pleistocene to recent depocentre of the larger Neogene Vienna Basin (e.g. Decker, 1996; Hamilton et al., 2000; Häusler et al., 2002; Wagreich and Schmid, 2002), situated at the junction of the Eastern Alps and the Western Carpathians. The Mitterndorf basin is a still active pull apart basin, about 50 km long and a maximum of 10 km wide (Fig. 7). It formed along prominent sinistral strike-slip faults (e.g. the Leitha fault system, Hinsch et al., 2005; Decker et al., 2005) during Pleistocene to recent times within the Miocene Vienna Basin.

Sinistral displacement was quantified by a geometrical model for thin-skinned extensional strike-slip duplexes (Decker et al., 2005). Accordingly, 1.5 to 2 km sinistral slip accumulated during the

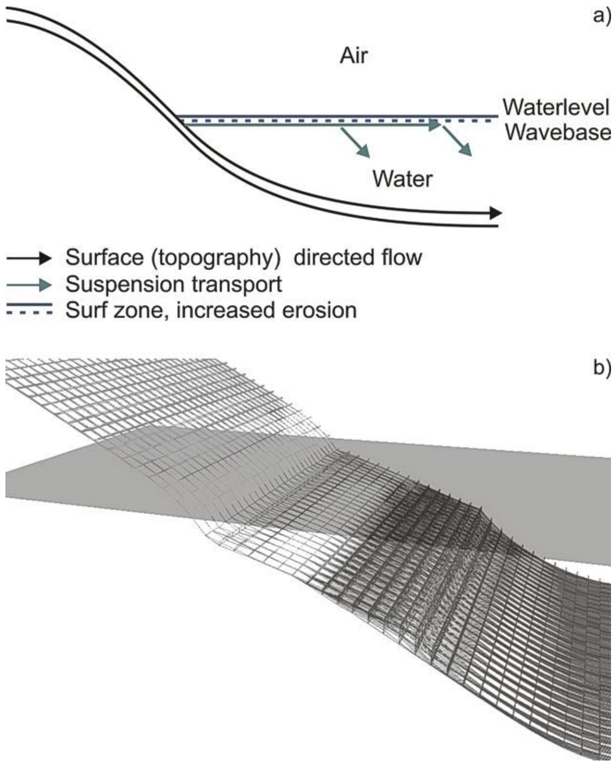


Figure 5: (a) Depositional environments and main types of sediment transport implemented in WinGeol/SedTec. (b) Geometrical effect of increased erosion within the surf zone: Directly below the water level additional erosion caused by waves increases the slope gradient. The eroded material is transported to deeper areas where it causes a decrease of the slope gradient (upper dark area); further below the original slope gradient stays fairly constant (lower dark area).

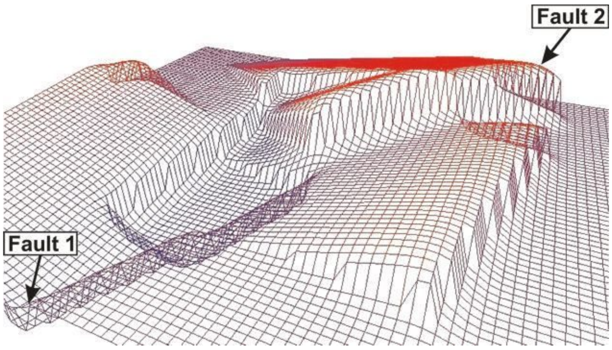


Figure 6: Geometric alterations of the surface caused by application of the tectonic module to simulate movement along 2 linear faults. The amount of vertical translation depends on the distance to a vector element which describes the fault orientation.

