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**Documentation of the Nagra regional
3D Geological Model 2012**

May 2013

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Nationale Genossenschaft
für die Lagerung
radioaktiver Abfälle

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1 Introduction

1.1 Motivation

In order to better understand groundwater flow in the main bedrock aquifers of Northern Switzerland, Nagra set up regional and local scale hydrogeological models. Since hydrogeological models depend on the regional and local geology, a regional 3D geological model of Northern Switzerland and parts of southern Germany had to be constructed. The present report documents the current version of the geological 3D model (GeoMod 2012).

1.2 Basis

The 3D GeoMod 2012 is based on an existing 3D model started in 2011. The so called GeoMod 2011.1¹ was built by compiling information from three previous geological models (Nagra (2008); LGRB (2008) and Roth et al. (2008), see below), each covering a part of the region of interest.

The base horizons of the GeoMod 2011.1 were created from pre-existing ESRI-grids or GoCAD surfaces. These include, in stratigraphic order:

- The Topography (Swisstopo 2008; ADV 2010; Green et al. 2010).
- The base of the Quaternary: Nagra (2008)
- The base of the Tertiary: Nagra (2008), Roth et al. (2010), LGRB (2008)
- The base of the Malm: Nagra (2008), Roth et al. (2010), LGRB (2008)
- The base of the Opalinus Clay: Nagra (2008), Roth et al. (2010), LGRB (2008)

The GeoMod 2012 finalizes the former model. The work included filling gaps, flattening of transitions zones between the models and extending some horizons. The resulting base horizons have been used to construct new interlayer horizons using relative and absolute thickness models (isopach maps).

1.3 Need for model completion

As shortly described above, the GeoMod 2011.1 is a model consisting of independent horizons and fault surfaces. The strength of the model is the exact fit to the available information from geophysical exploration and existing boreholes. The weakness of the model is that only a few horizons cover the whole domain of the planned hydrodynamic model. Additionally, the triangles of the model horizons are not assigned to the correct sides of a fault plane. If a horizon cuts through a fault plane, this has to be corrected but the used automatic interpolation routine can't decide which triangle is on which side of the fault (see Fig. 1, case B and C).

¹ The technical details concerning the construction of GeoMod 2011.1 are documented in Nagra internal documents.

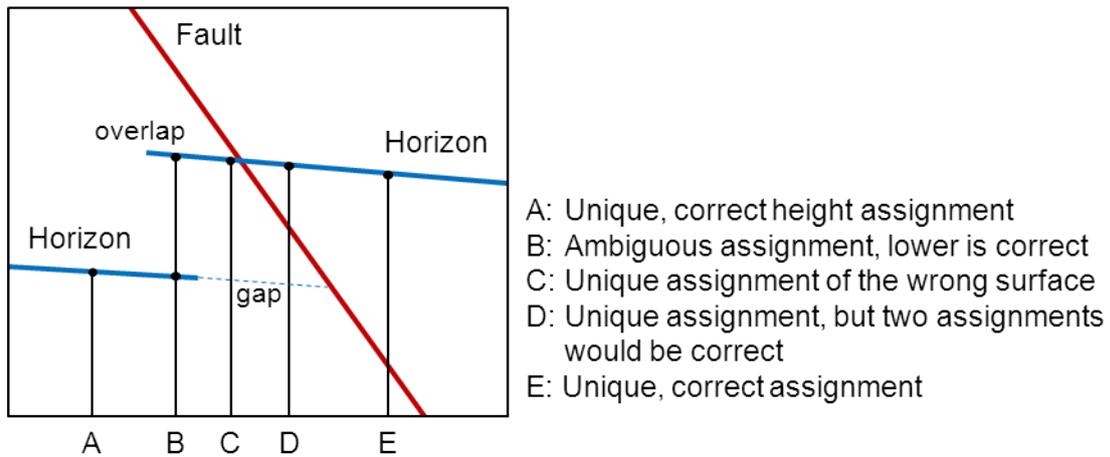


Fig. 1: Difficulties at the interpolation of horizon height to different points near faults.

Fig. 2 and Fig. 3 demonstrate the two main characteristics of the GeoMod 2011.1 that prevent a proper unit assignment in building up a hydrodynamic model. Some horizons do not reach topography and, because of the rather low dipping angle, this may lead to large gaps between the end of the horizon and its outcrop at the topography. Fig. 3 also shows some horizons crossing faults. This originates from the method of constructing new horizons using isopach maps that were continuous over a fault surface. If a horizon crosses the fault, it exists on both sides of the fault and an automated routine for building up a finite element model is not able to correct for this.

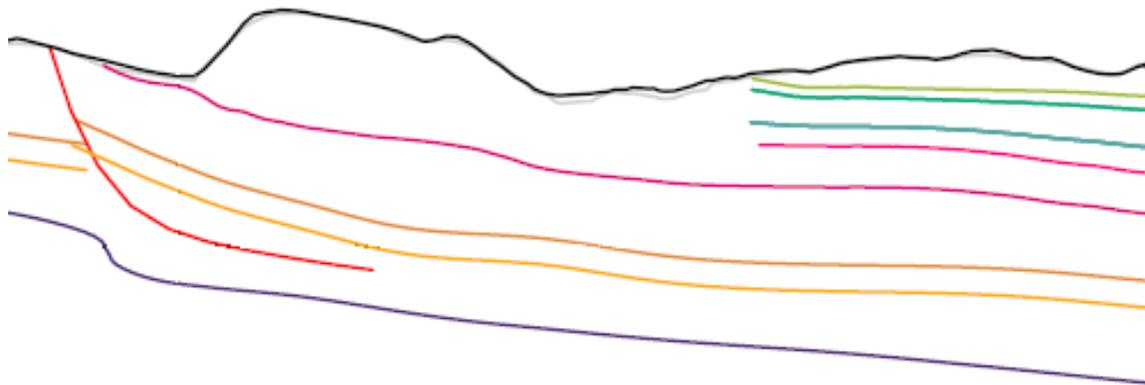


Fig. 2: Example of horizons ending near their respective outcrops in a section through the GeoMod 2011.1. The gaps between the end and the actual outcrop had to be interpolated.

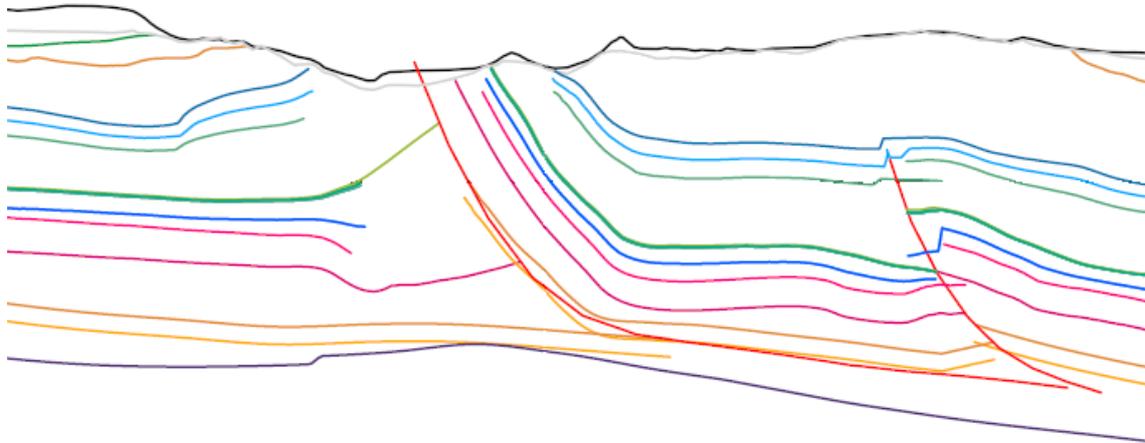


Fig. 3: Horizons near faults (red lines) in a section through the GeoMod 2011.1. If horizons cross-cut a fault plane, interpolation routines can not automatically decide on which side of the fault which part of the horizon is.

2 Workflow and Software

2.1 Geological model builder Geo3D

To build up a geological model, the bottom and top of every hydrogeological unit has to be defined correctly in all places without gaps (e.g. at fault zones or the topography). This usually is achieved by building the model from bottom to top. Beginning at the bottom, the top surface of the each geological layer is added to the model as a deposition, an unconformity or an erosion surface (Fig. 4). In the project documented here, the software used for this task is Geo3D (www.simultec.ch/it/geo3d).

Geo3D is capable of cutting triangulated surfaces with each other following the rules specified in Fig. 4. The resulting geological model can be visualized as a volume model confined by a prescribed boundary polygon. Geo3D is fully automatic, therefore surfaces and surface configurations have to be prepared beforehand. As the prerequisites of the used software define the necessary workflow, these will be shortly described here.

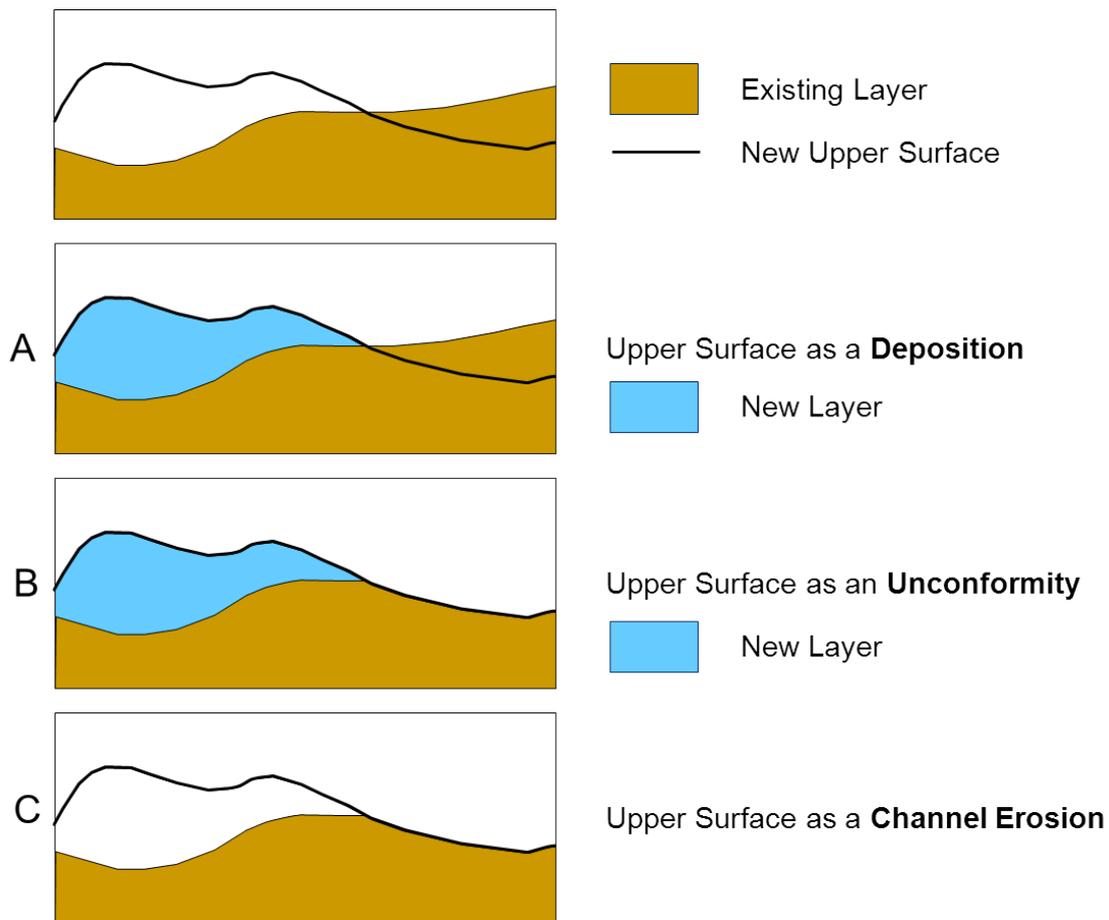


Fig. 4: Ways of adding a new layer surface to the geological model:
 A) the already existing layer is not cut by the new surface. A new layer is added where the new surface is higher than the existing.
 B) the already existing layer is cut away where the new surface is lower than the existing. A new layer is added where the new surface is higher than the existing.
 C) the already existing layer is cut away where the new surface is lower than the existing. No new layer is added.

To be able to cut the surfaces with each other, Geo3D asks for surfaces that observe the following rules:

- The boundary polygon must be covered completely by every surface
- Overlapping is not allowed (the proceeding at thrust faults is shown in Fig. 6)
- Every surface must be defined in the same triangulation mesh

It is recommended that two surfaces that have to be cut with each other, for example a horizon and the topography, cut at a minimum angle, otherwise the intersection line can become tortuous. In areas where two surfaces cut each other, the surfaces cannot have identical elevations because in this case the intersection is a plane and not a line and therefore the cutting is impossible.

During the cutting process, new triangles are generated depending on the intersection points between the surfaces (Fig. 5). These triangles may be very thin in shape or very tiny. If this happens, the resulting mesh cannot directly be used to generate a mesh suitable for a finite element code because it doesn't fulfill the angle criteria (Zlámal 1968).

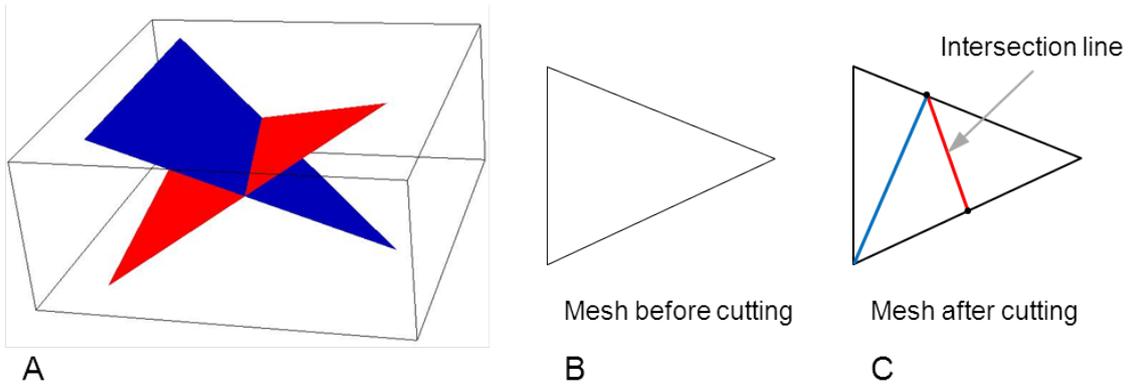


Fig. 5: Generating new triangles during the surface cutting process.
 A: 3D-view of two intersecting triangles
 B: Triangles before the cutting process (plan view)
 C: The triangles intersect each other at the red line. The blue line is added to avoid elements with four vertices.

Faults are treated in the same way as layer surfaces and therefore have to fulfill the same rules as the horizons. The layers at each side of the fault have to be built up separately (Fig. 6).

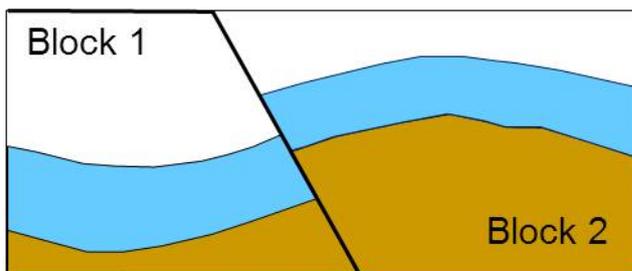


Fig. 6: Building up geological structures with a fault surface (thick black line).

Necessary simplifications of faults performed during the generation of the GeoMod 2011.1 lead to (unnatural) fault surfaces with opposite dip directions along their traces. These can't be used for cutting the geological layers because they can't be extended to cover the whole model region without creating ambiguous height assignments (Fig. 7).

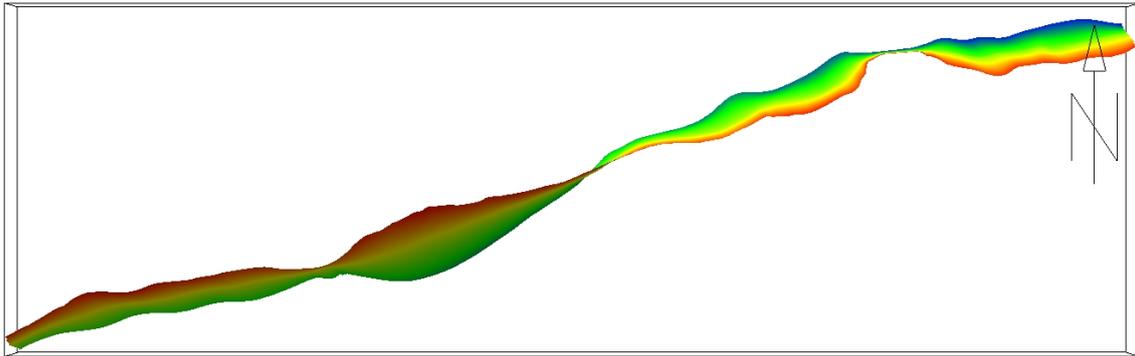


Fig. 7: The fault surfaces have to cover the whole model domain for the use in Geo3D. A fault with opposite dip directions along its trace can't be completed. Shown here is the example of the Baden-Irchel-Herdern Lineament, view direction from top. The changes of dip directions along the fault are clearly visible. Red colors denote the top of the fault, green colors the bottom.

As mentioned earlier, surfaces (and the layers between two surfaces) have to cover the whole model domain. Therefore, layers on one side of the fault can lack geological meaning. The meaningless parts of the layers are assigned a thickness of zero. For the subsequent usage in modeling software, the layer technically still exists, but is treated as non-existent because of its zero thickness.

2.2 Dividing into sub models

The existing 3D model contains 20 faults inside the model region (Fig. 8). As mentioned earlier, some of these faults change their dip direction within the model domain (e.g. the Baden-Irchel-Herdern-Lineament, see Fig. 7) while other faults are arranged perpendicular to each other. Since the succession of layers on each side of a fault has to be built separately, it is practically impossible to build a geological model of the whole model area at once using Geo3D. Therefore, the model region was divided into sub models. This has the added benefit of an increased calculation speed and decreased memory needs. To maximize these positive effects while minimizing the number of subdivisions, the following requirements for each sub model were formulated:

- The number of faults should be limited (about 5 – 6)
- The dip direction of faults should be continuous along the faults within each sub model.
- The faults should not be oriented perpendicular to each other.
- If possible, a fault should be entirely inside a sub model.
- Each local scale hydrogeological model should be fully enclosed in a single sub model.

The resulting subdivision of the whole model region is shown in Fig. 8. As the sub models had to be stitched together after properly modeling them, the sub models are separated by a thin gap (see Chapter 2.5). However, the horizon surfaces used for the sub model construction are larger than the sub model areas so that two adjoining sub models share an overlapping strip of approximately 3 km in width. This overlap guarantees that the sub models can easily be combined at their respective boundaries after cutting away the overlapping parts.

Two of the faults span almost the entire model (the Jura Main Thrust and the Baden-Irchel-Herdern Lineament) and had to be cut into separate parts to fulfill the above mentioned criteria.

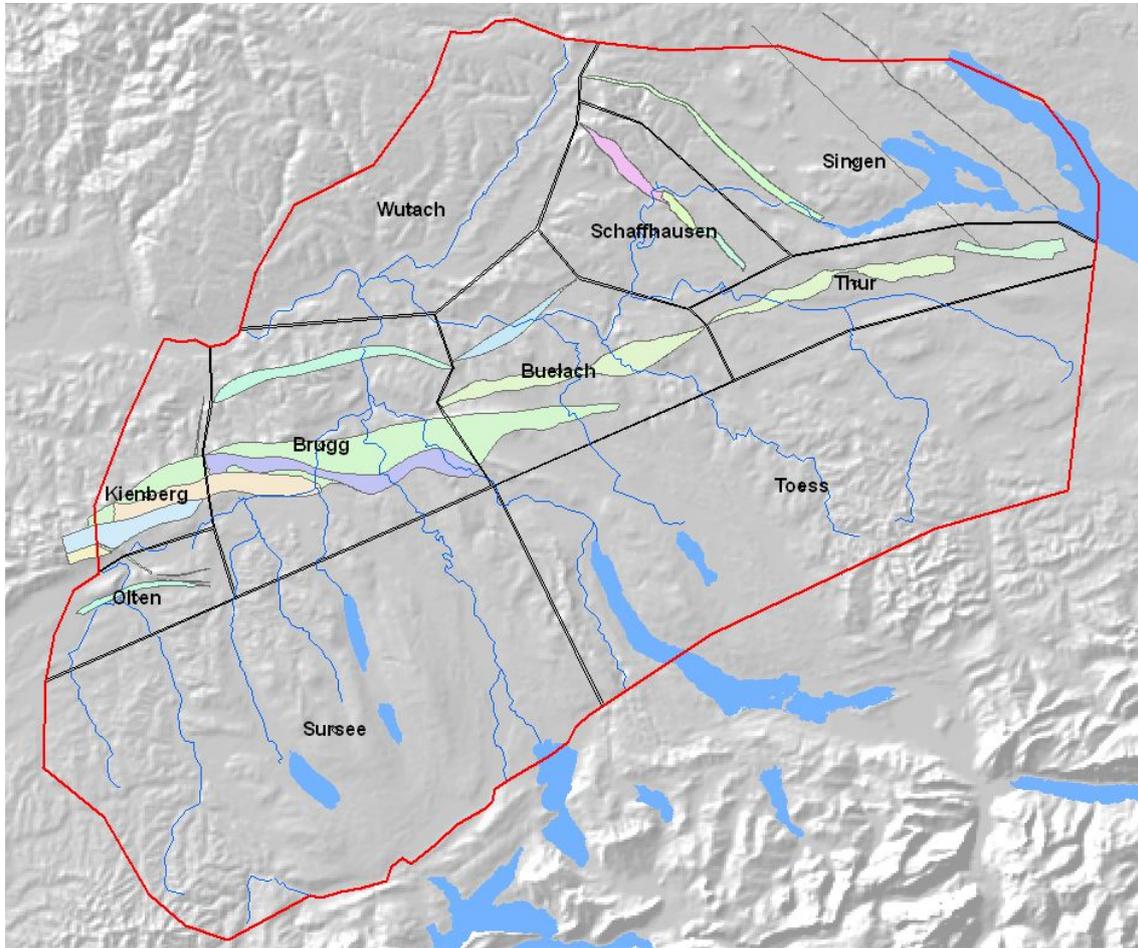


Fig. 8: Boundaries of the regional scale hydrogeological model and the sub models.

2.3 Extending horizons to the sub model area

After defining the sub model boundaries, the surfaces had to be prepared for use in Geo3D.

As a first step, a common triangulation covering the overall model region was created using the triangle tool (Shewchuk, 1996). The triangulation of the whole model resulted in 63314 nodes and 125903 elements. The mesh generator was forced to allocate element sides to the river network and sub model boundaries. The refinement of the mesh was adapted so that outcrop areas and fault traces have a finer mesh while in the southern part of the model, where no structural elements necessitated a fine mesh, a coarser mesh was allowed. The element side lengths range from 200 to 500 m. From this mesh, the sub models (including the overlapping parts) were cut out.

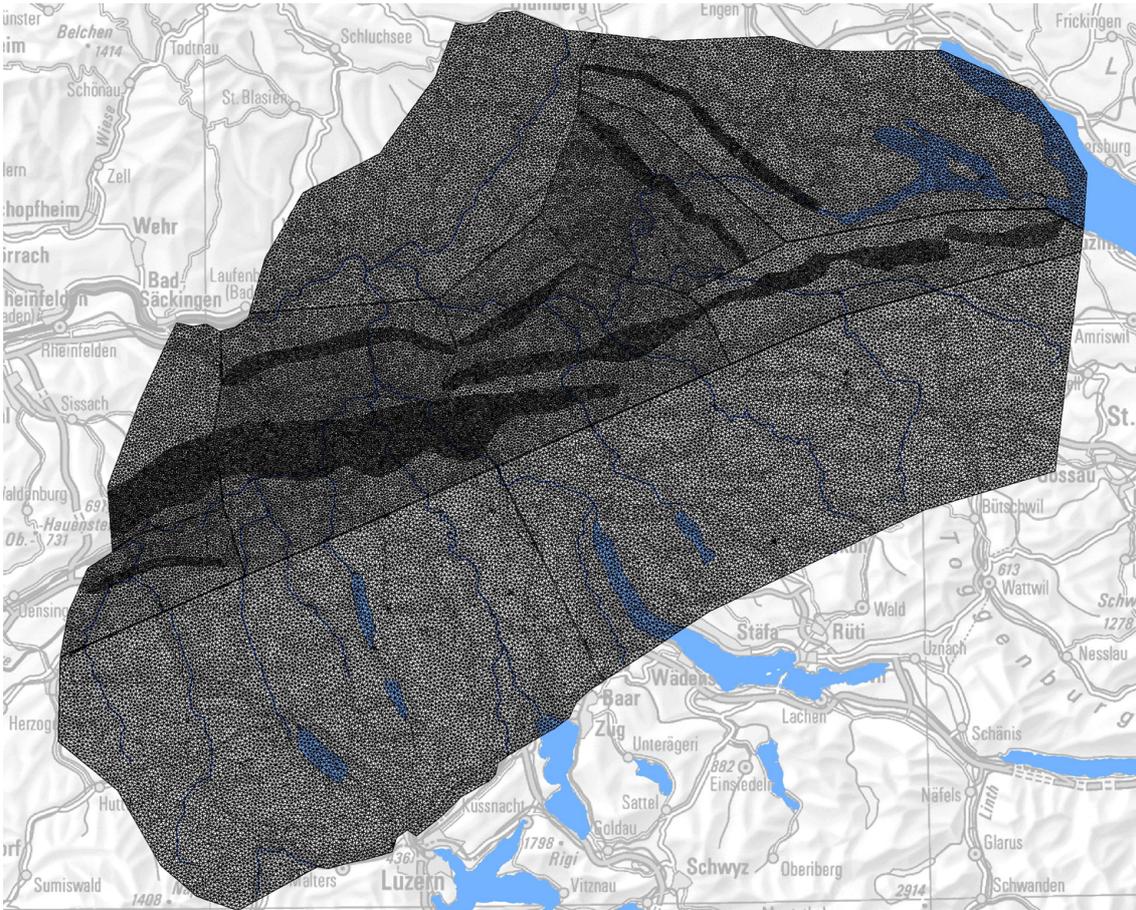


Fig. 9: Common triangulation grid used for the GeoMod 2012. The mesh is more detailed in the faulted areas.

The second step was to interpolate all the horizons to the sub model mesh, to meet the needs of Geo3D for cutting. The elevations of GeoMod 2011.1 were interpolated linearly to the nodes of the sub mesh. Problems occurred along the faults because some horizons were defined twice due to overthrusting and an elevation assignment was ambiguous (see Fig. 1). Therefore, the GeoMod 2011.1 horizons were first split into parts and restricted to either side of a fault. After splitting, some remaining triangles crossing the faults had to be cut off. This worked well with the base of the Opalinus Clay, the base of the Malm and the base of the Tertiary, because these horizons had been sealed against the fault surface.

Some horizons contained large, ambiguous areas on both sides of the faults. This could only be treated by cutting the surface crossing the fault and reconstructing the missing parts. The process is highlighted in Fig. 10: If the overlapping area and the area along the fault are cut off, a subsequent splitting of the surface along the fault does result in a correct assignment of the surface parts to the sides of a fault.

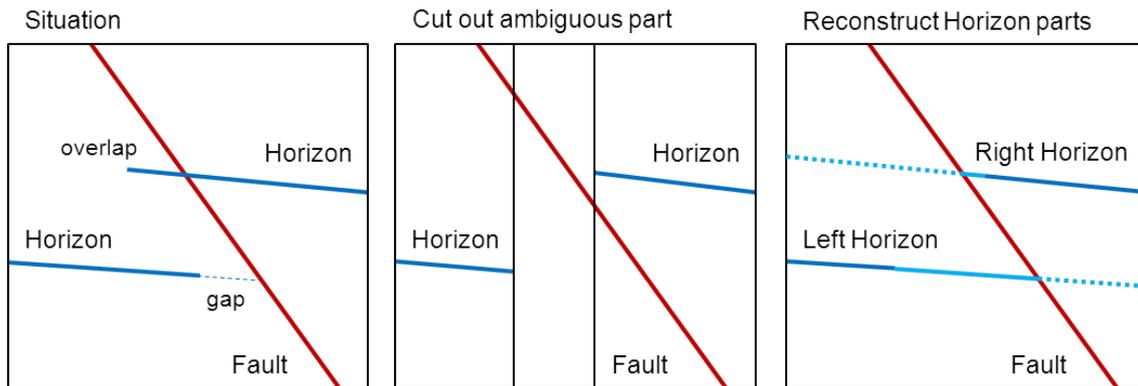


Fig. 10: Cutting and reconstruction process at places where the assignment of the horizon heights was ambiguous. Left: The situation in GeoMod 2011.1. Center: The ambiguous parts are cut out. Right: The surfaces are reconstructed (light blue line) to cover the whole model region as required by Geo3D. The dotted parts are later withdrawn by cutting the model with the fault surface.

The third step was to extrapolate the horizons so that each horizon covers the whole sub model region. The following methods were used:

- Direct extrapolation of the horizon surface
- Extrapolation of the geologic layer thickness

The thickness extrapolation was used for layers with a rather constant thickness, like the Opalinus Clay. The extrapolation algorithm is described in Appendix A. However, the method could not be used for the Molasse layers with their varying thicknesses. The Molasse layers had to be extrapolated directly, sometimes using additional information of known outcrop lines.

After extrapolation, the outcrop lines at the topography were constructed and compared to the mapped outcrop lines (Swisstopo 2005). If the outcrop lines could not be matched, the mapped outcrop lines were used as additional data sources and the gaps between the outcrop lines and existing horizons were filled by interpolation.

2.4. Building up the 3D volume models

For every sub model region, a 3D volume model was created using Geo3D. The model was built up by defining the sequence of surfaces to add to the model obeying the rules for cutting and adding layers (according to Fig. 4). The overlapping regions were cut off after model creation.

2.5 Joining the sub models together

As mentioned in Chapter 2.2, a gap was left between the sub model areas. This gap was filled with exactly one element row at the triangulation process with the horizon elevations on both sides of the gap belonging to two different sub models. For joining the horizons, the nodes on both sides of the row had to be connected again. Because of the cutting process, some new nodes were created on the model borders. However, the original elements of the common grid are preserved in the model grids, so the definition of new elements is rather easy. The new

nodes are connected to the opposite side of the row and new elements are defined inside the original element.

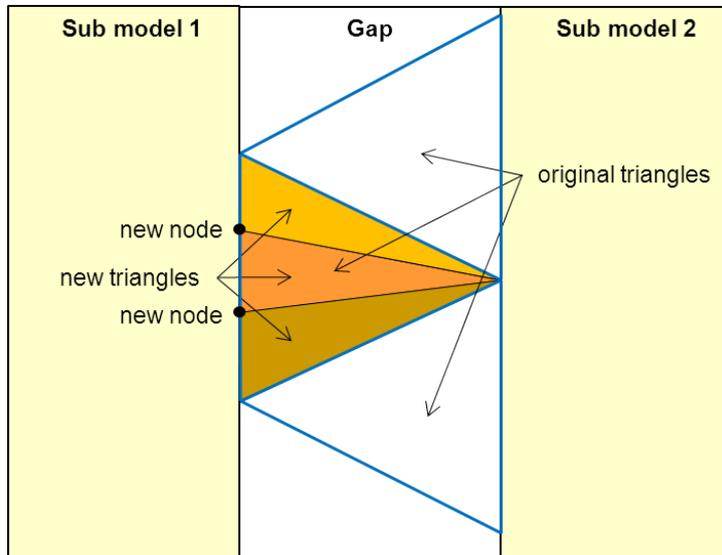


Fig. 11: Principle of adding new elements to the gap in between two sub models: The original mesh contained the blue triangles. Inside these triangles, new triangles were defined connecting the new nodes with the existing node on the other side of the gap.

A special situation occurs, when a fault crosses the gap between two sub models. Triangles from above and underneath the fault can exist at the same place. The joining algorithm therefore has to know the relative position of the node compared to the fault. This information was created by assigning a unique number to the blocks between the faults (Fig. 114).

2.6 Software modules

As instruments for the horizon constructions, the following software modules have been used:

- Interpolate.c
- Extrapolate.c
- Split.c
- Cleantri.c
- Join.c
- Tricalc.pl
- Triop.pl

The modules were developed by Simultec AG in the course of former projects or specifically with regard to the needs of the model build up presented in this report. The sources are published in the digital attachments and further described in appendix A; the commercial rights remain with Simultec AG.

During the preparation of the surfaces and the creation of the layers, the quality of the resulting horizons were controlled and, where necessary, corrected manually. FEFLOW was used to manually change the elevations of single nodes in some special cases. Fig. 12 shows an example of manual editing of the Jura fault to cut off some odd parts of the Muschelkalk layer.

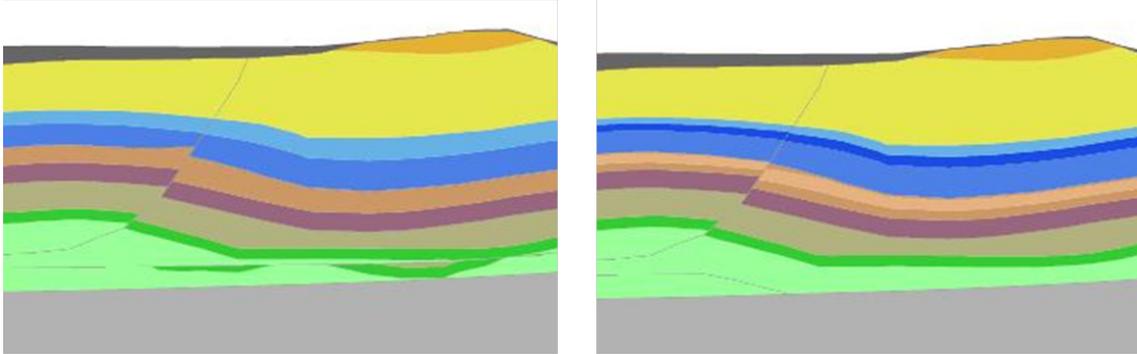


Fig. 12: Manual editing of the Jura Fault surface: Left: model without editing, right: model after moving down the Jura fault and as a consequence omitting the odd parts of the green unit.

3 Surface Preparation

3.1 Horizons

The following subchapters describe the rules used in general for the construction of every horizon (the operations described below were done separately for each sub model). Depending on the situation, deviations from these general rules were necessary. They are listed in Chapters 4.2 to 4.11, according to the sub model they occurred.

3.1.1 Base Mesozoic

In the GeoMod 2011.1, the horizon “Base Mesozoic” covers nearly the whole model region (see Fig. 13). In the missing part at the northern boundary, the Base Mesozoic horizon had to be calculated from the base Opalinus Clay horizon by subtracting the thicknesses of the Keuper, Lias and Muschelkalk layer using isopach maps.

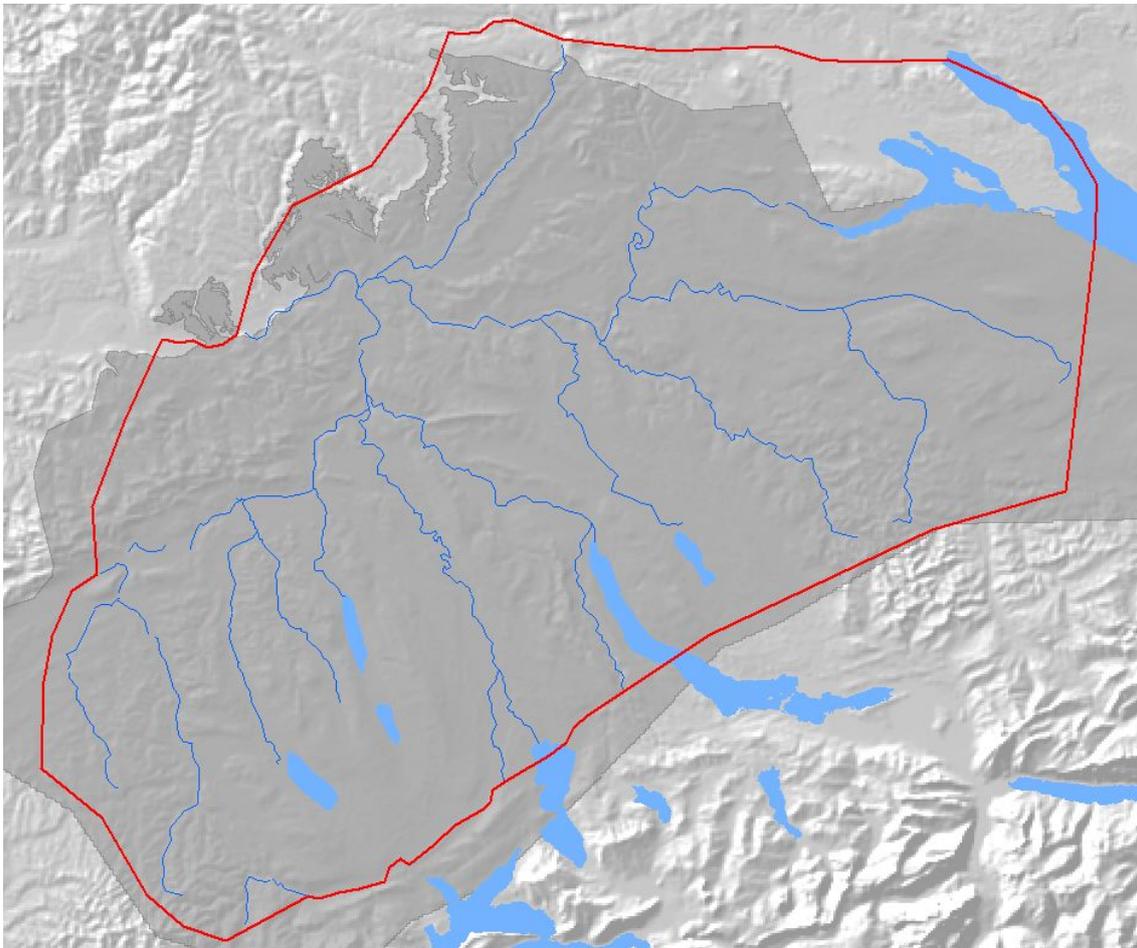


Fig. 13: Red polygon outlines the extend of the model area. Darker grey area represents the extension of the Base Mesozoic horizon in GeoMod 2011.1.

3.1.2 Base Upper Muschelkalk

The horizon “Base Upper Muschelkalk” in the GeoMod 2011.1 covers the southern part of the model region (see Fig. 15). In the north east, the horizon is missing. Towards the north west, the horizon extends to below the outcrop line of the top of Muschelkalk. As Fig. 15 shows, a rather large area is missing between the outcrop line of the top Muschelkalk and the Base Upper Muschelkalk according to the resulting model. For the completion of the horizon, two different strategies were used:

North East: The missing part of the horizon is calculated by adding the extrapolated lower Muschelkalk thickness to the Base Mesozoic horizon (see previous chapter).

North West: The missing part of the horizon is created by triangulating the area between the mapped outcrop lines of the Upper Muschelkalk base and the border of the existing horizon. The node elevations along the outcrop lines were taken from the digital elevation map. The resulting triangles were then used as a patch for the horizon interpolation.

Along the fault surfaces, the horizon had to be expanded in order to get an intersection of horizon and fault. This was done performing the following steps (steps 2 – 7 are illustrated in Fig. 14):

1. Interpolate Base Opalinus Clay and Base Upper Muschelkalk horizons to the common triangulation grid (see Fig. 9). The part where these horizons are not unique are cut out (see Fig. 10).
2. Calculating the thickness distribution of the Upper Muschelkalk layer as a difference between Base Opalinus Clay and Base Upper Muschelkalk
3. Extrapolate the Upper Muschelkalk thickness distribution to cover the missing parts
4. Split the Base Opalinus Clay along the faults to create separate parts for each interspace between faults (see Fig. 16).
5. Extrapolate the Base Opalinus Clay parts to the whole sub model area. A high extrapolation quality is only requested in the vicinity of the part boundaries. The more distant nodes will be cut off during the model build process (Fig. 10).
6. Subtract the Keuper & Lias thickness distribution and the Upper Muschelkalk thickness distribution from the Base Opalinus Clay parts (Fig. 17 left).
7. At the outcrop area, the horizon had to be calculated from bottom up, adding the thickness of the lower Muschelkalk layers to the Base of the Mesozoic (Fig. 17 right). In outcrop areas the extension of the underlying horizons is larger than that of the overlying horizons. As a consequence, the horizon construction is more accurate when done from bottom to top.

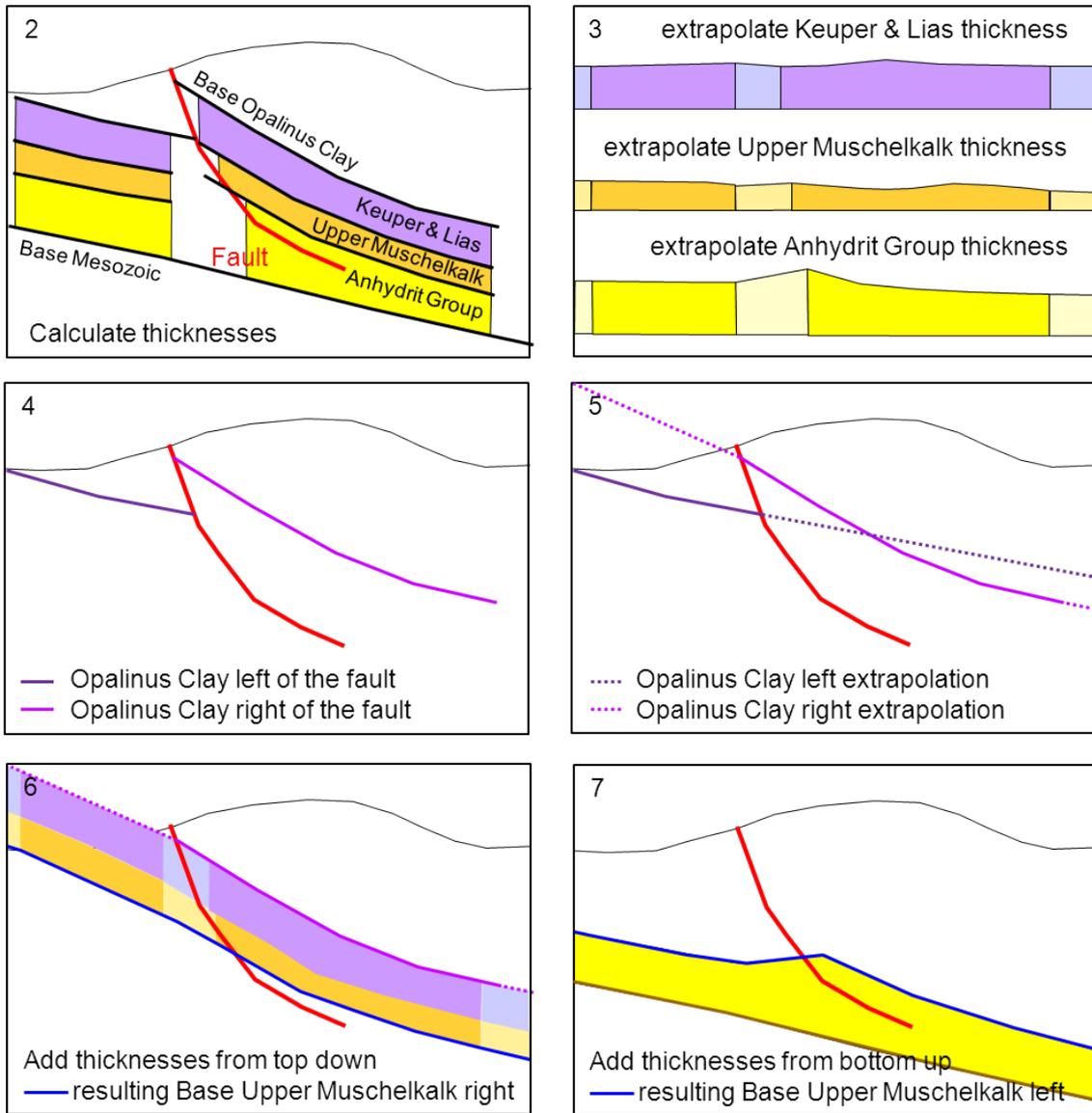


Fig. 14: Procedure followed to generate the Base Upper Muschelkalk horizon.

