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Reflection seismic study of cenozoic sediments in an overdeepened valley of northern Switzerland: The Birrfeld area

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Keywords: Fluvio-glacial sediments; Swiss Molasse; high-resolution reflection seismics; valley deposits

ABSTRACT

Most of the major valleys in Switzerland contain a complex infill of glacial and fluvial Quaternary sediments. Information from boreholes provide some insights into the internal structure of those valleys, but reflection seismic profiling often yields a more complete and detailed image of the complex internal sediment architecture. To obtain an overview of the internal structure of the Birrfeld valley, we shot two perpendicular high-resolution reflection seismic profiles in the central part of the valley with a total length of 5.1 km. Based on reflection characteristics, we distinguish five different seismic units on the seismic sections interpreted together with information from boreholes and outcrops located near the profiles. An uppermost unit S1, 30 to 40 m thick, consists of fluvial and glaciofluvial gravel. Separated from this unit by a strong reflection, unit S2 consists mainly of (glacio-) lacustrine sediments, which reach a thickness of more than 100 m. In places, a third unit (S3) of subglacial deposits is identified below S2. It is not continuous across the profiles and generally less than 100 m thick. It is not clear whether all parts of S3 correspond to the same deposits. Unit S4, characterized by a band of strong reflections, is interpreted as a Molasse (Tertiary) layer. Underneath the Molasse Jurassic sediments (Malm) are expected. However, because of the limited strength of our seismic source we observe these sediments (S5) only in the northern part of Profile 1. The top of Malm, which outcrops further north, coincides with a strong seismic reflection. These high-resolution reflection data provide insight into the complex three-dimensional structure of the Quaternary package of sediments variation and help to elucidate the complex palaeoclimatic history.

ZUSAMMENFASSUNG

Die meisten Schweizer Täler enthalten komplexe Abfolgen quartärer Sedimente, die durch glaziale und fluviale Prozesse abgelagert wurden. Informationen aus Bohrungen liefern nur einen begrenzten Einblick in die interne Struktur dieser Sedimente. Reflexionsseismische Methoden führen meist zu einem vollständigeren Bild der abgelagerten Sedimente. Um einen Überblick über die internen Strukturen des Birrfeldes zu erhalten, haben wir im Zentrum des Tales zwei sich kreuzende hochauflösende seismische Profile mit einer Gesamtlänge von 5.1 km geschossen. Basierend auf den Unterschieden im Reflexionscharakter haben wir fünf verschiedene seismische Einheiten identifiziert, deren Entstehung wir unter Berücksichtigung von zusätzlichen Informationen aus Bohrungen und Aufschlüssen interpretiert haben. Die oberste Einheit S1 besteht aus fluviatilen und glaziofluviatilen Kiesen. Darunter folgt, getrennt durch einen deutlichen Reflektor, die Einheit S2, die hauptsächlich aus (glazio-) lakustrinen Ablagerungen besteht. In einigen Teilen der Profile konnte unterhalb von S2 eine Einheit S3 aus subglazialen Ablagerungen identifiziert werden. Einheit S4, die sich durch ein Band starker Reflexionen hervorhebt, interpretieren wir als tertiäre Molasseablagerungen. Unterhalb der Molasse erwarten wir jurassische Sedimente (Malm), die nördlich des Profils 1 aufgeschlossen sind. Nur im nördlichen Teil von Profil 1 konnten Reflexionen der Oberkante des Malm (Einheit S5) zugeordnet werden. In den übrigen Teilen der Profile war die seismische Energie zu schwach, um Reflexionen von mesozoischen Sedimenten unterhalb der Molasse zu bekommen. Diese hochauflösenden Daten liefern erstmals einen Einblick in die komplizierte Struktur quartärer Sedimente und deren räumliche Änderungen im Birrfeld-Becken. Sie helfen, die komplexe paläoklimatische Vergangenheit zu verstehen.

Introduction

A valley is called "overdeepened" if bedrock lies below the actual river level. Overdeepened valleys can be related to either tectonic activity or to glacial fluctuations as a result of climate change or to both. As a consequence, overdeepened valleys are filled with sediments related to later fluvial, lacustrine and glaciogenic activity. The sedimentary fill in some valleys of Switzerland represents the longest and most complete Quaternary paleoclimate records of the Alpine foreland (Schlüchter 1988/89). This information is relevant for today's society as it reflects past climate changes, which in turn will influence future hazards in the Alps and their forelands. The knowledge of the shallow sedimentary structure will also help to solve prob-

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lems which arise from societal needs relying heavily on groundwater reservoirs, geothermal exploration and natural envelopes of waste disposal sites.

The determination of lateral and vertical structure of sediment units in overdeepened valleys is important for understanding the origin and process of overdeepening and refilling, and it provides essential inputs for all palaeo-glaciological or genetic modelling. Up to now, the reconstruction of deeper valley infill architecture has usually been based on singular and rare drilling locations only, without lateral information (Wildi 1984). The geometry of bedrock relief is only known to a limited extent. This deficit in structural information of deep valley or basin infill makes meaningful modelling of basin evolution and paleoglacial conditions nearly impossible.

Seismic surveys are a prime tool for determining the basic structural information based on seismic travel times and velocities. Detailed seismic surveys of lacustrine and glacio-lacustrine sediments in Switzerland began in the 70s (e.g. Matter et al. 1971; Finckh & Kelts 1976). During the last ten years techniques for high-resolution seismic surveys to map shallow sedimentary structures have improved significantly. Several studies demonstrate the potential for mapping valley fill structures in Switzerland (e.g. Pfiffner et al. 1997; Büker et al. 1998, 2000).

In this paper, we report on a detailed seismic investigation of the Birrfeld area (Fig. 1), a Quaternary valley in northern Switzerland. This area is particularly well suited to study overdeepened Quaternary basins because it is part of the northern alpine confluence of Quaternary drainage where sediments have accumulated into a deep basin which has been subjected to at least five glacial cycles before present (Graf in press). The main targets were to determine the topography of the top of Molasse sediments (or base of the Quaternary), and the internal subdivisions of the Quaternary deposits.

