Bedrock, Quaternary sediments and recent fault activity in central Lake Neuchâtel, as derived from high-resolution reflection seismics

0012-9402/03/01S003-8
Birkhäuser Verlag, Basel, 2003

Eclogae geol. Helv. 96 (2003) Supplement 1, S3–S10

Bedrock, Quaternary sediments and recent fault activity in central Lake Neuchâtel, as derived from high-resolution reflection seismics

GEORGES GORIN[1], DIDIER MOREND[1] & ANDRÉ PUGIN[1,2]

Key words: fault, glacial sedimentation,. high-resolution seismic, Molasse, neotectonics, Quaternary infill, seismic facies

ABSTRACT

A high-resolution seismic reflection survey (ca. 65 km) was conducted in the central part of Lake Neuchâtel in order to trace the continuation of the major strike-slip fault of La Lance across the lake. On seismic data, this dextral fault appears at the top Molasse/Mesozoic bedrock as a ca. 1 km wide zone affecting the top Molasse and offsetting the Mesozoic. These seismic observations can be correlated with onshore data. Four seismic facies are distinguished and interpreted from bottom to top within the Quaternary: glacial, subglacio-lacustrine, glacio-lacustrine and lacustrine. They show similarities with other perialpine lakes (Lake Geneva, Lake Annecy, Lake Le Bourget). Slumps and faults affecting the upper part of the Quaternary may be associated with the recent activity of the La Lance fault zone. Moreover, glacial erosion of the Molasse bedrock seems to have been locally guided by active tectonics.

RESUME

Une campagne de sismique réflexion à haute résolution (environ 65 km) a été effectuée dans la partie centrale du Lac de Neuchâtel pour étudier la continuation à travers le lac de la grande faille décrochante dextre de La Lance. Sur les données sismiques, cette faille est interprétée au sommet du bedrock molassique/mésozoïque comme une zone faillée d'environ 1 km de large qui décale le Mésozoïque. Cette zone peut être corrélée avec les données existant sur les deux rives du lac. Quatre faciès sismiques sont distingués et interprétés dans les sédiments quaternaires, dans l'ordre stratigraphique: glaciaire, sous-glaciaire-lacustre, glacio-lacustre et lacustre. Cette séquence ressemble à celle d'autres lacs périalpins (Lac Léman, Lac d'Annecy, Lac du Bourget). Des slumps et failles affectant la partie supérieure du Quaternaire peuvent être associés à une activité récente de la zone de faille de La Lance. De plus, l'érosion glaciaire du substrat molassique semble avoir été localement influencée par l'activité tectonique.

1.- Introduction

Investigation of Quaternary perialpine lake sediments and underlying bedrock using reflection seismic has been carried out since the 1970's, essentially using single channel recording systems (Houbolt & Jonker 1968, Matter et al. 1971, Vernet & Horn 1971, Vernet et al. 1974, Moscariello et al. 1998, Van Rensbergen et al. 1998, 1999). Similarly, Finckh et al. (1984) have tried to detect the bedrock forms of various European lakes, including Lake Neuchâtel, and to draw conclusions on their sedimentary fill. Schwalb (1992) also acquired some profiles in the eastern part of Lake Neuchâtel.

More recently, the use of multichannel high-resolution reflection seismic in lakes has considerably improved the data quality and resolution within the Quaternary infill, as well as in the underlying bedrock. Investigations carried out in Lake Geneva (Morend 2000, Morend et al. 2002) allowed the identification of various seismic facies in the upper part of the Molasse bedrock. The Molasse is of Oligocene-Miocene age and consists essentially of detrital formations, mainly derived from the rising Alps (Trümpy 1980). Three-dimensional high-resolution seismic reflection methods have also been recently applied to the same stratigraphic intervals in Lake Geneva (Beres et al., this volume).

For the first time in Lake Neuchâtel, a high-resolution survey was acquired in the southern part of the lake. It was located so as to intersect the continuation across the lake of a major dextral strike-slip fault regionally known as the "Décrochement de la Lance" (Fig. 1). This fault is well known from surface mapping on the northern side of the lake where it

[1] Department of Geology-Paleontology, Univ. of Geneva, 13 rue des Maraîchers, 1211 Geneva 4, Switzerland, e-mails: Georges.Gorin@terre.unige.ch, didier.morend@steria.ch
[2] Present address: Illinois State Geological Survey, Champaign, IL 61820, USA, e-mail: pugin@isgs.uiuc.edu