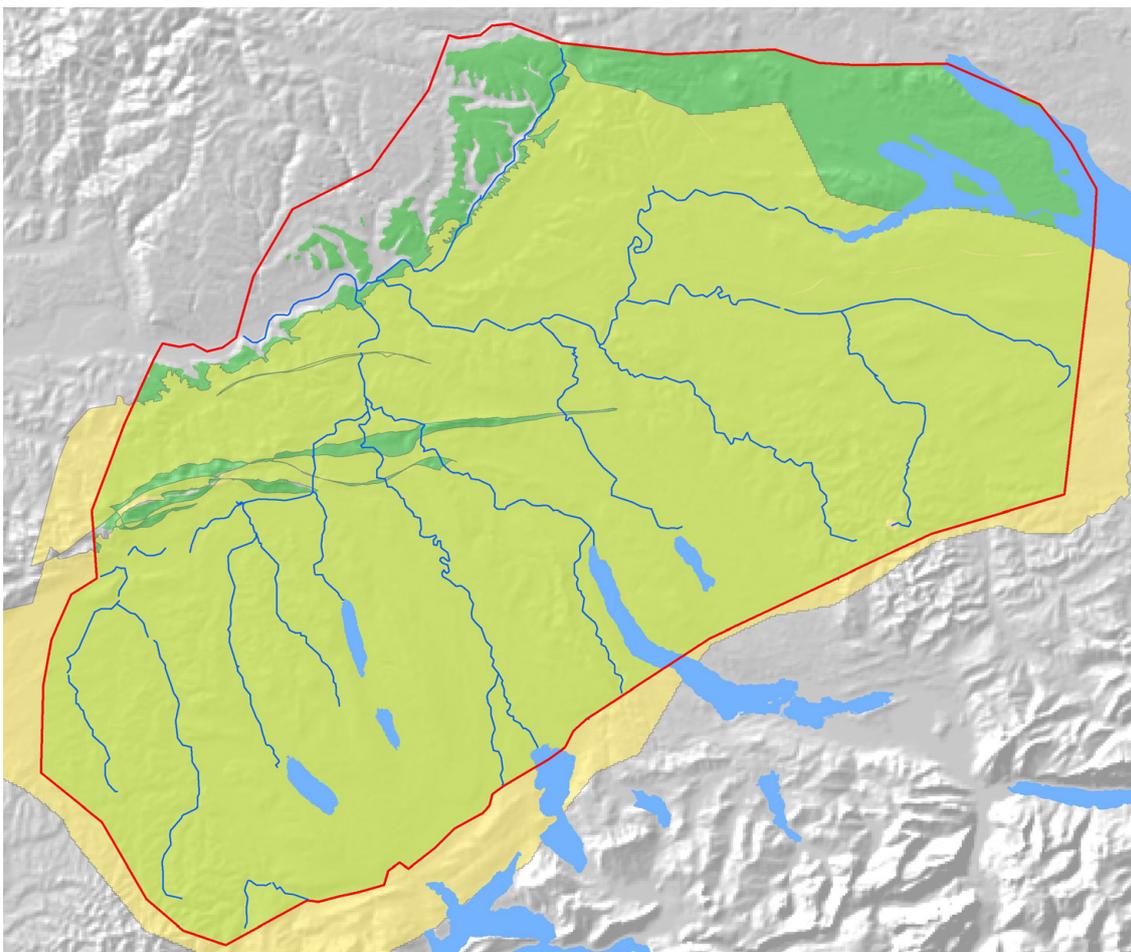


Fig. 15: Extensions of the Base Upper Muschelkalk horizon in GeoMod 2011.1 (yellow color). The green underlayed area indicates the resulting horizon extension in GeoMod 2012.



Fig. 16: Resulting parts after splitting the Base Opalinus Clay horizon along the faults.

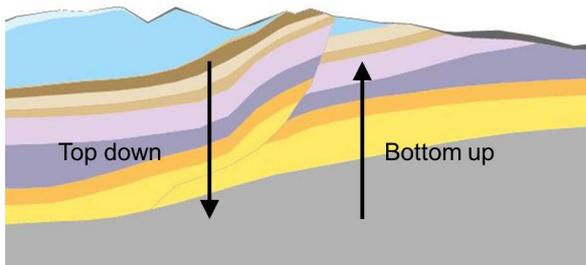


Fig. 17: Generating horizons by subtracting (left) or adding (right) layer thicknesses.

3.1.3 Top Muschelkalk

The Top Muschelkalk horizon of the GeoMod 2011.1 covers the same area as the base Upper Muschelkalk horizon. It covers nearly the whole model domain (see Fig. 18), but had to be extended in the north eastern part. This has been done by adding the Muschelkalk thickness to the previously calculated Base Mesozoic horizon (see Chapter 3.1.1).

Along the faults, the same procedure was followed as with the Base of the Upper Muschelkalk described above.

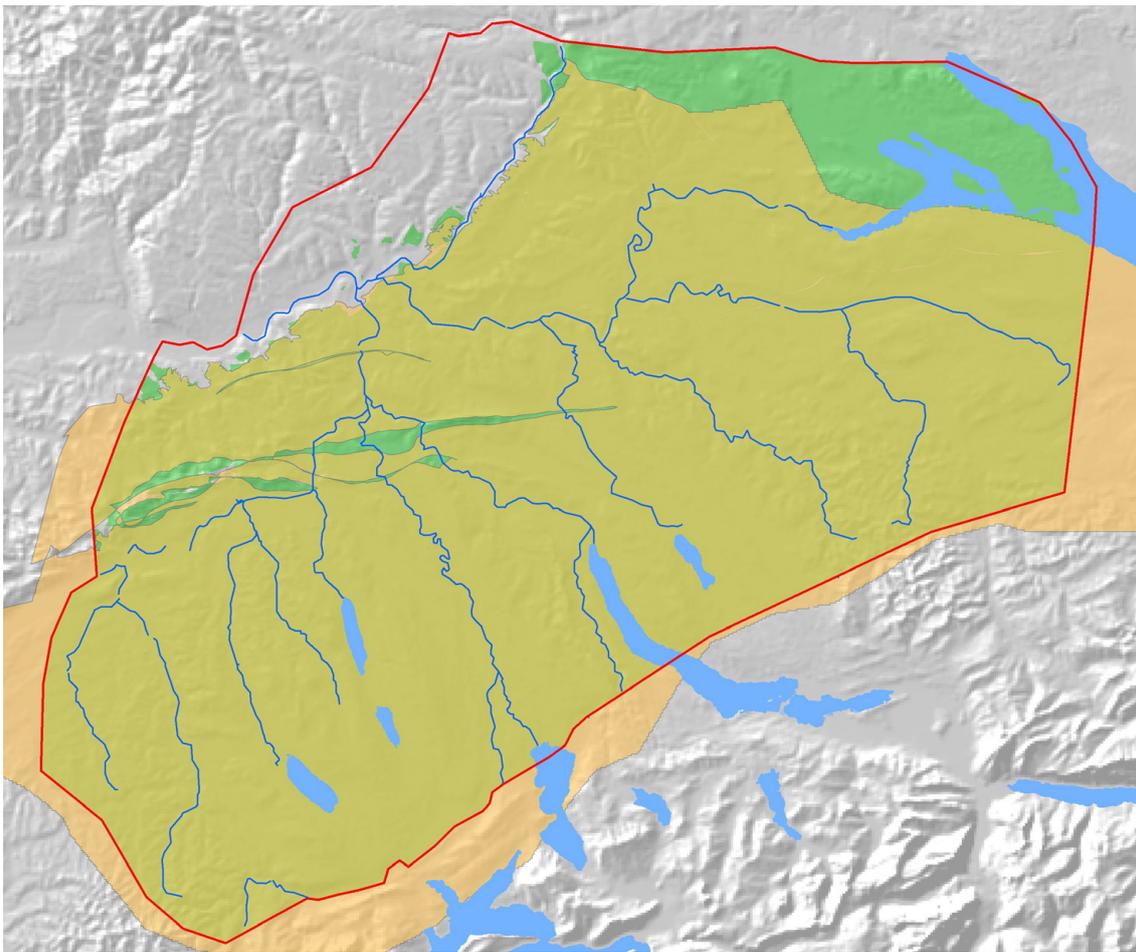


Fig. 18: Extensions of the Top Upper Muschelkalk horizon in GeoMod 2011.1 (orange color). The green underlayed area indicates the resulting horizon extension in GeoMod 2012.

3.1.4 Base Opalinus Clay

The Base Opalinus Clay horizon was one of the base horizons of the GeoMod 2011.1. The horizon covers almost the whole model area and also includes parts outside of the model area (see Fig. 19). It is mostly sealed against the Quaternary base and the fault surfaces. However, the seals are not perfectly matching the respective horizons. To guarantee a perfect seal of the base Opalinus Clay and e.g. the Quaternary Base or the fault surfaces, the following steps had to be performed:

- Split the horizon along the faults to create separate parts for each interspace between faults, since the assignment is not known from GeoMod 2011.1 (Fig. 16).
- Cut remaining elements on the “wrong side” of the fault (imperfection of the seal).
- Extrapolate the horizon to cover the whole sub model region.

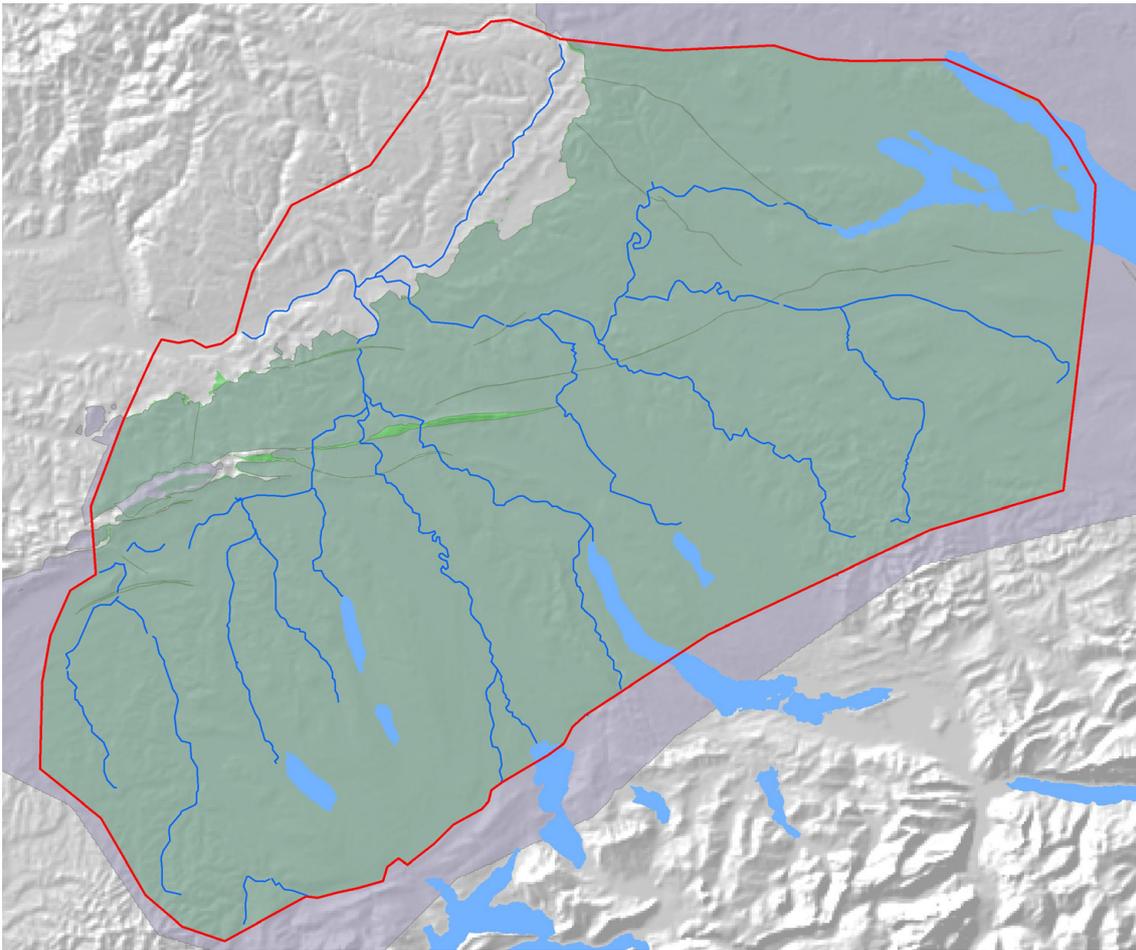


Fig. 19: Extension of the Base Opalinus Clay horizon in GeoMod 2011.1 (purple). The green underlayed area indicates the resulting horizon coverage in GeoMod 2012.

3.1.5 Top Opalinus Clay

Fig. 20 shows the extensions of the Top Opalinus Clay horizon in GeoMod 2011.1, together with the resulting horizon extension in GeoMod 2012. It can be seen that at the central and eastern part along the outcrop line, only small parts are missing. However, a larger area is missing south of the Jura faults. Fortunately, the thickness of the Opalinus Clay layer is rather homogenous. It was therefore possible to calculate the Opalinus Clay thickness from the Top and Base horizons and to extrapolate it over the missing areas. For the thickness calculation, the ambiguous parts along the faults were cut out (see Fig. 10). The thickness was then added to the Opalinus Clay base generated as described above.

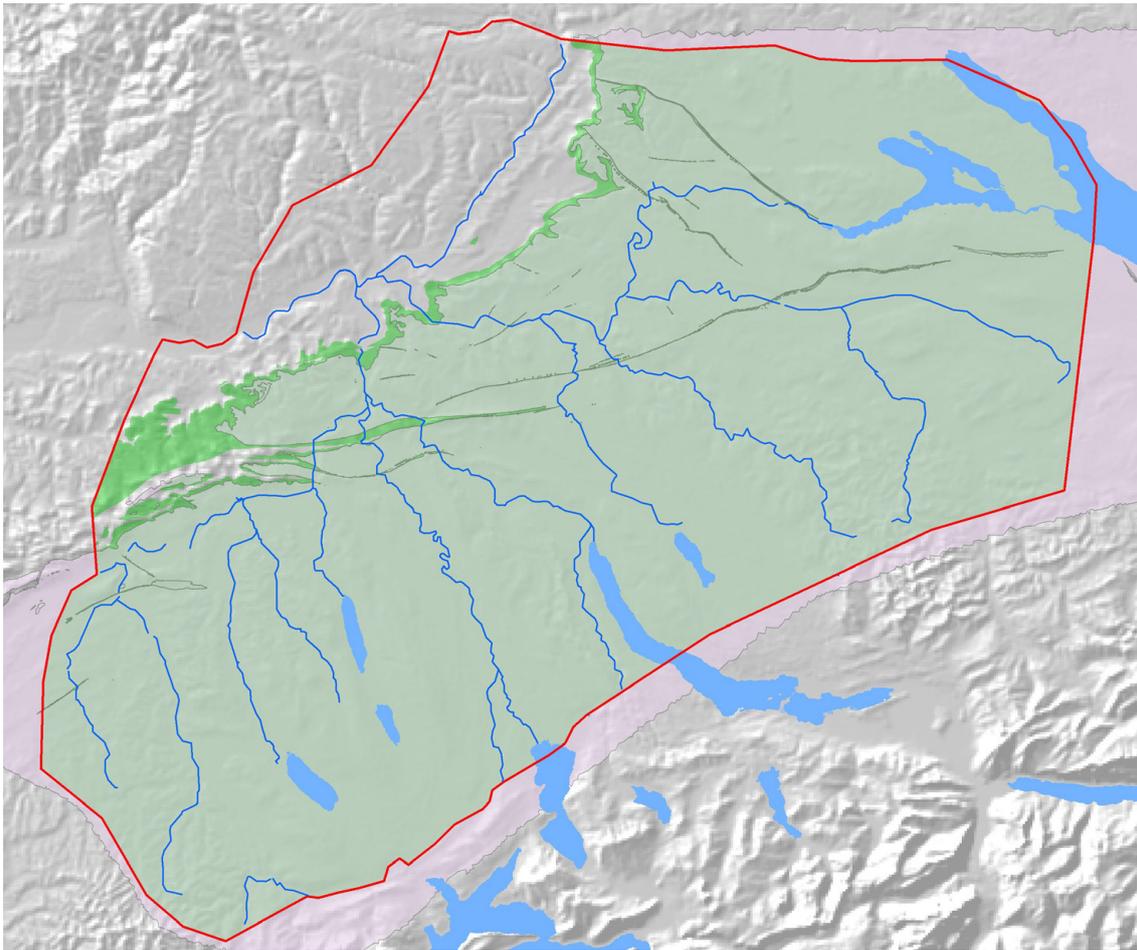


Fig. 20: Extension of the Top Opalinus Clay horizon in GeoMod 2011.1. The green underlayered area indicates the resulting horizon extension in GeoMod 2012.

3.1.6 Top Passwang

Fig. 21 shows the situation of the horizons between the base Malm and top Opalinus Clay. The Passwang Formation covers the whole model region while the Hauptrogenstein and Klingnau Formation cover overlapping parts. The remaining thin layer between the top of the Hauptrogenstein, the Klingnau Formation and the base of the Malm is called Upper Dogger.

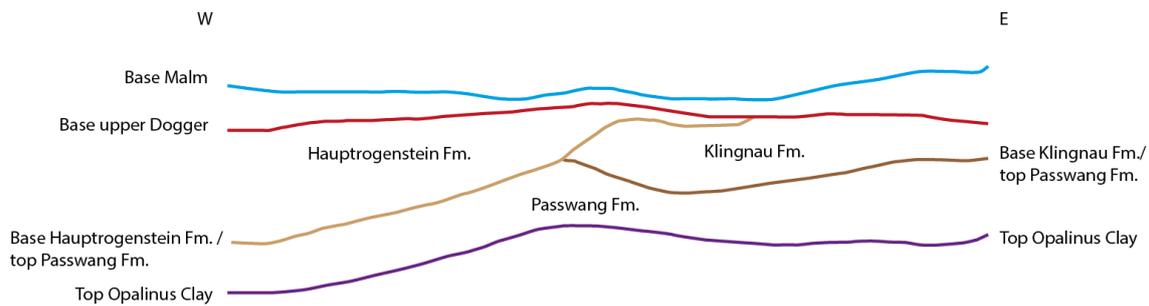


Fig. 21: Sketch showing the different horizons and their relationship between the base Malm and top Opalinus Clay.

In the GeoMod 2011.1, the Dogger horizons have been constructed using isopach maps, added to, or subtracted from, the Base Opalinus Clay and the Base Malm horizons. The lateral extensions of the Dogger horizons therefore cannot exceed the coverage of the Base Malm horizon. They had to be completed towards the outcrop lines and along the faults. In some places, the Dogger layers did not show the same thickness at different sides of a fault. Therefore, the thicknesses had to be calculated separately on both sides. The general procedure for generating the Dogger horizons was:

- Split all the Dogger horizons along the faults to create separate parts for each interspace between faults, since the assignment is not known from GeoMod 2011.1 (Fig. 16).
- Interpolate the parts to the common triangulation grid of the GeoMod 2012 (Fig. 9).
- Calculate the thickness distribution between the horizons.
- Extrapolate the thickness distribution to the whole sub model area.
- Add the extrapolated thickness distribution to the Base Opalinus Clay horizon.

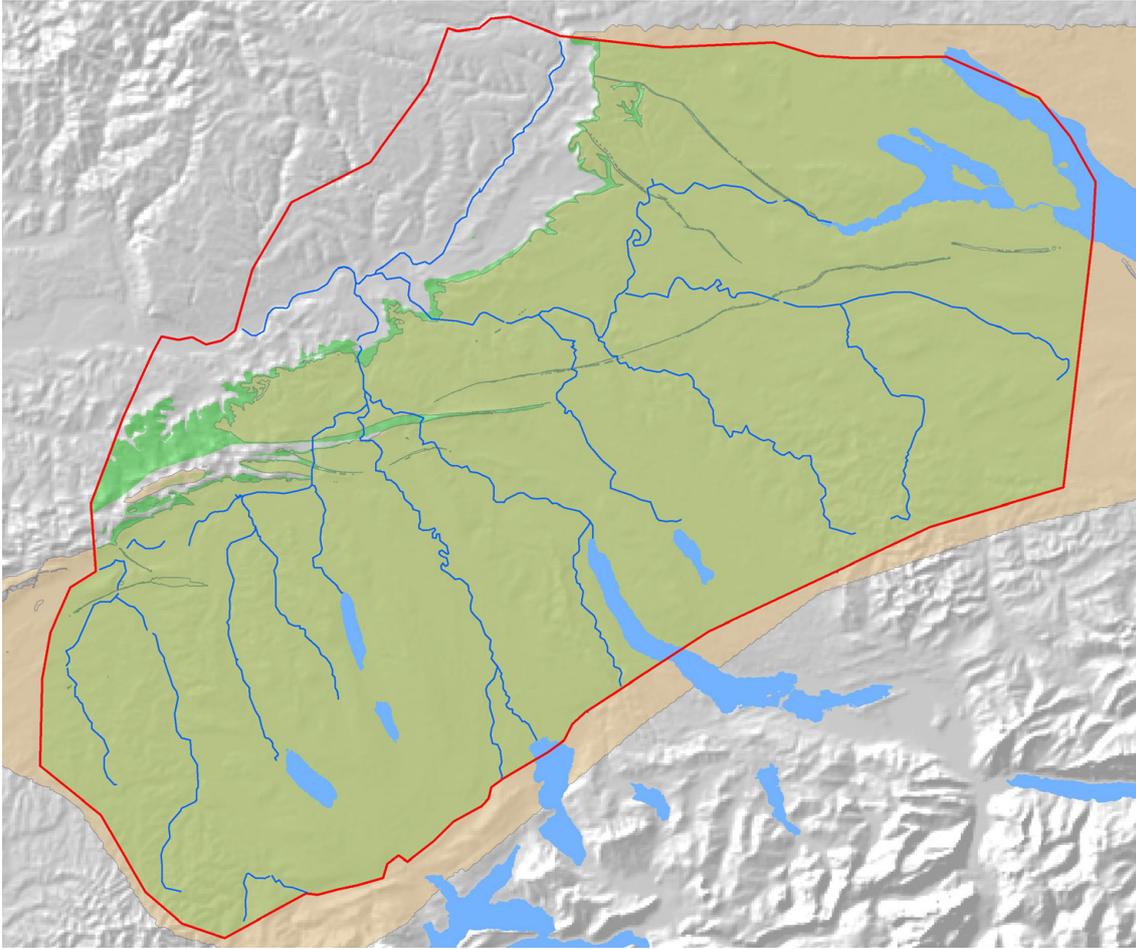


Fig. 22: Extension of the Top Passwang Formation horizon in GeoMod 2011.1. The green underlayed area indicates the resulting horizon extension in GeoMod 2012.

3.1.7 Top Klingnau

Sediments of the Klingnau formation are restricted to the eastern part of the model region. To the west, they are replaced by the Hauptrogenstein formation (see Fig. 21). The GeoMod 2011.1 horizon covers the whole area of the formation. As Fig. 24 shows, the Top Klingnau horizon had not to be determined in the sub models “Kienberg” and “Olten”. In order to extend the Top Klingnau horizon to the whole area of the remaining parts, the horizon was defined as the maximum of Top Klingnau and Base Hauptrogenstein horizon.

To construct the Top Klingnau horizon, the same rules as for the construction of the Top Passwang horizon were applied. Because the Klingnau formation is wedging out, the thickness had to be extrapolated by extrapolating the normal vectors on the thickness surface. Fig. 23 illustrates the extrapolation method used. In contrast to an extrapolation of the thickness values, the extrapolation of the normal vectors leads to a surface that crosses the zero thickness plane. The extrapolated thicknesses are used to calculate the Top Klingnau surface. Due to the negative values, the resulting surface crosses the underlying Top Passwang horizon and leads to a clean intersection line during the model build up.

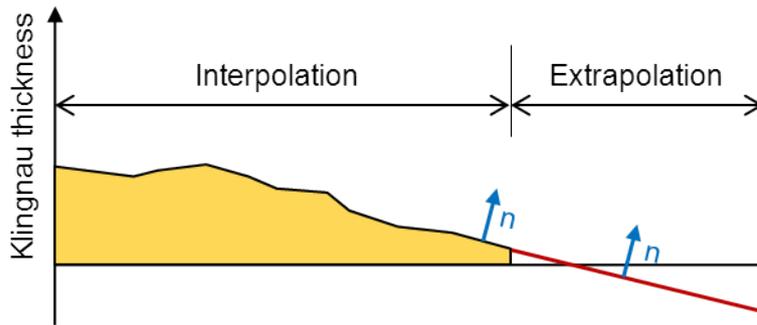


Fig. 23: Thickness extrapolation by extrapolating the normal on the thickness surface.

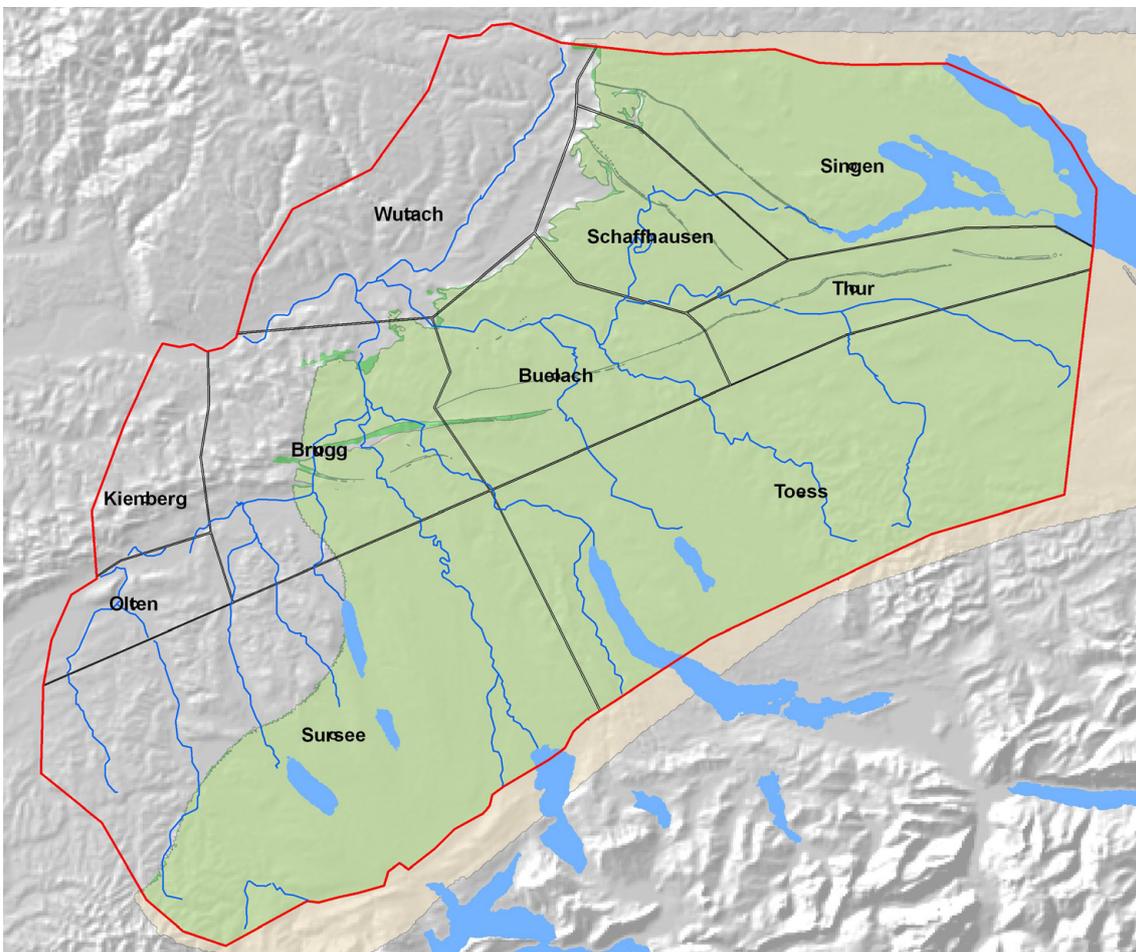


Fig. 24: Extension of the Top Klingnau horizon in GeoMod 2011.1 together with the sub model boundaries used for 3D-model build up. The green underlayed area indicates the resulting horizon extension in GeoMod 2012.

3.1.8 Top Hauptrogenstein

Sediments of the Hauptrogenstein formation are restricted to the western part of the model region. To the east, they are replaced by sediments of the Klingnau formation (see Fig. 21). The GeoMod 2011.1 horizon covers the whole area of the formation, except a smaller area around the mount Kienberg. As Fig. 24 shows, the Top Hauptrogenstein horizon are absent in the sub models “Toess”, “Thur”, Singen” and “Schaffhausen”. In order to extend the Top Hauptrogenstein horizon to the whole area of the remaining sub models the Base Upper Dogger horizon from the GeoMod 2011.1 was used. This horizon is identical to the Top Hauptrogenstein horizon, but has a larger extension (it also includes the Top Klingnau, see Fig. 21).

The rules used for the construction of the Top Hauptrogenstein horizon were the same as for the Top Klingnau horizon described above.

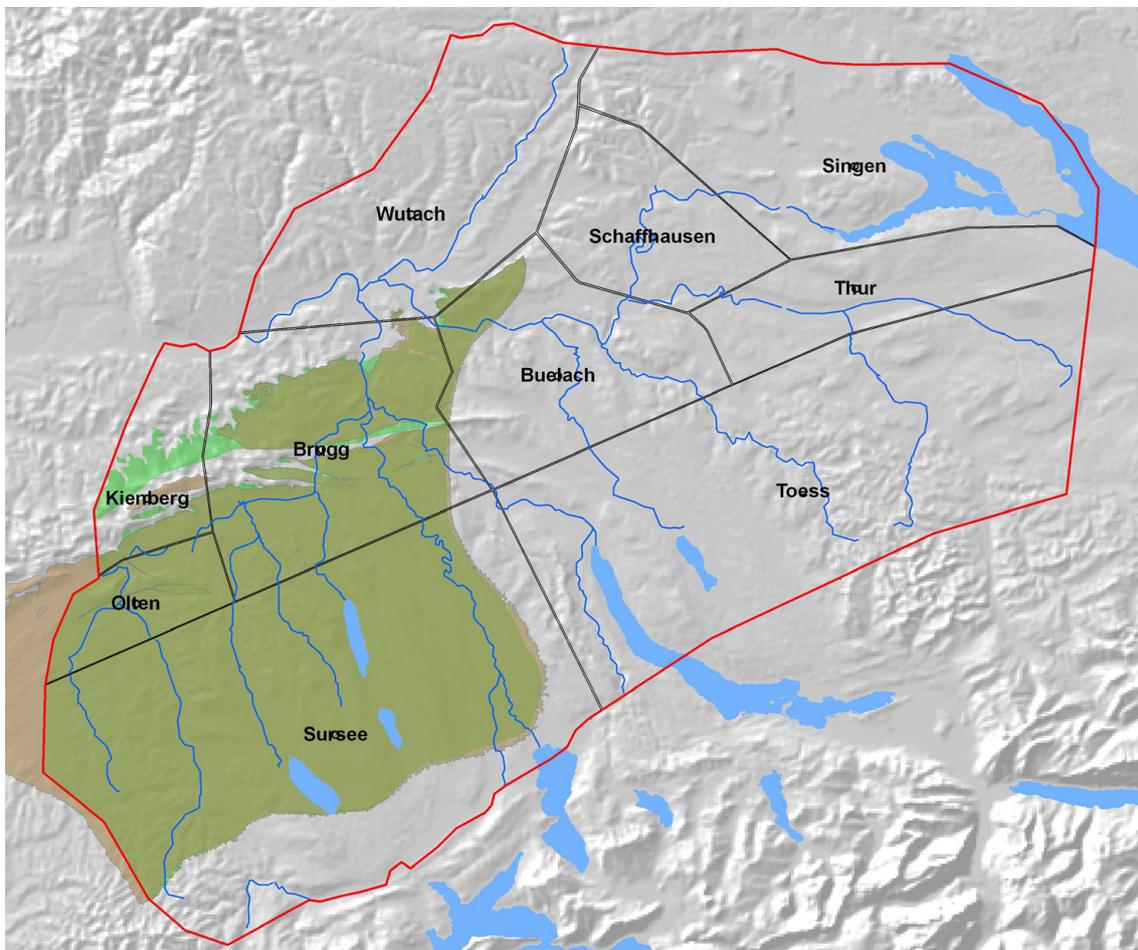


Fig. 25: Extension of the Top Hauptrogenstein horizon in GeoMod 2011.1 together with the sub model boundaries used for 3D-model build up. The green underlayed area indicates the resulting horizon extension in GeoMod 2012.

3.1.9 Base Malm

The base Malm horizon is one of the base horizons of the GeoMod 2011.1. It covers the whole model area and was sealed against the Quaternary base and the fault surfaces; however, sealing was not perfect. To guarantee an intersection of the horizon with the Quaternary base and fault surfaces, the following steps had to be performed:

- Split the horizon along the faults to create separate parts for each interspace between faults, since the assignment is not known from GeoMod 2011.1 (Fig. 16).
- Cut elements away that remained on the “wrong side” of the fault (imperfection).
- Extrapolate the horizon to the whole sub model area.

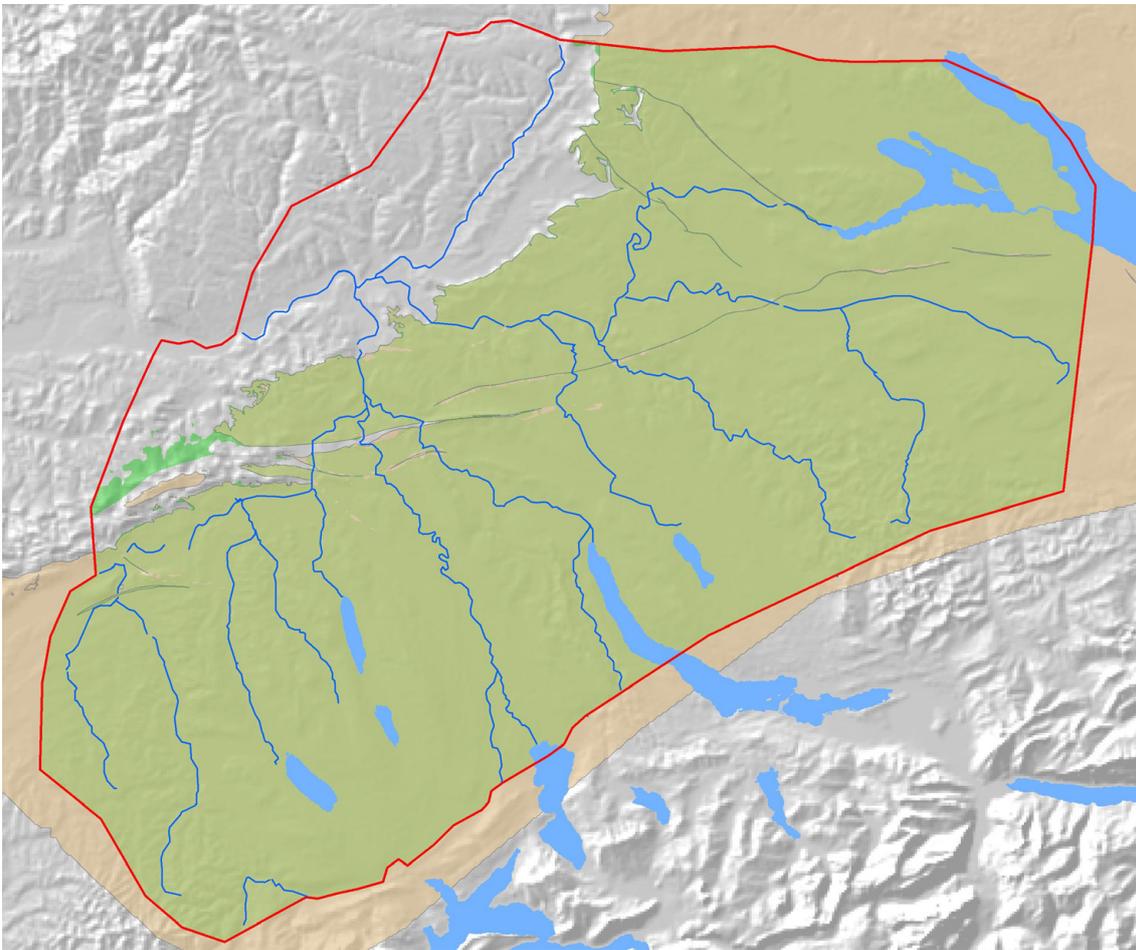


Fig. 26: Extension of the Base Malm horizon in GeoMod 2011.1. The green underlayed area indicates the resulting horizon extension in GeoMod 2012.

3.1.10 Top Effingen

Fig. 27 shows the extension of the Top Effingen horizon in the GeoMod 2011.1 and the resulting horizon extension in GeoMod 2012. Along the outcrop line, a strip of the Top Effingen horizon is missing. Towards the north, the strip expands to a width of about 10 km.

The Top Effingen horizon is calculated by adding the Effingen Member thickness to the base of the Malm. The determination of the Effingen thickness is rather difficult because it is not continuous over the faults and at some places, the extensions of the Effingen Member between two faults is rather small. Therefore, the rules for the thickness calculation had to be locally adapted. In general the following procedure has been done:

- Split the Base Malm and Top Effingen horizons along the faults to create separate parts for each interspace between faults (Fig. 16).
- Interpolate the resulting parts to the common triangulation grid (Fig. 9).
- Calculate the thickness distribution by subtracting the Base Malm horizon from the Top Effingen horizon.
- Extrapolate the thickness distribution (east of the Wutach valley, a minimum thickness of 60 m had to be postulated to fit the mapped outcrop).
- Extrapolate the Base Malm horizon parts as described above (Chapter 3.1.9)
- Add the Effingen Member thickness to the Base Malm parts.

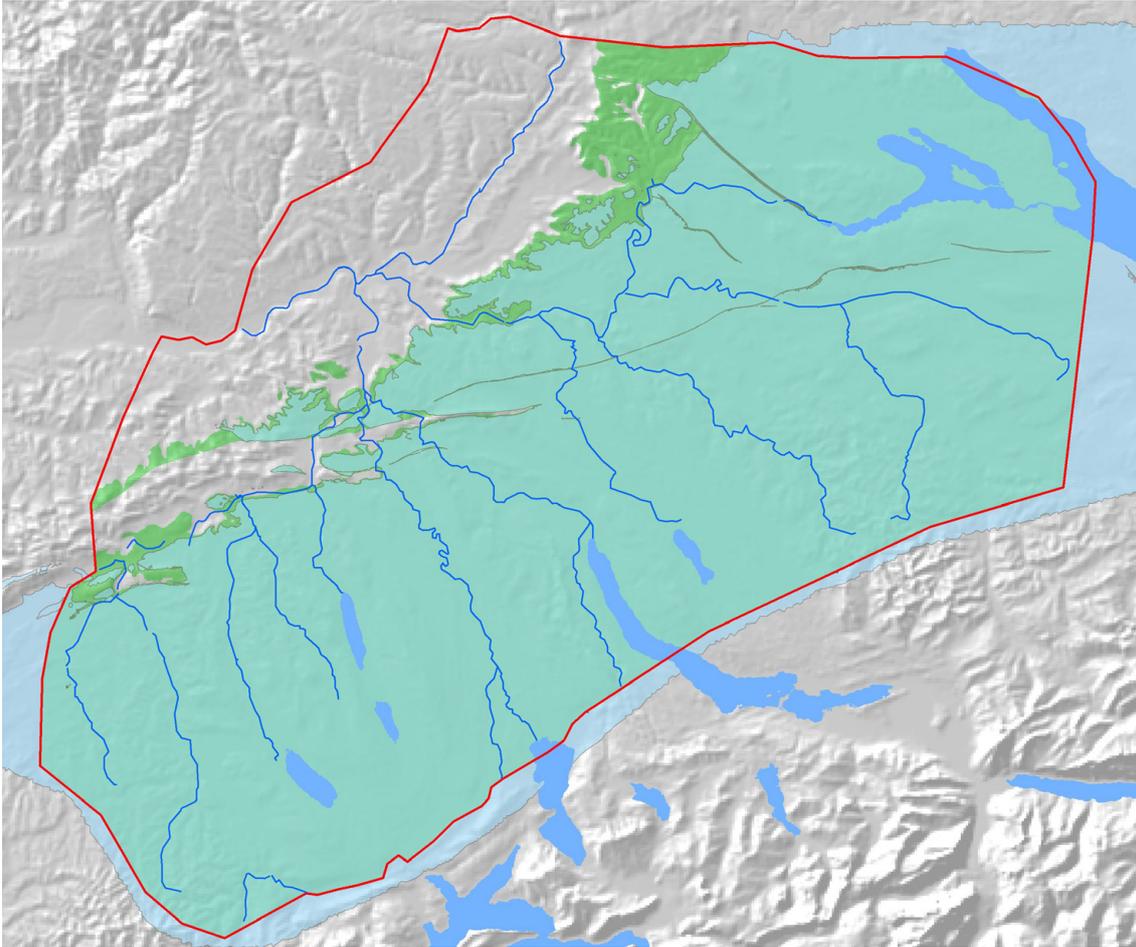


Fig. 27: Extension of the Top Effingen horizon in GeoMod 2011.1. The green underlaid area indicates the resulting horizon extension in GeoMod 2012.

3.1.11 Base Tertiary

The base Tertiary horizon is one of the base horizons of the GeoMod 2011.1. It covers the whole horizon extension inside the model area, except of a small part in the north. It was sealed against the Quaternary base and no problems with sealing accuracy were discovered. Because of the overthrusting, the Tertiary crops out before it reaches most of the faults. In these cases, no splitting had to be done, because no ambiguous zones exist.

The outer boundaries of the Base Tertiary horizon in GeoMod 2011.1 agree with the mapped outcrop line of the base tertiary. To guarantee the same outcrop line in GeoMod 2012 the elevations were interpolated inside the given area and set to a value higher than the Quaternary base outside the given area (see Fig. 28). This method assures that the intersection between the Tertiary Base and the Quaternary Base is precise and the area of the Tertiary formations is restricted to the area defined in GeoMod 2011.1.

