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**DEVELOPMENT OF HIGH RESOLUTION SEISMIC METHODS
TO LOCATE DEEP SEATED BASE METAL OREBODIES**

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DEVELOPMENT OF HIGH RESOLUTION SEISMIC METHODS TO LOCATE DEEP SEATED BASE METAL OREBODIES

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ABSTRACT

The research project, under the auspices of the CEC Brite-EuRam Programme, aimed to develop a three dimensional high resolution seismic system suitable for mineral exploration and development. The final objective was a prototype system of hardware and software capable of defining structures and possibly detecting sulphide mineralisation at depths up to 1,000 m below surface.

The start point for prototype design was the SEAMEX (Seismic Apparatus for Mining and Exploration) system used extensively in the coal industry. The SEAMEX system employs up to 120 Remote Units, each with two geophones, and feeds data from 240 channels to a Central Control Unit.

Prototype development involved design and construction of high resolution equipment and development of new signal acquisition and control software. The final version of the prototype, named SUMMIT, has a data transmission rate ten times faster than SEAMEX, a large dynamic range from up to 1,920 channels, and significantly improved data resolution. The SUMMIT system is the most advanced of its type in the world and has won two German design awards.

Four field surveys were carried out over part of the Navan zinc-lead orebody in Ireland at a location where ore lenses occur at around 650 m below surface in gently inclined limestone strata cut by major faults. The first survey used the “ SEAMEX system whereas the following three surveys used progressively improved versions of the prototype SUMMIT system. To support the seismic interpretation, a total of 14,352.9 m of diamond drilling was completed for the project comprising 20

drill holes to a maximum depth of 847.2 m and down hole surveys were carried out to log rock density, resistivity, natural gamma responses, sonic responses and conductivity in 5 deep holes to depths up to 800 m.

Data from the SEAMEX survey was low resolution, but there was a marked improvement using the prototype SUMMIT system and data interpretation improved correspondingly. Deep drilling was used as a control throughout the project and the final interpretations were based on a combination of seismic and drilling data. Significant geological structures, including faults and unconformities, were identified and in some cases plotted in three dimensions.

The information on faulting proved particularly useful for exploration and development activities at Navan. The seismic data showed clearly that both the major and minor faults which control ore disposition behave unexpectedly at depth, in some cases splitting, curving and joining together. This type of variable fault geometry cannot be detected by drilling alone and is of considerable importance for selecting drill targets at depth.

The zinc-lead orebodies in the areas surveyed proved too small and laterally impersistent for confident detection. There is, however, a strong possibility that the Navan sulphide ore bodies would have been identified if the surveys had been carried out over the main part of the orebody. The results indicate that the method has potential for exploration in areas such as parts of the Pyrite Belt in Spain and Portugal, where the mineralisation is in massive bodies or sheets and there is no significant glacial overburden.

Future research should concentrate on improving seismic data processing techniques to produce detailed interpretation at specific depths, combining surface seismic surveys with refraction seismic techniques and down-hole seismic surveys in order to maximise useful data generated by a single seismic field survey, and creating broad images of the geology at depth for regional mineral exploration in the way that the method is applied in the hydrocarbons industry.

INTRODUCTION

Deep penetration geophysical methods are essential for exploration in the main ore fields of Europe, such as Ireland, where potential targets can be expected at depths over 500 metres below surface. Seismic reflection methods are used in the hydrocarbon and coal industries, but have rarely been applied in mineral exploration due to problems with interpretation and cost. Exploration for large orebodies depends heavily on deep diamond drilling, which is high risk and expensive, and any geophysical method which can define targets at depth is of considerable importance in terms of exploration success and cost savings.

On this basis, Tara Prospecting Limited (Ireland), Deutschemontan Technologies (Germany) and the TNO Institute for Applied Geophysics (The Netherlands) considered that research within the frame of the Brite-EuRam programme was warranted in order to develop a prototype high resolution seismic system capable of providing information for exploration and mine development in complex hard rock situations. No such seismic system was available for commercial usage at the start of the project. The final product was envisaged as a prototype seismic system fully tested in field surveys and requiring only a small amount of refinement for commercial sales. Specific objectives were to;

- design and construct a prototype high resolution system of hardware and software capable of detecting mineralisation and defining geological structures at depths up to 1,000 m below the land surface,
- test the system using profiling and 3D configuration field layouts over a drilled part of the Navan zinc-lead orebody in Ireland,
- undertake full-scale seismic surveys over ground with mineral potential, and
- support the seismic work with diamond drilling and geological interpretation.

TECHNICAL DESCRIPTION OF THE PROJECT

The project had three main stages; concept development, prototype development and tests, and full systems tests. These involved reviews and assembly of relevant data, establishing technical parameters and field operational procedures for the

prototype system, constructing the prototype hardware and software, and undertaking field tests to evaluate the effectiveness of the new system. The main aspects are described below.

Prototype Development

Currently available seismic systems fall into two main categories; inexpensive small-scale refraction systems with a restricted range of applications and large telemetry reflection systems which are versatile, but highly expensive and difficult to adapt to mineral exploration.

The start point for prototype design was the SEAMEX (Seismic Apparatus for Mining and Exploration) system developed by DMT in 1991 which combines both categories by recording refraction and reflection data whilst retaining mobility and relatively low-cost operation. The SEAMEX system consists of:

Power Supply: usually Ni-Cd batteries with an operating life around 6 hours, but other power units can be used for surface surveys.

Central Control Unit: a video monitor, floppy disc drive and microprocessor system housed in a light transit-type vehicle for surface work.

Remote Units: each unit containing an analog board, a digital board, connections for two external geophones and microprocessors which control preamplifiers, filters, multiplexer, instantaneous floating point amplifiers, and data memories.

For conventional surveys, up to 120 Remote Units are sited at regular intervals (say 12 metres) and connected to each other and to the Central Control Unit by pulse code modulation cable. Two geophones feed each Remote Unit with data from small controlled explosions in shallow drill holes or from drop-weight impacts. The data are stored temporarily in the Remote Units and retrieved sequentially from them by the Central Control Unit.

The SEAMEX system was designed primarily for coal mining where the strata tends to be flat-lying and the structure is relatively simple. Mineral exploration in hard rock

situations has different problems, with smaller targets, rapid changes of rock type and complex structures.

Prototype development involved re-design of the SEAMEX system, development and assembly of remote units, and development of acquisition and control software. The first field test, over part of the Navan zinc-lead orebody (Survey A1), used the SEAMEX system and was carried out to establish parameters for the prototype instrumentation and software. Design specifications for the new system, named SUMMIT, were then drawn up, the first prototype instruments were constructed and new software was written for low-level communication between the Remote Control and Central Control Units. Laboratory tests were used to assess the effectiveness of the instruments and new communications system.

Subsequent field surveys (A2, B and C) used the prototype SUMMIT system and modifications were made following each field test. In particular, the software was optimised and traceview methods together with user dialogue were refined using laboratory tests. Modifications to the system included refining geometry definition and increasing the speed of display utilities.

A total of 80 Remote Units were constructed for the first field test using the SUMMIT system (Survey A2), with each Remote Unit handling data from two geophones. The number of Remote Units was increased subsequently during the project to 130 and then 283, all handling data from at least two geophones and feeding a single Central Control Unit. Each Remote Unit sets the gains, amplifies, digitises, correlates and stores the data until ordered to transmit it digitally to the Central Control Unit and this gives the system high noise immunity.

The new package of hardware and software was designed to record accurate data with a large dynamic range from up to 1,920 channels. The final version of the prototype SUMMIT system has a data transmission rate ten times faster than the SEAMEX system and an improved resolution of up to 24 bit instead of 16 bit. Cross units were designed to allow 3D field layouts and repeater units which allow theoretically unlimited line lengths. Technical specifications for the SUMMIT system are shown in Table 1.

PC-Version:
Operating System
 MS-DOS or compatible from Ver 5.0

Hardware Requirements
 Harddisk, one full size expansion slot
 VGA color display, minimum 286 processor, 640 kByte RAM

Software Capabilities
 Main menu items are selectable via function key. Full graphics spread information. Auto-check of all input values. Variable scaling of data traces. Full spread control and preview. 2D and 3D version.

