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Imaging Molasse and Quaternary Sediments in Lake Geneva, Switzerland, with 3-D High-Resolution Seismic Reflection Methods: A Case Study

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Key words: high resolution, 3-D seismic reflection, seismic facies, lake, Molasse, thrust fault, Quaternary
Mots clés: haute résolution, sismique réflexion 3-D, sismofaciès, lac, Molasse, chevauchement, Quaternaire

ABSTRACT

A high-resolution three-dimensional (3-D) seismic reflection survey was conducted in Lake Geneva, near the city of Lausanne, Switzerland, as part of a project for developing such seismic techniques. Using a single 48-channel streamer, the 3-D site with an area of 1200 m x 600 m was surveyed in 10 days. A variety of complex geologic structures (e.g. thrusts, folds, channel-fill) up to ~150 m below the water bottom were obtained with a 15 in.^{3} water gun. The 3-D data allowed the construction of an accurate velocity model and the distinction of five major seismic facies within the Lower Freshwater Molasse (Aquitanian) and the Quaternary sedimentary units. Additionally, the Plateau Molasse (PM) and Subalpine Molasse (SM) erosional surface, "La Paudèze" thrust fault (PM-SM boundary) and the thickness of Quaternary sediments were accurately delineated in 3-D.

RESUME

Une campagne de sismique réflexion de tridimensionnelle (3-D) à haute résolution a été réalisée sur le Lac Léman, près de la ville de Lausanne en Suisse, en tant qu'élément d'un projet pour développer de telles techniques sismiques. Le site 3-D est contenu dans une zone de 1200 m x 600 m qui a été couverte en 10 jours en utilisant une flûte de 48-hydrophones. Une variété de structures géologiques complexes (chevauchements, plis et remplissage de chenaux par exemple) ont été obtenues jusqu'à ~150 m au dessous du fond d'eau avec un canon à eau de 15 in.^{3} Ces données 3-D ont permis de construire un modèle de vitesse précis et de distinguer cinq faciès sismiques principaux dans la Molasse d'eau douce inférieure (Aquitanian) et dans des unités sédimentaires quaternaires. De plus, la surface d'érosion de la Molasse du Plateau (PM) et de la Molasse subalpine (SM), le chevauchement de "La Paudèze" (frontière entre PM et SM) et l'épaisseur des dépôts quaternaires ont été délimités en 3-D avec précision.

1.- Introduction

In order to better understand geologic processes in lacustrine settings, detailed information on geologic features within a wide range of depths is required. This information includes sedimentation and erosion rates and patterns, characteristics of gas occurrences and geometries of tectonic structures. Many investigation targets beneath lakes may be complex due to the abundance of rapidly changing factors, such as climate, human activity and tectonism.

Conventional offshore investigation techniques include seismic reflection surveying with a high-resolution source along a grid of widely-spaced intersecting lines. As in the oil industry, such two-dimensional (2-D) methods are sufficient for mapping the major targets on a regional scale, but their imaging capabilities fall short when greater detail of complex or particularly interesting features is desired. In such cases, it is necessary to employ three-dimensional (3-D) methods, which already have been proven to provide significantly more subsurface information than 2-D methods in shallow-offshore oil exploration (e.g. Reymond & Stampfli 1994, Weimer & Davis 1996). As positioning systems continue to develop and as relatively inexpensive computers increasingly allow quick processing of large data volumes, the application of 3-D seismic reflection methods to environmental and engineering problems is becoming more feasible. Recently, several 3-D high-resolution seismic reflection studies have been successful in accurately mapping complex structures offshore (e.g. Davies et

