Mem. Descr. Carta Geol. d'It.
LXXVI (2007), pp. 175-192
figg. 12, tabb. 5

High Resolution Seismic Reflection Imaging of Complex Stratigraphic Features in Shallow Aquifers

Sismica a riflessione ad alta risoluzione per la definizione di relazioni stratigrafiche complesse in acquiferi superficiali

FRANCESE R.G. (*), HAJNAL Z. (**),
SCHMITT D. (***), ZAJA A. (****)

ABSTRACT - A series of near surface multifold high-resolution seismic reflection experiments were recently conducted in the Western Canada basin and in the Po Plain in Italy. The primary objectives of the investigations were to define stratigraphy and physical properties of shallow fresh water aquifers contained in late tertiary and quaternary deposits. The seismic signature of the major geologic units was recorded down to the target depth of exploration. The local hydrogeological framework and the spatial extents of the most prominent aquifers were defined in details.

The different experiments faced typical shallow exploration problems. Source deployment was, in some cases, complicated because of difficulties in placing the explosive charge at the proper depth. Shallow P-wave velocity anomalies introduced significant time shifts reducing the effectiveness of stacking common mid point traces. Near surface geology caused also strong coherent noises when elastic energy was propagated in the subsurface and the resulting records exhibited very low signal to noise ratio. The urban environment with its associated complications introduced further difficulties to accomplish the expected results.

Some of these problems were resolved relying on the results of forward modeling of wellbore information. The numerical simulation was vital in assisting the design of the data acquisition, in the preliminary choices of the processing parameters, and ultimately in tying borehole stratigraphy to the reflecting horizons.

The better quality seismic sections were reprocessed to gain a better insight in the aquifer sedimentology and some attempts to predict petrophysical properties from the stacked data outlined the potentials of this post-processing analysis when the signal to noise ratio is sufficiently high.

Functional data acquisition and processing procedures were developed for seismic mapping of shallow alluvial and glacial deposits and these techniques could be utilized in other regions with similar near surface stratigraphy.

KEY WORDS: High-Resolution Shallow Seismic, Near-Surface Deposits, Aquifer Sedimentology, Groundwater Flow Modeling.

RIASSUNTO - Una serie di rilievi sismici a riflessione ad alta risoluzione, in onde P, sono stati recentemente condotti nelle pianure centro-meridionali del Canada occidentale e nella pianura Padana in Italia settentrionale. I principali obiettivi dell'investigazione geofisica consistevano nella definizione della stratigrafia e di alcune proprietà petrofisiche di acquiferi di bassa profondità ospitati in depositi del Quaternario e del tardo Terziario. Le principali unità idrostratigrafiche hanno evidenziato una discreta riflettività con distinte risposte caratteristiche nell'intervallo di profondità studiato. L'architettura deposizionale e le geometrie dei principali acquiferi sono state risolte con elevato grado di dettaglio.

Nei diversi esperimenti, in fase di acquisizione, elaborazione ed interpretazione dei dati, sono state incontrate le tipiche difficoltà del rilievi sismici a riflessione di bassa profondità. La preparazione della sorgente è stata, in molti casi, piuttosto complicata con varie difficoltà nel posizionamen-

(*) Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Borgo Grotta Gigante 42/c, 34130 Sgonico, Trieste.
Corresponding Author: rfrancese@inogs.it
(**) Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK, Canada
(***) Department of Physics, Institute for Geophysical Research, University of Alberta, Edmonton, AB, Canada
(****) Dipartimento di Geologia, Paleontologia e Geofisica, Università di Padova, Via Giotto 1, 35137 Padova

to della carica esplosiva alla profondità desiderata. Le forti variazioni vertico-laterali di velocità in vicinanza della superficie hanno determinato degli sfasamenti temporali dei dati che hanno ridotto l'efficacia del processo di somma delle tracce con punto di riflessione comune. Questa variabilità acustico-elastica dei primi terreni è stata anche la causa della generazione di un forte rumore coerente con conseguente abbassamento del rapporto segnale/rumore in molte registrazioni. L'ambiente urbano con tutte le sue problematiche di difficoltà logistiche e di diffusa presenza di rumore ambientale è stato infine un ulteriore ostacolo per il raggiungimento del risultato finale.

Alcuni di questi problemi sono stati risolti avvalendosi dei risultati della modellazione diretta di dati acustico-stratigrafici di pozzo. La simulazione numerica della propagazione delle onde elastiche nel sottosuolo si è infatti rivelata di vitale importanza nella progettazione della campagna di acquisizione, nella scelta iniziale dei parametri di elaborazione ed infine nella correlazione tra orizzonti riflettenti ed informazioni stratigrafiche.

Dopo una prima elaborazione, che ha consentito di definire le geometrie delle principali unità stratigrafiche presenti nel sottosuolo, i dati sismici sono stati elaborati "*ex novo*" con procedure mirate ad ottenere informazioni di tipo petrofisico quali ad esempio la porosità delle diverse unità geologiche. I risultati migliori sono stati raggiunti nei casi in cui il rapporto segnale/rumore era sufficientemente elevato dimostrando le grandi potenzialità di queste tecniche di analisi anche in dati di bassa profondità.

Tra i risultati della sperimentazione va infine menzionato lo sviluppo di robuste procedure di acquisizione ed elaborazione di dati sismici a riflessione superficiali per la definzione delle strutture deposizionali in terreni alluvionali e glaciali. Queste tecniche potranno essere impiegate con successo in quelle aree che presentino caratteristiche confrontabili nella stratigrafia superficiale.

PAROLE CHIAVE: Sismica a riflessione ad alta risoluzione, Depositi superficiali, Sedimentologia degli acquiferi, Modelli di flusso.

1. - INTRODUCTION

With the depletion and diminishment of the quality of water from underground reservoirs, the exploitation and, just as importantly, the protection of such resources has become not only a technical but a social issue for communities. The most prominent reasons are certainly increasing demand, lower infiltration and recharge due to urban development, and pollution from both industrial and agricultural sources. The natural recharge by infiltration is significantly reduced because of the changes in the precipitation regime and of the relatively rapid surface runoff. Many studies (BOOTH & JACKSON, 1997) demonstrate how erosion or deforestation in a watershed can increase the degradation of the water systems. The severity of this the problem is recognized as evidenced by a recent directive of the European Parliament for establishing a framework for Community action in the field of water policy (EUROPEAN COMMUNITY, 2000) as just one example of actions now being taken globally.

Addressing this problem requires knowledge in many different forms. The aquifers must be first characterized in order to understand their structure and how water may flow through them. Such knowledge is necessary to allow for proper hydraulic modeling of the groundwater flow that is required to reduce the impacts of existing or future development on water quality. The comprehensive understanding of the depositional framework of the sediments became then vital for a successful simulation and prediction and this is particularly so in alluvial and glacial plain sediments that can be particularly complex.

Geophysical methods can play a role in the characterization of such reservoirs. Among the variety of geophysical techniques suitable in imaging the near surface, shallow reflection seismic profiling can play a major part due to its vertical (2 m with a dominant frequency of 200 Hz) and horizontal resolution and the potential information on acoustic impedance, shale fractions, or porosity, to name only a few, carried back by the seismic wavelet.

In recent decades the seismic reflection technique has been used for many geotechnical and environmental purposes with different degrees of success (e.g. STEEPLES *et alii*, 1986; STEEPLES & MILLER, 1990; MILLER *et alii*, 1995). Other authors used the method with some success in glacial depositional environments (LANZ *et alii* 1996; SIAHKOOHI & WEST, 1996; BRADFORD *et alii* 1998; BUKER *et alii* 1998, SHARPE *et alii*, 2004), or to assist in the investigation of ground water resources (BRADFORD, 2002a, 2002b; JUHLIN *et alii* 2002). The recent advances in the data acquisition and processing make this technique an excellent tool for mapping the geometry of shallow aquifers. In many cases, with adequate data quality, it may also possible to estimate near-surface petrophysical properties (PENNINGTON, 1997; JARVIS & KNIGHT, 2002) from the final stack.

Some high-resolution P-wave reflection seismic surveys from the Western Canada Basin and from the Po Plain in Italy are presented and discussed. The objectives of the surveys were to image structure and stratigraphy of Quaternary and Tertiary deposits to define the hydrogeological framework of the shallow subsurface.

Each survey was carefully designed relying on extensive noise and walk away tests prior to production. Data acquisition, processing and interpretation were conducted utilizing oil industry standards with a continuous assistance provided by forward numerical modeling of available geological information. Synthetic data generation was crucial to design the survey, to assess the effectiveness of noise filtering and velocity analysis and to correlate reflecting horizons with stratigraphic boundaries. A variety of typical problems of shallow exploration were encountered in the different surveys and some potential solutions have been devised and tested.

The good quality of the shot gathers and of portions of the final stack suggested to further process the seismic section in order to attempt the estimation of some petrophysical properties of the near-surface deposits.

2. - PROBLEMS AND RECENT ADVANCES

A successful shallow reflection survey requires a careful "state of the art" design and attention to details during acquisition. Minimal requirements are an adequate selection of the recording system and parameters, the choice of the source, of the detectors and of the spread geometry and the application of proper data processing and interpretation techniques.

In recent years, the availability of greater digital resolution in modern acquisition equipment, better fidelity in both receivers and digitization, and greater channel capacity has led to major improvements in data quality and reliability. This enlarged acquisition ability represents the key to reduce shallow seismic profiling costs (VAN DER VEEN *et alii*, 2001) and broadens the application potentials for this technique.

The manner in which elastic energy is generated and propagated into the subsurface is the second relevant issue to shallow seismic exploration. Ideally, a seismic source should generate the broadest possible signal frequency spectrum, yield sufficient energy to reach the target depth, be easily and safely employed, generate a minimum of coherent noise, have low or negligible environmental impact, and be inexpensive to operate. The cost-effectiveness of the shallow source has long been a research topic and in the literature a variety of field tests and result comparisons are documented (MILLER *et alii*, 1986, 1992, 1994; WIEDERHOLD *et alii*, 1998). Such tests have demonstrated a generic site-dependency for most of the tested devices. Of these differing source types, explosive charges and small to medium size vibrators appear to have the widest adaptability to differing conditions and geological environments. In many ways, explosives are preferred because of their ready scalability and production of a near minimum phase and high frequency signature, but severe restrictions in the use and transportation permits results in significant delays for industrial projects. Portable and truck-mounted vibrators provided excellent results in a variety of environments (NIJHOF, 1990; MATSUBARA *et alii*, 1995; WARDELL *et alii*, 2003). This source, up to now, represents a valid and realistic alternative (with a lower site dependency), to the explosive charge.

Receiver station spacing should be tightly spaced in order to minimize spatial aliasing (YILMAZ, 1987) of the surface waves and to be able to identify reflected energy at early traveltimes via their coherence. At the same time the offset should be large enough to have a wide optimum window (HUNTER *et alii*, 1984) and perform a reliable velocity-traveltime analysis. Higher folds could be required in cases of low contrasts in acoustic impedance. In many real cases, however, the available equipment and the minimum budget for the survey are serious obstacles to the satisfaction of these geometry requirements. The final solution may be a compromise that despite the best efforts of survey planning may result in less than optimal data acquisition. Forward modeling of borehole data is crucial at this stage to assist survey design and optimize the acquisition geometry.

Data processing of near surface seismic data is slightly different from seismic processing for oil exploration. Source generated and environmental noise generally interferes severely with the weak reflected signal such that shallow field records often exhibit poor signal to noise ratios. The high amplitudes of the coherent noise are often related to the surface geologic conditions and particularly to the high lateral and vertical variability in the interval velocities in the uppermost layers. This interference is perhaps the most serious pitfall of near-surface surveys. 2-D filtering should be done selectively and very carefully, targeting events with peculiar spatial and temporal properties, to avoid the introduction of processing artifacts.