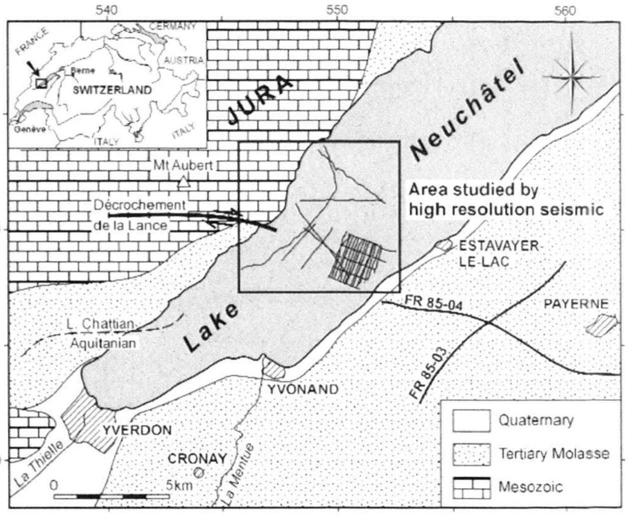

Fig. 1. Map showing location of study site and simplified regional geology. Lines labelled FR 85-03 and -04 are seismic lines acquired by British Petroleum in 1985.

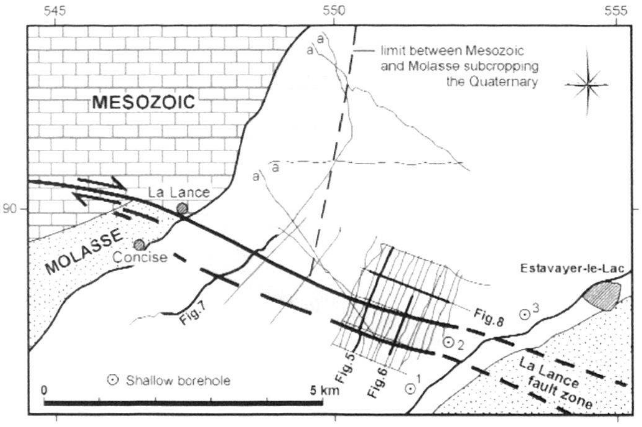

Fig. 2. Seismic line location map: the four lines labelled "a" were acquired in 1997, the others in 2000. Locations of shallow boreholes are indicated. Seismic interpretation shows the extension of the La Lance fault zone on the Molasse top (shaded zone), as well as the western limit of the Molasse onlapping the Mesozoic units underneath the Quaternary deposits (dashed line).

offsets the Mesozoic outcrops (Figs. 1 and 2; Meia 1969, Alleman 1996, 1:25'000 Swiss geological map, sheet Grandson, in press). Its continuation on the southern side of Lake Neuchâtel can be identified on petroleum seismic lines shot by British Petroleum in 1985 (Fig. 1): in particular, on line FR 85-03, the "Décrochement de la Lance" appears as a flower structure at top Mesozoic level, with a fault system continuing in the overlying Molasse over a width of more than 1 km. Surface evidence can also be observed in the Molasse southwest of Estavayer-le-Lac (Fig. 2; 1:25'000 Swiss geological map, sheet Payerne, in prep.). Regionally (Fig. 3), the La Lance fault is interpreted as one of the NW-SE trending, dextral, conjugate strike-slip faults associated with major N-S trending, sinistral strike-slip faults, such as those of Pontarlier, La Tourne and La Ferrière (Sommaruga 1997). The latter author refers to these strike-slip faults as "tear" faults. The La Lance fault is subparallel to the dextral faults known in the Yverdon (Jordi 1993) and La Sarraz areas (Fig. 3).

The purpose of this study was threefold:

1.- to map the top of the Molasse/Mesozoic bedrock subcropping the Quaternary and identify the signature at this level of the La Lance strike-slip fault.

2.- to investigate the seismic facies of the Quaternary deposits.

3.- to look for traces of recent tectonic activity (slumps, faults) in the Quaternary package overlying the fault zone.

2.- Geological data

In the studied area, the bedrock subcropping the Quaternary sequence is of two types: a) north of La Lance fault zone on the west side of Lake Neuchâtel, it consists of Lower Cretaceous carbonates (Figs. 1 and 2) outcropping near La Lance (1:25'000 Swiss Geological map, sheet Grandson, in press); b) south and east of the fault zone, i.e. in most of the survey area, it is represented by the Plateau Molasse. The latter consists of the alluvial deposits of the lithostratigraphic group of the Lower Freshwater Molasse (USM), and more specifically of its upper part represented by the "Molasse grise de Lausanne" (MGL) Formation of Aquitanian age (Berger 1996), an alternating sequence of fluviatile sandstones and marls. The latter sediments outcrop in quarries on the southern side of Lake Neuchâtel, such as Le Vallon quarry (Swiss coordinates: 562'300, 192'700; M. Weidmann, pers. comm.) or the Wallenried quarry (Swiss coordinates: 574'320, 192'400; Becker 1996, Becker et al. 2001, Python et al. 1999). The MGL overlies the lacustrine-dominated "Grès et marnes gris à gypse" Formation of Late Chattian age. On the western side of Lake Neuchâtel, between Yverdon and the La Lance fault zone, the Molasse onlapping onto the Mesozoic dips southeasterly, and its top is an erosional surface becoming younger to the southeast (Jordi, in press). Near the villages of La Lance and Concise (Fig. 2), the MGL has been eroded and the "Grès et marnes gris à gypse" are known from shallow boreholes to subcrop the Quaternary units. This geological situation might be expected in the westernmost part of the seismic survey area. High-resolution onshore seismic investigations of the contact between the MGL and the overlying Upper Marine Molasse (OMM) in the Cronay area (Fig. 1; Morend 2000) provide lit-