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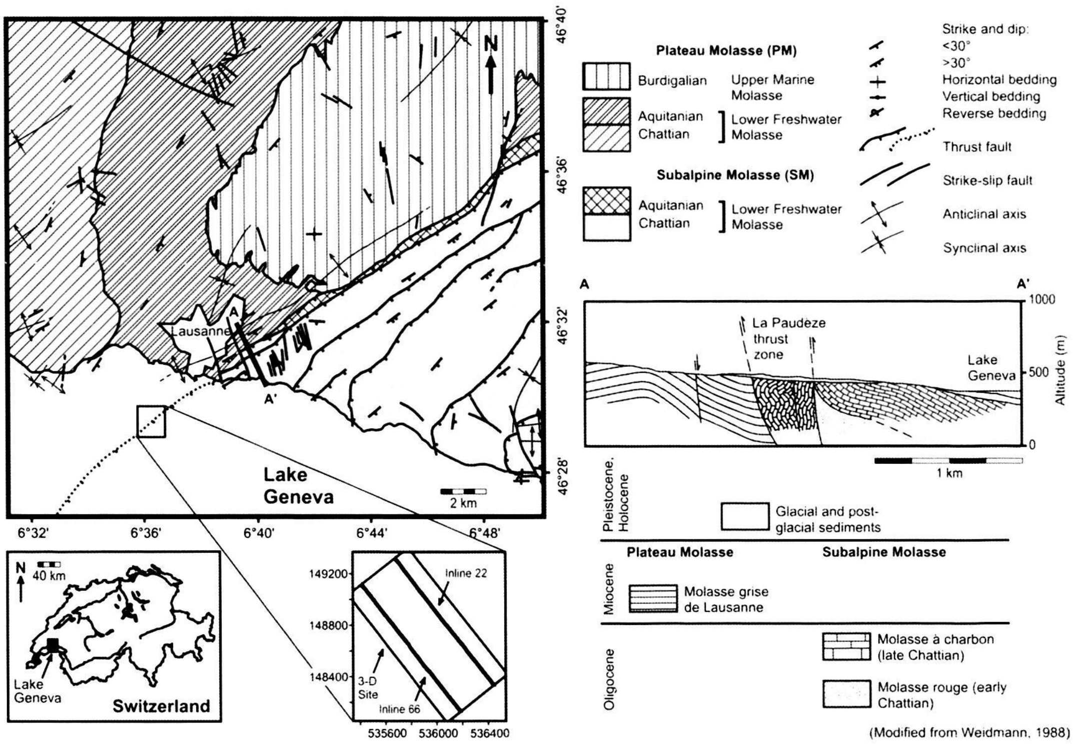

Fig. 1. Geologic structure map of the north-central shore of Lake Geneva, Switzerland (inset map), showing location of 3-D seismic survey area (small rectangle). Enlargement of rectangle shows extent of 3-D survey and locations of inlines 22 and 66 (Figs. 2 and 3); axes labels are Swiss coordinates in meters. Right half shows lithostratigraphy of cross-section AA' near the city of Lausanne.

al. 1992, Henriet et al. 1992).

This paper presents a basic interpretation of data from an offshore high-resolution 3-D seismic reflection survey and illustrates the possibilities and limitations of using such data in constructing a detailed geologic model of Molasse and Quaternary sediments. In general, our aim is to develop an efficient 3-D seismic reflection system that is suitable for studying a wide variety of lacustrine settings. Deep signal penetration and high data resolution are pursued with the use of multiple recording channels, accurate source-receiver positioning and interchangeable and adjustable seismic sources. Earlier publications describe certain aspects of acquiring and processing data from a single-streamer 3-D survey (Scheidhauer et al. 2000). More recent experiments involve multi-streamer surveying, developing more accurate positioning systems and applying special processing techniques (Scheidhauer et al. 2002).

2.- Study Site

2.1. Geological Setting

The northern Alpine foreland basin, spanning a distance of ~700 km from the French Savoy area in the west to Linz (Austria) in the east, is filled with Molasse deposits, which are subdivided into two shallowing-upward megasequences by the Aquitanian/Burdigalian unconformity (Homewood et al. 1986). The sedimentary succession comprises four lithostratigraphic groups: Lower Marine Molasse (Rupelian), Lower Freshwater Molasse (Rupelian?-Chattian-Aquitanian), Upper Marine Molasse (late Aquitanian-Burdigalian), and Upper Freshwater Molasse (Langhian-Serravalian).

The study area is located in the western part of the Swiss Molasse Basin, which comprises two tectonic units: the relatively undeformed, southeast-dipping Plateau Molasse (PM) and the Subalpine Molasse (SM), a complex assemblage of imbricated thrust slices (Gorin et al. 1993). "La Paudèze" fault, a major thrust fault system with a total vertical throw of ~1 km and a southwest-northeast trend, divides these units (Weidmann 1988, Fig. 1). Lake Geneva, one of Europe's biggest perialpine lakes, formed in a glacial trough that was carved in the PM and SM units from the Alpine frontal thrust to the Jura in France and western Switzerland (Fig. 1). Pleistocene glacial deposits and Holocene fluvial and lacustrine deposits in the eastern part of the lake are >350 m thick, but <40 m thick along the steep northern slope (Vernet et al. 1974).