Numerical models of field records are helpful at this stage in guiding the development of strategies to separate the expected reflections from coherent noise.

Primary signals can be further enhanced by the application of spectral balancing or deconvolution. Surgical muting of the refracted first arrivals and the air-wave is necessary to avoid introducing this noise in the final section by improper stacking (STEEPLES & MILLER, 1998). Migration of the results should be determined on a case-by-case basis as this process may introduce only marginal changes in shallow data (BLACK *et alii*, 1994). Accurate refraction and datum static computations are important in the processing of near surface data as the reflected events are generally less continuous and their high frequency in relation to static shifts can also be detrimental during stacking (SCHMITT, 1999).

The interpretation of the resulting near surface profile is the last and most important step. The majority of the standard oil exploration techniques can be easily adapted to near surface sections. The computation of synthetic traces from borehole data is always recommended to tie reflections to lithological interfaces and constrain the velocity-depth function. As already noted, seismically imaging depths shallower than 200 m is complicated and requires particular attention because of the mixing of the primary reflections and the surface waves. In many cases processing and interpretation pitfalls are closely related (STEEPLES & MILLER, 1998). For example interpreters should be aware that steeply dipping reflectors (40 degrees or more in the unmigrated stack) and events occurring at traveltime less than 0.05 s are likely to be processing artifacts that must be verified by examination of the shot gathers.

3. - RESULTS OF SEISMIC PROFILING

In this contribution, the results of four different high-resolution seismic reflection experiments devoted to groundwater exploration are presented. The profiles were acquired both in the Western Canada basin and the Po plain of northern Italy. The geological settings of the different sites are somewhat similar with a subsurface comprised of variably thick Quaternary deposits lying on a Tertiary or Mesozoic bedrock. The targets consist of aquifers and of the bounding geologic structures all above depths of 200 m. Although the geometry of the seismic lines differ slightly in station spacing, number of channels and energy sources employed, the data are otherwise comparable in folding, dominant frequency and resolution.

Briefly, the sites and some of the pertinent information include: the Cory site near Saskatoon, Saskatchewan where wellbores, drilled before acquisition, were utilized to assist with velocity structure determination and after drilling to ground truth the seismic images; the Dalmeny site in central Sakatchewan where its very small scale channeled aquifers required a very high resolution survey to be properly imaged; the Rocanville site, located in southern Saskatchewan, very close to the United States border, where drilling the shotholes was somewhat prohibitive and part of the collected records were badly noise contaminated requiring forward modeling to assist processing and interpretation of the seismic data; the Parco Lambro site in Milano in the Po Plain with the typical problems of conducting a seismic survey in an urban area.

All the surveys were successful in mapping the geometry and establishing the spatial relationships of the major hydrogeological units. Many structural details within the different depositional sequences were also outlined by the seismic images.

3.1. - PCS CORY EXPERIMENT

The objective of the seismic survey was to define the near surface aquifer system in the vicinity of a large tailing pile consisting primarily of discarded halite and low quality sylvite ore and ponds from a potash (KCl) mine in the vicinity of Saskatoon, Saskatchewan. The dump area of these salt mines is generally a major concern for the local community because of the possibility of vertical infiltration of polluting brines into the underlying fresh water aquifers. For this reason there are in place strict environmental regulations that force regular monitoring of the environment surrounding the production plant.

The local stratigraphy is comprised of diamicton and clay units with embedded gravel and sand bodies with lateral dimension ranging from few tens to hundreds of meters. The bedrock occurs between 50 and 70 m and is composed of Cretaceous shales.

The sand and gravel lenses have been interpreted as buried braided stream channel deposits formed during deglaciation (HOOGE *et alii*, 1994). These high permeability paleo-channels are the potential pathways for brine migration and consequently are the main target of the seismic investigation.

Five boreholes were available in the vicinity of the seismic line (three inline plus two offline) to correlate reflecting horizon and aid interpretation (SCHMIDT, 2000). The inline boreholes were specifically drilled during the seismic experiment to collect well logs to tune horizontal correlation and estimate petrophysical properties of the different geological units. Vertical seismic profiles (VSP) at the inline well locations were also acquired (CARR *et alii*, 1998; CARR & HAJNAL, 1999). The acquisition parameters for the reflection profile are reported in tab. 1.

Sharp reflections were already visible in the raw data, with a dominant frequency of 150-170 Hz, although the initial stacks were not satisfacto-

Tab. 1 - *Data acquisition geometry and recording parameters for PCS Cory experiment.*
- Geometrie di acquisizione e parametri di registrazione nell'esperimento PCS Cory.

PCS -CORY: Acquisition parameters	
CMP lines	2 x 1000 m
Amplifier	BISON
A/D conversion	21-bit
n. live channels	48
Geometry	split spread
receiver array	single 40 Hz geophone
receiver spacing	2.0 m
shot spacing	2.0 m
minimum offset	2.0 m
average CMP spacing	1.0 m
maximum fold	24
shot location	0.5 m depth
shot type	blasting cap
Recording	
sampling rate	0.125 ms
low-cut filter	off

ry and the horizontal coherency of reflectors was very low due to event misalignment. Ground roll and air-coupled waves significantly reduced the window of stackable signal. Despite these problems, the stacking velocity function was accurately estimated and additional control was introduced by processing the P- and S-wave VSP data collected at the inline boreholes (CARR *et alii*, 1998). The section was improved but the signal level was still poor. To overcome these problems a variety of 1-D and 2-D filtering techniques were tested. Finally, the key processes were the application of a minimum phase deconvolution and the accurate estimation of a near surface velocity model to compute refraction statics. For this last purpose first arrivals were picked in each shot gather.

The seismic section outlines the major stratigraphic features along the CMP profile (fig. 1) down to the depth of about 100 m, as estimated from the velocity field.

A first group of reflectors occur at early traveltimes in the interval 0.015-0.025 s and correlate from CMP 2500 to 5500. These events have been interpreted as the boundaries of the upper till group (diamicton and alluvial clays). The most prominent event is a group of reflectors occurring at traveltime ranging from 0.03 to 0.05 s. The reflectors mark top and bottom of the lower till (diamicton-clay) group and could be correlated along the entire section. A clear interruption of the lateral continuity of this unit is visible from CMP 3000 to 5000. The upper and lower till groups are separated by a variable thickness (from 0 to 5 m) silty transition zone which has no specific signature in the stacked section. Many other reflectors occur at traveltime later than 0.05 s and are mostly related to the bedrock contact.

The interruption from CMP 3000 to 5000 (fig. 2) was interpreted as a channel infill sequence sealed by the diamicton and alluvial clay units. The bottom truncation surface has a maximum dip of about 25 degrees on the east flank. Some complex patterns are visible in the infill sequence and they were better defined after migration. Particularly a series of dipping surfaces (20 degrees) with west vergence were interpreted as sand bars or more generally as fluvial sedimentological structures.

Stratigraphic information and core analysis from the post-seismic boreholes confirmed the seismic interpretation: a sand unit with dipping layering was lying on the top of a gravel unit. These gravel deposits exhibit a specific signature with a variety of diffraction patterns in the unmigrated stack. Mapping of the geometry of these high permeability bodies was one of the major goals of the seismic investigation.

3.2. - NSERC DALMENY EXPERIMENT

The seismic survey targeted some aquifers, embedded in channeled deposits, to be exploited to supply fresh water to a major urban settlement. Standard, borehole based, geological exploration did not successfully locate the potential production zones because of their small scale and the lateral discontinuity of the structures.

At this site, the local near surface stratigraphy is underlain by Cretaceous bedrock at depths of approximately 140-150 m, with overlaying formations consisting of Plio-Pleistocene glacial, interglacial and alluvial deposits. The bedrock, formed by marine shales, was deeply incised by fast flowing rivers (HOOGE, 1996) producing topography of tens of meters over lateral dimensions of many hundreds of meters. The Tyner Valley channeled sequence is a large scale example of the deposition of these rivers. It has a lateral extension of about 20 km with a maximum thickness larger than 50 m. The three major Tertiary sections include a Pleistocene unit comprised of sand, gravels and interbedded clays; a Lower Pleistocene till unit formed by glacial diamicton

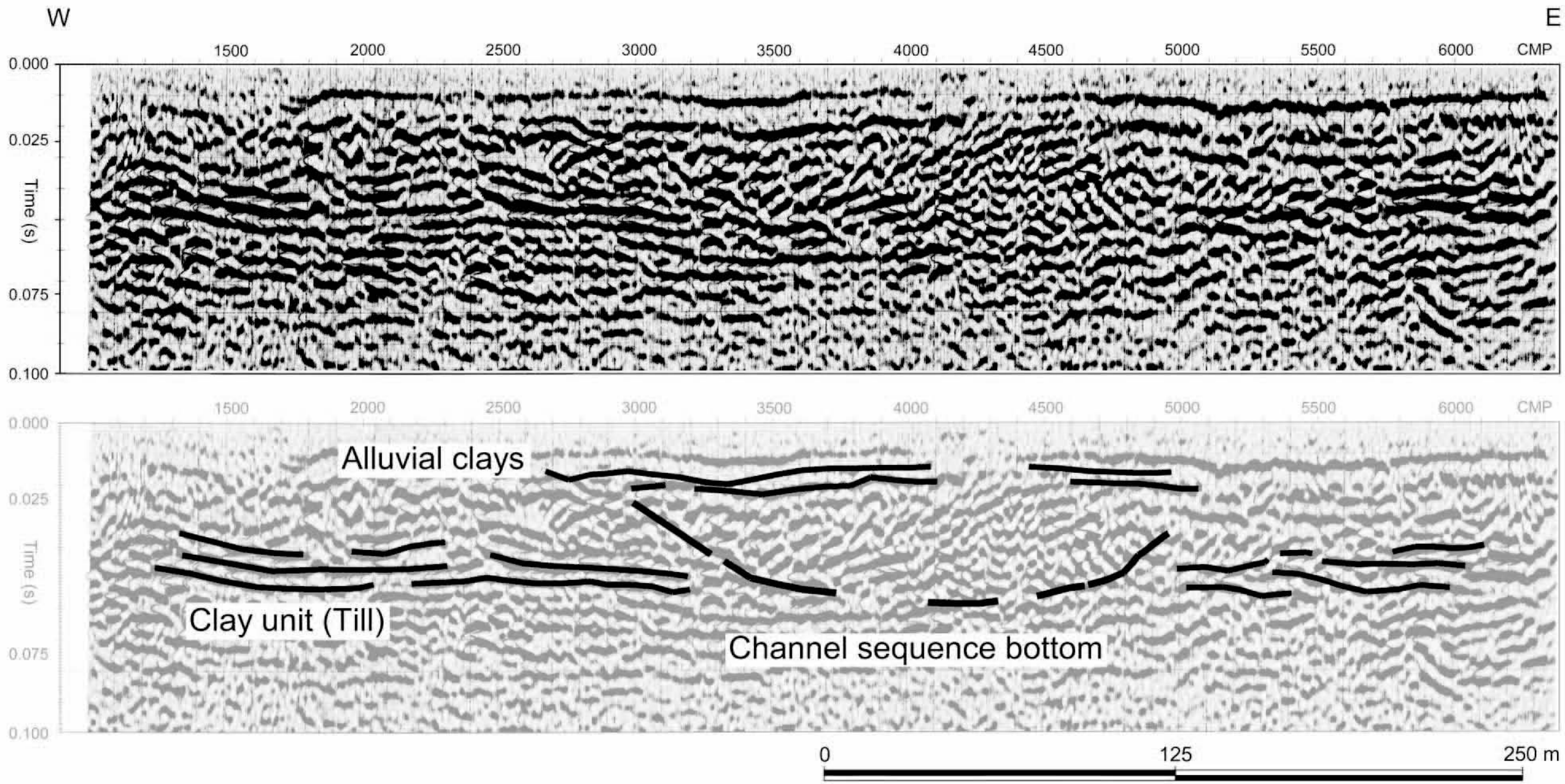

Fig. 1 - PCS Cory experiment: inner portion of the final stack after migration (above) and the associated interpretation (below). Reflected energy is clearly visible at two-way traveltimes ranging from 0.05 to 0.15 s. The continuity of a clay unit, outlined by horizontal reflections, is interrupted from CMP 3000 to 5000 by a channel infill sequence. A flat bedding diamicton and alluvial clay unit seals the channel sequence.