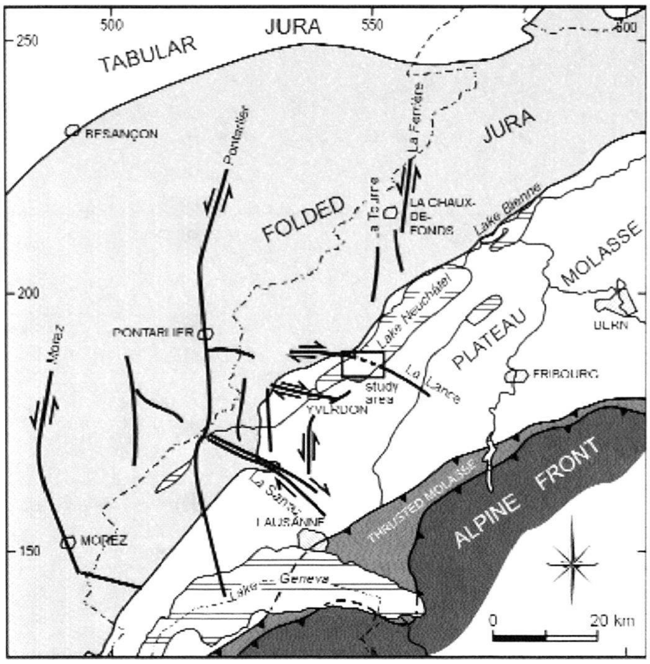

Fig. 3. Megatectonic framework of the central part of the Jura and Swiss molassic Plateau. This area is affected by major, N-S trending, sinistral strike-slip faults and by conjugate, NW-SE trending, dextral strike-slip faults. The studied La Lance fault is one of the latter. Modified after Sommaruga (1997).

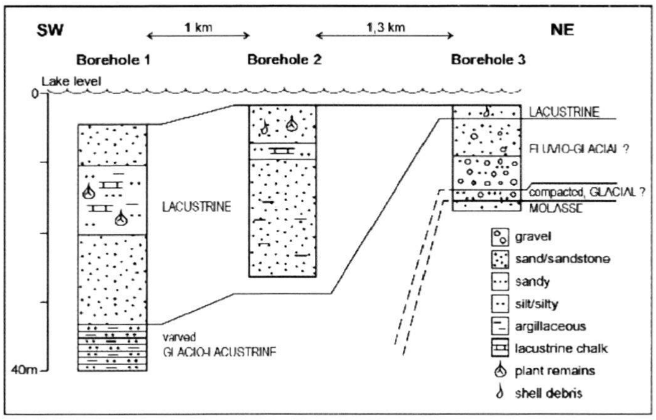

Fig. 4. Sedimentological interpretation of three shallow boreholes close to the study area (see figure 2 for location). Lithology after Bureau Schopfer & Karakas (1971).

tle information on the seismic facies of the MGL because of very poor resolution. More relevant to the present study are the very high-resolution seismic facies data from the MGL of Lake Geneva, where channel-fill complexes and floodplain deposits can be identified (Morend 2000, Morend et al. 2002).

It is not possible to properly calibrate the Quaternary interval on the seismic data due to the lack of deep boreholes in Lake Neuchâtel. Near the survey (Fig. 2), some shallow geotechnical boreholes (Fig. 4; Bureau Schopfer & Karakas 1971) have penetrated the Quaternary units very close to the southern shore of the lake. They are difficult to correlate with the seismic data, because they are located in very shallow water. Borehole 1 reaches a depth of 40 m, penetrating some 33 m of lacustrine sands and silts with some chalk, which overlie 7 m of more compacted glacio-lacustrine varved silts. Borehole 2 reaches a depth of 26 m in lacustrine sands and silts and some chalk. Borehole 3 reaches the Molasse at a depth of 16 m, which is overlain by some 12 m of gravels and sands of probable fluvio-glacial origin (the base of which is compacted) and some 4 m of lacustrine sands.

