Article

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Claude Signer, Georges E. Gorin, André Pugin, Walter Wildi

Résumé
Une étude de sismique réflexion à haute résolution a été menée sur le Plateau suisse au sud de Fribourg. Son but était de déterminer la géométrie de corps sédimentaires quaternaires d'origine glaciaire et périglaciaire pouvant atteindre une épaisseur de 100 mètres. Cinq unités/ sous-unités sédimentaires, associées à deux importants cycles glaciaires, remplissent un réseau de paléo-vallées glaciaires creusées dans le soubassement molassique tertiaire. Ces unités consistent essentiellement de dépôts fluviatiles, fluvio-glaciaires et glacio-lacustres. Parmi ceux- ci, une importante série fluvio-glaciaire formée par un système de sandurs présente un intérêt particulier, car sa partie inférieure contient un aquifère.
Quelques cinq kilomètres de données sismiques à haute résolution ont été acquises en utilisant un marteau comme source, puis traitées sur PC. L'énergie sismique a été suffisante pour pénétrer jusqu'à 100 m de sédiments glaciaires. Les profils sismiques ont été calibrés à l'aide de puits et d'affleurements. Les paléo-vallées glaciaires y sont clairement identifiables, ainsi que trois à quatre unités quaternaires les remplissant. Les tills sous-glaciaires, compactés et latéralement discontinus sont identifiés par des réflexions à forte amplitude. La séquence fluvio-glaciaire étudiée a une bonne continuité latérale et sa base se marque généralement par une bonne réflexion. Le sommet de cette séquence est soit très réflectif lorsque qu'elle est recouverte de diamictes peu perméables, soit peu réflectif lorsque ces dernières ont été érodées et que la séquence est directement recouverte par des dépôts fluvio-glaciaires poreux. Par conséquent, ce changement de réflectivité permet de mettre en évidence les zones où l'aquifère est exposé aux risques de pollution de surface («fenêtres hydrauliques»).
Bien que d'extension limitée, les données acquises dans cette étude démontrent la contribution de la sismique à haute résolution pour la délinéation dans le sous-sol de corps sédimentaires glaciaires et périglaciaires. En particulier, elles permettent de cartographier l'extension verticale et latérale du réservoir aquifère fluvio-glaciaire. Elles fournissent également des informations sur la nature et la géométrie des roches formant l'encaissant du réservoir poreux, permettant ainsi de mieux connaître les cheminements possibles des eaux pouvant atteindre l'aquifère.

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Although patchy, the data acquired in this study demonstrate how high resolution seismic can contribute to delineate glacial and periglacial sedimentary bodies in the subsurface. In particular, the vertical and lateral extension of the aquifer-bearing outwash sequence can be mapped. Seismic information also helps to identify the nature and geometry of the rocks encasing the porous reservoir (e.g. the capping sediments, or the flanks of the palaeovalleys), thereby giving clues of possible pathways for the water to reach the reservoir.

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INVESTIGATION OF A GLACIAL OUTWASH SEQUENCE ON THE SWISS PLATEAU USING HIGH RESOLUTION SEISMIC REFLECTION

■

Claude SIGNER*, Georges E. GORIN**, André PUGIN** and Walter WILDI**

ABSTRACT

High resolution reflection seismic investigations were carried out on the Swiss Plateau south of Fribourg to delineate the geometry of glacial and periglacial, up to 100 m thick, Quaternary sedimentary bodies. Five main sedimentary units/subunits associated with two major glacial cycles are infilling a network of glacial palaeovalleys cut into the Tertiary Molasse bedrock. These units consist mainly of fluvial, fluvio-glacial and glaciolacustrine deposits, with two intervals of diamictons. Among those, a major outwash sequence formed by a sandur system is of particular interest, because its lower part contains a significant aquifer.

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Key-words : Aquifer, glacial and fluvio-glacial sediments, high resolution seismic, outwash sequence, Swiss Plateau.

RÉSUMÉ

ÉTUDE D'UNE SÉQUENCE FLUVIOGLACIAIRE SUR LE PLATEAU SUISSE A L'AIDE DE SISMIQUE RÉFLEXION A HAUTE RÉSOLUTION

Une étude de sismique réflexion à haute résolution a été menée sur le Plateau suisse au sud de Fribourg. Son but était de déterminer la géométrie de corps sédimentaires quaternaires d'origine glaciaire et périglaciaire pouvant atteindre une épaisseur de 100 mètres. Cinq unités/sous-unités sédimentaires, associées à deux importants cycles glaciaires, remplissent un réseau de paléo-vallées glaciaires creusées dans le soubassement molassique tertiaire. Ces unités consistent essentiellement de dépôts fluviatiles, fluvio-glaciaires et glacio-lacustres. Parmi ceux-ci, une importante série fluvio-glaciaire formée par un système de sandurs présente un intérêt particulier, car sa partie inférieure contient un aquifère.

Quelques cinq kilomètres de données sismiques à haute résolution ont été acquises en utilisant un marteau comme source, puis traitées sur PC. L'énergie sismique a été suffisante pour pénétrer jusqu'à 100 m de sédiments glaciaires. Les profils sismiques ont été calibrés à l'aide de puits et d'affleurements. Les paléo-vallées glaciaires y sont clairement identifiables, ainsi que trois à quatre unités quaternaires les remplissant. Les

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Mots-clés : Aquifère, fluvio-glaciaire, glaciaire, Plateau suisse, sismique haute résolution.

INTRODUCTION

The Swiss Plateau is a densely populated area. Its youngest sedimentary cover is largely composed of glacial and periglacial Quaternary sediments. These deposits comprise a large amount of gravels and sands that present a twofold interest : on one hand, they provide ideal raw material for construction purposes. On the other hand, being generally poorly consolidated and highly porous, they contain nearly 80 % of Switzerland drinkable water. These aquifers are often quite close to the surface and, consequently, quite exposed to pollution risks.

Fluvio-glacial deposits are characterized by rapid lateral and vertical lithological changes. High resolution seismic reflection, associated with other direct or indirect investigation methods, is a means to identify the morphology of and to map the complex network of glacial paleovalleys, in which gravels and sands were deposited. This paper presents the results of high resolution seismic investigations carried out in the Gruyère area, south of Fribourg, in the vicinity of the present-day canyon of the Sarine River (fig. 1 and 2). The feasibility of mapping the architecture of Quaternary deposits in this area has a direct

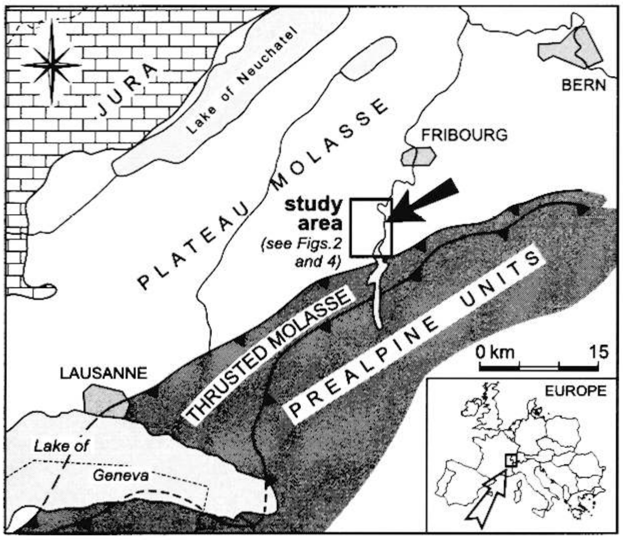


Fig. 1 : Location map of study area.
Fig. 1 : Localisation de la région étudiée.

