Quantum nodal system – Asse 3D survey success story

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discuss recent advances in seismic nodal technology that have resulted in improved operational efficiency due to the reduction in size, weight, and increased field endurance of nodes.

Introduction

This article presents the successful implementation of recent advances in seismic nodal technology that have resulted in improved operational efficiency due to the reduction in size, weight, and increased field endurance of nodes. These improvements enable the seismic industry to deliver client requirements for increased spatial sampling for improved subsurface imaging while still maintaining or increasing offset and azimuth distributions and productivity. The Asse project, the largest live channel count 3D survey conducted so far in Europe, is an illustration of taking advantage of such improvements to respond to the challenges posed by a seismic project implemented in a sensitive environment, within a specified tight timescale. Simultaneously, we demonstrated the need to develop robust equipment and data management, efficient hardware and dedicated software to handle the huge amount of resulting seismic data. A different approach to field processing quality control due to high data volume was introduced. Tender and contract specifications for equipment, quality control (QC) and field operations process supervision need to be revised to reflect these new procedures and system developments.

Historical background

The Schachtanlage Asse II is an old salt mine located near Remlingen in the district Wolfenbüttel. From 1909 until 1964 it was used for the extraction of potash and saltstone and from 1967 to 1978, for the storage of low and intermediate-level radioactive waste. Until 1995, the mine was used as an underground rock laboratory (URL) to test handling and storage techniques of radioactive waste in a salt repository. The mining chambers were excavated leaving pillars and stopes which only provided short term stability. The upper chambers at the southern flank are located very close to the neighbouring overburden mountains. The extraction of rock salt resulted in a high number of open chambers on the southern flank. Due to the insufficiently dimensioned support elements and long open standing time, significant damage and fracture processes have occurred both in the supporting elements and in the adjacent overburden and is still occurring today as can be seen in the high pillar sprain rates. This shows itself in the run up of several metres of transverse total sprain of the supporting elements. Strong convergence movement has caused damage to the covering overburden and a loss of barrier integrity. In conse-

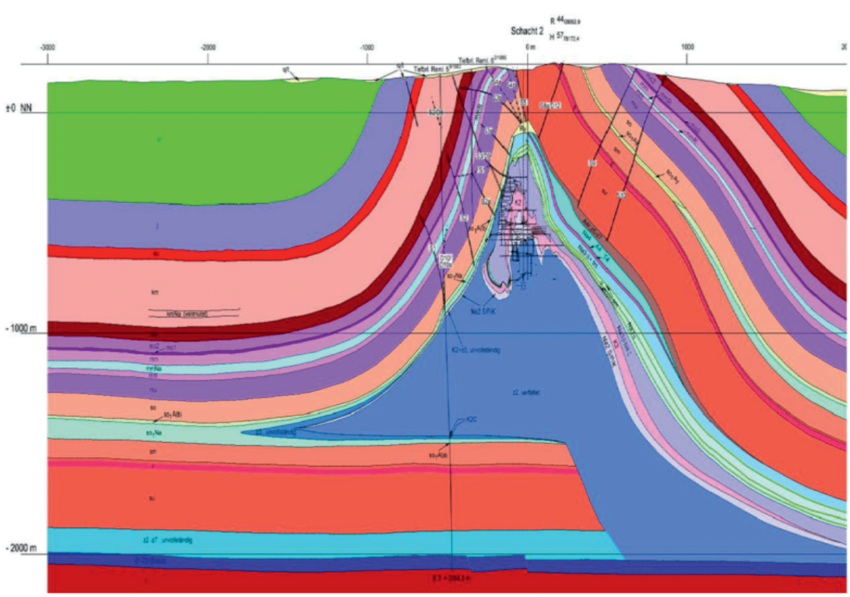

Figure 1 Schematic geological section of the structure of Asse II with salt body (blue).

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DOI: 10.3997/1365-2397.fb2021003

quence, weakening and fracturing in the load-bearing elements occurred and a brine inflow has been observed since 1988 (for more information see Kamlot et al. 2015).

In 2013 a law was passed in the Bundestag to speed up the recovery of radioactive waste and the closure of the Asse II mine. The Asse II has therefore to be closed in accordance with § 57b (2) AtG immediately after the recovery of the radioactive waste. The BGE (Bundesgesellschaft für Endlagerung (formally BfS/ Asse GmbH)) is responsible for this task.

