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Objekttyp: **Article**

Zeitschrift: **Swiss bulletin für angewandte Geologie = Swiss bulletin pour la géologie appliquée = Swiss bulletin per la geologia applicata = Swiss bulletin for applied geology**

Band (Jahr): **21 (2016)**

Heft 1

PDF erstellt am: **24.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-658185

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Swiss Bull. angew. Geol. Vol. 21/1, 2016 S. 45-51

Applications of 3D Subsurface Modelling Tools in the Geothermal Power Plant Project St.Gallen

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Keywords: Geothermal Power Plant Project St.Gallen, 3D seismic, 3D static modelling, subsurface modelling, structural modelling, well planning, visualization, data exchange

Abstract

For the siting decision and well planning of a deep geothermal exploration project for power and heat, the largest ever shot 3D seismic in Switzerland was acquired in and around the city of St. Gallen in winter 2009/2010, giving invaluable insight into the deep underground of the larger project area. 3D subsurface techniques were applied in all major steps of the evaluation of the seismic data, including 3D seismic interpretation, 3D structural modelling, horizon modelling, depth conversion, well planning, visualization and tailor-made data exchange with other involved parties. After the drilling of the geothermal exploration borehole «St.Gallen GT-1» (SG GT-1) in 2013, the seismic interpretation, the time to depth conversion and the static 3D model were entirely revised. Sankt Galler Stadtwerke (SGSW), client and owner of the seismic data, is intending to make these data available to help answer specific technical and scientific questions.

Zusammenfassung

Für den Standortentscheid und die Bohrplanung für ein tiefes Geothermie-Projekt für Strom und Wärme wurde im Winter 2009/2010 in und um die Stadt St.Gallen die bis heute grösste 3D-Seismik der Schweiz gemessen. Dieser neue Datensatz ermöglicht einen unschätzbaren Einblick in den tiefen Untergrund des Projektgebiets. In allen wichtigen Auswertungsschritten des seismischen Datensatzes wurde mit 3D-Technologie gearbeitet: 3D seismische Interpretation, 3D strukturelle Modellierung, Horizontmodellierung, Tiefenumwandlung, Bohrplanung, Visualisierung und letztlich der massgeschneiderte Datenaustausch mit den weiteren Projektbeteiligten. Nach dem Abteufen der Explorationsbohrung «St. Gallen GT-1» (SG GT-1) im Jahr 2013 wurden die seismische Interpretation, die Tiefenumwandlung und das statische 3D Modell komplett überarbeitet. Die Sankt Galler Stadtwerke (SGSW), Bauherr und Eigentümer der seismischen Daten, plant diesen Datensatz für die Untersuchung ausgewählter, technischer und wissenschaftlicher Fragestellungen zur Verfügung zu stellen.

1 Introduction

2D seismic data shot by the oil industry in the 70s and 80s were used in the feasibility phase of this project initiated by Sankt Galler Stadtwerke (SGSW) for a deep geothermal power and heat plant (Geowatt et al. 2009). This network of widely spaced seismic lines with medium to low data quality led to the assumption that two distinct fault zones with potentially high transmissivities in Mesozoic reservoirs may exist in the east and west of the city of St.Gallen, both in favourable depth and thus temperature ranges for power generation and in close distance to already existing or planned dis-

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trict heating. To evaluate which of the two fault zones would be more prospective and to establish a target for a first deep well, it was decided to conduct in winter 2009/2010 a 3D seismic survey covering a CMP (common midpoint) area of approximately 218 km^2 (DMT 2010), the so far largest seismic campaign in Switzerland. A fast track interpretation of the preliminary processing versions revealed that the fault zone in the west (named St. Gallen Fault Zone or SFZ) transects the 3D area from NNE to SSW in a complex pattern of mostly steep normal and reverse faults, whereas no detectable expression of a fault zone assignable to the fault tentatively mapped with the 2D seismic line in the east could be observed. More careful interpretation of the final processing versions (Petrologic 2011), 3D structural modelling and depth conversion using the processing velocities led to a structural depth model of the Mesozoic strata that was the basis for the final selection of a site in the west of the city (location Au in the Sittertobel) and for the well track planning of the geothermal exploration well St.Gallen GT-1 (SG GT-1) (Zingg & Kuhn 2011).