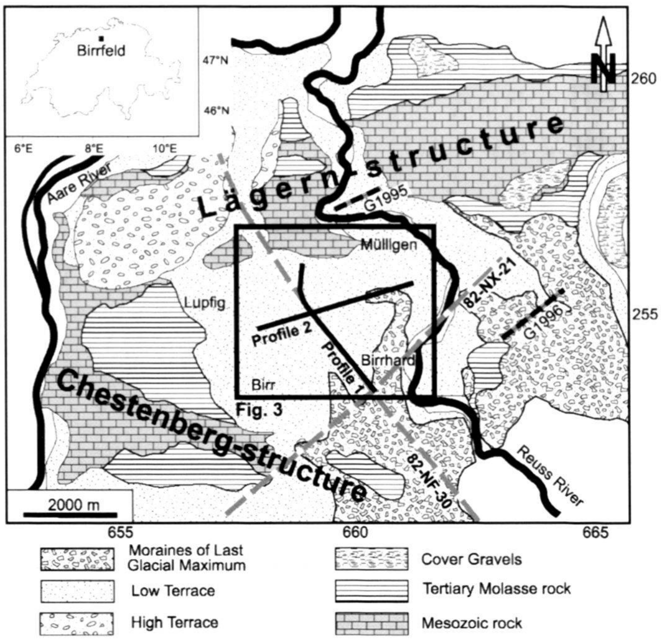

Fig. 1. Location and geological overview of the investigated area and surroundings. The Birrfeld area, enclosed by the rectangle, is enlarged in Figure 3. Location of earlier NAGRA seismic profiles (82-NF-30, 82-NX-21) is shown by gray dashed lines and location of GeoExpert lines (G1995, G1996) is shown by black dashed lines. Two continuous black lines indicate the position of the seismic reflection lines of this study. The Chestenberg- and Lägern-structures are anticline folds of the eastern part of the Jura mountain range. Coordinates around the main map refer to the Swiss reference system.

Geological setting

The Birrfeld area is situated in the centre of the Swiss Northern Alpine Foreland, between the rivers Aare and Reuss (Fig. 1) both of which traversed and filled the basin along changing courses over time. Present day knowledge of the subsurface sediments relies on information obtained from boreholes and outcrops as well as on regional studies (Sprecher & Müller 1986; Diebold et al. 1991). The study area is located at the northern rim of the Swiss Molasse basin and is bound by frontal belts of the Jura mountains between the two most easterly fold-structures visible from the surface, the Lägern-structure in the north and the Chestenberg-structure in the south (Fig. 1) of Middle Triassic to Upper Jurassic rocks (Diebold et al. 1991). Both structures consist of a main anticline fold complicated by several frontal and internal thrusts.

During the late Oligocene (Lower Freshwater Molasse) and the early Miocene (Upper Marine Molasse) the region was part of the northern margin of the Molasse basin. At this time, both the Lägern and the Chestenberg-structures already existed to some extent, as is documented by Oligocene slope-sediments (Büchi & Hofmann 1960) and by synsedimentary tectonic tilting of Miocene deposits (Naef et al. 1985). According to Diebold et al. (1991) these structures were created by compression and uplift of the Swiss Jura since middle Miocene. They possibly followed pre-existing weakness zones created during early Mesozoic extension. Today, in the area between the Lägern- and Chestenberg-structures the Mesozoic rocks are overlain by Lower Freshwater Molasse deposits, consisting of poorly cemented sand-, silt- and claystones (Naef et al. 1985).

In Pliocene to early Pleistocene time, which is represented in northern Switzerland by extended gravel deposits (Swiss Cover Gravels) (Fig. 1), the Birrfeld-region was already part of the main northern alpine drainage system. There is little information about the paleohydrography of this time interval. The available data indicate frequent changes of river valleys as the whole drainage system was cutting progressively into the pre-Quaternary rocks (Graf 1993), of which the Lägern-structure was the major obstacle (Fig. 1). In the area of the Molasse basin, where relatively soft rocks are abundant, the rivers were more or less free to choose their way. At the solid Mesozoic rocks of the Lägern-structure rivers were forced to find weakness-zones for a crossing: i.e. along some transversal faults-zones. The present rivers Reuss and Aare are crossing the

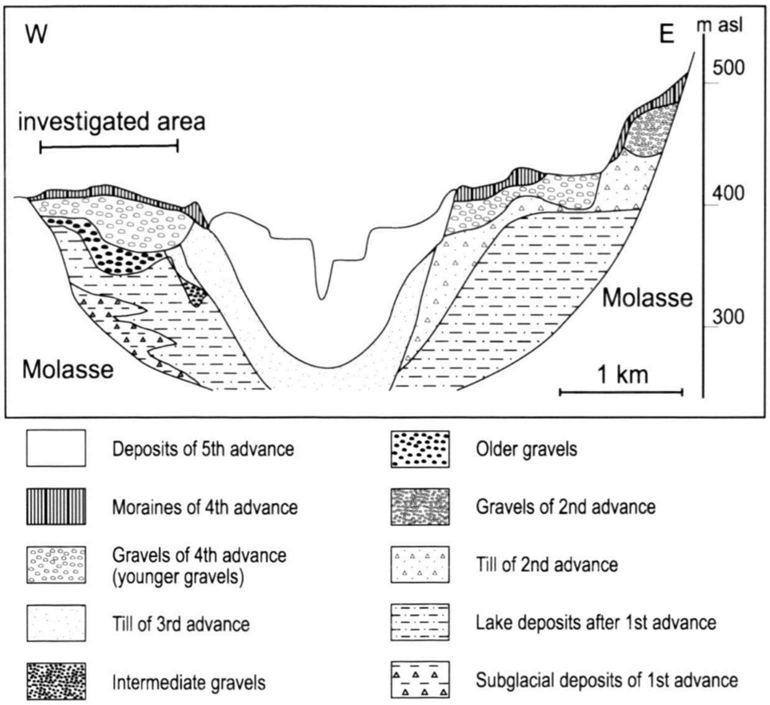

Fig. 2. Sketch demonstrating the schematic arrangement of infilling sediments in the Birrfeld area deposited by five different glaciations or glacial advances (after Graf, in press). It represents relative position and succession of erosional events based on outcrop and borehole information. The detailed shape and timing is not known.

Lägern- and Chestenberg-structures along such transversal fault-zones.