In order to plan and implement the recovery and subsequent decommissioning a robust description of the geological and hydrogeological situation is required. This forms, among other things, a basis for the necessary evidence and safety analysis as a prerequisite for approval. Such a description must be based on the targeted application of comprehensive and reliable data that is up to date with the current state of science and technology.

Survey objectives

The aim of the 3D seismic survey was to create a geological model that will deliver the best resolution of:

- the boundaries of the salt dome,
- the salt level in the central area of salt structure,
- the characterization of potential migration paths of infiltration,
- the covering of the overburden and its detailed structure,
- large-scale mapping of the faults or fault systems and their characterization.

In order to obtain a re-enforceable and resilient 3D geological model for the Asse, the existing database had to be improved and expanded, with high resolution 3D seismic data. Due to the geological situation and the complex boundary between overburden and saline formation, an acquisition depth of up to 2000 m was required (Figure 1).

Survey area

The survey covered an area of 36.5 km^2 and included the urban areas of Wittmar, Remlingen, Groß Vahlberg, Mönchevahlberg, Weferlingen and Klein Biewende. In addition, parts of Dettum and Sottmar were included (Figure 2). Apart from the urban areas mentioned, the survey area is mainly made up of agriculture and forest. In the centre is the Asse-Hill, which is noted for its steep flanks along a SW-NE axis. Its absolute altitude is 220 m above sea level, about 80 m above the southern landscape and approx. 130 m above northern lowland Altenau.

Survey design and planning

In 2013 the first seismic test measurements confirmed that a 3D seismic survey could satisfactorily map the Asse structure and overburden and which basic parameters were needed. In the

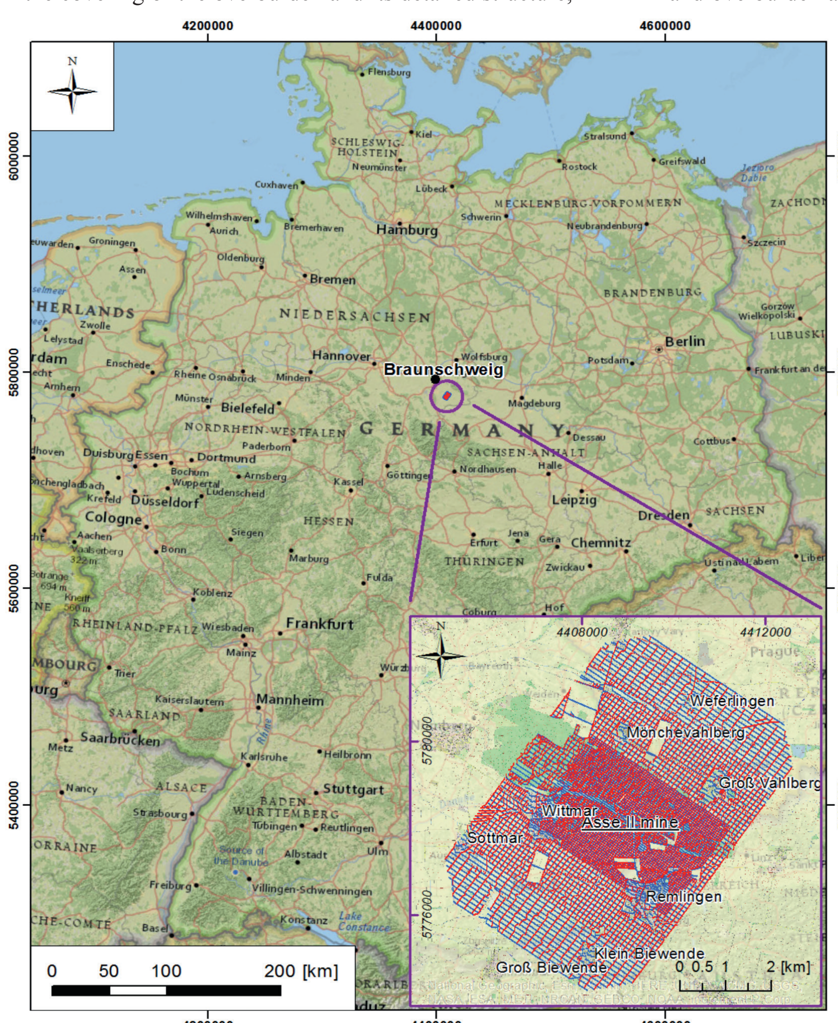

Figure 2 Location of the survey area.