Seismic Facies	Reflection Character	Stratigraphy, Sedimentology	Facies of Previous Studies Chapron (1999)	Morend (2000)
1	trough, wavy, very continuous, high amplitude	PM, channel-fill and floodplain	M	1, channel-fill 2, floodplain 3, weathered, sheared zone
2	contorted to chaotic, variable amplitude	SM, deformed channel-fill and floodplain	C	SF1
3	continuous, high amplitude	SM, channel-fill and floodplain	C	SF2
4a	parallel discontinuous to chaotic, diffractions, low amplitude	G, waterlain till	2a, glacial advance	
4b	parallel continuous to hummocky, diffractions, high amplitude	G, glacio-lacustrine, slump	3c and 3d, glacial fluctuations	
5a	parallel continuous, low amplitude	P, lacustrine	5	
5b	parallel to hummocky, low amplitude	P, reworked lacustrine, slump		

PM = Plateau Molasse, SM = Subalpine Molasse, G = Glacial, P = Post-Glacial

Table 1. List of seismic facies analyzed in this study and correlated with those from previous studies.

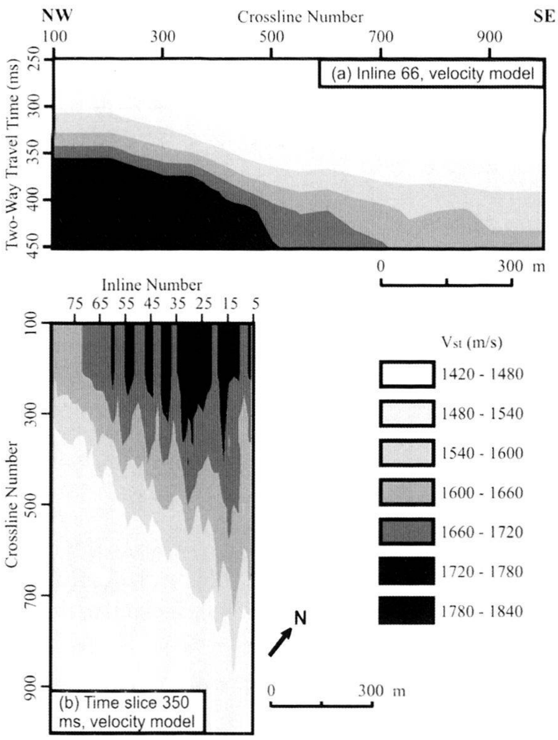

Fig. 2. Model of stacking velocities (V_{st}) along (a) inline 66 and (b) time slice at 350 ms for all 80 navigated lines. See Figs. 1 and 3 for location.

This paper focuses on the upper part of the Lower Freshwater Molasse, i.e. the Aquitanian "Molasse grise de Lausanne" and Chattian "Molasse à charbon" formations (Fig. 1), and on the Quaternary lake fill. Among the authors that describe the stratigraphy and sedimentology of the Molasse grise de Lausanne are Bersier (1958a,b), Rigassi (1977), Weidmann (1988) and Weidmann & Morend (2002). This formation is a thick succession (800-1100 m) of laterally discontinuous, channelized sequences composed of coarse sandstone bodies with concave-upward erosional bases (channels), fine-grained sandstones, silty marls, and scarce clays. The depositional environment of this formation is depicted as a wide, low-relief floodplain with meandering rivers that was locally invaded by tidal channels at the end of the Aquitanian (Berger, in Weidmann 1988, Berger 1992). The Quaternary fill unconformably overlies the Molasse and, as in other areas of Lake Geneva, may be composed of esker, till, glaciolacustrine, lacustrine and deltaic deposits (Moscariello et al. 1998, Chapron 1999, Table 1).

2.2. Previous Seismic Investigations

Past high-resolution seismic studies in this lake, mostly single-channel 2-D surveys, covered extensive areas but were unable to provide detailed information on deep structures (e.g. Chapron 1999, Finckh et al. 1984, Girardclos 2001, Loizeau 1991, Moscariello et al. 1998m, Vernet et al. 1974). Furthermore, all but the most recent of these surveys consisted of widely-spaced grids that made it difficult to correlate complex features from line to line.

In north-central Lake Geneva, just offshore the city of Lausanne (Fig. 1), recent surveying of a tight grid of 2-D multi-channel seismic lines attained a generally deeper signal penetration and a higher signal-to-noise ratio than those of the earlier studies (Morend 2000, Morend et al. 2002). The authors presented high-resolution images of shallow Quaternary sediments as well as deeper incised-valley fill within the consolidated Molasse units (Table 1). Surprisingly, even a line spacing as low as 50 m was insufficient in allowing correlation of some major structures, especially in the area of the thrust faults. This part of the lake, therefore, was chosen in order to test our 3-D system and to simultaneously complement the recent seismic work by providing much less spatially aliased and deeper seismic images, especially from the highly deformed zones.