1. Menu Items
 Initialization, Read, Save, Display Data, Plot Data, Noise Monitor, Trigger Enable/Disable, Test Mode, Stack Mode, Spread Wake/Sleep, Monitor Spread, System Quality, Roll Along/3D Layout Preview

2. Test Functions
 Sine 1, Sine 2, Pulse Sep, Instrument Noise, Geophone Test, Broken Cable Test, Active/Passive Boxes, Roll-Along Preview

Software Limits
 up to 12 Lines, maximum 480 channels

Storage
 after every shot or after stacking onto harddisk

Data Format
 SEG-2

Wof?K-STATION-Version
Operating System
 SunOS 4.13 and later

Hardware and Software Requirements
 36 Mbyte RAM, 600 Mb Harddisk, X-Windows, OSF-Motif Libraries, Ethernet via TCP/IP protocol, Color Graphics Monitor

Storage
 Harddisk or/and tape via SCSI interface SEG-Y format

Software Modes
 impulsive source, Vibroseis

Software Capabilities
 3-component recording
 2D and 3D mode
 3 D grid display
 gain settings
 VA/WT display
 zoom full windows
 system parameter control
 intuitive user interface
 full spread control
 user module implication possible

System Tests
 sine, pulse, internal step noise
 geophone step, power status

Handheld Telemetry Computer (HTC)

Case
 Waterproof housing, shock resistant, immine-safe, LCD display

Battery
 NiCd batteries, for 60 hours continuous operation @ 20°C

Plug
 waterproof, can be connected under water, mud and dust resistant

Weight
 1 kg

software
 positions a SUMMIT Remote Unit in LINE #, STATION#, offset inline, offset offline coordinates, reset function

Protocol
 RS232 Interface

Cross Unit (CU) Distribution Unit (DU) Repeater (RP)

Case
 as SUMMIT Remote Unit

Color
 Red/Blue to differ between recording unit and CU, DU or RP

Mode
 Programmable via HTC to set mode to be either CU, DU or RP

Battery
 80 hours continuous operation @ 20°C

Line Control Unit (LCU)

Input
 LIP to 16 channels from 16 DU lines

Connectors
 SCSI (for tape device), Ethernet for workstation

Power Consumption
 220 V, 50 Watt

Line Terminator (LT)

120 Ohm resistor with CLICK&ON technique

One-Channel Remote Unit (RU)

Capacity
 maximum 5760 channels (all sampling rates) on max 16 lines with max 360 RUs each line

Line Length
 max 250m between R? and RP
 max 250m between LCU and DU
 max 250m between DU and RP
 max 250m between LT and RP
 m principal, the length of one line is not limited having a RP every 250m

Sampling Rate
 0.25, 0.5, 1, 2, 4, 8 ms
 up to 0.125 ms for Summit Compact

Record Length
 512, 1024, 2043, 4096, 8192 or 15192 sampling points in Vibroseis and Dynamite mode

Calibration
 Automate Gain Control

Correlation
 directly in Remote Unit

Stacking
 directly in Remote Unit

System Resolution
 16 bits plus oversampling
 24 bits @ 2ms sampling Rate

Dynamic Range
 132 dB @ 0.25ms Sampling Rate
 DOUBLE-DYNAC oversampling

Equivalent Input Noise
 smaller than 0.5µV RMS
 @ 2-2000 Hz

Maximum Input Signal
 2.0 Volt RMS

Gain Accuracy
 smaller than 1%

Crossfeed
 Not Applicable N/A

Distortion (TDH)
 better than 0.01%

Input Inductance
 4,7 kOhm

Analog Anti-Alias Filter
 2 kHz 6dB/octave

Analog Low-Cut Filter
 not necessary

Digital Anti-Alias Filter
 2 kHz @ 0.25ms sampling rate

1 kHz @ 0.5ms

500 Hz @ 1ms

250 Hz @ 2ms

125 Hz @ 4ms

62,5 Hz @ 8ms

Rejection at Nyquist Frequencies
 -125dB

Passband Ripple
 +/-0.04 dB

Common Mode Rejection Ratio
 greater than 100 dB

Operating Temperature
 -30°C to +70°C

Humidity Range
 0-100%

Dimensions (HxWxD)
 21x-22x7 centimeters
 (8.3x8.7x2.8 inch)

Weight
 less than 3kg

Battery
 NiCd cells rechargeable, more than 70 hours continuous operation, more than 40 hours for Vibroseis @ 20°C
 Batterys are rechargeable in 10 hours.

Build-in battery processor monitors the battery and stores following information:

battery voltage
 number of charge cycles
 defect cells
 SUMMIT temperature

Storage
 -30°C to +70°C
 Remote Units can be stacked onto each other.

Status lights
 Low Power LED lights green and red for status indication

Connectors
 Geophone or String Connector
 Line Concession position variable through CLICK&ON technique
 Hand-Held Connector for telemetry Input
 All connectors are waterproof and can be connected under water
 Connector plugs are dust and mud-resistant without cap

Cables
 Simple low cost Two-Conductor cables for CLICK&ON technique

Case
 DROP&PICK solid plastic housing
 100% waterproof, deployable in any surface environment

Test Functions
 System dynamic Range
 Equivalent Input Noise
 Sine Wave - System Pulse Test
 System Step Test - Geophone Test

Typical Shot-Intervals
 30 seconds
 @ 1ms sampling rate, 2K trace length with 256 channels including tape storage using an LCU

Mine Safety
 on request

Table 1. Specifications of the prototype SUMMIT system

Field Tests

Geology *of the Navan Orebody*

The Navan zinc-lead orebody occurs as a series of superimposed, generally stratiform sulphide lenses within a sequence of gently south-west dipping Lower Carboniferous limestones (Fig. 1). The main lens complex is confined to a 2CJ0 m thick limestone unit known as the Pale Beds and the complex extends down-dip from the surface for at least 1 km with an overall width of 500 m. Individual sulphide lenses vary in thickness from a few centimetres to 10 m.

The ore is formed predominantly of sphalerite and galena with subsidiary amounts of pyrite, marcasite, barytes, dolomite, calcite and rare sulphosalts. It may be massive or disseminated and displays a great variety of mineral textures including layering, coarse grained intergrowth, brecciation and crustiform veins. The mineralisation appears to have been emplaced in relatively unconsolidated sedimentary rocks during the Lower Carboniferous by migrating hydrothermal solutions.

The mineralisation is influenced by several sets of major faults, some of which appear contemporaneous with ore formation and others which are clearly later and offset individual orebodies. In addition, the larger orebodies occur below pre-ore dolomitic layers within the Pale Beds which seem to have acted as local barriers to upward migration of the mineralising fluids. Within the Pale Beds, there are local layers with significant quantities of quartz sand or darker argillaceous material which form important stratigraphic markers and guides to the ore lenses.

The deposit is overlain by a thick sequence of interbedded limestones and shales which, near the land surface, have been subjected to Tertiary and/or Quaternary Palaeo-karst weathering resulting in an irregular surface with sink-holes up to 100 m deep. This irregular topography is buried beneath unconsolidated Quaternary sediments that fill the sink-holes and cover the bedrock beneath 5 m to 15 m of fluvio-glacial deposits. The present land surface is gently rolling farmland crossed by the River Boyne with small tributary streams.