Drilling and testing of SG GT-1 took place between March and October 2013 (Naef 2015). The production tests yielded disappointing amounts of formation water but at the expected temperatures of around 145 °C. The water was produced together with significant hourly rates of high quality gas. Gas analyses proved that the gas is thermogenic and must have its source in the Carboniferous units. To assess these results volumetrically, to support a planned (but later cancelled) second step of induced seismic hazard study (testing operations triggered a widely felt M_L 3.5 earthquake) and last but not least to provide a comprehensive 3D depth model that fully reflects the results of SG GT-1, a further refinement of the seismic interpretation including an assessment of the assumed Permocarboniferous trough and a complete overhaul of the 3D depth model was carried out (Heuberger & Kuhn 2014). This latest 3D seismic interpretation work and its results were recently published by Heuberger et al. (2016) who covered all aspects of the geological and tectonic setting and the reasoning behind the interpretation of the seismic data. In the following, the focus lies on the techniques applied and steps achieved in the refinement study by using 3D modelling tools.

2 3D model in time

To preserve full flexibility for later modifications of the velocity model, it was decided to develop a detailed 3D structural model (faults and horizons) in time prior to depth conversion. This allows the application of repeated time-to-depth conversions with different velocity models without the need to repeat the numerous time consuming editing steps in the depth domain.

The fault interpretation in time was imported as fault lines («fault sticks») into the 3D modelling software Jewel Suite (®Baker Hughes, Version 4.0.65.0), where triangulated surfaces were computed (Fig. 1). A relatively small lateral (5 m) and vertical (2 m) tolerance compared to the input data was allowed in the triangulation algorithm resulting in a very mild smoothing. The surface outlines to the top and the base of the surfaces were kept as close as possible to the interpretation, whereas on the side of the surfaces an extrapolation of half of the seedline interval distance was carried out. The next processing step in Jewel Suite was the creation of a water-tight fault model. «Watertight» means that fault surfaces do in no case cross each other, a very important requirement for the later creation of a 3D volume grid. In case of fault branches or connected faults, undesired gaps between surfaces were closed using guided extrapolation and, in complex cases, manual editing.

The interpretation of the four Mesozoic horizons was carried out semi-automatically on N-S and W-E lines («inlines» and «crosslines») with a general seed line distance of 125 m (i.e. every 5th line). Around the drill path of SG GT-1, the seed line interval was reduced to 50 m and partly even to 25 m, i.e. corresponding to the bin size. Starting from this seed line interpretation and using appropriate autocorrelation functions for the four horizons («auto-tracking») a dense grid with 25 × 25 m cell size was obtained. Since the auto-tracker in case of weak reflector continuity may follow the wrong loop, it was necessary to manually edit these data in the relevant areas. This was done only away from intersections with faults. In the proximity of faults, the horizons were edited in a later 3D modelling editing step.

As for the faults, the edited auto-correlated horizon data were loaded into Jewel Suite and converted to triangulated surfaces. The unsmoothed horizon surfaces with a triangle side length of 25 m were directly used to produce dip and illumination maps, showing also minor discontinuities in the data which might have been overlooked in the fault interpretation process and could be indications of small offset faults or lineaments.

In a next step, the horizon surfaces were combined with the water-tight fault model. In the vicinity of faults, horizon triangles were cut within a corridor of 50 m width on both sides of the faults. The horizon surfaces were then extrapolated towards the fault surfaces to establish a water-tight hori-