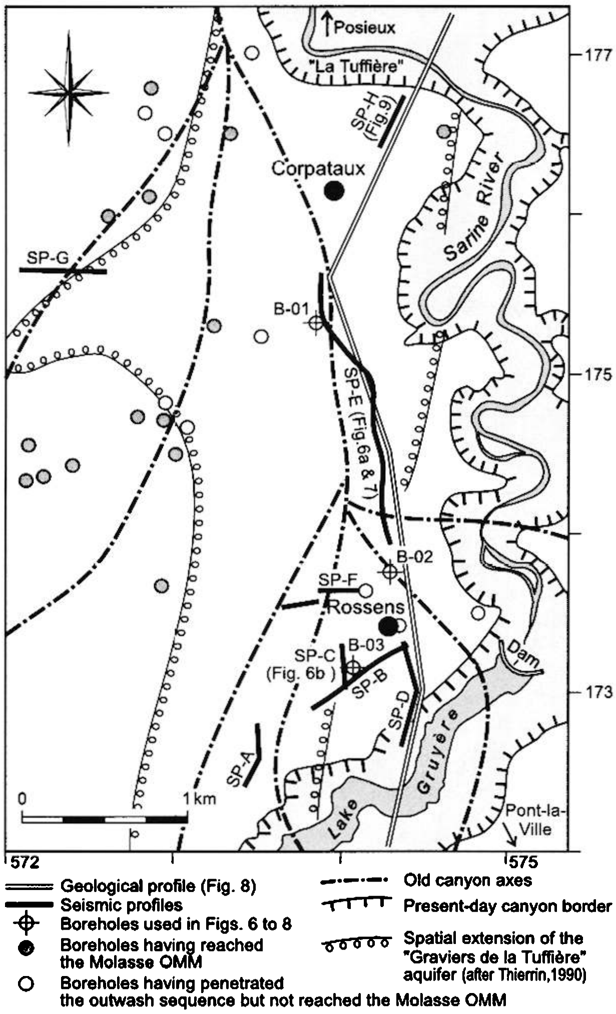


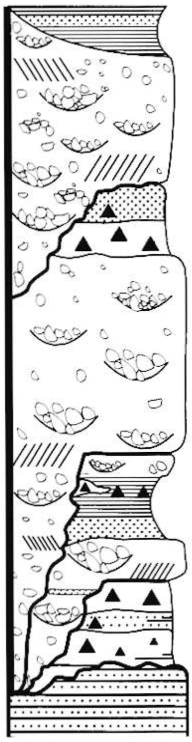
Fig. 2 : Rossens-Corpataux area : location of high resolution seismic profiles (fig. 6, 7 and 9), borehole data and geological profile (fig. 8). This map also shows the location of Quaternary palaeovalleys cut into the molasse bedrock (old canyons of the Sarine River) and filled up by Quaternary sediments. The actual canyon cuts across the whole Quaternary sequence down to the molasse ; it is bordered by cliffs up to 130 m high. Coordinates are plotted according to the Swiss topographical Atlas.
Fig. 2 : Région de Rossens-Corpataux : localisation des profils sismiques haute résolution (fig. 6, 7 et 9), des données de puits et du profil géologique (fig. 8). Cette carte montre aussi la position des anciens canyons de la Sarine creusés dans la molasse. Le canyon actuel est bordé de falaises pouvant atteindre 130 m de haut.

economic interest : part of this sequence comprises an important outwash sequence (fig. 3), whose gravels contain a significant aquifer. Subsequently to erosion by glaciers, which locally removed overlying glacial clays, these gravels may locally subcrop porous fluvio-glacial to glaciolacustrine deposits, making the aquifer quite exposed to surface pollution. Consequently, being able to distinguish areas where the aquifer is, or is not sealed, is critical for the protection of groundwater.

GEOLOGICAL FRAMEWORK AND QUATERNARY SEDIMENTS

The investigated area is located on the Swiss Plateau, north of the Alpine front and some 10 km south of the city of Fribourg (fig. 1). It is bordered to the south by the damed Sarine River (Lake Gruyère) and to the east and north by the present-day canyon of the Sarine River (fig. 2). The pre-Quaternary bedrock is constituted by the Upper Marine Molasse (Molasse OMM = "Oberes Meermolasse", Trümpy, 1980 ; Homewood *et al.*, 1986) of Burdigalian age (Dorthe, 1962 ; Schoepfer, 1989). The molasse OMM is essentially made of sandstones. It outcrops in the Sarine River canyon, which can be over 100 m deep.

In this area, the Plateau Molasse is close to the thrusted Molasse and the Alpine front. It may have been affected by low-relief anticlinal structures, which have influenced the geomorphology (Van der Meer, 1982). This bedrock is cut by a complex system of palaeovalleys corresponding to old canyon axes of the Sarine River (fig. 2 ; Büchi, 1926 ; Dorthe, 1962 ; Weidmann, in press). The Quaternary infill of this system has registered the signature of at least two major glacial cycles (fig. 3). The last Würmian glaciation has completely filled in the palaeotopography and remodelled the landscape, so that palaeovalleys can now be observed only in outcrops along the present-day Sarine River canyon, in boreholes or through geophysical prospections. The topography of the area between Corpataux and Rossens (fig. 2) displays a rounded morphology made of small valleys and hills with a maximum height of a few tens of metres. The Quaternary sedimentary sequence is known from surface geology (Weidmann, in



Lithostratigraphy	Units	Ages	Seismic Interval Velocity
Lacustrine deposits	IV	Late-Post-glacial	Low velocity layer
Upper fluvio-glacial and glaciolacustrine deposits	III	Würm	1200 - 1600 m/s
Upper proglacial diamict sequence	IIb	Würm	1200 - 1900 m/s
Outwash sequence "Graviers de la Tuffière"	IIa	Würm	1650 - 1950 m/s
Lower fluvio-glacial and glaciolacustrine to lacustrine deposits (Creux de l'Enfer Sequence)	Ib	Pre - Würm	1700 - 2000 m/s
Lower sub-glacial diamict sequence	Ia	Pre - Würm	2200 -2400 m/s
Molasse OMM (Bedrock)		Burdigalian (Miocene)	2800 - 3600 m/s

Fig. 3 : Lithostratigraphic column of the Quaternary deposits in the study area. Two major glacial cycles can be highlighted (Unit I and Units II + III respectively). The outwash sequence of Unit IIa («Graviers de la Tuffière») constitutes the main objective of this research. Seismic interval velocities are derived from stacking velocities using Dix (1955) formula and have been tentatively calibrated with boreholes (see fig. 6). Velocities in the Molasse OMM (=Upper Marine Molasse) are derived from a shallow seismic survey (calibrated with boreholes) carried out in 1974 to analyze the weathered zone prior to shooting petroleum seismic data.
The term «Würm» is used herein *sensu* Penck and Brückner (1909) ; it refers to the last glaciation between 28"000 and 14"600 yBP (Schlüchter and Röthlisberger, 1995 ; Schlüchter and Müller-Dick, 1995).
Fig. 3 : Lithostratigraphie du Quaternaire de la région étudiée. Deux cycles glaciaires sont mis en évidence : l'unité I et les unités II + III. La séquence fluvio-glaciaire de l'unité IIa («Graviers de la Tuffière») représente l'objectif principal de cette étude. Les vitesses sismiques d'intervalle dans le Quaternaire sont dérivées des vitesses de stack en utilisant le formule de Dix (1955).
Le terme «Würm» est utilisé ici sensu Penck and Brückner (1909) ; il se réfère à la dernière glaciation entre 28"000 et 14"600 aBP (Schlüchter and Röthlisberger, 1995 ; Schlüchter and Müller-Dick, 1995).