TARA PROSPECTING LTD.
Navan Orebody

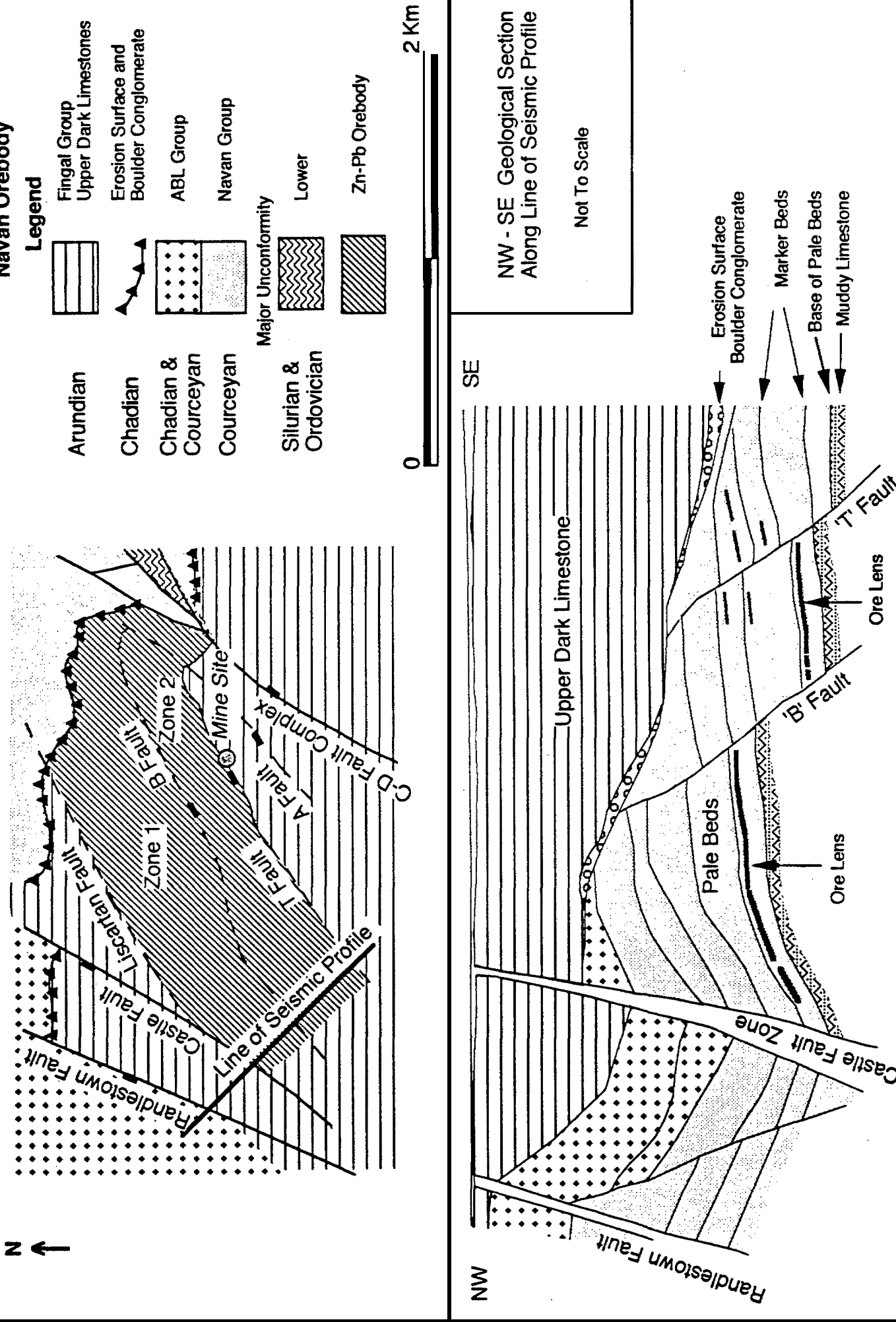


Figure 1. Geology of the Navan orebody and location of the Survey A1 seismic profile line.

Initial exploration drilling at Navan is normally targeted on the continuation of known geological trends and assisted by geophysical techniques such as gravity and induced polarisation surveys. Orebody delineation is undertaken by systematic drilling programmed from the surface at 80 m centres to depths up to 700 m and subsequently by a combination of underground and surface infill drilling as mining extends into the ore. Exploration of the deeper parts of the orebody, around 500 m to 600 m below the land surface, relies heavily on interpretation from diamond drill holes and this is particularly difficult in zones where the orebody is fragmented by faulting or occurs in small discrete lenses.

The area selected for seismic test work was about 1 km south-west of the mine at a location where preliminary drilling had established that the ore occurs at depths around 600 m in a series of separate lenses broken by faults. The main objectives were to provide information on the faults which control the disposition of the ore lenses, delineate marker horizons such as unconformities and, if possible, identify the orebodies.

Seismic Surveys

Four seismic surveys were completed during the project, all during the late Autumn or Winter periods in order to avoid disturbing local agricultural crops. Permissions were required for access to farmland and this restricted the choice of suitable areas.

Prior to each survey, shot-hole drilling was carried out by up to 4 tractor mounted 'Hilltwister' rigs using tricone rotary drilling through the glacial overburden and diamond drilling in bedrock. Including all four surveys, a total of 250 shot holes were drilled to depths between 5 m and 149 and lined with casing to prevent collapse. The hole collars, together with planned geophone locations were surveyed accurately before the seismic field work commenced. This preparatory activity took up to 3 months for the larger surveys.

Each seismic survey took between 10 and 14 days field work with a team of up to 164 together with several four wheeled drive vehicles. On-site quality control was

provided by the van-based Central Control Unit and supported by office-based personal computers. Following each survey, the pre-processed data was taken to the DMT offices in Bochum, Germany for detailed processing and interpretation.

Deep drilling for geological control was carried out continuously during the period of the surveys and down-hole geophysical logging was carried out on several holes. These are described in more detail in later sections.

Survey AI

The survey was carried out using SEAMEX equipment along a 1.47 km long line (Fig. 1) and aimed to provide parameters for prototype design and establish field operational procedures.

A total of 142 holes were drilled at 12 m spacing to 5 m depth with two additional holes at every 20th site, one 2 m deep and the other 2 m into bedrock. The depth of glacial till varied between 2 m and 15 m and the water table was at depths around 100 m due to draw-down from the mining operations.

The seismic survey used a spread of 40 Remote Units each connected to 2 geophones and test work included determining the effects of background noise, checking the effectiveness of drop-weights and establishing optimum explosive charges and filter level requirements.

The seismic reflection data was of poor quality due to the relatively low resolution of the SEAMEX equipment, the complexities of the geological structures, and the effects of varying ground water levels in the area. Background 'noise' swamped the majority of high frequency reflections from the target horizons. A crude interpretation of the results is shown in Figure 2, but even this interpretation was only possible because there was some deep drilling already in the area. Positive operational conclusions included:

- a) Explosive shot charges are essential; the drop-weight (VACIMPAC) gave signals too weak for successful detection.

FARA FILDECOMUTE SINGLE SHOT. SHOT 7. 18. 28. 37. 49. 65 76. 88. 96. 105. 118. 130. 150. 151 NMO=VEL_SHT2

NW - SE PROFILE 1993 Survey

COP 2 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 190 200 210 220 230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 420 430 450 460 470 480 509

SW

NW

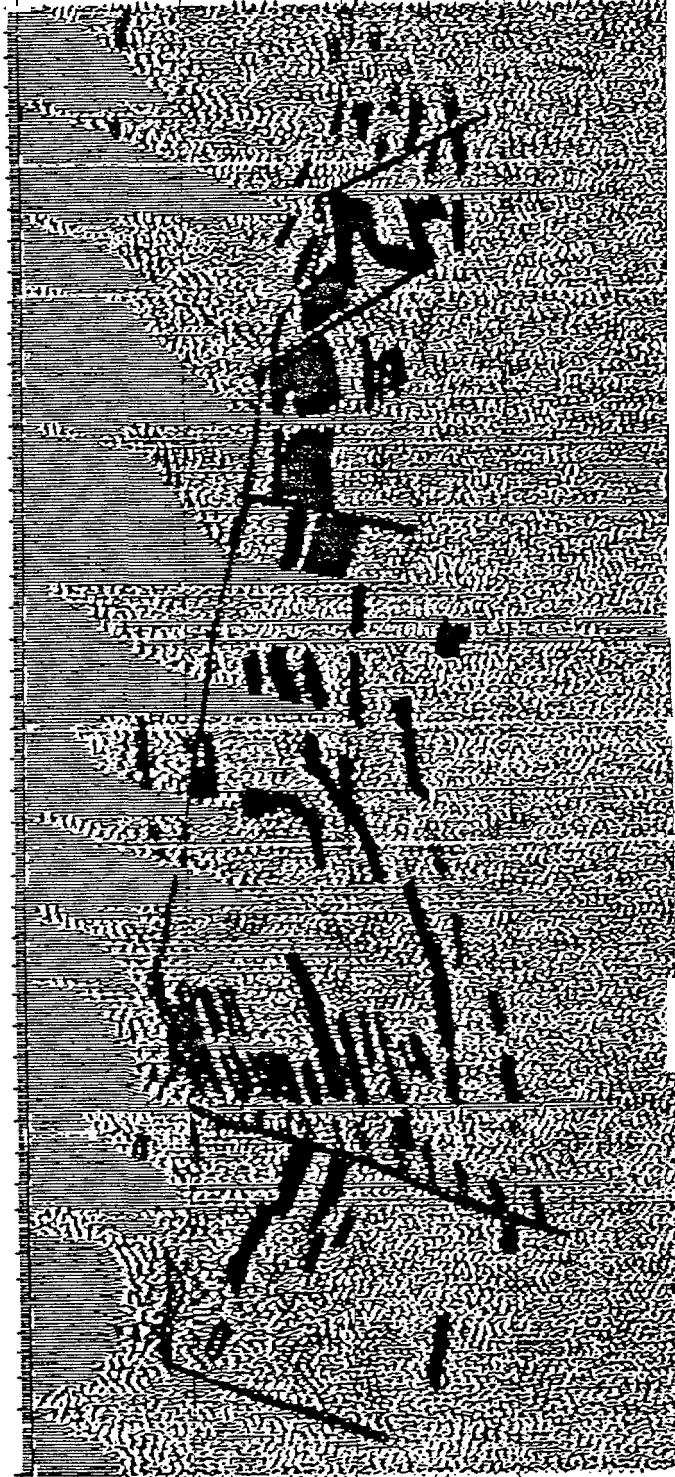


Figure 2. Interpretation of seismic data from Survey A1. The cross section is 1.47 km NW-SE.