- *Esperimento PCS Cory: porzione mediana della sezione finale migrata (sopra) con la relativa interpretazione (sotto). Una serie di eventi riflessi sono chiaramente visibili al tempo compreso tra 0.05 e 0.15 s. Un livello a prevalente litologia argillosa, evidenziato da un riflettore orizzontale, appare interrotto, dal CMP 3000 al CMP 5000, da una sequenza di riempimento di un canale. Un'unità di diamicton e di argille alluvionali a prevalente stratificazione orizzontale sigilla la sequenza di riempimento del canale.*

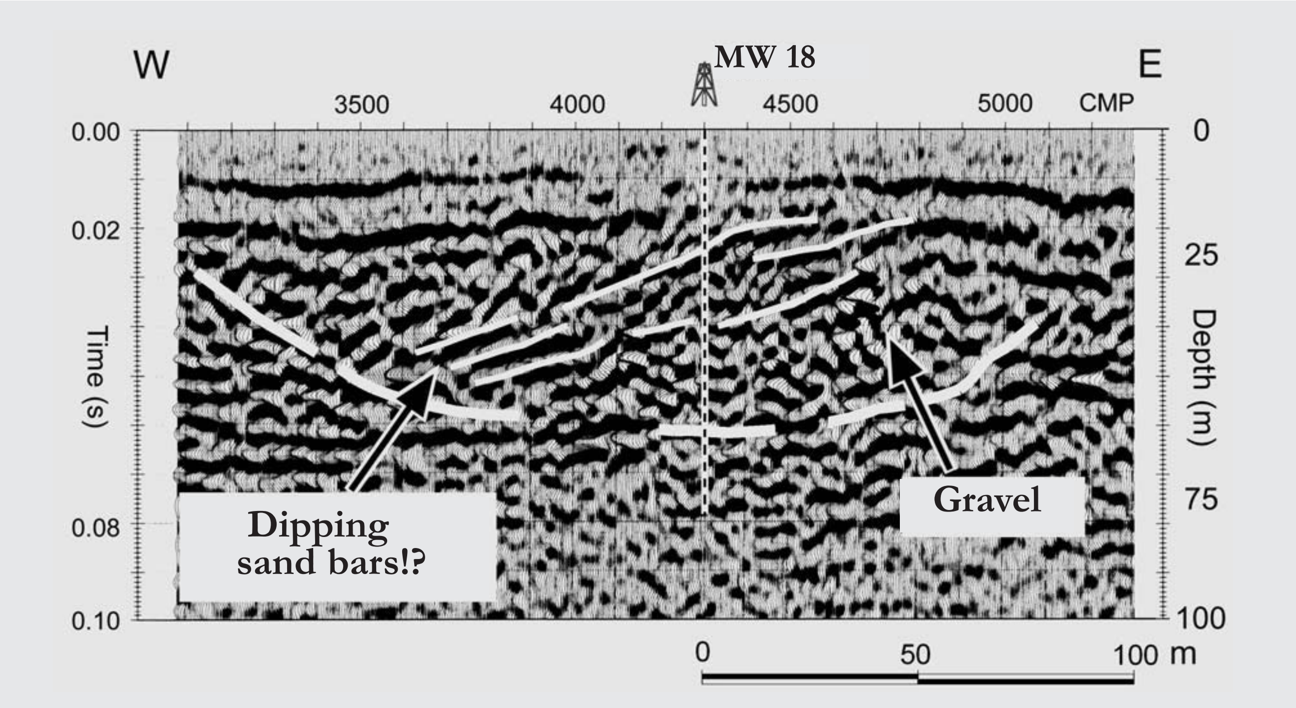

Fig. 2 - PCS Cory experiment: detail of the final stack after migration. The base of the channel sequence truncates some flat reflecting horizons. A series of dipping reflectors are visible within the channel sequence. These reflectors were interpreted as sand bars and borehole information, from well MW - 18, confirmed the initial interpretation.
- *Esperimento PCS Cory: dettaglio della sezione finale migrata. Si noti come la base della sequenza di canale tronchi alcuni riflettori orizzontali. Una serie di riflettori inclinati sono visibili all'interno della sequenza di canale. Questi riflettori sono stati interpretati come barre fluviali come confermato dall'analisi della stratigrafia del pozzo MW-18.*

and inter-glacial silt, sand and clays; an Upper Pleistocene till unit mainly comprised of diamicton and silty clays.

The acquisition parameters for the reflection profile are reported in table 2. The raw records exhibit clear reflections at various traveltimes (fig. 3) with a dominant frequency of 200 Hz and higher. The processing sequence was straightforward with particular attention given to the refinement of deconvolution parameters and the estimation of a stacking velocity function. Some extended spread shot gathers, with a maximum offset of 200 m, were utilized to pick accurate values in the semblance domain and gain a better control on the stacking velocity (fig. 4). Assuming an interval velocity of 1600-1700 m/s, down to a depth larger than 50 m, the wavelength is about 8 m and the vertical resolution of this wavelet is approximately 2 m (YILMAZ, 1987).

Pre-seismic well control was available for reflecting horizon assessment and interpretation. Two inline wells (1521 and 2407) were utilized to correlate reflecting horizons in the stacked section.

The CMP stack (fig. 5) exhibits sharp reflecting horizons at various depths. The lower part of the stacked section has a reverberatory character that is likely to be either processing related or caused by the near surface conditions.

Tab. 2 - *Data acquisition geometry and recording parameters for NSERC Dalmeny experiment.*
- Geometrie di acquisizione e parametri di registrazione nell'esperimento NSERC Dalmeny.

NSERC DALMENY: Acquisition parameters	
CMP lines	2 x 1000 m
Amplifier	2 BISON 9024
A/D conversion	16-bit
n. live channels	48
Geometry	split spread
receiver array	buried 50 Hz geophone
receiver spacing	2.0 m
shot spacing	2.0 m
minimum offset	2.0 m
average CMP spacing	1.0 m
maximum fold	24
shot location	~1.1 m depth
shot type	blasting cap + 10g dynamite
Recording	
sampling rate	0.250 ms
low-cut filter	on (192 Hz)

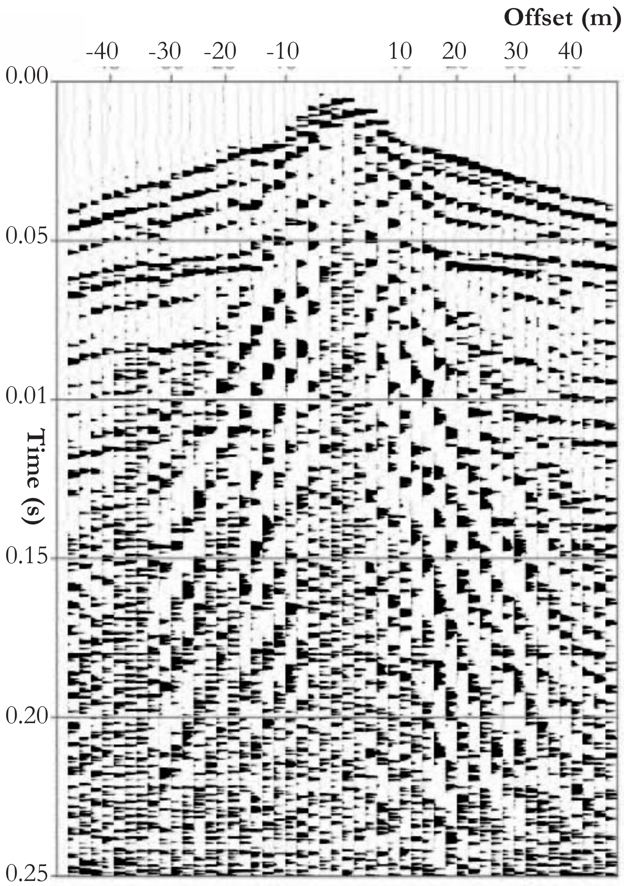

Fig. 3 - NSERC Dalmeny experiment: a typical shot gather with 0.1 s AGC applied for display purposes. Reflected energy is visible in the two-way traveltime interval ranging from 0.05 to 0.12 s. The inner cone of the record is dominated by the ground roll energy. Air blast with its typical velocity is also visible.
- Esperimento NSERC Dalmeny: esempio di registrazione sismica con applicato un guadagno AGC di 0.1 s. L'energia riflessa è chiaramente visibile nell'intervallo compreso tra 0.05 e 0.12 s. La porzione centrale della registrazione è dominata dall'energia del "ground roll". L'onda d'aria con il suo tipico carattere delimita il cono centrale della registrazione dove prevale il "ground roll".

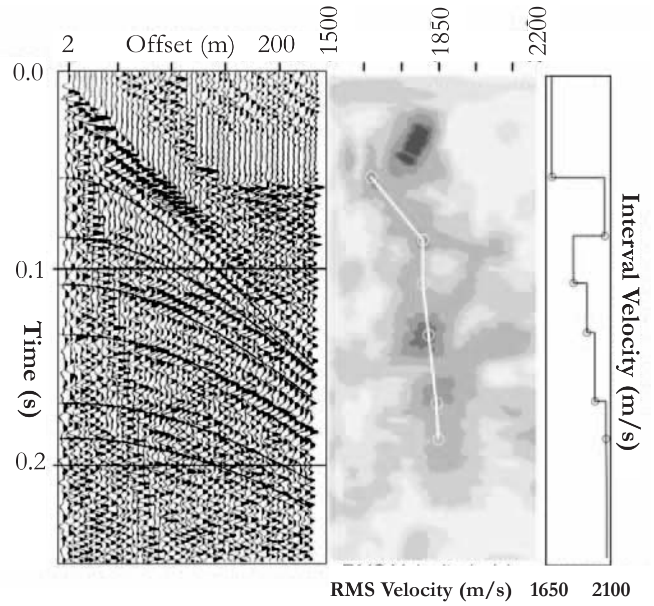

Fig. 4 - NSERC Dalmeny experiment: semblance plot of an extended spread shot gather. A 0.1 s AGC is applied for display purposes. The stacking velocity function is defined with a better accuracy recognizing and picking events at large offsets.
- Esperimento NSERC Dalmeny: analisi di velocità con tecnica "semblance" condotta su una registrazione aggregata ("extended spread") con applicato un guadagno AGC di 0.1 s.La funzione velocità di stack - profondità è definita con maggior grado di accuratezza quando è possibile analizzare gli eventi riflessi sino agli "offset" più lontani.