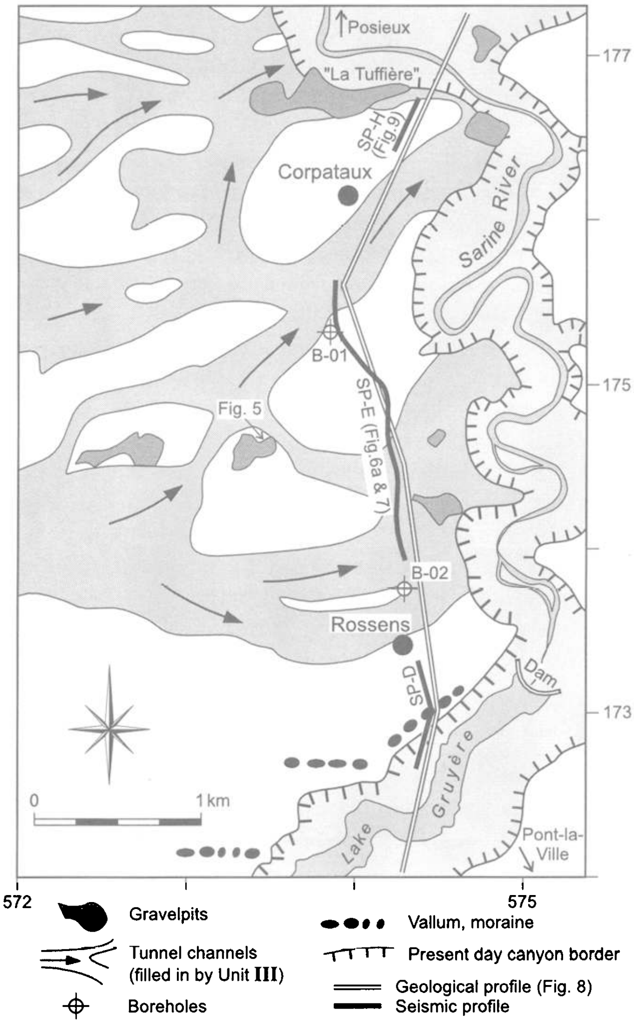


Fig. 4 : Rossens-Corpataux area : location map of the dominantly E-W trending tunnel channels having eroded and often completely removed the diamict sequence of Unit IIb. These channels were subsequently filled by the fluvio-glacial and glaciolacustrine deposits of Unit III, which often directly overlies the outwash sequence of Unit IIa (see also fig. 3, 7 and 8). Gravel pits are usually dug into Units II and III. The alignement of morains south of Rossens corresponds to the last Würmian stage of the Rhône glacier.

Fig. 4 : Région de Rossens-Corpataux : localisation des chenaux tunnels d'orientation E-W, qui ont érodé et souvent complètement enlevé les diamictes de l'unité IIb. Ces chenaux ont ensuite été remplis par les dépôts fluvio-glaciaires et glacio-lacustres de l'unité III, qui sont souvent directement superposés à la séquence fluvio-glaciaire de l'unité IIa (voir aussi fig. 3, 7 et 8). Les gravières sont creusées dans les unités II et III. L'alignement de moraines au sud de Rossens correspond au dernier stade würmien du glacier du Rhône.

press), numerous gravel pits (fig. 4) and boreholes (fig. 2). It outcrops at different places along the present-day Sarine River canyon, where it has been recently studied (Van der Meer, 1982 ; Pugin, 1989). Part of the research presented here has been carried out as a contribution to the 1:25'000 mapping of the Swiss Hydrological and Geological Survey (Signer and Pugin, 1994).

The subdivision of the Quaternary sequence used in this work is adapted to the scale of high resolution seismic reflection studies (fig. 3). The term "Würm" is used herein *sensu* Penck and Brückner (1909) ; it refers to the last glaciation between 28'000 and 14'600 yBP (Schlüchter and Röthlisberger, 1995 ; Schlüchter and Müller-Dick, 1995). Six units/subunits have been distinguished :

- **Unit Ia** is a sub-glacial diamict sequence of Rissian age or older (Weidmann, in press), which is encountered only in overdeepened troughs, where it uncomformably overlies the Molasse OMM. It outcrops on the eastern edge of Lake Gruyère and is identified in boreholes. Its thickness varies from 0 to 15 m, and can increase up to 50 m (based on high resolution seismic reflection data in the Pont-la-Ville area, on the eastern side of Lake Gruyère, see figure 2).

- **Unit Ib** consists of fluvio-glacial and glaciolacustrine to lacustrine deposits referred to as "Creux de l'Enfer Sequence". Similarly to Unit Ia, it is present in overdeepened troughs or old infilled canyons. Its thickness varies from 0 to 50 m and it oucrops on the eastern edge of Lake Gruyère. It contains a lignite interval corresponding to an Eemian (?) interglacial stage (Mornod, 1947 ; Weidmann, in press).

- **Unit IIa**, referred to as the "Graviers de la Tuffière", corresponds to a major outwash sequence formed by a sandur system of the Sarine glacier. The progradation of

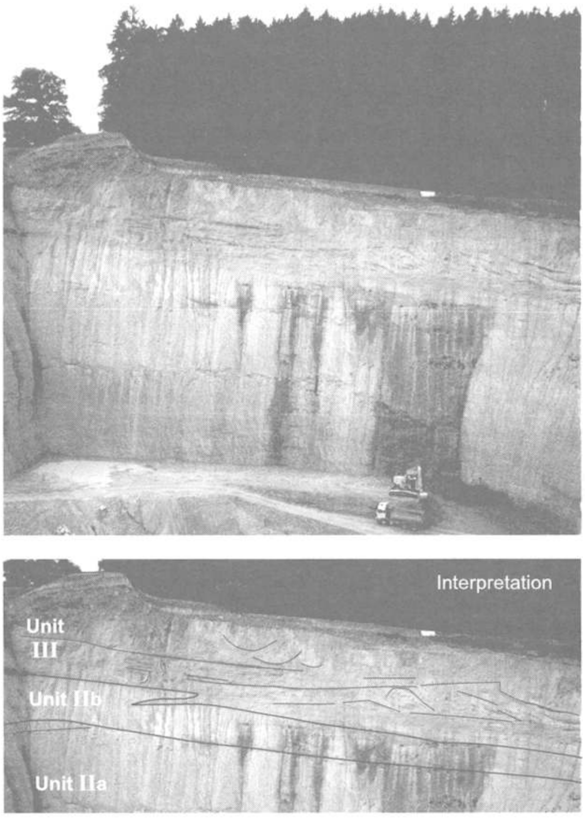


Fig. 5 : The Channey gravel pit at the edge of a tunnel channel (see fig. 4 for location).
Unit IIa **: outwash sequence of the « Graviers de la Tuffière ».**
Unit IIb **: till overlying Unit IIa with a sharp erosional contact. The upper part of the till is deformed (dragfolds) and interstratified with the overlying Unit III.**
Unit III **: foresetted subglacial gravels affected by shear deformations (dragfolds) and overlain by supraglacial meltout gravels. This gravel pit is ca. 35 m deep.**