At the transition from early to middle Pleistocene, when the period of Swiss Cover Gravels in the Northern Alpine Foreland ended, a fundamentally new style of valley formation began when areal glaciations changed to valley glaciations. Overdeepened valleys formed. Their genesis still is not entirely understood. We know, that there were several phases when overdeepening happened, therefore, not all of the existing deep valleys have the same age. Consequently, their filling may consist of deposits from only one glaciation or a complex succession of sediments from several glacial/interglacial periods. Generally, the valleys (or valley-segments), in or close to the Alpine region, contain deposits of the last glacial period only. The distal or lateral parts of some overdeepened valleys that were not affected by the last glacial period contain a multi-phase sediment succession (e.g. Schlüchter 1988/89). The Birrfeld area belongs to the latter category. The present study is intended to improve understanding of the evolution of these multi-phase valley fillings.

Instead of a simple elongated structure, which is common for most valleys, the Birrfeld basin has a more bowl-like morphology with two adjoining canyons crossing the Lägern-structure towards the north. A large number of shallow drillings have been carried out in the area for different purposes. At least five times the area was reached by alpine glaciers producing a very complex and yet not entirely understood succession of sediments (Fig. 2). In the bottom part of the basin, abundant coarse grained subglacial gravels and tills act occasionally as aquifers (Jäckli & Kempf 1972). They intercalate with or are overlain by quite thick lacustrine sediments, partly being interpreted as waterlain till, partly as non-glacial deposits. The geometrical and, therefore, chronological relationship between the different types of deposits is not yet clear, because very few drillings penetrate deep enough into these sediments. Presently, there is evidence of four superimposed glacial basins in the Birrfeld area (Advances 1, 2, 3, 5, Fig. 2). An additional fifth glacier-advance reached the area, but no basin infilling sediments remain (Advance 4, Fig. 2). The three younger basins are located in the southeastern part of the area, which is not covered in this study. The westerly part of the Birrfeld area was chosen for these first detailed investigations because, to our knowledge, deposits of earlier glacial advances were expected there, which were not as much affected by later advances as in the central part.

Earlier sub-surface studies in the Birrfeld area

Most of our present knowledge of the subsurface in the Birrfeld area relies on a large number of drill holes (Fig. 3), and the geological interpretation presented above draws heavily on their findings. In particular they indicate the presence of lacustrine sediments in several places, but without laterally continuous investigation it is impossible to know whether they are linked together.

Two earlier seismic reflection profiles were carried out by NAGRA as part of the Swiss nuclear waste disposal site survey in northern Switzerland (Fig. 1) (Sprecher & Müller 1986, Diebold et al. 1991). These long profiles provided information about the Mesozoic sediments and important thrusts at the

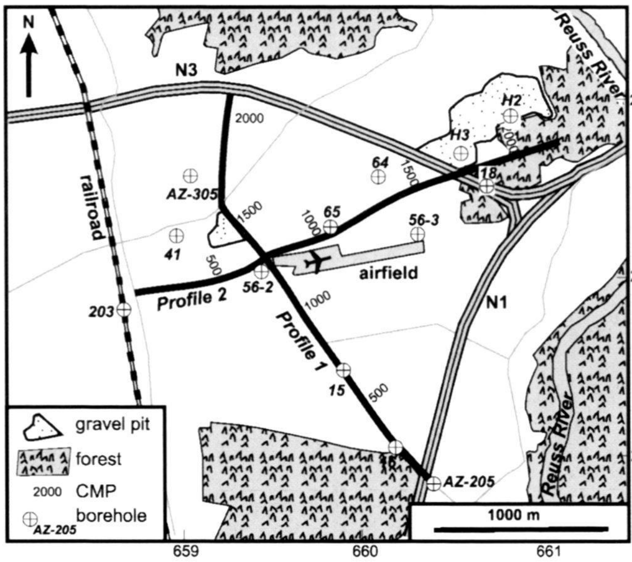

Fig. 3. Site map with detailed location of seismic profiles and boreholes. Highways and railroad tracks that encircle the study area are major sources of seismic background noise (borehole information by courtesy Matousek, Baumann & Niggli AG, Baden).

foothills and in the Jura Mountains, but observations were not dense enough to unravel the Quaternary structure in any detail and barely outline the top of the Molasse sediments. A few more recent seismic reflection profiles (Geoexpert ag 1995, 1996) at the edge of the basin lack the required resolution, especially when it comes to identify and outline the top of the bedrock. They are also too short and poorly located for the present purpose of a general overview of the basins sedimentary structure (Fig. 1).

Data Acquisition and Processing

To study the sedimentary fill of the Birrfeld valley we collected seismic reflection data along two profiles. Profile 1 is located along the NAGRA Profile 82-NF-30, and it links two drill holes (AZ-205, AZ-305) that reached Molasse basement (Figs. 1, 3). Profile 2 was designed to improve our 3D knowledge of the basin.

The study area is surrounded by national highways to the north and to the south and by a busy railway line along a local road with nearby industry in the west (Fig. 3). The centre is occupied by a local sports-airfield. A high local background noise was to be expected. Therefore, test measurements were carried out at three different sites in May 1999 during daytime in order to check the noise level and to select the best suited configuration and energy source for the planned seismic survey. The test profiles were 240 m long with a geophone spacing of 2 m. Energy sources were a sledge hammer for single and stacked signals, a pipe gun with single and two stacked shots,

Table 1. Acquisition parameters

	Profile 1 / Profile 2
Geophone type	vertical 30Hz
Geophone spacing	2.5m
Active channels	120
Source type	pipe gun
Shot spacing	2.5m
Number of shots	1017 / 1014
Total length	2627.5m / 2602.5m
Recording system	Jupiter Bison
Sample interval	0.5ms
Recording length	700ms
Nominal fold	60

Table 2. Processing sequence applied to seismic data

trace editing
geometry
refraction static corrections
amplitude scaling
spectral balancing
band pass filtering
CMP sorting
velocity analysis
residual static corrections
NMO corrections
first break muting
stacking
Kirchhoff time migration

and shots of 50 g explosives. Overall, the pipe gun source turned out to be the best source with respect to efficiency and higher frequency content.

Subsequently, two perpendicular profiles oriented roughly NS and EW (Figs. 1 and 3) were shot across the central part of the Birrfeld basin with a length of 2.6 km each. The acquisition parameters were the same for both profiles and based on the previous test experiment (Table 1). Vertical 30-Hz geophones were deployed at 2.5 m intervals and shooting was carried out with a pipe gun except for some road crossings where a 4-kg sledge hammer was used. Data were recorded with a Bison Jupiter system using 120 channels in roll-along mode with a record length of 700 ms and a sampling interval of 0.5 ms. Because of the strong background noise, the recording was done at night when traffic was significantly reduced. Shots were placed at every geophone position (i.e. 2.5 m interval) which resulted in a high nominal stack fold of 60. In total 1017 shots were recorded on Profile 1 and 1014 shots on Profile 2 during a period of three weeks in fall 1999.