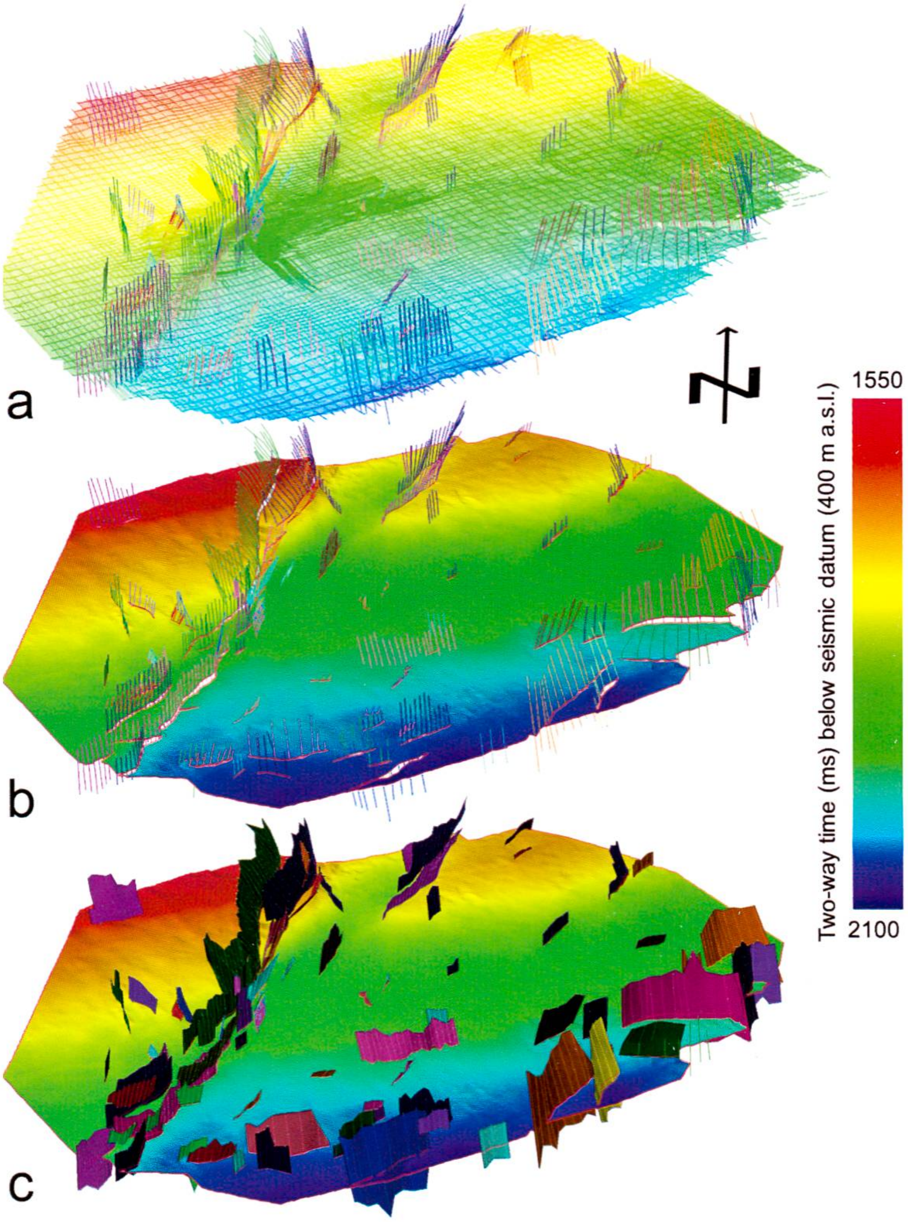

Fig. 1: Demonstration of the main steps in surface modelling in the time domain: a] Horizon interpretation (seed lines) of Base Mesozoic and fault sticks of the Mesozoic, b] unsmoothed horizon surface of Base Mesozoic and fault sticks of the Mesozoic and c] unsmoothed horizon surface of Base Mesozoic and water-tight fault surfaces of the Mesozoic. The orientation of the perspective 3D view is South to North and the vertical exaggeration of the time domain is three times.

zon/fault model. This automatic extension of the horizon surfaces had to be visually inspected fault by fault and manually edited where necessary. For the creation of isochrone maps, the time surfaces were smoothed by keeping the horizon-fault intersections fixed.

3 Time to depth conversion

Seismic velocities from the PSTM processing were used for the time to depth conversion and the well prognosis. SG GT-1 hit the target horizon Top Malm at -3,230 m ss (true vertical depth), only 46 m deeper than predicted, a stunning result considering the fact that no further deep wells exist in a radius of circa 30 km. However, the uncalibrated PSTM velocity of the Malm at the SG GT-1 location was about 25% too slow, compared