A series of channeled structures are visible at traveltimes ranging from 0.090 to 0.125 s in the CMP intervals 350-375, 300-250 and 225-100. These structures are directly incised in bedrock. The small channel on the west side of the section was the key for interpreting the other structures as it is was the only one intersected by a wellbore (at location 2047). The flanks of the two small western channels are steep and were not clearly resolved while the gentle flank of the eastern channel is better imaged.

In the upper part of the section the seismic image outlined a second channel infilling sequence, from CMP 150 to 300, whose bottom is marked by an erosional surface (fig. 6). The channel base occurs approximately at a traveltime of 0.065 s. The uppermost unit of the infilling sequence was interpreted, referring to borehole 1521, as sand layer.

3.3. - Parco Lambro experiment

The objective of the seismic experiment was two-fold: primarly to support hydrological modeling imaging the structure and the stratigraphy of the shallow Pleistocene and Holocene deposits and of the associated aquifers; secondly the application of the reflection technique in an urban setting, an environment contaminated with cultural noise and with severe restrictions in the deployment of the seismic source and of the spread layout.

The near surface geology in the study area consists of a 250 m thick sequence of continental and transitional deposits overlying an early Pleistocene marine clay bedrock. This sequence, in the hydrological literature (REGIONE LOMBARDIA & ENI-AGIP, 2002), is divided in three aquifer groups (namely A, B and C). The water table is located approximately 15 m below the surface. The upper unit (group A) is composed by sand and gravel deposits and represents a primary source of fresh water for the local community and the entire urban settlement. The middle unit (group B) is comprised of silt and clays with embedded thick sand and gravel layers. In some areas these gravel deposits are partially cemented and very similar to

Tab. 3 - *Data acquisition geometry and recording parameters for the Parco Lambro experiment.*
Geometrie di acquisizione e parametri di registrazione nell'esperimento del Parco Lambro.

PLAMBRO: Acquisition parameters	
CMP lines	1 x 850 m
Amplifier	GEOMETRICS GEODE
A/D conversion	24-bit
n. live channels	240
Geometry	variable split spread
receiver array	single 30 Hz geophone
receiver spacing	1.0 m
shot spacing	6.0 m
minimum offset	1.0 m
average CMP spacing	0.5 m
maximum fold	18
shot location	~1.0 m depth
shot type	blasting cap + 30g dynamite
Recording	
sampling rate	0.125 ms
low-cut filter	off

Tab. 4 - *Acoustic parameters utilized for forward modeling in the Parco Lambro experiment.*
- Parametri acustici utilizzati per la modellazione diretta nell'esperimento del Parco Lambro.

Acoustic unit / Lithology		Hydrostrat. unit	Thickness (m)	density (g/cmc)	Vp (m/s)	Z1/Z2
Sd0	Silt and clay	*Surface drifts*	1.0	1.50	500	0.53
Gs0	Gravel and sand	*Aquifer group A*	14.0	1.65	850	0.47
Gs1	Gravel and sand		18.5	1.80	1650	0.73
Cs0	Clay and silt		3.5	2.10	1950	1.20
Gs2	Gravel and sand		11.5	1.85	1850	0.80
Cs1	Clay and silt		4.0	2.15	2000	1.19
Gs3	Gravel and Sand	*Aquifer group B*	20.5	1.90	1900	0.56
Cg0	Conglomerate		4.0	2.40	2700	1.75
Gs4	Gravel and Sand		11.0	1.90	1950	0.57
Cg1	Conglomerate		4.0	2.40	2700	1.75
Gs5	Gravel and Sand		7.0	1.90	1950	0.82
Cl0	Clay		7.0	2.15	2100	1.17
S0	Sand	*Aquifer group C*	4.5	1.95	1975	0.82
Cl1	Clay		25.0	2.15	2150	1.17
S1	Sand		17.0	2.00	1975	0.84
Cl2	Clay		--	2.15	2200	

conglomerates. The lower unit (group C) is mainly comprised of clays and silts with embedded thin sand lenses.

Data acquisition (tab. 3) faced some major problems: because of the use of explosives recording was carried out in daylight hours with a high cultural noise level; drilling the shotholes deeper than 1 m, with the manual bit, was almost impossible for the coarse gravel nature of the deposits.

Reflected energy is clearly visible in the raw data although the records appear to be badly contaminated by low frequency surface waves and noisy because of the nearby ring highway vehicular traffic (fig. 7). The strong reflector (Cg0) occurring at 0.13 s was interpreted as the seismic signature of a conglomerate layer and represented a stratigraphic marker for the final interpretation. The horizon was also visible in the walk away test carried out before the real survey.

Major data processing efforts were dedicated to attenuating the coherent noise in order to be able to include the maximum number of traces in the final stack. Spectral balancing after a selective f-k filter (targeting the direct and guided waves) enhanced the reflected signal in the near offset traces. Although this filtering was effective, the inner near-source noise cone was partially muted out before stacking the data in the CMP domain. Stacking velocity was estimated via semblance analysis of the shot gathers and the COFF (Common Offset Stack).

The final seismic section (fig. 8) outlines a series of sharp reflecting horizons, clearly visible in the time window ranging from 0.07 to 0.20 s, which correspond to the major hydraulic boundaries laying in the depth interval ranging from 30 to 150 m.

Three boreholes (W3/4, W5/6 and W7/8), approximately aligned along the East-West direction very close to the reflection profile have been utilized to constrain the stratigraphic interpretation. The direct comparison of the reflections and synthetic zero-offset traces generated at borehole W5/6 (CMP 3200) helped in marking boundaries and establishing lateral correlation of primary events. The seismic signature of this synthetic trace was comparable to the stacked traces. Minor perturbation of the reflectivity series led to a further tuning of the correlation of real and synthetic data.

The acoustic parameters (tab. 4) utilized to compute synthetics were derived from different data sources. Material densities for each unit were estimated from geotechnical tests on core samples and from previous hydrogeological studies (M. Giudici, pers. comm.). P-wave velocities were estimated from refraction data, semblance velocity analysis, and measurements carried out

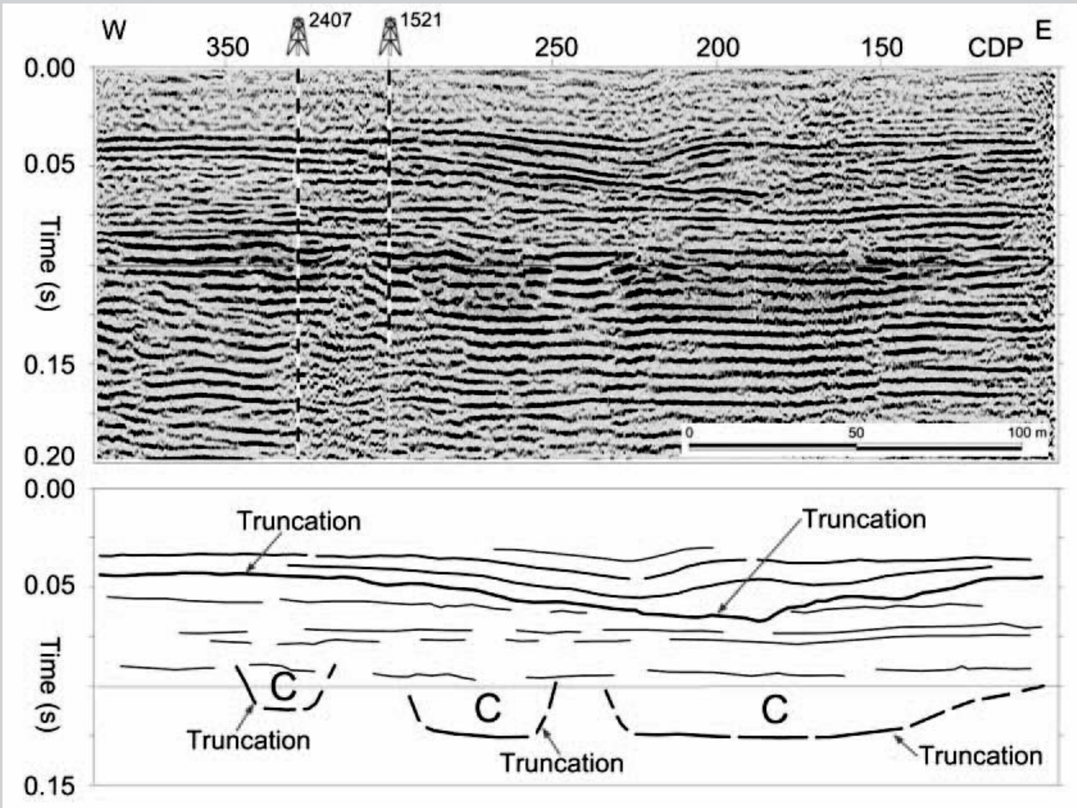

Fig. 5 - NSERC Dalmeny experiment: portion of the final stack of line 1 after migration (above) and the associated interpretation (below). Various small scale channeled structures (C) are visible in the two-way traveltime interval ranging from 0.090 to 0.125 s. These channels have a flat bottom and step flanks. The dipping flanks are not clearly resolved in the seismic image. A large erosion surface is visible at traveltime earlier than 0.065 s and in the CMP interval ranging from 150 to 300.

- Esperimento NSERC Dalmeny: segmento della sezione finale migrata della linea 1 (sopra) con la relativa interpretazione (sotto). E' visibile una serie di sequenze di canale nell'intervallo temporale compreso tra 0.090 e 0.125 s. Queste sequenze presentano una base quasi piatta e dei fianchi molto ripidi. I fianchi, in relazione alla forte inclinazione, non appaiono chiaramente risolti nell'immagine sismica. Un'importante superficie di erosione è visibile nell'intervallo di CMP compreso tra 150 e 300 ed a tempi inferiori a 0.065 s.

directly on core samples (REGIONE LOMBARDIA & ENI-AGIP, 2002).

Various small and medium scale channel infill sequences were recognized in the seismic section (FRANCESE *et alii*, 2003). The most prominent feature is a complex structure in north-east end of the profile. The bottom of the structure (BT) is marked by a clear discontinuity from CMP 3300 to 3600 at times from 0.13 to 0.16 s. The body of the structure, with a thickness ranging from 35 to 40 m, exhibits consistent clinoforms with a clear south-west vergence and an apparent dip ranging from 10 to 15 degrees. The depositional nature of the structure is somewhat problematic and up to now there is not enough geological insight to allow a reliable interpretation. A realistic hypothesis is the presence of a thick channel sequence in depositional group B that infer the continuity of the clay layer located at the boundary between aquifer groups B and C.

The subsurface geometry imaged by seismic was utilized to improve and refine a quasi-three dimensional model of the ground water flow (ROMANO *et alii*, 2002) in an area where the Municipality drilled several production wells currently active. The main purpose of the model is to predict the response of the aquifer to changes in the exploitation of the water resource.

3.4. - PCS ROCANVILLE EXPERIMENT

The seismic experiment addressed a problem similar to the one targeted by the PCS Cory survey. Borehole information and remote sensing analysis suggested the presence of a preglacial-channel incised within the Cretaceous bedrock, in the vicinity of the tailing pile and ponds of a potash mine.