- b) The shot depth of 5 metres was too shallow, resulting in powerful surface waves.
- c) Single shot processing should be used for future surveys; shot data stacking did not improve data interpretation.
- d) The prototype instrument must have a higher dynamic range and 60 Hz or 100 Hz geophones instead of 28 Hz geophones.

Survey A2

This was a small survey added to the original work programme and designed to provide additional data for prototype type design parameters. **It was also used as the first field test for the prototype SUMMIT system (Fig. 3).**

The survey covered part of the **A1 survey** line and was designed as a square with 150 m long sides. Ten holes were drilled at the locations shown on **Figure 4** and 281 geophone sites were surveyed. A deep hole was drilled in the centre of the area to a depth of 559 m for geological control and for a vertical seismic profile survey. The SUMMIT system comprised 80 Remote Units each receiving data from a single geophone.

The data were far better than those from Survey A1, mainly because the SUMMIT system has a markedly higher dynamic range than the older SEAMEX system and 'noise' was controlled by using a configuration of 6 geophones for each shot point enabling low frequency filtering during the data processing.

The SUMMIT system was also considerably more efficient than SEAMEX, incorporating power sources that did not require changing every evening and thereby enabling the work day to be extended from 6 to 10 hours. Better data was facilitated by deeper shot holes, optimizing shot depth and loading parameters, and improved quality control.

The data showed a number of well defined seismic reflectors at depths up to 1 km and indicated a number of features, including the overall dip of the Carboniferous strata and several major faults. The data set was too small, however, to make a

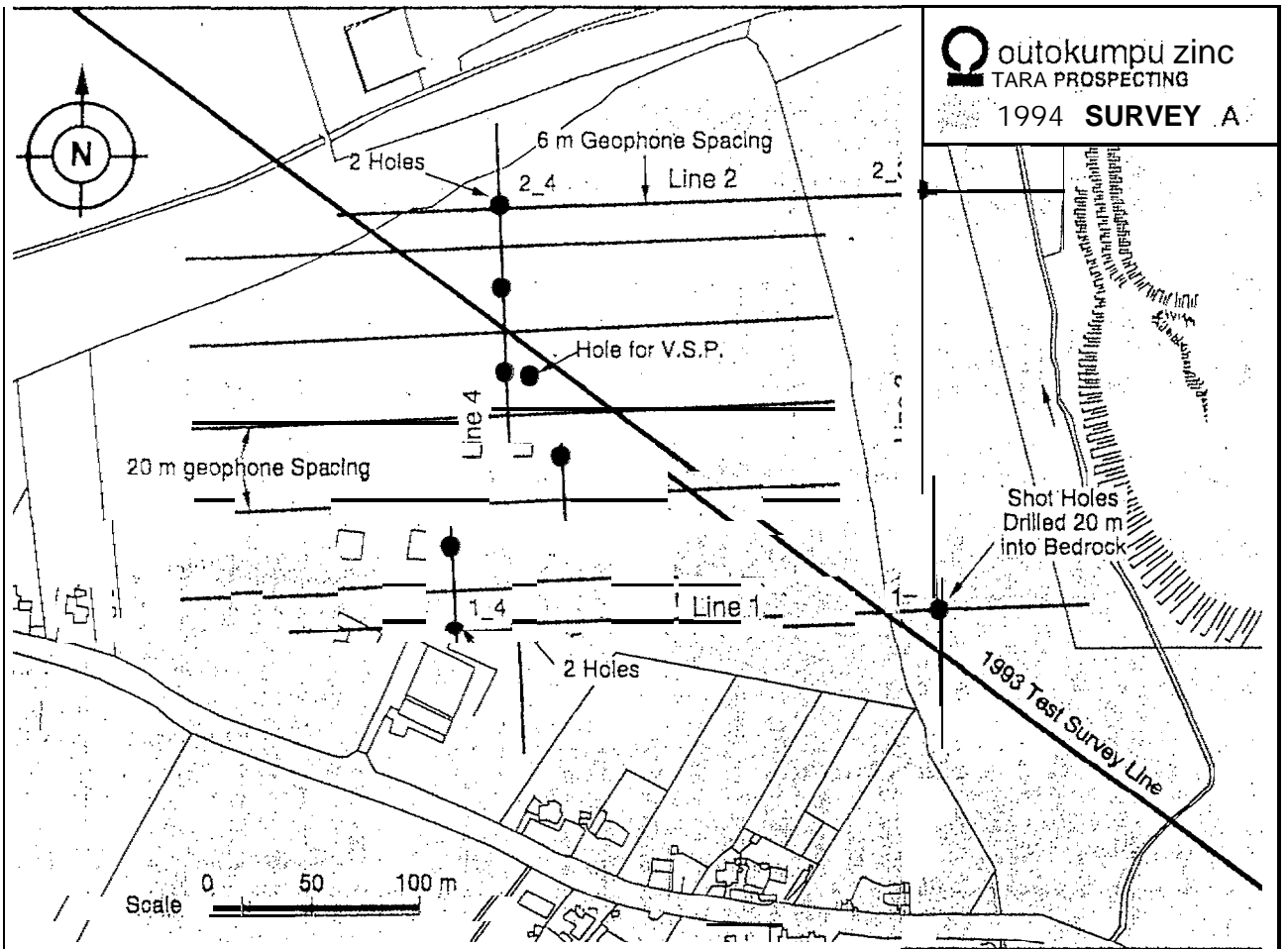


Figure 3. Survey A2 - SUMMIT Remote Units (above) and survey layout (below).