Processing of the seismic data followed a standard scheme (Table 2). After loading the data into a seismic processing system, bad and reversed traces were edited. This was followed by amplitude scaling and refraction static corrections. To suppress the dominant ground roll energy in the raw data, spectral whitening and band pass filtering (40-70-180-250 Hz) were applied. Figure 4 shows an example of a pipe-gun shot before and

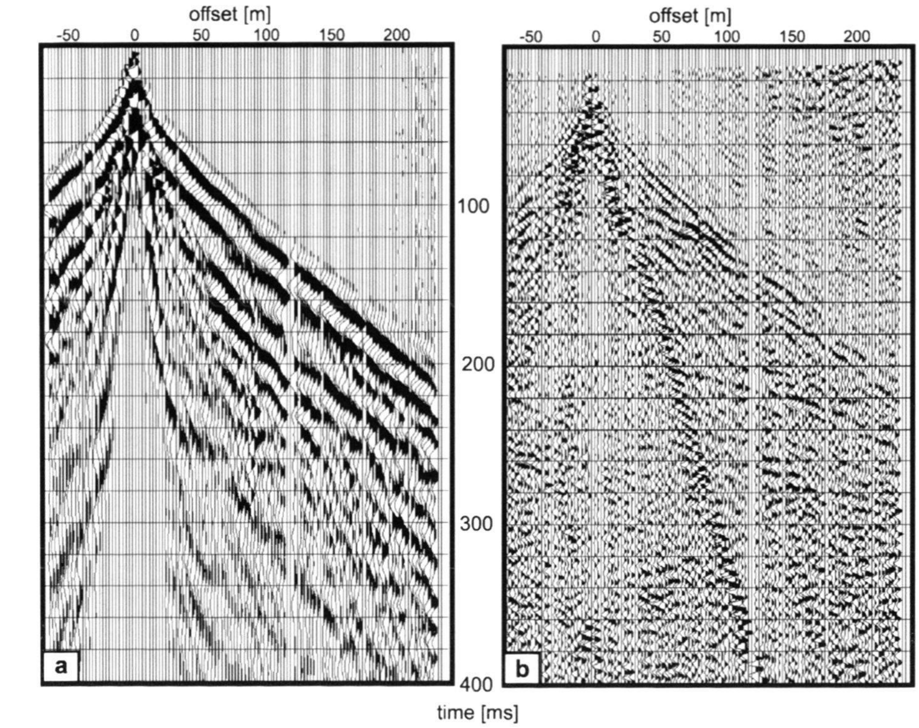

Fig. 4. Example of a shot gather of (a) raw data with only trace equalisation applied, and (b) the same data after applying initial processing including amplitude scaling, refraction static correction, spectral whitening, and frequency filtering.

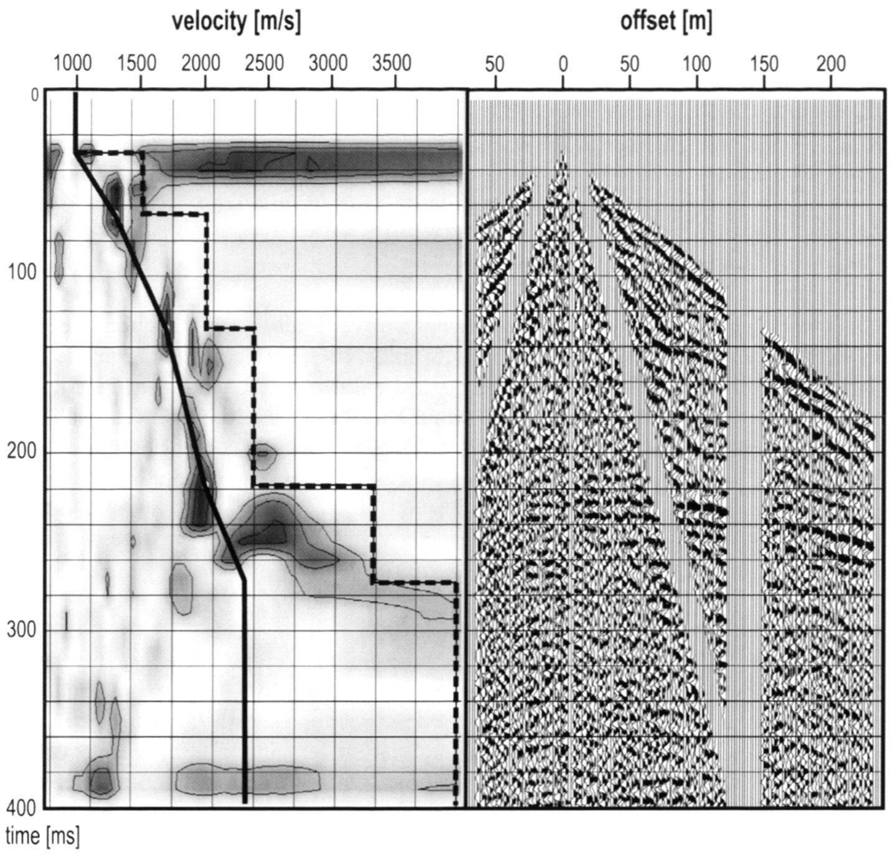

Fig. 5. Velocity panel of CMP 200 from Profile 1. Left side shows the semblance analysis with velocity picks and model. Right side shows the associated CMP supergather, a combination of three adjacent CMP's. Velocity picks were chosen based on a combination of maximum semblance, fitting of reflections on the CMP gather and optimum stacking results. Solid black line is the picked stacking velocity curve. Dashed line represents the resulting interval velocity.

after initial processing. On the processed section, reflections are visible at larger offsets between 100 ms and 250 ms two-way-traveltime (TWT) which corresponds roughly to a depth of ~60 m to 250 m. The near-offset range is still dominated by noise and other phases.