The seismic data acquired with a 3.5 Khz echosounder by Schwalb (1992) and calibrated with 9 to 12 m long cores are located too far in the northern part of Lake Neuchâtel and can not be used for correlation in the study area. Moreover, the penetration depth of less than 40 m permits only the calibration of the late and post-glacial sediments (Schwalb et al. 1994, 1998). Using single-channel seismic data from perialpine lakes (5 cu. inch airgun source), Finckh et al. (1984) show that, as in most of the other lakes, two intervals in the Quaternary fill can be distinguished in the deepest zone of the eastern and western parts of Lake Neuchâtel: a thin, layered upper "glacio-lacustrine fill" related to the last glaciation, and a much thicker lower "glacio-lacustrine fill" characterized by a complex, mainly chaotic seismic reflection pattern and higher seismic velocities. By comparing with Lake Zürich core information (Finckh & Kelts 1976), they interpret this lower sequence as probably related to older glacial stages. Sediments spanning more than one glacial cycle also have been found in the catchment area of Lake Neuchâtel (Pugin 1988) and, in particular, very close to the study area near Concise (Fig. 2; Jordi 1996).

3.- Methods

Data acquisition was carried out in two phases. In the preliminary phase, four lines totalling some 20 km were shot in 1997, extending very close to the northern side of the lake (labelled "a" in Fig. 2). The main survey was acquired in 2000 and comprises 23 lines totalling some 45 km. It consists of three lines south of the "a" lines and a ca. 2 km x 2 km grid close to the southern shore of the lake and straddling the offshore continuation of the La Lance strike-slip fault (Fig. 2).

The acquisition parameters and the processing flowchart of both surveys are similar to those listed in Morend et al. (2002). The only major difference is the size of the airgun

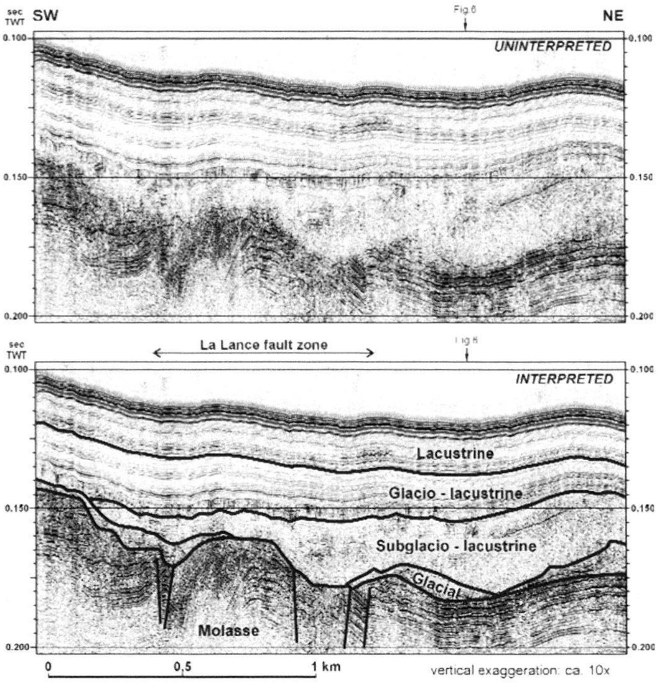

Fig. 5. Seismic expression of the La Lance fault zone at the Molasse bedrock surface and the seismic facies of Quaternary infill in the central part of the survey area (data acquired in 2000 with a 1 cu. inch airgun). See Fig. 2 for location.

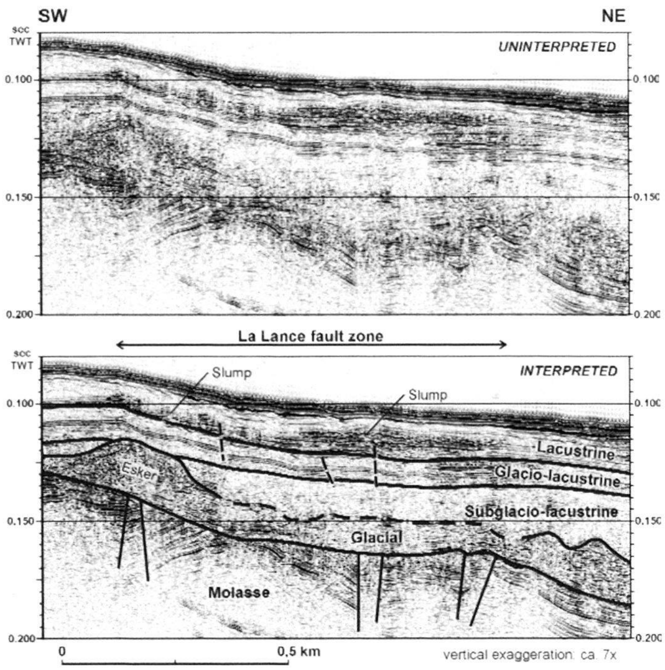

Fig. 6. Seismic expression of the La Lance fault zone at the Molasse bedrock surface and the seismic facies of Quaternary infill in the eastern part of the survey area (data acquired in 2000 with a 1 cu. inch airgun). See Fig. 2 for location.