3.- Data Acquisition and Processing

For the acquisition, we used a single 48-channel streamer, a 24-bit seismograph and a differential GPS (dGPS) with the antenna on the ship and with a maximum accuracy of 0.5 m. A 15 in.^{3} water gun (150-1700 Hz range, 750 Hz dominant frequency), operated at a nominal pressure of 140 bars, was employed as the seismic source.

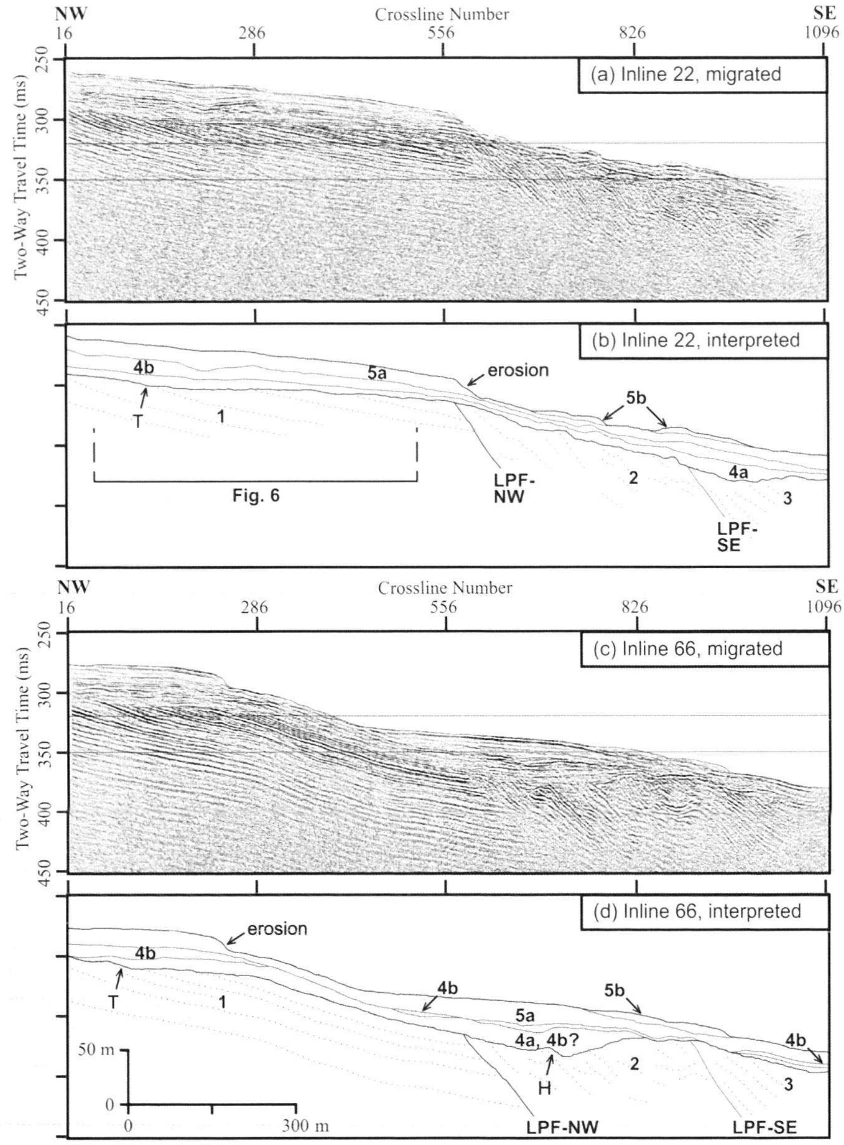

Fig. 3. Selected migrated inlines from 3-D survey: (a) inline 22, (b) interpreted inline 22, (c) inline 66 and (d) interpreted inline 66. Interpretation: 1 - Plateau Molasse, 2 - deformed Subalpine Molasse, 3 - Subalpine Molasse, 4a/ 4b - glacial sediments, 5a/5b - post-glacial sediments, LPF-NW/LPF-SE - northwest/southeast faults of La Paudèze thrust zone and H/T - highs and troughs on Molasse paleosurface. Thickened lines correspond to mapped horizons in Fig. 5, and dotted lines highlight Molasse bedding structures. Location of image in Fig. 6 is indicated in (b), and horizontal lines in (a) and (c) show time slice location (Figs. 2 and 4). Depth scale in (d) is approximate and only for uppermost sedimentary units. See Fig. 1 for inline location.