LINE 3 N-S DECONA

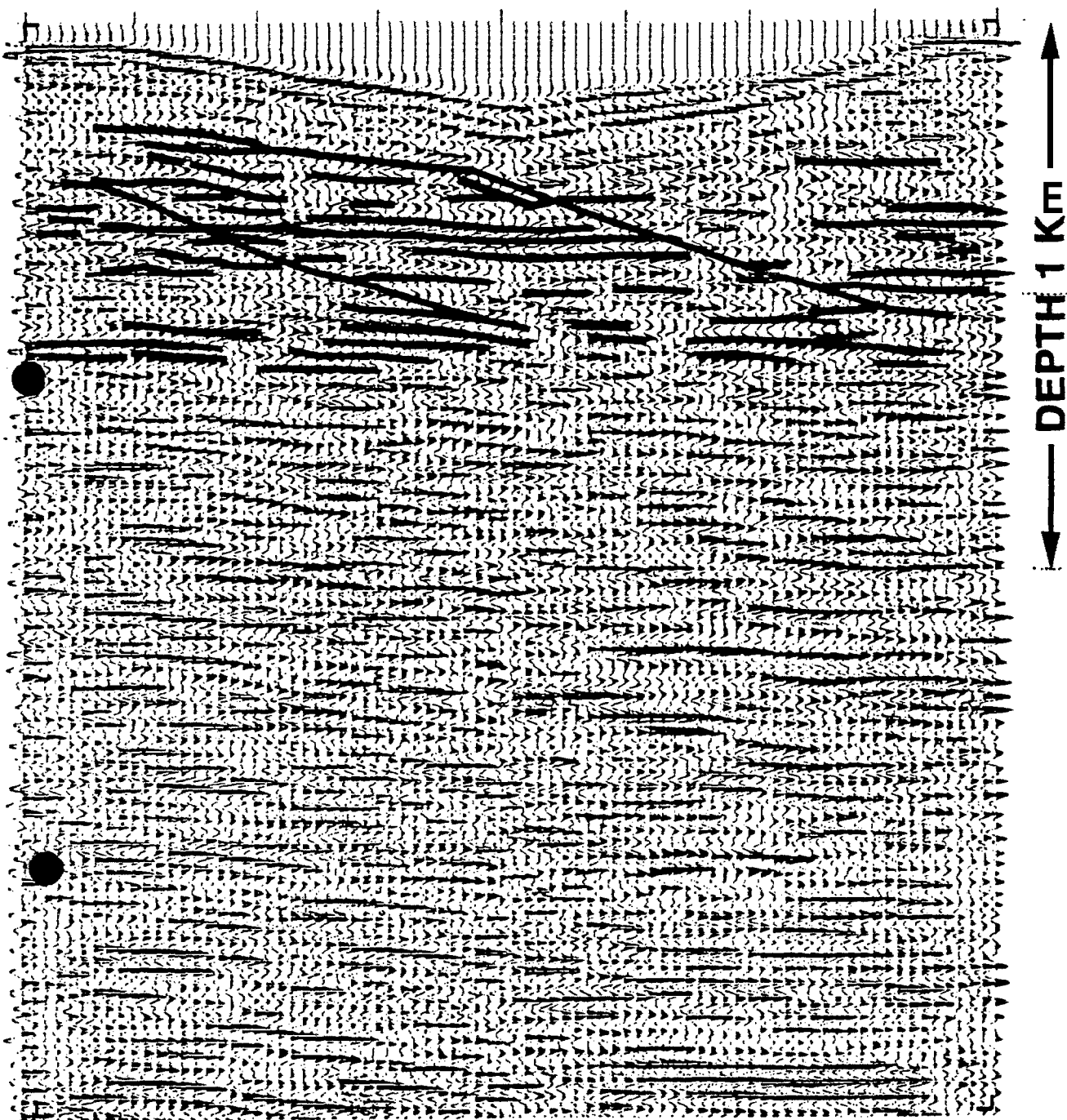


Figure 4. Survey A2 - seismic data interpretation showing reflectors. The cross section is approximately 300 m long.

detailed geological interpretation and it also became clear that deep drilling information is essential for any firm interpretation of seismic data at this detailed scale.

Survey B

Survey B was the first real test of the prototype SUMMIT system, with shot holes laid out in a grid suitable for three dimensional (3D) interpretation and covering an area of approximately 0.2 km². The selected area was outside the zone of mine de-watering and the average depth of the water table was 20 m.

The survey grid was located immediately south-east of Survey A2 and extended 600 m north-east by 400 m north-west (Fig. 5). Thirty three holes were drilled in 3 rows aligned north-east to south-west, with each hole penetrating 20 m into bedrock. The underlying karst surface meant that the depth of holes varied from 28 m to 149 m. The hole collars and 600 geophone positions were surveyed accurately. The SUMMIT system comprised 130 Remote Units each receiving data from 2 geophones and feeding it to the van-mounted Central Control Unit.

The quality of seismic data was good overall, but it rapidly became apparent that the only horizons which could be clearly interpreted using the seismic data alone were at depth within the Lower Paleozoic basement and in parts of the Carboniferous sequence above the Pale Beds. Data from 21 deep holes drilled for mine planning and 9 drilled specifically for the project were added to the data base and the depths to selected horizons were calculated in milliseconds from a synthetic seismogram carried out previously on the single deep hole. Down-hole times for three major faults were also added to the data base and this proved to be critical for interpretation of the surface seismic data. The results of the combined seismic and geological data interpretation can be summarised as follows:

- a) A surprisingly good picture of the Visean unconformity surface at depths around 600 m, but less detailed information for the underlying Carboniferous sequence which hosts the orebodies.

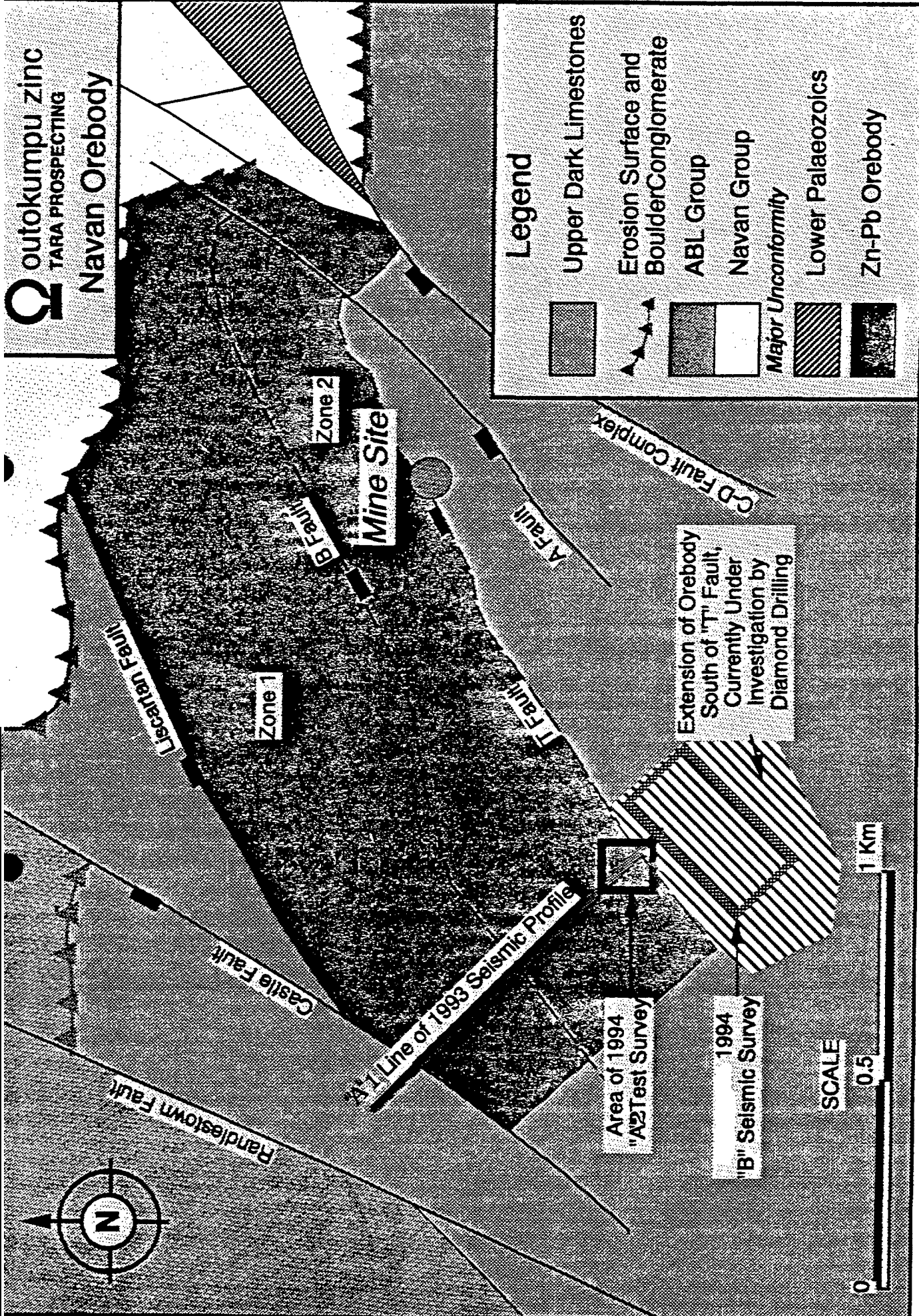


Figure 5. Plan of Navan orebody showing location of Surveys A1, A2 and B. "

- b) An interpretation of the Paleozoic basement surface at depths up to 1 km which indicates that the surface is inclined to the north-west. The interpretation also indicates some major north-east aligned **lineaments** in the basement which could be localised feeders for ore-bearing solutions.
- c) The orebodies provided local strong reflectors, but **the** ore lenses are extremely erratic in size and shape and could not be clearly defined.
- d) **Fault** planes in the Carboniferous sequence form reflective **horizons** and the combined seismic and drilling data indicated that they often branch or splay (split) along curved paths which at times extend almost parallel to the **stratigraphic** layering (Fig. 6). This makes drill hole intersections extremely difficult to correlate and in at least one case **the** seismic interpretation indicated that a particular fault identified using geological data alone may be a **totally** different structure. In addition, the frequency of faulting indicated by the seismic work was far greater than anticipated by the geological data.

During the interpretation, it was realised that fault traces on the seismic sections were commonly confused with reflections caused by **lithological** variations. This was because **the** field survey grid lines and cross sections were aligned north-east to south-west which is approximately parallel to the main fault systems. The faults were originally thought to be vertical or steeply dipping, but in fact they curve at depth and show on the cross sections as almost flat lying traces which gently cross the different **lithologies**.

