

Development of tomographic systems for mining, mineral exploration and environmental purposes

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Synopsis

A research project was carried out to develop and test a prototype seismic tomographic system suitable for use in the exploration, mining and civil engineering industries. Tomographic techniques are attractive because they can provide information from the unknown areas between drill-holes and are non-destructive, which is particularly important for civil engineering and radioactive waste disposal projects.

The starting point was the SEAMEX-Compact seismic system, developed in 1991 for use in the coal industry, which had limited capabilities. Prototype development involved the redesign of existing seismic systems, development and assembly of compact units and production of new acquisition and control software. Emphasis was placed on high dynamic range and control mechanisms. The prototype system was named SUMMIT-Compact and the final version is much advanced from the SEAMEX system.

The prototype was calibrated and tested at two Ruhrkohle AG sites in Germany, the Reocín zinc-lead mine in Spain, a nearby Reocín exploration area and the Grimsel rock laboratory for radioactive waste disposal in Switzerland. Work at Reocín mine and in the exploration area was supported by studies of matrix porosity, fluid inclusions and isotopes to model the zinc-lead sulphide orebodies. The seismic tomographic technique proved highly successful for short-hole surveys in the Reocín mine and at the Grimsel rock underground laboratory. These surveys demonstrated clearly the effectiveness of seismic tomography in holes drilled both from the surface and underground, and in wet or dry conditions. The technique can be used immediately for surveys of the type required by many civil engineering projects, for underground radioactive waste-disposal projects and to address specific mining problems.

Exploration area testwork, carried out in deep drill-holes, gave poor results because the open joints and cavities in the karstified dolomites reduced the strength of the seismic transmissions. The seismic equipment operated well and the results might well have been good if the rocks had been less affected by deep weathering. The technique has considerable potential for use in deep-hole mineral exploration in suitable geological environments such as the Scandinavian Shield and the Spanish-Portuguese Pyrite Belt.

The prototype SUMMIT-Compact system is the

most advanced of its type in the world and the field tests demonstrated the effectiveness of seismic tomographic techniques in small-scale surveys of the type required for many industrial applications. Mineral exploration is a large market waiting to be developed, but tomography is in its infancy in this field and the technique has yet to be proved effective in deep drill-holes. The prototype system is being modified and manufactured for marketing worldwide. Further research is warranted to refine the resolution and penetration of the system and additional research is urgently required to test the seismic tomographic technique in deep holes in a variety of suitable geological environments.

The project was coordinated by Asturiana de Zinc S.A. (Spain) and the partners were Deutsche Montan Technologie GmbH (Germany), Escuela Técnica Superior de Ingenieros de Minas de Madrid (Spain) and the British Geological Survey.

The basic technique of seismic tomography is to place explosive charges in a drill-hole and record the seismic wave transmissions by use of receiver strings in other drill-holes. The technique is attractive because it can provide information from the unknown areas between drill-holes and is non-destructive, which is particularly important for some civil engineering projects. Seismic tomography is at an early stage of development and industrial applications are manifold in mining, civil engineering and mineral exploration for a commercial system of hardware and software capable of production of satisfactory results.[†]

On this basis, Asturiana de Zinc S.A., Deutsche Montan Technologie GmbH (DMT), the Escuela Técnica Superior de Ingenieros de Minas de Madrid and the British Geological Survey considered that research within the framework of the BRITE-EURAM programme was warranted to develop a prototype high-resolution seismic system for tomographic surveys. No comparable seismic systems were available at the start of the project on 1 December, 1993. The main objectives were: (1) to develop a prototype high-resolution seismic tomographic system, including hardware and software, suitable for mining, mineral exploration and civil engineering requirements; (2) to test the system at the Reocín zinc-lead mine and a nearby exploration area in northern Spain and at the Grimsel rock laboratory for radioactive waste disposal in Switzerland; and (3) to undertake mineralogical, fluid inclusion and isotopic studies of rocks associated with the Reocín orebodies to facilitate interpretation of the seismic data.

Technical description of project

Seismic tomographic methods are used in the petroleum and coal industries, but, prior to the present project no suitable seismic systems were available for use in commercial hard rock applications. The starting-point was the SEAMEX-Compact seismic system, developed by DMT in 1991, which had limited capabilities and was aimed primarily at the coal industry.

The project was carried out in three main stages—concept development, prototype development and prototype field tests. Concept development included a worldwide literature search on the use of seismic systems for mineral exploration and development with particular emphasis on the mathematical methods of data processing and interpretation.

Prototype development

The SEAMEX-Compact system used as a basis for prototype development consists of a chain of receiver units (SCU), each with 12 seismic input channels, linked by cable to one or more central control units (standard personal computers). After each seismic shot the data are stored temporarily in the SCU and retrieved sequentially from them by the central control units. The maximum cable length is 500 m and the data transfer is 333 kbits/s.

SEAMEX-Compact was designed for use in large-diameter drill-holes and in geological situations where the strata are flat-lying and the structure is relatively simple. The aim of the project was to refine and extend the SEAMEX-Compact system by development of new equipment and software capable of accurately recording data with a broad dynamic range from narrow diameter drill-holes.

Prototype development involved redesign of the SEAMEX-Compact system, construction and assembly of new receiver and central control units and the writing of new acquisition and control software. The new equipment and software included multiwave borehole receiver chains, coupled geophones–accelerometers for particle motion and

polarization and hydrophones for first seismic wave arrivals. Software development was directed at three-component particle motion and phase identification and at multi-hole evaluation, which included geometry definition, amplitude inversion, data plots/displays and inversion results. The system was developed with particular emphasis on high dynamic range and control mechanisms with use of the DOUBLE-DYNAC oversampling technique.

The prototype was named SUMMIT-Compact and the final version has receiving units each of which handles 24 seismic input channels. Up to 20 receiving units (480 channels) can be linked to a standard PC central control unit via a simple two-wired cable and the linkage can be at any position on the cable so that, by using repeaters at 250-m intervals, the maximum cable length is theoretically unlimited. The data transfer time is 35 ms for one trace with 1024 samples.

Each SUMMIT-Compact receiving unit contains an automatically controlled pre-amplifier, an analog high-cut filter, an a-d converter and a high-performance, 24-bit digital signal processor. This circuit allows high-speed data conversion, digital filtering and has a dynamic range of more than 130 dB. The data are sampled at high frequency and reduced to the desired sample frequency by use of the oversampling technique, which improves system resolution. The central control unit contains data-acquisition software, as well as plot facilities and final data storage on various PC-controlled devices (hard disk, DAT, etc.) in standard SEG-2 format. The equipment and specifications of the prototype SUMMIT-Compact system are shown in Fig. 1 and Table 1.

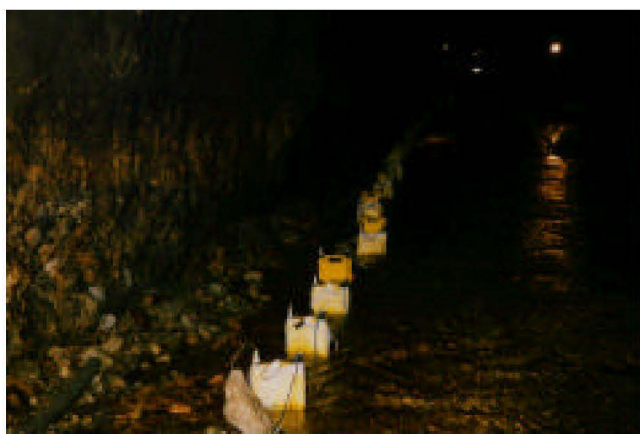


Fig. 1 SUMMIT-Compact receivers in Reocín underground mine

Table 1 Technical specifications of SUMMIT-Compact system

Number of channels per unit	24
Maximum number of units	20
Total number of channels	480
Sample interval	1/128, 1/64, 1/32, ..., 8 ms
Number of samples per trace	512, 1k, 2k, 3k, ..., 16k
Maximum input signal	2 V rms
System input noise	0.6 μ V rms @ 1/4 ms
Dynamic range	>130 dB @1/4 ms
System resolution	24 bits @ 2 ms
Preamplification	Automatically controlled
Gain accuracy between channels	<1%
Input impedance	4.7 kohm
Common mode rejection ratio	>80 dB
Total harmonic distortion	<0.01%
Alias filter, analog	6 dB/octave 2 kHz @ up to 1/4 ms 16 kHz @ up to 1/128 ms
digital	>120 dB/octave 1800 Hz @ 1/4 ms, 900 Hz @ 1/2 ms, ..., 56,25 Hz @ 8 ms
Crosstalk	>100 dB
Data format	24-bit fixed-point
Weight	13 kg
Dimensions	551 \times 199 \times 199 mm
Power supply	+12 V dc @ 0.4 W/channel
Operating temperature range	–20°C to +50°C –30°C on request

Field tests

Tomographic seismic fieldwork was undertaken at the Reocín zinc–lead mine in Spain, the Grimsel rock laboratory for radioactive waste disposal in Switzerland, an exploration area near to the Reocín mine and two Ruhrkohle AG coal-mining operations near Duisberg in Germany.