Source line spacing	Variable (50 m, 100 m, 200 m)
Receiver line spacing	Variable (50 m, 100 m)
Source point spacing	10 m
Receiver point spacing	10 m
Number of active channels	41,190
Vibrators type	Hemi 50
Number of vibrators	4 – 5 in slip-sweep technique
Sweep frequency range	5 – 120 Hz
Sweep length	60 s
Sweeps	1
Record length	4 s
Sample rate	1 ms
Recording system	Nodal Quantum* with internal 5 Hz geophone

Table 1 Basic acquisition parameters.

* Tremornet was the original product name of Quantum, now manufactured and sold by Inova Geophysical.

next stage of designing and planning the seismic acquisition works, it was necessary to take into account all geological and environmental constraints.

The structure of Asse, with its steep flanks and geological formations, requires a very dense spatial sampling of the seismic wavefield. Simultaneously, in order to map the steep formations, a long offset and wide azimuth distribution was necessary. For the 3D seismic survey an orthogonal geometry layout was selected. Due to the existing grid of forest roads it was decided to lay out the source lines in a NW-SE direction corresponding to the strike direction of the Asse salt structure. According to the above the receiver lines had to be orientated in a SW-NE axis. The line spacing near to the Schachtanlage Asse II (Asse Mine) and along the Asse-Hill was reduced in order to achieve a higher resolution. A summary of all the most important acquisition parameters is given in Table 1.

Due to the environmental sensitivity of the area, nature conservation expertise and the consent of all responsible institutions with public interests (environment, water, forestry, agriculture, monuments, traffic, etc.) were required. In addition, permits from the owners and tenants of the agricultural and forest land were required. It was a prerequisite that the seismic measurements, including pre- and post-work, was carried out exclusively in one season from October to the end of March. This extremely tight timescale meant all permits had to be obtained before commencement in October 2019. Starting in September 2018, information events were held for the owners and tenants of agricultural and forestry lands within the survey area, which was continued in 2019 and 2020. Via various information events and the BGE website (https://www.bge.de/de/asse/themenschwerpunkte/themenschwerpunkt-3d-seismik/) the public were kept informed about the project by BGE. With the commencement of work, in October 2019, the BGE invited the public to an information event, which was held at the village community centre in Remlingen, to inform them about the survey work to be carried out over the coming months. During the seismic measurement an open day was held. Apart from the above the BGE reported weekly on the current progress of the 3D seismic acquisition on its internet site. In order to minimize the impact of the survey on the environment, all planned source and receiver positions were scouted and placed along roads and tracts conforming to acquired permits both from local authorities and landowners. During the scouting, the appropriate source type (vibroseis or explosive) was selected for each shot point.