The 3-D site covered an area of 1200 m x 600 m (Fig. 1). Receiver spacing for the profiles was 2.5 m in the inline direction and 7.5 m in the crossline direction. The greater crossline spacing was justified by the presence of a known structural trend perpendicular to the inline direction. We chose a 5-m shot spacing, which yielded a nominal 12-fold data coverage. With the single-streamer/single-source array, the total survey was conducted in 10 days.

Data processing basically followed the oil industry standard (Yilmaz 1987). It included trace editing, geometry assignment, flex binning, amplitude recovery, bandpass filter, gain, 3-D dip-moveout correction, stack and 3-D migration. For the last three steps, a detailed semblance velocity analysis was performed on every second inline and every 50th common-depth point. During geometry assignment, the dGPS data showed that the distance between the shots varied only slightly, which was expected because the dGPS triggered at time intervals that could be adjusted to changes in the ship velocity (Pugin et al. 1999). All shot and receiver positions were extrapolated from the boat position in a way that took into account streamer feathering (Scheidhauer et al. 2000).

4.- Results and Discussion

4.1. General

Due to the multi-fold coverage, the stacks reveal a deeper pe-

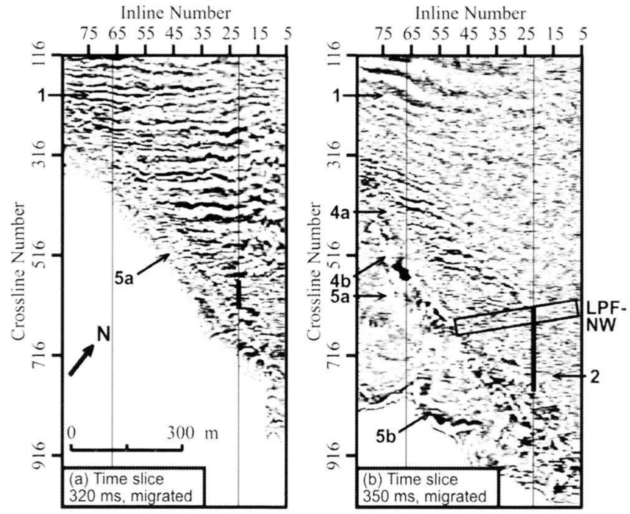

Fig. 4. Selected migrated time slices from 3-D survey: (a) time slice at 320 ms and (b) time slice at 350 ms. Interpretation: 1 - Plateau Molasse, 2 - deformed Subalpine Molasse, 4a/4b - glacial sediments, 5a/5b - post-glacial sediments and LPF-NW - northwest fault of La Paudèze thrust zone. Vertical lines show inline location (Figs. 2 and 3), and thickened portions indicate extent of facies 2. See Fig. 3 for time slice location.

netration and a better signal-to-noise ratio than single-channel sections from the same location (Scheidhauer et al. 2000), and the gathers permit accurate determination of stacking velocities (Fig. 2). Beneath the water bottom, the water gun reflections generally reach >100 ms of penetration, which represents a thickness of ~150 m where the bedrock is shallow. According to the velocity analysis, interval velocities range from 1450-2100 m/s for the unconsolidated sediments and 2200-4600 m/s for the consolidated sediments.

With the help of results from previous studies (Section 2.2), five major seismic facies can be distinguished in vertical and horizontal sections from the 3-D data set: 1 - Plateau Molasse (PM), 2 - highly deformed Subalpine Molasse (SM), 3 - less deformed Subalpine Molasse (SM), 4 - glacial sediments, and 5 - post-glacial sediments (Table 1). The various facies are represented in selected inlines 22 and 66 (Fig. 3, location in Fig. 1) and time slices at 320 ms and 350 ms (Fig. 4, location in Fig. 3). Comparing Fig. 2 with Figs. 3 and 4 demonstrates the correspondence between stacking velocities and facies: high velocities for facies 1 (>1700 m/s), intermediate velocities for facies 2-3 (1600-1700 m/s) and low velocities for the water column and facies 4-5 (<1600 m/s). With the delineation of the major boundaries in 3-D, i.e. horizon contour maps (2 ms interval) of the water bottom, the top of the Molasse units and the PM-SM boundary (Fig. 5), new insight into small-scale geomorphological aspects and geological processes is possible.

4.2. La Paudèze Fault

The northwest fault of La Paudèze thrust system (Fig. 1) can be easily distinguished on the inlines. A dip of nearly 30° and a maximum depth of 430 ms are visible in the inline profiles (LPT-NW in Figs. 3 and 4). On the horizon map (Fig. 5a), this fault strikes ~043°, nearly parallel to the crosslines, and shows slight undulations, which suggest the presence of complex small-scale structures. These complexities are indicated on inline profiles and include minor faults along both sides of the main fault. On a larger scale, it can be seen that this fault is slightly concave towards the northwest. This curvature is part of a larger-scale fault-plane undulation observed in 2-D seismic profiles from the same vicinity (Morend 2000). Previously published geological and structural maps do not show such detail in the PM-SM boundary, even on land (Vernet et al. 1974, Weidmann 1988). Moreover, this study has determined the location of this boundary within the site up to an accuracy of a few meters.