Advanced computer techniques were then used to generate seismic cross sections aligned at about 45° to the field grid and these not only defined the fault systems more clearly, but also showed that the faulting is much more complex than has been interpreted previously. In addition, the Visean **unconformity** immediately above the Pale Beds could be mapped in considerable detail.

Survey C

The original intention was that the final field survey should be regional and cover approximately 2 km². However, the previous surveys had shown clearly the need

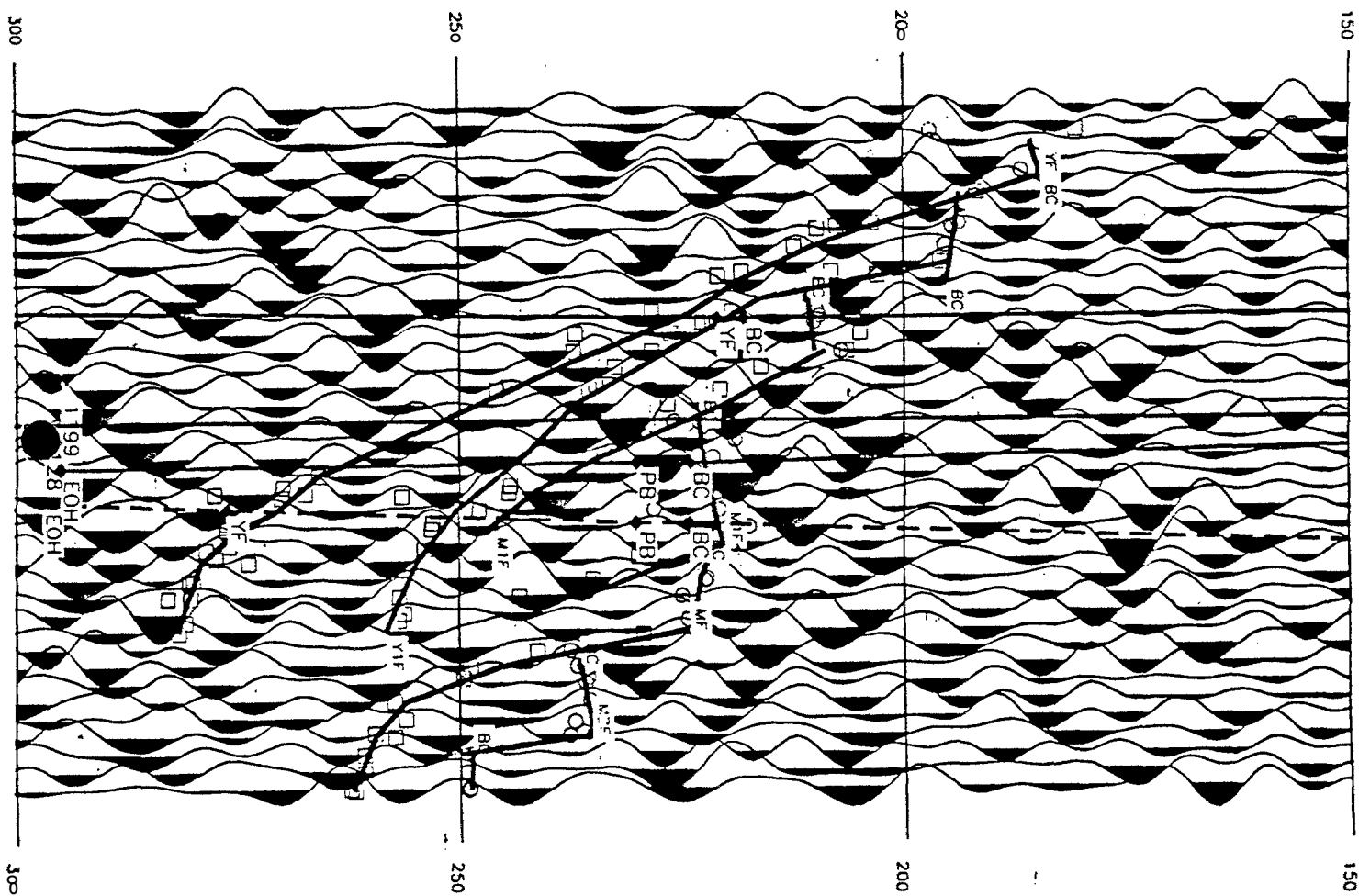


Figure 6. Survey B - seismic cross section from surface to about 1,000 m depth showing faults. Vertical lines show horizontal distances in metres at the surface.

for deep drill hole information to supplement the seismic data and it appeared more sensible to concentrate on a small well drilled area than extend to a larger unknown region. Furthermore, it was also clear that Survey B would have been more effective if the grid lines had been aligned north-west to south-east at right angles to the main fault systems rather than parallel to them.

Survey C was planned, therefore, to cover an area of 0.2 km² with shot hole lines aligned north-west to south-east and to effectively cover the area of Survey B so that data from both surveys could be combined (Fig. 7). The objective was to complete an intense seismic study of a well drilled area with the aim of defining structures in three dimensions and, if possible, locating orebodies at depths around 500 m to 600 m.

Sixty five shot holes were drilled 20 m into bedrock or to a maximum depth of 40 m in glacial overburden involving a total of 1,540 m of drilling. The holes were laid out at intervals of 32 m in 5 parallel lines 160 m apart and their collars, together with 960 geophone positions were surveyed accurately. The SUMMIT system comprised 280 Remote Units, each receiving data from 2 geophones feeding the data to the Central Control Unit.

The seismic data was a major improvement compared with that from the previous surveys. Data from the north-west of the survey area, where the overburden was thin and the geology relatively simple, proved to be excellent with well defined reflectors from the Pale Beds sequence. Data from the southern margin of the area was less clear due to more complex geology and problems with static corrections caused by thick overburden in Palaeo-karst troughs. Theoretical seismograms were calculated from a programme of down-hole geophysical test work and formational velocities together with down-hole times were calculated for intersections of various horizons in 45 deep drill holes.

The improvement in data quality, coupled with additional geological data available from the deep drilling programme, allowed for a much more detailed interpretation than had been previously possible. The results included:

- a) Three dimensional models of several important marker horizons including the top of the Pale Beds (which host the orebodies), the Upper Dark Marker Unit above the orebodies (Fig. 8), the Boulder Conglomerate near the base of the Carboniferous sequence, and the top of the Lower Paleozoic basement.
- b) Definition of major faults on both vertical and horizontal cross sections which confirm that in many cases the faults do not behave as predicted by drill data interpretation.
- c) Possible detection of some ore lenses marked by strong discontinuous amplitudes.

The identification of orebodies was inhibited by the presence of unrelated high reflecting surfaces in the host rocks, but there was some success with horizontal time and amplitude slices. Down hole density measurements indicate that massive ore should be a high amplitude time reflector and time slices through the area covered by the survey show a number of suitably strong reflectors adjacent to major faults (Fig. 9, strong reflectors coloured red and orange, faults marked by small squares). The problem is that drilling has intersected mineralisation in some high amplitude zones, but not in others, and has also intersected mineralisation in zones of low amplitude. This could be due to the fact that the horizontal time slices are cutting across inclined layers of mineralisation so that high amplitude areas simply represent locations at which the ore body intersects the time slice. Additional work is warranted on this aspect of the interpretation because the time-slice technique offers the possibility of a direct guide to mineralisation.

Down-hole Surveys

Down-hole surveys using slim-line equipment to determine rock density, resistivity, natural gamma and sonic responses and conductivity of the rocks were carried out to depths up to 800 m in five deep drill holes. Synthetic seismograms were prepared from the data for comparison with results of the field seismic surveys.