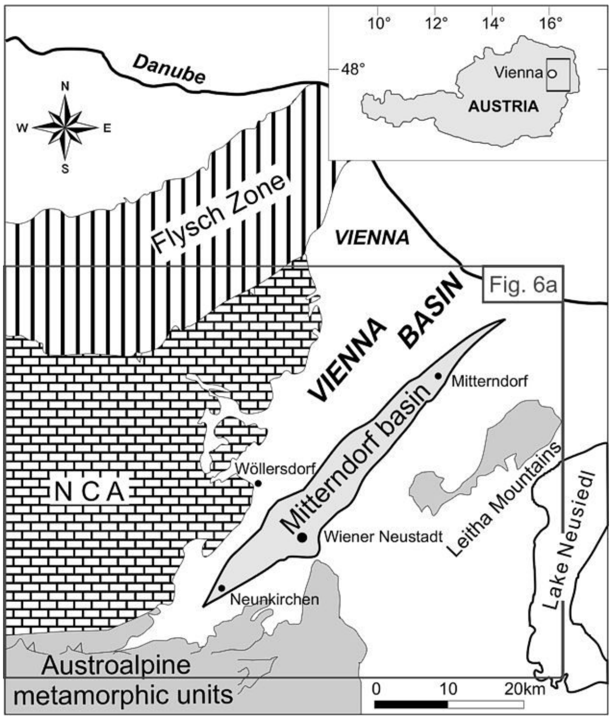


Figure 7: Schematic geological map of the Vienna Basin, the Pleistocene, fault-bounded Mitterndorf basin and the surrounding mountains of the Flysch Zone, the Northern Calcareous Alps (NCA) and the Austroalpine metamorphic units. Inset indicates approximate area of simulation shown in Fig. 6a.

Pleistocene and Holocene along these faults. The Mitterndorf basin is filled with up to 150 m of mainly (glacio-)fluvial gravels. Sand layers and grey to red paleosoils are very rarely observed (Küpper, 1950). Scarce biostratigraphic data from boreholes indicate mainly Late to Middle Pleistocene ages. Two red paleosoil horizons in the middle and close to the base of the gravel section have been related to interglacial intervals. The upper paleosoil revealed a terrestrial gastropod fauna of the Riss-Würm Interglacial (Küpper, 1950; ca. 120.000 – 130.000 years) and indicates probably for the lower soil a post-Mindel Interglacial age (< 400.000 years; Van Husen, 2000). This results in an estimated maximum time span of about 400.000 years for the sedimentation of the gravel and soil succession in the southern Mitterndorf basin (Decker et al., 2005).

Simulation of the Mitterndorf basin with WinGeol/SedTec incorporates a strongly simplified digital elevation model including the nearly flat Vienna Basin, a low relief eastern (Leitha Mountains) and southeastern (Austroalpine units of the Rosalia-gebirge and Wechsel area) mountainous metamorphic basement source area, and a western higher relief carbonate mountainous source area (Northern Calcareous Alps). The Mitterndorf basin was modeled by a simplified rhombic fault bounded subsidence area according to the model by Decker et al. (2005; comp Fig. 8a). The simulation concentrated mainly on the southern part of the basin, as sediment transport paths and sedimentation patterns were simpler in that area (e.g. Küpper, 1952, 1954; Prohaska, 1983). Sediment input was mainly controlled by paleovalleys of the rivers Schwarzau and Piesting, resulting in a fan-like sedimentation pattern of the Neunkirchen fan and the Wöllersdorf fan (Küpper, 1954; Brix & Plöchinger, 1988). The simulation also accounted roughly for decreased sedimentation rates during interglacial periods and increased and coarser sediment input during glacial periods.

Simulation results indicate a complex interplay of erosion and sedimentation of different lithologies