Further processing steps comprised common midpoint (CMP) sorting, velocity analysis (Fig. 5), residual static and normal moveout (NMO) corrections. Due to the large vertical velocity gradient of the data a rather high NMO-stretch mute of 80% was chosen to avoid removal of shallow reflections. Before stacking, energy of first arrivals and shallow events that could not be reliably identified as reflections was muted. Finally, Kirchhoff time migration was applied to both sections using 80% of the stacking velocity and a maximum dip of 35°. Data were processed independently at Institutes of Geophysics, ETH Zürich and University of Lausanne and the results iteratively improved after comparison and discussion.

Results

The resulting sections of the seismic profiles are shown in figures 6 and 7. Variations in reflection strength and character are obvious on the stacked sections (Figs. 6a, 7a). Based on these changes and on major reflections (R1-R4) we distinguish five major units (S1-S5).

North-south profile – Profile 1

Topmost unit S1 on Profile 1 (Fig. 6) is only partly imaged. It reaches down to ~50-60 ms. The upper part is missing due to muting of unreliable energy on shots and CMP gathers. Therefore, S1 yields no clear internal reflections. The strong reflection R1 marks the bottom of S1. R1 can be followed across most of the profile except the northern part (CMP 1600-2100) where the reflections are covered by first arrivals (e.g. refracted energy) on shot gathers. Below R1, unit S2 is characterized by weak reflectivity; its lower limit corresponds to reflection R2 which can only be seen on the southern half of the profile. Beneath S2, seismic unit S3 (southern half of profile) is characterized by moderately coherent reflections which occur between ~120-200 ms. This unit is clearly differentiated at the southern end of the profile (CMP 800-1000), where it is onlapping on reflection R3, but cannot be delineated on the northern part of the line.

The zone of high-amplitude, moderately continuous reflections labelled S4 can be traced across most of the profile. This unit forms a depression filled by unit S3 (CMP 300). In the middle of the profile (CMP 1200-1600) S4 appears to rise. Unfortunately, the data quality is low in this part of the profile and the top of S4 cannot be traced with confidence. In most parts of the profile the amplitudes within S4 are decreasing with depth, probably because the pipe-gun source was not strong enough to fully penetrate this unit. Only in the northern end (>CMP ~1600) a separate dipping unit S5 is imaged which is clearly separated from units S2 and S4 above by reflection R4.

Table 3. Interval velocities of different sedimentary units (s. Fig. 5)

seismic unit	interval velocity [m/s]	interpretation
S1	800–1200	fluvial and glaciofluvial
S2	1600–1900	lacustrine
S3	2000–2400	subglacial
S4	2400–3200	Tertiary Molasse
S5	~3500	Mesozoic limestone (Malm)

West-east profile – Profile 2

Profile 2 (Fig. 7) crosses the S-N profile at CMP 720 (~CMP 1300 on Profile 1). Between CMP 1600 and 1700 a shot gap is related to the crossing of a highway. This section shows similar seismic units to those observed on Profile 1. Again the topmost unit S1 is separated from S2 to by reflection R1. This reflection can be followed across most of the profile except for the first 500-600 CMP's. In this part, the reflection is too shallow to be followed. R1 dips towards the east from 60 ms to ~100 ms.

As on Profile 1, unit S2 is characterized by weak reflectivity. S2 appears as a thin unit of 40-50 ms in the west that thickens and deepens towards the east (from 100 to 200 ms thickness) which represents a general trend of all units identified on Profile 2. The boundary between units S2 and S3 (~210 ms, CMP 1900-2100) is not as well defined as on Profile 1. Moderately coherent reflections between 200 and 250 ms at the eastern end of Profile 2 (CMP 1700-2150) are observed within a trough in the underlying unit S4.

The strong coherent reflections of unit S4 are again the outstanding feature of this profile. They consist of a ~100 ms thick zone of reflectivity that is dipping towards the east. Below this unit no reliable reflections appear. There is no indication of a unit similar to S5 on Profile 1.

Analysis of seismic velocities

Beside the reflection character of the seismic sections, seismic velocities obtained from NMO velocity analysis provide further information to distinguish different units (Fig. 5). We found velocities within the same layer to be generally consistent. The lateral variation of velocities along both profiles is low. Although the offset range provides reliable results for reflections down to 300 ms, the uncertainty increases with depth. Table 3 lists the range of velocities found in the data.

Interpretation

The seismic profiles were interpreted in combination with borehole data, NAGRA profiles and outcrop information. This resulted in two cross-sections shown in Figure 8. Depth values are based on migration velocities and the results of the NAGRA profiles. The depth of seismic reflections fits well with the depth of lithologic changes found in the boreholes.