Reocín mine

The Reocín open-pit and underground mine is the second-largest base-metal producer in Europe with an annual output of around 2 000 000 t ore/year. The ore deposit is a stratiform body consisting of massive sulphide minerals (sphalerite, marcasite and galena) dipping at about 23° within thick dolomitized limestones of Cretaceous age (Fig. 2). The grade of the ore normally ranges between 7 and 25% Zn with local areas up to 40% Zn.

Late Cretaceous karstic weathering produced erratic sink-holes in both the dolomitized limestones and the orebody, with the result that working faces can pass suddenly from

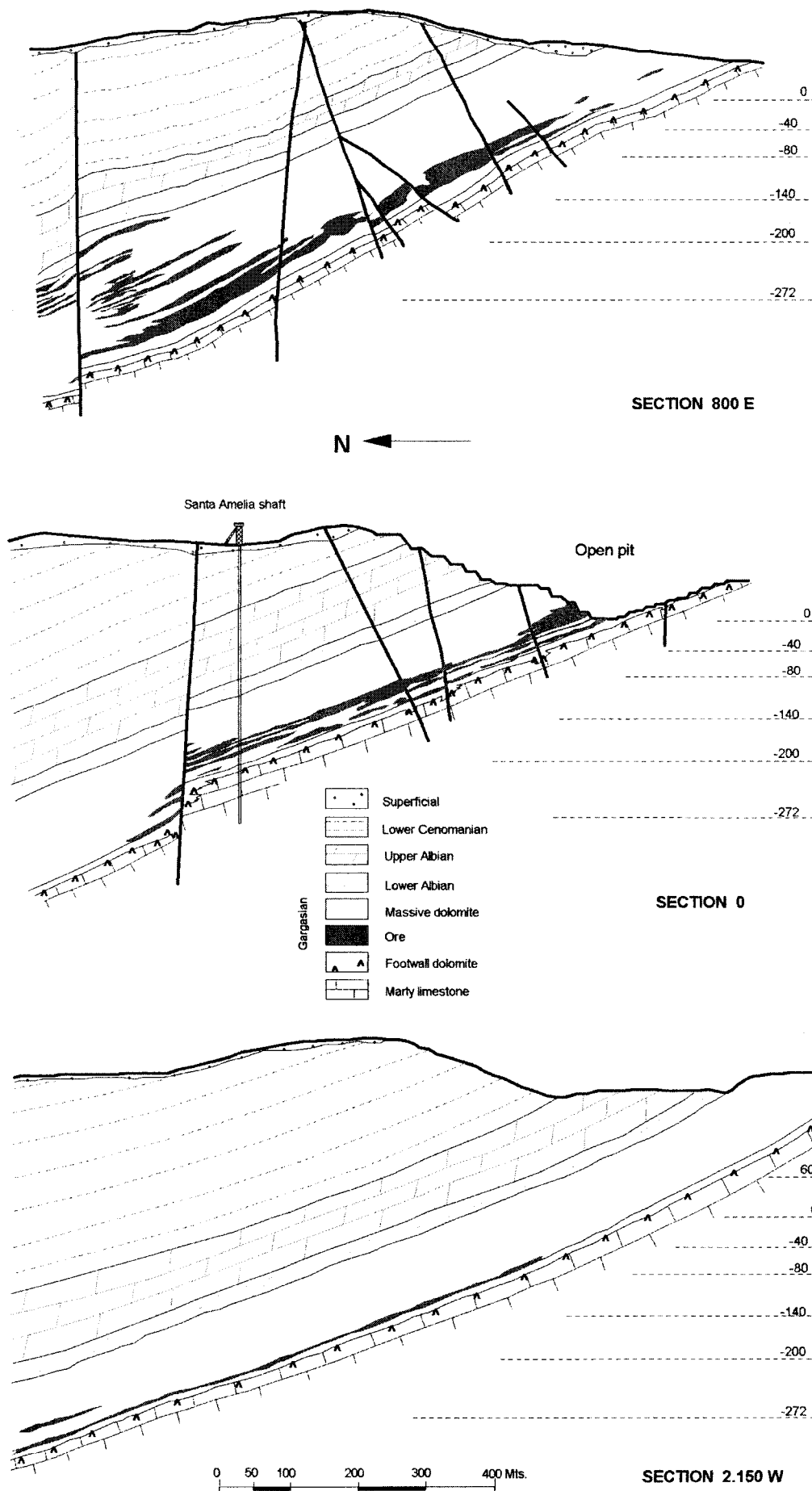


Fig. 2 Reocín mine geological sections

massive sulphide ore to unstable arenaceous and argillaceous karstic fill material. The orebody is also cut by major and minor faults, together with three joint sets, all of which affect mining conditions. The lower parts of the underground mine have a strong inflow of groundwater, averaging 1.2 m³/s, caused by penetration of surface waters through the ancient karst profile and along joint systems in the ore and enclosing dolomite.

Open-pit survey The Reocín open-pit benches are eminently suitable for seismic tomographic testwork and the selected bench (Bench -25) contained sulphide ore in two parallel bodies separated by barren dolomite. The survey used existing SEAMEX-Compact equipment and was intended to establish optimum field operating procedures and to determine design parameters for the prototype seismic system.

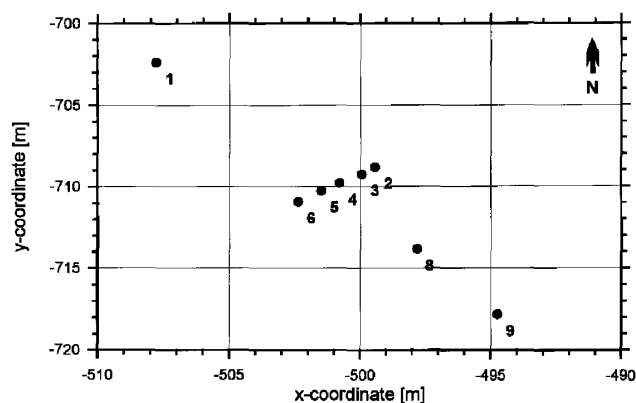


Fig. 3 Reocín open-pit bench 25, location of drill-holes

Nine rotary percussion holes were drilled on Bench -25 to an average depth of 16 m (Fig. 3). Four of these holes were used for receivers (geophone strings) and were cased with 75-mm diameter PVC pipes. The seismic source holes were cased with several types and diameters of PVC or PE-HD pipe, depending on the seismic source (detonator, sparker or hammer). Joints between the pipes were glued, and casings in all the drill-holes were plugged at the bottom with Teflon or wood and the holes were filled with water. Wooden plugs gave the best results because the wood expands on contact with water and seals the bottom of the hole. Spaces between the casing and the enclosing rock were filled with water and drill cuttings to ensure good contact; concrete would have been preferable, but its use was not practical because of the small-diameter (2-in) drill-holes and the narrow spaces between casing and wallrock.

In essence, the work consisted of putting a string of 24 detonators down a source hole, firing them sequentially and using a string of 24 geophones down a receiving hole some 5–15 m away to record the seismic data. Geophone strings at the surface also recorded seismic data. Tests were carried out with various combinations of single or double detonators, different downhole hammers, accelerometers and two types of geophones, as illustrated in Table 2. The acquisition parameters were: sampling rate, 0.125 ms; 4096 samples per trace; and up to 48 traces recorded per shot point.