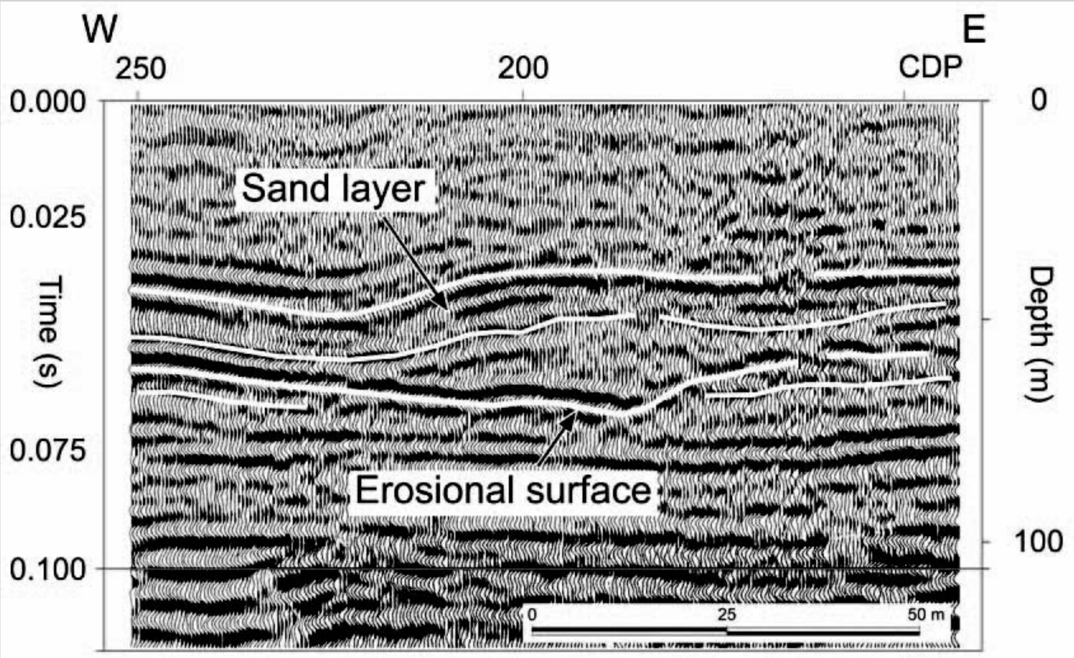

Fig. 6 - NSERC Dalmeny experiment: detail of the final stack of line 1 after migration. The shallower erosion surface is depicted in the seismic section and it defines the base of a channel sequence. Top and bottom of a sand layer, above the erosion surface, are also clearly imaged by seismic reflections.
- *Esperimento NSERC Dalmeny: dettaglio della sezione finale migrata della linea 1. La superficie di erosione più superficiale appare chiaramente risolta nell'immagine sismica ed essa costituisce la base di una sequenza di canale. Al di sopra della superficie di erosione una serie di eventi riflessi evidenziano la base ed il tetto di un livello sabbioso.*

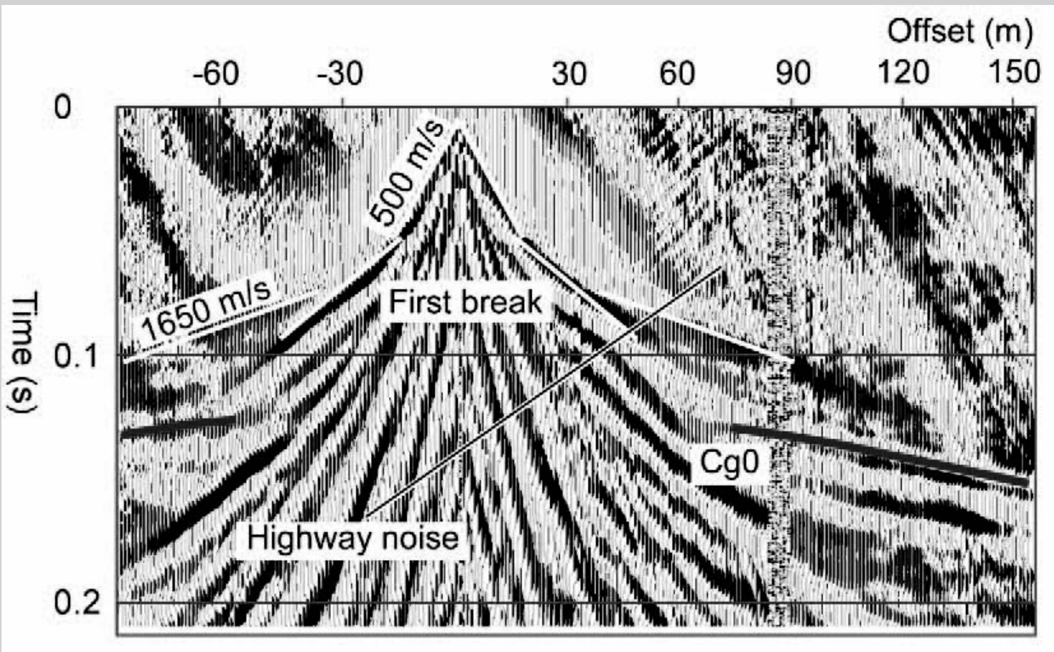

Fig. 7 - Parco Lambro experiment: a typical shot gather from the south-west side of the seismic line. A 0.1 s AGC was applied for display purposes. The record is overpowered by coherent noises. Reflected energy occurs in the two-way traveltime interval ranging from 0.10 to 0.15 s. The signature of a conglomerate layer is marked "Cg0". A series of noise arrivals from nearby ring highway are also clearly visible.
- *Esperimento del Parco Lambro: tipica registrazione relativa al lato sud-occidentale della linea sismica. Un guadagno AGC pari a 0.1 s è stato applicato per bilanciare le ampiezze. La registrazione e' dominata da eventi di rumore coerente. Alcuni eventi riflessi sono visibili da 0.10 a 0.15 s. La risposta di uno strato di ghiaie parzialmente cementate (conglomerato) è stata evidenziata con la lettera "Cg0". I treni di onde con tipico "move-out" lineare sono causati dal traffico veicolare sulla vicina tangenziale.*

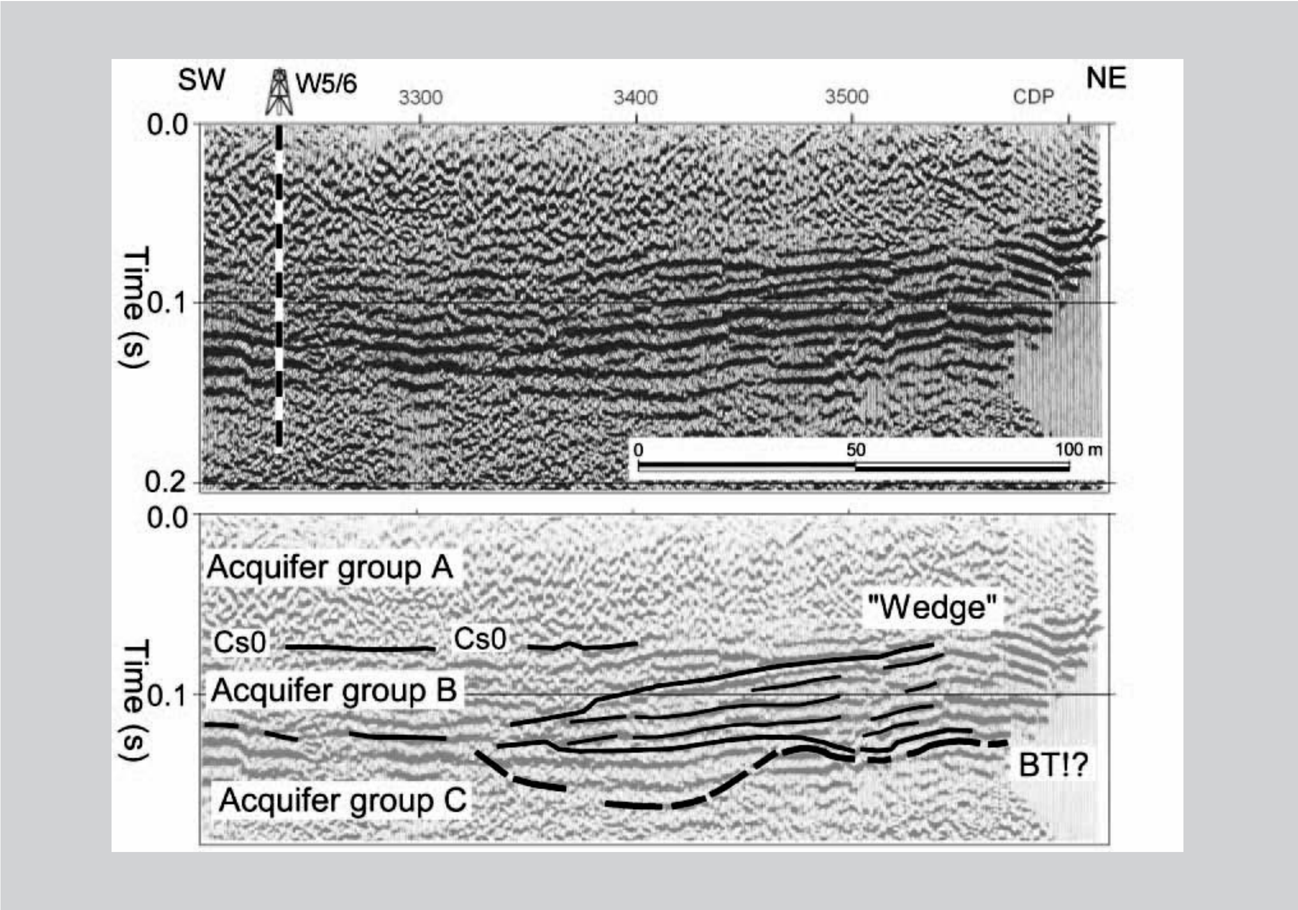

Fig. 8 - Parco Lambro experiment: north-eastern portion of the final stack (above) and associated interpretation (below). The seismic reflection "Cs0" outlines the boundary between aquifer groups A and B and the boundary between aquifer groups B and C is also outlined by a reflecting horizon. Both the two events were recognized based on borehole correlation. A complex depositional feature with dip layering is visible in the right side of the profile. The base of this unit is marked by an erosional surface ("BT") that truncates the underlying stratigraphy.

- Esperimento del Parco Lambro: segmento nord-orientale della sezione finale (sopra) e relativa interpretazione (sotto). La riflessione evidenziata con la lettera "Cs0" corrisponde al limite tra i complessi acquiferi A e B. Il limite tra i complessi acquiferi B e C è evidenziato da un secondo orizzonte riflettente. I due eventi sono stati interpretati sulla base di correlazioni stratigrafiche con dati di pozzo. Una struttura deposizionale complessa, con stratificazione inclinata, e' visibile sul lato destro del profilo. La base dell'unità ("BT") è di tipo erosivo e tronca gli strati sottostanti.

The possibility of a rapid migration of the salty brines into the known fresh water aquifers embedded in the sand and gravel deposits of the channel sedimentary infill was a major concern for the government and the local community.

The infilling sequence was then targeted with a 2-D high resolution seismic reflection survey to outline its thickness to a depth of 100-120 m and to assist in constraining petrophysical properties (density, porosity and permeability) of the different deposits.

In the study area the near surface geology consists of a thick sequence of alluvial, interglacial and glacial deposits, lying uncomformably on Cretaceous bedrock formed by marine shales the top of which ranges in depth from only a few 10's to 200 metres. In the overlying Quaternary deposits there are various high permeability gravel and sand units. The major aquifer is hosted in a 13-15 m thick gravel layer with a top boundary located 35-40 m below the surface.

The shot gathers exhibit low signal to noise ratios (Fig. 9) especially in the south-eastern portion of the profile were the shotholes were not deeper than 1 meter. A variety of coherent noise phases are recognizable in the raw records. Each noise was selectively filtered out from the data after an accurate recognition of its temporal and spatial properties. First breaks, air blast and ground roll were partially or entirely muted out prior to sort the data in the CMP domain and stack. Reflected energy is clearly visible in the raw data in the traveltime interval 0.05-0.10 s and its dominant frequency ranges from 180 to 200 Hz.