The density logs show clearly the ore lenses and small mineralised horizons due to the higher density of the sulphides. The sonic logs show variations due to lithologies. Together, the combined density and sonic logs produce a reflection co-

outokumpu zinc
TARA PROSPECTING
BRITE-EURAM SEISMIC PROJECT
1994 "B" SURVEY & 1995 SURVEY AREAS
SCALE 1: 5 000

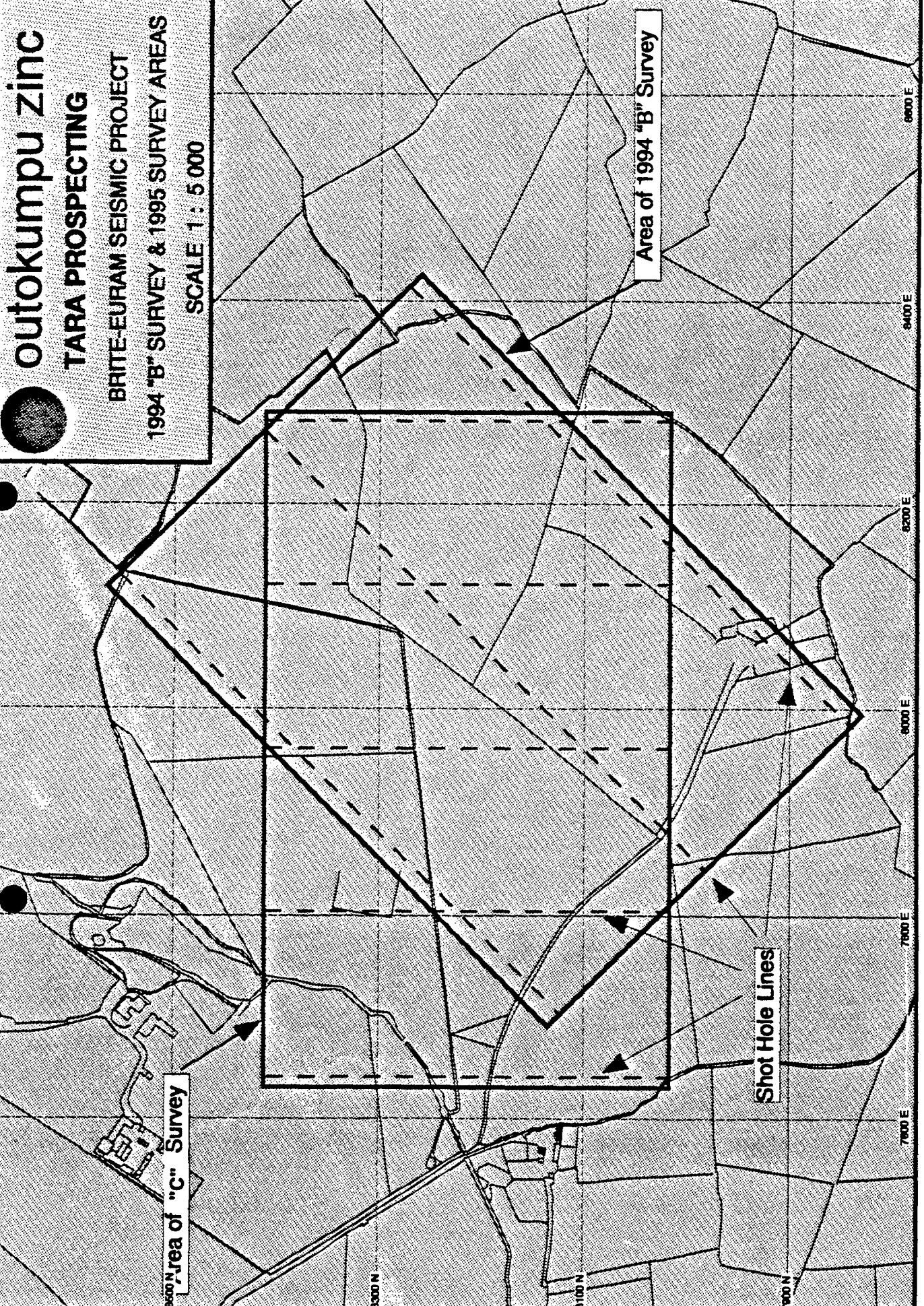
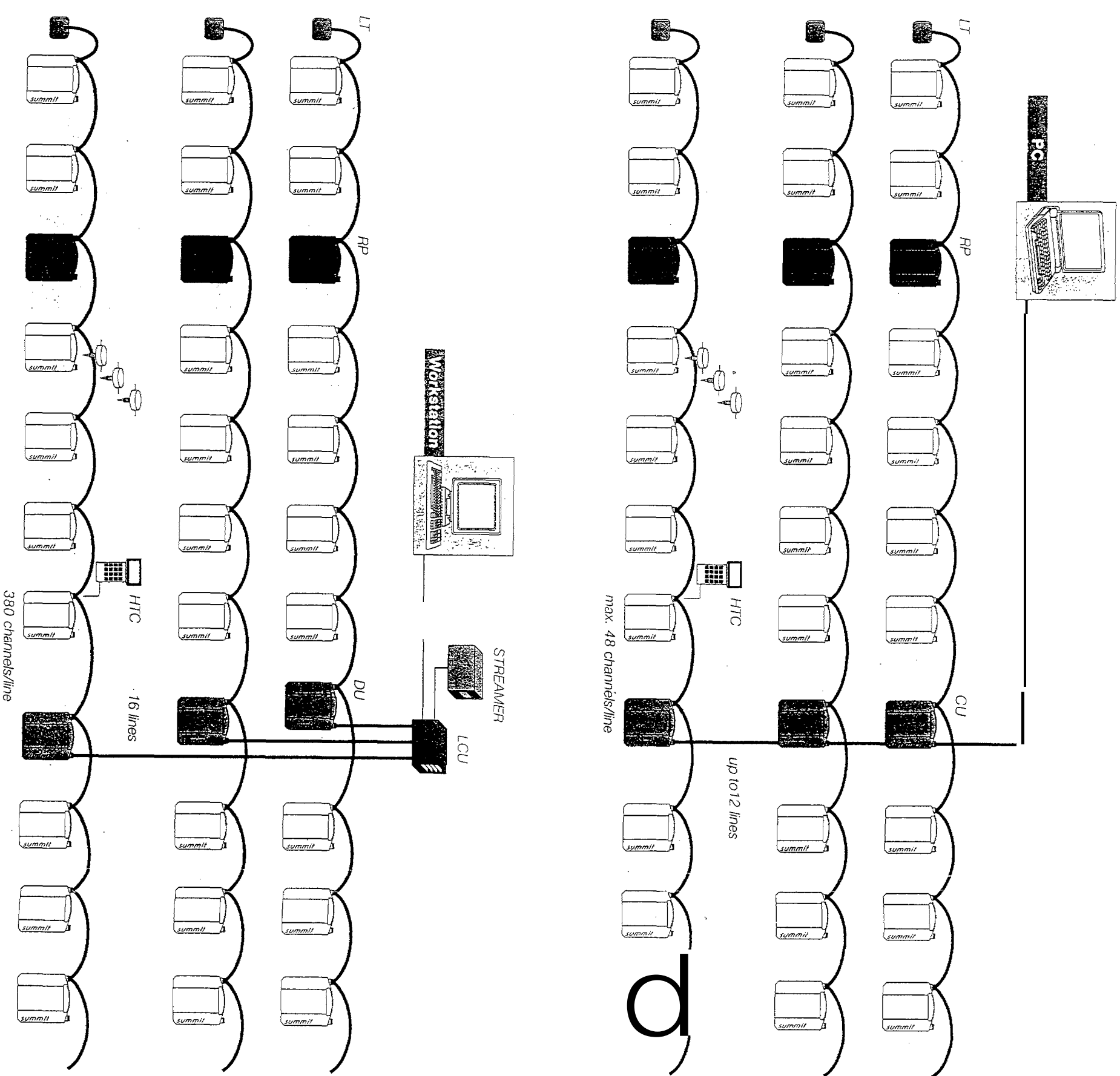


Figure 7. Survey C - orientation in relation to Survey B.



A PC-driven spread connects up to 12 lines with a total number of 576 channels. Cross Units (CU) enable the line connection and support a simple spread architecture.

max. 48 channels/line

up to 12 lines

380 channels/line

16 lines

Being able to choose between the two computer platforms gives the system a unique flexibility for surveys of different dimensions, for hardware independence and for mobility.

Using a workstation you can drive 16 lines, each line with up to 380 SUMMIT boxes connected. The parallel LCU connection speeds up the data transfer yielding a very high production rate.

The simplicity with which a SUMMIT spread or 3D array can be built and driven is unique. Each single-channel unit is located directly beside the geophone and clicked on anywhere along the inexpensive two-conductor line wire. The DOUBLE-DYNAC oversampling technique with its automatic calibration places a dynamic range of 0.5µV up to 2V maximum input at your disposal. Together with its sampling rate options of 0.25ms up to 8ms with up to 16K sampling points this system is equally well suited for high resolution investigations and for mineral and oil exploration.

Every SUMMIT unit includes its own processor which relieves the workstation (or PC) of calculation load thus permitting a very short off-time between shots. This processor also monitors battery status, charge cycles, broken cells and case temperature. The software, either on a UNIX workstation or a Laptop PC, gives the operator full instrument control. It makes the spread graphically visible thus supporting the acquisition of high quality data.