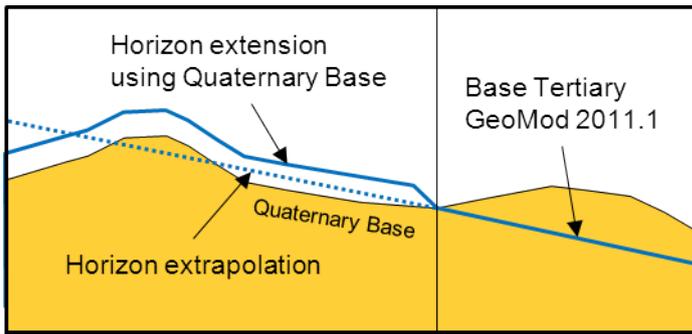


Fig. 28: Extending the Tertiary Base by setting it to a value above Quaternary Base outside the defined area.

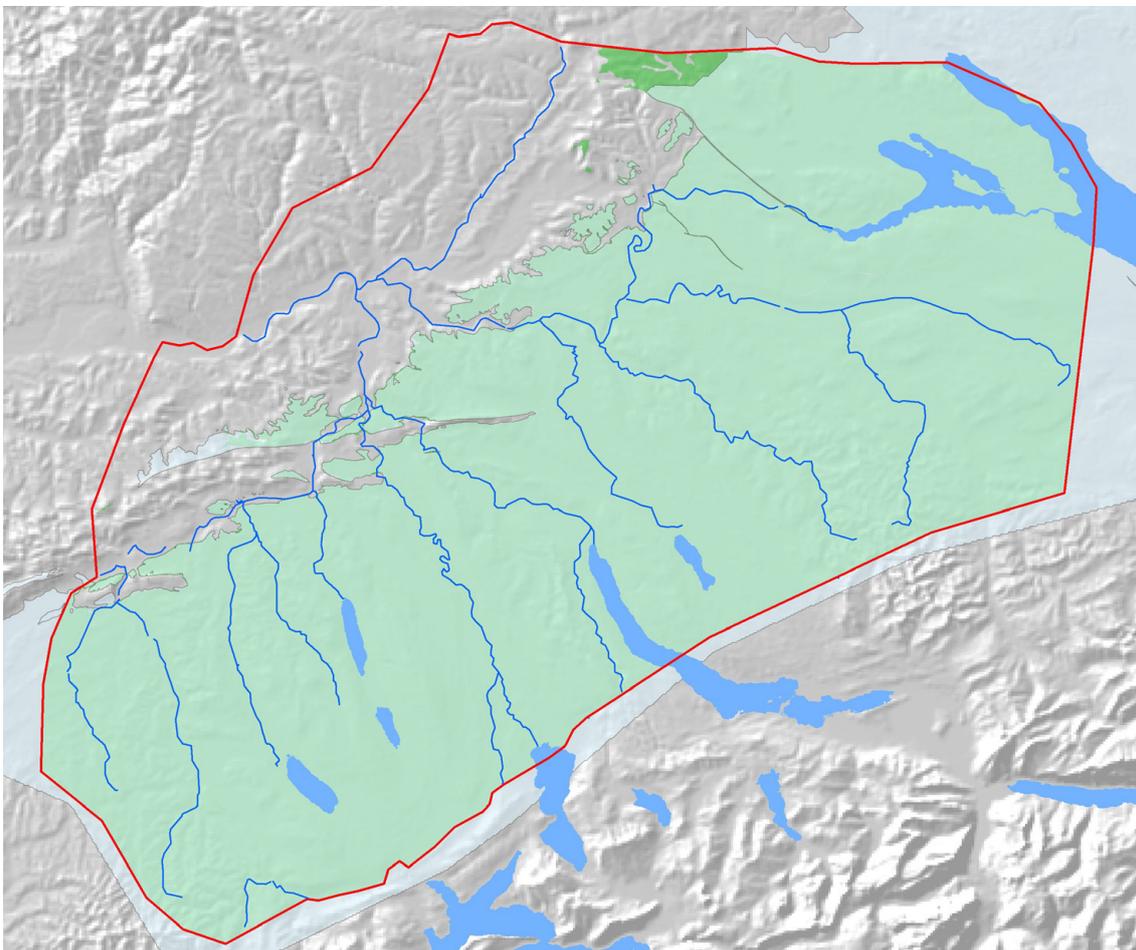


Fig. 29: Extension of the Base Tertiary horizon in GeoMod 2011.1. The green underlayed area indicates the resulting horizon extension in GeoMod 2012.

3.1.12 Base OMM (Obere Meeresmolasse)

In GeoMod 2011.1 the Base OMM horizon is build up from contour lines and is sealed against the Quaternary base. To guarantee the same outcrop line in GeoMod 2012, the elevations were interpolated inside the given area and set to a value higher than the Quaternary base outside the given area (compare Fig. 28).

The horizon does not cover the whole model region. Because the thickness of the Molasse layers is not continuous, the horizon can't be build up from the Molasse base. The missing gap at the western part was filled with a patch triangulation, constructed between the outcrop lines of the geological map (Swisstopo 2005) and the border of the GeoMod 2011.1 horizon. The elevations along the outcrop lines were adopted from a digital elevation model (Swisstopo 2008).

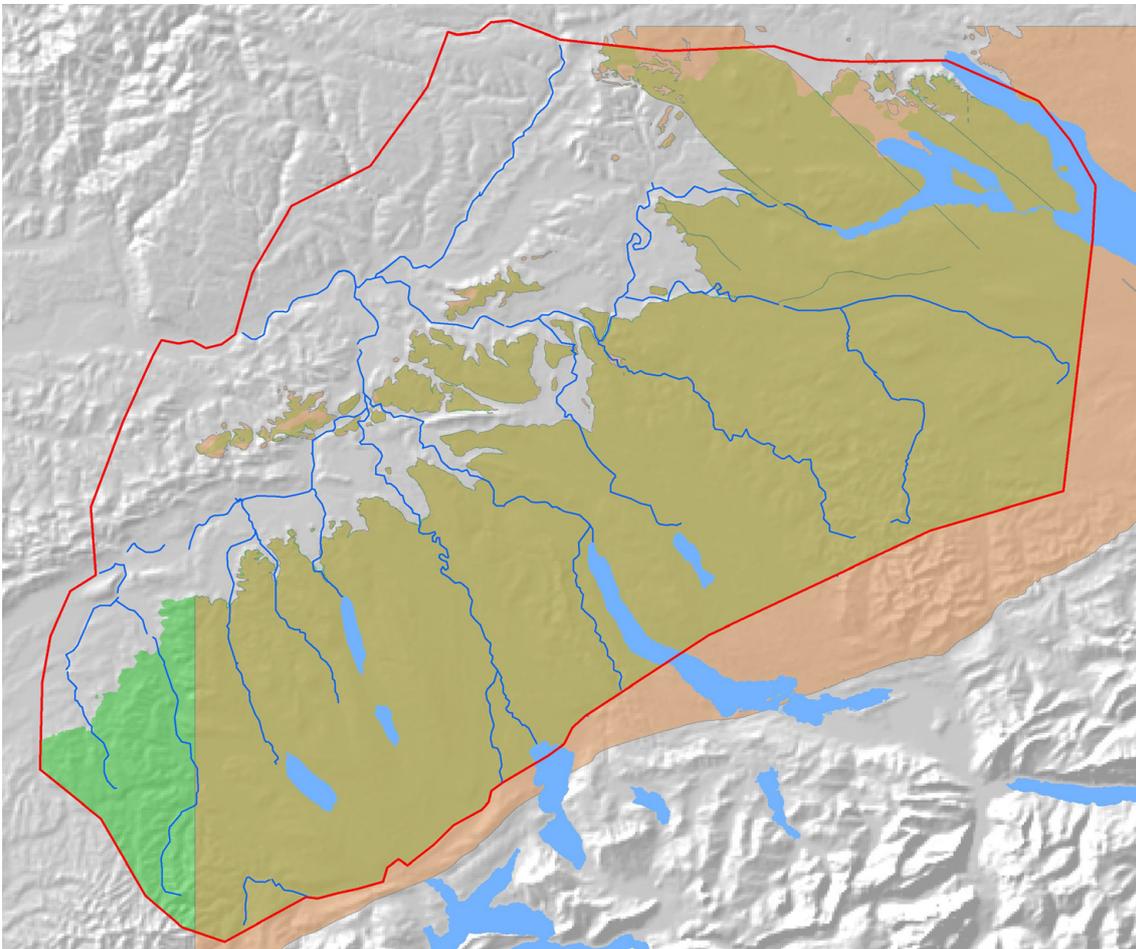


Fig. 30: Extension of the Base OMM horizon in GeoMod 2011.1. The green underlayed area indicates the resulting horizon extension.

3.1.13 Base OSM (Obere Süsswassermolasse)

In GeoMod 2011.1 the Base OSM horizon is build up from isopach maps and is sealed against the Quaternary base. To guarantee the same outcrop line in GeoMod 2012 the elevations were interpolated inside the given area and set to a value higher than the Quaternary base outside the given area (compare Fig. 28).

The horizon does not cover the whole model region. Because the thickness of the Molasse layers is not continuous, the horizon can't be build up from the Molasse base. The missing gap in the south-western part was filled with a patch triangulation, constructed from the outcrop lines of the geological map (Swisstopo 2005) and the border of the GeoMod 2011.1 horizon. The elevations along the outcrop lines were adopted from the digital elevation model (Swisstopo 2008).

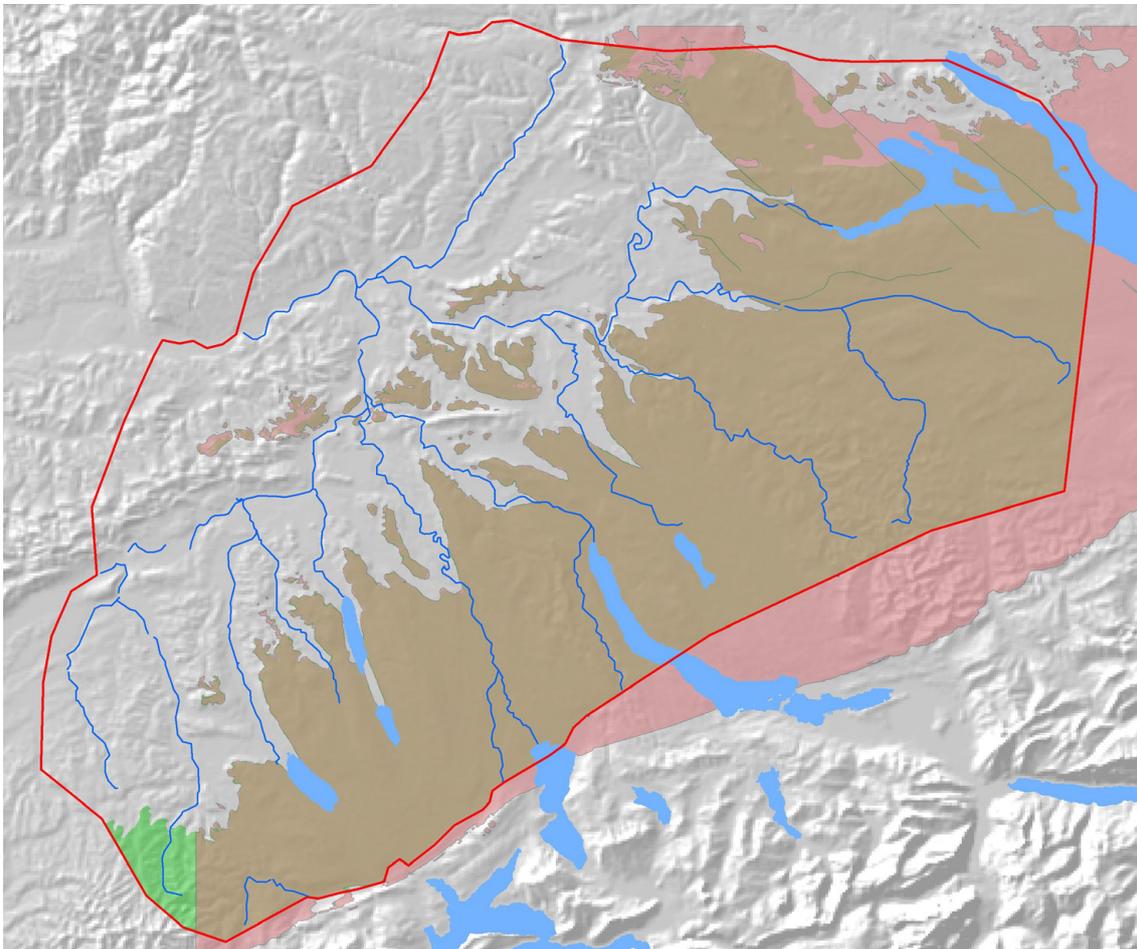


Fig. 31: Extension of the Base OSM horizon in GeoMod 2011.1. The green underlayed area indicates the resulting horizon extension in GeoMod 2012. The Base OSM extends the model area in the south and east (red color). Inside the model area, parts of the horizon were cut out when cutting the Base OSM with the Quaternary base.

3.1.14 Base Quaternary

The Base Quaternary horizon in GeoMod 2011.1 does not extend over the whole model region. While for the gaps in the North, West and South it can be argued that the horizon is identical to the topography, this is not true for the northeast. This gap was filled with a local interpretation of existing borehole data, information from publications and geological maps and the quaternary base provided by the LGRB (LGRB 2009). After this completion, the Quaternary base could be interpolated to the common grid without further adjustments. The Quaternary base is not subject to any displacements along faults.

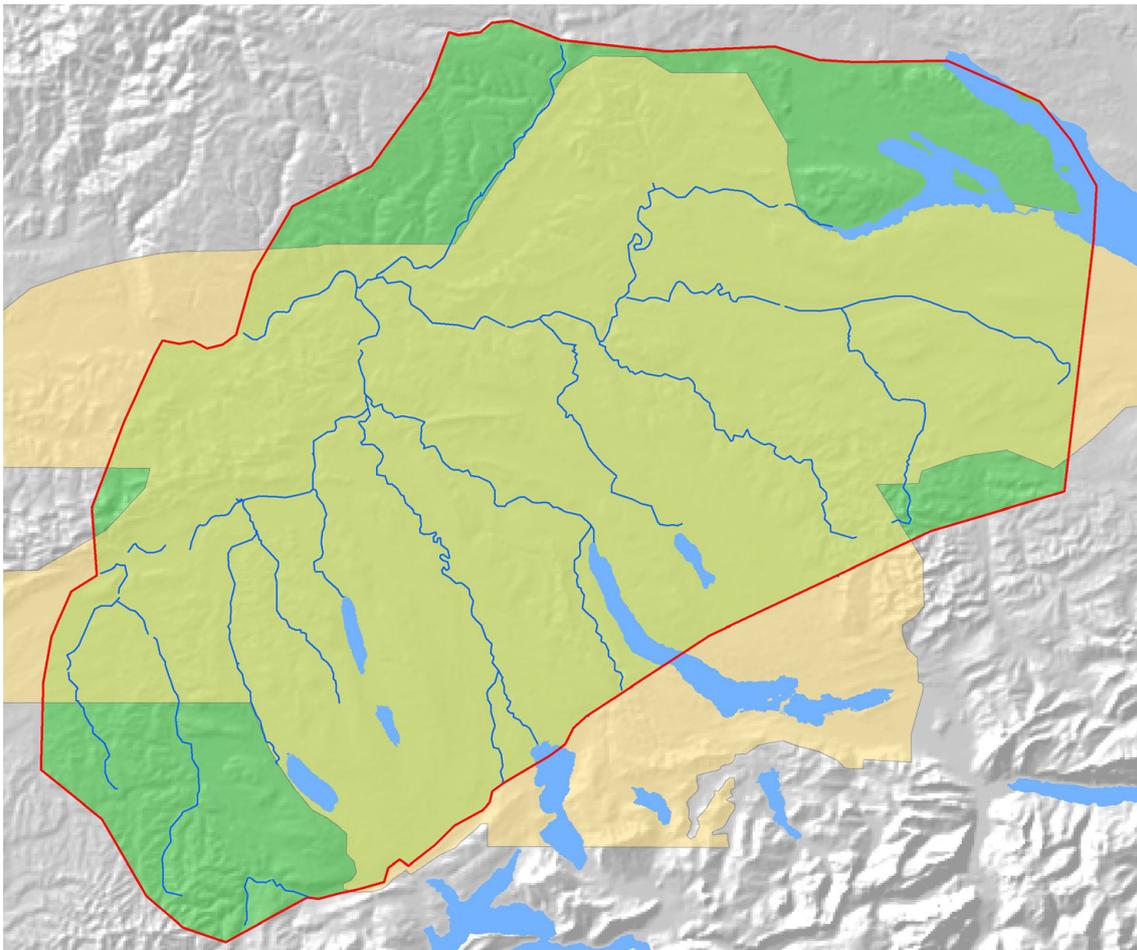


Fig. 32: Extension of the Base Quaternary horizon in GeoMod 2011.1. The green underlayed area indicates the resulting horizon extension in GeoMod 2012.

3.1.15 Topography

For the interpolation of the Topography, the digital elevation grid of the GeoMod 2011.1 which covers the whole model region was used.

3.2 Fault surfaces

3.2.1 Overview

The faults structures introduced in the GeoMod 2011.1 represent a moderate simplification of important structures known from outcrop and/or seismic data. Generally, fault zones are simplified to one or only a few fault surfaces. The fault surfaces are defined as triangulations, to use them for cutting the layers in GeoMod 2012 they had to be interpolated to the same common triangulation grid as the horizons (see Fig. 9) and had to be extended to cover all of a single sub-model (see Chapter 2.1).

3.2.2 Fault surface preparation

The fault surfaces of GeoMod 2011.1 sometimes contained triangles that were vertical or had a dip direction opposite to that of the neighboring triangles. Faults containing such triangles could not be interpolated to a grid because the elevation is ambiguous at some places. The dip of every fault was therefore restricted to one side (no change of dip direction inside a sub model was allowed) and to values less than 85 degrees. The affected faults were "Born Anticline 02", "Baden-Irchel-Herdern Lineament", "Randen Fault" and the "Neuhausen Faults". However, the required changes of the fault geometry were very small and negligible for the purpose of hydrogeological modeling.

For the model building process, every fault must cut the whole layer sequence. The faults therefore had to be extended vertically to cut the topography and the base of the Mesozoic. Optimal results were achieved if the extension begins with the existing fault dip at the fault boundary and gets steeper with increasing distance until the dip reaches 85 degrees. Laterally the faults have been extended to the sub model boundaries as planes with a dip of 85 degrees as well. The lateral extension was done by manual editing of additional triangles. Note that these extensions of the faults are only necessary for model building. In subsequent hydrogeological simulations, these surfaces were assigned a material property of the surrounding geological unit and therefore do not influence the simulation results. For visualization purposes, the fault planes have been cut to the boundaries defined by GeoMod 2011.1.

In addition to the software modules used for horizon preparation, the modules `dipmin.c` and `interfaults.c` were used. These modules are shortly described in appendix A.

3.2.3 Model build up

Table 1 shows the faults of GeoMod 2011.1 used for the model build up in the different sub models. The following faults were not included in the model build up:

- Häggenschwil Fault: outside model boundaries
- Singen Fault: vertical fault, no vertical shift of horizons
- Stahringen Fault: almost vertical fault, no vertical shift of horizons
- Wölflinswil Fault: almost vertical fault, no vertical shift of horizons

Tab. 1: Faults used for model build up in the sub models (see also Figures in Chapters 4.2 to 4.11).

Sub model	Faults	General Dip direction
Brugg	Mandach Thrust Jura Main Thrust 01 Jura Main Thrust 02 Jura Main Thrust 03	SSE
Buelach	Ruemi Fault BIH (Baden-Irchel-Herdern) Lineament Jura Main Thrust 01	SSE
Kienberg	Jura Main Thrust 01 Jura Main Thrust 03 Jura Main Thrust 04 Jura Main Thrust 05	SSE
Olten	Born Anticline 01 Born Anticline 02 Born Anticline 03 Trimbach-Olten Fault	NNW S S SW
Schaffhausen	Neuhausen Fault 01 Neuhausen Fault 02 Neuhausen Fault 03	SW
Singen	Randen Fault	SW
Sursee	includes no faults	
Thur	BIH (Baden-Irchel-Herdern) Lineament Homburg Fault	NNW
Toess	includes no faults	
Wutach	includes no faults	

4 Sub models

4.1 Overview

The general workflow to build up the sub models was:

- Divide the overall model area into sub model areas described earlier
- Adjust the horizons and faults for each sub model where necessary
- Build the sub models from the adjusted horizons

The following chapters document the resulting three-dimensional sub models. To ensure that the models fit together at their common border, the horizons were adjusted in overlapping areas. The horizons were then cut at the sub model boundaries and joined together for the overall model (see Chapter 5).

The following chapters, describing the sub models, are all structured the same way. To avoid unnecessary repetition, only very short descriptions of the respective sub models are given. First the horizon and model boundaries are shown in a figure together with the faults existing in the model region.

A schematic section illustrates the construction process (e.g. Fig. 35). The model composition always followed the same sequence: The geologic layers existing below the first fault are built up from bottom to top. Most of the layers are treated as depositional layers. The Quaternary base is treated as an unconformity (see Fig. 4). The layer package is then cut by the first fault. At the hanging wall of the fault now the horizons of the next block are built up. The package is cut by the second fault. This procedure is continued until no more faults exist in the model area.

If a special situation asked for a deviation from the general rules described above it is mentioned in a short comment.

The resulting model is shown in a 3D view without the Quaternary layer. The outcrop areas of the units at the Quaternary base are shown in a map view. Sections along some selected geological profiles visualize the geological structure. All 3D-views and sections are vertically exaggerated by a factor of 2.

The visualizations of the resulting models follow the common color convention illustrated in Table 2.

Tab. 2: Color schema for the geologic model visualizations.

Geological unit	Red	Green	Blue
 Quaternary	232	232	232
 OSM	255	226	135
 OMM	214	133	137
 USM	222	158	102
 Upper_Malm	220	242	253
 Effingen	161	220	250
 Upper_Dogger	222	192	140
 Hauptrogenstein	171	140	87
 Klingnau	237	221	193
 Passwang	222	192	140
 Opalinus_Clay	228	208	232
 Keuper_and_Lias	163	158	189
 Upper_Muschelkalk	252	194	87
 Anhydrit_Group	255	234	104
 Kristallin	179	179	179

4.2 Sub Model “Brugg”

4.2.1 Model Composition

The model size is shown in Fig. 33. Fig. 35 shows a schematic section through the model. The four faults divide the model into 5 blocks. The Mesozoic base is treated as a continuous surface without any offset; faults were not allowed to cut this horizon.

A special situation occurs between the Jura Main Thrusts 01 and 02. The real tectonic situation is very complex and can't be matched with the fault surfaces available. It was therefore decided to simplify the geologic layers between these faults by a single layer package. A similar situation occurs between the Jura Main Thrusts 02 and 03. The GeoMod 2011.1 horizons did not fit well enough with the outcrop lines known from the geologic map. Some manual edits were done to adjust the fit: in the area of Rohr SO the Jura Main Thrust 03 was shifted about 300 m to the south (Fig. 34) and the Base Opalinus Clay horizon was adapted to the outcrop lines (Fig. 53). All the other horizons in block 2 were then calculated by adding or dividing thicknesses to the Opalinus Clay base.

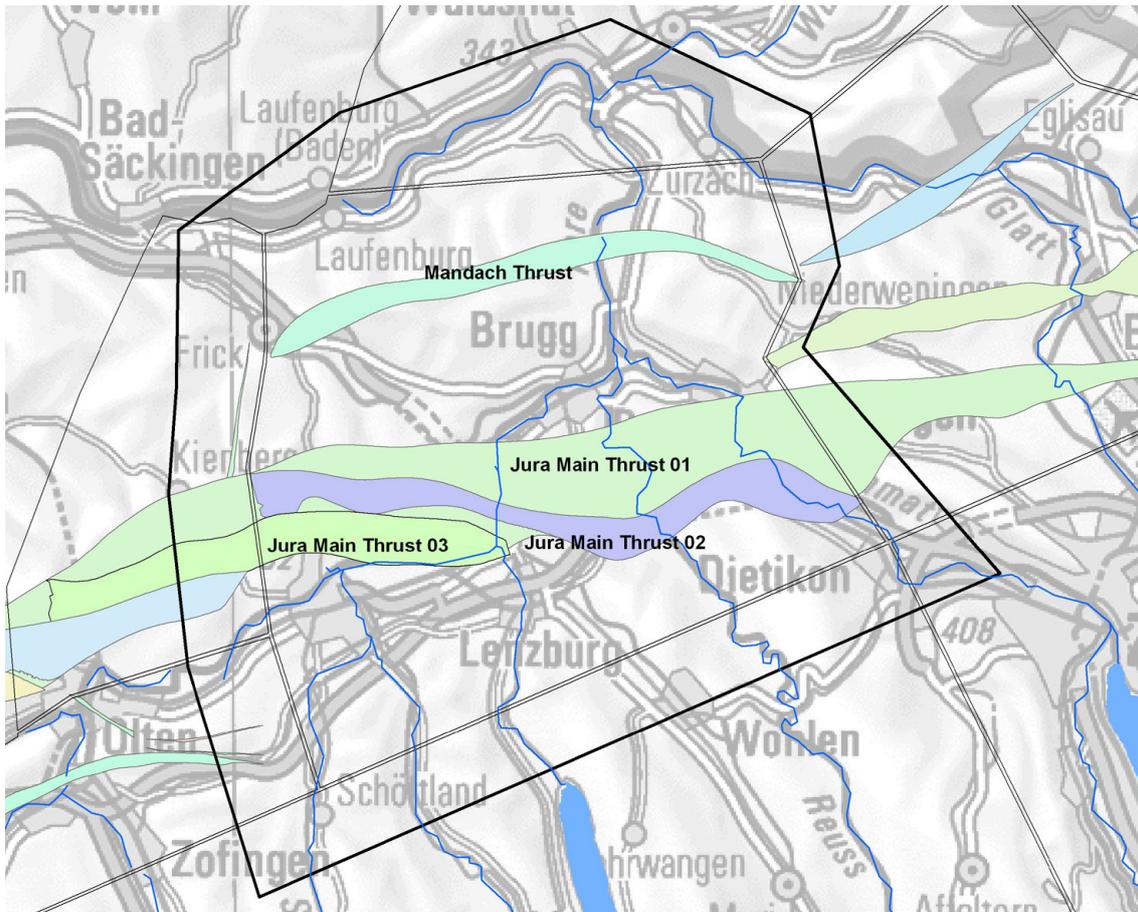


Fig. 33: Sub model „Brugg”. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines) and faults used in the model construction.

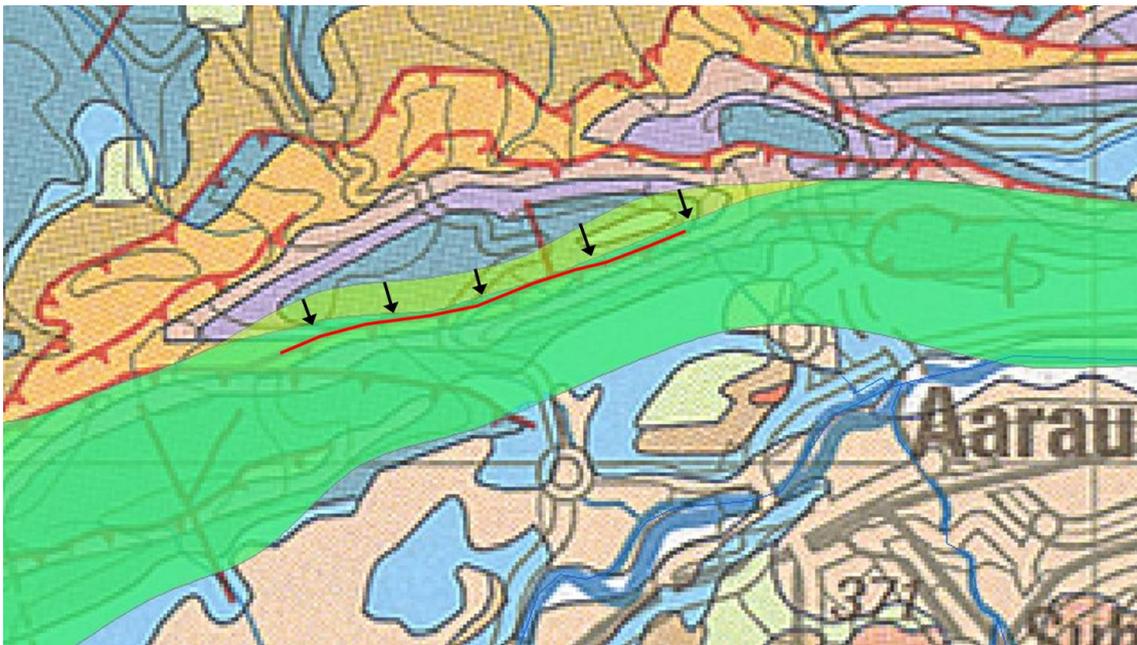


Fig. 34: Outline of the Jura Main Thrust before (light green, GeoMod 2011.1) and after (dark green, GeoMod 2012) the shift. The outline of Geomod 2012 better fits the fault outcrop according to the geological map (red line).

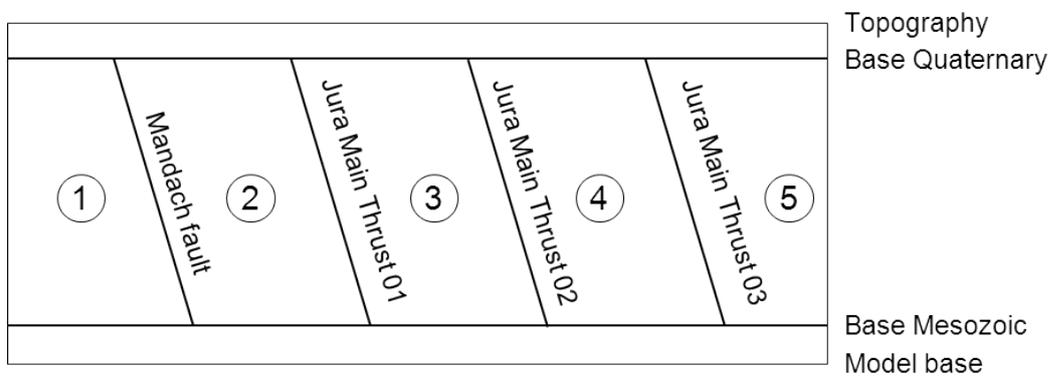


Fig. 35: Schematic section through the sub model „Brugg“.

4.2.2 Resulting Sub Model

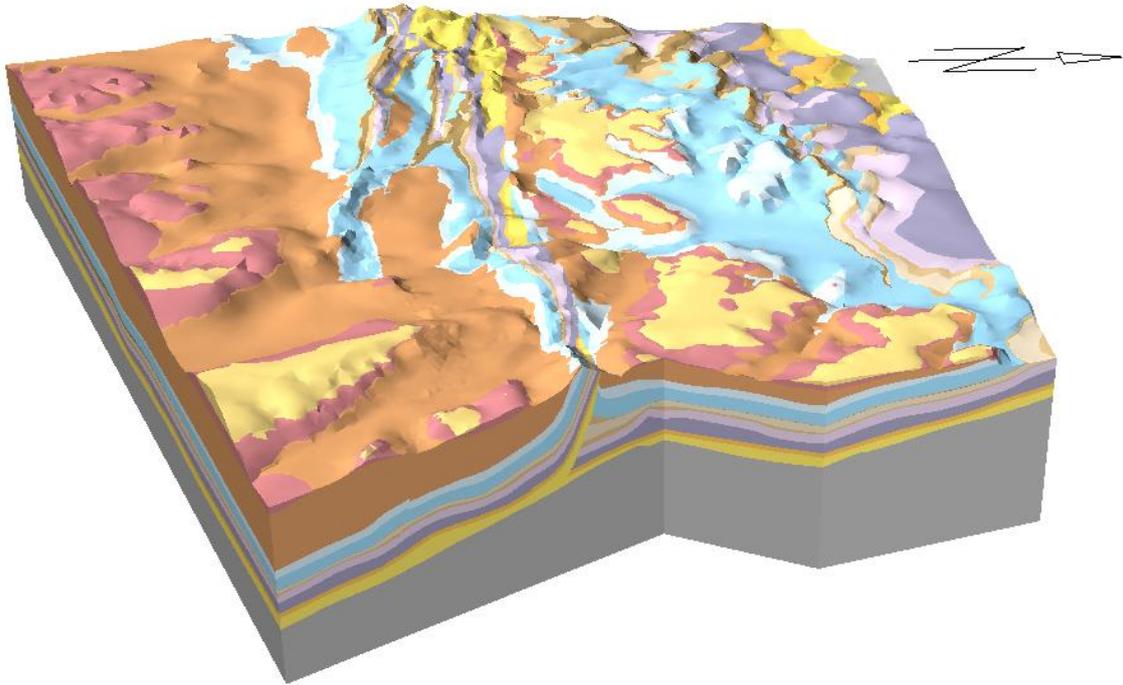


Fig. 36: Perspective view on the sub model „Brugg“ from East.

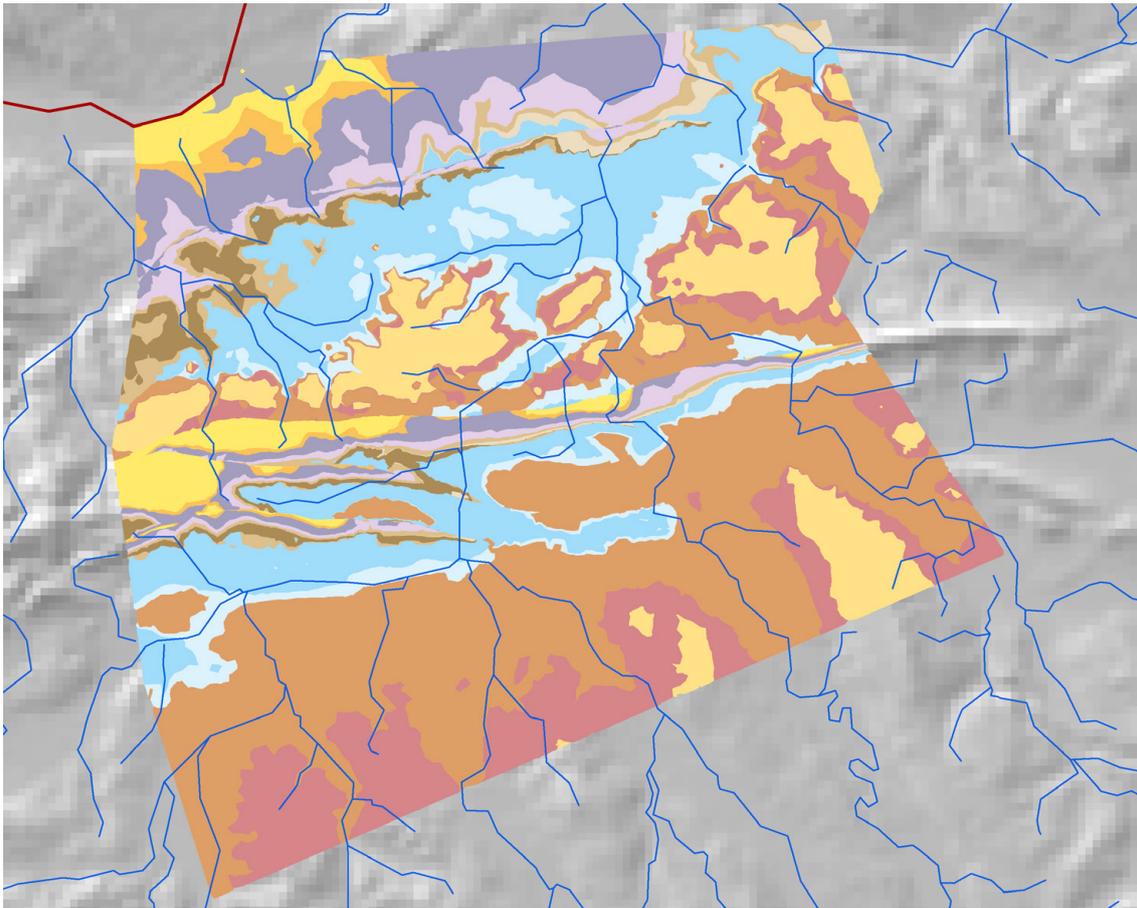


Fig. 37: Sub model “Brugg”: Outcropping units at the Quaternary base.

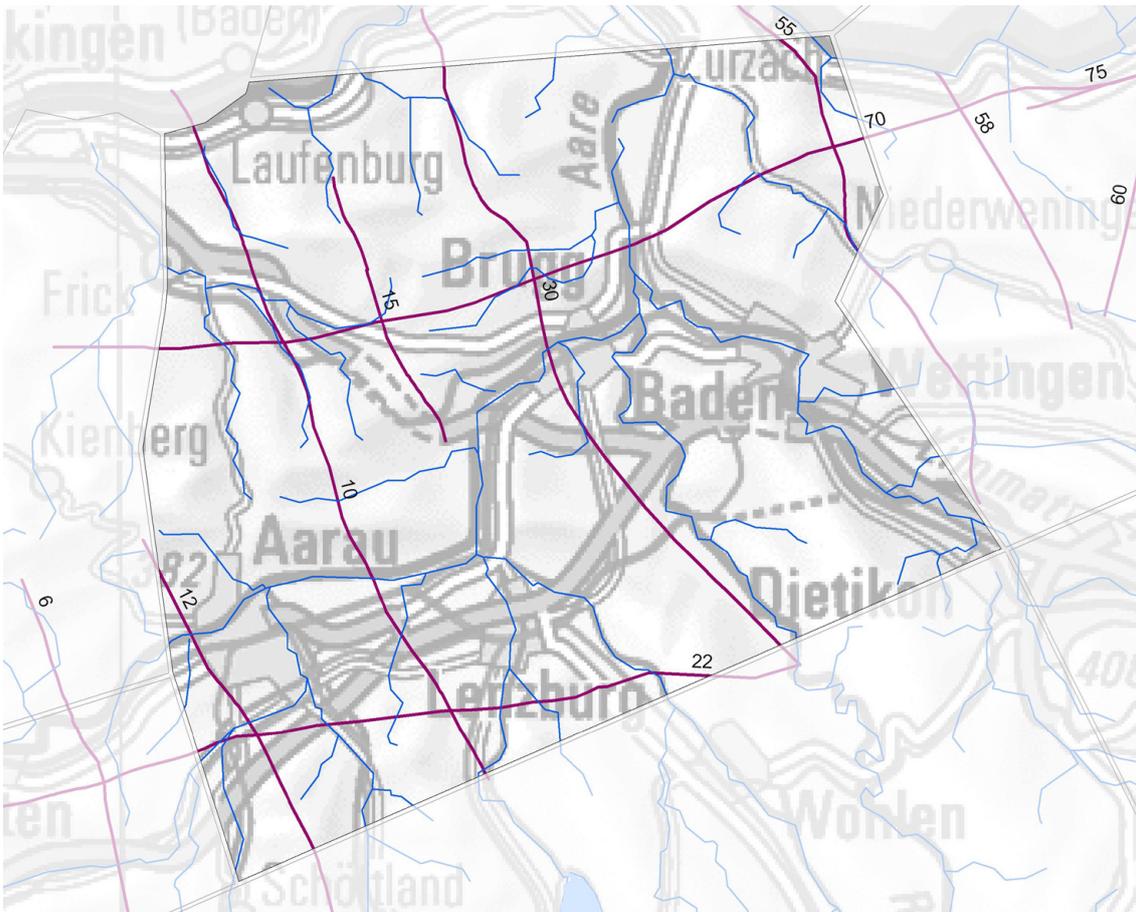


Fig. 38: Position of the sections according to Nagra (2008). Numbering corresponds to Nagra (2008).

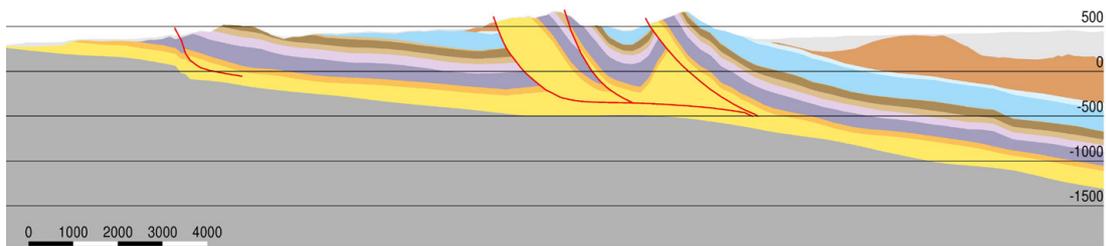


Fig. 39: N-S Section 10, vertical exaggeration 2.

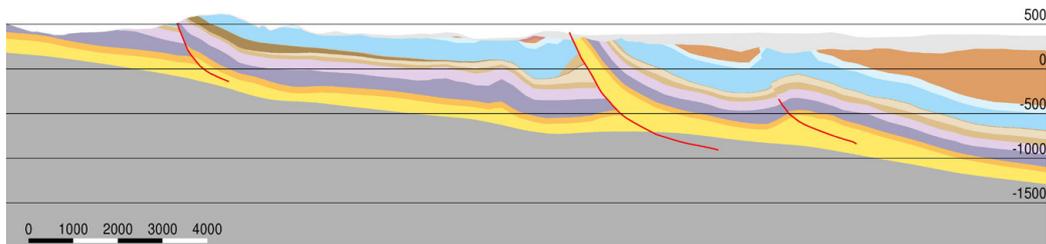


Fig. 40: N-S Section 30, vertical exaggeration 2.

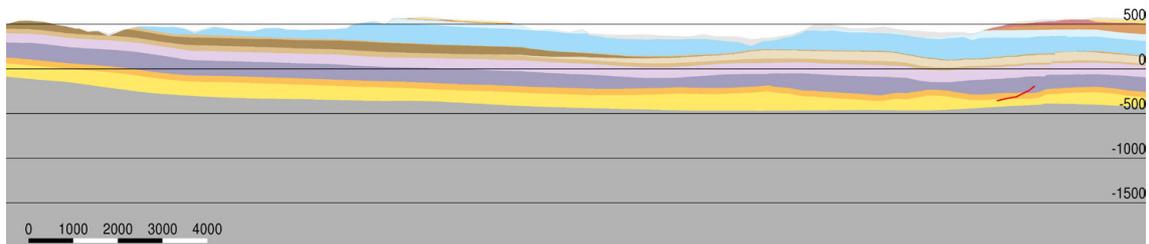


Fig. 41: W-E Section 70 (part inside sub model “Brugg”), vertical exaggeration 2.

4.3 Sub Model “Buelach”

4.3.1 Model Composition

The situation is shown in Fig. 42. Fig. 43 shows a schematic section through the model. The 3 faults divide the model into 4 blocks. The Mesozoic base is treated as a continuous surface without any offset; faults were not allowed to cut this horizon.

The outer borders of the horizons had to cover the area of the planned local numerical model “Nördlich Lägern”. The overlapping area to the neighboring sub models “Brugg” and “Wutach” is therefore rather large.

At the north-western side of the model, the eastern part of the Mandach Thrust had to be integrated into the model construction. It was attached to the Ruemi Fault by manually adding some additional triangles.