The data were preprocessed on site with a TomCat software package and were then taken to Bochum to be processed by DMT. Additionally, 11 core samples of rocks with similar characteristics to those in Bench -25 were selected from stored core material and taken to Bochum for laboratory-scale tests to determine seismic velocities and elastic constants. The following important points were estab-

lished in respect of field operations. (1) Detonators are the best seismic source, but the firing equipment and detonators used in the survey were for open-pit blasting and there were trigger delays of up to 1.5 ms, which caused problems in data processing. (2) 28- and 100-Hz geophones are the best receivers. (3) Firm coupling between the PVC casing and the

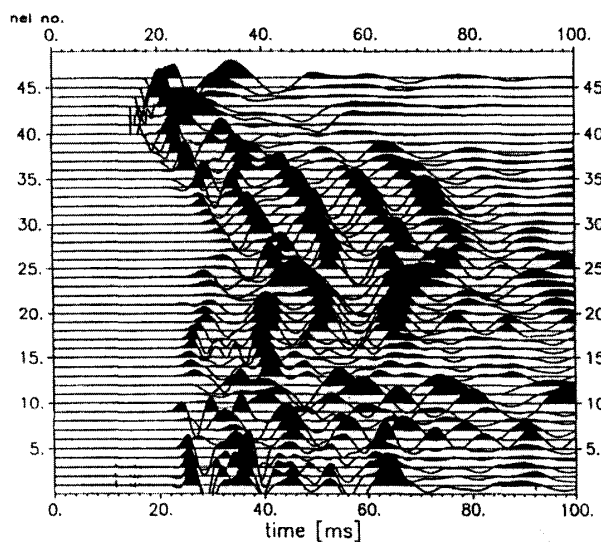
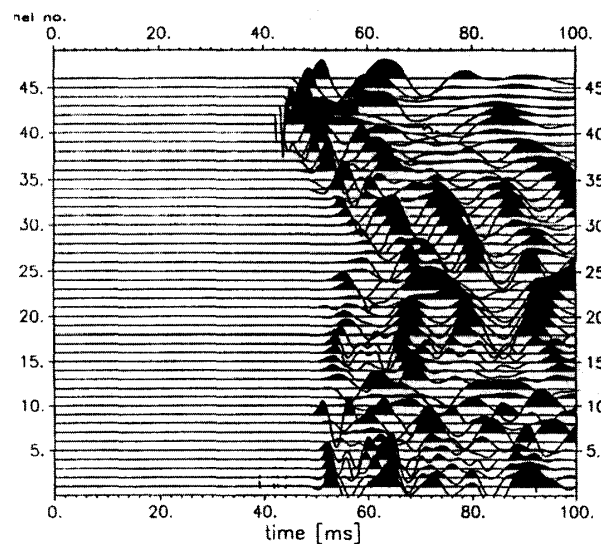
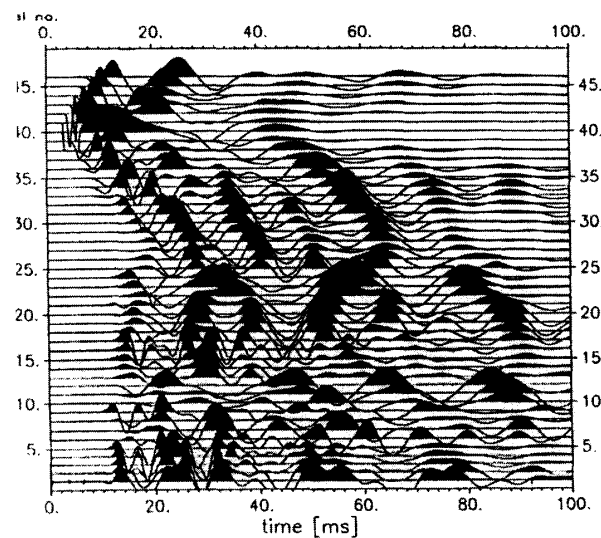


Fig. 4 Variable delay times caused by 'zero delay' detonators

Table 2 Reocín open-pit, combinations of seismic sources and receivers

Source	Source hole	Surface receiver	Borehole receiver	Receiver hole
Pneumatic borehole hammer, large	6	28-Hz geophones	28-Hz geophones	9
Pneumatic borehole hammer, large	6	100-Hz geophones	28-Hz geophones	9
Pneumatic borehole hammer, large	6	Accelerometers	28-Hz geophones	9
Pneumatic borehole hammer, small	3 and 4	28-Hz geophones	28-Hz geophones	9
Mechanical borehole hammer	2	28-Hz geophones	28-Hz geophones	9
One detonator	5	28-Hz geophones	28-Hz geophones	8, 9
Two detonators	5	28-Hz geophones	28-Hz geophones	1, 9

enclosing rock is essential, and this was best achieved with the use of 3-in PE-HD casing in a 9-in hole and with water and drill cuttings to form the coupling. (4) Data processing was affected by fracturing in the rock because of open-pit production blasting in Bench -25 and the bench above.

Data processing was carried out by DMT in Bochum and the interpretation was undertaken by personnel from DMT and Asturiana de Zinc working closely together. For this survey 22 000 seismic traces and more than 88 000 000 data points were processed. The survey also included ray paths between shotholes and lines of surface receivers. No software was available to handle the type and volume of processing required and DMT wrote new programs specifically for the project.

The use of unsuitable 'zero-delay' detonators resulted in substantially more data processing than had been expected. The detonators used in Survey A were those known as 'zero-delay' in mining circles, which actually have trigger times of about 10–40 ms, the precision varying from shot to shot. This variable delay caused real problems for the data processing (Fig. 4). 'Zero-delay' detonators normally used for seismic work have a maximum trigger delay of 2 ms and much higher precision than those used during the survey. Specialized seismic detonators were used for all future surveys.

The data interpretation results were very satisfactory and show the distribution of different rock types, such as massive dolomite, porous dolomite and sulphide ore, in considerably more detail than was possible previously from geological mapping of the bench face and surface (Fig. 5).

Underground mine survey The objective of the mine survey was to test the prototype SUMMIT-Compact system in wet underground conditions and, if possible, identify different rock types and detect fracture zones that can influence water flow into the mine workings.

The underground workings selected were in the deepest part of the Reocín orebody on Level -305, where there is a strong water flow. Mining on this level was stopped during the seismic tomographic measurements to minimize extraneous noises that could affect the seismic readings. The seismic equipment was waterproofed for working in wet conditions underground with particular attention to electrical contacts and parts containing electronic components.

Seven vertical or steeply inclined percussion holes (totalling 140 m) were drilled in the drive floor, as shown in Fig. 6. The holes had a diameter of 3.5 in and four were cased with PVC pipes with an inner diameter of 50 mm, whereas the other three had PE-HD casing with an inner