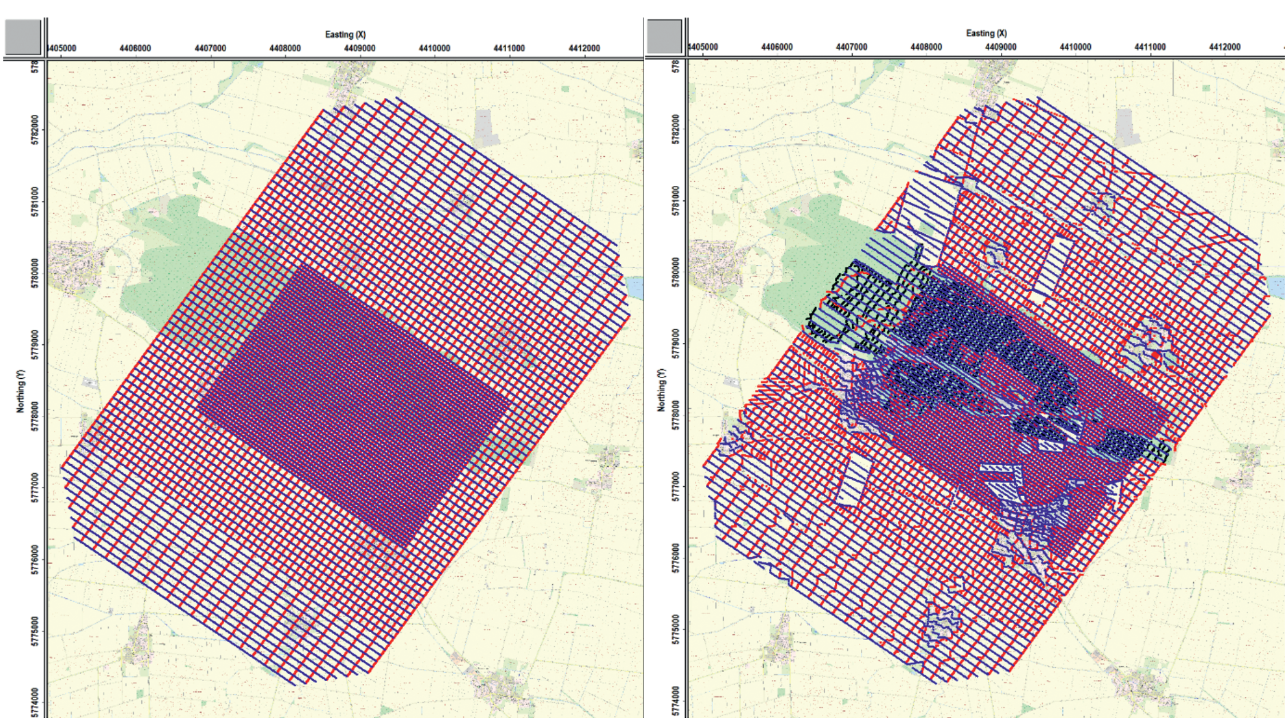

Figure 3 Survey geometry layout – theoretical (left) vs after acquisition (right); sources (balck: explosives, red: vibro) and receiving lines (blue).

Imaging this salt dome structure, consisting of very steep flanks and overlayed by outcropping geologic formations, was a very demanding task in the logistical management of source and receivers due to the very tight permitted timescale. A successful completion of the 3D seismic survey would not have been possible without the use of the combination of wireless node technology with slip-sweep source acquisition. The node system and field data acquisition approach drastically shortened the time for the seismic data collection.

Nodal system implementation at Geofizyka Toruń (GT)

Since 2017 GT has actively participated in the development and implementation of nodal technology, focusing this solution on large-scale seismic projects. During the development process, numerous tests were carried out leading to the implementation of substantial improvements such as quick QC status, live converter using a database approach and redesigned architecture of SEGD generation software. These and other solutions mainly combined with downloading and transcriptions process optimization were implemented during several projects carried out in Europe in 2018 and 2019 using the nodes.

Survey challenges

Cooperation with the local community and land owners was demanding due to a conflict of interest in the area of seismic activities. The works had to be completed within a given short time window, with the lowest possible impact on the environment and the local community. In this situation, the nodal system was the only solution.

Figure 4 Vibrators finishing the experimental work programme.

The narrow time window for data acquisition in combination with the required fine spatial sampling, made it necessary to use a very large active channel count which in the situation could only be efficiently accomplished with a nodal system. This, in turn resulted finally in a huge amount of recorded data (in the order of 1 PB), which had to be retrieved, transcribed and processed on-site, immediately after acquisition, in a one-time data saving operation. The tight time window did not allow for intermediate read-save operations, therefore all data conditioning processes had to be done simultaneously.

Seismic data acquisition process

The project required the use of two types of seismic sources, explosive in the central, mountainous and hard to reach part of the area and vibroseis in the agricultural and urban areas (Figure 3).

All explosive source points had to be prepared before the start of seismic data recording. Therefore, the explosive parameter tests were carried out in October 2019, three months before the seismic data acquisition commenced. The field tests were carried out and analysed at three different locations over the survey area, then optimum shot hole depths and the charge sizes were determined. The predrilling process took 11 weeks. During this time, more than 6300 shot holes with a depth of 6-12 m were drilled using various drilling equipment from portable to tractor-mounted rigs.