Fig. 5 : Gravière de Channey, d'une profondeur d'environ 35 m, sur la bordure d'un chenal tunnel (localisation sur fig. 4). Unité IIa : séquence fluvio-glaciaire des «Graviers de la Tuffière». Unité IIb : till recouvrant l'unité IIa avec une base érosive nette. Unité III : graviers sous-glaciaires montrant des foresets et affectés par des déformations de cisaillement ; ils sont recouverts par des graviers supra-glaciaires de fonte.

this system varies from northwards to eastwards. It consists of monotonous, poorly sorted and sometimes cemented gravels showing subhorizontal or trough-shaped stratifications. They may contain elements up to 30 cm in size. This sequence fills in a N-S elongated, ca. 5 km long and up to 2 km wide depression crossing the study area. Its average thickness is 30-40 metres, and can reach a maximum of 70 metres. These deposits outcrop in numerous gravel pits (fig. 4 and 5). Their lower part contains the aquifer of the "Graviers de la Tuffière", whose spatial extension is narrower than that of the outwash sequence (fig. 2). This aquifer has been recently studied by Thierrin (1990). The thickness of the water column varies from 0 to 8 metres. The water flows essentially from south to north along grooves at the base of the gravels. The water comes from infiltrations along the flanks of the grooves and from the poorly permeable surrounding rocks. Hydraulic links with Lake Gruyère constitue a third type of water supply. The aquifer is exploited from springs and low-flow wells southeast and north of Corpateaux ("La Tuffière" area) along the Sarine River canyon (fig. 2). The southern part of the aquifer is less known and has been so far prospected only by geophysical methods. High resolution seismic reflection may be a means of better delineating potential sites for wells in this area.

The gravels of Unit IIa may overlie Unit Ib or Ia, or directly the Molasse OMM. Their interface with the overlying sediments is variable, which has an important bearing on the seismic response. The latter will be good when Unit IIa is overlain by the compacted deposits of the proglacial till of Unit IIb (fig. 5), but poor when the overlying sediments are the sands and gravels of Units IIb or III.

- **Unit IIb** is a Würmian, pro- to subglacial complex associated with the Sarine and Rhône glaciers. At its base, it contains a compacted, massive sandy and pebbly till, which may be a few meters thick. Pebbles are generally rounded. Because of its low permeability, this till is considered as a regional acquitard (Boyce *et al.*, 1995). The interstratification of this till with gravel channels of Unit IIa suggests that this diamicton has been deposited in a proglacial environment, while the glacier front was advancing. It was essentially deposited as debris flows. Shear deformations occurred subglacially, as the ice overrode the diamicton.
- **Unit III** is genetically related with the retreat of the Sarine and Rhône glaciers. It consists of sandy to gravely fluvio-glacial sediments, deposited in localized depressions associated with molten ice or tunnel channels (fig. 4). These sediments can be up to 50 metres thick, are often channelized, or show progradational and stratified sedimentary structures (fig. 5). Shear deformation related to ice flow are often observed (fig. 5). Deposits of Unit III found on low-relief hills have escaped fluvio-glacial reworking. They are interpreted by authors as drumlins, eskers or kame terraces (e.g. Shaw, 1985).

The basis of this unit is marked by a regional unconformity eroding into the underlying Unit II. This erosion is associated with tunnel channels and may have removed the whole of Unit IIb : from surface geology and borehole data, a system of tunnel channels can be mapped (fig. 4). In these channels, the infilling gravels and sands of Unit III most often directly overlie the gravels of Unit IIa, thereby creating "hydraulic windows" into the aquifer, because of the absence of the sealing till of Unit IIb. Such major unconformities resulting from the meltwater action have been described in Canada, where tunnel channels play an important role in the hydrostratigraphic descriptions (Brennand, 1994 ; Sharpe *et al.*, 1996 ; Pugin *et al.*, 1996 ; Pugin *et al.*, 1999).

- **Unit IV** comprises Late to Post-glacial, lacustrine deposits. They occur only locally, are normaly quite thin and too shallow to be identified on seismic data.

METHOD

The bases of land-based, high resolution seismic reflection applied to engineering problems have been developed since the early 1980's, particularly in Canada, where excellent results were obtained in glacial sediments (Hunter *et al.*, 1984 and 1985). Hunter *et al.* (1984) introduce the notion of *optimum window*, which allows to acquire good quality high resolution scismic data using 12 to 24 channel seismographs. Processing and acquisition of multifold seismic reflection has been introduced by Steeples and Miller (1990). In Switzerland, Quaternary sediments of the Swiss Plateau have been investigated by this method since the early 1990's (Pugin and Rossetti, 1992 ; Signer *et al.*, 1995), in particular for solving hydrogeological problems (Signer and Pugin, 1994). It is mainly in Canada that this type of studies have been carried out on a large scale in glacial sediments (Pullan *et al.*, 1994 ; Pugin *et al.*, 1996 ; Pugin *et al.*, 1999).

Eight high resolution seismic reflection profiles, totalling some 5 km, have been acquired in the area studied in this paper. During the same survey, six more profiles totalling an extra 5 km of data were acquired : two in the Posieux area, some 2 km north of Corpataux (fig. 2) and four in the Pont-la-Ville area, 5 km south of Rossens (fig. 2). Data were shot with a roll-along using a 24-channel engineering seismograph. The seismic source was a 5 kg hammer hitting a steel plate lying exclusively on tarmac roads. This seismic configuration has permitted to acquire seismic data with a frequency spectrum between 80 and 350hz (high resolution seismic), with penetration of seismic energy down to more than 100 m, depending on the nature of the ground at surface and on the depth of the water table. The latter should be ideally as close as possible to the surface.

Seismic data were processed using PC-based softwares, as well as additional seismic processing modules developed at the University of Geneva by A. Pugin. The details of the field configuration and of recording and processing parameters used for line SP-E are shown in table 1.