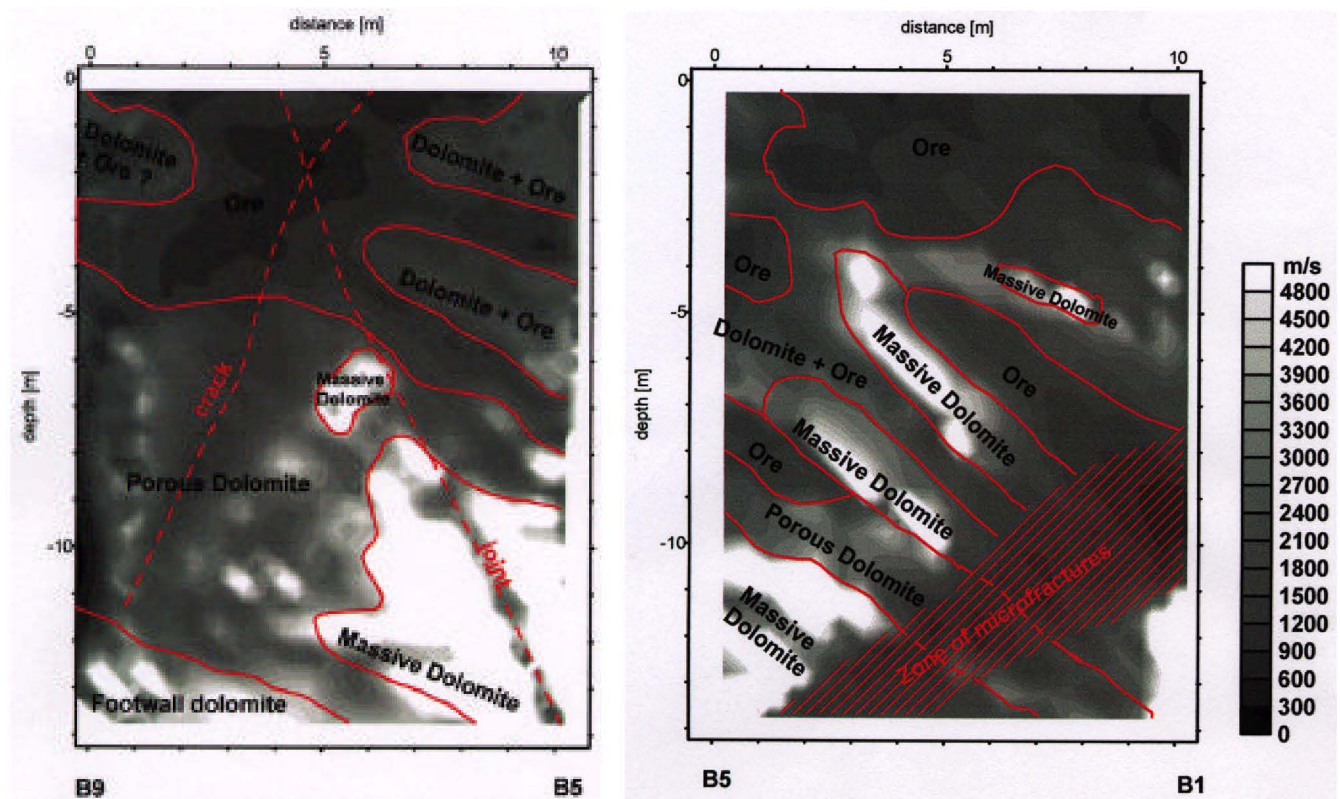


Fig. 5 Tomographic results after 20 SIRT-iterations with geological interpretation between drill-holes B1, B5 and B9