The testing of vibroseis sweep parameters took place just before the commencement of data recording and finally a single sweep with frequency range 5-120 Hz and sweep length 60 s was selected. In order to obtain productivity allowing us to record all planned source points in the settled time window, the slip sweep technique, with slip time 26 s, was used. Acquisition was carried out using five fleets of a single 50,000 lbs. vibrator. This allowed minimization of obstacle detours and other down time. The acquisition with the vibrators was stopped for 2-3 hours each day, during which explosive source points were recorded. Each source point was recorded using 41,190 active channels made of Quantum nodes. A single channel (wireless node) being de facto a small autonomous seismic recorder consisting of a 5 Hz natural frequency, high sensitivity analogue geophone, 16 GB storage memory, powerful battery and GNSS receiver. Each node has a built-in system allowing it to conduct self-test and store QC data. The trace density was variable and reached 184,000,000 trace per km^2 at the project centre. The distance between receivers and shot points was a constant 10 m, while the source and receiver lines intervals varied from 50 m in the centre of the survey, to 200 m at its edges.

Figure 5 Quantum nodes and data harvesting centre.

Figure 6 Examples of Quantum nodes layout in urban areas and drilling operation in forest areas.

Figure 7 Mobile data processing centre installed in a 40 ft container.

The whole process of data recording was completed in a single node battery charging cycle. To reduce power consumption and limit the amount of recorded data in continuous mode, the operation time of the nodes was scheduled for 6am to 10pm to fit in with the daily field acquisition time. All nodes were settled to run a self-test during the night. The quality control of the nodes was carried out daily by several teams. As a result, each sensor had been checked, laid out and adjusted, when necessary, every 3 days.

Thanks to such an approach, with this dense grid, mixed source project, the average daily productivity of ca. 1000 shot points was achieved.

In addition, several dozen nodes placed in the mine's tunnels were used to record data for a pilot monitoring project combining passive and active seismic during the whole acquisition period.

Collection of all 41,190 Quantum nodes from the work area could only start after the acquisition of all planned shot points was completed. The transcription process started with the simultaneous downloading of recorded data in four mobile harvesting units. The data was transferred directly to the mobile processing centre via an efficient 4*10 Gigabit Ethernet. Metadata was imported into the project's main database at the same time. The matching process (assigning each node to its position in the geometry grid of the survey) was performed automatically along with data downloading. The whole process was quality controlled by two geophysical engineers using dedicated multi-tasking software.

Raw, unsorted, continuously recorded data together with metadata were inputted to generate final field records (shot gathers). The transcription process consisted of (1) separating events from each node, (2) the process of data correlation with appropriate pilots, (3) removal of harmonic disturbances resulting from the slip sweep technology used, and (4) saving the data as the final records.

In this one-time input-output process three sets of data were generated: uncorrelated records, correlated records, records correlated with removed harmonic distortions. Finally, more than 1.4 billion seismic traces were generated for each of the three sets of data. All the above steps are usually performed one after the other with intermediate data output. However, due to time limitations for this project everything had to be generated during one input-output operation. The whole process had a zero-error margin.

The achievement of such an efficiency of data processing was only possible by developing and building dedicated hardware and software solutions.

In search of such new and innovative concepts, a computational power test was carried out at the beginning which showed a significantly higher computing performance of the Graphics Processing Units (GPU) based system. In this benchmark test, a solution based on 10 GPU card was 6.5 times faster than an equivalent solution based on 20 CPU. As a result, the mobile data processing centre was built. The core of this unit was hybrid scale-out NAS and HPC Cluster with graphics cards. It consisted of 15 nodes, each equipped with two GPU, NVIDIA cards with CUDA (*Compute Unified Device Architecture)*, providing a theoretical performance for GPU: 405.2 TFLOPS and CPU: 30.1 TFLOPS. Data storage was provided by short access time, hybrid scale-out NAS. All infrastructure was connected via a 40 Gigabit Ethernet. The whole system was placed in a specially developed container with an efficient cooling system and fire protection (Figure 7).