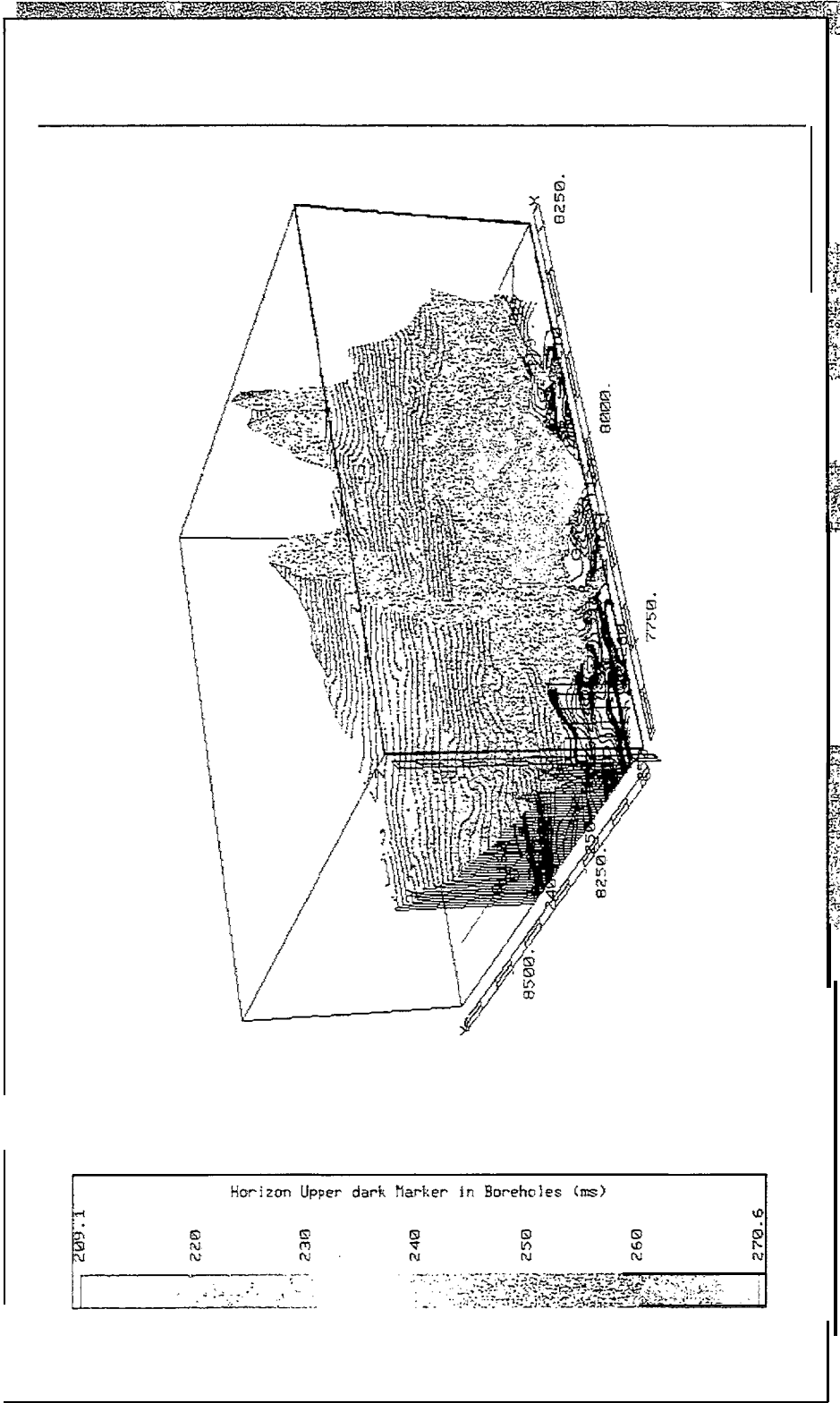


Figure 8. Survey C - contour map of the Upper Dark Marker Unit showing cross-cutting major fault.

efficient which indicates horizons most likely to produce reflectors, and several such potential reflectors indicating specific lithological discontinuities, such as the top of the Pale Beds and the Upper Dark Marker, in the zone of interest. In at least one case, the discontinuance maximum amplitudes are related to high velocity sulphides in the U lens orebody.

Diamond Drilling

It was envisaged at the start of the project that deep drilling would be used to confirm or modify data interpretation from the seismic field work. However, it rapidly became clear that considerably more deep drilling was required to interpret the seismic data than had been anticipated.

As a result, a total of 14,352.9 metres of diamond drilling was completed for the project comprising 20 drill holes to a maximum depth of 847.2 metres. All the holes were logged geologically and the data used in combination with the seismic results to provide the final geological interpretations.

Discussion of Results

Data interpretation improved during the life of the project as the quality of seismic data improved and additional information became available from deep drilling. Significant geological structures were identified and in some cases plotted in three dimensions during the project. These included:

- The Pale Beds lithostratigraphic carbonate unit which hosts the zinc-lead orebodies at depths around 600 metres.
- Discontinuous units within the Pale Beds.
 - . The Viséan unconformity above the Pale Beds.
 - . The Lower Paleozoic Basement surface at depths to 1 km.
- Lineaments within the Lower Paleozoic Basement which may be passageways for fluid movement.
 - . Major and minor faults which affect the distribution of the orebodies.

The information on faulting is particularly useful for exploration and development activities at Navan. The orebodies in the surveyed areas occur in lenses and patches at depths around 600 m and the size and location of individual orebodies are controlled by systems of major and minor faults. The seismic data showed clearly that both the major and minor faults behave unexpectedly at depth, in some cases splitting, curving and joining together. This type of variable fault geometry cannot be detected by drilling alone and the result was that all deep drill holes in the surveyed and adjacent areas were re-examined and the fault systems re-interpreted in the light of the seismic information.

However, the zinc-lead orebodies in the areas surveyed proved too small and laterally impersistent for confident detection. Seismic reflections from some ore lenses could be identified, but they were obscured by a mass of reflections from the surrounding strata and the orebodies could not be clearly delineated. Interpretation of the seismic data was also confused by the effects of the glacial overburden which varied in thickness from less than 5 metres to more than 140 metres and caused major problems for static corrections.

Four main problems for future work of this type were outlined by the project:

- a) Seismic surveys are expensive, not only for the actual surveys and the data processing, but also for the amount of preparatory drilling required. The four surveys carried out in this project required 245 shot holes drilled to depths between 5 m and 149 m within an area of less than 1 km² at a cost of more than 150,000 ECU. This density will be decreased for commercial applications.
- b) Data processing and interpretation took longer than expected due to the large volumes of seismic data and the complex geology. Techniques developed during the project will shorten the time required for this activity in future projects.
- c) Surface reflection surveys are successful in delineating structures and will almost certainly detect major bodies of massive sulphides, but they cannot at this stage clearly detect discrete lenses and broken fragments of orebodies. Future research, particularly on time and amplitude slices, will improve the situation.

d) Far more deep drilling is needed for successful **interpretation of the seismic data** than was previously anticipated, The drilling information and the seismic data complement each other and can **be** combined to produce **a** sensible interpretation of the geology which could not be obtained by either method alone.

CONCLUSIONS

The main achievements of the project were:

- . Development of a prototype seismic system of hardware and software (SUMMIT) which is being further developed for commercial use and has already won two German design awards.
- . Extensive field test work using the prototype system over part of the Navan **zinc-lead** orebody in Ireland for both two and three dimensional **surveys**.
- . Detection of significant geological structures which control the shape and disposition of the orebodies at depths around 600 m and of broad structures and geological features to depths of 1,000 m. The seismic data stimulated **a** re-interpretation of the geology at depth by indicating specific structures in three dimensions which may control the form and distribution of the orebodies.

There is a strong possibility that the Navan **sulphide** ore bodies would have been identified if the surveys could have been carried out over the main part of the orebody. The results at **Navan** indicate that the method has potential for deep exploration in areas, such **as parts** of the Pyrite Belt in Spain **and Portugal**, where the mineralisation is in massive bodies and there is no significant glacial overburden.

Future research should concentrate on improving seismic data processing techniques **to** produce detailed interpretation at specific depths, combining surface seismic surveys with refraction seismic techniques and down-hole seismic surveys in order to maximise useful data generated by a single seismic field survey, and

creating broad images of the geology at depth for regional mineral exploration in the way that the method is applied in the hydrocarbons industry.

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