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Geothermal Exploration in Megacities – Results from Reflection Seismic Surveying in Berlin (Germany)

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ABSTRACT

Geothermal exploration in sedimentary basin settings requires essentially seismic surveying to image the subsurface structure. Urban areas are favorable areas for geothermal development because the high demand on heat and electricity is accumulated especially in megacities. Reflection seismic surveys in megacities are however challenging due to seismic noise, infrastructural issues and high population density. A vibroseismic pilot study was conducted at the former city airport Berlin-Tempelhof, basically located in the center of Germany's capital city. Two major questions were addresses to this reflection seismic experiment: (I) Can vibroseis provide sufficient data quality despite the intensive background noise of a mega city, and (II) what is the subsurface geological structure of Berlin focusing on depth and thickness of the Middle Triassic and Lower Permian as potential hydrothermal reservoirs.

Various layouts were applied for the seismic survey on both day and at night to evaluate the impact of background noise. With modern processing approaches like CRS stacking unavoidable shortcomings during acquisition like high noise and coverage irregularities could be compensated without unacceptable quality loss in the final results. The final interpretation shows a general southwest dipping of Cenozoic to Paleozoic strata obviously caused by uplifted Upper Permian (Zechstein) salt rock. In particular, seismic stratigraphy was used to identify successions in Lower, Middle and Upper Triassic, in Upper and Lower Permian. This new results help to extend the hitherto incomplete picture of deep subsurface geology in Berlin and to define seismic survey layouts with subsequent processing techniques for mega city environments.

1. INTRODUCTION

Seismic reflection profiling in urban regions is always a huge challenge not only due to the general extensive logistics but also due to the recording methods and parameters to be used in the presence of a permanent, very high noise-level from various sources. Especially within large cities with a wide public transportation system, street traffic, factories and lots of other background noise origins, special acquisition and processing techniques are needed to achieve a sufficient signal/noise ratio down to greater depths, if for the realization of specific projects (e.g geothermal exploration, underground gas-storage) a reliable interpretation of surface-seismically imaged subsurface structures is mandatory.

A collaborative research and development project of the Deutsches GeoForschungsZentrum (GFZ) and the GASAG - Berliner Gaswerke AG performed a pilot study in the center of Germany's capital Berlin aiming the feasibility and limits of reflection seismic surveys in 'mega cities'. The main question was of technical nature and should answer with which technique and with how much effort seismic waves would penetrate into which depths and can be recorded with which resolution. A comprehensive vibroseis field campaign was carried out at the former city-center airport Berlin-Tempelhof (Fig. 1). After detailed start-up tests, the acquisition consisted of a comparison between day and night measurements and between high- and low-force measurements. Data processing should improve the acquisition results by comparing between conventional (NMO stacking) and recently developed specific methods (CRS stacking).

Additional to the methodological questions in seismology, geological questions regarding the deep subsurface structure of Berlin could have been answered. Geophysical exploration in urban areas is challenging due to logistic efforts. Effectively, geophysical data are lacking to interpret Berlins subsurface structure of Cenozoic and Mesozoic strata on a resolution that is suitable for geothermal exploration. The known regional geological knowledge of Cenozoic and Mesozoic strata was adapted to mechanical stratigraphy in order to advance the interpretation of identified seismic marker horizons. The result is a seismic stratigraphy applicable for the metropolitan region of Berlin. With our geophysical-geological methodology we want to demonstrate that parts of the white spots of unknown geology beneath Berlin could be clarified. Ultimately our methodology can be applied and transferred to exploration campaigns in other urban areas provided the regional geology is known for an adaption to mechanical stratigraphy.

2. GEOTHERMAL GEOLOGY AND PLAY TYPE

Berlin is located in the North German Basin which is part of the modern Central European Basin System. The North German Basin evolved since the Lower Permian as part of the South Permian Basin as response to wrench tectonics related to the post-orogenic deformation of the Variscan orogeny and subsequent thermal subsidence in the Mesozoic (Baltrusch & Klarner, 1993; Moeck et al.,

2009) (Fig. 1). The North German Basin can be considered therefore as intracratonic play type (Moeck, accepted). Upper Permian thick rock salt caused salt tectonics since the Lower Triassic and culminated in the Late Cretaceous. Effectively the present-day structure of the North German Basin is a result of salt tectonics forming salt ridges, diapirs and salt lows. While the overlaying Mesosoic strata is highly affected by the salt tectonic structure the Paleozoic strata in particular the Lower Permian is affected by post-orogenic andesitic volcanism and wrench tectonics along NW-SE oriented major strike-slip faults and NE-SW trending secondary graben structures (Moeck et al., 2009).