chamber, i.e. 5 cu. inch in 1997 and 1 cu. inch in 2000. The number of receivers was 12 (1 receiver/channel), with a receiver spacing of 7 m, which yielded a nominal CMP fold of 6. The 1997 survey was recorded with an EG&G2401 Geometrics seismograph, and the 2000 survey was recorded with a Geometrics R-48 Strataview. Using a triggering system linked to a real-time Differential Global Positioning System (DGPS) (Pugin et al. 1999a), the firing interval was continuously adjusted to ensure a constant 7-m shot interval.

The seismic data were processed with PC-based software (Eavesdropper from the Kansas Geological Survey and Vista for Windows 2.0 from seismic Image Software). The processing sequence included geometry editing, band pass filtering, predictive deconvolution, velocity analysis , NMO corrections, CMP stacking and phase-shift migration.

The effective bandwidth of stacked data varies considerably between the two surveys. It ranges from 100 to 400 Hz on the 1997 data, with an average dominant frequency of ca. 220 Hz. On the 2000 data, the frequency spectrum ranges from 200 to 1400 Hz, with dominant frequencies in the range of 600-1200 Hz. The interpretation of seismic data was carried out with the Kingdom Suite software of Seismic Micro-Technology Inc.

4.- Results and interpretation

Four seismic lines have been chosen to illustrate the main results (see location in Fig. 2). Three cross the La Lance fault zone in a SW-NE direction (Figs. 5 to 7) and the fourth one is oriented NW-SE and located just north of and subparallel to the fault zone (Fig. 8).

Seismic facies of the La Lance fault zone at the top of the Molasse / Mesozoic bedrock

In the eastern part of the survey area, where the seismic grid is dense (Figs. 5 and 6), deep seismic penetration into the Molasse bedrock is observed. Outside of the fault zone, the MGL seismic facies displays fairly continuous high amplitude reflections. In the central part of these two profiles, a ca. 1-km-wide disturbed zone can be identified, bounded on both sides by several faults. In the central part of this zone, strata in the Molasse seem to form a sort of anticline (e.g. Fig. 6). In figure 5, the heavily faulted bounding zones display a completely chaotic facies and appear as distinct topographic depressions. In the western part of the survey area, figure 7 is the most illustrative profile and shows significant differences with respect to the eastern part of the survey. This line, recorded in

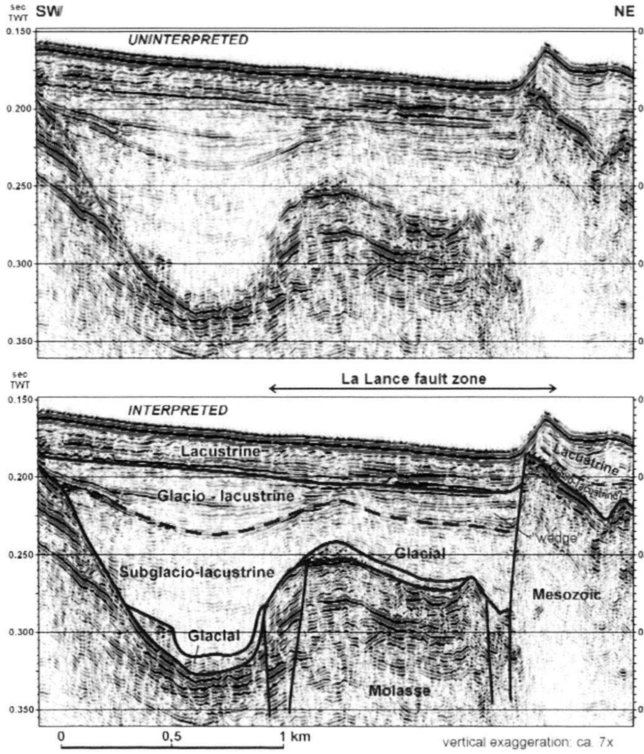

Fig. 7. Seismic expression of the La Lance fault zone at the Molasse/Mesozoic bedrock surface and the seismic facies of Quaternary infill in the western part of the survey area (data acquired in 1997 with a 5 cu. inch airgun). Note the lower frequency content in both bedrock and Quaternary images with respect to the 2000 data (Figs. 5, 7 and 8). Also note the poor penetration within the Mesozoic carbonates with respect to the Molasse siliciclastics. See Fig. 2 for location.