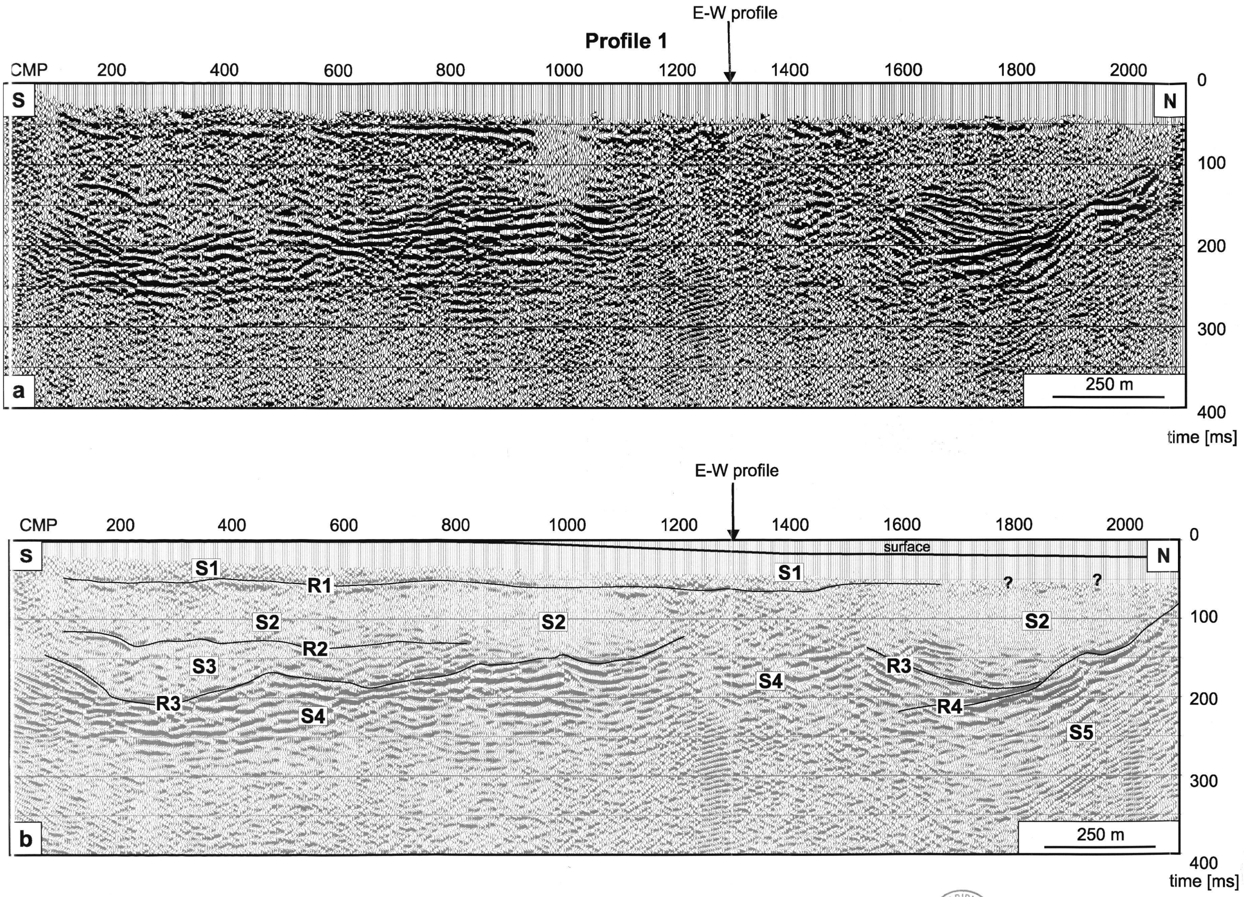

Fig. 6. (a) stacked section of Profile 1 (north-south profile). Note changes in amplitude character with increasing two-way traveltime. (b) Migrated section of (a) with interpreted units and main reflectors. Arrow on top marks the intersection with Profile 2 (E-W profile). For identification of units see text and Fig. 8.

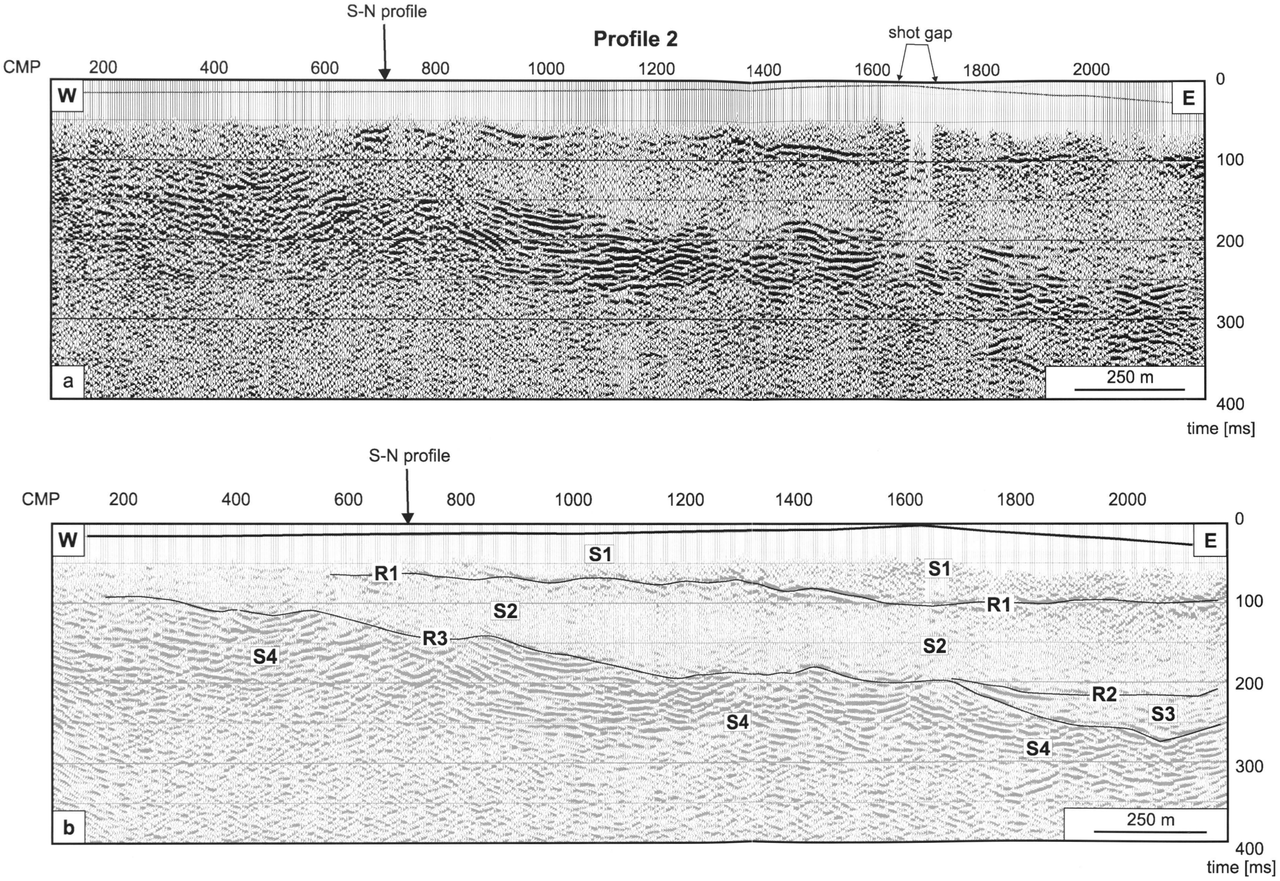

Fig. 7. (a) stacked section of Profile 2 (east-west profi le). Note changes in amplitude character with two-way traveltime as in fig. 6a. (b) Migrated section of (a) with interpreted units and main reflectors. Arrow on top marks the intersection with Profile 1 (S-N profile). For identification of units see text and Fig. 8.