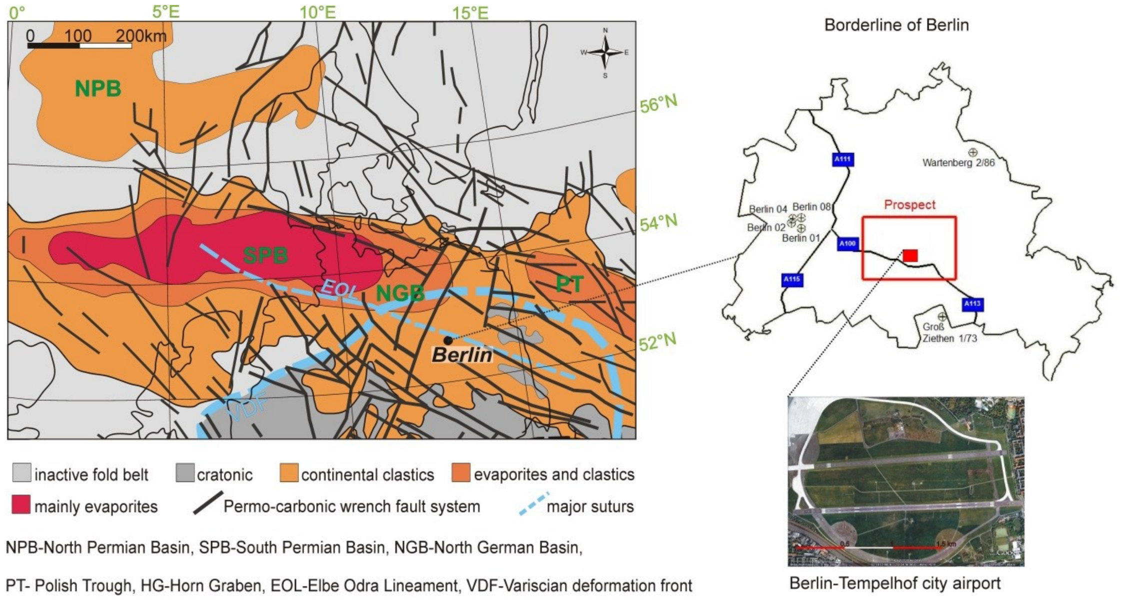

Figure 1: Location of Berlin in the North German Basin as part of the South Permian Basin. The seismic acquisition was conducted along the two runways of the former city airport Tempelhof. The interpretation of these seismic data incorporated neighboring wells. The blue tags in the Berlin map indicate the three city highways.

The major potential geothermal resources are Mesozoic porous sandstones (Wolfgramm et al., 2009). The varying reservoir quality of these sandstones is caused by different depositional environments ranging from fluvial to lacustrine to brackish deltaic. Fluvial sandstones may exhibit angular grain shape and poor sorting causing low primary permeability. Eolian sandstones have well rounded and sorted grains, low clay content and exhibit high primary permeability (Wolfgramm et al., 2008). Deltaic sandstones show good reservoir qualities and thickness in areas of main conductor channels. As typical for sandstone, diagenesis influences primary reservoir quality. Generally, sandstones have a proportional ratio of porosity and permeability (Moeck, accepted).

In the area of Berlin-Tempelhof, the fluvial sandstones of the Middle Buntsandstein Fm (Lower Triassic) may contain sufficient reservoir quality and temperature. A second potential reservoir formation due to high prospected temperature > 120°C might be the Lower Permian Rotliegend which is investigated test formation at the geothermal research site Groß Schönebeck of the Deutsches GeoForschungszentrum GFZ. Groß Schönebeck is located about 40 km north of Berlin where a well doublet was completed and massively stimulated in 2007. However, a continuous circulation over more than a week with a flow rate > 10 l/s could not have been established from this Lower Permian fluvial sandstone since then. Nevertheless, the Lower Permian sandstone was considered as potential reservoir formation at the Berlin-Tempelhof field with the question if this formation is deposited or if only volcanic rock is existing (Fig. 2). The seismic experiment should clarify if there is a volcanic plateau or a synform due to graben tectonics or channel erosion in the Tempelhof area. A volcanic high west of the prospect area is known from existing well and seismic data.