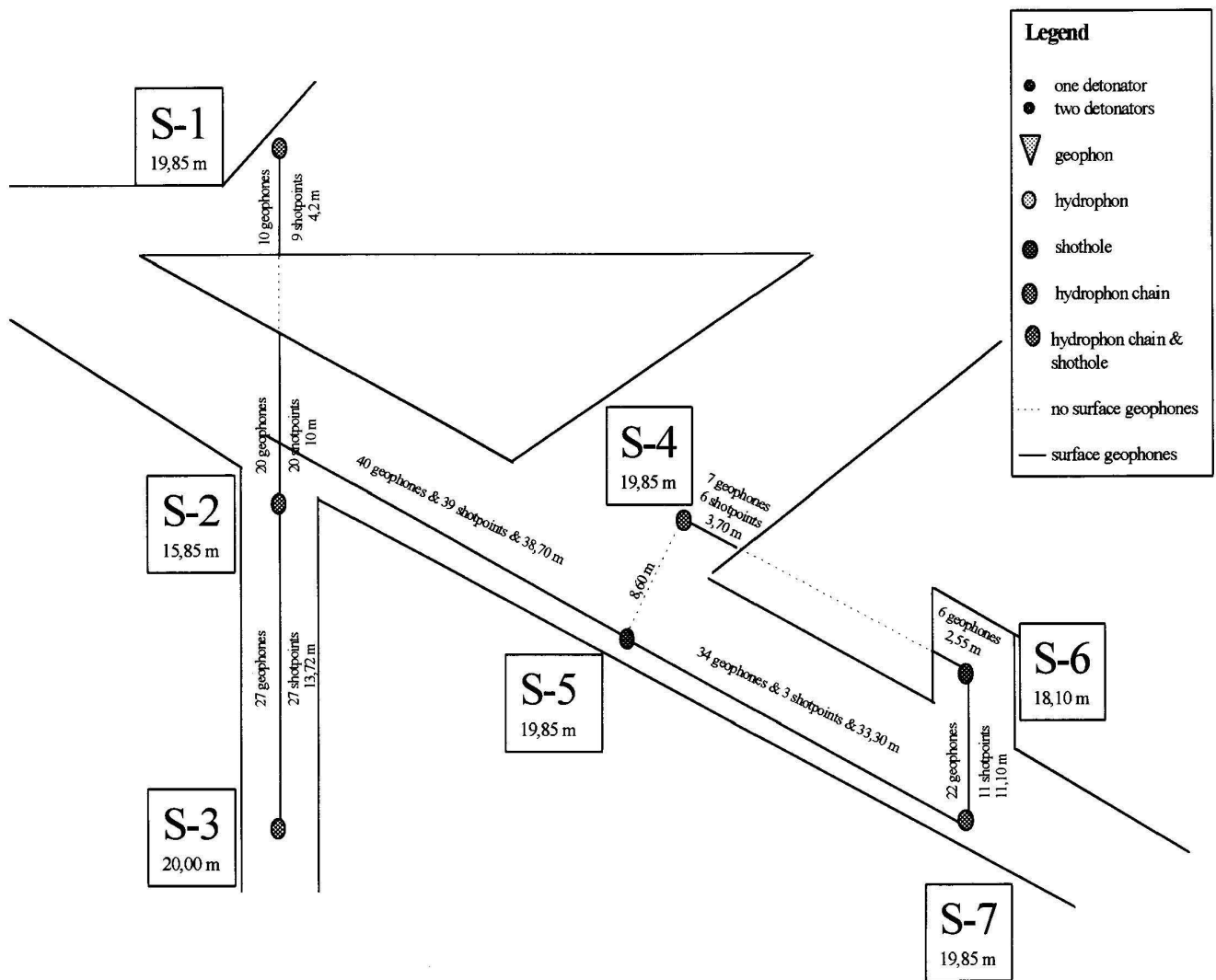


Fig. 6 Reocín underground mine, drill-hole locations

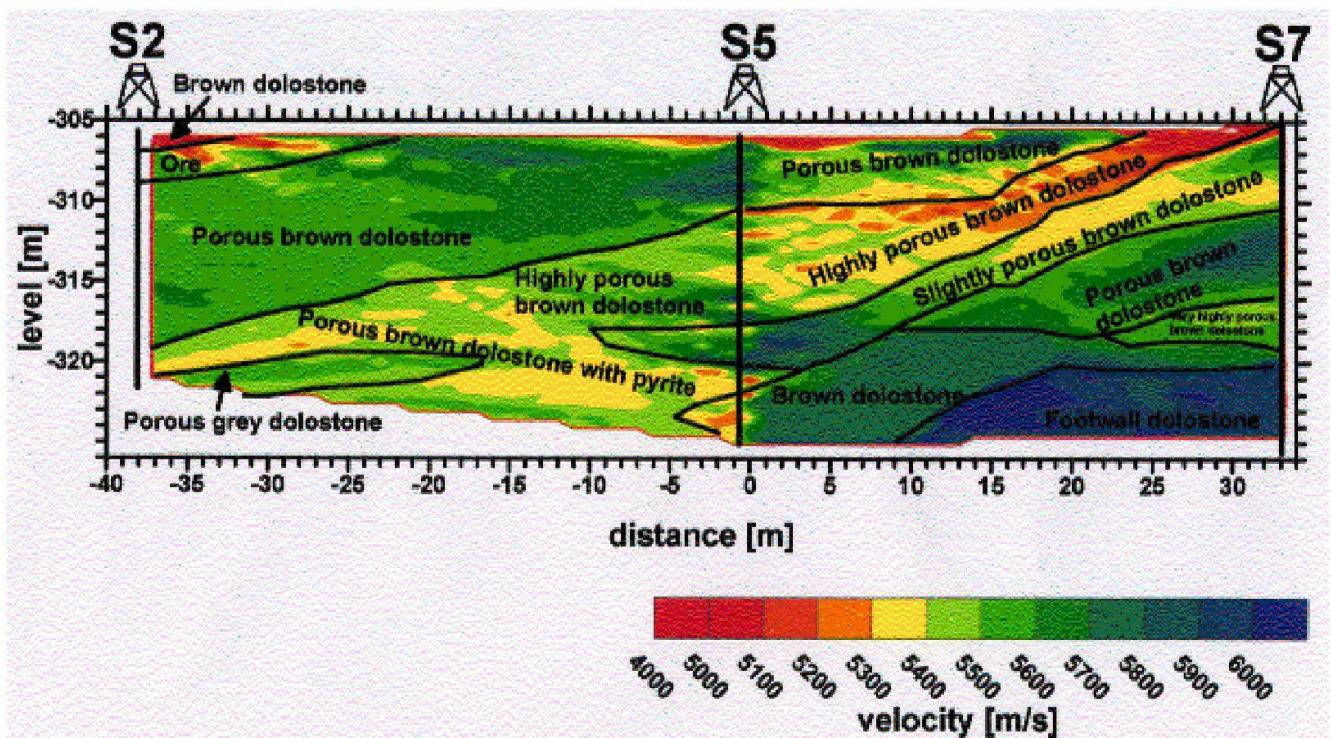
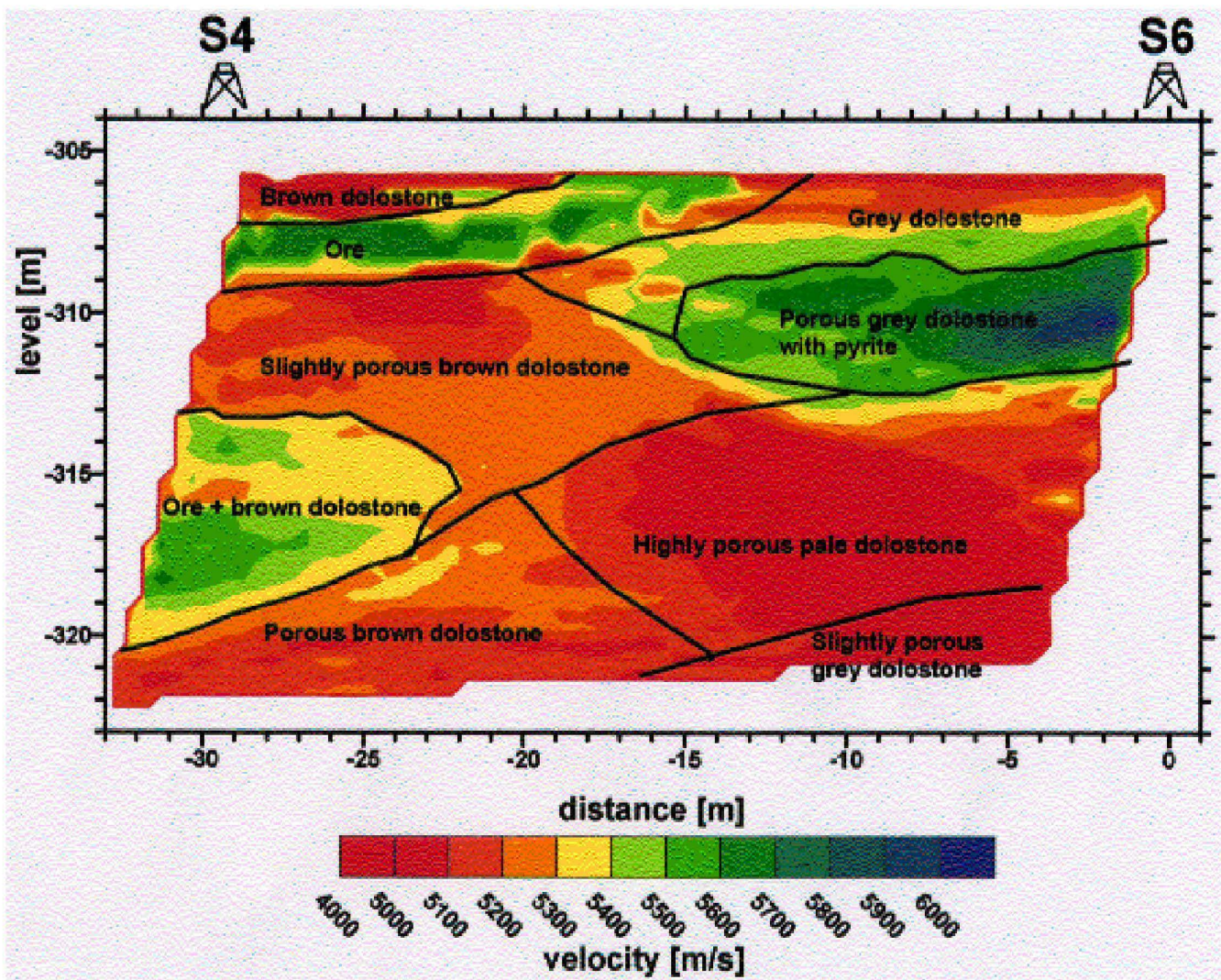


Fig. 7(a)



(b)

Fig. 7 Tomographic results between (a) drill-holes S2, S5 and S7 and (b) drill-holes S4 and S6

diameter of 61.2 mm. The holes intersected porous dolomite, zinc-lead ore and massive footwall dolomite.

In total approximately 35 000 seismogram traces were recorded with four prototype SUMMIT-Compact strings for the borehole receivers and up to 50 receiving units (one chan-

nel) along the drive floor between boreholes. The locations of sources and receivers were chosen to provide dense ray coverage over the zone of interest, which is essential to obtain a reliable velocity image.