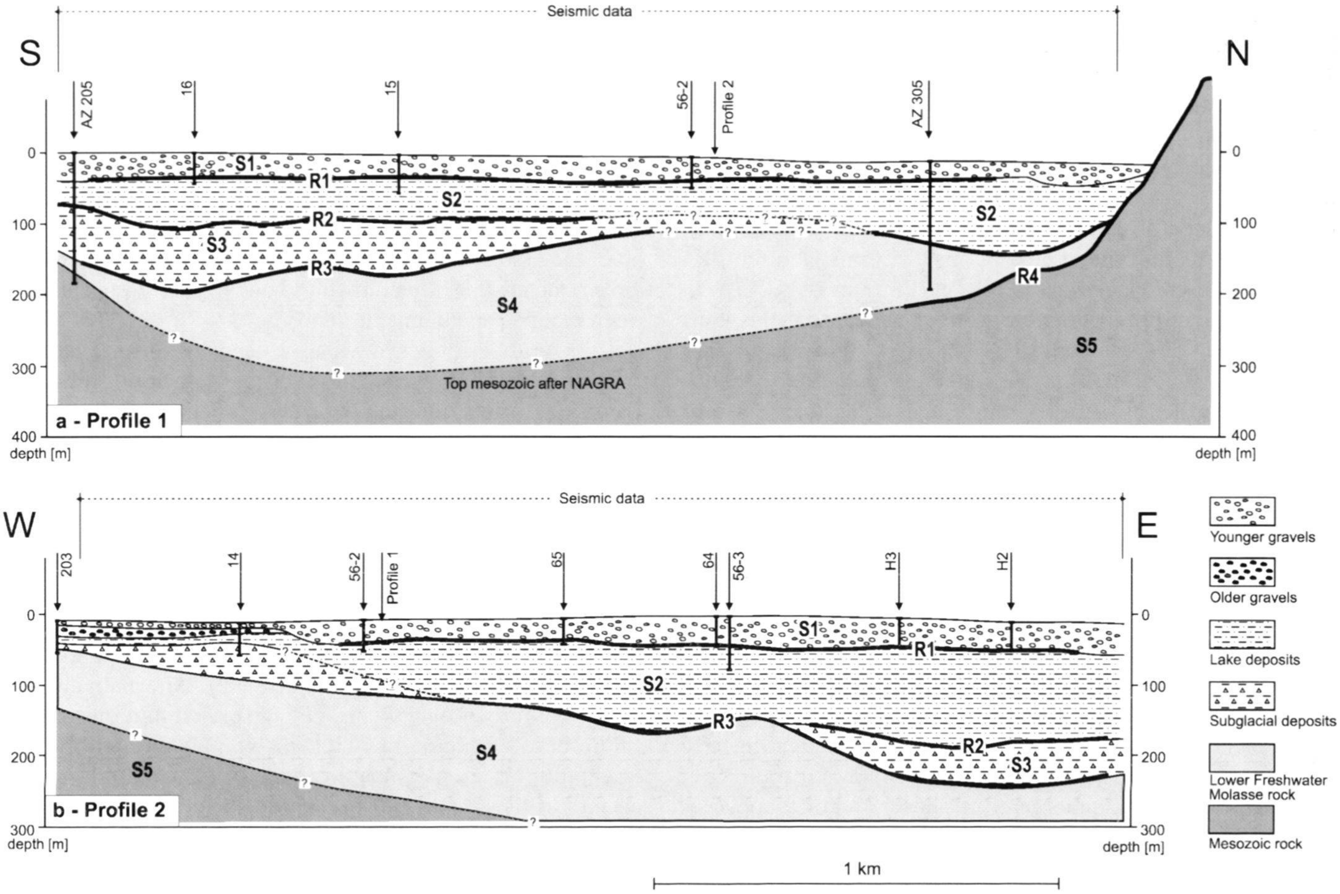

Fig. 8. Sketch of depositional model based on the interpretation of profiles 1 and 2 (Figs. 6 and 7) and borehole records. Information on Molasse-Mesozoic boundary is from the NAGRA profiles (Sprecher & Müller 1986) and borehole AZ-205. Note that several boreholes are projected from some distance to the profiles (Fig. 3). Thick black lines show the location of seismic reflections R1-R4 identified in the time sections of Figs. 6 and 7. S1-S5 represent the seismic units as described in Figs. 6 and 7 and in Table 3.

Because both profiles yield basically the same units, they are discussed together.

Top gravel

The top unit S1 on both profiles is hardly imaged due to the disturbance by refracted and related energy. Where it has been imaged it is characterized by a low reflectivity and the absence of internal reflections. Several shallow boreholes provide good information on the lithology (Figs. 3 and 8). The unit consists mostly of clean gravels and few sandy gravels and reaches a thickness of 30-40 m across the whole study area (Graf in press). Most of the gravels are unsaturated with water, and, therefore, yield a low seismic velocity (<1000 m/s). Unit S1 is interpreted as glacio-fluvial gravels mainly deposited during the last glaciation. Some paleosoils found at the eastern end of Profile 2 (not visible in the seismic data) suggest that some of the lower gravels were deposited prior to the last glacial advance (Fig. 8b). Therefore, S1 probably represents deposits of more than one glacial period. Unfortunately, our seismic data do not yield further details of this unit. The bottom of S1 defined by the strong reflection R1 coincides with a lithological change observed in boreholes.

Lacustrine deposits

The uniformly weak reflectivity of unit S2 is typical for low energy environments found in lakes. Similar seismic units interpreted as lacustrine sediments have been reported from the Suhre valley (Büker et al. 1998), Rhone valley (Pfiffner et al. 1997) and several Swiss lakes (Finckh et al. 1984). Boreholes AZ-205 and AZ-305 respectively report ~95 m and ~35 m thick units of silt and clay rich lacustrine material. In addition, all the boreholes that have reached the top of this unit show fine grained sediments (Fig. 8). The top of this layer is, therefore, well established along both profiles. In unit S2 seismic velocities range from 1600 m/s to 2000 m/s in agreement with uphole-velocities of 1800-2000 m/s measured in boreholes AZ-205 and AZ-305. This is comparable to lacustrine deposits found at other places (Finckh et al. 1984; Pfiffner et al. 1997; Büker et al. 1998). Timing of deposition of this layer remains unclear. Although the seismic resolution is probably reduced by the surface gravels and small variations in unit S2 may not be resolved, the absence of internal reflections suggests that deposition was not interrupted by major events as often observed in glacio-lacustrine deposits (Pfiffner et al. 1997; Nitsche et al. in press). Therefore, we conclude that this unit was deposited during an inter-glacial period. According to the four-basin model (Fig. 2) it must have been an older one, although no further information on the age of this layer is available.