RESULTS

Calibration of seismic data (fig. 6)

Many boreholes have been drilled in the study area, often down to the Molasse bedrock (fig. 2). Calibration relies mainly on those located on or very near the high resolution profiles. Unfortunately, none of these wells have downhole geophysical logs. Consequently, seismic interval

RECORDING PARAMETERS	**PROCESSING PARAMETERS**
Recorder: seismograph Geometrics EG & G 2401	*PC-based software*
Nominal coverage: 12 fold	*Format conversion*
Sample interval: 0.2msec	*Refraction analysis*
Record length: 307msec	*Automatic Gain Control*: 75msec
Filters: LC 50Hz, HC 500Hz, Notch Out	*Band pass filter*: 200-400Hz
FIELD CONFIGURATION	*Surgical mute*
	CMP Sorting
Energy source: 5kg hammer on steel plate	*NMO (stretch mute 0.8)*
Shot spacing: 5m	*Residual statics*
End-on offset: 5m	*Stack*
Receiver spacing: 5m	*Mix 3 traces*
No. geophones/station: 1	*Least-square predictive deconvolution*
Geophone frequency: 50Hz	*Automatic Gain Control:* 200msec
Recording channels: 24	*Band pass filter*
	Large wavelength static correction on DP: DP=750m

Table 1 : Acquisition and processing parameters, seismic profile SP-E.
Table 1 : Paramètres d'acquisition et de traitement du profil sismique SP-E.

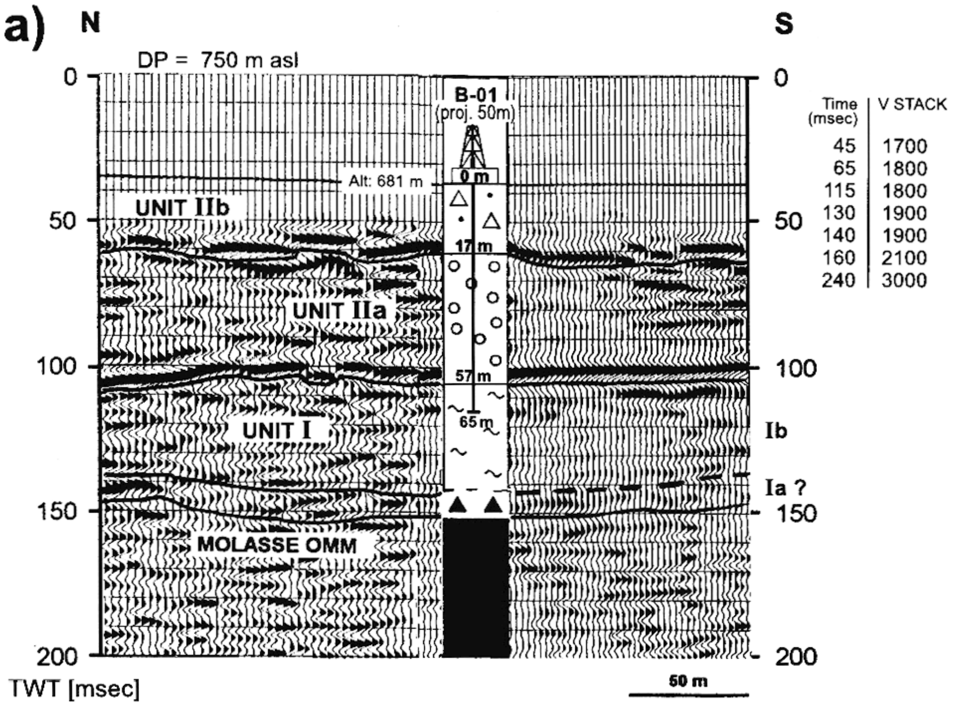
velocities in the Quaternary section can be derived only from stacking velocities (fig. 3). Outcrops along the present-day Sarine River canyon and adjacent valleys provide another important source of direct informations and give a "third dimension" to the interpretation of seismic profiles.

Extra information can be derived from other geophysical exploration carried out in this area :

- In association with petroleum vibroseis seismic data shot in 1974, a shallow seismic survey calibrated by boreholes was acquired to evaluate the low velocity surface zone. Some of these profiles are crossing the study area and provide valuable information on the depth of the molasse bedrock. They also give a good evaluation of the average velocity of the Quaternary sediments and the Molasse. Average velocities vary between 1700 and 2100 m/s in the Quaternary and between 2800 and 3600 m/s in the Molasse.
- Electro-magnetic VLF-R multifrequency 12-240Khz profiles (Müller, 1983) were acquired in the area by Thierrin (1990), in order to better define the spatial extension ans the thickness of the "Graviers de la Tuffière" (Unit IIa).

Seismic interval velocities in the Quaternary (fig. 3) have been derived from stacking velocities using Dix (1955) formula. They are derived from the seismic lines shot in the Rossens, Corpataux and Posieux area (fig. 2). These velocities can be compared with those obtained after calibration of boreholes with the seismic data. Two examples of calibration are illustrated in figure 5 :

- Borehole B-01 has been used to calibrate the northern part of profile SP-E (fig. 6a). Seismic data north of the borehole is very noisy with respect to the southern part. This illustrates the influence of climatic conditions on data quality : the northern part was acquired in wet, muddy conditions, the southern part in dry conditions. Correlation with the well shows the good impedance contrast between the diamict sequence (Unit IIb) and the outwash sequence (Unit IIa), and that between Unit IIa and the glacio-lacustrine deposits of Unit Ib. Based on this interpretation, the interval velocity of Units IIb and IIa can be estimated at ca. 1700 and 1800 m/s respectively, i.e. within the range derived from stacking velocities (fig. 3). Borehole B-01 reached total depth in Unit Ib. A much lower amplitude