4.3. Plateau Molasse

Reflections of the PM, which comprise the majority of the seismic data set along the northwest, are slightly inclined, relatively high-amplitude and very continuous (facies 1). The inclination corresponds to a ~10° bedding dip towards the southeast. Large-scale variation in this dip indicates that these reflections are from the southeastern flank of the Lausanne anticline (Fig. 1). The cyclic pattern of reflections along the depth direction, visible in both vertical sections (Fig. 3) and time slices (Fig. 4), represents the alternating shale (high-amplitude, low-frequency) and sandstone (moderate-amplitude, variable-frequency) sequence of the Lower Freshwater Molasse (Morend et al. 2002). Shallow time slices (e.g. 320 ms) of the PM clearly reveal a bedding strike of 044°, nearly parallel to the crosslines and the main fault (see Section 4.2 and Fig. 4a). Deeper time slices (e.g. 350 ms), however, show a change in strike to 075° (Fig. 4b), which may indicate small transpressive faults within the thrust system. Alternatively, bedding deformation by a large landslide or slump at the flank of an incised valley (Weidmann & Morend 2002) may explain the change in strike with depth.

Although generally flat (Fig. 5b), the PM paleosurface is characterized by slight irregularities. These indicate small-scale differential erosion throughout areas of inclined bedding planes, which have variable strength due to the differing lithologies (Fig. 3). The shallowest recognizable erosional pattern is found on the subhorizontal northern portion of the PM. In outcrop data (Choffat & Aubert 1983) and in vertical seismic sections (Morend et al. 2002; this study), it shows a step-like relief of several meters (Fig. 3), and it is interpreted as differential erosion of the inclined sandstone-shale cycles, i.e. small cuestas. On the horizon map (Fig. 5b), these cuestas