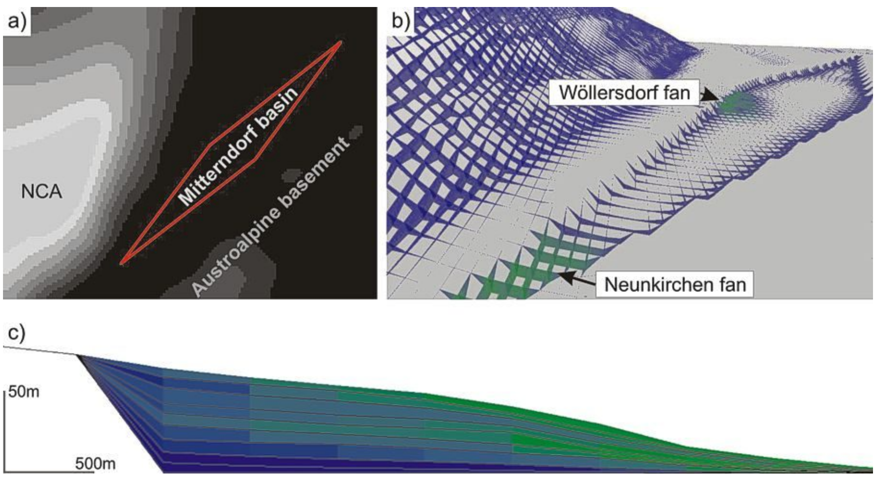


Figure 8: (a) Strongly simplified topographic model used for forward simulation of sedimentation in the Mitterndorf basin in WinGeol/SedTec (grid size 500 m, time steps 40.000 years, 4 bedrock lithologies). (b) 3D view of model result after 80.000 years: coarse channel sediments (green) build out fans into the subsiding basin (blue indicate areas of erosion or deposition of other sediment types). (c) Northwest-southeast section through the Wöllersdorf fan after 360.000 years of sedimentation. Black lines are time lines; green colour indicates sediments rich in carbonate clasts, blue colour indicates other sediment types. Note sediment cycles due to glacial (stronger carbonate clast input) and interglacial periods (less carbonate clast input).

according to the chosen parameters for bedrock erodability and grain size reduction. The two fans have been successfully modeled by coarse channel sediment building fans from point sources where channel-like paleovalleys enter the basin (Fig. 8b). The internal sediment architecture of the fans displays some variations due to different lithologies and irregularities as a consequence of the coarse cell size (500 m), the large time steps (40.000 years), and the simple geometry used for this preliminary simulation. However, a clear cyclic trend in carbonate sediments can be recognized, indicating low sedimentation rates and low carbonate clast input during interglacial periods (blue areas in Fig. 8c) to high carbonate input during glacial times (green and mixed blue-green areas in Fig. 8c).

5. Conclusions and outlook

WinGeol/SedTec provides a stratigraphic simulator which incorporates simulation of sedimentation and erosion during active faulting along basin margins. Simple sedimentation experiments (Fig. 9) calculated with this software package indicate the strength of the software as compared to commercially available stratigraphic simulators such as PHIL (Bowman & Vail, 1999) or Fuzzim (Nordlund, 1999) in its 3D- approach, the full integration of faulting, and the variety and accuracy of topographic modeling based on the interplay of different bedrock lithologies, erosion and faulting. Different source rock lithologies can be incorporated which result in different geometries and grain size distributions along fault scarps (Fig. 9a). Simulated grain size distributions in active basins display a classical proximal-distal fining trend and can be interpreted in terms of coarse alluvial fans or fan-deltas at basin margin faults and a significant fining (shaling) trend resulting in fine-grained muddy sediments in the basin centre (Fig. 9b). A first application to model the filling of the Pleistocene Mitterndorf pull-apart basin showed the ability of the software to simulate large-scale stratigraphic patterns, grain size trends and source area/compositional variations in such a tectonically complex setting. Future simulations with an improved sediment transport model, a more detailed digital elevation model and complex fault geometries will result in a more realistic model for the fill of the Mitterndorf basin, e.g. in modeling known lithology differences between the Wöllersdorf fan and the Neunkirchen fan (Brix and Plöchinger, 1988).