The stacking velocity function was estimated via picking in the semblance domain on the CMP gathers (fig. 10). Velocity analysis was particularly difficult because of the presence of interfering

Tab. 5 - *Data acquisition geometry and recording parameters for the PCS Rocanville experiment.*
- Geometrie di acquisizione e parametri di registrazione nell'esperimento PCS Rocanville.

PCS- ROCANVILLE: Acquisition parameters	
CMP lines	1 x 1000 m
Amplifier	OYO DAS-1
A/D conversion	21-bit
n. live channels	144
Geometry	split spread
receiver array	10 gathered 10 Hz geoph.
receiver spacing	1.0 m
shot spacing	4.0 m
minimum offset	1.0 m
average CMP spacing	0.5 m
maximum fold	24
shot location	surface / 1.0-3.0 m depth
shot type	EWG / seismocap + 20g dyn.
Recording	
sampling rate	0.500 ms
low-cut filter	on

reverberations. Results from numerical modeling of borehole data, extended profiles and VSP data were utilized to establish an initial velocity function. This initial function was iteratively refined looping through the residual static computation until no further improvements in events hyperbolic move out was observed. The accuracy in estimating the velocity for the move out correction was also a key process in stacking out undesired events (FRANCESE & HAJNAL, 1997; FRANCESE *et alii*, 2002).

The final section reveals a complex subsurface and many well-defined reflecting horizons (fig. 11). The wavelet has a vertical resolution of 2.5 m and a horizontal resolving power of about 6 m (with a velocity of 1800 m/s at a depth of 50 m). Primary reflection energy is clearly present at traveltimes ranging from 0.025 to 0.150 s well within the target depth. Pre-survey borehole information (well A3) provided an initial assessment of the reflecting horizons and synthetic zero-offset traces were direct markers to correlate the seismic events with the local stratigraphy.

Three gravel units (G1-G3) and the associated aquifers are clearly imaged in the seismic profile.

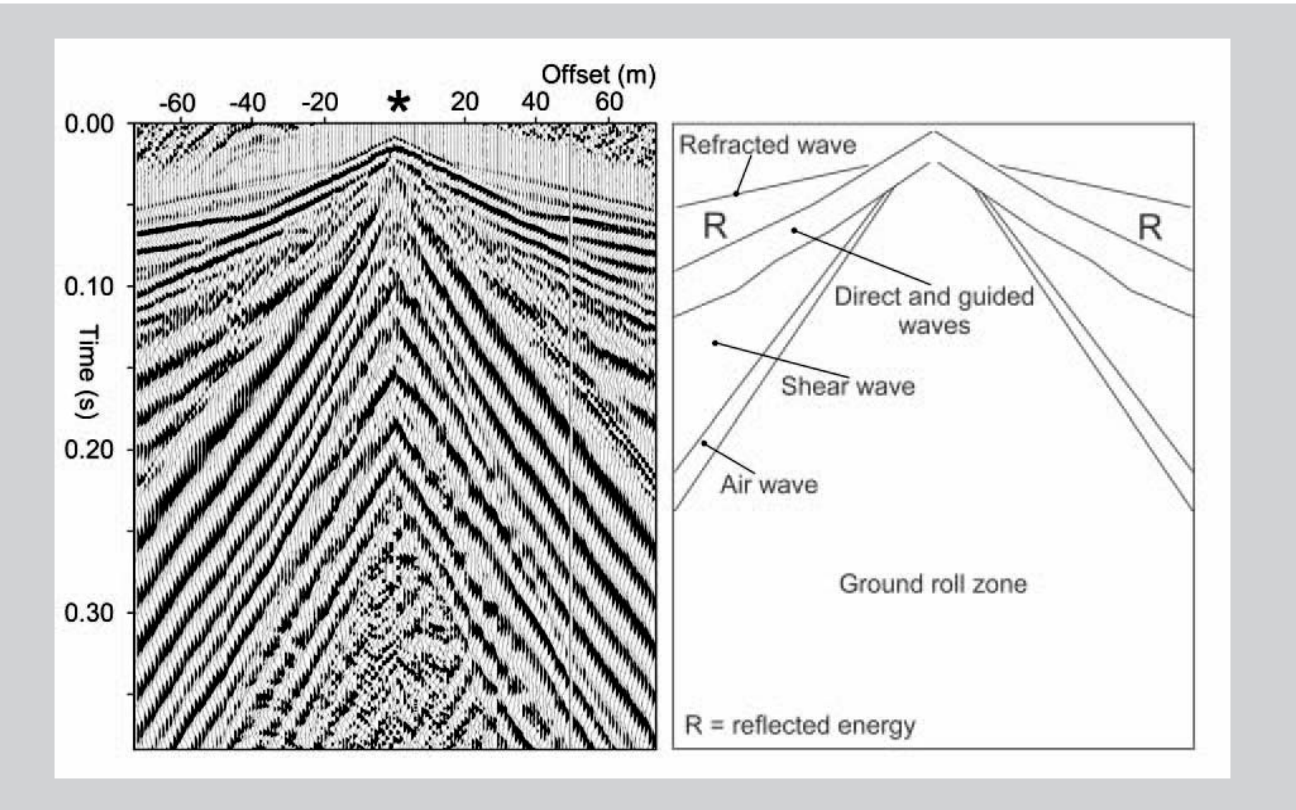

Fig. 9 - PCS Rocanville experiment: a typical shot gather from the north-western side of the seismic line (left) with the indication of the different phases (right). A 0.1 s AGS was applied for display purposes. A variety of coherent noise events are visible in the recorded wavefield. Reflected energy occurs only at far offsets in the traveltime interval 0.05-0.10 s.
- *Esperimento PCS Rocanville: tipica registrazione relativa al lato nord-occidentale della linea sismica (a sinistra) con indicazione delle principali fasi (a destra). Ai dati è stato applicato un guadagno AGC pari a 0.1 s. Nei dati grezzi il campo d'onda appare dominato da diversi tipi di rumore coerente e gli eventi riflessi appaiono solamente nell'offset lontano a tempi compresi tra 0.05 e 0.10 s.*

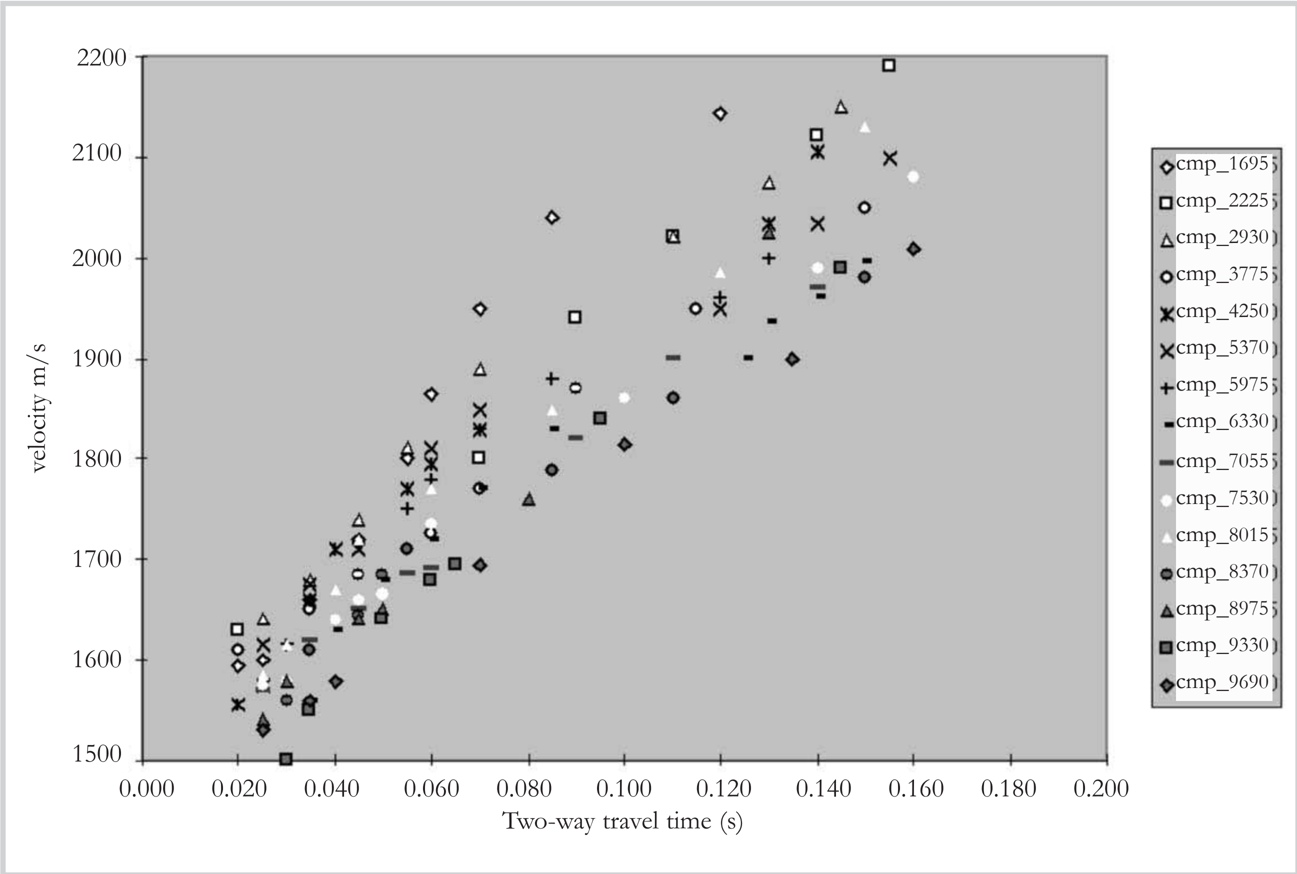

Fig. 10 - PCS Rocanville experiment: stacking velocity function at various CDP locations along the seismic line. Stacking velocities range from 1500 to 2200 m/s. - *Esperimento PCS Rocanville: funzione velocità-tempo utilizzata per lo "stack" a varie stazioni CDP lungo la linea sismica. La velocità di "stack" varia tra 1500 e 2200 m/s.*

The top of unit G2 is marked by a strong reflection and it is clearly imaged from the north-west boundary of the profile to CMP 3900 where it terminates beneath unit G1. This zone is gently south-east dipping. This unit is the most important aquifer embedded in the channel infill sequence and the successful mapping of its geometry was one of the major goals of the seismic survey. The gravel unit G1 is imaged from the south-east boundary of the profile to CMP 4500 where its northern limits are reached. The unit exhibits a north-west prograding geometry, with a 10 degree dipping stratification (these clinoforms appear to be periodic depositional events of a stream delta in a lacustrine environment). In the 2D seismic image there is not evidence of contact between gravel units G1 and G2 and the two layers have been interpreted as stand alone aquifers. The top and the bottom of gravel unit G3 are outlined by weak reflections. The unit overlays the Cretaceous shales and has its maximum thickness on the south-east boundary of the profile and pinches out at CMP 4300.

Boreholes B1 and B2, which were drilled following the seismic investigation, validated the interpretation (fig. 11) and confirmed the aquifer framework as outlined by the seismic response.

The good quality of the stacked section suggested achieving a better insight about the physical properties of the underground deposits with further processing.