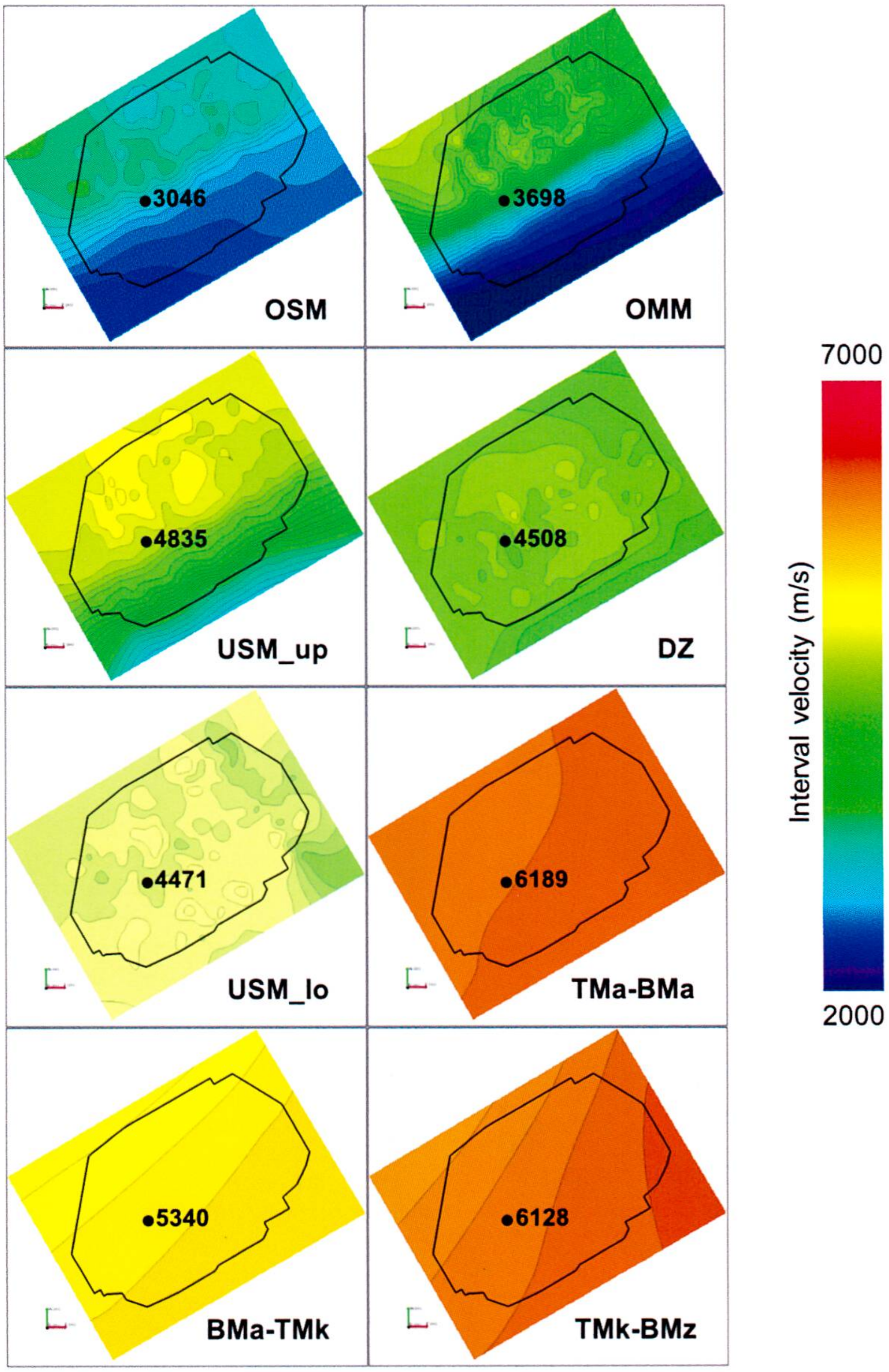

Fig. 2. Interval velocities used for depth conversion (see text for explanation). The colour code and contour interval of 100 m/s are identical for all subfigures. The black dot indicates the position of well SG GT-1 with the interval velocity value of the relevant interval at the well position in (m/s). Abbreviations: OSM: Upper Freshwater Molasse, OMM: Upper Marine Molasse, USM_up: Upper part of Lower Freshwater Molasse, DZ: Triangle Zone, USM_lo: Lower Freshwater Molasse, TMa-BMa: Top Malm to Base Malm, BMa-TMk: Base Malm to Top Muschelkalk, TMk-BMz: Top Muschelkalk to Base Mesozoic.

to the later acquired checkshot velocities, causing a considerable depth prognosis error for the base of the Malm. For the depth conversion after drilling of SG GT-1, it was therefore decided to use an interval velocity model calibrated at the well with the checkshot data (Roth 2013, Kuhn 2014).The Cenozoic was subdivided into five and the Mesozoic into three velocity layers, each layer being associated with a 2D velocity map (Fig. 2). These velocity maps were derived in case of the Cenozoic from the PSTM velocity model and in case of the Mesozoic layers from the work by Roth et al. (2010). While the Cenozoic and the Malm interval velocity maps could be calibrated with the GT-1 well data, this was not possible for the two bottommost intervals Lias-Dogger-Keuper and Muschelkalk since the well did not penetrate these intervals. Whereas for the Lias-Dogger-Keuper interval the regional velocity data was considered to be realistic (velocities around 5,340 m/s), the interval velocities of the Muschelkalk seemed to be too high (around 6,450 m/s) and were reduced by 5%. Below the Base of the Mesozoic, a constant velocity of 6,000 m/s was used throughout.