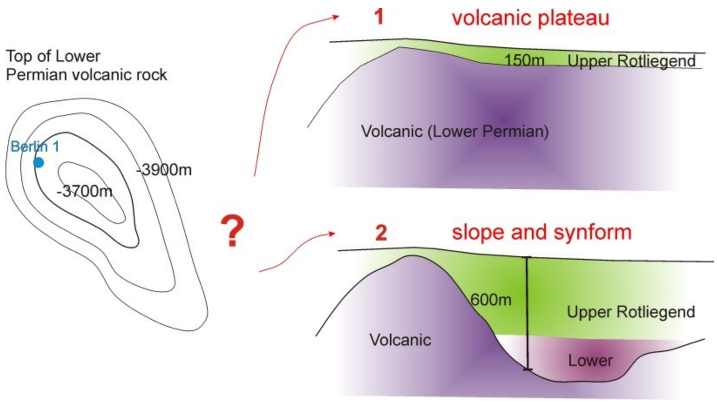

Figure 2: Possible conceptual models for the Lower Permian in the Berlin-Tempelhof area which could be revealed by the seismic experiment. The volcanic high west of the prospect is known from existing data. The green and the purple color represent sandstone, blue is volcanic rock.

3. SEISMIC DATA AQUISITION AND PROCESSING

3.1 Data acquisition

In March 2011 on the area of the in 2008 closed airport Berlin-Tempelhof, a 3-day vibroseismic test survey was carried out. This historic site ('Airlift' during 'Berlin Blockade'), presently used as a public park, is perfectly suited for such a pilot study, since it is on the one hand located in the center of a pulsating metropolis with enormously high, direct noise from close-by highway and arterial roads, underground- and city trains, factories and permanent a background noise, and on the other hand no complicated permission work at numerous authorities or heavy influence on the flowing traffic and the public city life is related.

Along two WE-trending parallel lines, each 2 km in length (the former runways, about 480 m spaced), single digital geophones were deployed with 10 m spacing. An extended start-up test was performed first to fix the optimum sweep parameters by variation of start frequency, end frequency, frequency-time curve, length, vertical repeat rate and peak-force based on a well-prepared test scheme. After a sophisticated evaluation it turned out that, with the usage of two simultaneously operating vibrators, a linear up-sweep of 10-70 Hz with a length of 13 s and 9-fold vertical stacking is a good compromise between high near-surface resolution, sufficient depth penetration and acceptable measurement time/costs.

Using these source parameters, vibroseismics was then conducted along both receiver lines with a source-point spacing of 40 m while all 404 channels were active (no roll-along). Each point was vibrated once with high- and once with low-force (75 % or 40 % of the maximum peak-force of 218 kN/vibrator), as well as in a day-time and a night-time survey. Unstacked and uncorrelated recordings allow for a simulation of several combinations and scenarios.

Due to the fixed, simultaneously on both runways active receiver lines (and sources on both as well) a total of 3 CDP profiles is generated: (1) a northern one, when all sources and receivers on the northern line are combined, (2) a southern one, when all sources and receivers on the southern line are combined, and (3) a center one (with twice the fold) when all those traces are combined, for which vibrator and geophone positions were on different lines, respectively. With these 3 parallel seismic lines, with around 240 m spacing between each other, it is also possible to at least recognize possible horizon dips perpendicular to the profile direction.

3.2 Data processing

As an initial step the data were contractor-processed using a conventional robust sequence, consisting of: correlation of vertically-stacked single sweeps, bad-trace elimination, static corrections, minimum-phase transformation, spherical divergence correction, surface-wave suppression/mute, surface-consistent deconvolution, dynamic correction after velocity analyses, residual static corrections, automatic gain-control, time-varying bandpass filter, CDP stack and fx-deconvolution. This processing scheme was carried out independently for the different possible combinations (north/centre/south profile, day-/night-time measurements, high-/low-force application) and the results then evaluated. Figure 3a shows one of the resulting conventionally stacked time sections for the northern profile (night-time, high-force).