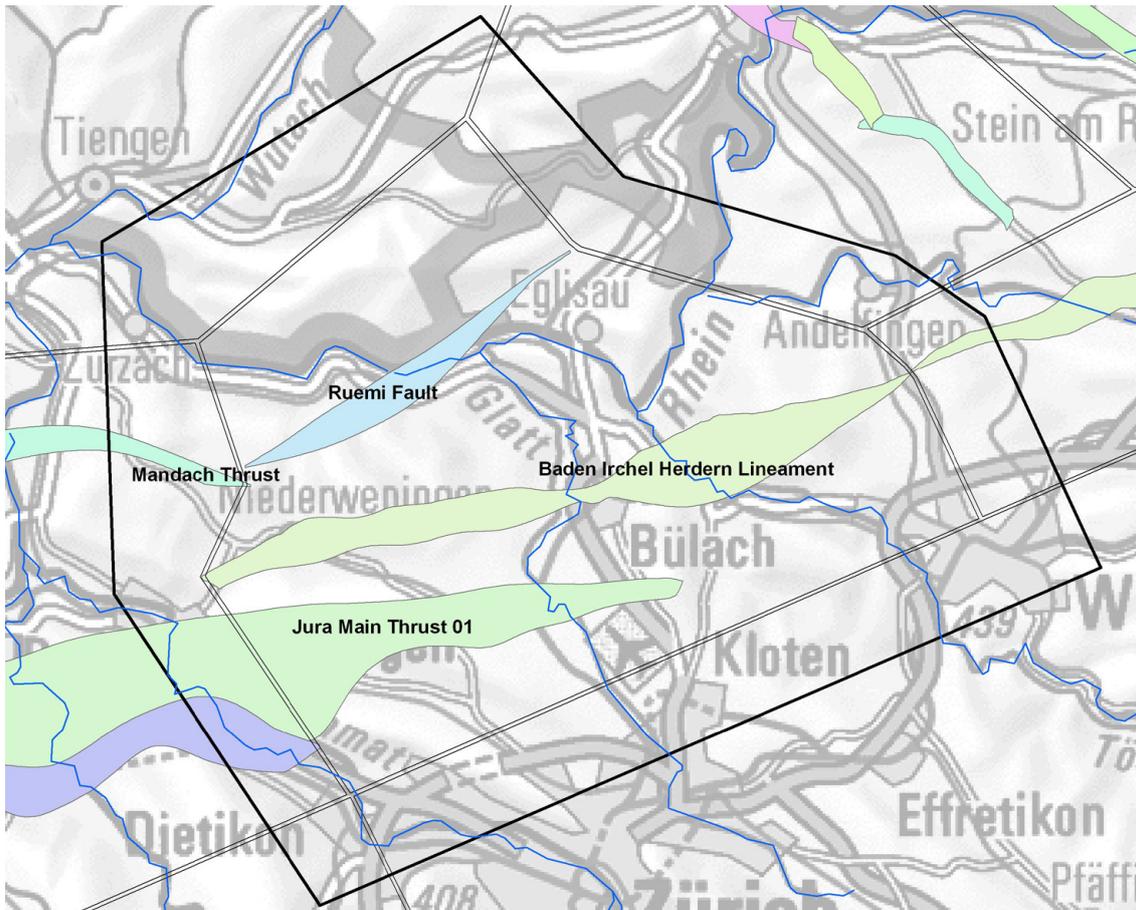


Fig. 42: Sub model „Buelach”. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines) and faults used in the model construction.

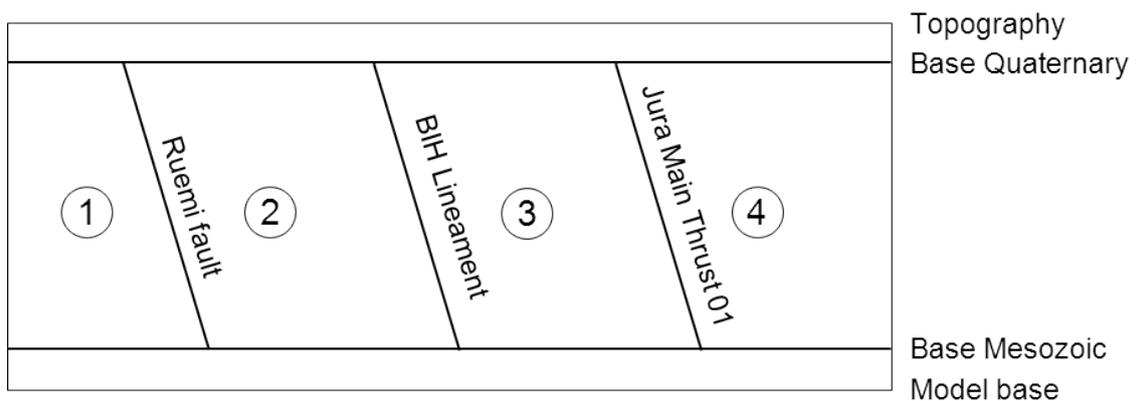


Fig. 43: Schematic section through the sub model „Buelach“.

4.3.2 Resulting Sub Model

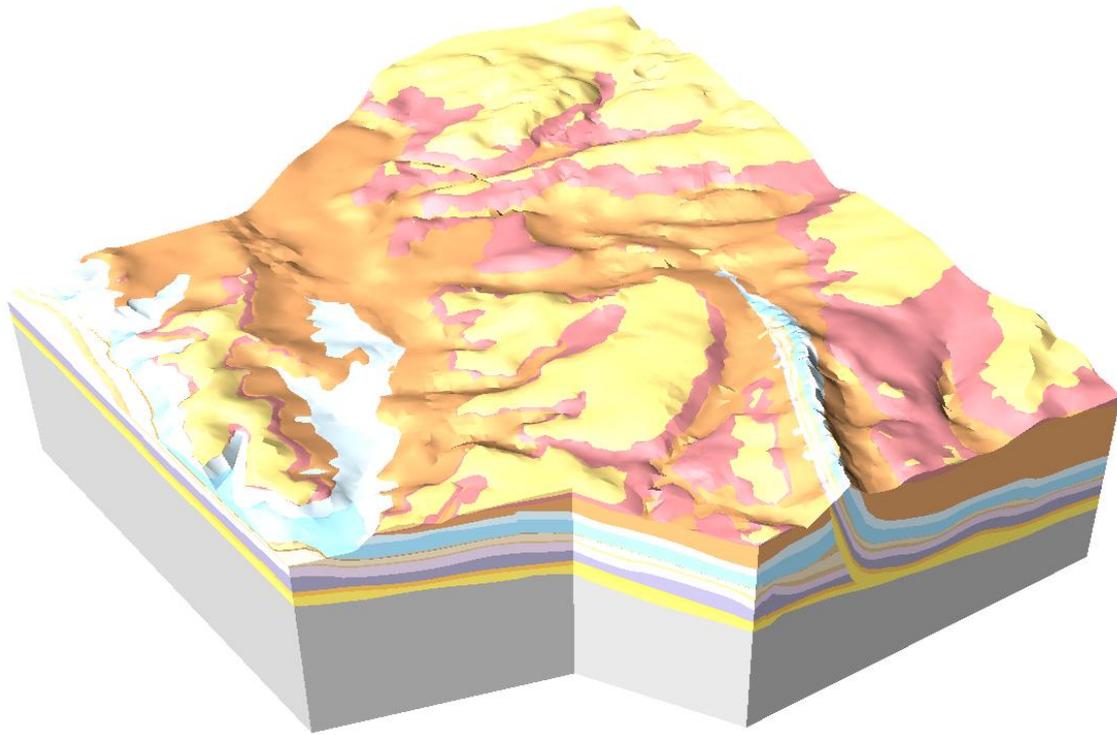


Fig. 44: Perspective view on the sub model „Buelach“ from North-West.

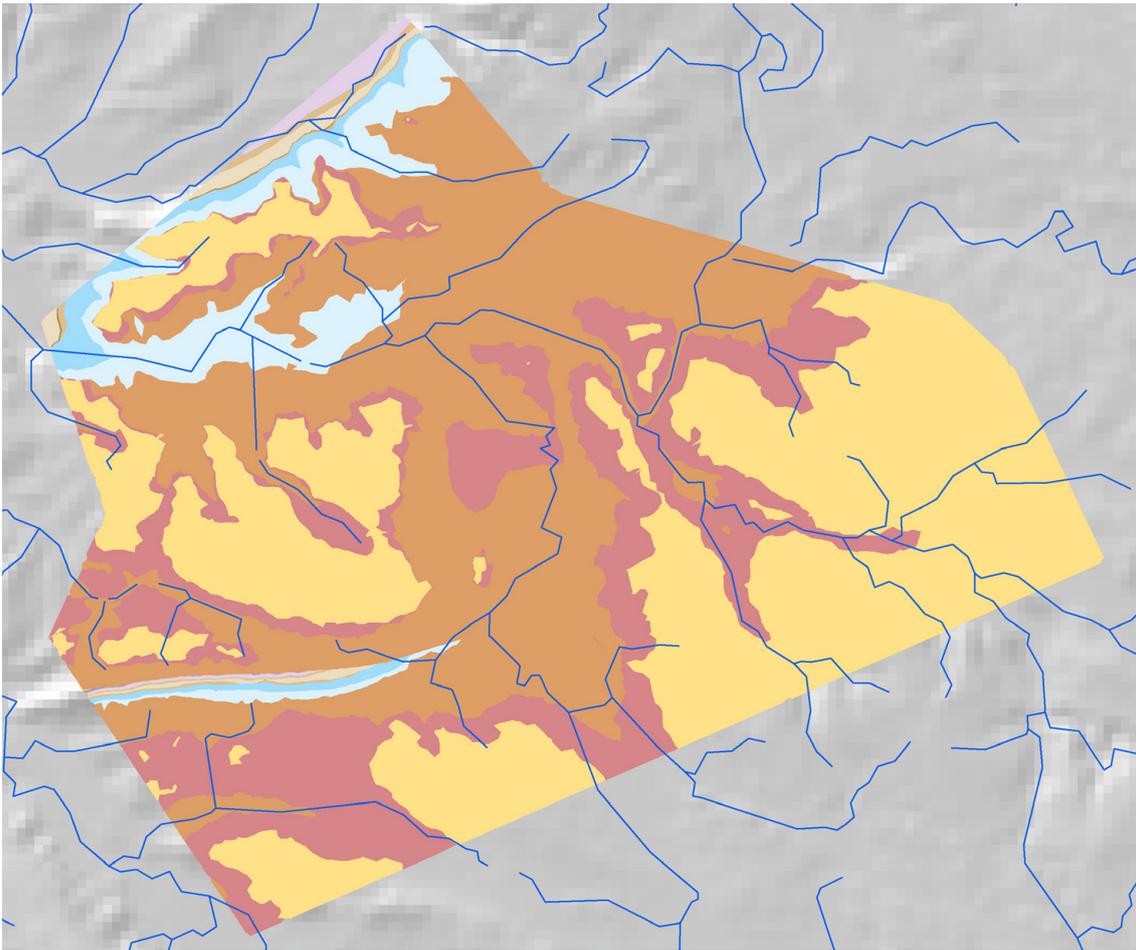


Fig. 45: Sub model “Buelach”: Outcropping units at the Quaternary base.

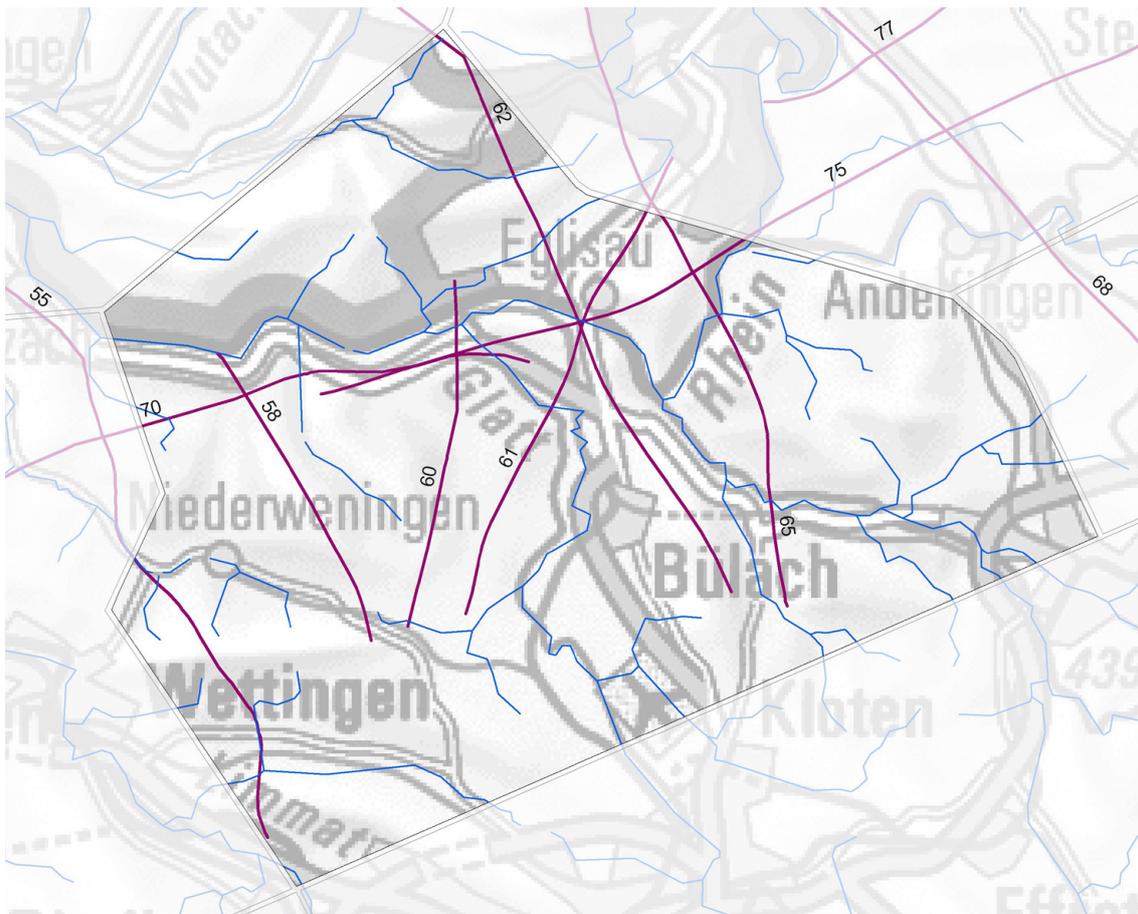


Fig. 46: Position of the sections according to Nagra (2008).

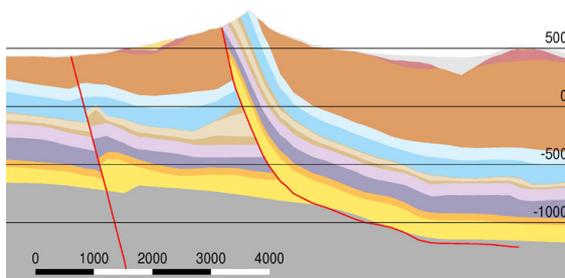


Fig. 47: N-S Section 55 (part inside sub model „Buelach“), vertical exaggeration 2.

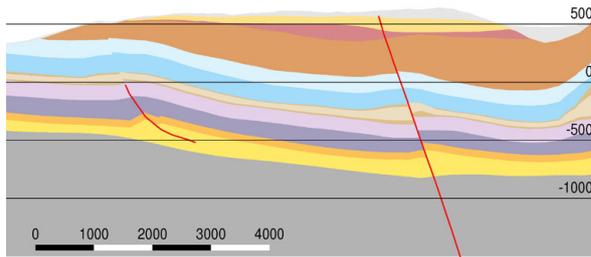


Fig. 48: N-S Section 58, vertical exaggeration 2.

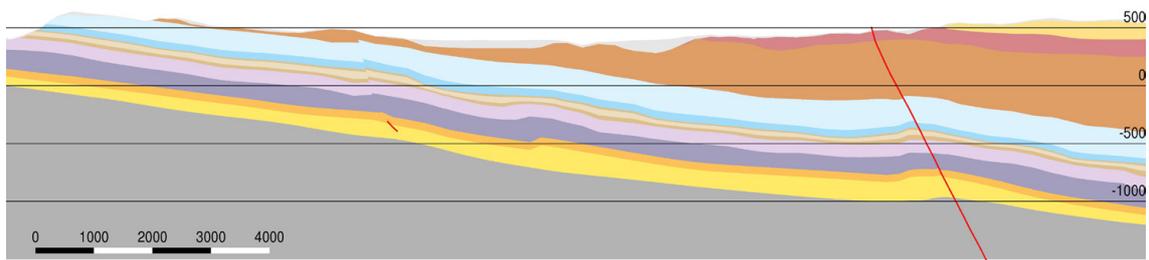


Fig. 49: N-S Section 62 (part inside sub model „Buelach“), vertical exaggeration 2.

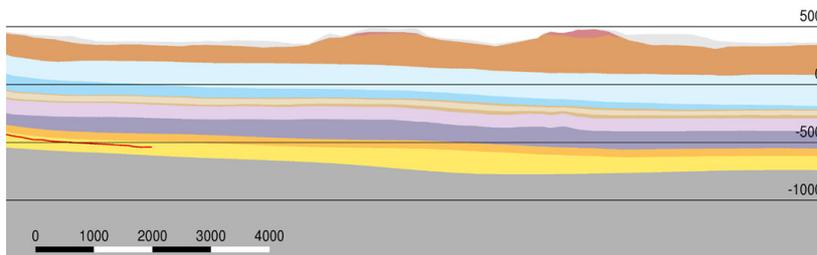


Fig. 50: W-E Section 75 (part inside sub model „Buelach“), vertical exaggeration 2.

4.4 Sub Model “Kienberg“

4.4.1 Model Composition

The situation is shown in Fig. 51. Fig. 52 shows a schematic section through the model. The 4 faults divide the model into 5 blocks. The Mesozoic base is treated as a continuous surface without any offset; faults were not allowed to cut this horizon.

The sub model contains a rather large area between the Jura Main Thrust 01 and Jura Main Thrust 03 with only sparse information about the horizons above the Opalinus Clay base (see Fig. 20) and the Opalinus Clay base given in GeoMod 2011.1 did not satisfy the outcrop lines mapped in the geological map. Therefore the geological units had to be reconstructed. Fig. 53 shows the simplified Opalinus Clay Base used in GeoMod 2012. The other horizons were

constructed by adding or subtracting extrapolated thickness distributions to the Opalinus Clay Base.

In the area of Rohr SO the Jura Main Thrust 03 was shifted about 300 m to the north and the Base Opalinus Clay horizon was adapted to the outcrop lines.

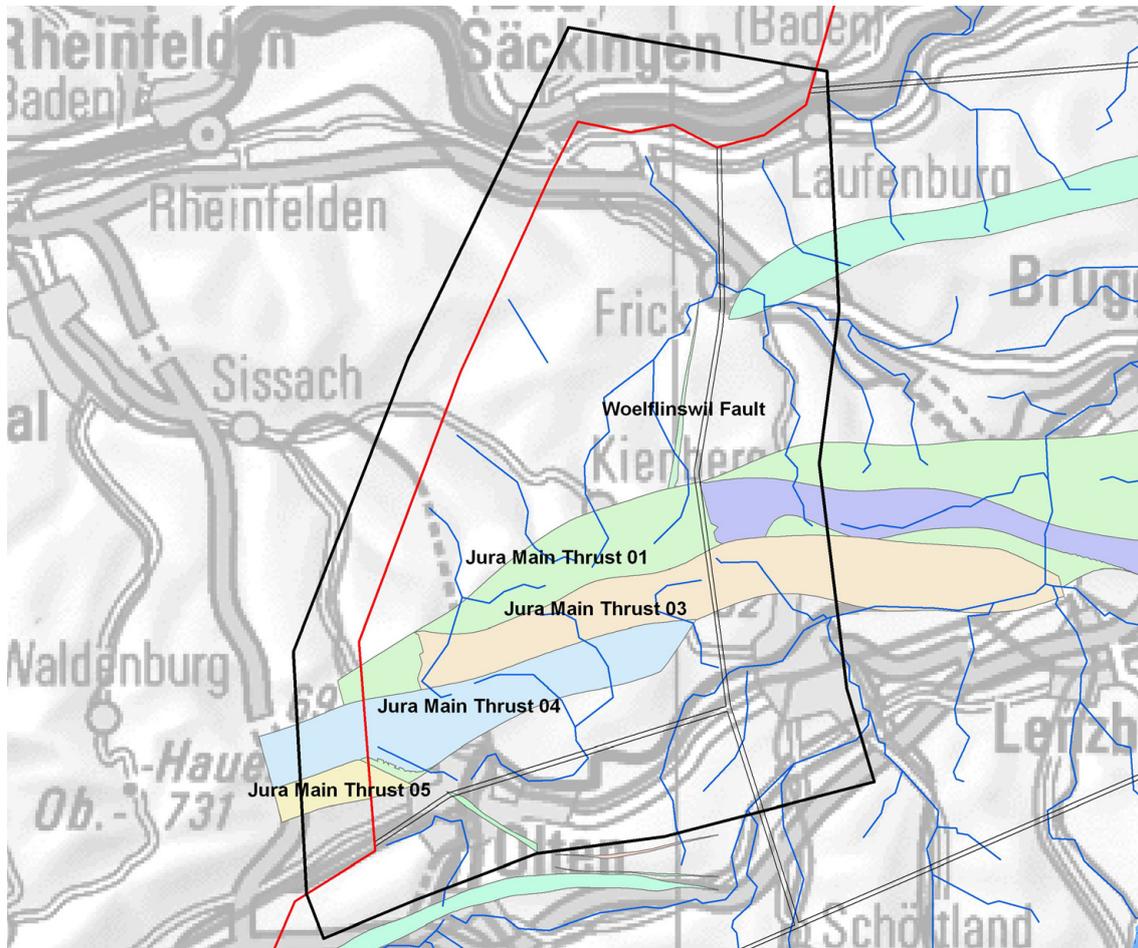


Fig. 51: Sub model „Kienberg”. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines) and faults in the sub model area. The western boundary is defined by the regional model boundary (red line).

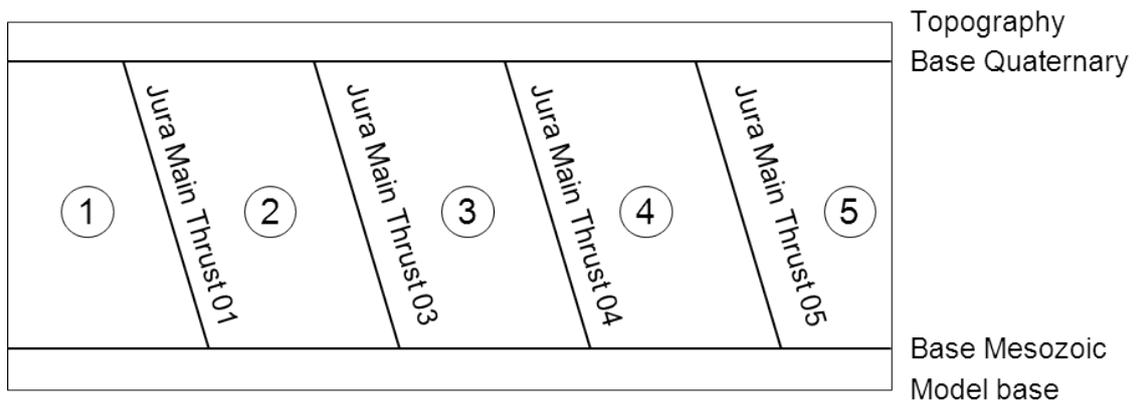


Fig. 52: Schematic section through the sub model „Kienberg“.

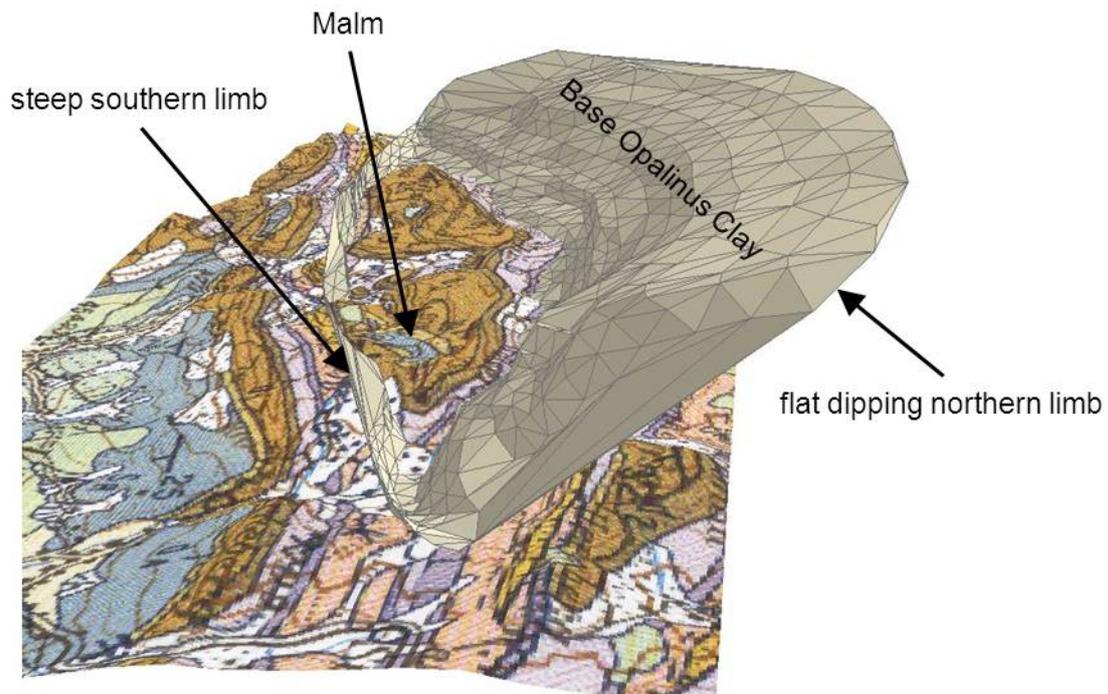


Fig. 53: Simplified Opalinus Clay Base between Jura main Thrust 01 and Jura Main Thrust 03. The surface was constructed by using the outcrop lines of the geological map (Swisstopo 2005) and the indicated dip angles in the more detailed map (1:25'000).

4.4.2 Resulting Sub Model

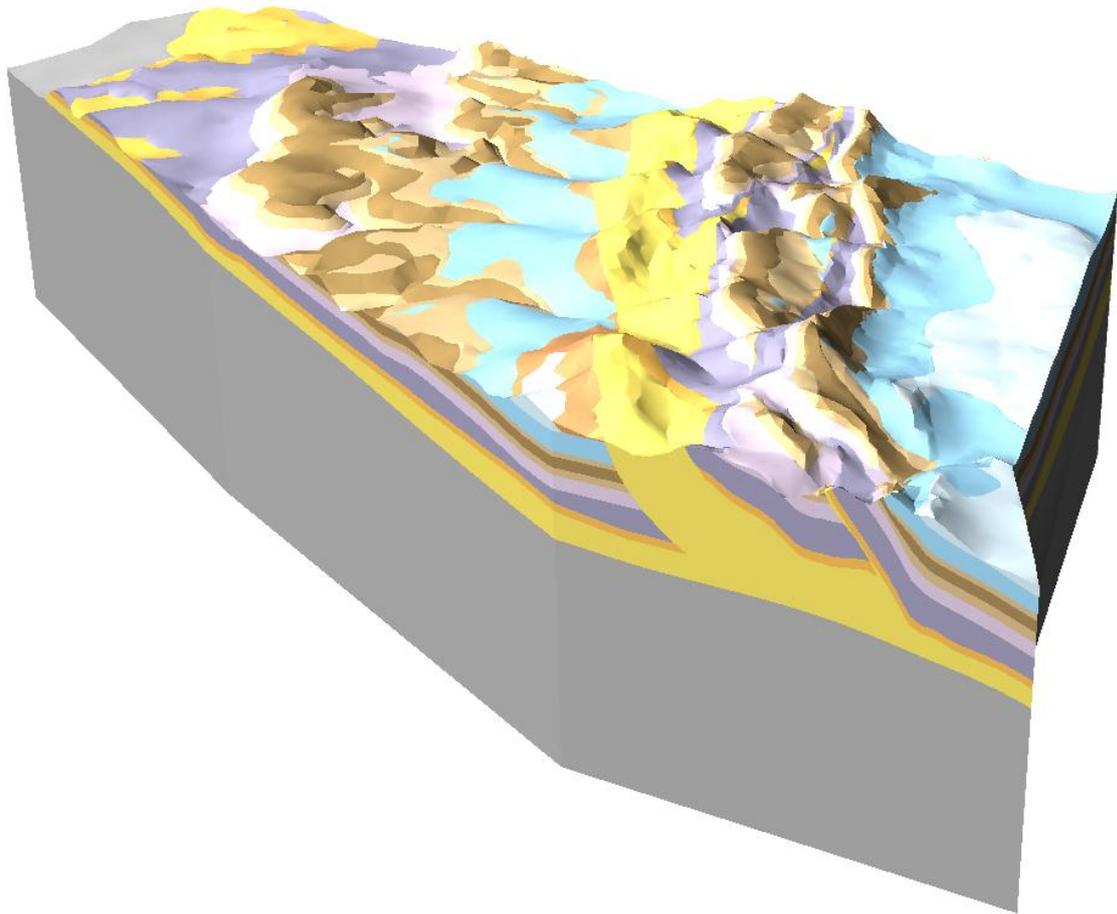


Fig. 54: Perspective view on the sub model „Kienberg“ from West.

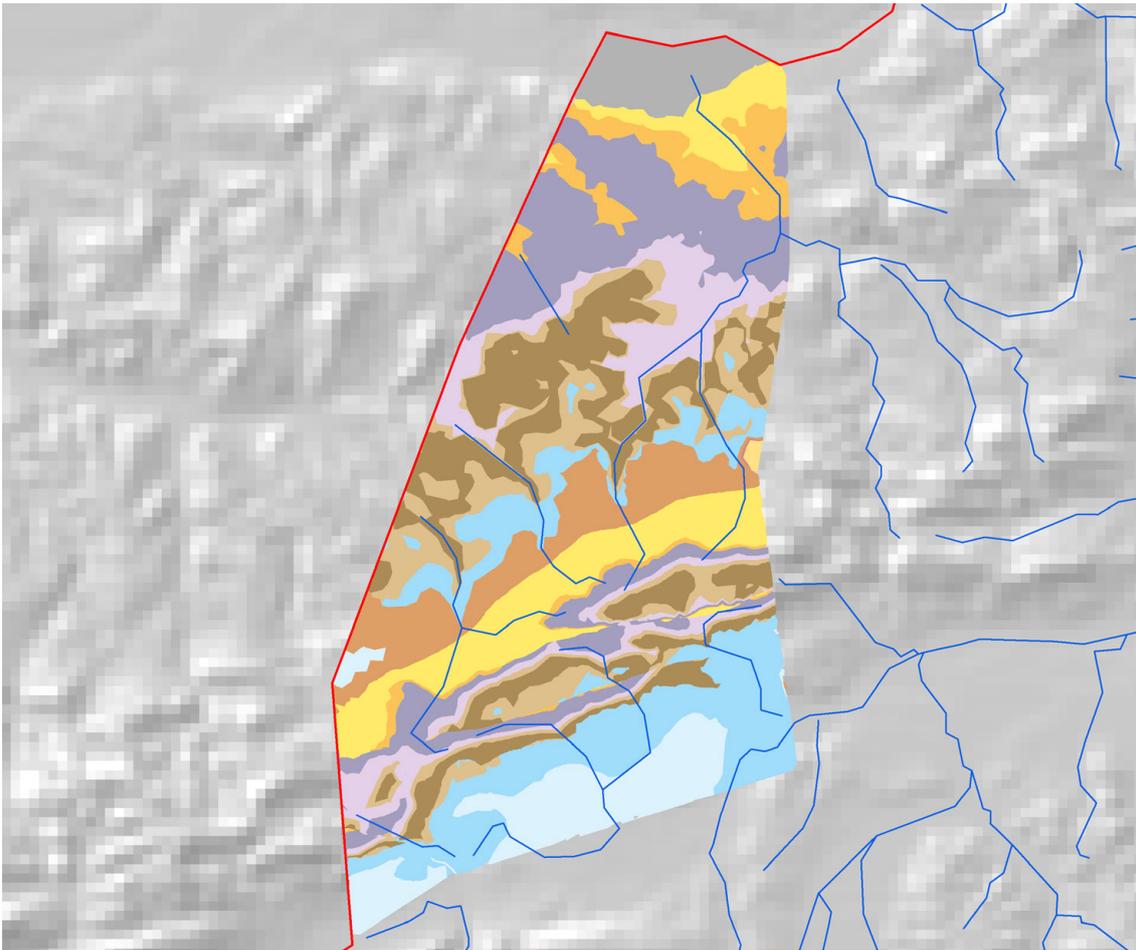


Fig. 55: Sub model “Kienberg”: Outcropping units at the Quaternary base.

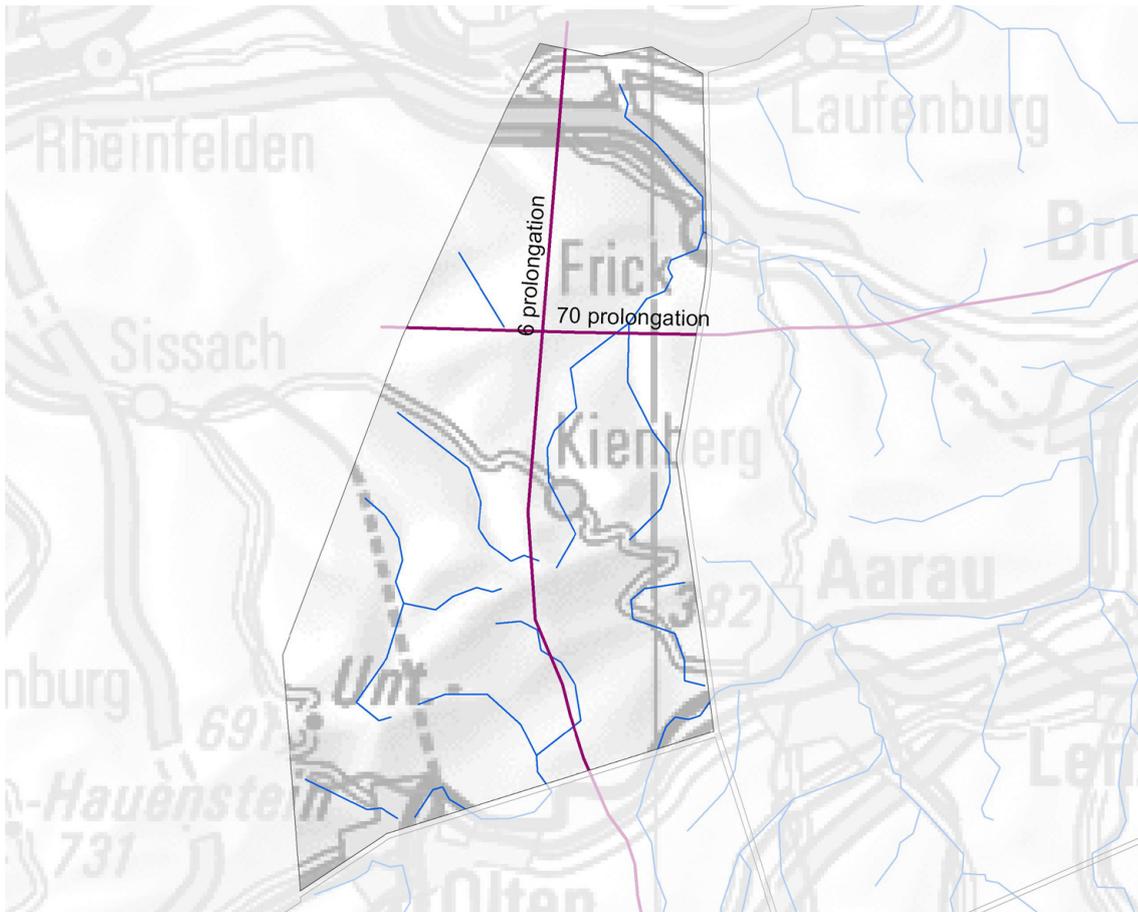


Fig. 56: Position of the sections used for visualisations. The profiles Nr. 6 and 70 have been prolonged to reach the northern resp. western sub model boundary.

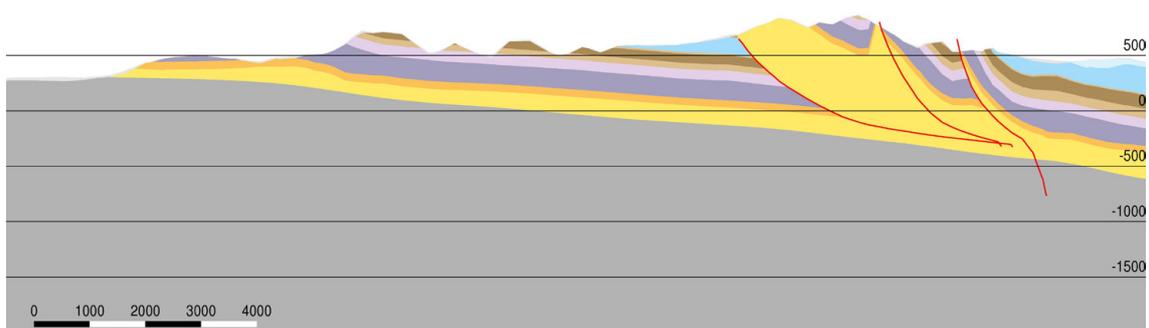


Fig. 57: S-N Section 6 (prolongated to the northern boundary of the sub model “Kienberg”), vertical exaggeration 2.

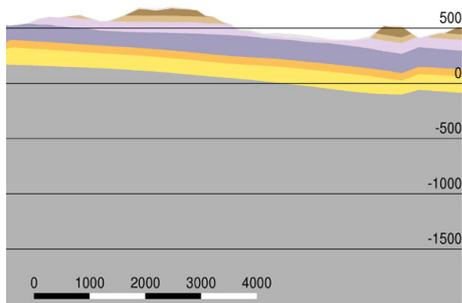


Fig. 58: W-E Section 70 (prolongated to the west, part inside sub model „Kienberg“), vertical exaggeration 2.

4.5 Sub Model “Olten”

4.5.1 Model Composition

The situation is shown in Fig. 59. Fig. 60 shows a schematic section through the model. The Trimbach-Olten Fault and the Born 03 Fault were joined together by manually adding some triangles. The combined fault was connected to the Born Anticline 02 underneath the Mesozoic base. This allowed us to cut off the geological units to the south of the Born Anticline 02 and to the north of the Trimbach-Olten Fault and the Born 03 Fault in one step. For the use in the numerical simulations the faults have been used in their original outlines.

The Mesozoic base is treated as a continuous surface without any offset; faults were not allowed to cut this horizon.

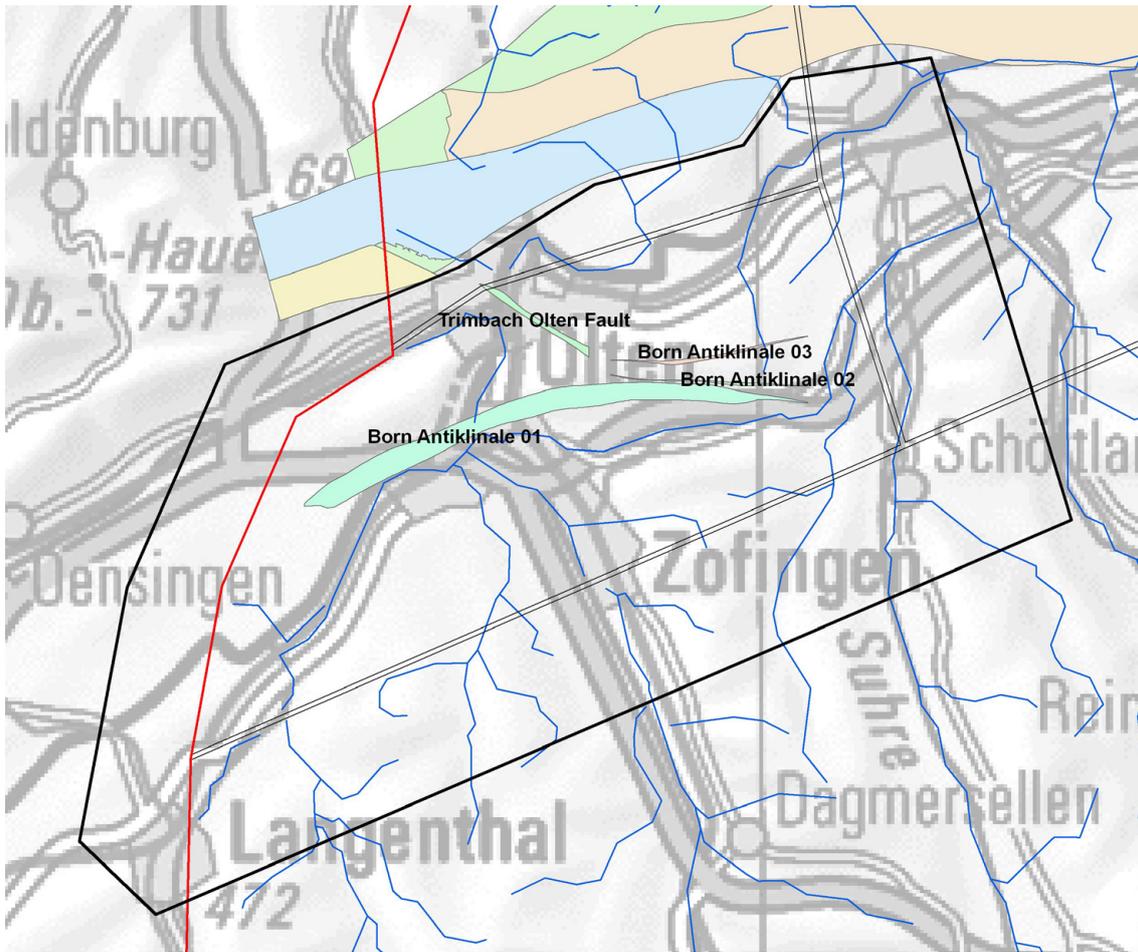


Fig. 59: Sub model „Olten“. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines) and faults in the sub model area.

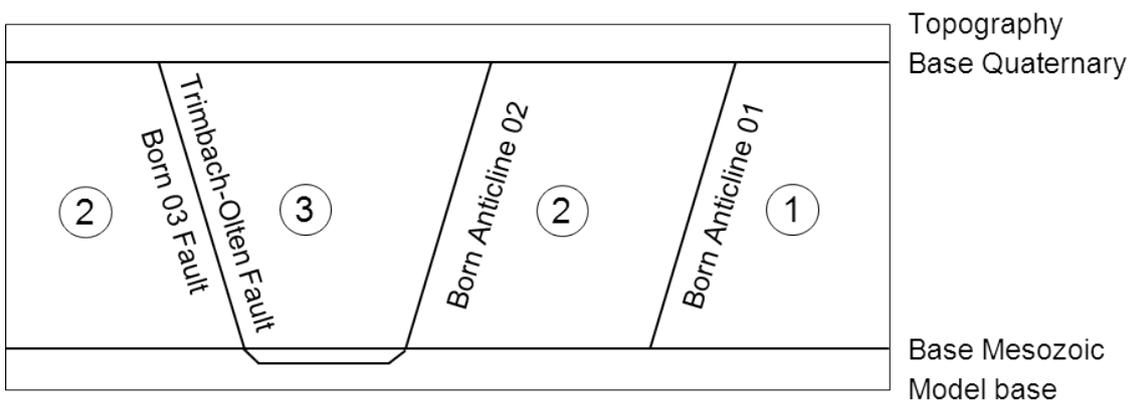


Fig. 60: Schematic section through the sub model „Olten“.