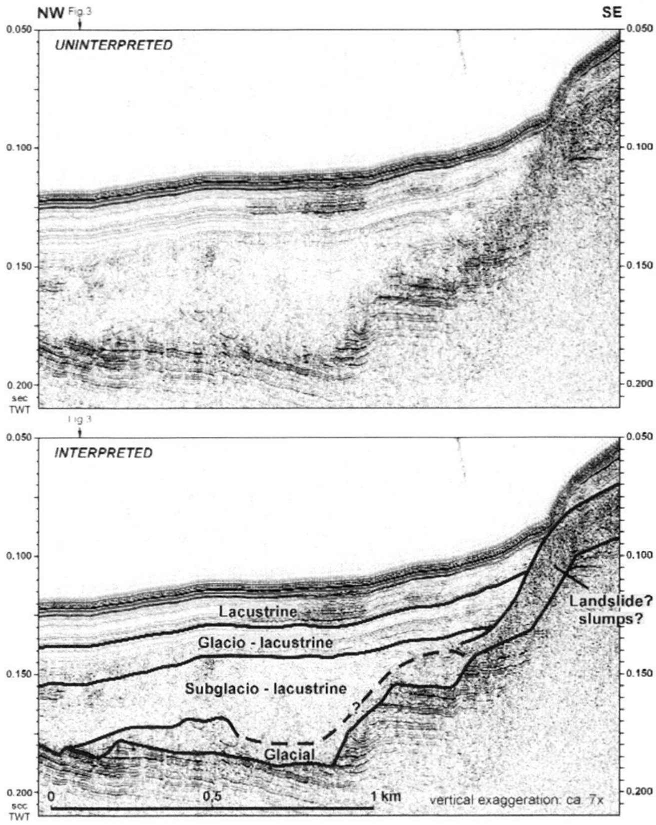

Fig. 8. Seismic expression of the top Molasse bedrock surface and the seismic facies of Quaternary infill along a line oriented NW-SE and located just north of the La Lance fault zone (data acquired in 2000 with a 1 cu. inch airgun). See Fig. 2 for location.

1997, has a frequency content much lower than that in figures 5 and 6 (see Methods section). Two types of bedrock subcropping the Quaternary display a different seismic response and are separated by a major fault. The top of the Mesozoic carbonates is marked by a very high-amplitude reflection, often irregular because of the karst topography. The poor reflectivity of the Mesozoic sequence results probably from the lack of penetration of seismic energy into the high-velocity carbonates. The seismic facies of the Molasse resembles that observed in figures 5 and 6, i.e. a sequence of high-amplitude continuous reflections, but with a lower frequency content. The seismic facies boundary marks the northern edge of the La Lance fault zone and illustrates the dextral offset of the Mesozoic with respect to the Molasse (Fig. 2). By mapping this difference in facies, it is possible to determine the extent of both the offset and the western limit of the Molasse onlap onto the Mesozoic north of the fault zone (Fig. 2). In the southern part of figure 7, the Molasse top is deeply incised: the northern flank of this depression is considerably steeper than the southern one and appears to be associated with faults in the Molasse (note the vertical exaggeration). The latter zone is interpreted as the southern limit of the La Lance fault zone.

Consequently, the signature of the "Décrochement de la Lance" at the top of the Molasse/Mesozoic bedrock can be mapped across Lake Neuchâtel as a NW-SE striking, ca. 1 km-wide faulted zone (Fig. 2). The fault separating the Mesozoic and Molasse deposits in figure 7 appears as the direct continuation of the outcrop near La Lance (Fig. 2). Nevertheless, the compilation of geological, seismic and gravity data (Alleman 1996) indicates that this fault is more complex and that subparallel secondary faults exist between La Lance and Concise, in line with the trend observed offshore (Fig. 2).

In figure 8, the Molasse appears as a southeasterly dipping sequence of high-amplitude, continuous reflections similar to those observed in figures 5 and 6. This facies is quite similar to that observed in the MGL of Lake Geneva and interpreted as floodplain deposits (Morend 2000, Morend et al. 2002). The alternation of more competent sandstone beds with softer overbank fines is demonstrated by the stepwise erosion particularly visible at the western end of figure 8. In many zones, the topography of the top Molasse seems closely associated with deformation and faulting (e.g. Figs. 5 and 7). This may be an indication that active tectonics has partially guided glacial erosion.