Based on these results, a reprocessing was then carried out at the GFZ Potsdam, where the parameters for each processing step were analyzed and optimized, as well as other processing steps were added or exchanged. Improvements were mainly achieved by: (1) optimization of the diversity-stack parameters to weight the traces time-variantly during vertical stacking of the vibrograms in case of temporary noise; (2) automatic detection of bad traces by energy comparisons before and behind the first-arrival times; (3) careful and data-driven suppression or elimination of surface-wave portions which are overlying and thus masking reflections; (4) application of the common reflection surface (CRS) stacking method (instead of the conventional NMO/DMO approach). Herewith, not simply the traces of a common subsurface reflection midpoint (CMP) are summed after appropriate dynamic time correction, but it is taken into account, that the information measured at a surface point is actually originating from a certain, larger (curved) reflector segment, defined by second order kinematic reflection attributes. Summing along these segments allows more traces per CDP to be stacked (compared to NMO stacking) and thus yields not only a physically more correct image, but also a drastically enhanced S/N ratio (*Fig. 3b*); (5) Kirchhoff depth migration (implicit Eikonal solver) using interval velocities additionally calibrated by extrapolation from existing distant deep boreholes built the final step of the reprocessing. Figure 4 shows a compiled montage of 3 adjacent profile sections, where an integrated interpretation not only shows the horizons ascending to the E within each individual section, but also ascending to the N when comparing equivalent horizons on the different depth sections. CDP spacing is 5 m and line spacing ~ 240 m.

4. RESULTS

The seismic pilot study about feasibility and limits for high-resolution seismics in large cities under most-difficult noise conditions has all in all given the following findings:

- Seismics in such a noise-intensive environment is feasible in principle, the established acquisition method and geometry is basically well-suited for seismic recording in the city of Berlin. Down to 1.3 s TWT a coherent imaging of sedimentary horizons is possible already with standard processing approaches (Fig. 3a).
- The utilised signal-strength (number and applied peak-force of simultaneously acting vibrators, as well as duration and repetitions of transmitted sweeps) has naturally a high influence on the quality of the resulting subsurface response. Hence, comprehensive start-up tests are mandatory.
- On the one hand a specialised, strictly data-dependent processing with optimisation of all parameters and additional application of recently developed or improved methods (mainly CRS stacking and depth migration) results besides a visibly improved signal quality in the upper depth range also in a more reliable interpretability with a clear detection of known marker horizons down to a depth of more than 2.2 s TWT (~ 4 km, Fig. 3b, Fig. 4).
- On the other hand the suggested way of processing is also able to compensate for unavoidable shortcomings during acquisition (strong and heterogeneous noise, irregular coverage, day- instead of night-time surveying, low- instead of

high-force) without unacceptable quality loss in the final results. The here gathered experiences might be as well applicable to similar conditions in other mega cities.

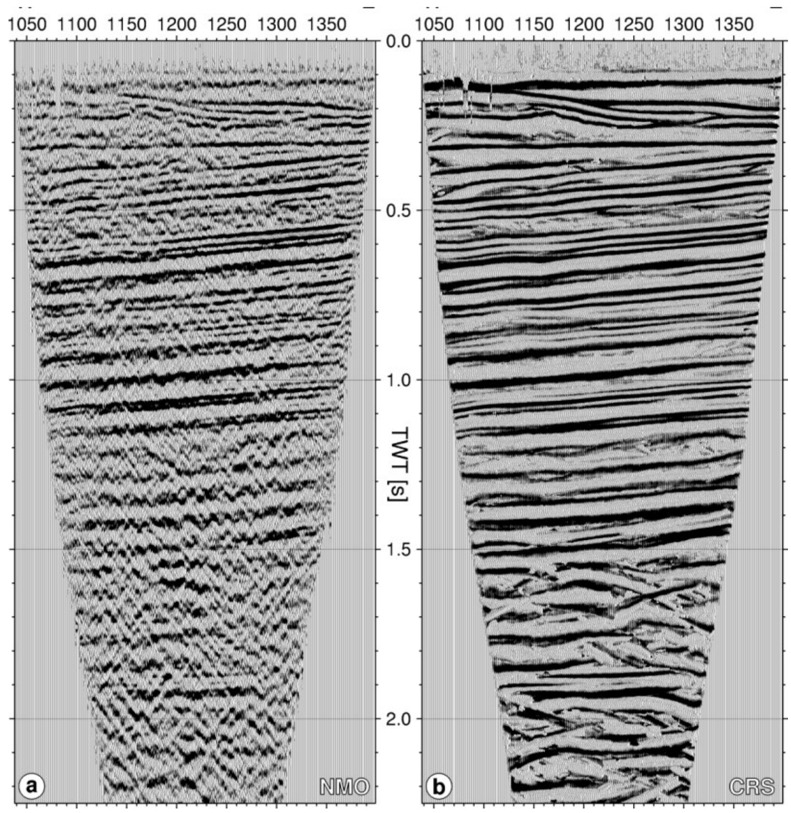

Figure 3: Comparison between unmigrated time sections of the northern profile (night time with high force) for (a) the initial processing (conventional NMO stack) and (b) improved reprocessing (CRS stack).