4.5.2 Resulting Sub Model

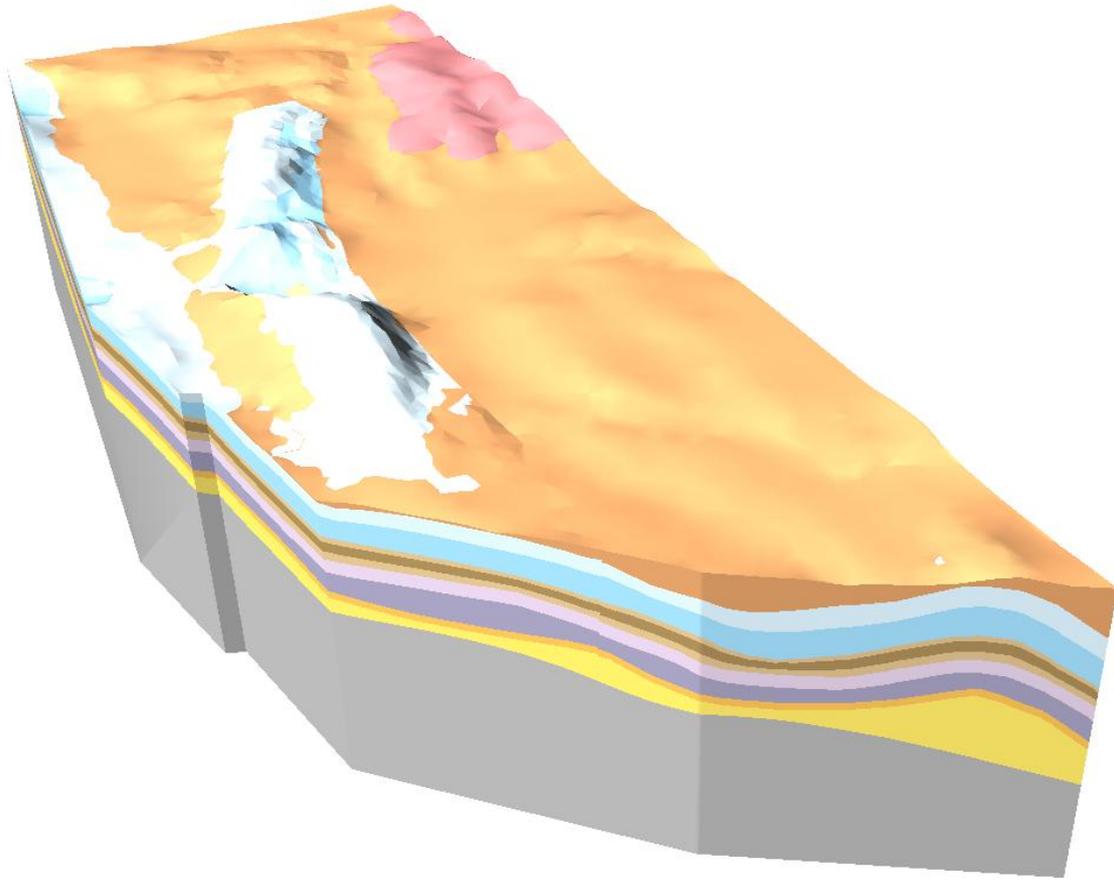


Fig. 61: Perspective view on the sub model „Olten“ from North-West.

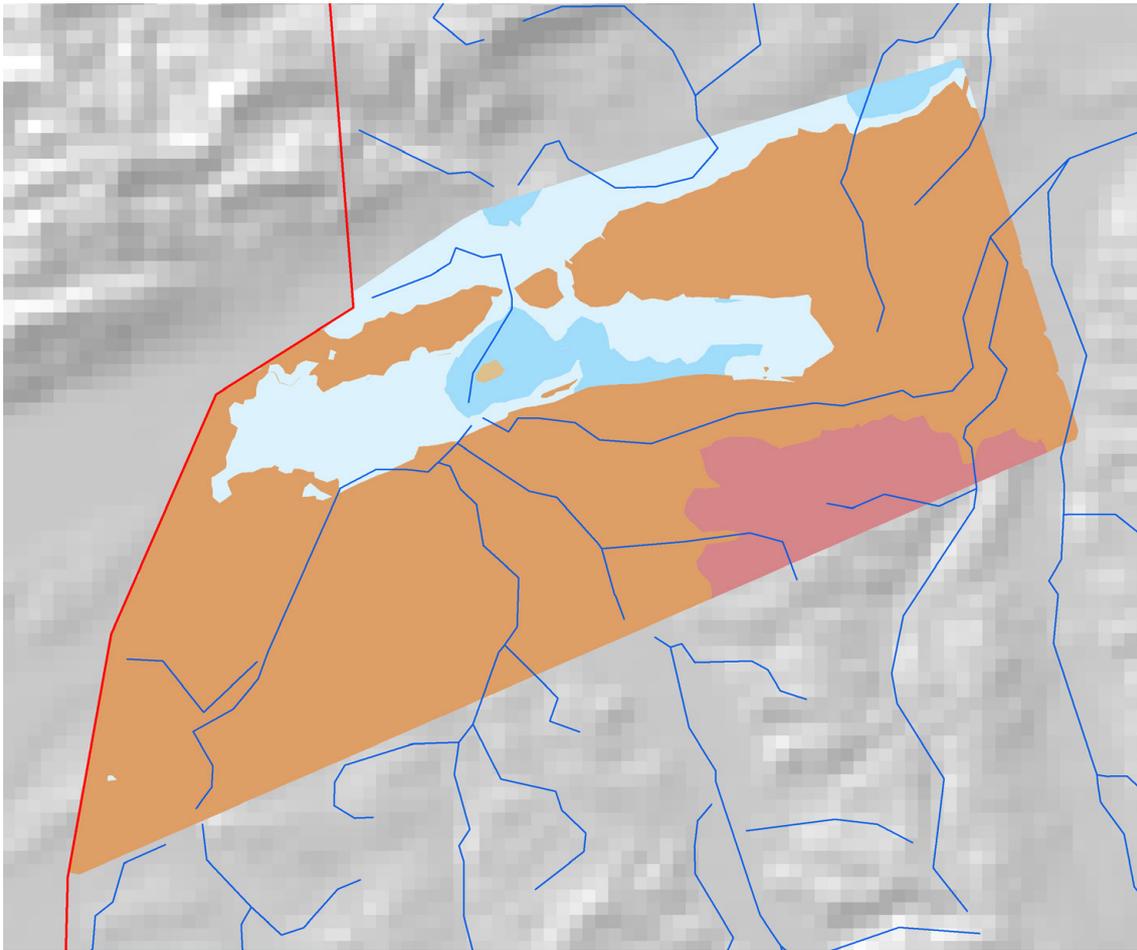


Fig. 62: Sub model "Olten": Outcropping units at the Quaternary base.

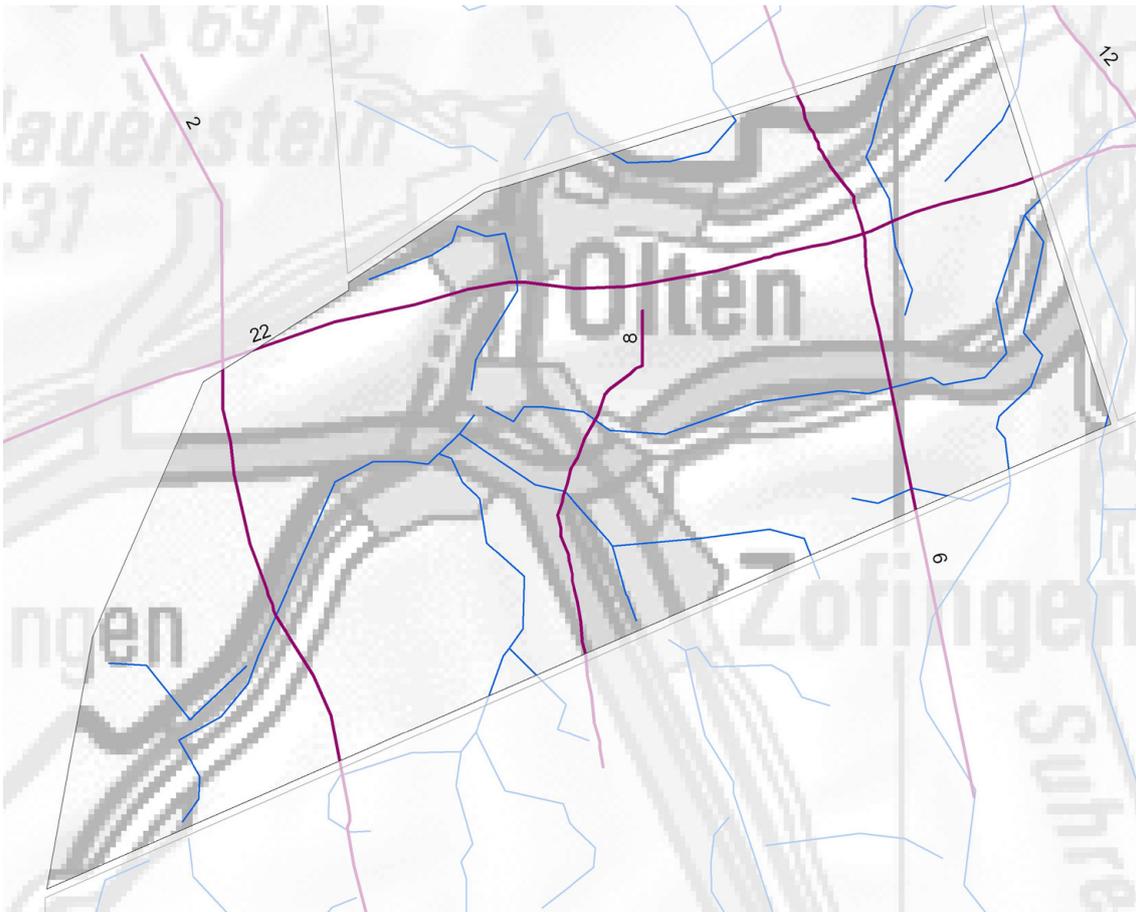


Fig. 63: Position of the sections according to Nagra (2008).

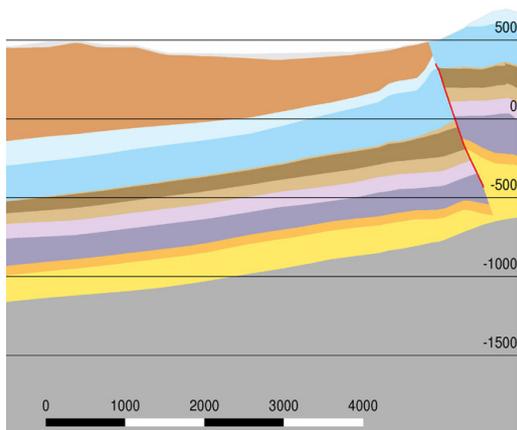


Fig. 64: N-S Section 8, vertical exaggeration 2.

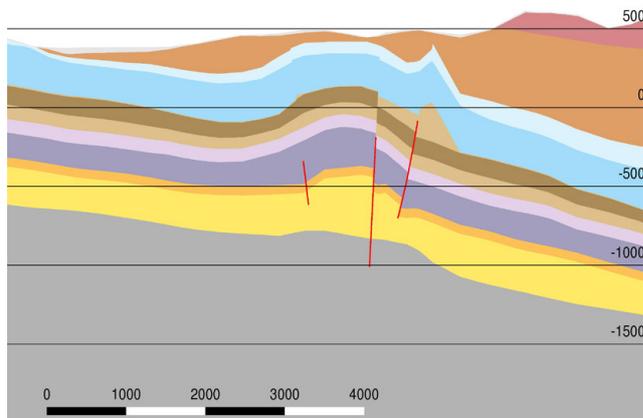


Fig. 65: N-S Section 6 (part inside sub model „Olten”), vertical exaggeration 2.

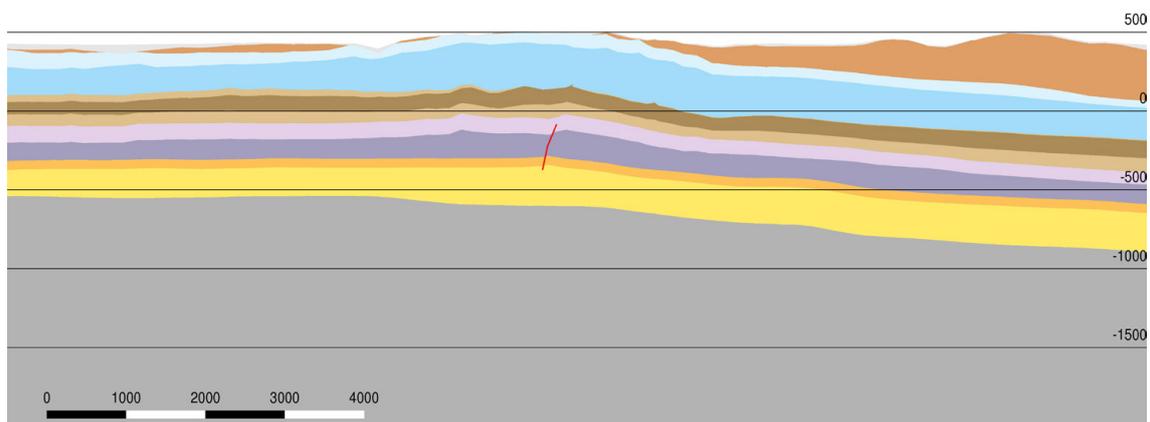


Fig. 66: W-E Section 22 (part inside sub model „Olten”), vertical exaggeration 2.

4.6 Sub Model “Schaffhausen“

4.6.1 Model Composition

The situation is shown in Fig. 68. The Neuhausen Fault build in GeoMod 2011.1 consists of three parts which overlap along small sections. Therefore, the three parts could not be combined to a single fault. Instead, a western fault including the western overlapping parts and an eastern fault including the eastern overlapping parts were constructed. Along the non-overlapping sections, both faults are identical.

Fig. 69 shows a schematic section through the model. First the geological units to the west of the western fault were built up. The layers were cut off by the western fault. The layer package was generated again to the east of the fault and cut off by the eastern fault. This step did only create very small model blocks between the two faults. The sub model was finished by creating the geological layers to the east of the eastern fault. The Mesozoic base is treated as a continuous surface without any offset; faults were not allowed to cut this horizon.

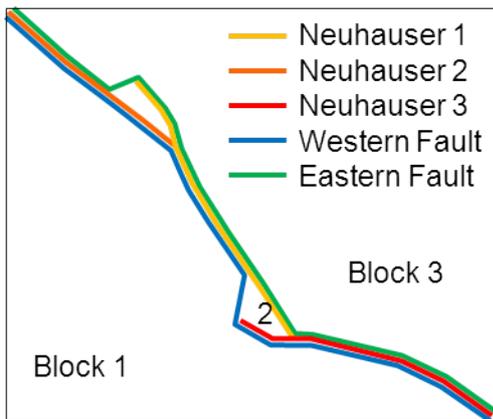


Fig. 67: Schematic view of the Neuhauser faults at their junction. Instead of the original faults, a western and an eastern fault were used to build up the model in three blocks.

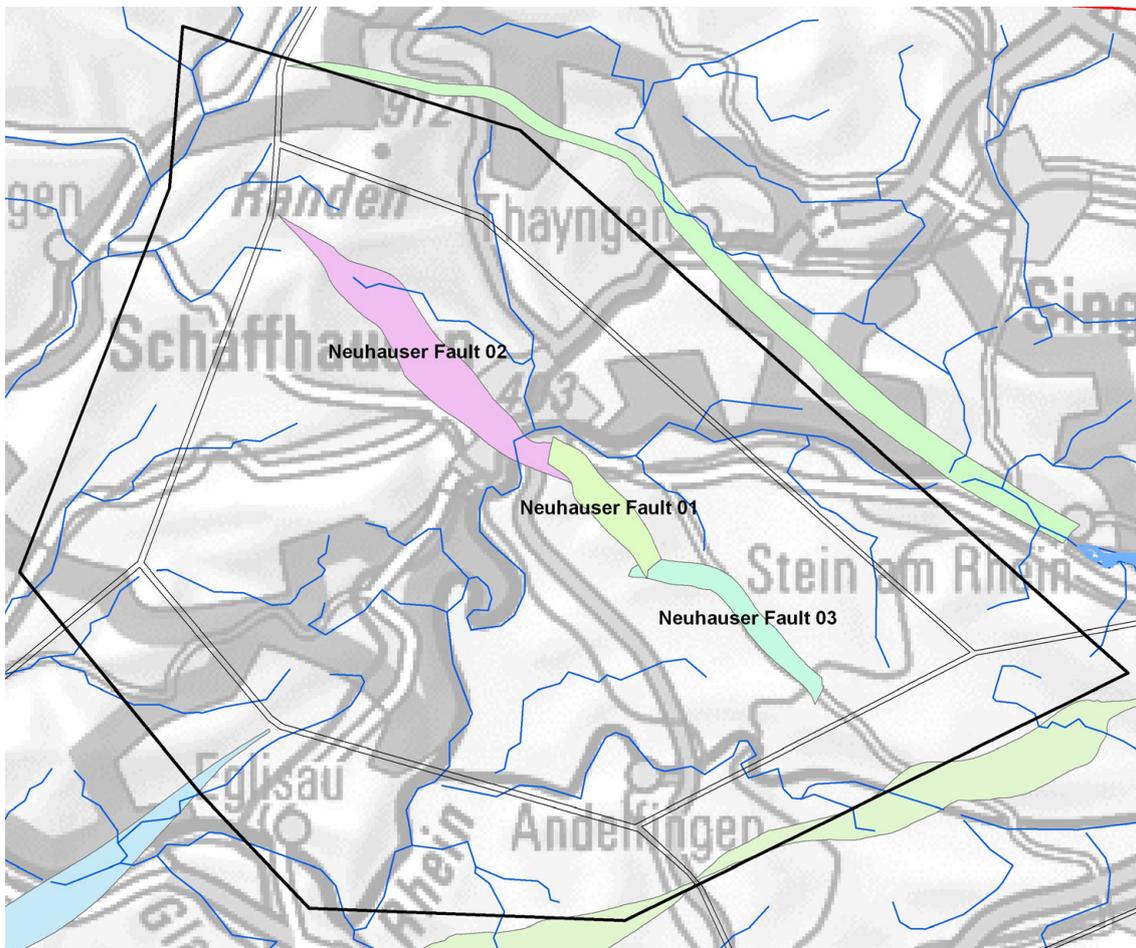


Fig. 68: Sub model „Schaffhausen”. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines) and faults in the sub model area.

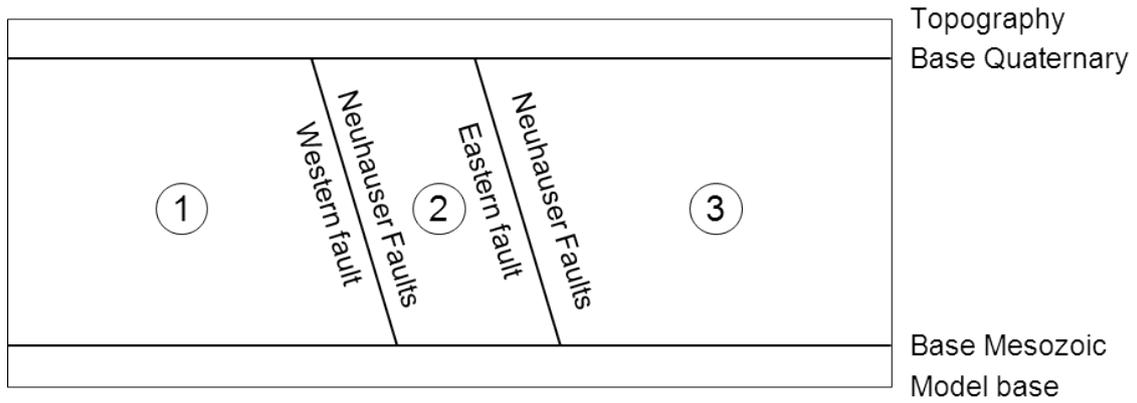


Fig. 69: Schematic section through the sub model „Schaffhausen“.

4.6.2 Resulting Sub Model

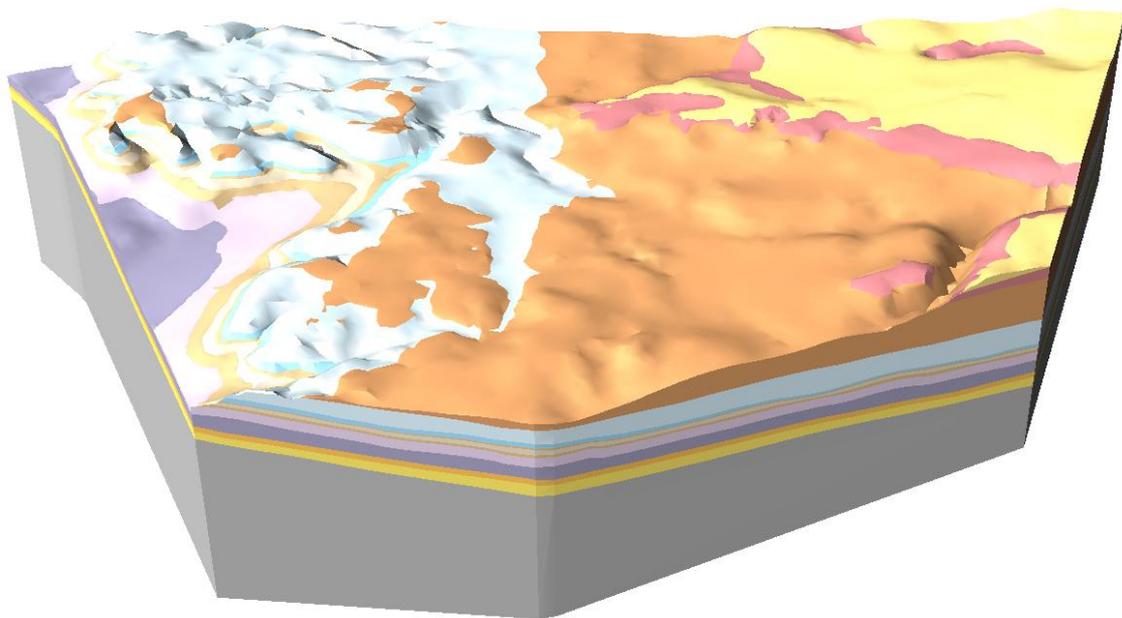


Fig. 70: Perspective view on the sub model „Schaffhausen“ from West.

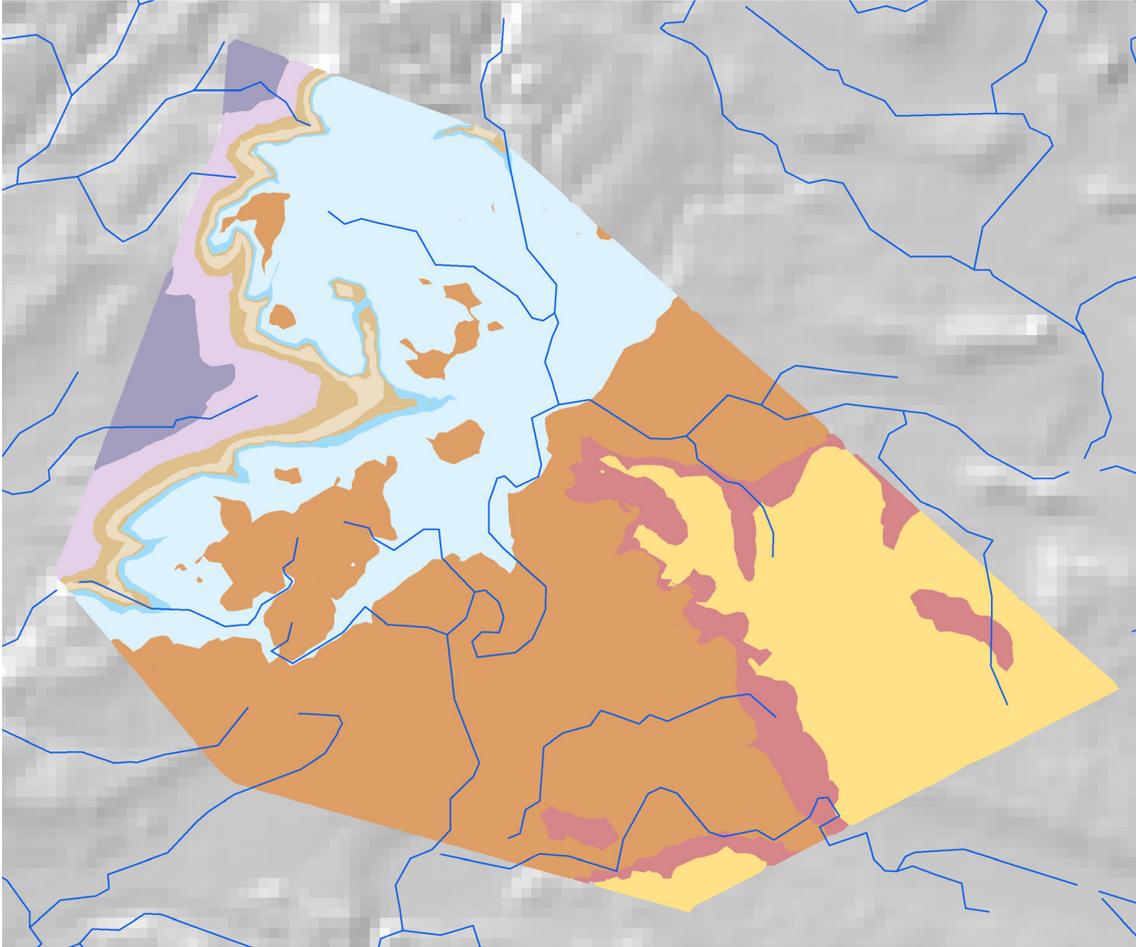


Fig. 71: Sub model "Schaffhausen": Outcropping units at the Quaternary base.

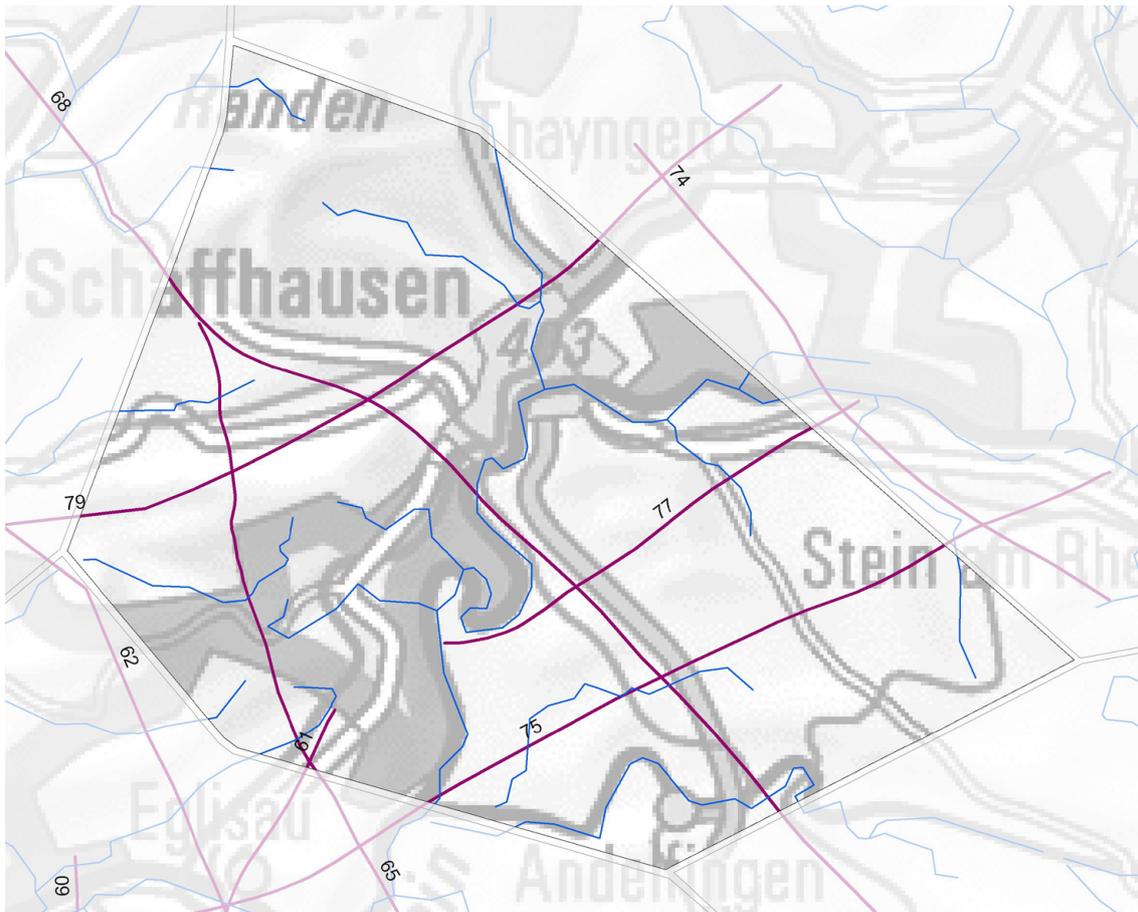


Fig. 72: Position of the sections according to Nagra (2008).

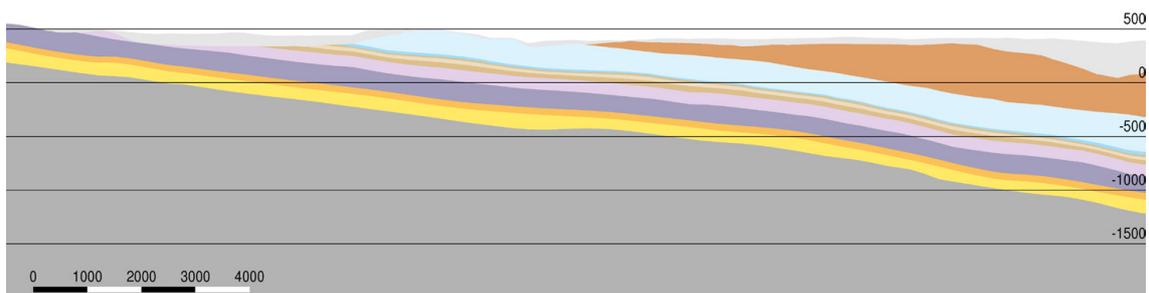


Fig. 73: N-S Section 68 (parts inside sub model "Schaffhausen"), vertical exaggeration 2.

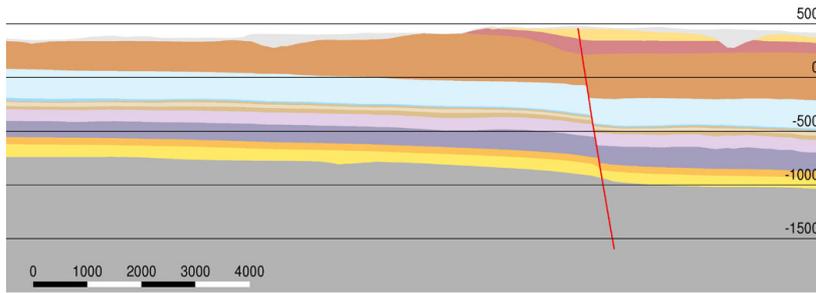


Fig. 74: W-E Section 75 (parts inside sub model “Schaffhausen”), vertical exaggeration 2.

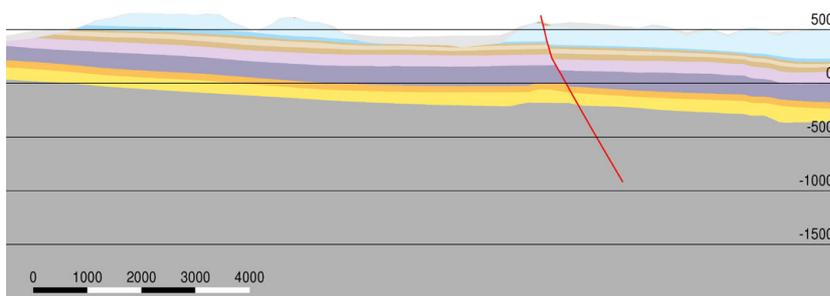


Fig. 75: W-E Section 79 (parts inside sub model “Schaffhausen”), vertical exaggeration 2.

4.7 Sub Model “Singen“

4.7.1 Model Composition

Fig. 76 shows the situation at the sub model „Singen“. The sub model contains three faults. The Randen fault is modeled as a non-vertical fault in GeoMod 2011.1 while the Singen and Stahringen Faults are vertical. No vertical shift of the geological units was modeled along these faults in GeoMod 2011.1. Therefore, only the Randen fault is relevant for the construction of the horizons. The two other faults were omitted, but they can be reintegrated in any further model by vertical elements along the fault traces if needed.

A schematic section through the model is shown in Fig. 77. The Randen fault splits the model into two parts. The analysis of the GeoMod 2011.1 horizons showed that the Mesozoic Base shows a vertical shift along the Randen fault. Therefore the Randen fault was allowed to cut this horizon. By cutting out the area along the Randen fault and re-extrapolating both sides, a clear shift could be modeled (Fig. 78).

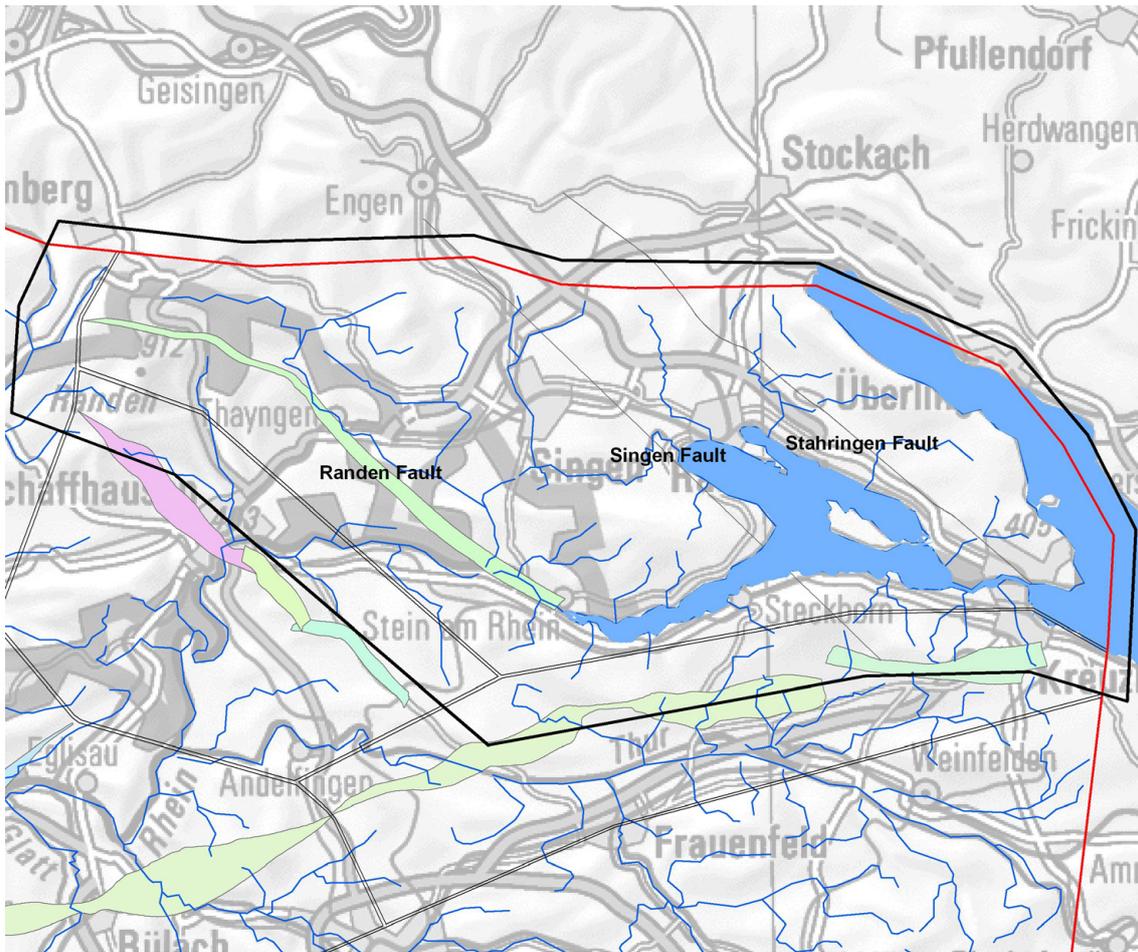


Fig. 76: Sub model „Singen“. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines) and faults in the sub model area.

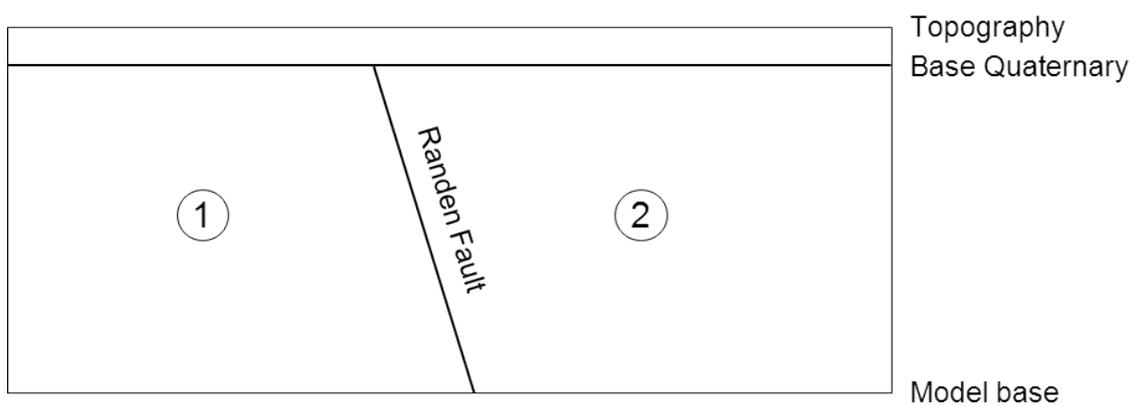


Fig. 77: Schematic section through the sub model „Singen“.

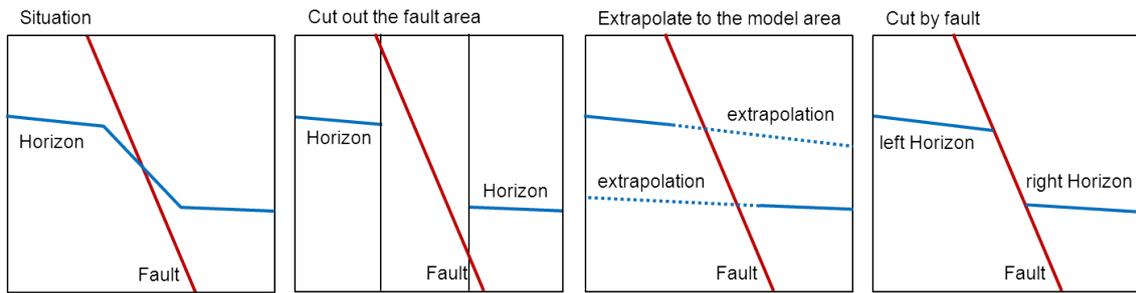


Fig. 78: Steps to create the Mesozoic Base along the Randen fault.

4.7.2 Resulting Sub Model

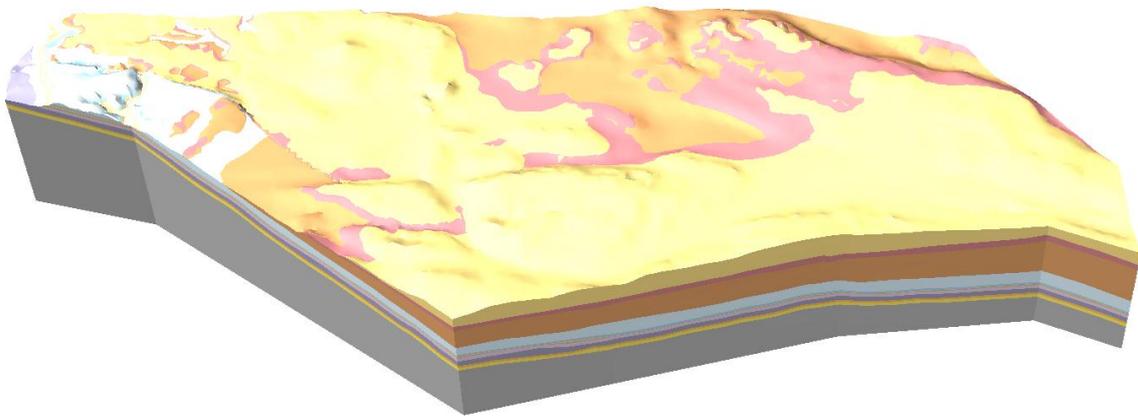


Fig. 79: Perspective view on the sub model „Singen“ from West.

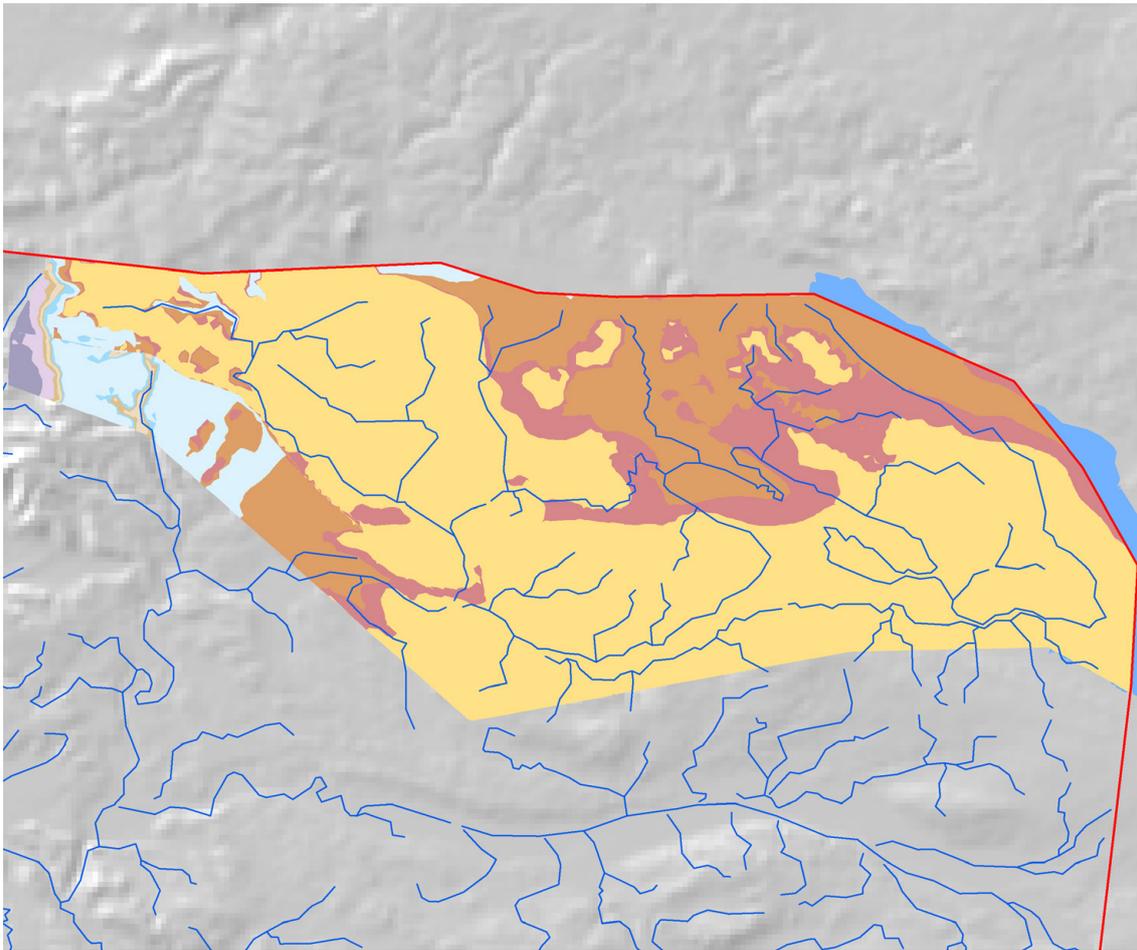


Fig. 80: Sub model "Singen": Outcropping units at the Quaternary base.