In the literature there are many analytical expression to convert seismic impedance data to porosity using deterministic procedures and various sand-shale models to examine velocity-porosity relationship (WYLLIE *et alii*, 1956; KUSTER & TOKSOZ, 1974a, b; XU & WHITE, 1995; etc.). The basic equations derived from XU & WHITE (1995) relate sonic log transit times (δt) (eq. 1) and bulk densities (ρ_b) (eq. 2) to volumetric shale fraction (F_{sh}) and porosity (φ_e).

$$\delta t = (1- \varphi_e - F_{sh}).\ \delta t_m + F_{sh}\ .\delta t_{sh} + \varphi_e + \delta t_f \qquad (1)$$

$$\rho b = (1- \varphi_e - F_{sh}).\ \rho m + F_{sh}\ .\ \rho_{sh} + \varphi_e\ .\ \rho_f \qquad (2)$$

where φ_e is the observed porosity value, F_{sh} is the observed shale fraction value, δt_{ms}, δt_{sh} and δt_f

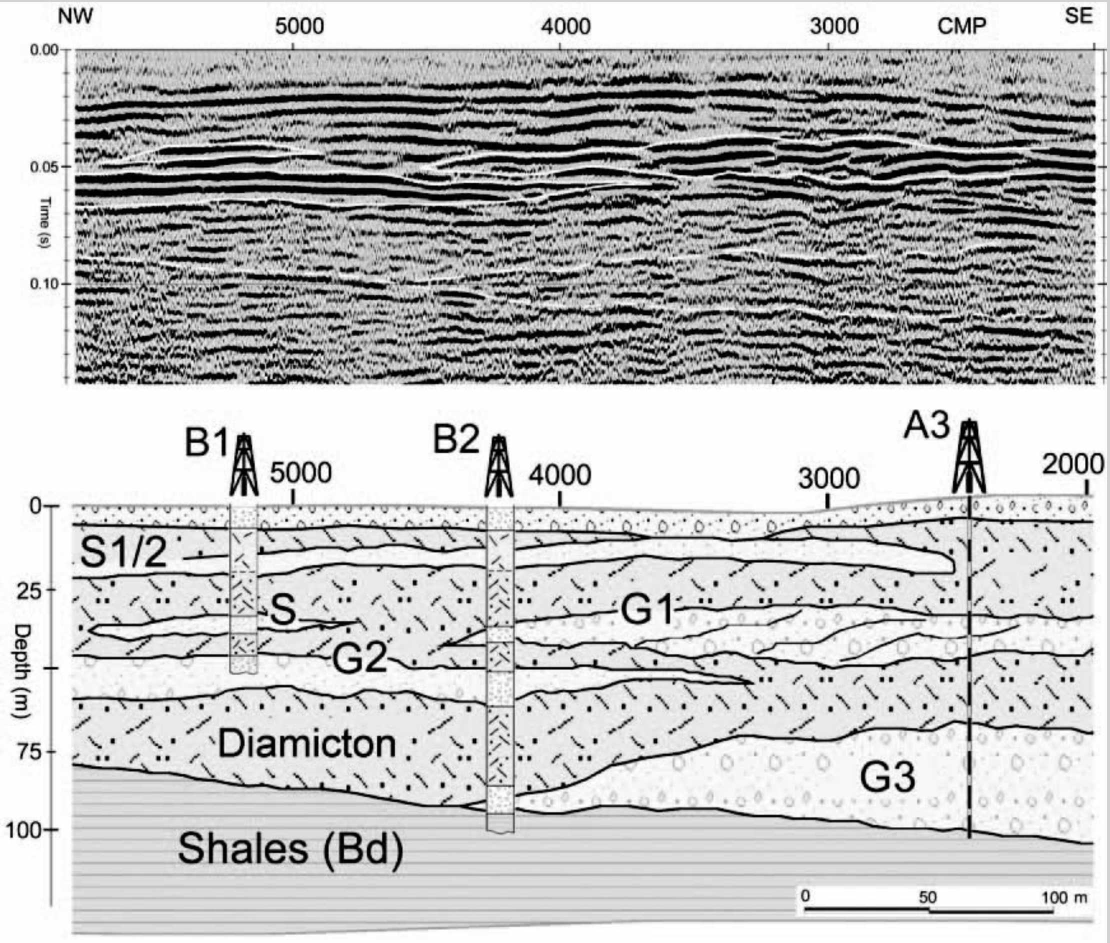

Fig. 11 - PCS Rocanville experiment: south-eastern segment of the stacked section (above) and associated interpretation (below, modified after FRANCESE *et alii*, 2002). A complex stratigraphic and structural framework above a seismically well defined uncomformity is outlined by primary reflections. Thin sand lenses appear at different depth in the upper deposits ("S" and "S1/2"). A prograding unit, with crossbedding stratification, is visible between CMPs 2035 and 4535 ("G1"). A gravel layer, terminating at CMP 3600 in the left side of the section, is also outlined by reflections in the traveltime interval 0.050-0.065 s. Post-seismic test boreholes B1 and B2 confirmed the former interpretation of the seismic profile.

- Esperimento PCS Rocanville: segmento sud-orientale della sezione finale (sopra) e relativa interpretazione (sotto) (modificata da FRANCESE et alii, 2002). Gli eventi riflessi evidenziano un'architettura deposizionale complessa sopra una "unconformity" chiaramente definita nell'immagine sismica. Alcune sottili lenti di sabbia appaiono a varie profondità nel complesso deposizionale superiore ("S" ed "S1/2"). Un'unità progradante, con stratificazione incrociata, è visibile nell'intervallo di CMP 2035-4535 ("G1"). Uno strato ghiaioso, che termina al CMP 3600 sul lato sinistrao della sezione, è ben evidenziato da eventi riflessi nell'intervallo temporale 0.050-0.065 s. I pozzi stratigrafici B1 e B2, perforati in base alle risultanze sismiche, hanno confermato l'ipotesi interpretativa.

are the matrix, the shale and the fluid transit time and ρ_m, ρ_{sh} and ρ_f are the matrix, the shale and the fluid bulk densities. Using these parameters, the acoustic impedance AI is:

$$AI = \frac{\rho b}{\delta t} \qquad (3)$$

Since the acoustic impedance is the ratio of density and sonic times (eq. 3), and assuming that equations (1) and (2) are reasonably valid, the porosity could be expressed in terms of acoustic impedance and shale fraction values (4).

$$\varphi = \frac{\left[\left(c_0 - AI \cdot c_1\right) - F_{sb} \cdot \left(c_2 - AI \cdot c_3\right)\right]}{\left(c_4 - AI \cdot c_5\right)} \qquad (4)$$

The coefficients c_0-c_5 express mathematical relationship between density and transit times of matrix, shale fraction and pore fluids. In the PCS Rocanville example, porosity prediction, based on the above relationship, was then attempted. The processing flow was slightly modified to better preserve the signal character and a new stack (limited offset stack) was generated. The acoustic impedance was computed (fig. 12) using the spar-

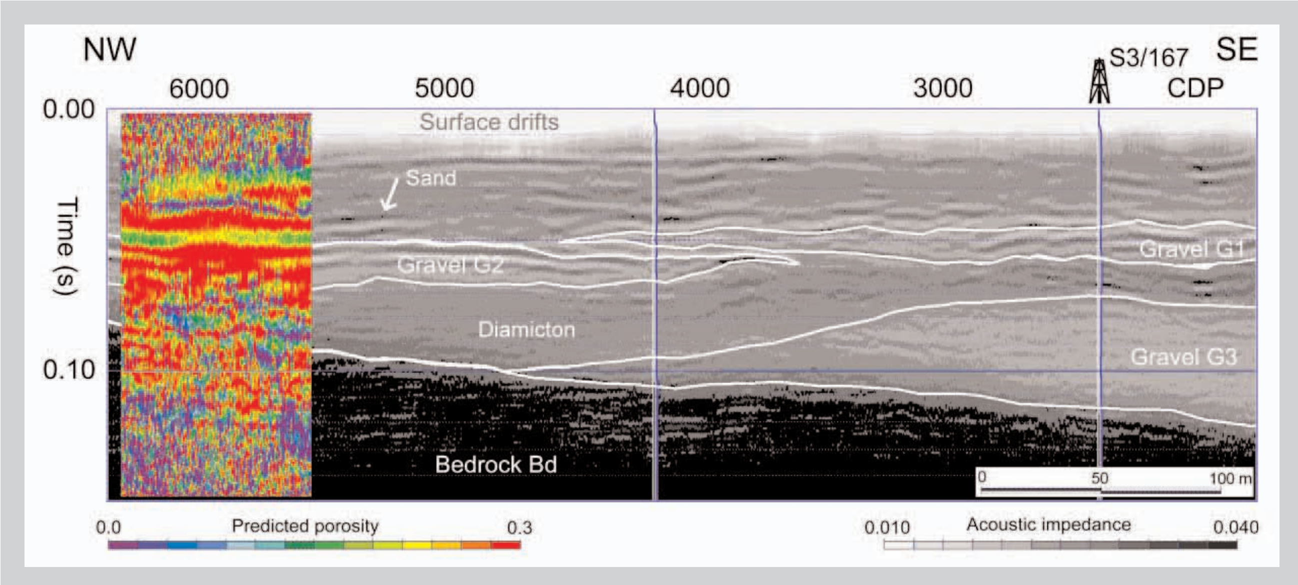

Fig. 12 - PCS Rocanville experiment: acoustic impedance section computed by sparse spike inversion of the seismic wavelet. Porosity prediction (on the left) for a limited portion of the stacked section was obtained combining the acoustic impedance section with the shale fraction values measured with well logs at nearby boreholes.

- Esperimento PCS Rocanville: sezione di impedenza acustica calcolata con la tecnica di inversione "sparse spike" dell'ondina sismica. La mappa di porosità, visibile per una porzione limitata della sezione (lato sinistro), è stata ottenuta eleborando la sezione di impedenza acustica ed i valori di frazione argillosa misurati mediante "logs" in foro in pozzi adiacenti alla linea sismica.

se spike wavelet inversion technique (LEVY & FULLAGAR, 1981). The shale fraction was derived from gamma-ray logs carried out on the same formations very close to the study area. Porosity was then predicted, for a limited portion of the stacked section (fig. 12), combining the acoustic impedance with the shale fraction. An initial analysis of the predicted values indicates a good agreement of porosity with the lithology of the different hydrogeological units.

4. - CONCLUSIONS

Some of the advances and problems associated with shallow CMP profiling in different geology settings and acquisition environments have been presented and discussed utilizing data from four different case studies. The survey results outlined how high resolution seismic reflection could be successfully implemented and generate vital results for shallow aquifer mapping in the quaternary deposits. Complex depositional structures are actually in the target resolution of this geophysical technique in view of its enhanced imaging capability.

The effectiveness of shallow CMP profiling greatly depends on the quality of the data acquisition and on the careful application of the processing procedures. Multi-stage modeling and field tests, although time consuming, are indispensable to aid both the survey design and the task of recognizing primary events in the raw and processed records.

To overcome the potential problems with acquisition, an elevate number of channels and buried sources were employed in the majority of our experiments. For these studies, small explosive charges appear to be still the best choice of seismic source although excellent results were obtained with small and medium size vibrators at different sites.

In the Dalmeny case the entire survey was carried out with single blasting caps only and no dynamite charge. Unfortunately the shots from the second line, because of the soil conditions, exhibited very low signal amplitude. In the Rocanville experiment the entire line was collected with an Elastic Wave Generator impact source with comparable results.

Velocity-depth function estimation and static corrections are critical issues in shallow exploration. In the Cory experiment data stacked poorly until high accuracy refraction static corrections were computed and applied to the data.