Despite the loose grid of data in the western part of the survey, a 3D representation of the pre-Quaternary bedrock topography has been attempted (Fig. 9). It shows an overdeepening of the Molasse/Mesozoic substrate of some 300 m below the lake surface, which is consistent with the isohypse values published by Pugin (1988). The topography of this overdeepening appears asymmetrical with a steeper eastern flank. Noteworthy is the more intense fluvio-glacial erosion of the Molasse top coinciding with heavily faulted zones in the Molasse (Fig. 5).

Quaternary infill

Based on seismic facies, the Quaternary interval has been subdivided from base to top into four seismic units well expressed in the eastern part of the survey (Figs. 5, 6 and 8), where the Molasse bedrock forms a kind of a topographical plateau (Fig. 9). Although Lake Neuchâtel data lack borehole calibration, this interpretation can be correlated with similar settings in Lake Geneva (Moscariello et al. 1998), Lake Annecy (Van Rensbergen et al. 1998) and Lake Le Bourget (Van Rensbergen et al. 1999).

Unit 1
Directly overlying the bedrock, a discontinuous interval with a very irregular topography contains high-amplitude, continuous to discontinuous or chaotic reflections. This high-reflectivity sequence has been tentatively interpreted as "*glacial*": the high impedance contrast with respect to the overlying, more transparent seismic facies suggests the presence of relatively compact sediments that could be attributed to subglacial deposition, i.e. tills or eskers (Moscariello et al. 1998, Pugin et al. 1999b). The interpreted esker in the western part of figure 6 can be traced across several lines. Other esker-shaped bodies can be observed in figures 5, 6 and 8. In the western part of figure 5, a trough cut into the Molasse seems to be related to a subglacial channel, although active faults may also have enhanced the erosion process. Without calibration it is not possible to tell how much of this sequence represents the latest glacial cycle: part of it may also be from older glacial stages observed in the area (Pugin 1988, Jordi 1996). This seismic facies can be correlated with the seismic units A, B and C encountered in western Lake Geneva (Moscariello et al. 1998) and with seismic units 1 in Lake Annecy (Van Rensbergen 1998) and Lake Le Bourget (Van Rensbergen et al. 1999). In these last three cases, the units are interpreted as glacier-derived sediments.

Unit 2
Above the "glacial" sequence, a transparent to low-reflectivity interval with dominantly discontinuous reflections can be mapped. Its upper limit coincides with the first sequence displaying continuous reflections. In places, it contains higher amplitude reflections that may or may not be continuous (Figs. 5 and 6). This sequence clearly onlaps the esker identified in figure 6. Similar seismic units are found in most glacial lakes, particularly in Lake Annecy (seismic unit 2 of Van Rensbergen et al. 1998) and Lake Le Bourget (seismic unit 2 of Van Rensbergen et al. 1999). Such a unit has been cored in Lake Zürich and described as subglacially deposited glacio-lacustrine sediments (Hsü & Kelts 1984). This unit may also be correlated with units D1 and D2 in Lake Geneva (Moscariello et al. 1998). Consequently, this interval may be interpreted as "*subglacio-lacustrine*" fine-grained sediments with intercalated coarser layers or blocks, yielding high-amplitude reflections. The lack of a high-amplitude reflection at the the boundary with the overlying interval indicates no major difference in compaction between the two and suggests that this "subglacio-lacustrine" sequence belongs to the last glacial stage.

Unit 3
This interval corresponds to a sequence with low-to moderate-amplitude reflections, which are continuous across the whole site and, therefore, may represent fine-medium grained sediments deposited underwater. It is interpreted as *glacio-lacustrine*, based on the following evidence: this unit comprises a sequence of sedimentary layers that clearly thickens towards the south (Figs. 5 and 6). Several regional seismic lines, acquired in 2001, link the studied area with the lake shore near Yvonand (Beres & Gorin 2002) and show that the sediment source of this interval is associated with the past activity of the La Mentue River (Fig. 1). During deglaciation, this river has been deeply eroding the Plateau Molasse south of Yvonand. This unit can be correlated with seismic units 3 and 4 in Lake Annecy (Van Rensbergen et al. 1998) and Lake Le Bourget (Van Rensbergen et al. 1999), and possibly with unit D3 in Lake Geneva (Moscariello et al. 1998).