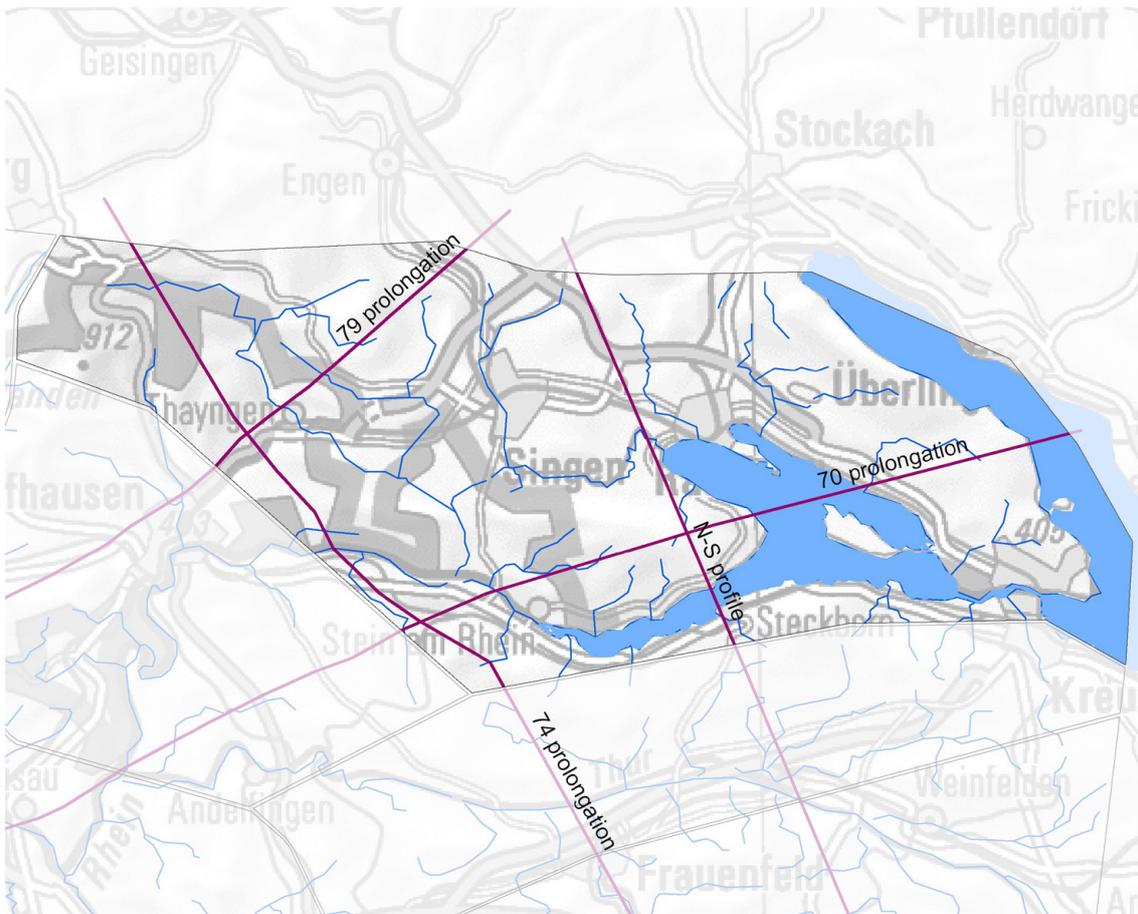


Fig. 81: Position of the sections according to Nagra (2008), prolonged to the northern, eastern and southern border of the sub model.

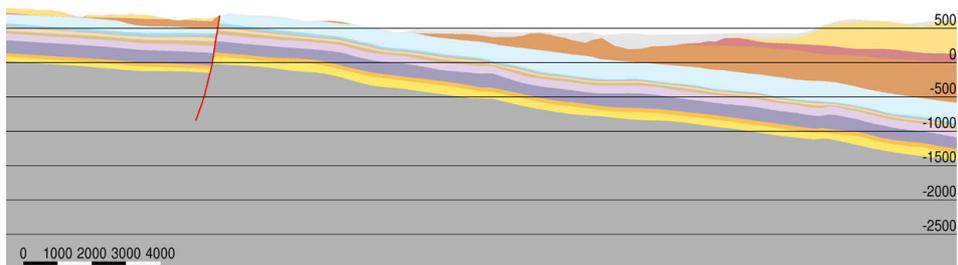


Fig. 82: S-N Section 74 (prolongation inside sub model "Singen"), vertical exaggeration 2.

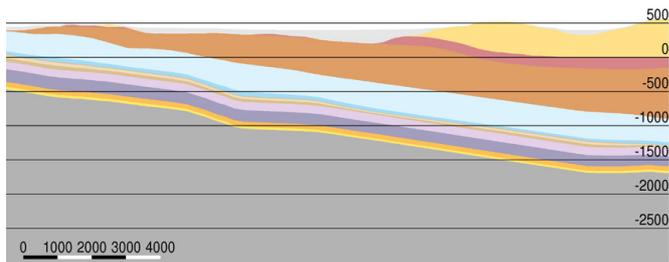


Fig. 83: S-N Section (part inside sub model “Singen”), vertical exaggeration 2.

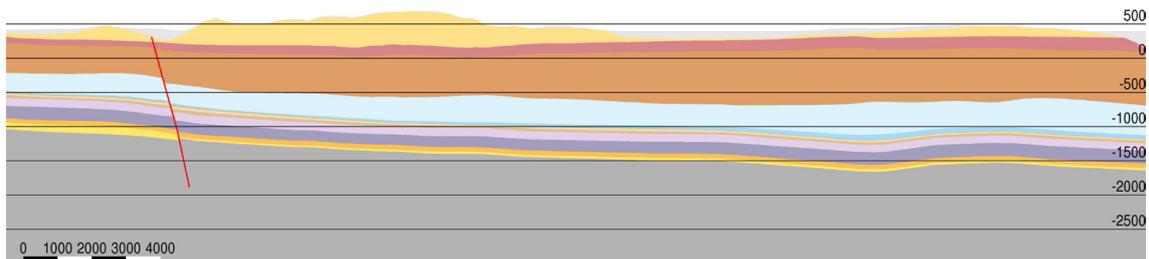


Fig. 84: W-E Section 75 (prolongation inside sub model “Singen”), vertical exaggeration 2.

4.8 Sub Model “Sursee”

4.8.1 Model Composition

The sub model „Sursee“ does not contain any faults. The model was therefore built up just adding the geological units from bottom to top and then cutting the sequence by the Quaternary Base.

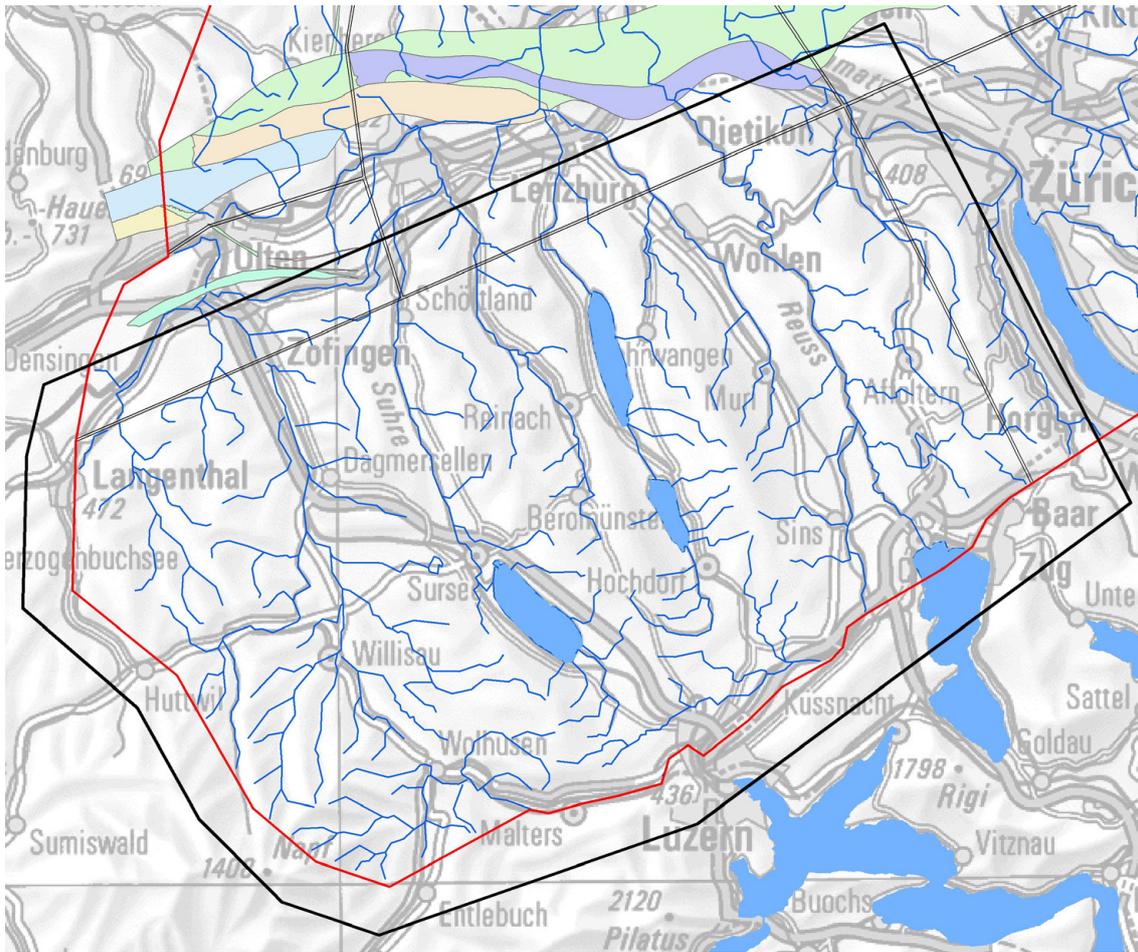


Fig. 85: Sub model „Sursee”. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines).

4.8.2 Resulting Sub Model

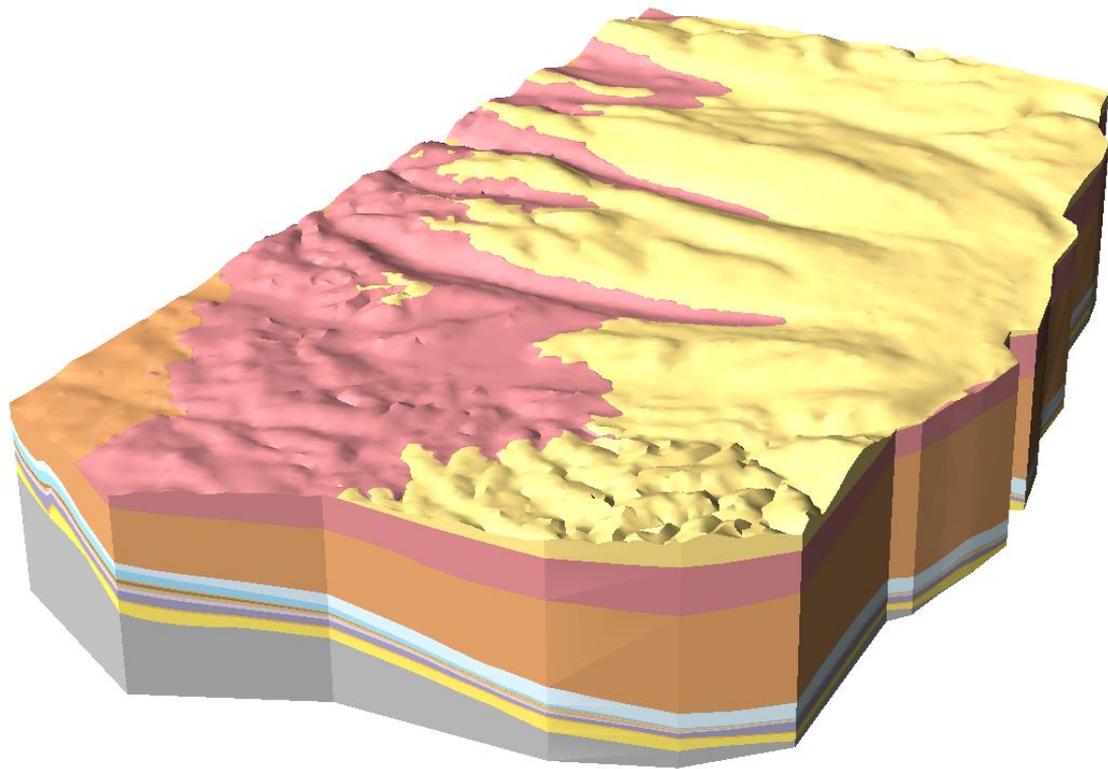


Fig. 86: Perspective view on the sub model „Sursee“ from South-West.

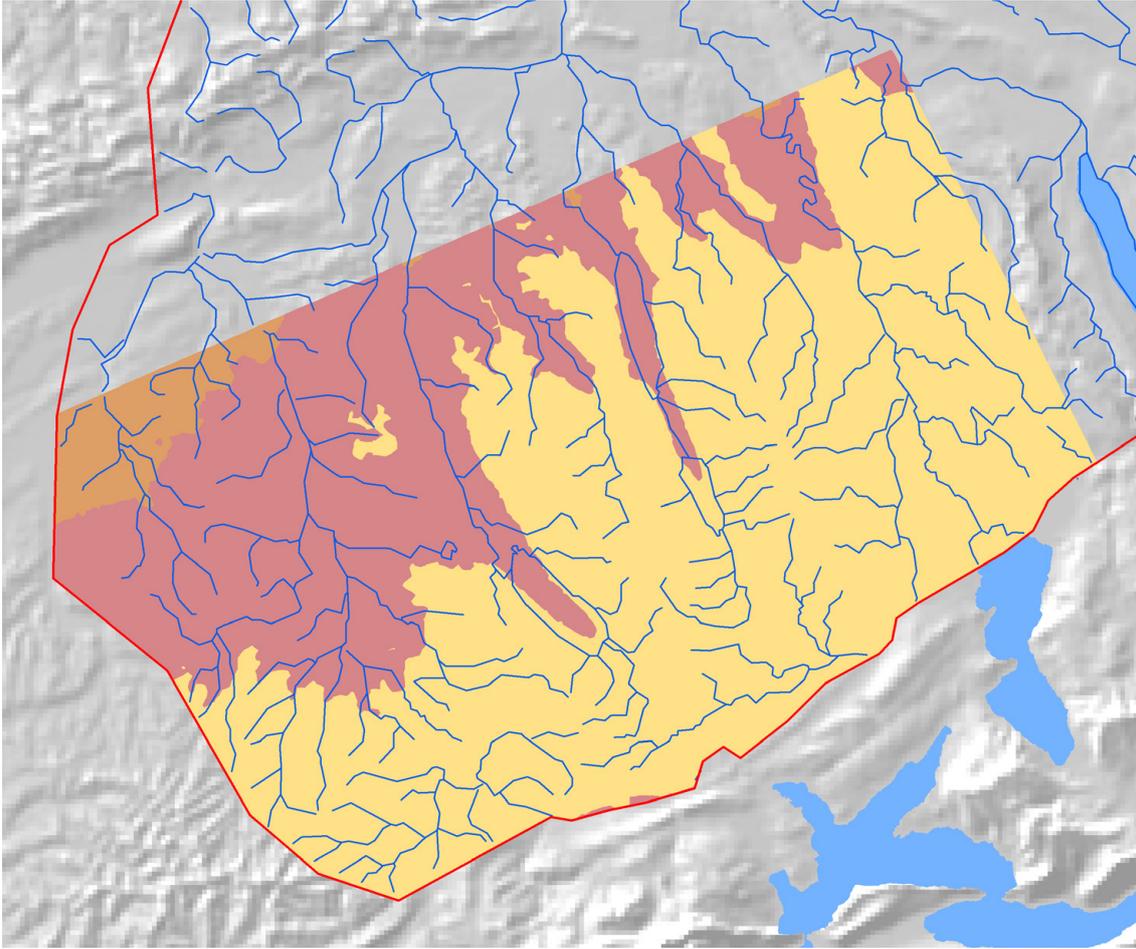


Fig. 87: Sub model "Sursee": Outcropping units at the Quaternary base.

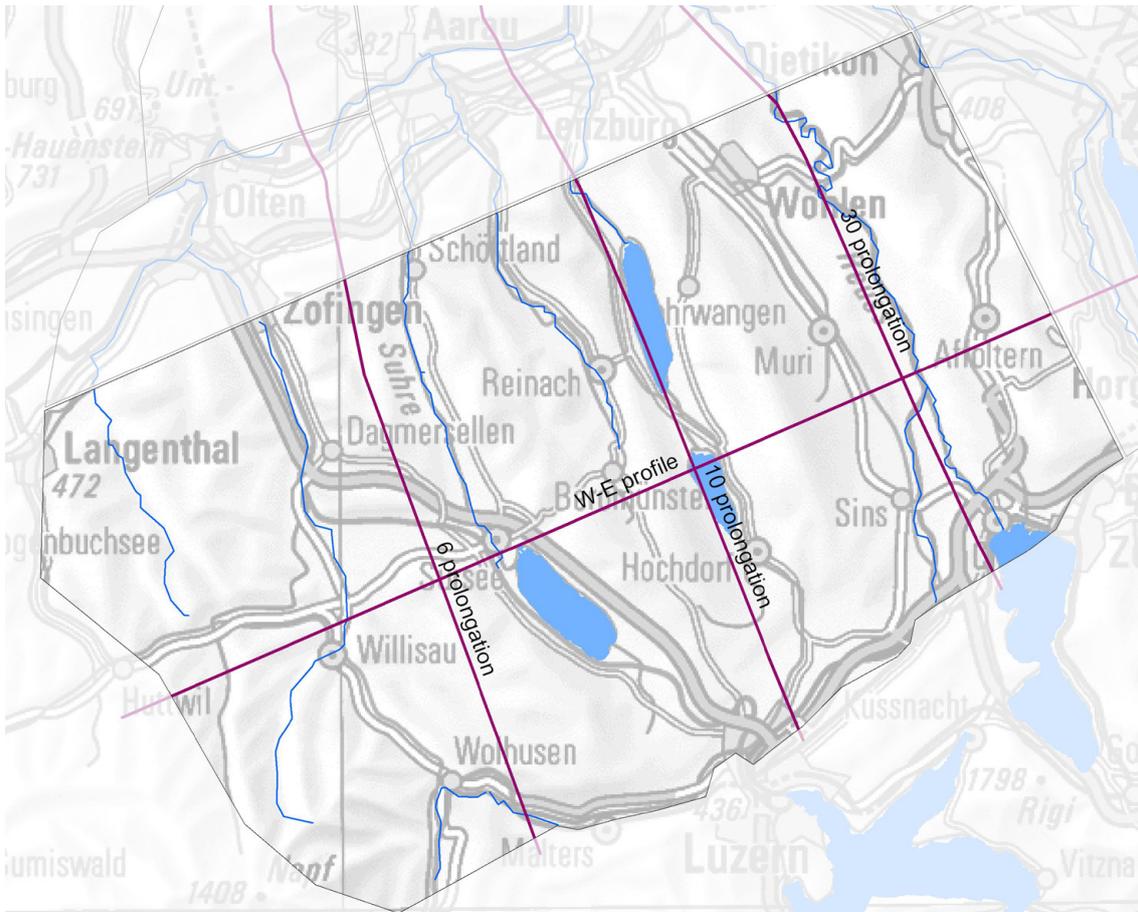


Fig. 88: Position of the sections according to Nagra (2008), prolonged to the western and southern border of the sub model.

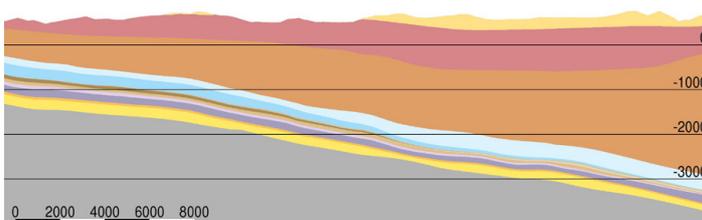


Fig. 89: S-N Section 6 (prolongation inside sub model “Sursee”), vertical exaggeration 2.

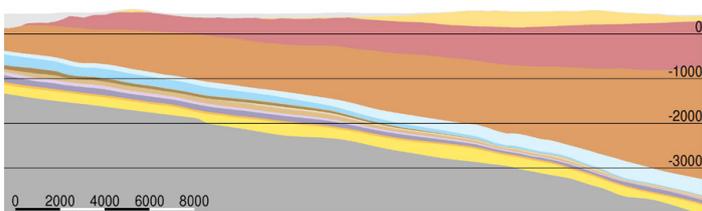


Fig. 90: S-N Section 10 (prolongation inside sub model “Sursee”), vertical exaggeration 2.

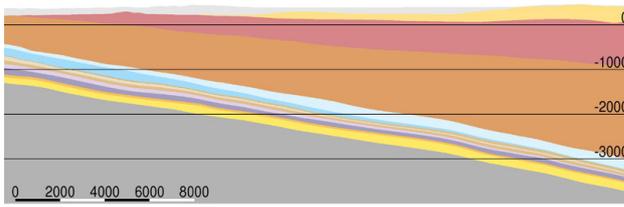


Fig. 91: S-N Section 30 (prolongation inside sub model “Sursee”), vertical exaggeration 2.

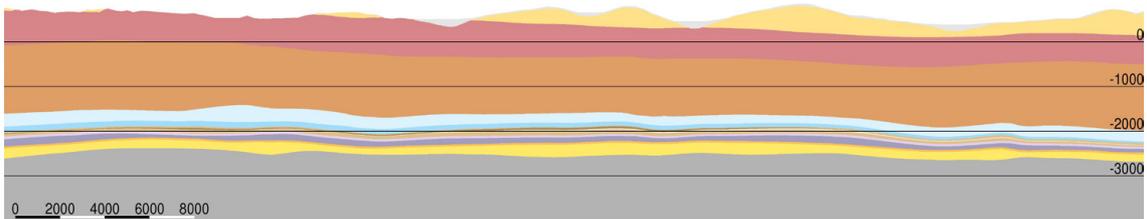


Fig. 92: W-E Section (part inside sub model “Sursee”), vertical exaggeration 2.

4.9 Sub Model “Thur”

4.9.1 Model Composition

The sub model „Thur“ contains the eastern part of the Baden-Irchel-Herdern Lineament (BIH) and the Homburg Fault, both dipping towards the north. For the model generation, the two faults were connected to a single fault by manually adding some triangles. The BIH defined in GeoMod 2011.1 also contained some triangles dipping to the south. To generate a fault suitable for cutting the horizons, all triangles had to be forced to dip towards north. The trace line was kept unchanged. The fault nodes below the trace line that did not show a dip of 85 degrees or less towards NNE were displaced towards NNE until the criteria was matched.

A schematic section through the model is shown in Fig. 94. The BIH and the Homburg faults split the model into two parts. The analysis of the GeoMod 2011.1 horizons showed that the Mesozoic Base shows a vertical shift along the Randen fault. Therefore the Randen fault was allowed to cut this horizon. By cutting out the area along the Randen fault and re-extrapolating both sides, a clear shift could be modeled (Fig. 78).

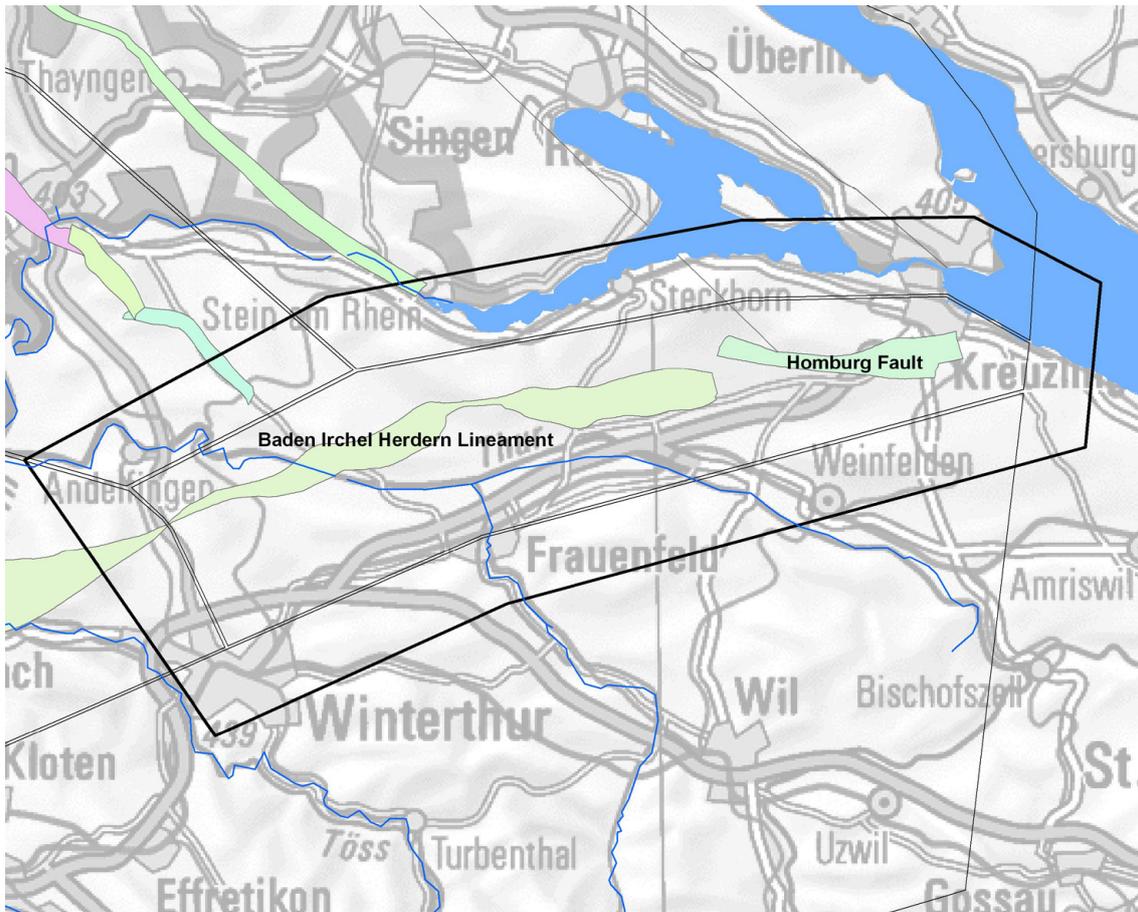


Fig. 93: Sub model „Thur“. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines) and faults in the sub model area.

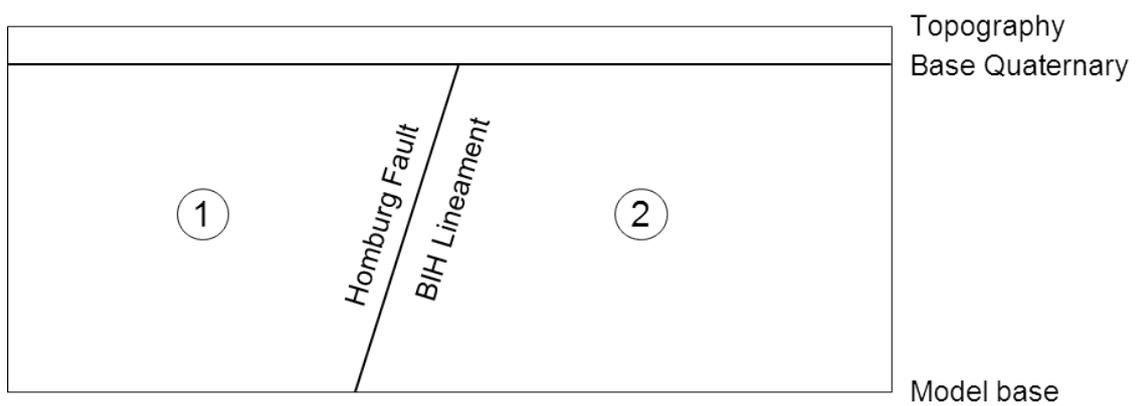


Fig. 94: Schematic section through the sub model „Thur“.

4.9.2 Resulting Sub Model

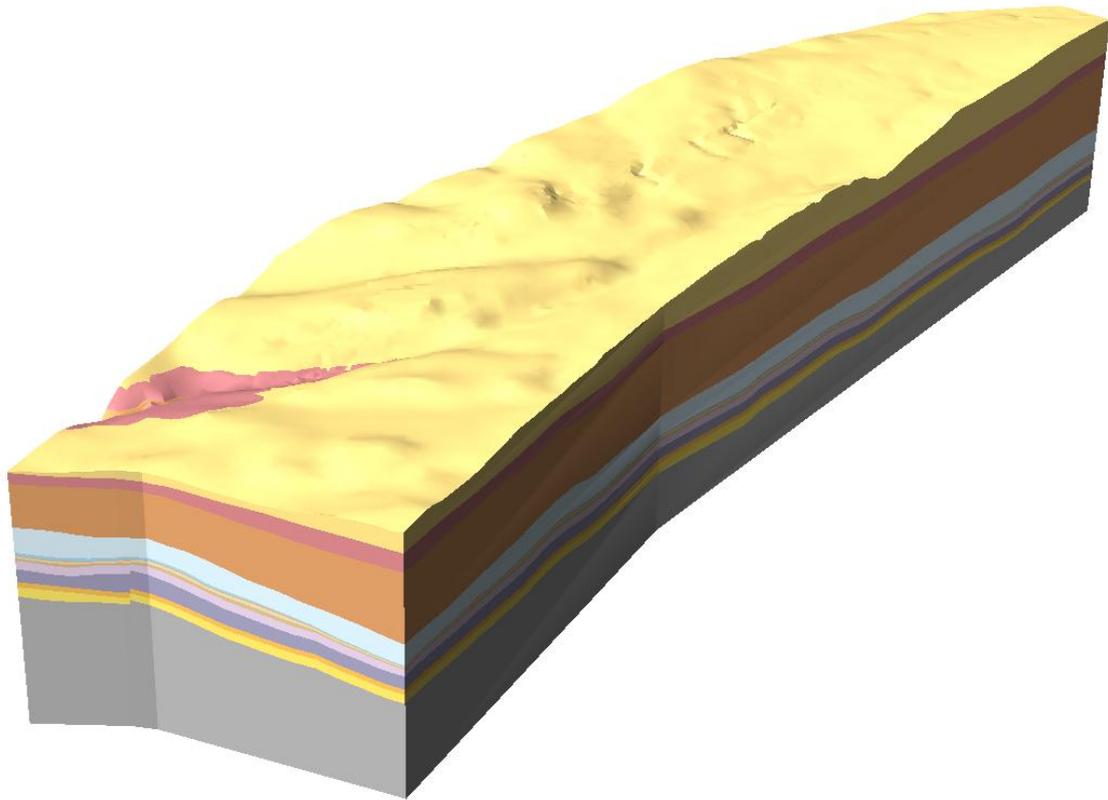


Fig. 95: Perspective view on the sub model „Thur“ from South-West.

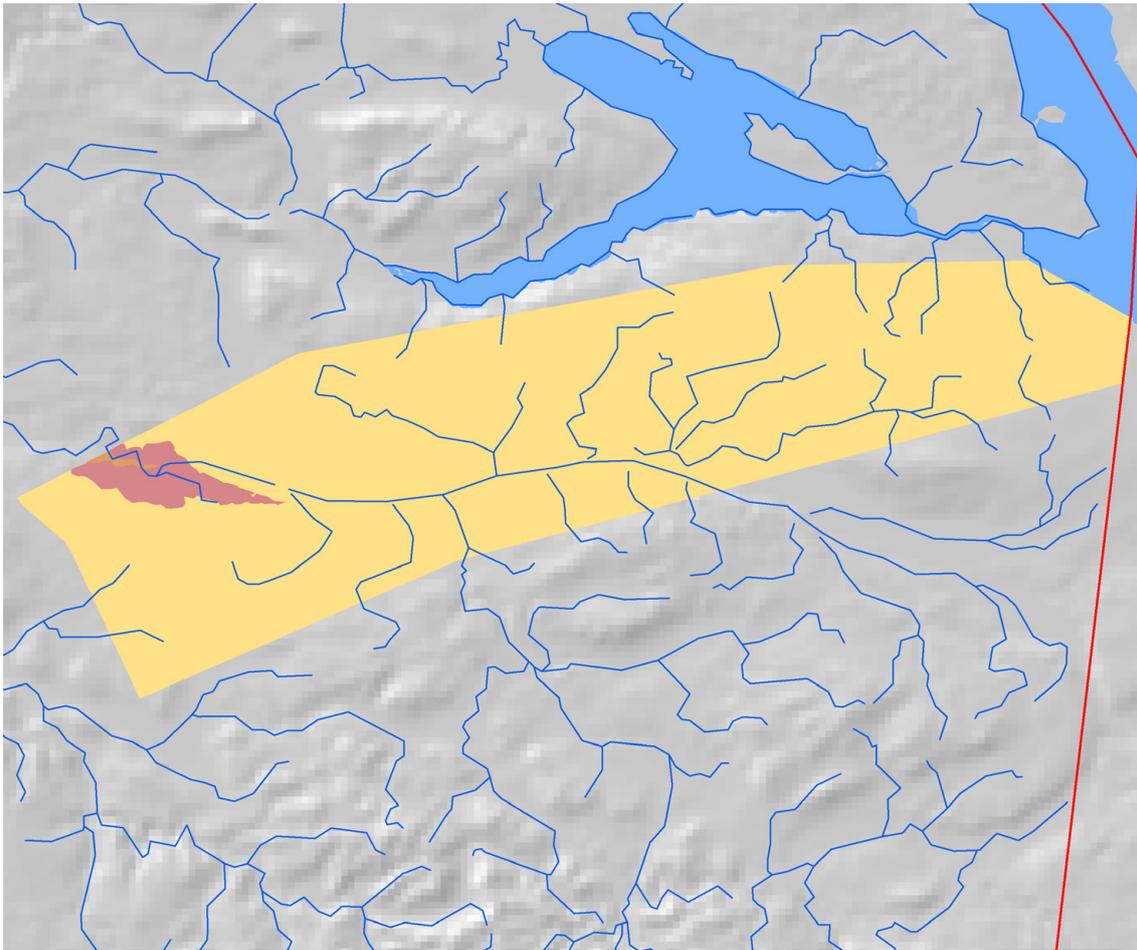


Fig. 96: Sub model "Thur": Outcropping units at the Quaternary base.

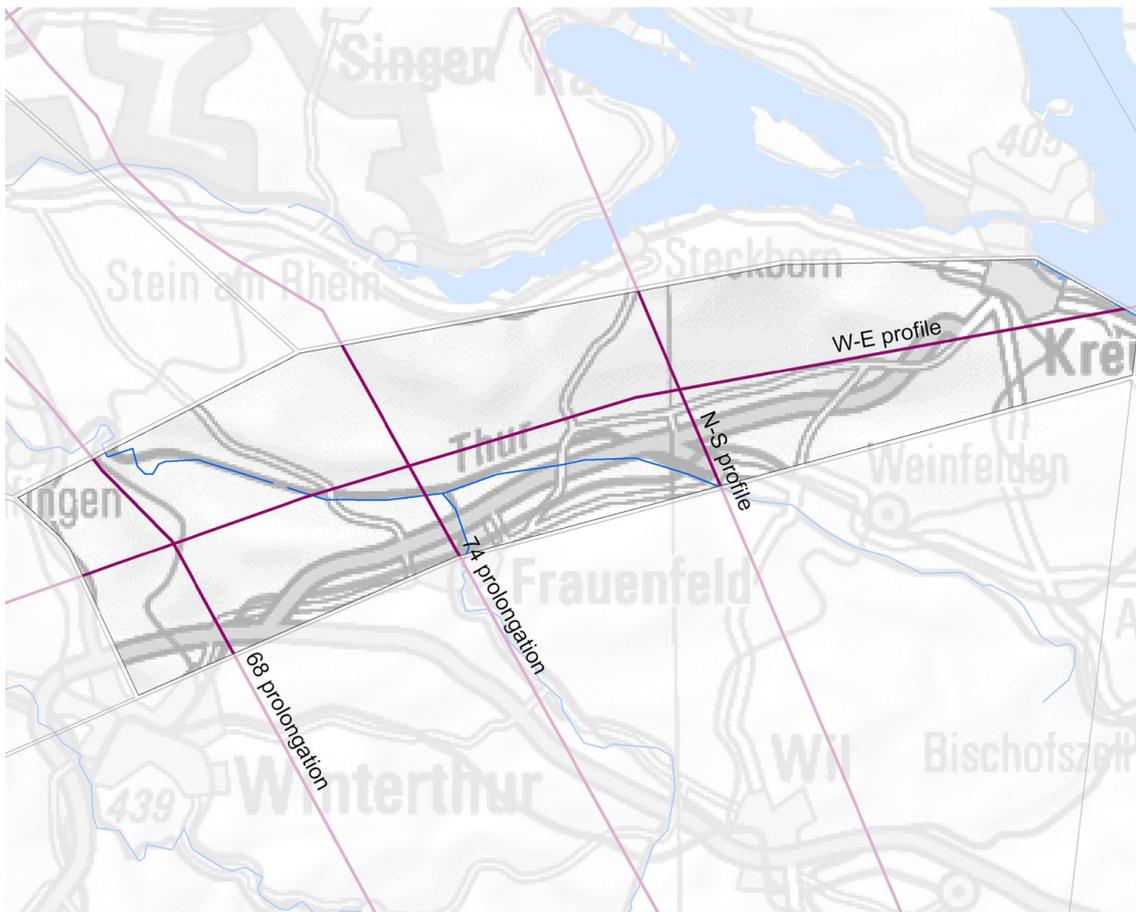


Fig. 97: Position of the sections according to Nagra (2008), prolonged to the southern border of the model. A W-E profile was added through the center of the sub model.

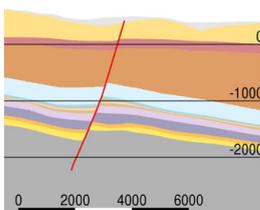


Fig. 98: S-N Section 74 (prolongation inside sub model "Thur"), vertical exaggeration 2.

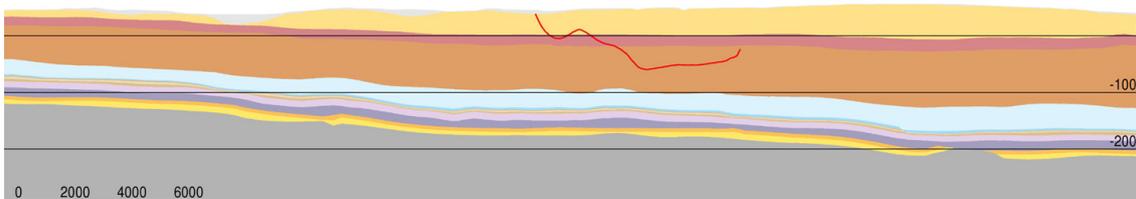


Fig. 99: W-E Section (part inside sub model "Thur"), vertical exaggeration 2.

4.10 Sub Model “Toess”

4.10.1 Model Composition

The sub model „Toess“ does not contain any faults. The model was therefore built up just adding the geological units from bottom to top and then cutting the sequence by the Quaternary Base.

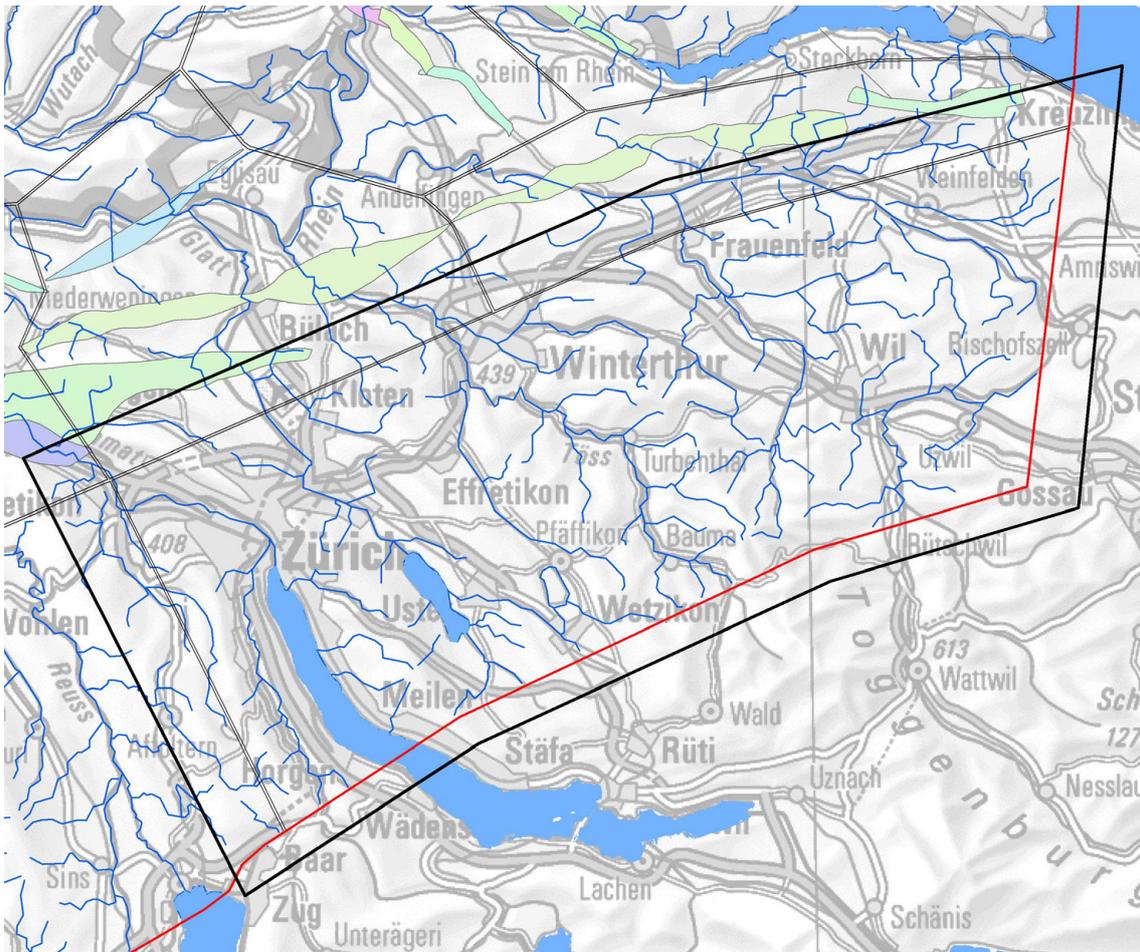


Fig. 100: Sub model „Toess”. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines).