The decision to use the GPU platform as the main processing unit generated another challenge. Such a platform cannot be used for existing software that works only with CPU-based machines, therefore it required rewriting the modules needed to perform the task from scratch. The new software also enabled direct and parallel access to the database while uploading data. An automatic matching process was also implemented. Additionally, an algorithm for removing harmonic distortions was applied. Both processes were performed automatically, during data downloading and final SEGD data generation, having the ability to be run on both CPU and Nvidia CUDA compatible GPU devices. This target-oriented solution allows us to create an extremely efficient environment for processing large amounts of data anywhere in the world.

Data in-field QC processing

Standard quality control procedures being carried out during seismic measurements consist of successive, as the acquisition work progresses, data quality analysis and verification of the position of shot and receiver points. In parallel, these data are pre-processed and stacked to verify the quality of the data against the geological task as well as their integrity.

In the case of the Asse 3D survey, due to the requirement to register all shot points using the full spread, this approach was not applicable.

In view of the above, final data quality control and positioning verification of source and receiver points was possible after collecting all sensors after completing the acquisition. The challenge of this part of the work was to perform a reliable data and geometry verification in a relatively short time. Additionally, the number of recorded traces made it impossible to perform this task in a conventional way. In the first approach, the procedures for verifying spread geometry, dead traces, and data quality focused on selected data attributes which significantly reduced the number of questionable records that had to be thoroughly verified. The attribute set for shot points preselection for manual analysis included signal to noise ratio,