Subglacial deposits

In some parts of the profiles we identified unit S3 characterized by medium to strong reflection amplitudes. We interpret this unit as subglacial deposits. A 75 m thick section in borehole AZ-205 was interpreted as glacial till by Sprecher & Müller (1986). Other boreholes in the region show that not only tills but also gravels and lacustrine deposits are abundant in unit S3 (Jäckli & Kempf 1972). Subglacial basin deposits are usually very heterogeneous. Such deposits may form directly under glacier ice or underneath a glacier floating above a glacial lake. Therefore, different types of tills and lacustrine sediments may be present in the same unit. In contrast to basin sediments deposited farther away from a glacier, the abundance of generally gravely to blocky sediments is a distinctive feature of this environment. Such deposits have been reported from many drillings in the Northern Alpine Foreland (e.g. Matousek & Graf 1998).

Unit S3 is not continuous on the seismic profiles and because of the orientation of the two profiles we cannot reliably trace this unit from one section to the other. More seismic lines or a three-dimensional seismic survey are necessary to image the complete extent of S3 and to verify whether all parts correspond to the same depositional unit or not.

Molasse sediments

The dominant feature on Profiles 1 and 2 is unit S4, a zone with strong amplitudes. Marl and sandstone have been found at depth of 41.50 m and 168 m (350.8 m and 235.0 m above sea level) at boreholes 203 and AZ-205, respectively. Sprecher & Müller (1986) interpreted these sediments as Lower Freshwater Molasse (USM). According to Naef et al. (1985) and Diebold et al. (1991) they were deposited onto the Malm sediments during late Oligocene and early Miocene. Using the projected top of Malm horizon from the NAGRA data (Sprecher & Müller 1986) we can estimate the thickness of unit S4 as 100 - 150 m. Detailed studies of the Molasse basin and its development suggest a phase of erosion which followed initial deposition when the area of the Swiss Jura was compressed, folded and uplifted during late Miocene (Naef et al. 1985). Later deposits of upper marine Molasse and upper freshwater Molasse were probably eroded during this phase. In addition to uplift related erosion, some Molasse sediments might have been eroded by later glacial activity. The top of unit S4 is not a clear continuous reflection. There might be no continuous lithological contrast between S3 and S4. Glacial till (basal till) lying on top of molasse sediments can produce a similar seismic reflection character. It is often difficult to distinguish seismically between molasse and diamictic deposits.

Comparative studies of Molasse deposits in other parts of Switzerland have shown that the seismic velocity of these deposits is highly variable and basically a function of overburden thickness (Diebold et al. 1991; Naef et al. 1995). These studies report velocities between 2000-3000 m/s for the USM in the upper 200 m, which fits with the 2400 - 3100 m/s found in our data.

The internal structure of unit S4 is complex. The discontinuous character of the reflections with contrasting dips may reflect the heterogeneous nature of USM-sediments. These sediments consist of alluvial fans and channels, overbank and levee deposits, and vary laterally (Keller 1992). Alternatively, the complex nature of unit S4 may be interpreted in terms of broken up blocks separated by faults. A combination of both interpretations is also possible. In addition, some features on the seismic profiles might not be related to reflection along the profile plane but originate from other features which lie out of the vertical plane of the 2D-profiles with a strong three dimensional structure (e.g. Profile 2, CMP 1500, ~200 ms). The Molasse sediments culminate in the western part of Profile 2 and CMP 1200 to 1600 in Profile 1. This is an important feature of the general basin-morphology, which can also be gained from borehole information (Graf in press).

Mesozoic rocks

The lowest unit that can be resolved is unit S5. It is clearly identified as Mesozoic rocks outcropping at the Lägern structure just north of Profile 1 (Fig. 1). The energy of the pipe gun source was not sufficient to penetrate the overlying sediments along the rest of profile 1 and 2. This unit has been interpreted as Mesozoic (Malm) limestone units based on seismic lines shot by NAGRA (Sprecher & Müller 1986; Diebold et al. 1991). Seismic velocities for this unit range from 3000 to 3500 m/s (Table 3), which is also comparable to the velocities measured in the NAGRA survey. In addition, limestone is observed at 168 m depth (235 m asl) in borehole AZ-205 (Sprecher & Müller 1986). Although we cannot detect the presence of Mesozoic sediments in the southern part of Profile 1 due to the low data quality, this information was used in the interpretation (Fig. 8). Because Profile 1 follows more or less NAGRA profile 82-NF-30 (Fig. 1), the top of Mesozoic rocks can be confidently projected into our model (Fig. 8a). However, the projection of this boundary into Profile 2 is less reliable, because of the distance to the other NAGRA lines, e.g. 82-NX21. There is Malm limestone outcropping ~1.5 km west of Profile 2 which is most likely dipping towards the east. Therefore, the model in figure 8b shows only an indication based on the cross point with Profile 1. The present E-W orientated depression of Mesozoic rocks between the Lägern- and Chestenberg structures (Fig. 1) is related to folding of the Swiss Jura since the Miocene (Diebold et al. 1991).

Conclusions

Two high-resolution reflection seismic profiles were successfully acquired in an overdeepened glacial basin area with strong seismic background noise due to heavy traffic. Although the main units of the Birrfeld basin filling were known on the basis of previous drillings (Fig. 2), the seismic sections yield new and improved details of the extent and architecture of the main units especially in the deeper parts of the basin. Five major units with variable thickness and extent were distinguished that we interpret on the basis of borehole information as

(1) top gravels deposited during the last glacial and interglacial cycles,
(2) lacustrine deposits, probably deposited during an older interglacial period,
(3) subglacial deposits of one of the first glacial advances that reached the area,
(4) sediments of lower freshwater Molasse, and
(5) Mesozoic limestone rocks in the northern part of Profile 1.

This survey fills the gap between the regional tectonic investigations conducted by NAGRA (Sprecher & Müller 1986) and the numerous shallow (<50 m) boreholes drilled in the area. The final model provides a detailed image of the main structural units. Shape and thickness of layers that have been predicted in Figure 2 appear more clearly. The seismic sections provide new information, especially on the topography of the base of Quaternary deposits (i.e. top Molasse).

Seismic data provide mainly structual and limited lithological information based on reflectivity pattern and seismic velocities. To establish better timing of deposition and to verify lithology and internal details of the deeper units deeper drillholes are necessary. Three-dimensional geophysical imaging should provide detailed information on some features which could not be resolved by the two-dimensional profiles.

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