4.10.2 Resulting Sub Model

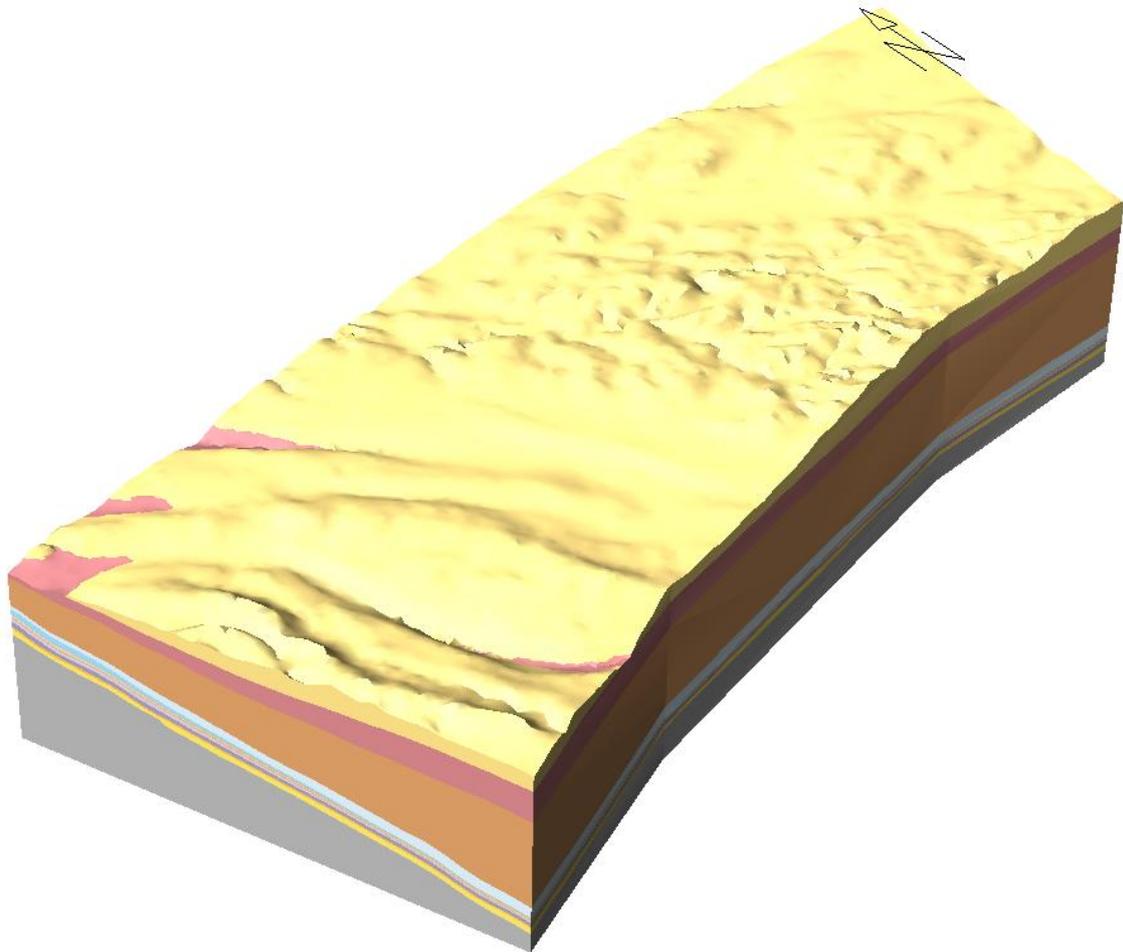


Fig. 101: Perspective view on the sub model „Toess“ from South-West.

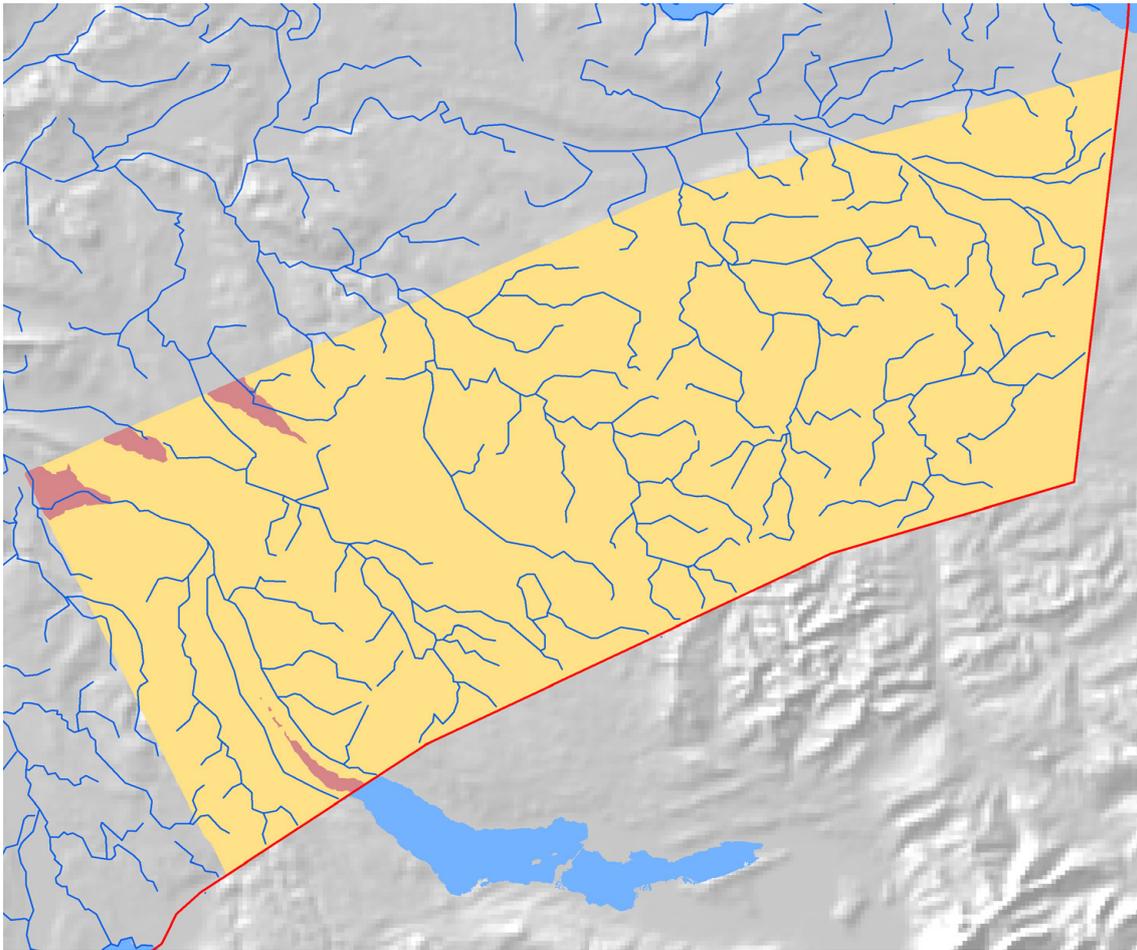


Fig. 102: Sub model “Toess”: Outcropping units at the Quaternary base.

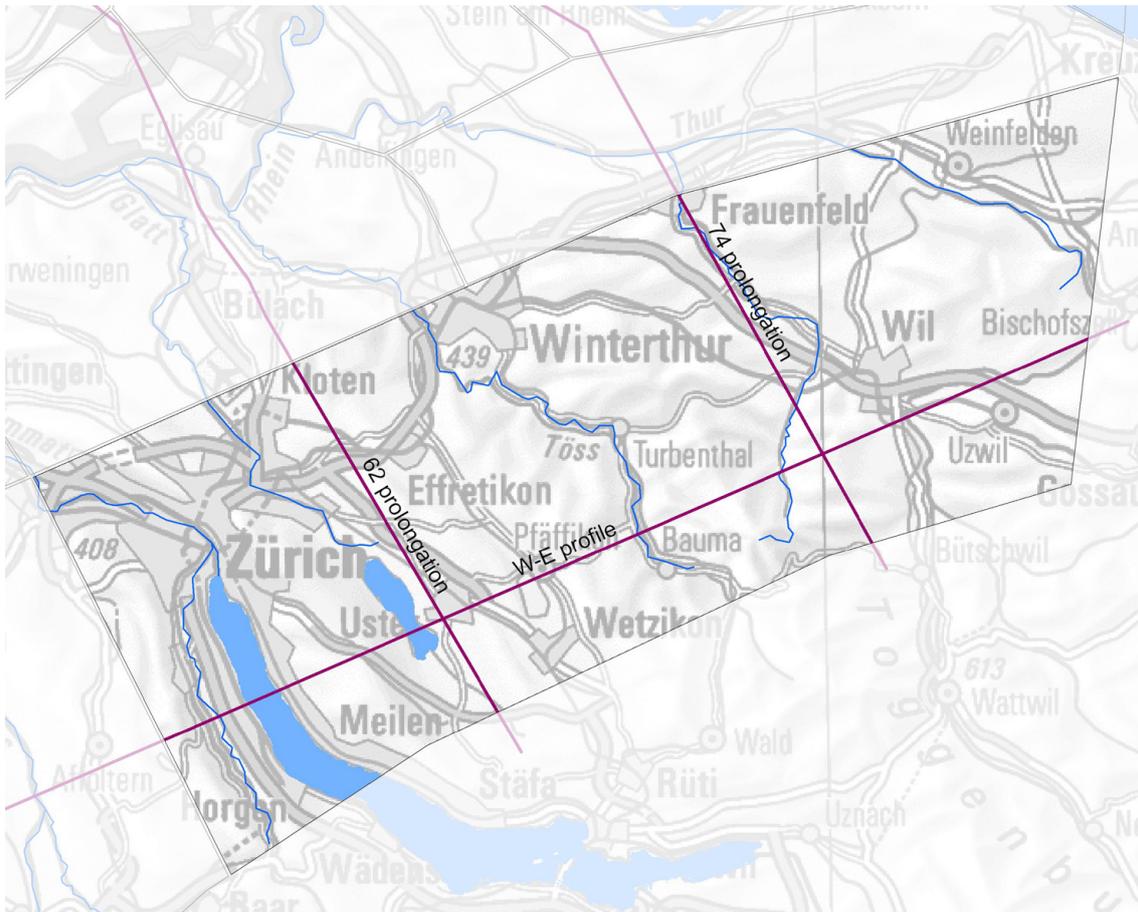


Fig. 103: Position of the sections according to Nagra (2008), prolonged to the southern border of the model. A W-E profile was added through the sub model.

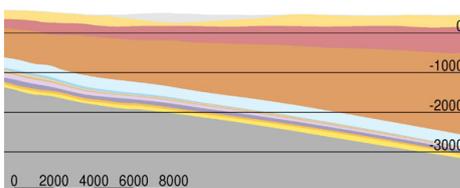


Fig. 104: S-N Section 62 (prolongation inside sub model "Toess"), vertical exaggeration 2.

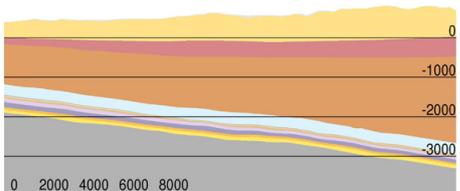


Fig. 105: S-N Section 74 (prolongation inside sub model "Toess"), vertical exaggeration 2.

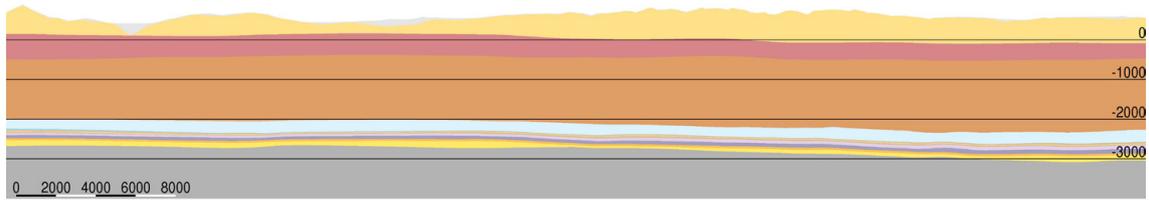


Fig. 106: W-E Section (part inside sub model “Toess”), vertical exaggeration 2.

4.11 Sub Model “Wutach”

4.11.1 Model Composition

The sub model „Wutach“ does not contain any faults. The model was therefore built up just adding the geological units from bottom to top and then cutting the sequence by the Quaternary Base.

The difficulty in building up the sub model was that rather large areas of the Muschelkalk horizon were missing in GeoMod 2011.1 (Fig. 15). The horizon had to be extrapolated and cut by the Quaternary base. The intersection line however was not identical to the mapped outcrop line of the Muschelkalk unit. To adjust the model outcrop line, points along the mapped outcrop line were added to the horizon. The space between the horizon limits and the outcrop was filled with a triangulation mesh.

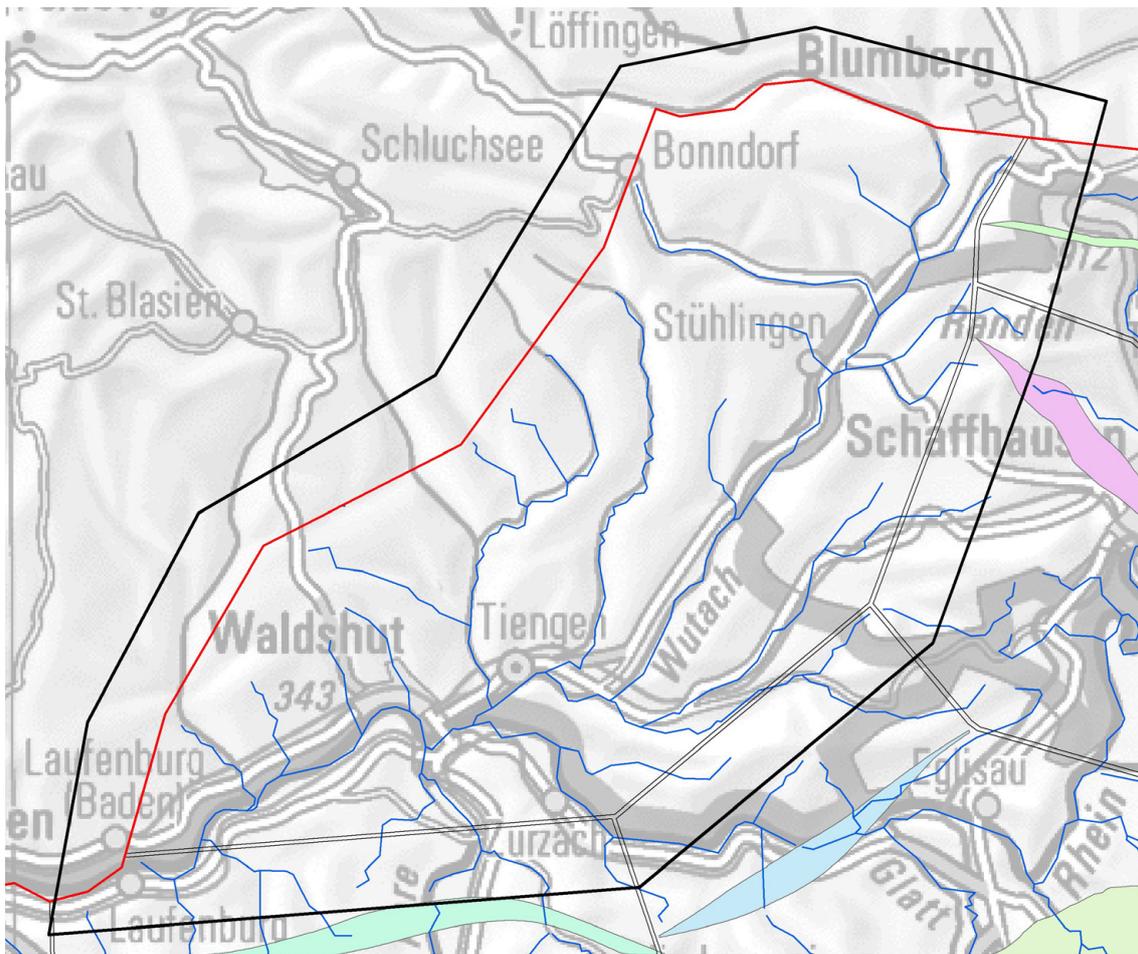


Fig. 107: Sub model „Wutach”. Situation with horizon boundaries (thick black line), model boundaries (inner line of the double black lines).

4.11.2 Resulting Sub Model

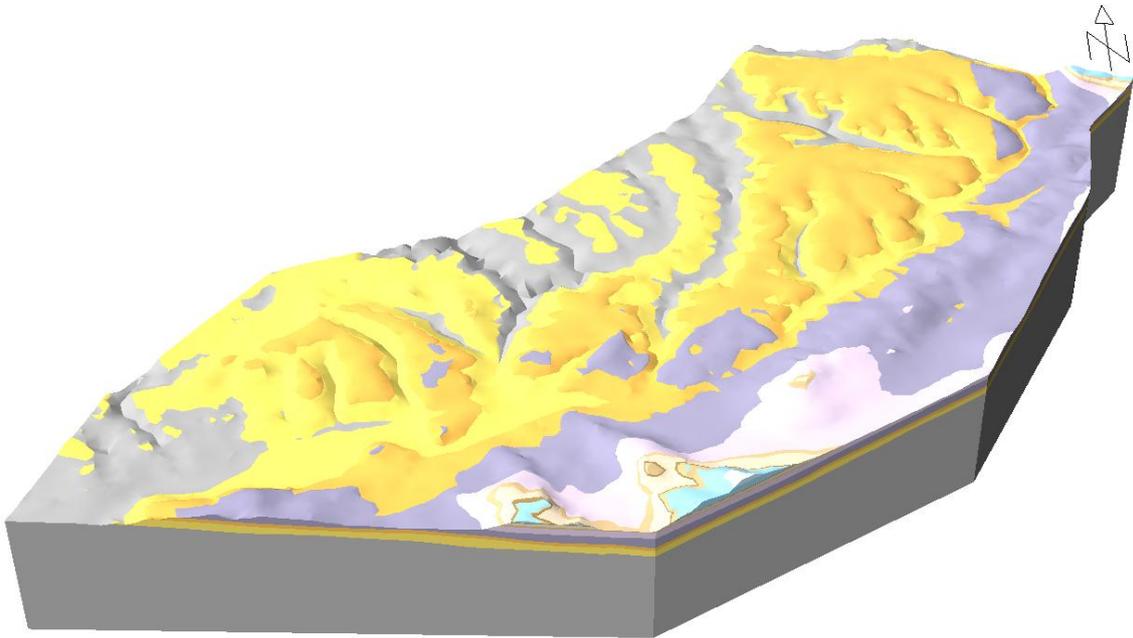


Fig. 108: Perspective view on the sub model „Wutach“ from South.

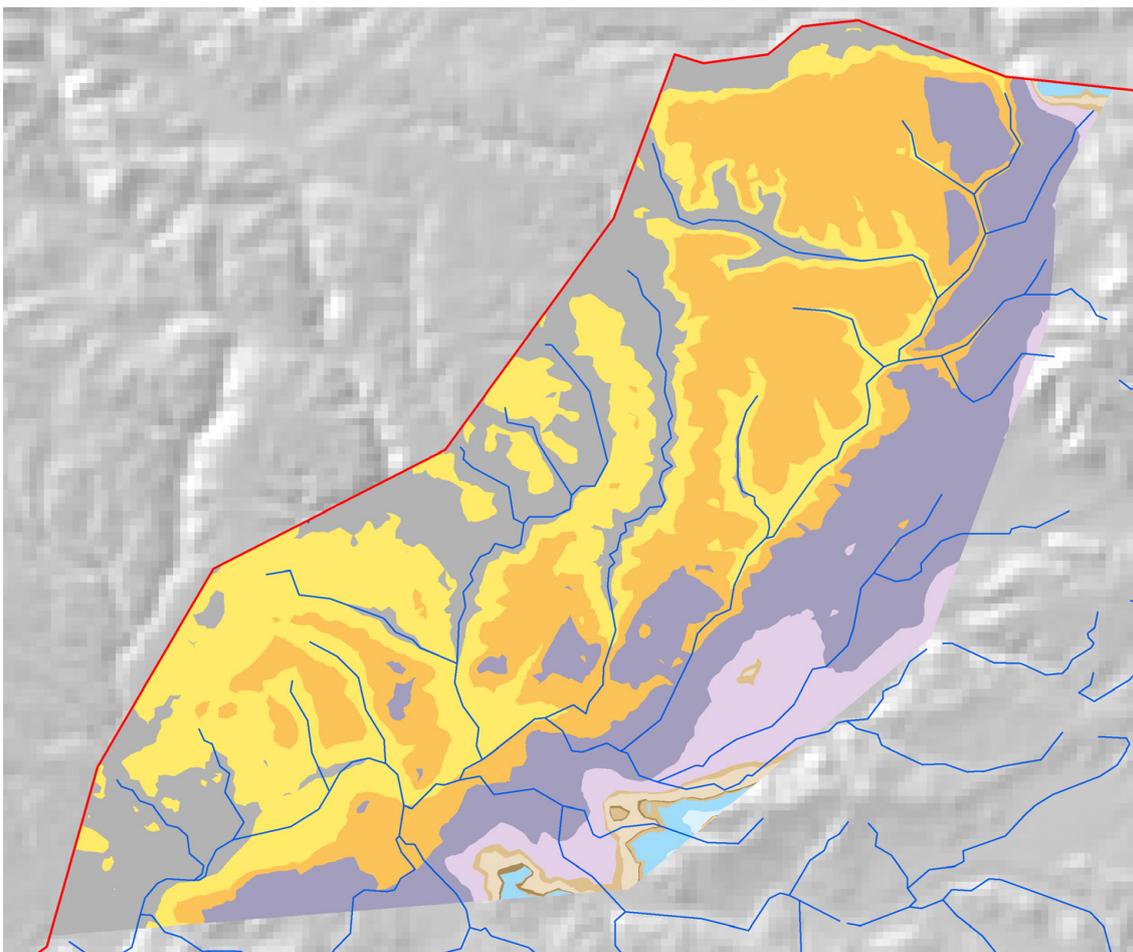


Fig. 109: Sub model "Wutach": Outcropping units at the Quaternary base.

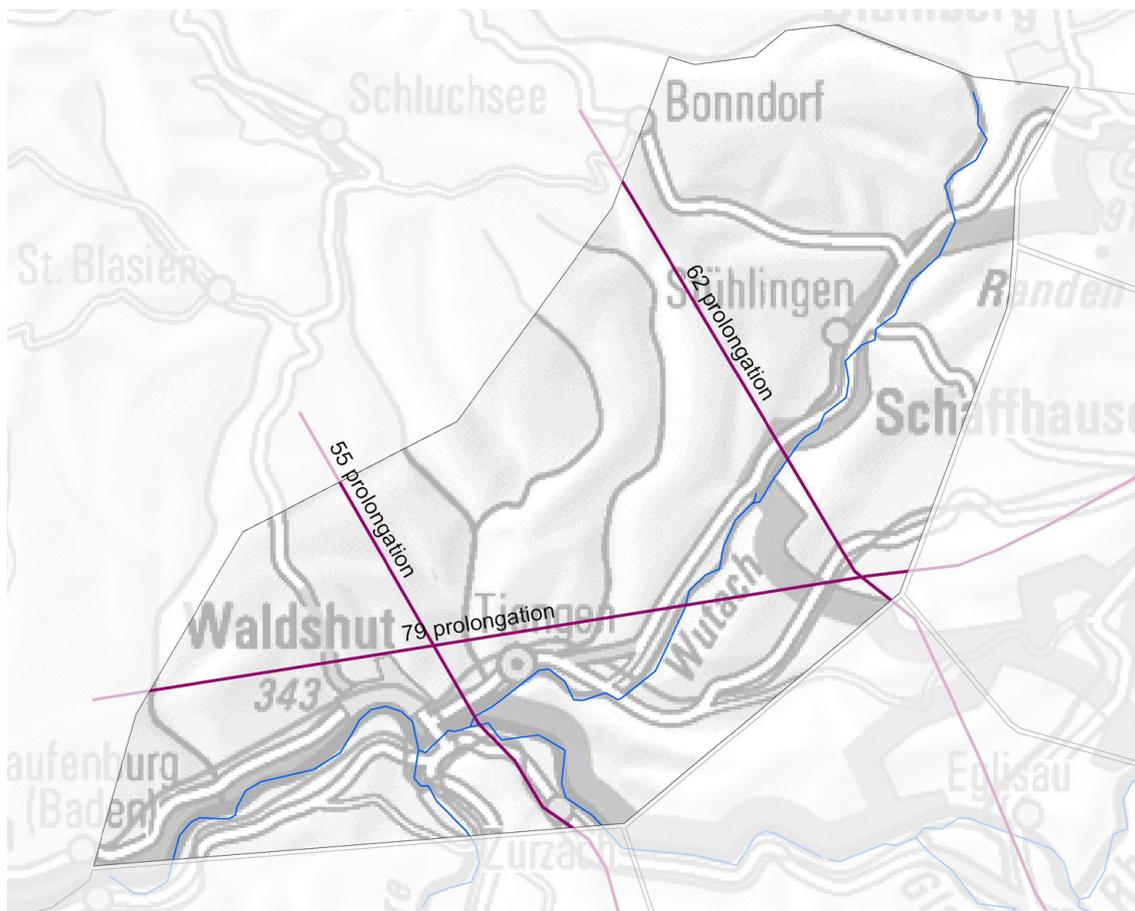


Fig. 110: Position of the sections according to Nagra (2008), prolonged to the western and northern borders of the model.



Fig. 111: S-N Section 55 (prolongation inside sub model “Wutach”), vertical exaggeration 2.

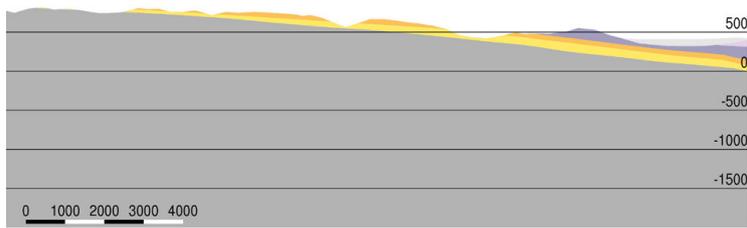


Fig. 112: S-N Section 62 (prolongation inside sub model “Wutach”), vertical exaggeration 2.

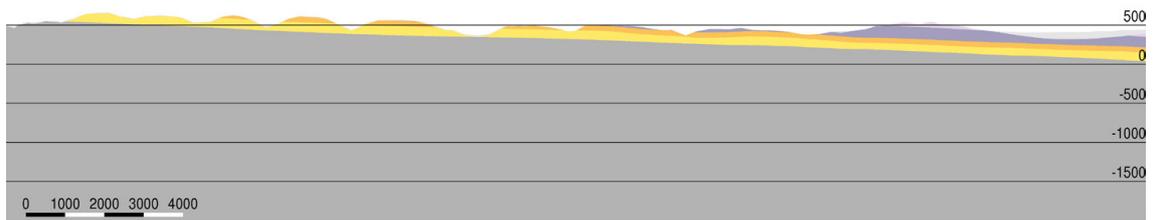


Fig. 113: W-E Section 79 (prolongation inside sub model “Wutach”), vertical exaggeration 2.

5 Overall Model

5.1 Joining the Sub Models together

The Sub model boundaries are separated from each other by one strip of triangles of the common grid. The horizons of the single sub models are joined together by connecting the boundary nodes with new elements (see algorithm in Chapter 2.4). A problem occurs along overthrusting faults where horizons are overlapping. Here, the algorithm has to decide which nodes belong to the same surface. Horizon nodes at one side of a fault should not be connected to nodes on the other side. To guarantee a correct joining, the blocks, generated by cutting the horizons with the fault surfaces, have been numbered (Fig. 114). The joining software was then provided with a list of allowed connections. For example the connection of blocks 3 and 9 is allowed, whereas the connection of blocks 3 and 8 is not allowed.

The joining process resulted in a set of 15 surfaces, describing the top of every geological unit to be considered. The accompanying DVD contains two files for each surface:

Horizon_name.tri: Triangulation file (GOCAD formatted). The file describes node coordinates, elevations and definition of triangles.

Horizon_name.att: Attributes file. The file describes the association of every element to the sub model, the block number inside the sub model, the block number according to Fig. 114 and the geological unit.

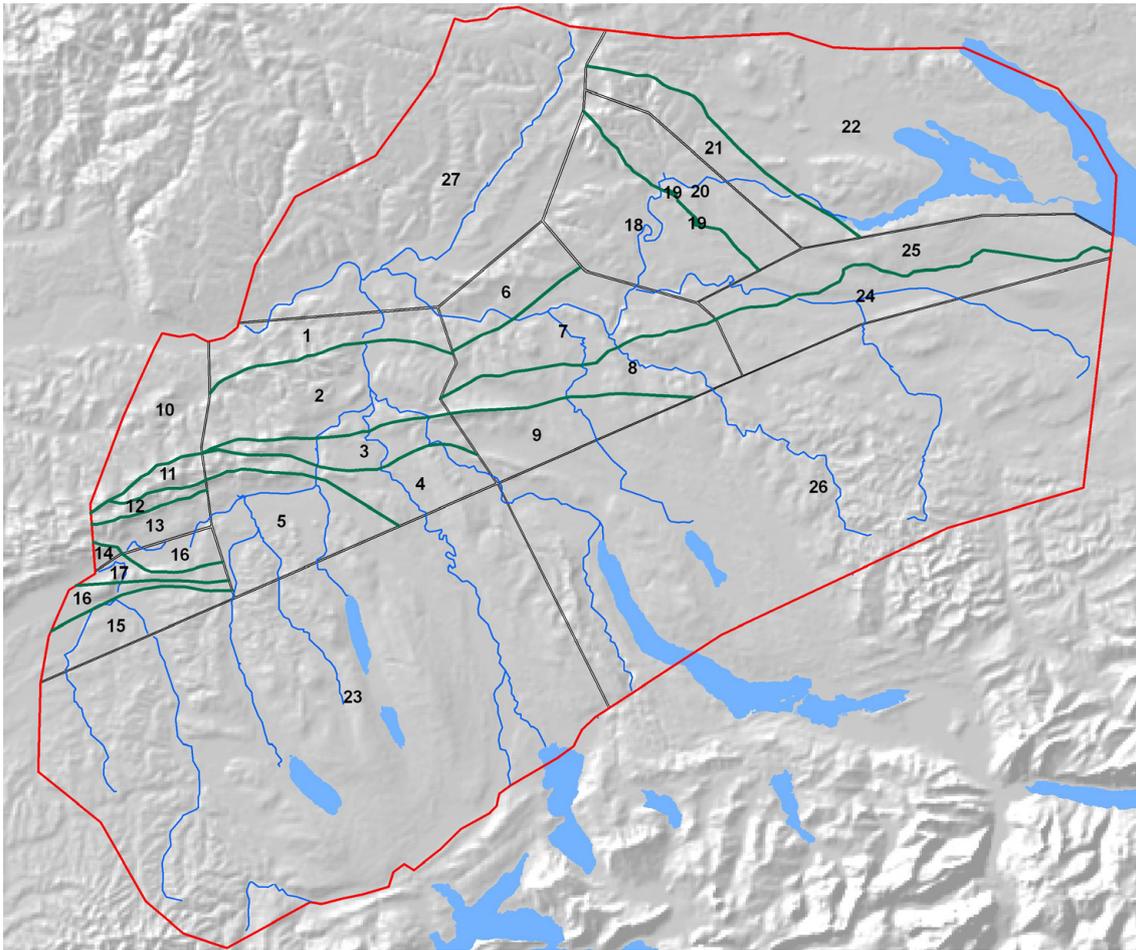


Fig. 114: Block numbers (blocks are generated by cutting the horizons by the fault surfaces).

5.2 Converting the Horizons to ArcGIS Multipatches

To allow an easy distribution of and access to the data, the files had to be converted into a file format which can be read by ESRI ArcGIS (<http://www.esri.com>). A new data type supporting complex (self-overlapping) triangulated meshes within the ESRI universe are ArcGIS Multipatches.

Conversion was done using the Software GOCAD (<http://www.gocad.org>). In a first step a file-header had to be inserted into the GOCAD like files, to load them into GOCAD. Here the files can be exported into Multipatch like features. These can be read by ESRI ArcGIS. The geometry of the Multipatches is defined via the coordinates and elevation of the nodes. The meshing is the same as it was in the original files. An advantage of Multipatches is that they can hold additional attributes. In contrast to some 3D modeling tools, the attributes are stored in each triangle and not node-based. Therefore, every triangle carries its average elevation and a special attribute describing each triangles relative position regarding to a fault. Attribution values are footwall and hanging-wall. In areas where the triangles do not overlap (away from faults), the attribute is set to null. Attribution was done using FME (<http://www.safe.com/>) applying a self-programmed routine.

In addition, contours were generated using the GOCAD Software in equidistant steps of 50 m.

Both sets of files can be found on the accompanying DVD.

5.3 Resulting Horizons

Fig. 115 shows a 3D-overview of the resulting horizons. The Top OSM and Top Quaternary surfaces are not shown because they cover the whole model region and would hide the other surfaces. Further visualizations of the overall model can be found in the appendix.

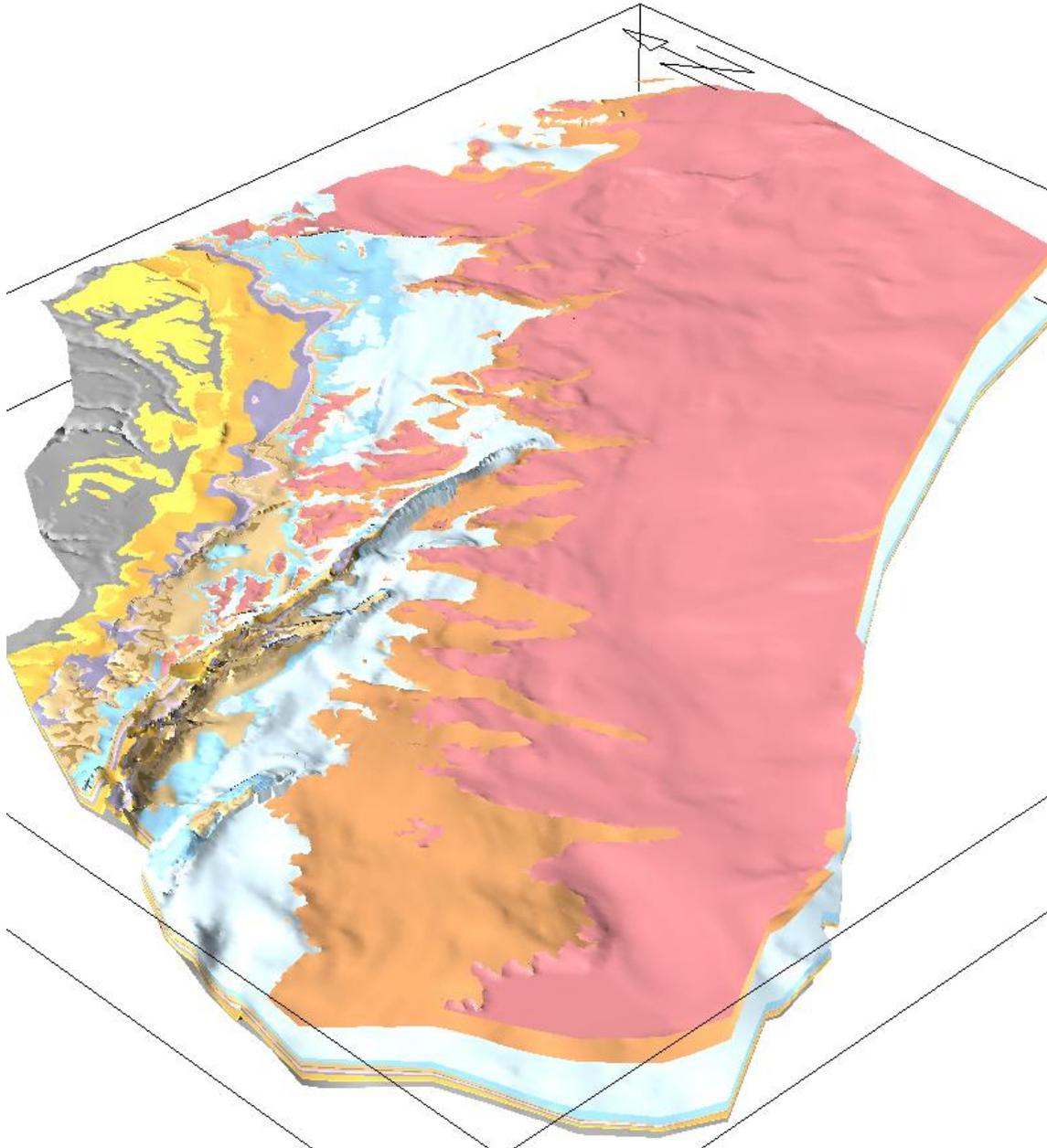


Fig. 115: 3D-view on the resulting horizons (Top Kristalline to Top OMM). Vertical exaggeration 2. The visualization is done by converting the resulting horizons to a VRML file, which can be viewed in the Cortona Player or the BS Contact viewer.

6 References

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Appendix A: Software modules

Interpolate.c: This program interpolates the elevations from one triangulation to another. The code searches the corresponding elements for every node of the resulting grid. Inside this element, a linear interpolation is applied. The program includes some additional options like:

- Cut out the values inside of a given polygon.
- Define a maximum distance to another horizon.
- Use the values of a patch horizon inside a given polygon.

The interpolation program is used to bring all the horizons to the same triangulation (see Fig. 9). This then allows for grid calculations like thickness calculations or minimum/maximum constraints.

Extrapolate.c: This program extrapolates the values at the “undefined” nodes (Fig. A116) from the known values in a triangulation. It either extrapolates the values itself or the normal vectors of the triangles. The algorithm weights the known values by their distance to the undefined node. By choosing the parameters of the distance function the extrapolation can be optimized. The algorithm tends to smooth out the local irregularities at the horizon borders, which often occurred.

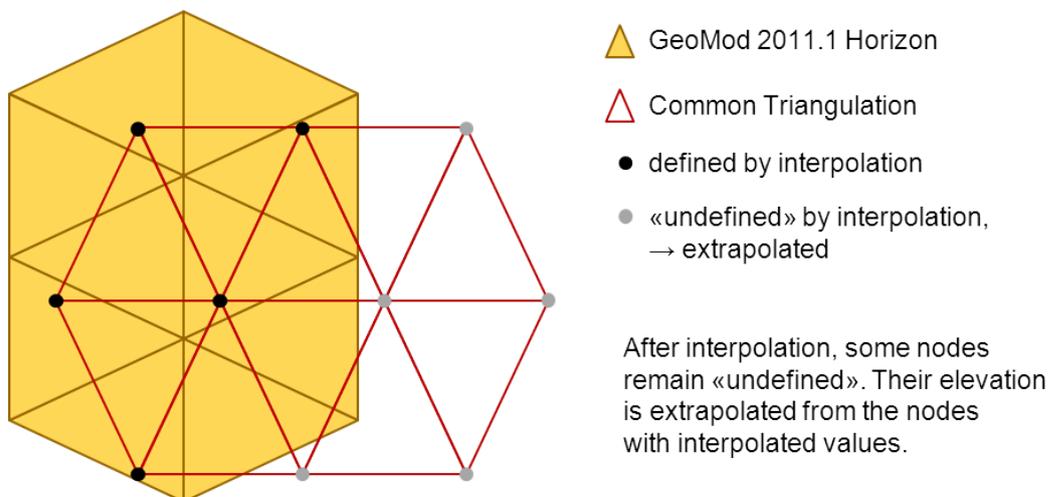


Fig. A116: Interpolation and extrapolation steps.

Split.c: This program splits horizons into parts along fault surfaces. To define each side of a fault surface, a direction has to be prescribed. The direction should be defined in a way that any arbitrary straight line of that direction does cut the fault surface only once (Fig. A117). Elements with nodes on both sides of the fault are associated to the side where the median point of that element is associated.

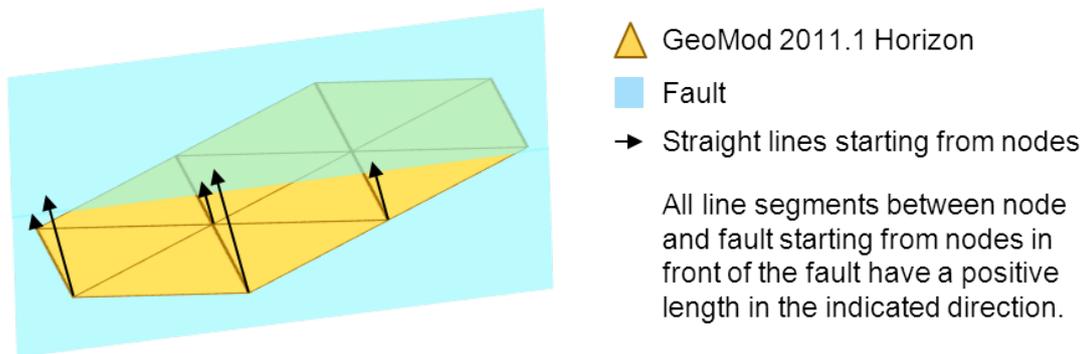


Fig. A117: Splitting algorithm used in split.c.

Cleantri.c: Because splitting of the horizons often leads to some singular elements associated to the wrong side of the fault, a cleaning routine is necessary. The cleantri.c module cuts away all elements not connected to others. Fig. A118 shows an example of remaining triangles after splitting the Opalinus Clay horizon along one of the Jura faults.

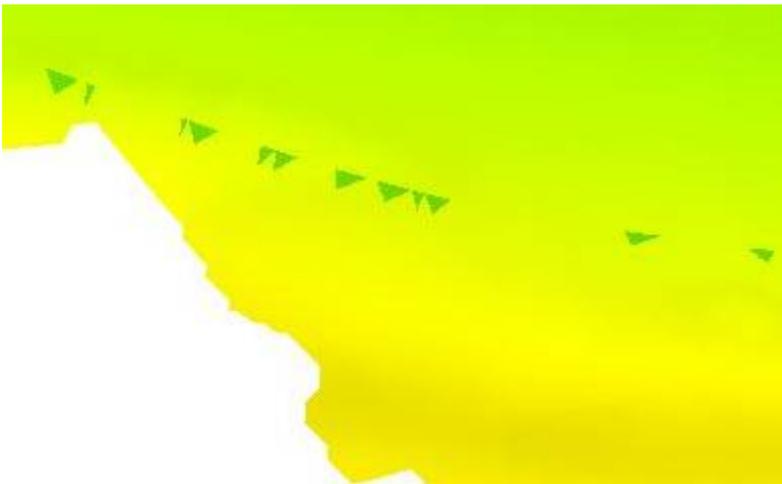


Fig. A118: Remaining elements after splitting (base Opalinus Clay detail view).

Join.c: This program joins all the triangles of one horizon belonging to several sub models together to a single horizon.