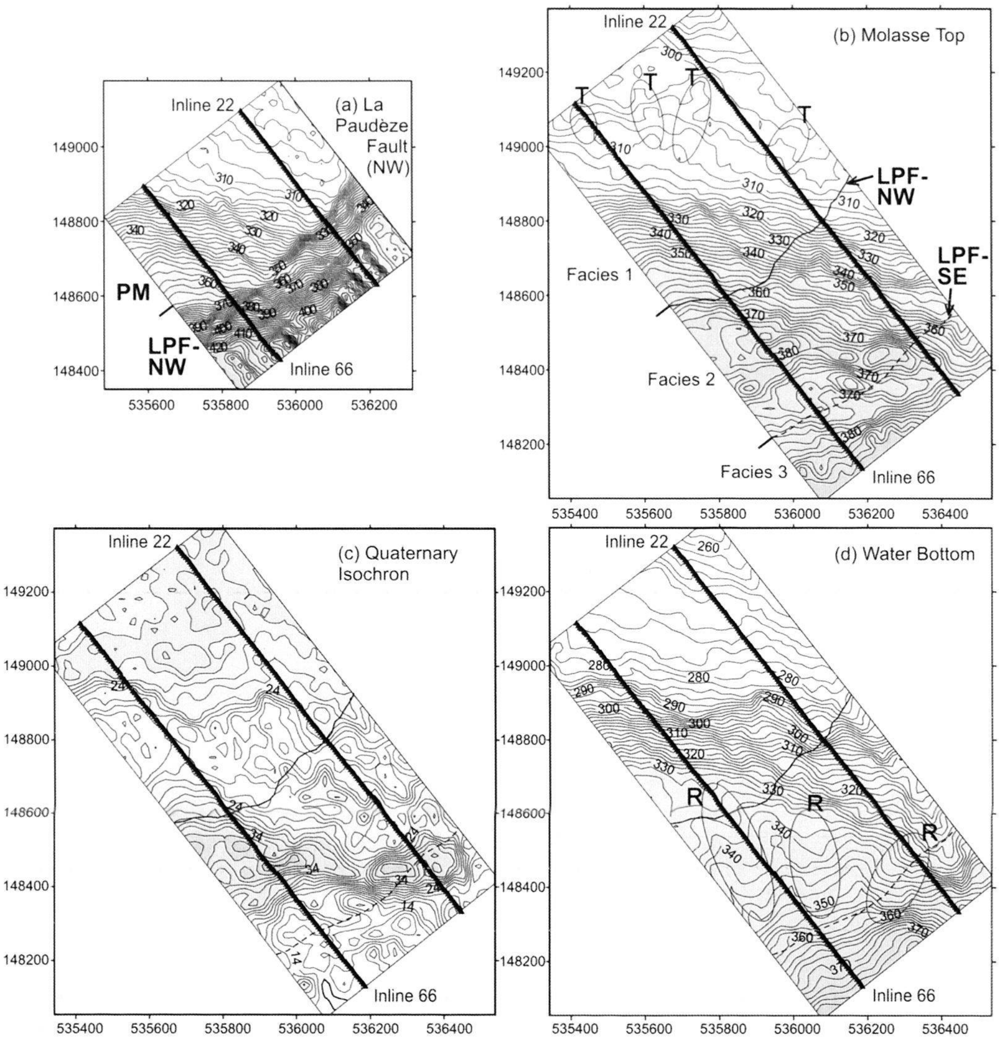

Fig. 5. Contour maps of interpreted horizons: (a) northwest fault surface of La Paudèze thrust zone (LPF-NW) and, towards the northwest, top of Plateau Molasse (PM), (b) top of Plateau and Subalpine Molasse units, (c) isochron of Quaternary sediments and (d) water bottom. Contour interval is 2 ms, and axes labels are Swiss coordinates in meters. Maps also show locations of inlines 22 and 66 and fault projections (see Figs. 1 and 3): solid line for LPF-NW and dashed line for southeast fault (LPF-SE). Stacking velocities of 1450 m/s for water and 1600 m/s for Quaternary sediments may be used for approximate depth conversion. Erosional troughs (T) and depositional ridges or slumps (R) are described in text.

appear as irregular troughs (T) trending generally north and, in places, oblique to strike direction. The dimensions (meters to tens of meters deep) and orientation of these troughs are similar to those mapped on land and indicate former ice flow during glaciation (Choffat & Aubert 1983).

In addition to accurately imaging complex structures, 3-D seismic methods also allow viewing any part of the structures from any angle. Fig. 6 shows the northwestern portion of the 3-D block that has been cut along a plane dipping in the inline direction. This plane is roughly parallel to the bedding dip of the PM and represents a time slice before tectonic tilting. Although the interpreted southwest-northeast flow direction (Morend et al. 2002, Weidmann & Morend 2002) is not completely obvious in this slice, the curved, broad reflections (M) very likely denote channel meanders within the ancient river plain.

4.4. *Subalpine Molasse*

Seismic images of the SM are dramatically different from those of the PM (Fig. 3). Seismic facies within this unit range from contorted and chaotic (facies 2) to parallel and continuous (facies 3). They signify tectonically deformed or tilted (~18° southeast dip) units. Facies 2 is generally low-amplitude

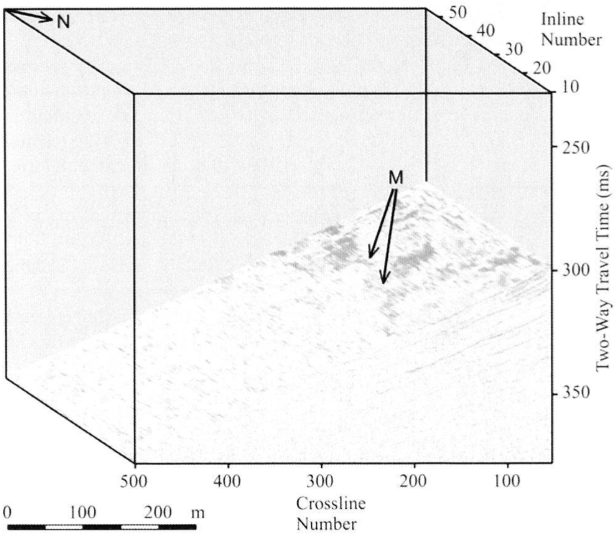

Fig. 6. Northwestern portion of 3-D data cube (location in Fig. 3b) cut to highlight dipping Plateau Molasse beds. The top is cut along a plane dipping southeast along the inline direction. This cut is roughly parallel to the bedding dip, allowing reflections from channel meanders (M) to be revealed.

with sparse "bright spots" that indicate intense folding. Facies 3 is high amplitude (see also Scheidhauer et al. 2000) and is concentrated along the southeastern margin of the data set. The two facies are separated by the southeast fault of La Paudèze thrust zone (LPF-SE), which is roughly parallel to the northwest (main) fault (Figs. 3 and 5b).