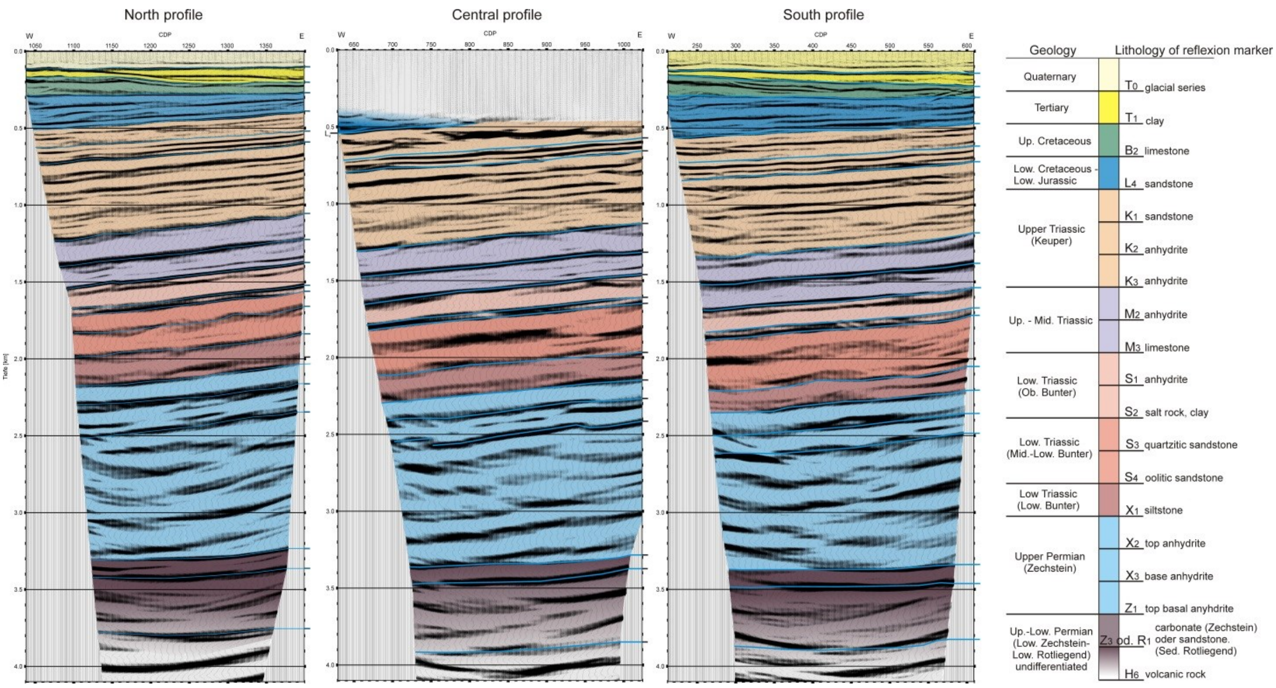

Figure 4: Geological interpretation of 3 adjacent reprocessed profiles (CRS stacked, Kirchhoff depth-migrated). (a) southern line, (b) central line, (c) northern line.

6. CONCLUSION

In the area of the former airport Berlin-Tempelhof a pilot study to test feasibility and limits of seismic exploration in the heart of mega cities was successfully conducted. New images of local subsurface structures were achieved as well as valuable findings with respect to necessary field and processing techniques and corresponding parameters for possible surveys in the future, e.g. related to present geothermal developments in Berlin. Similar campaigns in urban areas were successfully conducted by other geothermal project groups in Munich 2007, 2009 and 2012 (e.g. Lüschen et al., 2011), and in St. Gallen (Switzerland) in 2010 with the largest 3D seismic survey of Switzerland (Moeck et al., this volume). Urban areas are therefore no obstacle for seismic campaigns and geothermal field development provided the logistic effort and public communication is taken into account.

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