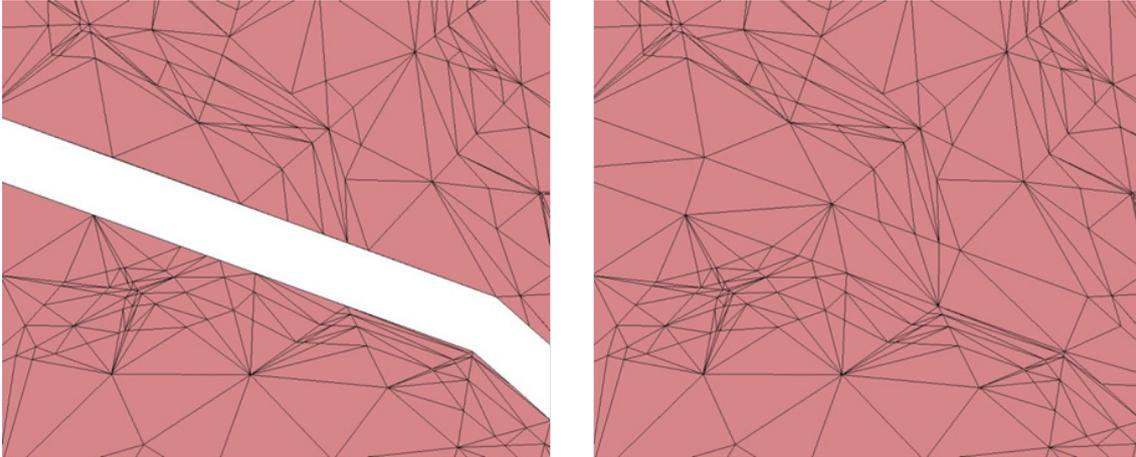


Fig. A119: Example of joining two triangulations together.

Tricalc.pl: This program is used for the grid operations. It calculates the sum, difference, maximum or minimum of two grids. “Undefined” nodes can be excluded from the operation.

Triop.pl is used for operations of grids with constants, for example a minimum thickness can be prescribed to a thickness model.

Dipmin.c: calculates the dip of all nodes of a fault along the trace of the fault. If the dip extends a given maximum, the node coordinates are corrected in perpendicular direction to the fault. The software module guarantees a maximum dip for every triangle in a fault.

Interfaults.c: interpolates the elevations of a fault surface to the common grid. Outside the defined area, the dip of the fault surface is extrapolated, adding some extra dip depending on the distance to the defined area until the dip reaches 85 degrees. The extrapolation distance can be restricted. Outside the extrapolation area, the grid gets an elevation higher than the topography on one side and lower than the Mesozoic base at the other side.

Appendix B: Isolines (height) calculated from Multipatches

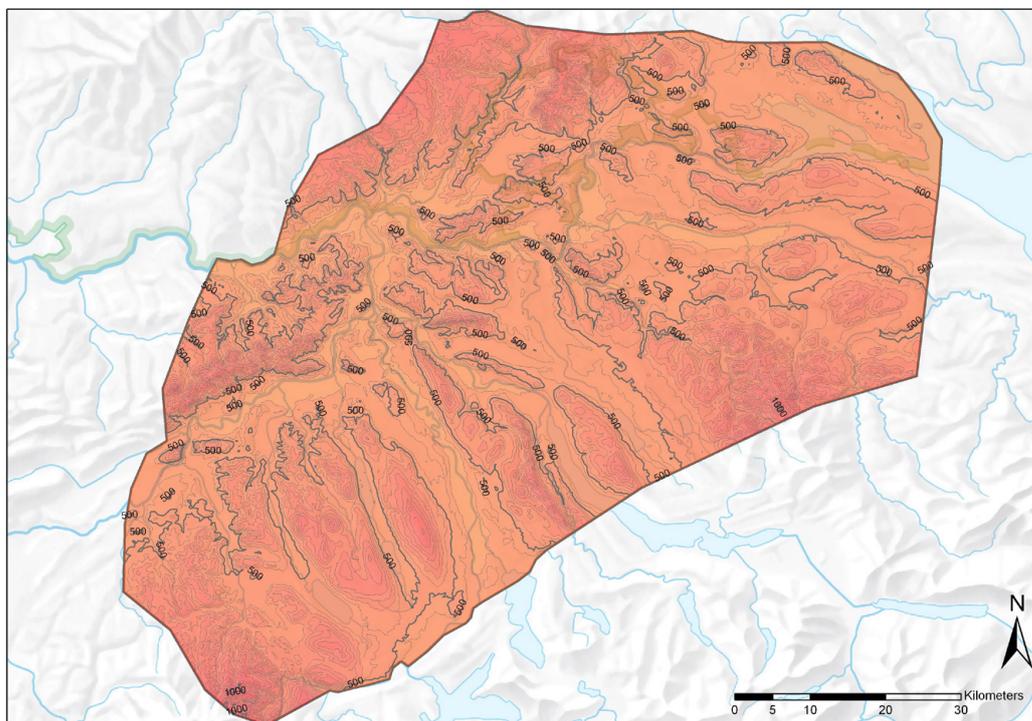


Fig. B1: Isolines (height) of the horizon top Quaternary.

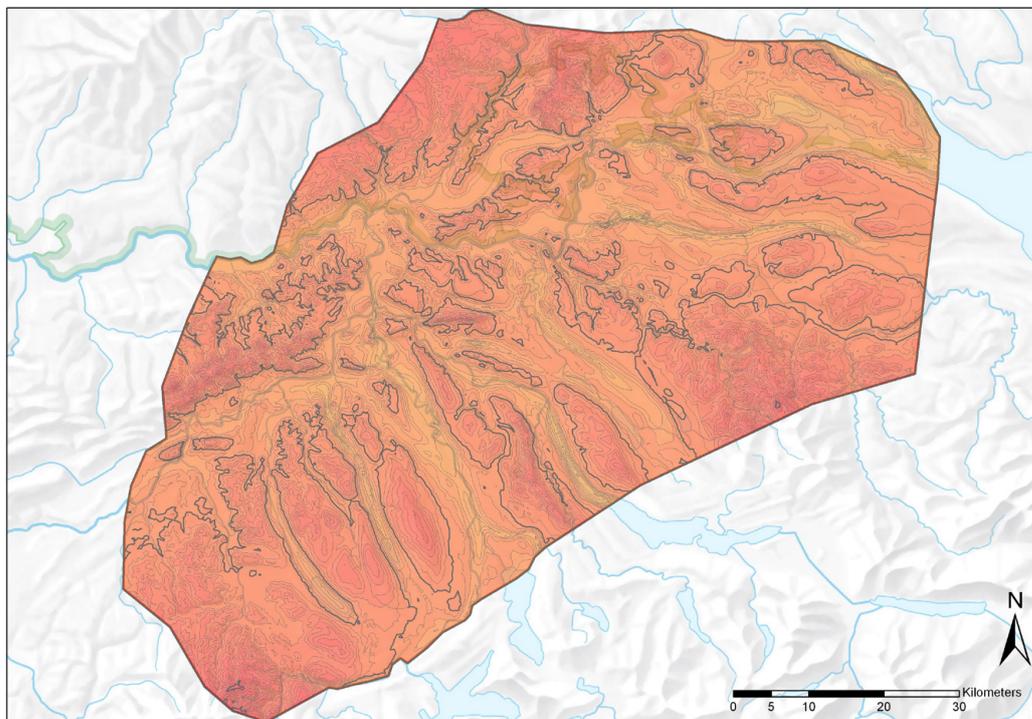


Fig. B2: Isolines (height) of the horizon base Quaternary.

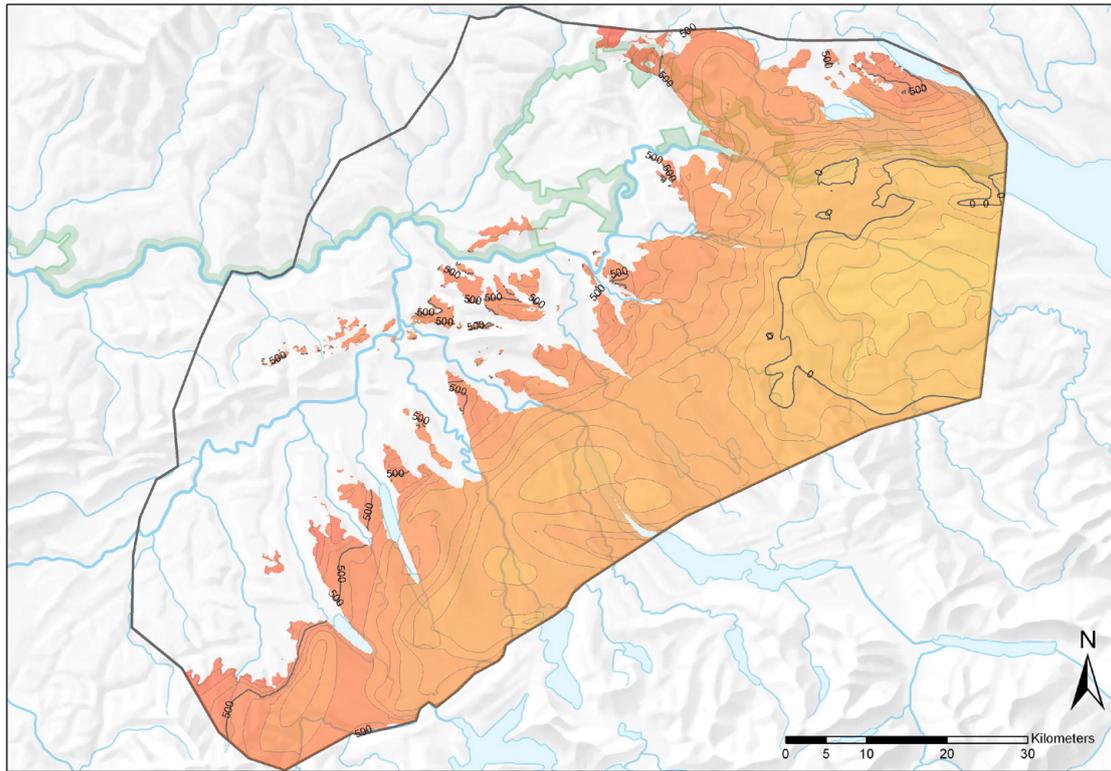


Fig. B3: Isolines (height) of the horizon base OSM.

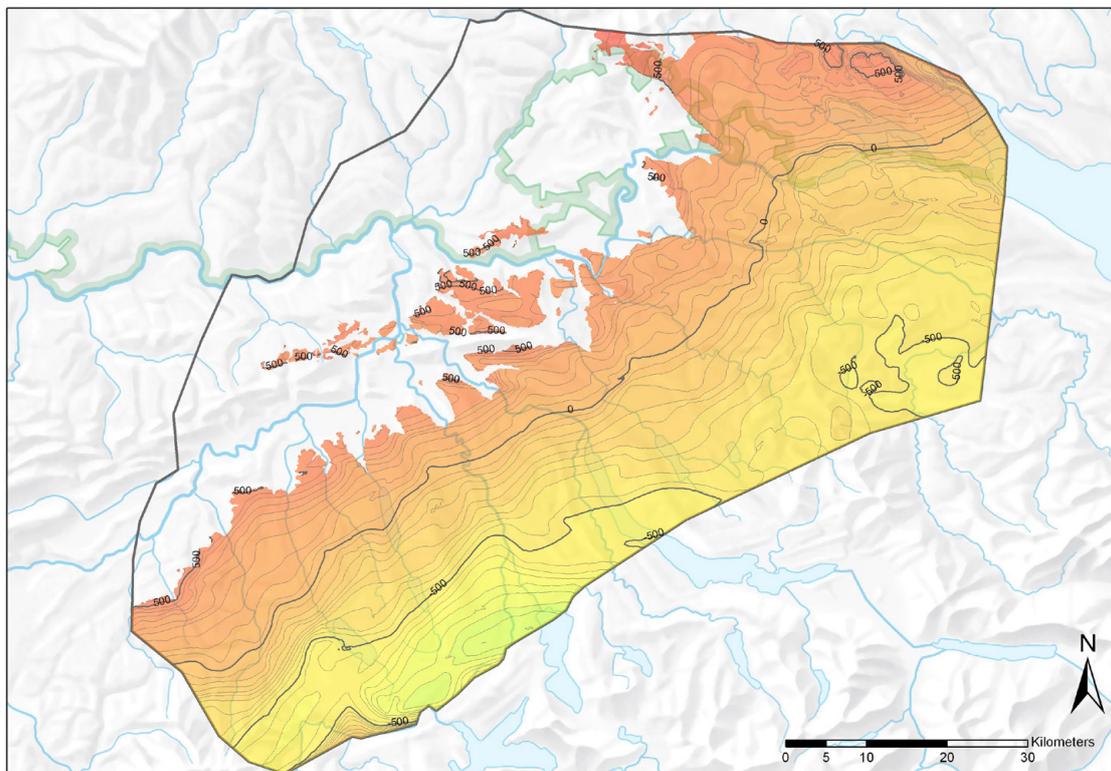


Fig. B4: Isolines (height) of the horizon base OMM.

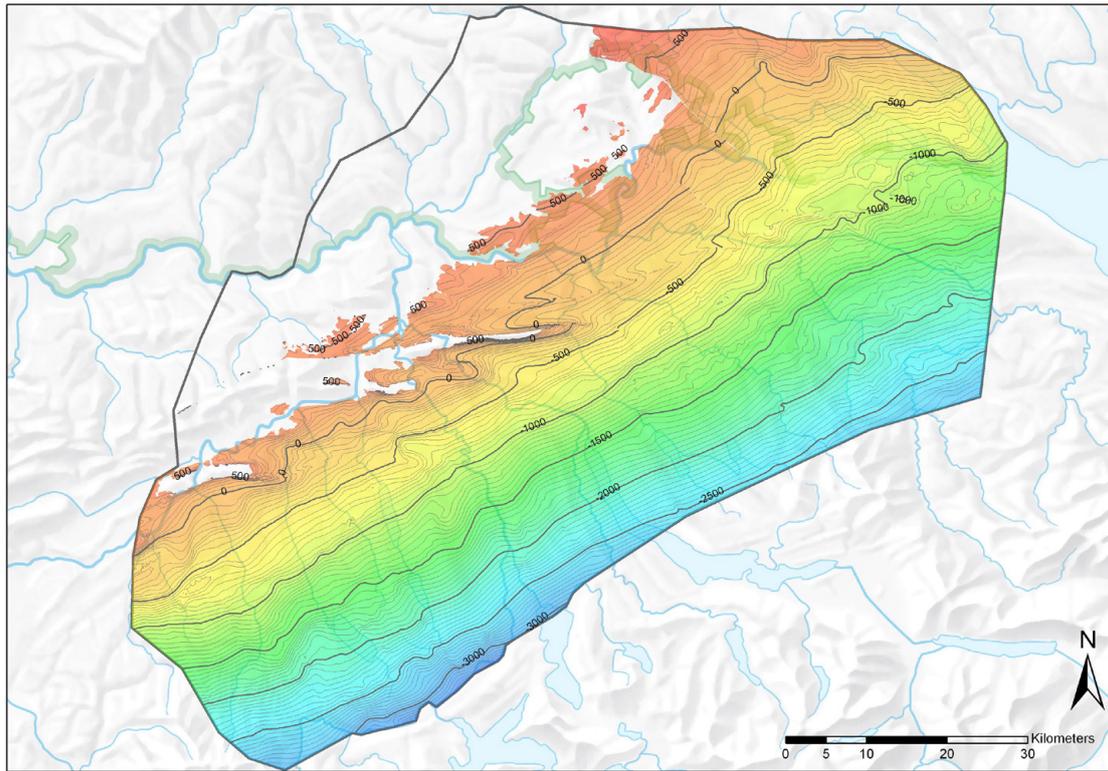


Fig. B5: Isolines (height) of the horizon base Tertiary.

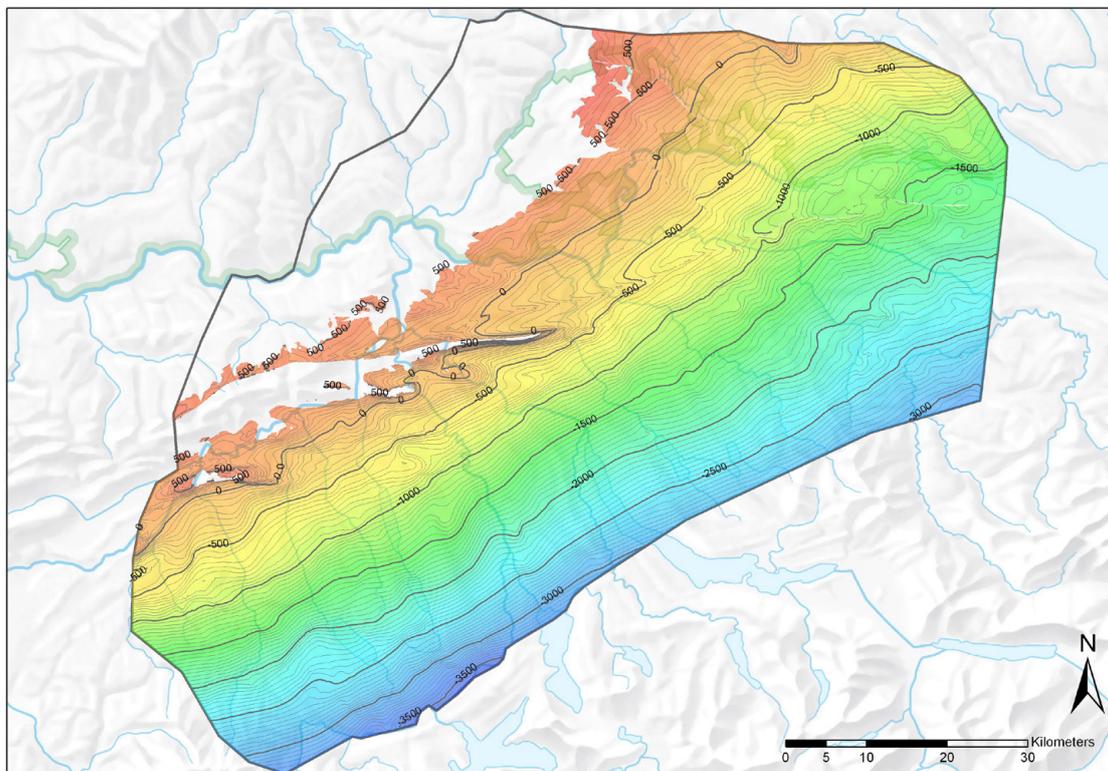


Fig. B6: Isolines (height) of the horizon top Effingen Member.

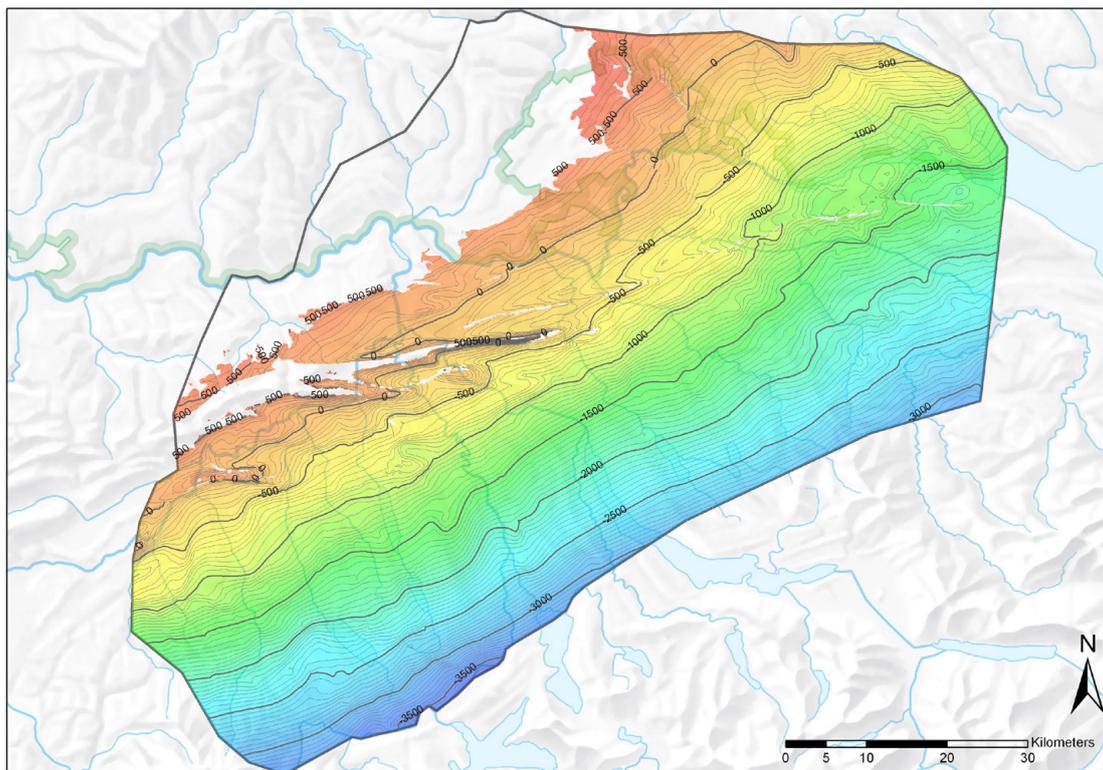


Fig. B7: Isolines (height) of the horizon base Malm.

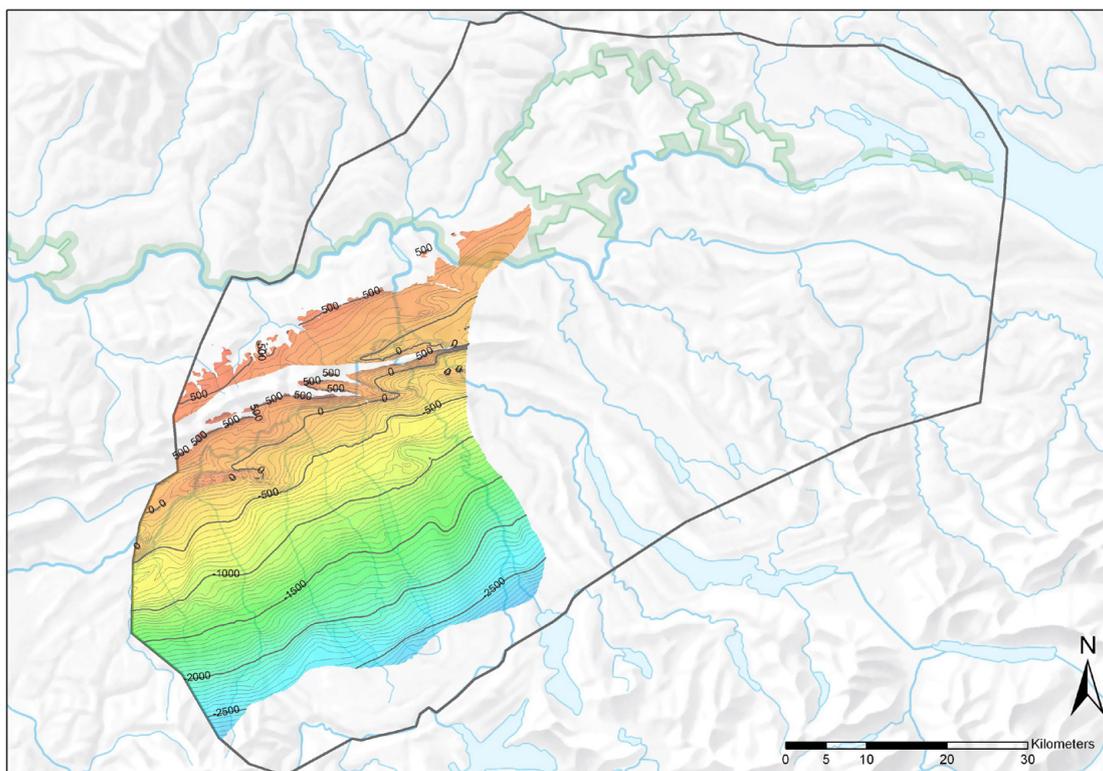


Fig. B8: Isolines (height) of the horizon top Hauptrogenstein.

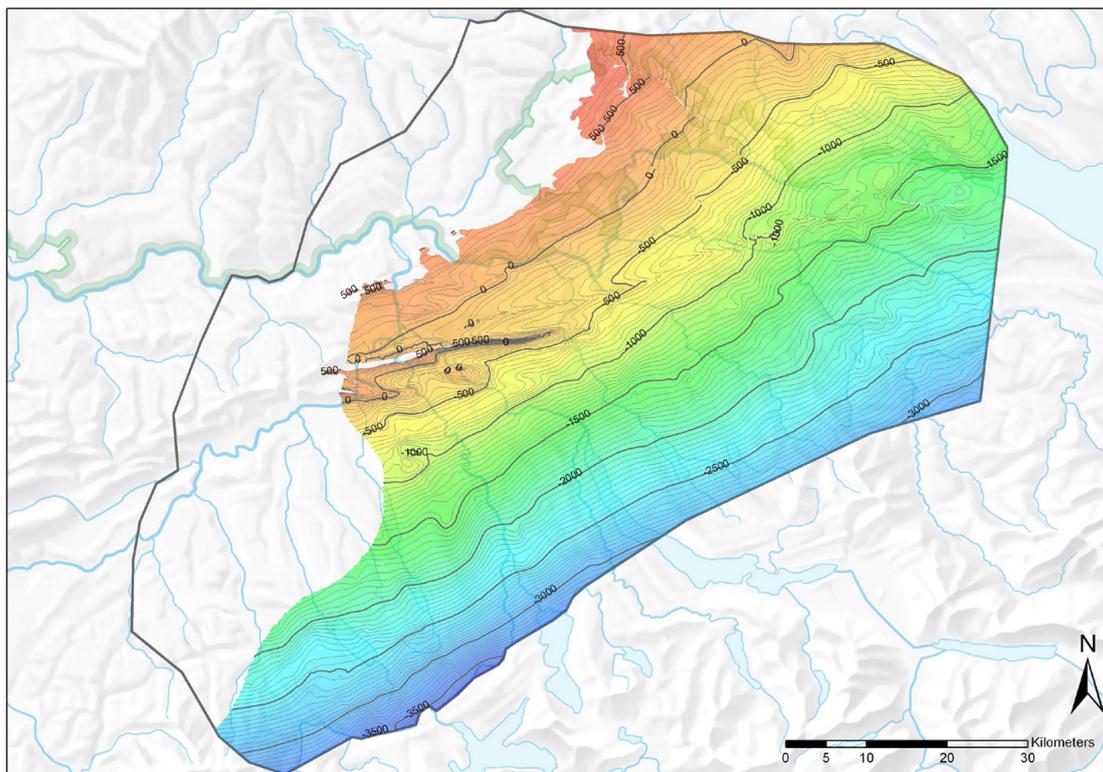


Fig. B9: Isolines (height) of the horizon top Klingnau.

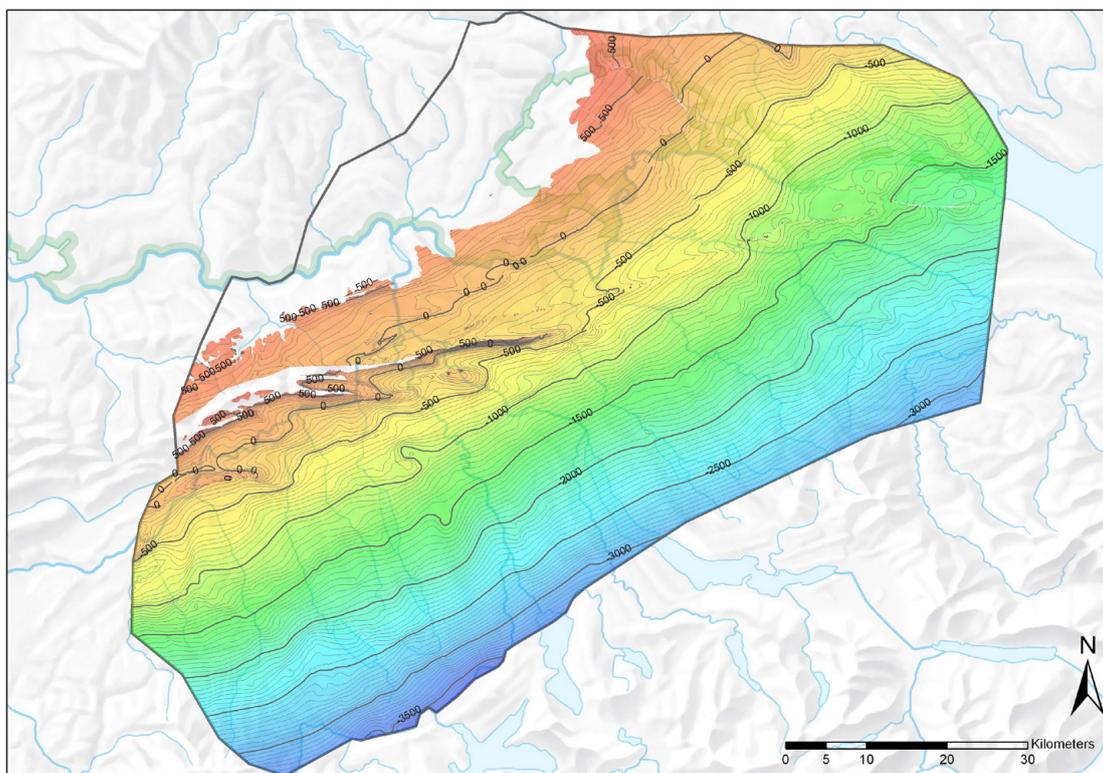


Fig. B10: Isolines (height) of the horizon top Passwang.

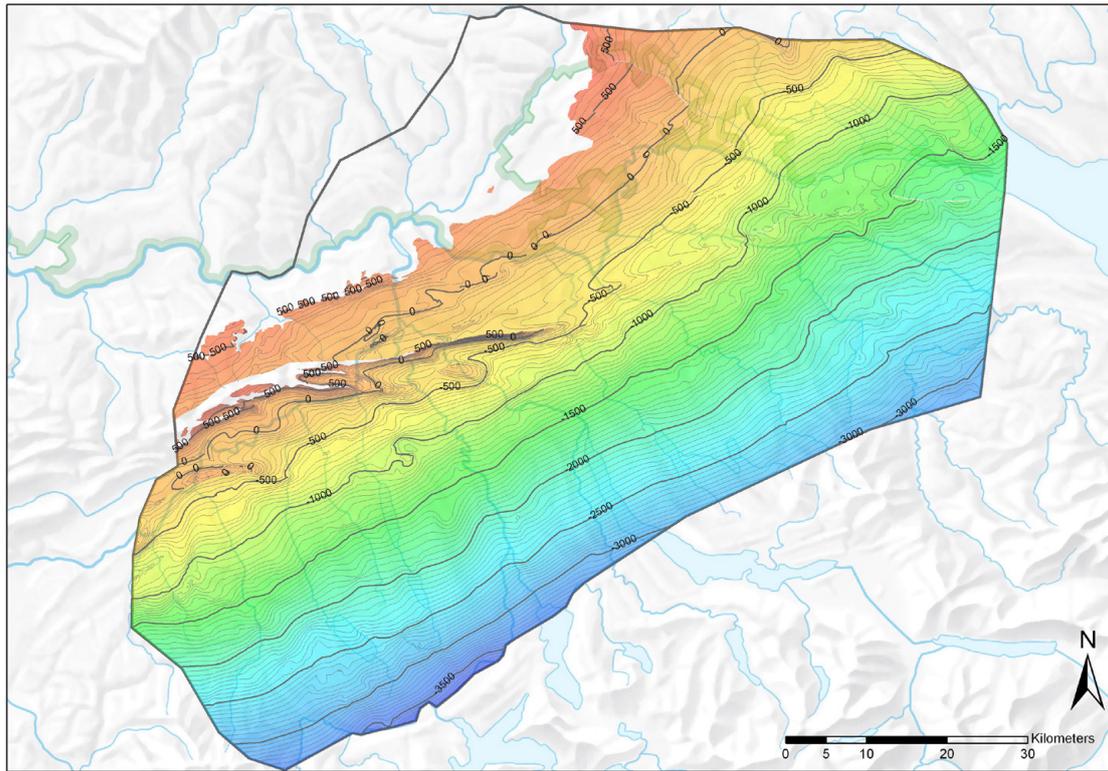


Fig. B11: Isolines (height) of the horizon top Opalinus Clay.

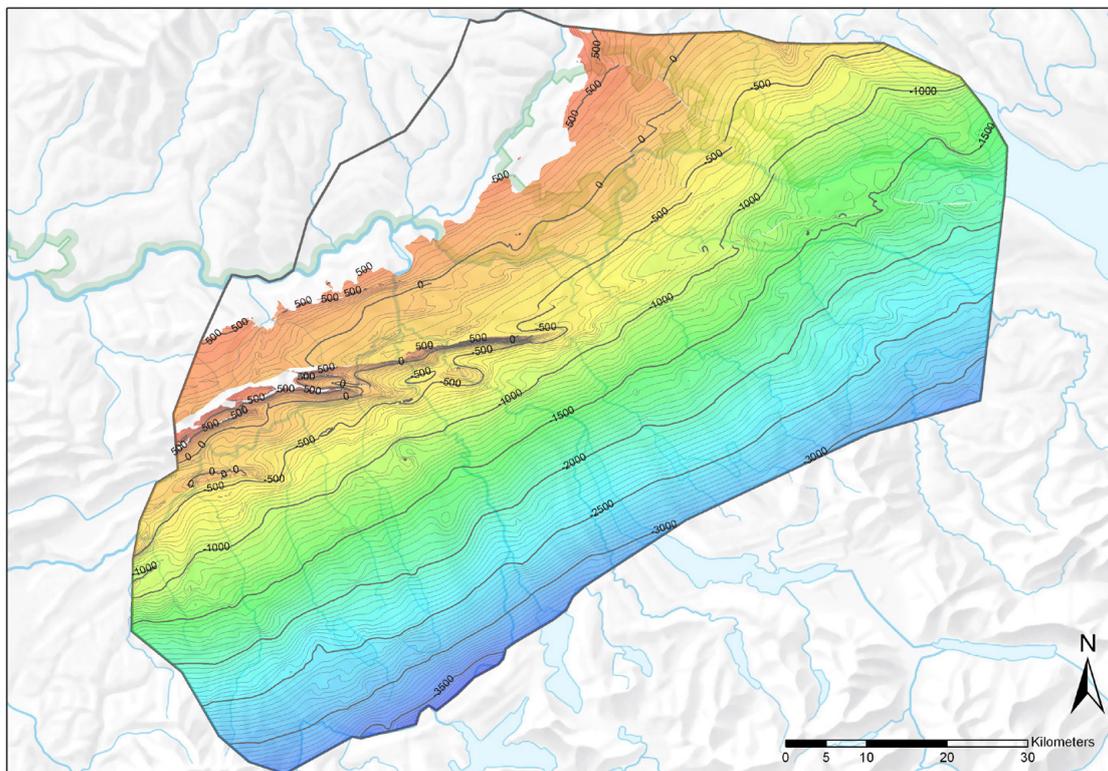


Fig. B12: Isolines (height) of the horizon base Opalinus Clay.

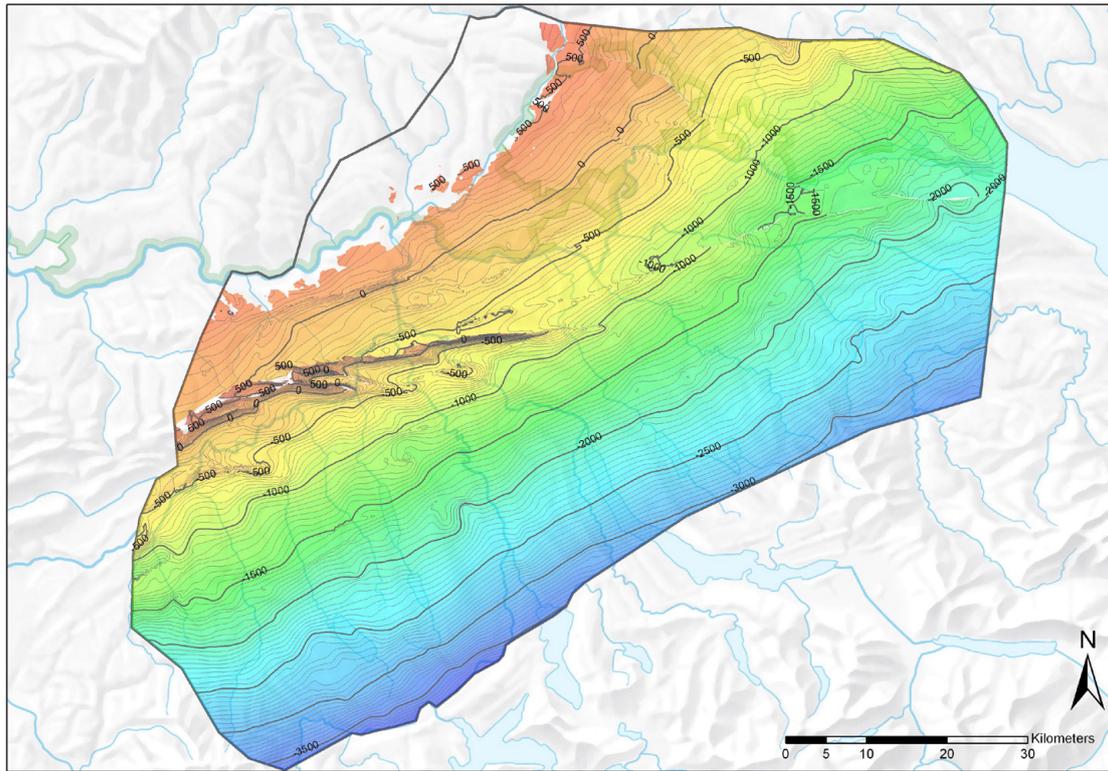


Fig. B13: Isolines (height) of the horizon top Muschelkalk.

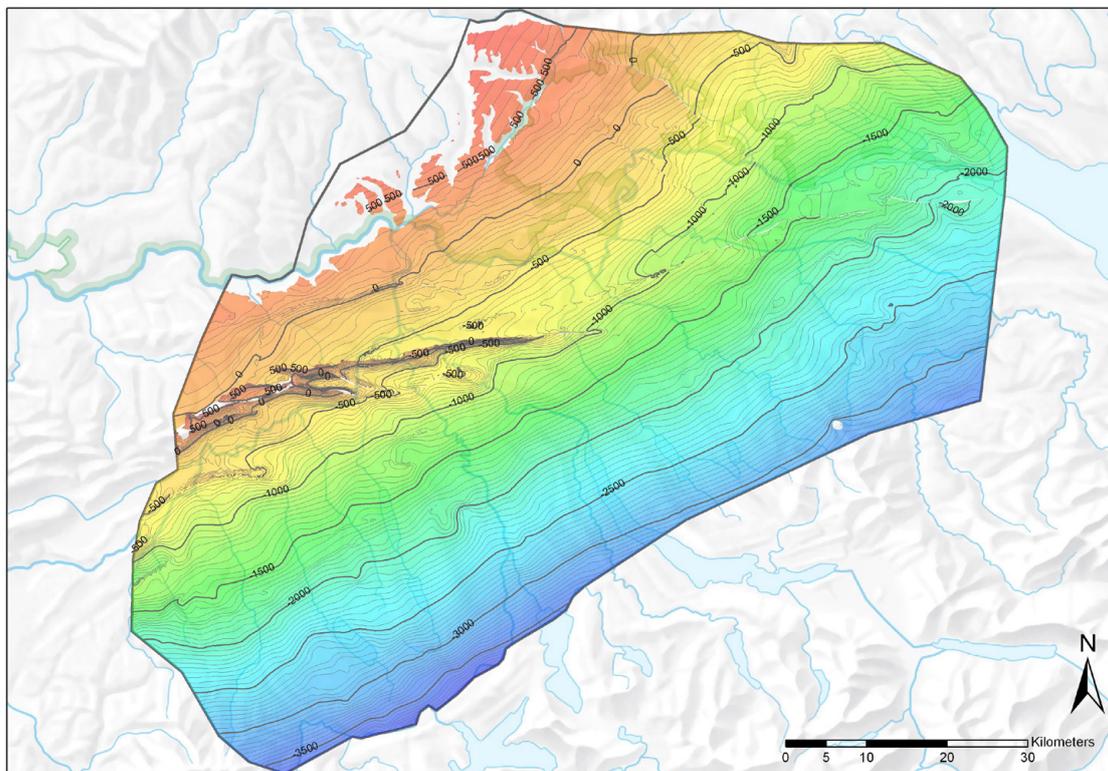


Fig. B14: Isolines (height) of the horizon base „upper“ Muschelkalk.

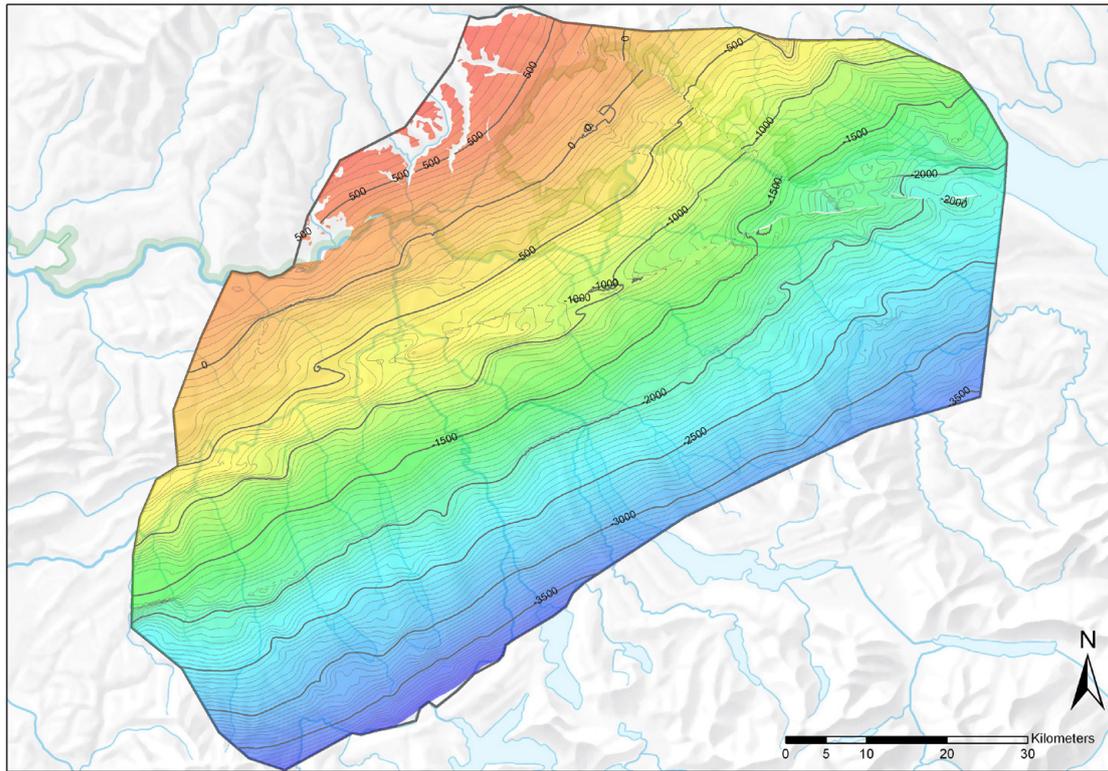


Fig. B15: Isolines (height) of the horizon base Mesozoic.