The tomographic results were very satisfactory (Fig. 7) and

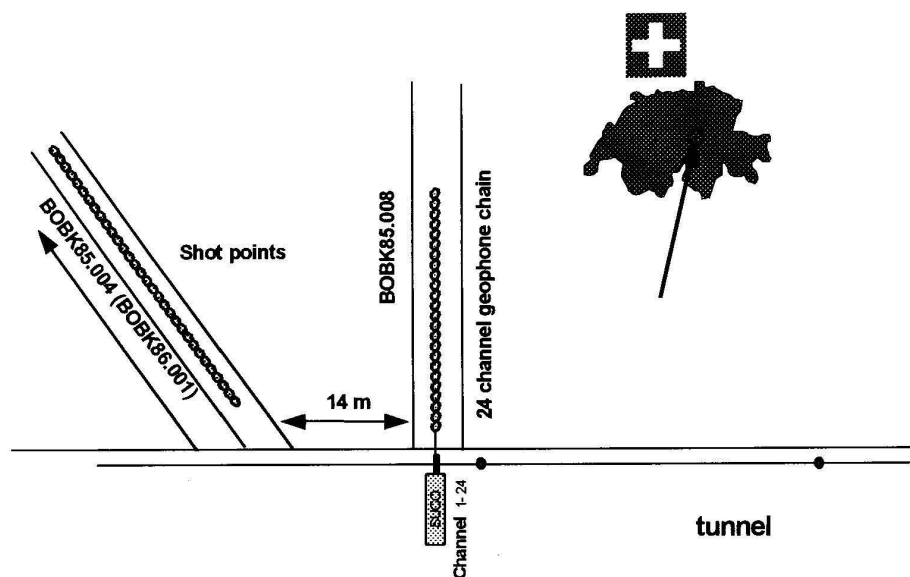


Fig. 8 Grimsel rock laboratory, field geometry of tomographic survey

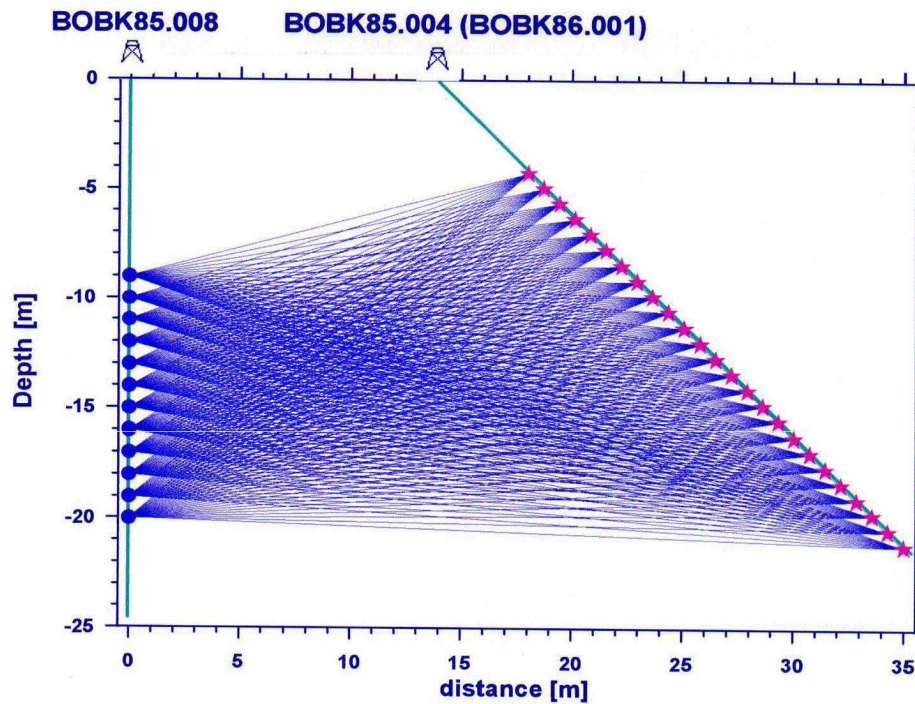


Fig. 9 Ray distribution of seismic tomography

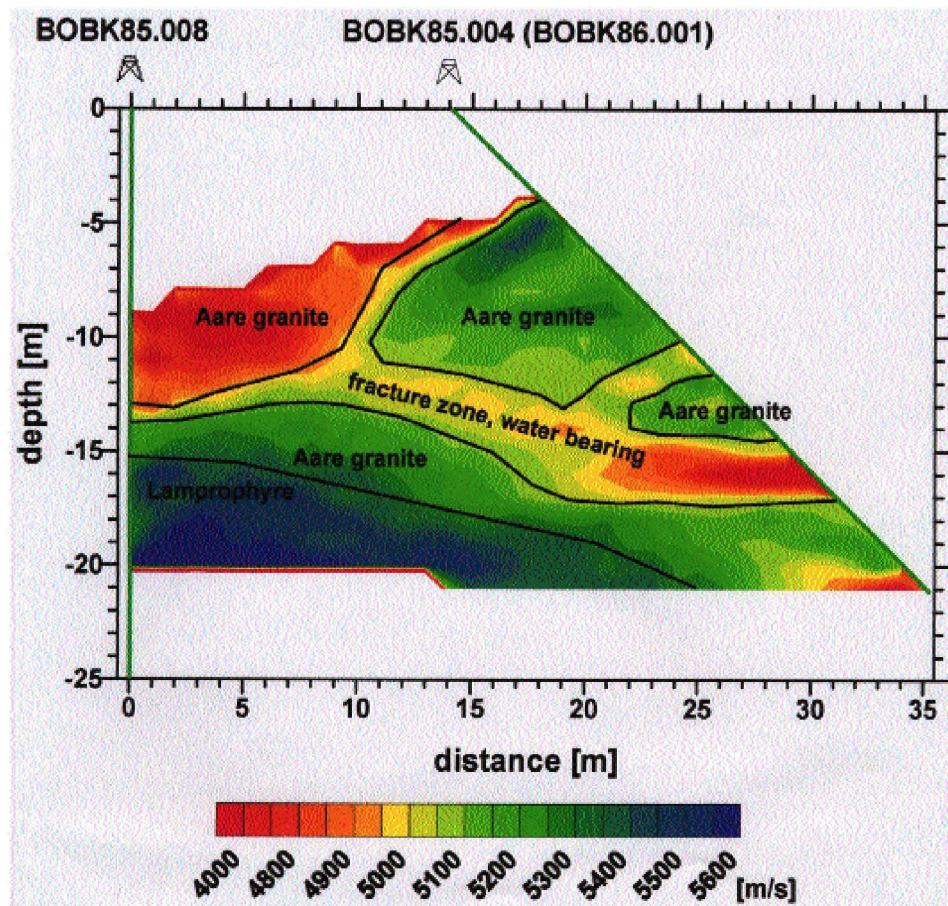


Fig. 10 Seismic tomogram, Grimsel, NAGRA

showed the distribution of different rock types, such as ore and porous brown and pale-grey dolomite, in more detail than was possible previously from geological mapping and cuttings or cores of the drill-holes. Furthermore, a good cor-

relation was found between the seismic tomographic results and those from the drill-hole logs. The survey confirmed that seismic tomography can be very effective for closely spaced surveys in underground wet conditions.

Grimsel lock laboratory

The Grimsel rock laboratory is an underground test facility of Switzerland's Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA) and is sited in massive granitic rocks. One survey was carried out at Grimsel and the objective was to detect zones of potential radioactive waste leakage within the crystalline rocks. Test facilities for the project were provided free of charge by NAGRA.

Two horizontal underground drill-holes were used for the survey (Fig. 8), with 25 seismic detonators spaced 1 m apart in the first drill-hole and a chain of 24 receivers that extended in pairs for 11 m in the second drill-hole. The seismic signals were recorded by 24 channels and a total of 600 seismogram traces were recorded on hard disk.

Fig. 9 shows the ray distribution with straight lines between the shot and receiver positions and represents the signals of one shot. Channels 1–12 are the vertical geophone and the others are the horizontal geophones in borehole BOBK85.008. The recordings of direct waves at frequencies of up to 2000 Hz were followed by various later arriving signals, which included S-waves and reflected/refracted waves.

Data interpretation was carried out by DMT and NAGRA personnel working together in Bochum and the results were of high quality. The seismic velocity distribution coincided very well with information available from drill cores, ultrasonic borehole measurements (e.g. full-wave sonic) and other rock testing methods.

The tomogram between the two drill-holes is shown in Fig. 10 and the velocity range is 4000–5600 m/s. Well-defined low-velocity zones cut across the rock mass at two angles, and these represent fracture systems that could allow leakage from stored radioactive waste. The survey demonstrated clearly that the tomographic technique is capable of providing important information for radioactive waste disposal and similar projects that is unobtainable by any other technique.

Reocin exploration area survey

The exploration area surveyed is located approximately 5 km from Reocin mine and contains a zinc sulphide orebody at around 500–525 m depth in the form of a gently inclined layer about 3 m thick. The host rocks are dolostone with thin marly layers.

Three surveys were carried out with the prototype SUMMIT-Compact, first to calibrate the system and then to test its effectiveness in detecting fault systems and the presence of mineralization.

A diamond drilling programme of holes targeted to depths of around 600 m was undertaken with the holes located along strike and downdip of the orebody in a configuration suitable for three-dimensional tomographic work. The holes were intended to penetrate at least 50 m below the ore to ensure an optimum number of seismic ray paths in the ore zone.

Major problems were encountered during drilling because of the karstic character of the dolomite and the presence of soft, unconsolidated, sandy material in the upper parts of the holes and in karstic cavities. All the holes had to be supported with steel casing during drilling, but such casing affects seismic wave transmissions; PVC or similar casing had, therefore, to be inserted inside the steel casing so that the latter could then be withdrawn. Removal of the steel casing was commonly obstructed by soft material packing the hole and this caused frequent breakages in either or both the steel and PVC casing. The result was that of six holes drilled for the project, only two, located 100 m apart, could be used for the surveys.

The seismic testwork involved firing seismic shots at various depths in one hole (E675) with special seismic detonators

plus up to 900 g of seismic gelatinous explosive. The second hole (E674) contained a hydrophone cable with 72 receiving channels and the surface layout comprised up to 100 receiving units in two lines, as shown in Fig. 11.

The prototype equipment performed well, but the overall results were poor because, for the most part, the hydrophones received only weak seismic signals or no signals at all. The disappointing results were attributable to a number of operating problems. (1) There was continual water leakage from joints in the PVC casing, which reduced the effectiveness of the hydrophone string in the receiving drill-hole. (2) The explosive charges had to be limited to two detonators and 900 g of Pentrite explosive or the casing would fracture and render the hole useless. (3) The coupling between the PVC casing and the wallrock was poor because of fractures and cavities in the karstified dolomites, and this affected seismic wave transmissions. (4) The dolomitic rocks proved to be markedly unsuitable for seismic work because they contained numerous cavities and joints (on average at 20-m intervals), which seriously reduced the strength of the seismic signals. (5) Given that this was an experimental research programme it would have been better, in retrospect, to concentrate the seismic work on a specific level around the known ore at a depth of 500–520 m rather than survey the entire hole.