4 3D model in depth

All data in time, i.e. horizon interpretation and horizon surfaces, fault sticks and fault surfaces, but also the seismic data cubes (CRS PSTM stack and similarity) were depth converted within Jewel Suite using the interval velocity model described in chapter 3. In analogy to the time contour maps, depth contour maps were derived from smoothed triangulated surfaces. Primarily for the creation of isopach maps, a 3D volume model of the Mesozoic was computed in Jewel Suite with a horizontal cell size of 25 × 25 m and a vertical subdivision into three intervals (Fig. 3). Such a volume model could be the starting point of a static reservoir model.
Using the powerful viewing options of Jewel Suite or any similar 3D modelling package like Petrel, Gocad or Move it is possible to visualize topographical, geological, geophysical and well data giving valuable information or just pleasing the viewer with precious insights into the usually hidden subsurface (Fig. 4).

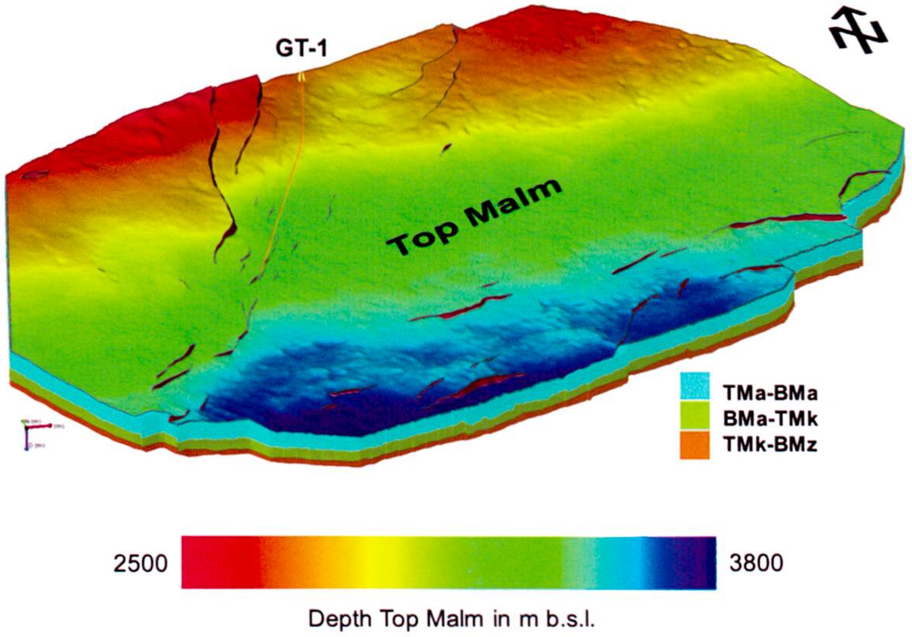

Fig. 3: Perspective view from South (no vertical exaggeration) of the 3D volume model with the layering of the Mesozoic in the depth domain (m a. s. l.). TMa-BMa: Interval Top Malm to Base Malm. BMa-TMk: Interval Base Malm to Top Muschelkalk. TMk-BMz: Interval Top Muschelkalk to Base Mesozoic. The depth map of Top Malm (TMa) is draped onto the model in illumination representation.

5 Conclusions

3D subsurface techniques were used in all phases of the St.Gallen deep geothermal exploration project including 3D seismic interpretation, 3D structural modelling, horizon modelling, depth conversion, well planning, visualization and tailor-made data