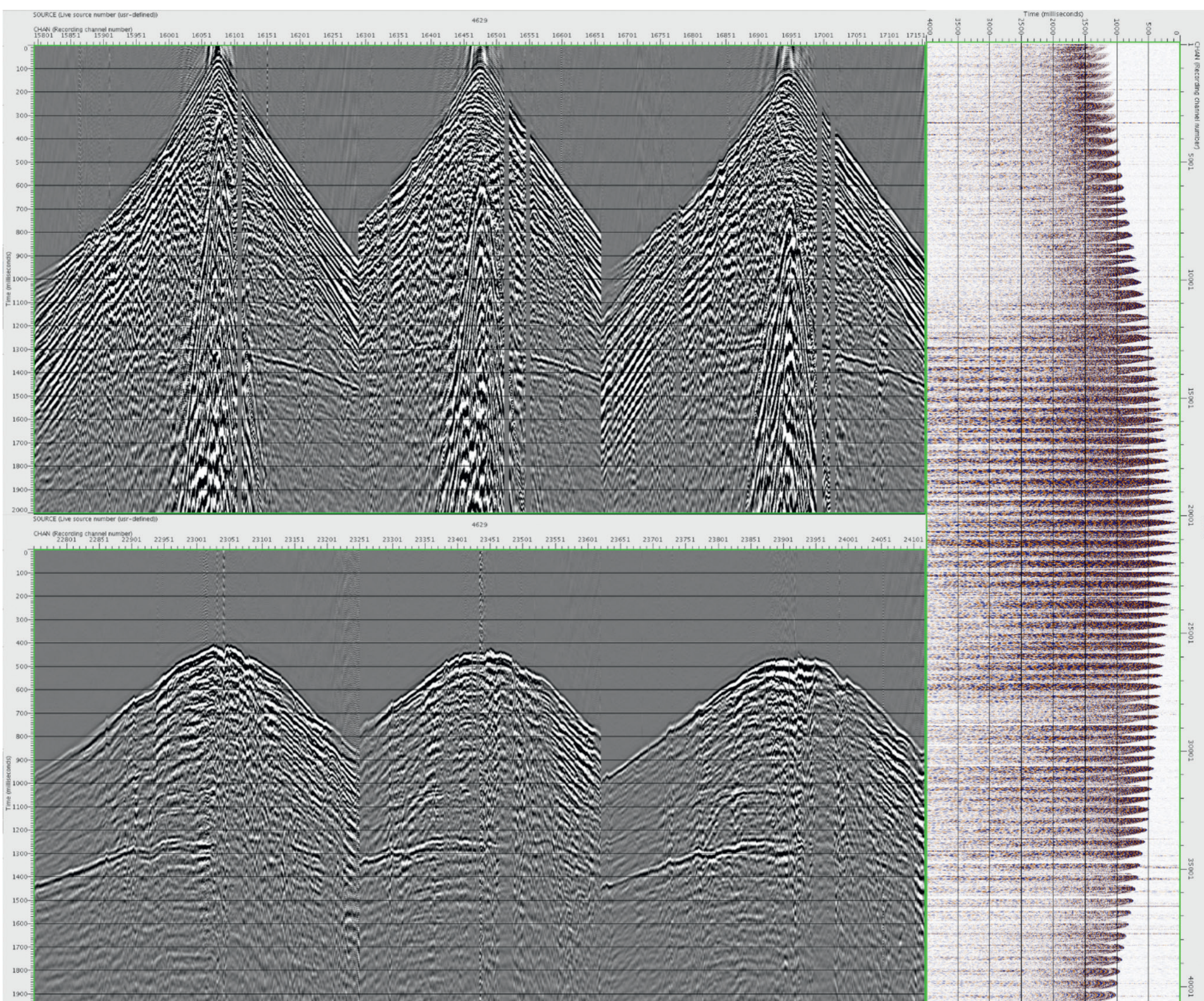

Figure 8 Example of full field record (right) and zoom of near and far offsets (left).

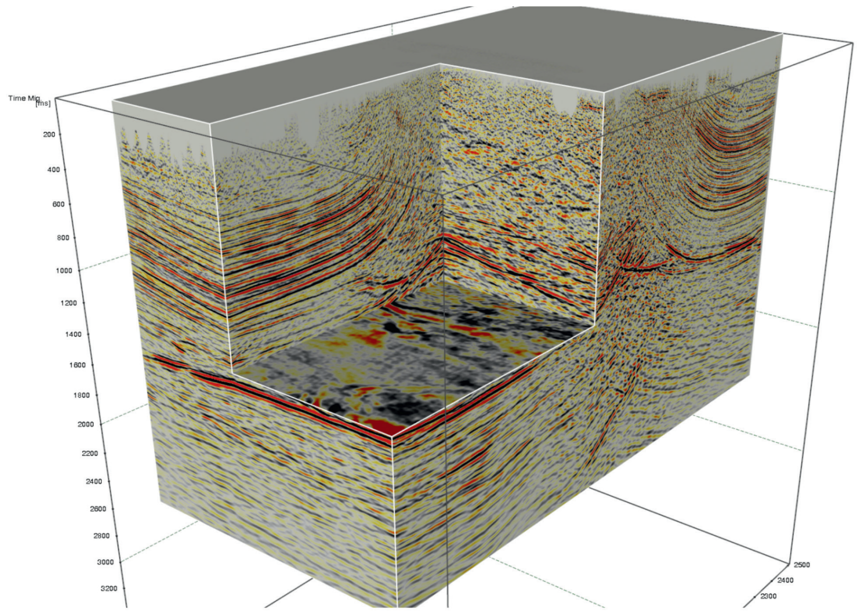

Figure 9 In-field data processing – Asse 3D post-stack time migration cube.

dominant frequency value, amplitude decay and others. As a result, only 18 shot point records were rejected due to wrong geometry or noisy data, less than 1% of traces were killed due to noise or zero amplitude.

Fast-track data processing was carried out as part of advanced quality control to verify integrity of the data, and to allow early seismic data interpretation. The final product of the processing was the post-stack time migration 3D volume shown in Figure 9.

The processing sequence contained basic procedures such as spherical divergence compensation, spiking deconvolution, elevation static corrections, velocity analysis (every 1 km^2), dynamic corrections, stacking, post-stack processing and Kirchhoff time migration.

Survey summary

Data acquisition was carried out in two stages. The south part of project was started on 17 January and completed on 31 January, 2020. After a two-day break in order to pick up and lay-out part of the nodes, production in the northern part was resumed on 3 February, 2020 and finished on 20 February 2020. In total 29,771 vibroseis points and 6349 explosive points had been completed. Due to the lack of access permission and field obstacles 4740 shot points and 1750 receiver points had to be skipped. It took seven days to collect all 41,190 nodes from the work area.

Despite such a large and dense survey grid and such a huge number of receivers, the matching process of nodes to receiver stations went smoothly thanks to the ability to match simultaneously during data retrieval. The transcribing process of all 36,120 seismic records (shot gathers) took 230 hours. Finally, three data sets have been produced, each containing 1.4 billion traces using almost 1 PB of data storage.

All deliverables related to QC and fast-track volumes, including post-stack time migration volumes, were prepared within 15 working days and delivered on 3 April.