Finally the reflected energy at early traveltimes is generally disturbed by high amplitude coherent noise, particularly surface waves. In the Parco Lambro and in the Rocanville datasets a diversity of complex and overlapping source-generated noises caused severe interference with the primary signal. These disturbances have to be independently recognized through their move-out velocities and spectral properties in order to design specific procedures for their suppression.

Prediction of petrophysical properties from well ties and wavelet inversion showed some potentials in shallow data when the signal to noise ratio is adequate. Well logs and specific processing is needed to achieve these results. Future research development will be focused on a comprehensive shallow reservoir characterization based on the inversion of the seismic data volume to fully support the groundwater flow modeling.

Major obstacles in the commercial growth of near surface reflection seismic profiling are the limitations of equipment and sources and the added difficulties in data processing and interpretation of the final data sets. The cost-per-channel is still too high as compared to other geophysical techniques and the number of available channels rarely meets the theoretical requirements. The additional nonproductive work to obtain permits to transport and use explosives generally introduces significant delays in the field data acquisition resulting in additional costs for the seismic exploration. Alternative sources are generally site dependant and small and medium scale vibrators are not easily available in the market. Data processing should be conducted by experienced analysts with a solid background on near surface elastic wave propagation and digital signal processing techniques. In many cases interpretation does not benefit from other data sources (e.g. borehole stratigraphy, geophysical logs, vertical seismic profiles) and it could easily fail despite the quality of the final stack.

The budget assessment for a high-resolution seismic survey is not straightforward because of the variability of logistics, site conditions, station spacing, required folding and a variety of other parameters. A rough estimate, partially based on ANAS (Italian Roads Agency) and FFSS (Italian Railways) compensation schedules, indicates a cost per meter ranging from 10 to 25 Euro. This quotation is valid for medium fold surveys (1200 to 1800 %) and close station spacing (1 m to 2 m). The daily production rate for a crew of three or four people, with the above source-station parameters could be in the range of 500-1000 m (in case of a source deployed separately of with an extra person operating the source).

In the Rocanville experiment the cost of drilling and loading the 400 shotholes was about 50% of the entire data acquisition cost while in the Parco Lambro survey 100 shotholes were drilled with a portable drilling device (operated by one person) in less than two days with marginal costs.

Acknowledgments

The different experiments have been financially supported by: Potash Corporation of Saskatchewan Inc.; Natural Sciences and Engineering Research Council of Canada; Canada Research Chairs program and infrastructural funding provided by the Alberta Science and Research Authority; Italian Ministry for Education, University and Scientific Research.

The authors also thank the Municipality of Milano for the permission to carry out the survey and dr. eng. RICCARDO AIROLDI, *head of the Municipal Water Works of Milano for his assistance. A special acknowledgement to* MAURO GIUDICI *for his review and helpful comments on the manuscript.*

REFERENCES

BLACK R.A., STEEPLES, D.W. & MILLER R.D. (1994). - *Migration of shallow seismic reflection data.* Geophysics, **59** (3): 402-410.

BOOTH D.B. & JACKSON C.R. (1997) - *Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation.* Journal of the American Water Resource Association, **33** (5): 1077-1090.

BRADFORD J.H. (2002a) - *Depth characterisation of shallow aquifers with seismic reflection, part I, -The failure of NMO velocity analysis and quantitative error prediction.* Geophysics, **67**: 89-97.

BRADFORD J.H. (2002b) - *Depth characterisation of shallow aquifers with seismic reflection, part II-Prestack depth migration and field examples.* Geophysics, **67**: 98-109.

BRADFORD J.H., SAWYER D.S., ZELT C.A. & OLDOW J.S. (1998) - *Imaging a shallow aquifer in temperate glacial sediments using seismic reflection profiling with DMO processing.* Geophysics, **63**: 1248-1256.

BUKER F., GREEN A.G. & HORSTMEYER H. (1998) - *Shallow seismic reflection study of a glaciated valley.* Geophysics, **63**: 1395-1407.

CARR B.J. & HAJNAL Z. (1999) - *P- and S-wave characterization of near-surface reflectivity from glacial tills using vertical seismic profiles.* Geophysics, **64**: 970-980.

CARR B.J., HAJNAL Z. & PRUGGER A. (1998) - *Shear-wave studies in glacial till.* Geophysics, **63**: 1273-1284.

EUROPEAN COMMUNITY (2000) - *Directive 2000/ 60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.* Official Journal **L 327**, 22/12/2000: 1-73.

FRANCESE R.G. & HAJNAL Z. (1997) - *Shallow reflection imaging of complex stratigraphic features in glacial deposits.* 59th Annual Meeting, EAGE, Geneva, Switzerland, Program and abstracts.

FRANCESE R.G., HAJNAL Z. & PRUGGER A. - (2002). *High-resolution images of shallow aquifers. A challenge in near surface seismology.* Geophysics, **67**: 177-187.

FRANCESE R.G., ZAJA A., GIUDICI M. & SCHMITT D. (2003). *Reflection seismic imaging of shallow aquifers in Milano (northern Italy). Annual Meeting, EGS-EGU-AGU* Joint Assemly, Nice, France, Program and abstracts.

HOOGE C.D. (1996) - *High resolution reflection imaging of a shallow groundwater aquifer.* M. Sc. Thesis, University of Saskatchewan.

HOOGE C.D., HAJNAL Z. & SCHREINER B. (1994) - *High-resolution reflection imaging of a groundwater aquifer in glacial tills, central Saskatchewan. 64th Ann. Internat.* Mtg., Soc. of Expl. Geophys., Extended Abstracts, 620-623.

HUNTER J.A., PULLAN S.E., BURNS R.A., GAGNE R.M. & GOOD R.L. (1984) - *Shallow seismic reflection mapping of the* *overburden-bedrock interface with the engineering seismograph - Some simple techniques*. Geophysics, **49**: 1381-1385.

JARVIS K.D. & KNIGHT R.J. (2002) - *Aquifer heterogeneity from SH-wave seismic impedance inversion*. Geophysics, **67**: 1548-1557.

JUHLIN C., PALM H., MULLERN C.F. & WALLBERG B. (2002) - *Imaging of groundwater resources in glacial deposits using high-resolution reflection seismic, Sweden*. Journal of Applied Geophysics, **51**: 107-120.

KUSTER G.T. & TOKSOZ M.N. (1974a) - *Velocity and attenuation of seismic waves in two-phase media - Part I: Theoretical formulations.* Geophysics, **39**: 587-606.

KUSTER G.T. & TOKSOZ M.N. (1974b) - *Velocity and attenuation of seismic waves in two-phase media - Part II: Experimental results.* Geophysics, **39**: 607-618.

LANZ E., PUGIN A., GREEN A. & HORSTMEYER H. (1996) - *Results of 2- and 3-D high-resolution seismic reflection survey of surficial sediments.* Geophys. Res. Lett., **23**: 491-494.

LEVY S. & FULLAGAR P.K. (1981) - *Reconstruction of a sparse spike train from a portion of its spectrum and application to high-resolution deconvolution*. Geophysics, **46**: 1235-1243.

MATSUBARA Y., TAKAHASHI T., GHOSE R. & KAIDA Y. (1995) - *Very shallow subsurface imaging using a portable vibrator. 65th Ann. Internat.* Mtg., Soc. of Expl. Geophys., Expanded Abstracts, 415-418.

MILLER R.D., ANDERSON N.L., FELDMAN H.R. & FRANSEEN E.K. (1995) - *Vertical resolution of a seismic survey in stratigraphic sequences less than 100 m deep in southeastern Kansas.* Geophysics, **60**: 423-430.

MILLER R.D., PULLAN S.E., STEEPLES D.W. & HUNTER J.A. (1992) - *Field comparison of shallow seismic sources near Chino, California.* Geophysics, **57** (5): 693-709.

MILLER R.D., PULLAN S.E., STEEPLES D.W. & HUNTER J.A. (1994) - *Field comparison of shallow P-wave seismic sources near Houston, Texas.* Geophysics, **59** (11): 1713-1728.

MILLER R.D., PULLAN S.E., WALDNER J.S. & HAENI F.P. (1986) - *Field comparison of shallow seismic sources*. Geophysics, **51**: 2067-2092.

NIJHOF V. (1990) - *Portable high-frequency vibrator implemented in a compact PC-based seismic system.* 60th Ann. Internat. Mtg, Soc. of Expl. Geophys., Extended Abstracts, 942-943.

PENNINGTON W.D. (1997) - *Seismic petrophysics: An applied science for reservoir geophysics.* The Leading Edge, **16** (3): 241-244.

REGIONE LOMBARDIA & ENI-AGIP (2002) - *Geologia degli Acquiferi Padani della Regione Lombardia.* A cura di C. CARCANO & A. PICCIN. S.EL.CA, Firenze, 130 pp.

ROMANO E., GIUDICI M., & PONZINI G. (2002) - *Simulation of interactions between well fields with nested models: a case study.* Acta Universitatis Carolinae - Geologica, **46**: 637-640.

SCHMIDT D.P. (2000) - *Geophysical investigation of the shallow subsurface using seismic reflection and wireline logging methods.* M. Sc. Thesis, University of Sakatchewan, Canada.

SCHMITT D.R. (1999) - *Seismic attributes for monitoring of a shallow heated heavy oil reservoir:* A case study. Geophysics, **65**: 368-377.

SHARPE D., PUGIN A., PULLAN S.E. & SHAW J. (2004) - *Regional unconformities and the sedimentary architecture of the Oak Ridges Moraine area, southern Ontario.* Can. J. Earth Sci., **41** - 183-198.

SIAHKOOHI H.R. & WEST G.F. (1996) - *3-D seismic imaging of complex structures in glacial deposits.* 66th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 873-876.

STEEPLES D.W., KNAPP R.W. & MCELWEE C.D (1986) - *Seismic reflection investigations of sinkholes beneath Interstate Highway 70 in Kansas.* Geophysics, **51**: 295-301.

STEEPLES D.W. & MILLER R.D. (1990) - *Seismic reflection methods applied to engineering environmental and groundwater problems.* In: WARD S.W. (Ed.) *"Geothecnical and environmental geophysics*". **1**: 1-30.

STEEPLES D.W. & MILLER R.D. (1998) - *Avoiding pitfalls in shallow seismic reflection surveys.* Geophysics, **63**: 1213-1224.

VAN DER VEEN M., SPITZER R., GREEN A.G. & WILD P. (2001) - *Design and application of a towed land-streamer system for cost-effective 2-D and pseudo-3-D shallow seismic data acquisition.* Geophysics, **66**: 482-500.

WARDELL N., SORMANI L., SINCERI R., ROSSI G., NIETO D. & DEL NEGRO E. (2003) - *Un rilievo sismico 3-D per scopi ambientali (Valeria).* 22nd Nat. Mtg. GNGTS, Extended Abstracts, 424-426.

WIEDERHOLD H., BUNESS H.A. & BRAM K. (1998) - *Glacial structures in northern Germany revealed by a high-resolution reflection seismic survey.* Geophysics, Soc. of Expl. Geophys., **63**: 1265-1272.

WYLLIE M.R.J., GREGORY A.R. & GARDNER L.W. (1956) - *Elastic wave velocities in heterogeneous and porous media.* Geophysics, **21**: 41-70.

XU S. & WHITE R.E. (1995) - *A new velocity for clay-sand mixtures.* Geophys. Prosp., **43**: 91-118.

YILMAZ O. (1987) - *Seismic data processing.* Investigations in Geophysics N.2*,* Soc. of Expl. Geophys, Tulsa, pp. 525.