The testwork confirmed that the seismic equipment works well and was able to record some strong signals, but the amount of data was insufficient for interpretation and this was a direct result of the character of the karstified dolomites. There is every possibility that the tomographic techniques would work successfully in deep drill-holes that penetrated unweathered massive rocks, such as granites or metamorphics.

Ruhrkohle AG surveys

Three small surveys were carried out at Ruhrkohle AG sites near Duisberg, Germany, to calibrate and test the SUMMIT-Compact system, particularly the equipment, before and after the surveys in Spain. Ruhrkohle AG provided test facilities for the project free of charge and the tests were carried out in several drill-holes that cut coal-bearing sedimentary strata, including sandstones and shales, to depths of between 70 m and 1500 m. No detailed data processing or interpretation was undertaken.

In the first test two drill-holes 24 m apart were used for seismic shots and hydrophone receivers. A line of surface geophones extended between the two holes. The results showed a strong signal reflection from the bottom of the receiving hole and a layer interface at a depth of 6 m (Fig. 12). These data represent specific clay-sandstone interfaces and showed that the prototype equipment was operating satisfactorily.

The second and third surveys were mainly to test the 600 m long hydrophone cable, which weighed 320 kg, and they were carried out in a drill-hole 1500 m deep. Stretching and tension in the cable can affect the hydrophone receivers and the testwork was to establish the importance of such effects. In fact, the results showed that the cable operation was unaffected (Fig. 13).

Matrix porosity, fluid inclusion and isotopic studies

Other studies were carried out to support the seismic work by providing specific information on rock characteristics and also to provide data for a metallogenic model of the Reocin zinc-lead orebody.

Matrix porosity measurements were of direct use for the seismic interpretation. This work showed that the matrix porosities of individual rock types, such as dolostone, sandstone and zinc-lead ore, are regular throughout the Reocin area but are likely to decrease with depth because of infilling of pores and fractures by unweathered anhydrite.

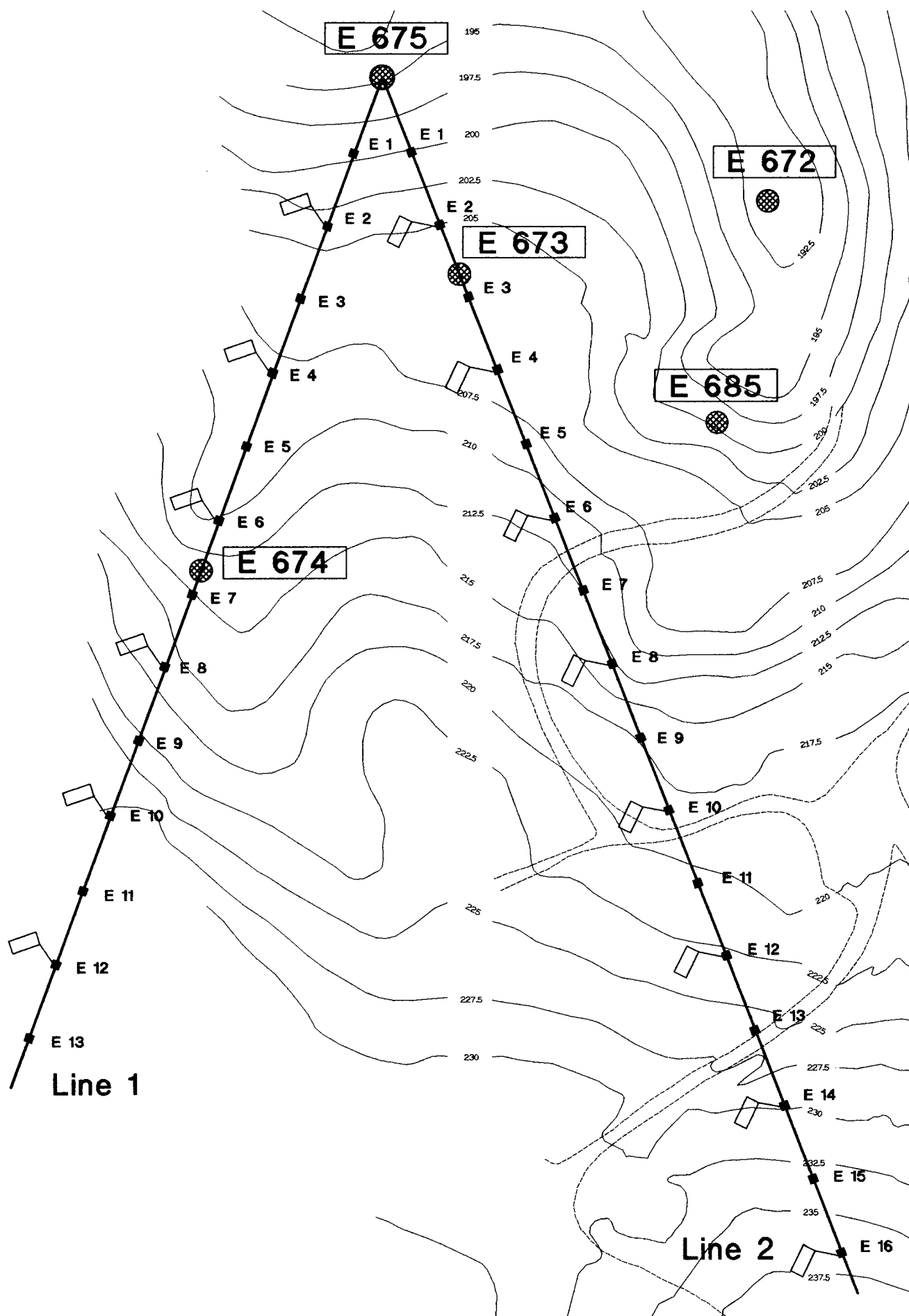


Fig. 11 Reocin exploration area, location of drill-holes and surface receiver chains

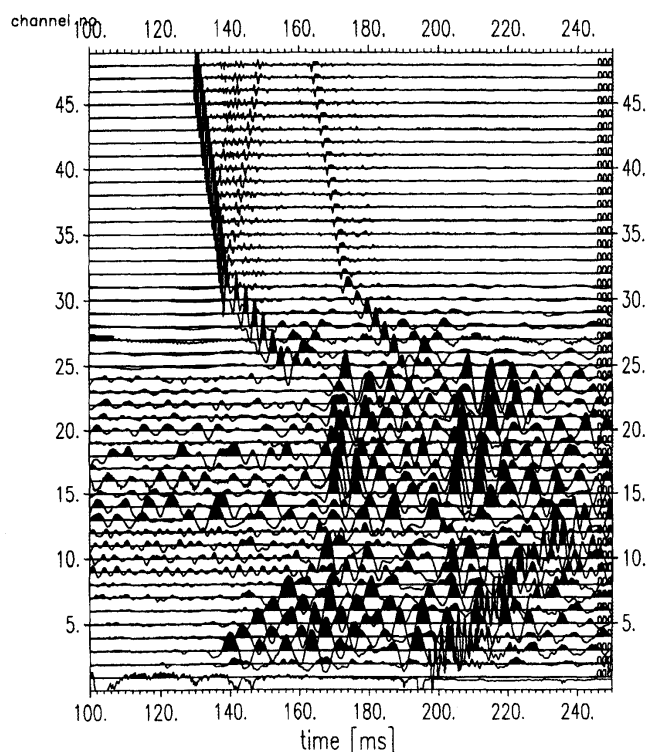


Fig. 12 Ruhrkhole AG survey, raw seismogram showing clay-sandstone interface at 6 m depth

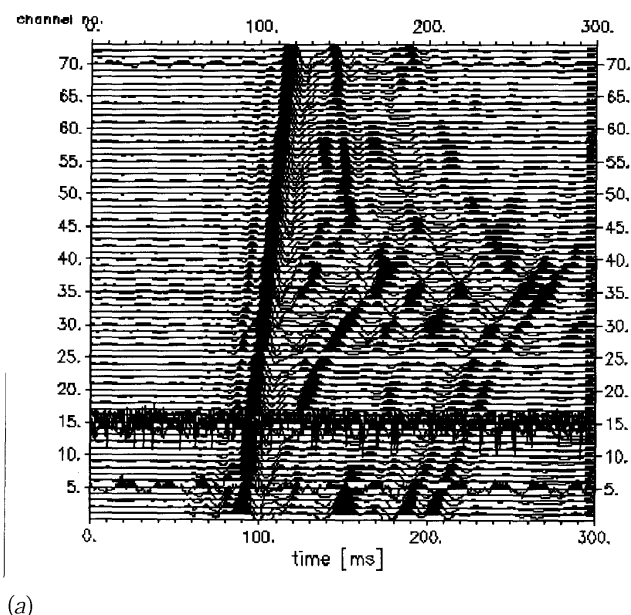
Petrographic, fluid inclusion and isotope data were obtained that suggest that the main phase of zinc-lead mineralization at Reocín is syngenetic-diagenetic and results from a single hydrothermal event, which consisted of at least three pulses. The temperatures of the mineralizing fluids were around 200–300°C close to hydrothermal vents in the Santillana Syncline and decreased to less than 100°C within a few hundred metres. Pathways of fluid migration and ore deposition are indicated by dolomites with high fluid inclusion salinities.