Even though the project lasted more than half a year, involved more than 100 employees, 90 vehicles, trucks and heavy machines operating in difficult weather and terrains, the crew was able to finish the operation successfully without any HSE incidents – accumulating 144,070 man hours of LTI-free operations. More than 328,975 km were driven without any vehicle incidents. There were also no major problems reported in the relationship with local community.

Conclusions

The location of the Asse-3D survey in an environmentally and socially sensitive area together with the difficulty of imaging of the main target, the salt dome structure, were the main obstacles that prevented its previous execution.

Considering environmental, time, and social constraints, this seismic survey only became possible when a large number of reliable nodes were available on the market. All previous plans to carry out this survey, based on cable seismic systems proved impossible to implement due to the above-mentioned circumstances.

The very high productivity required to meet the project timescale could only be achieved by using the slip sweep technique, shot hole pre-drilling, thorough geometry layout planning of sources and receivers, and logistics management at the highest level. It should be emphasized that three main factors were decisive for the survey success: the use of more than 41,000 Quantum nodes built into a well-functioning seismic system provided by Geofizyka Toruń S.A., excellent planning and survey preparation carried out by BGE, and then the effective survey execution by Geofizyka Toruń S.A supported by BGE staff. Unparalleled in European conditions, daily productivity of 1300 VP' recorded at more than 41,000 live channels was achieved, with a minimal impact on the environment.

Dedicated hardware and software solutions were built up to manage the large amount of data recorded by the nodal system. Simultaneously new approaches to the QC of field equipment and seismic data were developed and applied.

In order to fully benefit from these technological advances, it is necessary to relinquish some past paradigms. Traditionally, the focus of a recording crew's quality control was the necessity to monitor the continuity of tens of kilometres of cables and thousands of connections as a failure could have a significant impact on data quality. The greatly increased unit reliability of the latest generation of nodes, such as Quantum, which have proved to have negligible failure rates, must be appreciated. The advent of autonomous nodes has greatly reduced the risk of contiguous channel data loss. Therefore, the focus of recording crews has moved from the quality control of active spreads to quality assurance in the deployment and retrieval of nodes.

Next-generation seismic data will be characterized by greater spatial sampling and better distribution of offsets and azimuths. These acquisition requirements will mean that in complex areas such as Asse these challenges can only be met by autonomous nodal systems, which are characterized by low weight, long battery endurance and large memory. Furthermore, the large amount of recorded data implies a change in the philosophy of quality evaluation in the direction of statistics rather than excessive care for the quality of a single record.

The acquisition of seismic data using nodal systems introduces completely new challenges related to the need to transfer and process large amounts of data in a very short time at the work site. Today's seismic data acquisition practices and habits are based on cable systems, in which the data is transmitted in real time and saved to the required format. Nodal systems completely change this perspective. Therefore, the development of solutions enabling far-reaching optimization of computational processes as well as input/output processes is a fundamental challenge. This optimized innovative solution, designed and applied in the Asse project, based on a GPU, significantly shortens the timescale of required post-recording operations related to data transfer, transcription.

To take full advantage of these technology developments the existing quality specifications in tender and contract documents, developed for cable systems, need to be changed as they are no longer applicable to field operations using nodal systems both in terms of the method of conducting QC and certain quantitative parameters.

The current practice is to agree with the client, often after the tender has been settled, the rules of conducting work and quality standards from survey to survey. Thus, there is an urgent need to discuss and develop new quality standards for the next generation seismic data based on autonomous nodes.

Acknowledgments

The authors would like to thank BGE for permission to publish this paper. Special thanks goes to the entire Asse 3D seismic team for its cooperation and support. Dr Thomas Lautsch, technical CEO of BGE, pulled the trigger of the 'starting-gun' of this great seismic project Asse 3D and supported it to completion, Jens Köhler, BGE project leader, also put a lot of effort into overseeing the whole project from start to finish. We would also like to thank Dr Raimund Seitz and Dr Andreas Schuck for their valuable advice and supervision. Unfortunately, this successful project was the last one for Dr Raimund Seitz, who shortly after the completion succumbed to a terminal illness. Finally, thanks to Andrew Clark for valuable, substantive and linguistic comments.

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