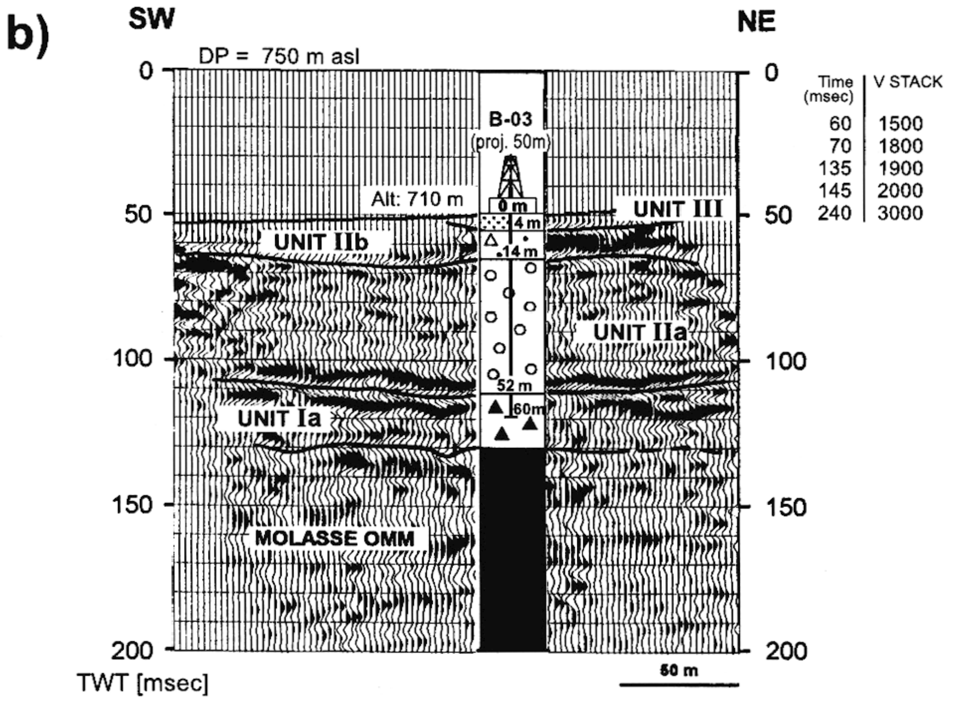


Fig. 6 : Tentative calibration of boreholes B-01 and B-03 with seismic profiles SP-E (fig. 6a) and SP-C (fig. 6b) respectively. See fig. 2 for location and text for explanations.
***Note* : the section on both sides of borehole B-01 displays quite different data qualities. The northern part is quite noisy, because it was shot in muddy winter conditions affecting the geophone connections, whereas the southern part was acquired in dry conditions.**
Fig. 6 : Essai de calibration des puits B-01 et B-02 avec les profils sismiques SP-E (fig. 6a) et SP-C (fig. 6b). Les données sismiques de chaque côté du forage B-01 sont de qualité très différente : la partie nord est bruitée car acquise en hiver dans un sol boueux affectant les connexions des géophones, alors que la partie sud a été acquise pendant une période sèche.

reflector occurs at ca. 150 msec. It is tentatively interpreted as the top of the Molasse bedrock. The presence of a thin interval of subglacial diamict sequence (Unit Ia) is hypothetical. The very poor impedance contrast between Unit I and the Molasse OMM is most probably due to the poor penetration of the hammer energy when the thickness of Quaternary sediments reaches 80-100 meters. It might also result from a weak impedance contrast between the weathered bedrock and Unit I. In the Pont-la-Ville area (fig. 2), at shallower depths, this interface is marked by a good reflector.

- Another calibration point is provided by borehole B-03 projected 50 m on profile SP-C (fig. 6b, see location in figure 3). Similarly to figure 6a, the interface between Units IIb and IIa, as well as that between Units IIa and I, are marked by high amplitude reflectors. The latter contrast is enhanced by the compacted nature of subglacial Unit Ia. Based on this interpretation, the interval velocity of Units IIb and IIa at this location can be estimated at ca. 2000 m/s and 1650 m/s respectively. The relatively high velocity of Unit IIb confirms the consolidated nature of these proglacial deposits at this location. A lower amplitude reflector observed at ca. 130 msec is tentatively interpreted as the top Molasse.

Other calibration points were used :

- Boreholes at the southern end of seismic line SP-E (borehole B-02) and at the eastern end of seismic line SP-F demonstrate the absence of the compacted diamict sequence of Unit IIb. These deposits have been eroded by the E-W trending tunnel channels (fig. 4) that were subsequently filled by the gravels of Unit III. Consequently, the interface between Units III and IIa has a much lower impedance contrast than that between Units IIb and IIa and is poorly expressed on seismic (e.g. southern end of profile SP-E, fig. 7). This change in acoustic impedance provides a means of identifying "hydraulic windows" above the aquifer of Unit IIa.

- Thickness variations in the "Graviers de la Tuffière" observed by Thierrin (1990) on electro-magnetic VLF-R data correlate well with the seismic data on profile SP-B (fig. 2).

- The palaeovalley cut into the Molasse identified by Thierrin (1990) on electro-magnetic VLF-R data is confirmed by seismic section SP-G (fig. 2).

Interpretation of seismic line SP-E (fig. 7)

The ca. 2 km long profile of figure 7 is considerably compressed horizontally with respect to the data shown in figure 6. Based on seismic facies, it has been subdivided into four parts labelled AB, BC, CD and DE.

Part AB displays a reflective sequence between ca. 50 and 150 msec. It exhibits two high impedance reflectors at ca. 50 and 100 msec and a lower amplitude reflector at ca. 145 msec. These reflectors delineate two sedimentary sequences exhibiting a seismic facies characterized by subhorizontal, poorly continuous reflections. In part CD, the reflective sequence has a reduced thickness. Its top is