The paleosurface of the SM has a highly irregular relief (nearly 90-ms range) mainly because of the presence of numerous thrust slices and steep-dipping beds with variable strength. A large topographic high extends along the southern portion, beneath which facies 3 predominates, especially in the southeast (Figs. 3 and 5b). Between this ridge and the major fault plane is an elongated topographic low, which trends east-west and represents a large erosional trough as well as the upper surface of facies 2 (facies 3 in the southeast). Its eastern portion is <50 m wide, and it widens to ~260 m towards the west (Fig. 5b). Small positive relief (up to 9 ms) structures, apparently signifying more resistant thrust blocks within facies 2, are located throughout this trough and correlate positively with higher amplitude zones (H in Fig. 3d). This 3-D interpretation indicates that faulted blocks with either a more erodable lithology or a greater tectonic deformation were preferentially eroded during Quaternary glaciations. Similar observations of tectonics controlling subsequent drainage patterns have been made with 2-D high-resolution seismic reflection profiling in Lake Neuchâtel, Switzerland (Gorin et al. this volume), and statistical analysis of data from numerous wells in southwestern Ontario, Canada (Eyles et al. 1997).

4.5. Glacial and Post-glacial Sediments

A variety of seismic facies characterize the sediments of the Quaternary overburden (Figs. 3 and 4, Table 1). Immediately overlying the Molasse units is a low-amplitude facies with a generally discontinuous to chaotic reflection pattern (facies 4a). According to Chapron (1999), this facies represents water-lain till. Within facies 4a, a subhorizontal, continuous reflection immediately above the oblique PM reflections may indicate the boundary between two different tills (Choffat & Aubert 1983). Facies 4b, a hummocky to continuous, parallel facies of high amplitude, overlies or interfingers with facies 4a throughout the site and is interpreted as glacio-lacustrine deposits (Chapron 1999). Drainage patterns in its upper boundary and possible slumping contribute to its variable thickness (0 to 13 ms). This facies underlies a continuous, parallel and low-amplitude reflection package (facies 5a), which is up to 18 ms thick in the southern portion and is interpreted as post-glacial lacustrine sediments (Chapron 1999). In the deep-lake portions of the site, several isolated, parallel to hummocky facies units extend laterally up to a few hundred meters and indicate reworked or slumped post-glacial sediments (facies 5b). Maximum thickness of this facies is 11 ms.

An isochron map of the entire Quaternary overburden is shown in Fig. 5c. Sediments are thickest (up to 41 ms thick) in the large east-west trough shown in Fig. 5b. The high variability of the entire trough-fill thickness is due to the differential erosion of the SM (lower boundary, Fig. 5b) and the variable sedimentation rates in this area (upper boundary, Fig. 5d). The irregular bathymetry comprises the upper boundaries of facies 5a and 5b and includes three elongated ridges (R) converging towards the deep-water (southernmost) portion in Fig. 5d. Other relatively thick post-glacial deposits are located on the subhorizontal PM surface in the northern portion of the site and correspond to in-fill of several small troughs (T in Fig. 5b).

The 3-D data do not indicate any faulting within the Quaternary sediments. This observation is consistent with that of the relatively recent seismic work in Lake Geneva (Finckh et al. 1984, Morend 2000; Moscariello et al. 1998). However, improving the 3-D migration of the data may help provide more definitive conclusions about neotectonics within the site.

5.- Conclusions

The 3-D high-resolution, multi-channel seismic reflection data from Lake Geneva, Switzerland, allow perialpine features within Cenozoic strata to be accurately mapped. These features include fault systems, detailed paleosurfaces and five major seismic facies visible to depths of ~150 m below the lake bottom. More conventional (i.e. oil industry) 3-D data and high-resolution 2-D data do not provide the same degree of resolution or accuracy for 3-D interpretation. Furthermore, the preliminary results show detailed images of SM deformation and tectonically influenced erosional and sedimentation patterns. Such information can be valuable for analyzing bedrock strength, groundwater flow in hydrological modeling and other environmental and engineering applications. Further developments of our 3-D seismic reflection system, including multistreamer surveys, more accurate positioning methods and improved 3-D processing, may provide answers to questions regarding the stress history of the SM and neotectonics in Lake Geneva.

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Imaging Molasse and Quaternary Sediments in Lake Geneva, Switzerland, with 3-D High-Resolution Seismic Reflection Methods: A Case Study

MILAN BERES, MAREN SCHEIDHAUER,
FRANÇOIS MARILLIER

The figures of this article published in Supplement 1 "Lake Systems from Ice Age to Industrial Time" were misprinted. These pages are considered as the erratum.

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