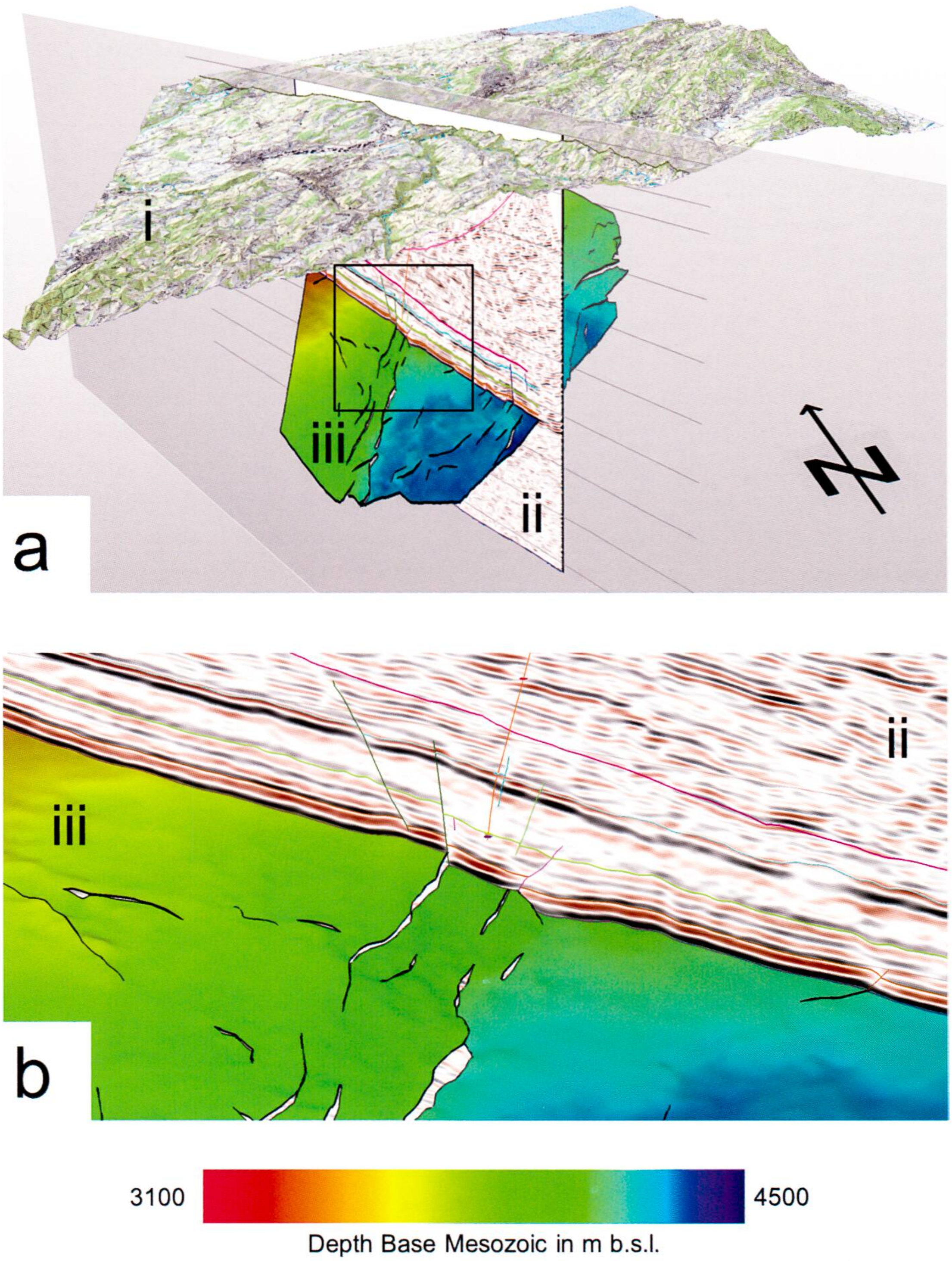

Fig. 4: a] 3D perspective view from South-West (two times vertically exaggerated) of several elements of the 3D model of the St.Gallen area: (i) Topographic map draped onto digital elevation model, (ii) section along SG GT-1 well track (orange subvertical line) showing the depth converted 3D seismic (CRS PSTM stack), and the intersection with all interpreted horizons and faults, (iii) illuminated horizon surface of Base Mesozoic in depth. The black rectangle represents the zoomed area in b].

exchange with other involved parties. After the drilling of the exploration well «St.Gallen GT-1» (SG GT-1), a static 3D model was developed both in time and depth based on the latest seismic interpretation and the results of the well. These data would now be available to assist in answering specific technical and scientific questions.

Acknowledgements

The author would like to thank the Sankt Galler Stadtwerke (SGSW) for allowing him to use and publish seismic and borehole data and the insights into the 3D model. He would also like to thank Philippe Roth and Bernhard Gunzenhauser for reviewing the manuscript.

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