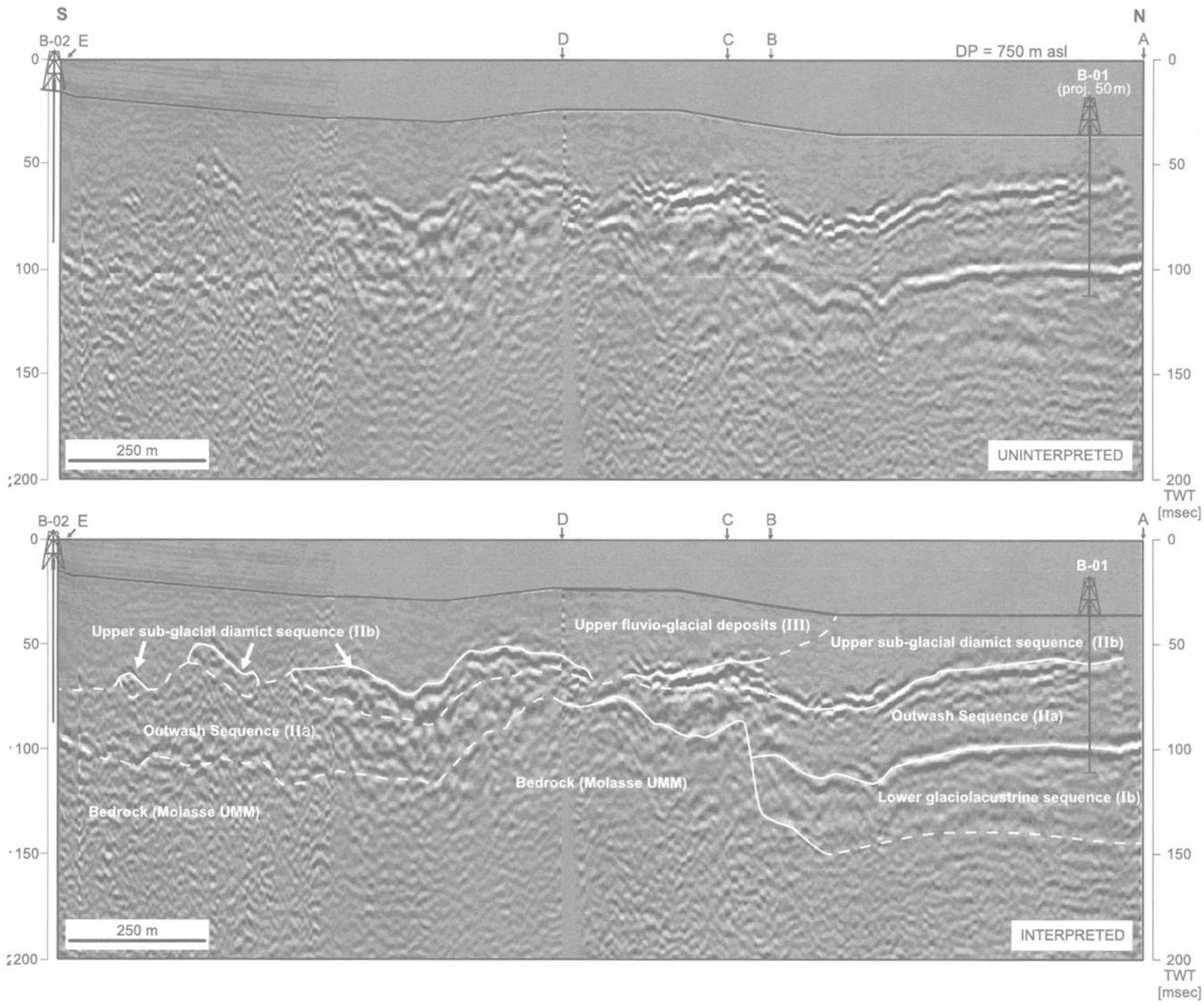


Fig. 7 : Uninterpreted and interpreted seismic profile SP-E (see fig. 2 for location). Two Quaternary palaeovalleys are separated by a molasse high. Note the strong difference in seismic facies between the sedimentary infills of these palaeovalleys. See text for explanations.

Fig. 7 : Profil sismique SP-E (localisé sur la fig. 2). Deux paléo-vallées quaternaires sont séparées par un haut de molasse. Noter la grande différence des faciès sismiques du remplissage sédimentaire de ces deux paléo-vallées. Voir explications dans le texte.

marked by a high amplitude reflector at ca. 60 msec (at the C location), and its base by a lower amplitude, discontinuous reflector at ca. 95 msec. Part BC shows the transition between sectors AB and CD, which is marked by a break in the reflector continuity and diffractions. In the southern part DE, the reflective sequence observed in AB vanishes progressively. The high amplitude reflector at ca. 50 msec (at the D location) becomes discontinuous southwards. The only subcontinuous reflector in part DE is that observed at ca. 100 msec.

Based on the calibration with boreholes B-01 and B-02, on outcrop data from the Sarine River canyon to the east and from quarries (fig. 2 and 4) and on other observations mentioned above, an interpretation of the profile can be proposed. Two palaeovalleys cut into the Molasse OMM and filled by Quaternary sediments are observed. The northern part AB shows the seismic expression of the N-S trending glacial palaeovalley (fig. 2). The calibration with borehole B-01 has been detailed above : the top of the Molasse is tentatively matched with the low amplitude reflector at ca. 145 msec. The two high amplitude reflectors above coincide with the interfaces between Units IIb, IIa and Ib, thereby giving a clear picture of the distribution of the outwash sequence of the "Graviers de la Tuffière" (Unit IIa) along the axis of the palaeovalley.

Part BC of the line corresponds to the eastern flank of the N-S trending palaeovalley. In part CD, the Quaternary sequence overlies a Molasse high, where the thickness of Unit IIa is considerably reduced. Interpretation of the top Molasse in this part of the section is supported by outcrop observations in the Sarine canyon. The interpretation of the interface between the upper fluvio-glacial/ glaciolacustrine (Unit III) and the upper diamict (Unit IIb) sequences is also supported by outcrop observations from nearby quarries. Subglacial erosion has locally completely removed Unit III, which is interpreted as pinching out where the high impedance contrast at the top of Unit IIa vanishes.

The southern part DE intersects two merging palaeovalleys (fig. 2). Interpretation in this area relies on correlation with boreholes (e.g. B-02), outcrops in the Sarine canyon and VLF-R data. The top of the Molasse is tentatively picked as corresponding to the irregular (because of weathering or erosion ?), but fairly continuous reflector at ca. 100 msec. No or very little sediments of Unit I seem to be present, which means that this lower fluvio-glacial to glaciolacustrine interval is mainly preserved in the N-S trending palaeovalley. Boreholes in this area confirm the absence of the upper diamict sequence (Unit IIb). Gravels of the upper fluvio-glacial and glaciolacustrine sequence (Unit III) are directly overlying the gravels of the outwash sequence (Unit IIa), resulting into a fairly transparent seismic facies. High impedance, discontinuous reflectors at ca. 50 msec are interpreted as indicating remnants of the compacted Unit IIb. Consequently, this interpretation of the southern part of line SP-E suggests that the aquifer of the "Graviers de la Tuffière" is largely exposed to surface pollution in this area (hydraulic windows).

DISCUSSION (fig. 8)

The high resolution seismic data acquired in the Corpataux-Rossens area was meant to investigate the contribution of this method to solving the geology of Quaternary deposits and, in particular, to the mapping of the lateral and vertical extension of the "Graviers de la Tuffière". The high resolution seismic grid is patchy, but seismic data can be used in association with unlogged borehole, outcrop and VLF-R data. Based on these informations, a N-S trending geological profile has been established (fig. 8), which runs parallel to the high resolution seismic profiles SP-D,-E and -H (fig. 2 and 4).

This profile crosses the Rossens-Corpataux area from the Lake Gruyère in the south to the Sarine canyon in the north ("La Tuffière" area), where springs yield water from the "Graviers de la Tuffière". Control on the top of the Molasse bedrock is provided by outcrops in the Sarine canyon, boreholes and seismic interpretation. The latter yields relatively good informations when the top Molasse is at shallow depths (e.g. on seismic lines SP-D and SP-H, fig. 8 and 9), but data quality deteriorates when the thickness of Quaternary sediments reaches 80-100 meters

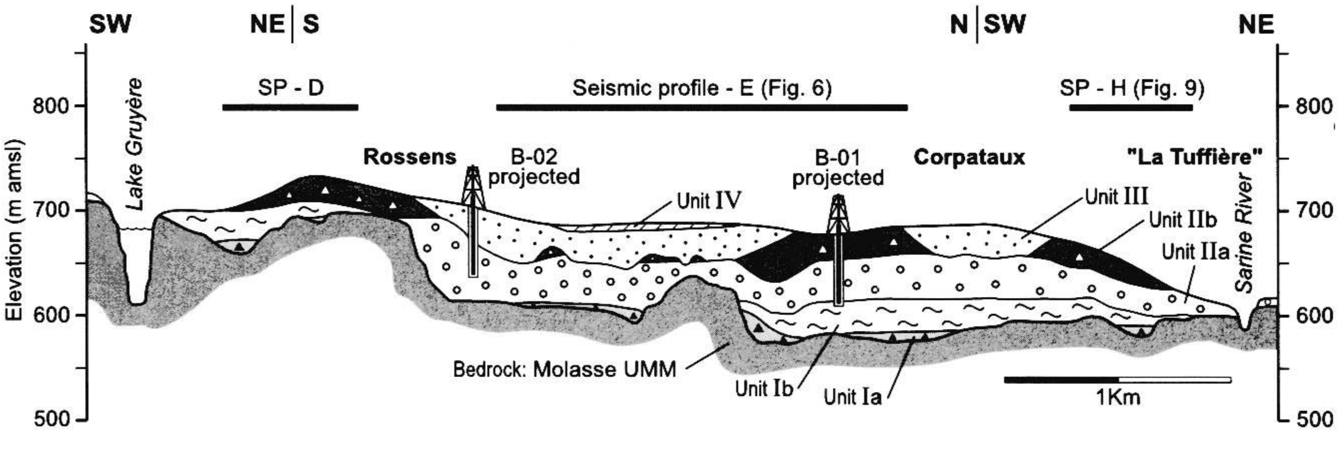


Fig. 8 : Synthetic geological profile based on high resolution reflection seismic data, borehole and outcrop data. See fig. 2 for location and fig. 3 for description of lithological units.
Fig. 8 : Profil géologique synthétique basé sur les sections sismiques à haute résolution et sur les données de puits et d'affleurement.