Discussion of results

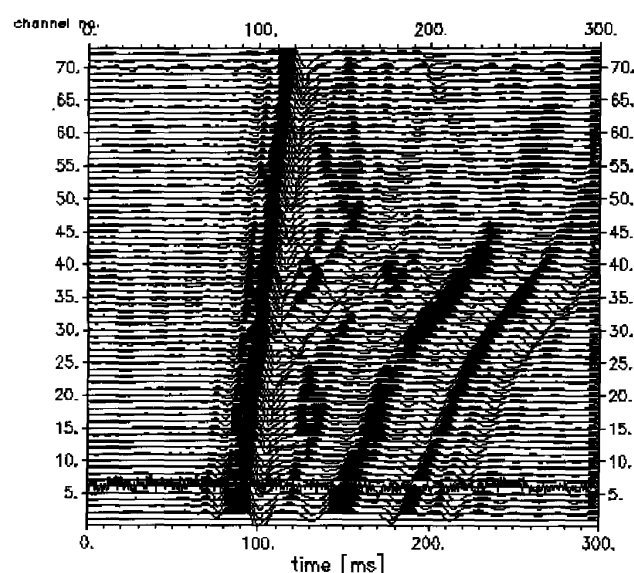
In the principal undertaking of developing an effective prototype seismic tomographic system the project made good progress, which culminated in a marketable product. There was a logical flow of activity, from use of the older SEAMEX system to establish field operational and prototype design requirements to development and testing of the new prototype SUMMIT-Compact system. Similarly, the geoscientific work on rock porosity and ore genesis made steady progress and contributed to interpretation of the seismic data.

Field tests showed that the prototype equipment and software performed well and gave excellent tomographic results in the small-scale surveys at Reocín mine and the Grimsel rock laboratory. The technique is clearly effective for short-hole operations of the type required in many civil engineering projects, such as dam construction, in radioactive waste disposal projects and to tackle specific mining problems. It is also very well suited for the non-destructive testwork required in projects concerned with radioactive and other waste disposal or the underground storage of liquids, such as petroleum.

The exploration testwork failed because the signals were too weak in deep drill-holes 100 m apart, and this was because of the jointed and karstified character of the dolomites, which caused drilling problems and reduced the strength of the seismic transmissions. There is a strong possi-



(a)



(b)

Fig. 13 Ruhrkhole AG survey, raw seismogram showing test measurement with hydrophone cable (a) before and (b) after tomographic survey of Reocín exploration area. Similarity between seismograms shows that cable has not stretched significantly during testwork in the Reocín 550 m deep drill-hole

bility that the results would have been good in different geological environments and future research would be valuable in such environments as the Scandinavian Shield and the Spanish-Portuguese Pyrite Belt.

The following specific operational problems were encountered during the project. (1) Deep drilling problems in the exploration area were caused by the unstable character of the enclosing karstified dolomite and sandy beds, which required casing during both the drilling and the seismic work. The process of replacing steel casing by PVC tubing became complex and time-consuming, but was unavoidable for strata of this type. (2) Data processing in the early stages of the project was more time-consuming and complex than expected because of the large volume of data. The first survey undertaken, in the Reocín open-pit, produced more than 22 000 seismic traces and 88 000 000 data points and there were no computer programs to handle this volume. New programs

were written as part of the SUMMIT-Compact software and were used successfully throughout the rest of the project. (3) The detonators used in the Reocín open-pit survey were supplied by the mine and are known as 'zero delay' detonators in mining circles. In fact, their trigger times vary between 10 and 40 ms and the precise time varies from shot to shot. This caused considerable difficulties in the seismic interpretation. The problem was addressed by the acquisition of special detonators with a maximum trigger delay of 2 ms for all later surveys.

The matrix porosity, fluid inclusion and isotopic studies continued throughout the period and provided data for both the seismic data interpretation and the metallogenic modelling. The matrix porosity work showed that porosity will decrease with depth owing to pore and joint filling by unweathered anhydrite, whereas the fluid inclusion and isotope studies indicated that the Reocín zinc-lead orebody is a variant of the SEDEX type of deposits.

Further research is warranted to develop the tomographic technique towards greater penetration and resolution and to test the SUMMIT-Compact system in more suitable geological environments. The SUMMIT-Compact system is technically highly advanced and tomography has considerable potential as an exploration tool, but further research is needed to make it effective.

Specifically, deep drill-hole seismic tomography tests directed at different types of mineral target should be carried out in a variety of locations favourable for seismic response. Examples are the German or British coal-bearing strata, the sulphide bodies of the Pyrite Belt in Spain and Portugal and exploration for base-metal bodies in the Scandinavian Shield.

Conclusions

The achievements of the project include: (1) development of the prototype SUMMIT-Compact system to the point at which it can be refined and marketed worldwide for seismic tomographic surveys; (2) successful testing of the SUMMIT-Compact system in tomographic surveys at the Reocín underground and open-pit mine in Spain, the Grimsel rock laboratory for radioactive waste disposal in Switzerland and two Ruhrkohle AG sites in Germany; (3) demonstrations that the tomographic technique can produce high-quality results in small-scale surveys from holes drilled from the surface or underground and in wet or dry conditions; (4) definition of the problems associated with the use of seismic tomography in mineral exploration for deep orebodies and an indication of rock environments where the technique could be effective; and (5) completion of matrix porosity, fluid inclusion and isotopic studies, which provided support for geological interpretation of the seismic data.

The tomographic technique proved highly successful in short-hole surveys in the Reocín open-pit, the Reocín underground mine and the Grimsel underground rock laboratory. In all three cases the distance between the shot holes and the receiving holes was not more than about 30 m, but it should be possible to extend this distance as more experience is gained with the technique. The technique has good potential for use in the civil engineering, mining and radioactive waste disposal industries—in particular, for projects that require non-destructive testwork.

The exploration area testwork failed because the seismic signals were too weak in deep drill-holes located 100 m apart. This was due mainly to the jointed and karstified character of the dolomites, which reduced the strength of the seismic transmissions. The seismic equipment operated well and there is a strong possibility that the results would have been good in more suitable geological environments. The tech-

nique has considerable potential for exploration for deeply buried large sulphide orebodies in such geological environments as the Scandinavian Shield and the Spanish-Portuguese Pyrite Belt.

Changes in emphasis and timing arose during the project in response to the need to develop new software to handle unexpectedly large volumes of data, unforeseen problems with drilling and casing in the exploration area and the need to waterproof the SUMMIT-Compact equipment for use in the wet conditions underground at Reocín.

The main objective of developing and testing a prototype seismic tomographic system was achieved. Subject to a small amount of additional refinement, the SUMMIT-Compact seismic system will be on sale worldwide and sales are expected in the mining, civil engineering and radioactive waste disposal industries. The main problems for use of the system in mineral exploration have been established and there is a substantial market once these have been overcome.

Seismic tomography is a rapidly developing technique and further research is warranted to improve the resolution of the system and to test the SUMMIT-Compact system in deep exploration drill-holes where the geology is favourable for seismic wave transmission. Research is also needed to improve the explosive power of charges in small-diameter holes to increase seismic wave penetration without rendering the holes unusable and to improve the techniques for processing very large volumes of seismic data.

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