Additional “behaviors” and properties may be added very easily to the SedTec module of the WinGeol software. In the actual program version each sediment package may have an - at least in theory - infinite number of properties. Additional properties

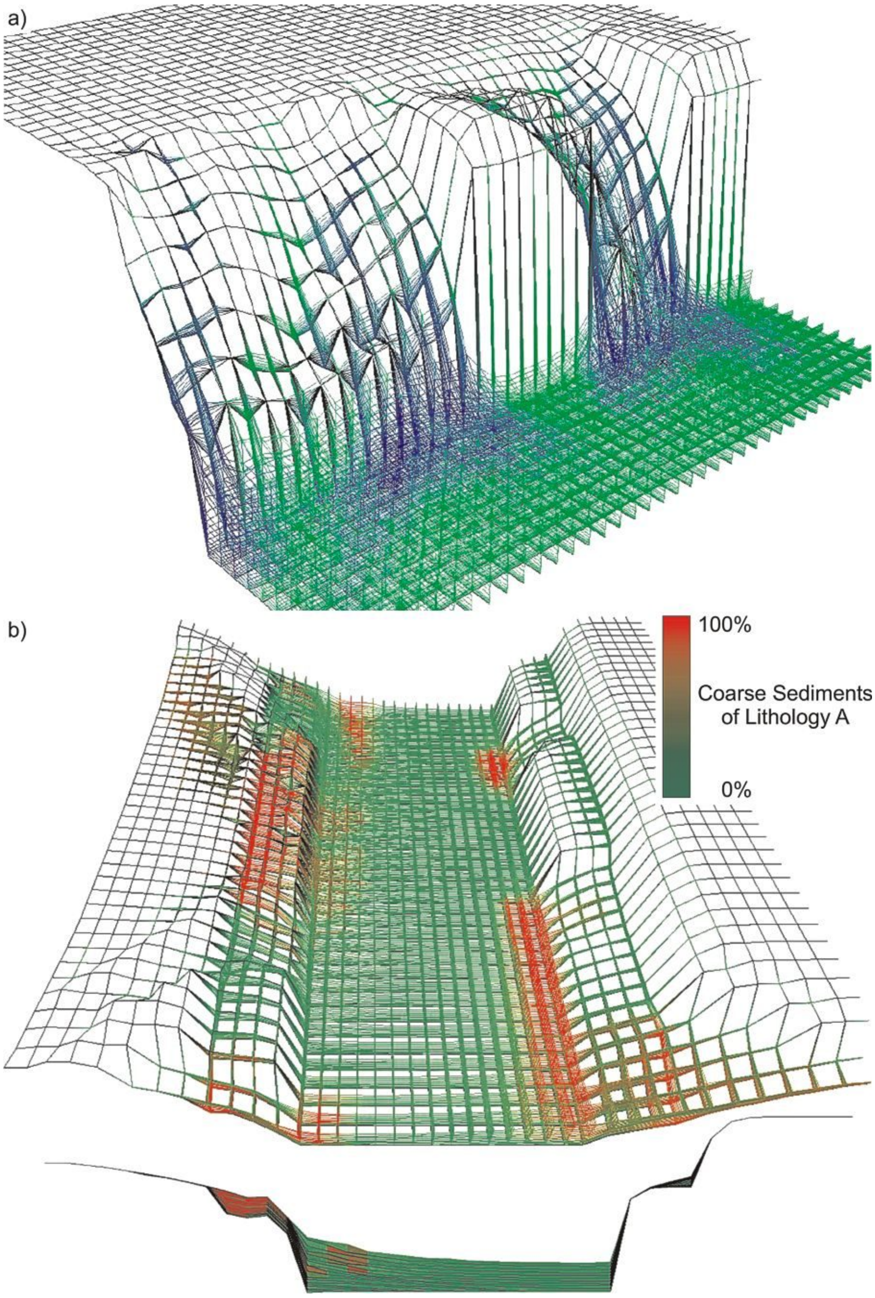


Figure 9: Simulation run examples calculated using WinGeol/SedTec. (a) Cliff erosion model used for topography evolution and scarp development along an active fault (high content of coarse sediment blue, low content green; strongly exaggerated). (b) Simulation of a rift graben: The 3D graph displays the different erosion rates and sediments due to lithological differences. In the profile the left rift shoulder is much more eroded due to erosion resistivity contrasts and yields a significant higher amount of coarse-grained sediments of lithology A (red colour).

included in future versions may be:

- Water content
- Porosity
- Temperature

Additional "behaviors" may include:

- weathering – including exposition and climate
- more advanced grain size reduction and different algorithms for additional sediment transport types

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