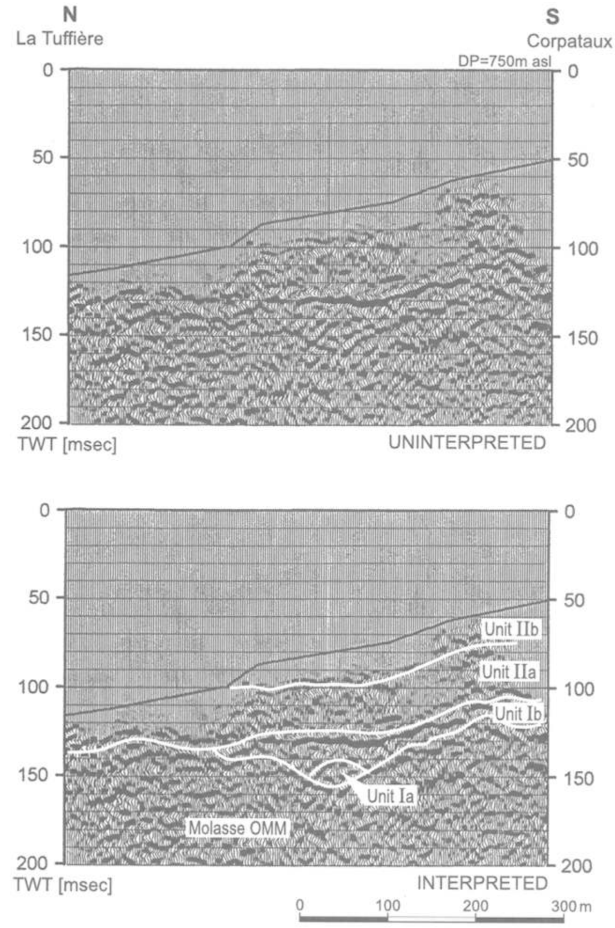


Fig. 9 : Uninterpreted and interpreted seismic profile SP-H (see fig. 2 for location). This section crosses the outcrops of the outwash sequence (Unit IIa) in the « La Tuffière » area. Note the quality of the top Molasse reflector (here at shallow depth) with respect to that observed at greater depths (e.g. in fig. 7). Also note the localized occurrence of the compacted lodgement tills of Unit Ia.

Fig. 9 : Profil sismique SP-H. Cette section intersecte les affleurements de la séquence fluvio-glaciaire (unité IIa) à «La Tuffière». Noter la qualité de la réflexion du sommet de la molasse (ici peu profonde) par rapport à celle observée à plus grande profondeur (fig. 7). Noter aussi la présence localisée du lodgement till de l'unité Ia.

(e.g. at the northern part of seismic line SP-E, fig. 7 and 8). This demonstrates that the maximum penetration of seismic energy yielded by the hammer is limited to one hundred meters in glacial sediments. Similar observations were made in the glacial sediments of the Geneva area (Signer, 1996). Moreover, severe weathering of the top Molasse interval will tend to lower the impedance contrast with the overlying glacial sediments.

In the Quaternary, four sequences corresponding to two glaciations can be distinguished on high resolution seismic data : Units I, IIa, IIb and III. Within Unit I, the subglacial diamict deposits (Unit Ia) are usually thin and patchy and are mainly identified by boreholes (e.g. borehole B-03, fig. 6b). Nevertheless, the local occurrence of a high amplitude reflector directly above the top Molasse (fig. 9) may be attributed to these deposits, knowing that compacted lodgement tills may reach velocities up to 2600 m/s (Signer, 1996).

On the basis of the recorded data, high resolution seismic appears as a good tool to identify the outwash sequence of Unit IIa. The base of this unit is usually marked by a good reflector, whether it overlies the fluvio-glacial to glaciolacustrine deposits of Unit Ib (fig. 6b) or the subglacial diamict sequence of Unit Ia (fig. 6b). Reflectivity at the top of the outwash sequence depends upon the nature of overlying sediments. There is a good impedance contrast with the proglacial diamict sequence of Unit IIb (fig. 6b). On the contrary, the seismic response is very poor when Unit IIb has been eroded by tunnel channels and the gravels of the fluvio-glacial Unit III directly overlie those of the "Graviers de la Tuffière" (southern end of line SP-E, fig. 7 and 8). Therefore, variations in acoustic impedance at the top of Unit IIa contribute to delineate "hydraulic windows" above the aquifer of the "Graviers de la Tuffière". Where no seismic is available, knowledge of the location of tunnel channels (fig. 4) helps to complement the geological cross-section, e.g. in the Corpataux area (fig. 8). The correlation of high resolution seismic data with electro-magnetic VLF-R data has proven particularly valuable for the identification and delineation of the outwash sequence, and locally of the Molasse bedrock. As far as detection of hydraulic windows is concerned, high resolution seismic appears as a much better tool in identifying the absence of sealing subglacial diamict deposits.

The N-S trending cross-section of the "Graviers de la Tuffière" illustrated in figure 8 is largely based on high resolution seismic. Such results are highly valuable to delineate the extension of the porous gravels and the morphology of the surrounding rocks. They provide the required elements for the hydrogeological modelling of the aquifer of the "Graviers de la Tuffière". The calibration of seismic data with boreholes and outcrops is in any case necessary. The quality of this calibration would be considerably enhanced if boreholes with geophysical logs were available.

CONCLUSIONS

This study demonstrates the potential of high resolution seismic in delineating the geometry of glacial and periglacial sedimentary bodies deposited mainly in glacial palaeovalleys. In particular, this method can considerably improve the mapping of porous reservoirs, which contain potential aquifers such as that of the "Graviers de la Tuffière" in the Rossens-Corpataux area. Apart from contributing to evaluate the volumetrics of the reservoir, such data may reveal the morphology of the rocks encasing the reservoir (e.g. Unit Ia, Ib or the Molasse OMM), thereby helping to identify possible pathways for the water charging the aquifer. Seismic has also proven extremely valuable in the identification of zones where the reservoir is, or is not, capped by sealing diamict deposits. Mapping of such zones highlights areas where surface pollutants can directly reach the reservoir ("hydraulic windows").

Using a hammer as energy source and a simple layout (12 fold coverage), this method requires little manpower : a team of four men can acquire up to 0.5 km/day. Although patchy, the data recorded in this study have demonstrated the validity of the technique in such a sedimentary environment. Accurate mapping of the reservoir would definitely require a more complete seismic grid, which should be ideally tied with logged boreholes. A better seismic resolution could also be obtained by increasing the fold coverage from 12 to 24, and by paying special attention to static corrections.

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