Unit 4
The uppermost unit displays low- to high-amplitude continuous reflections. Its thickness is constant over the studied zone, thereby indicating that authigenic lacustrine sedimentation prevailed. This *lacustrine* unit corresponds to the Holocene sediments analysed by Schwalb (1992) and Schwalb et al. (1994, 1998) in the northern part of Lake Neuchâtel and recovered by boreholes 1, 2 and 3 east of the survey area (Fig. 2). These sediments are essentially fine sands, silts and clays with intercalations of lacustrine chalk. The chalk layers may be responsible for the higher reflectivity observed locally in the lacustrine interval, particularly in its upper part (Figs. 5, 6 and 8). Holocene chalk has been encountered in the cores studied by

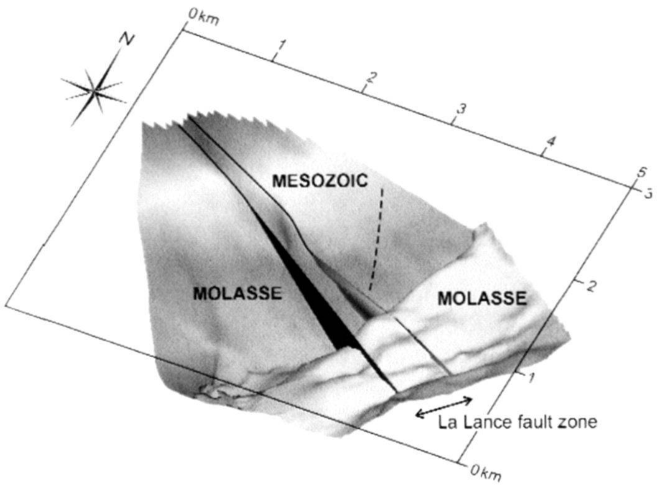

Fig. 9. 3-D representation of the bedrock top (Molasse and Mesozoic) subcropping the Quaternary units within the study area. North of the fault zone, the dashed line indicates the approximate limit of the Molasse onlap on the Mesozoic units (see Fig. 2). The difference in elevation between the highest (to the NW and SE) and the lowest areas (to the SW) is ca. 300 m, using an average velocity of 2'000 m/s for the Quaternary.

Schwalb et al. (1994, 1998) in the northern part of Lake Neuchâtel. This Holocene unit correlates with unit E in Lake Leman and with seismic units 5 in Lake Annecy and Lake Le Bourget.

Recent Quaternary fault activity

Instrumental seismicity since 1975 (S. Sellami, pers. comm.) shows that earthquakes of up to magnitude 3 have occurred near the La Lance fault zone, including the area beneath Lake Neuchâtel. Consequently, signs of neotectonic activity may be indicated on the high-resolution seismic data.

Because of the non-continuous or transparent seismic facies of the lower two Quaternary units, it is not possible to trace upwards the faults observed in the bedrock. Nevertheless, the continuous reflections of the unconsolidated glacio-lacustrine and lacustrine units permit fault interpretation. Faults with small offsets are visible in these units on line portions that overlie the La Lance fault zone (Fig. 6). Moreover, on the same figure, the lower part of the lacustrine unit displays contorted reflections suggesting slumps. Both faults and slumps may be associated with earthquakes. In figure 7, other features may be interpreted as evidence of recent Quaternary fault activity: on the upthrown side of the major fault, above the Mesozoic bedrock, reflections in the lacustrine sequence are abruptly interrupted; on the downthrown side of the fault, the eastern part of the glacio-lacustrine interval has a wedge shape that is more likely related to fault activity than to differential compaction of the underlying sequence. Landslides or slumps of unknown origin are also interpreted close to the lake shore (Fig. 8). Other important slumps are also observed on seismic data in the upper two Quaternary intervals between the studied area and Yvonand (Beres & Gorin 2000).

5.- Conclusions

High-resolution seismic reflection data from central Lake Neuchâtel allows different geological features to be mapped, both in the Molasse/Mesozoic bedrock and in the overlying Quaternary sediments:

1.- At the bedrock surface, the La Lance fault is mapped as a NW-SE-trending, ca. 1 km-wide zone, which links previous field and seismic observations from both sides of the lake. Based on seismic facies, the offset of the Mesozoic bedrock subcropping the Quaternary can be mapped below the lake.
2.- Glacial erosion of the Molasse bedrock seems to have been locally guided by active tectonics.
3.- The Quaternary infill of the lake is subdivided into four seismic facies interpreted as glacial, subglacio-lacustrine, glacio-lacustrine (with a sediment source from the La Mentue River to the south) and lacustrine (Holocene authigenic sedimentation). This sedimentary succession can be correlated with that observed in other perialpine lakes, namely Lake Geneva, Lake Annecy and Lake Le Bourget.
4.- Faults and slumps identified in the recent Quaternary sequence point to reactivation episodes of the La Lance fault zone.

Acknowledgements

The authors are grateful to Dr. Marc Weidmann for useful information and fruitful discussions about the Molasse and the « Décrochement de La Lance", to Dr. Milan Beres for his useful suggestions on this manuscript, to Dr. Souad Sellami for providing information on the seismicity of Lake Neuchâtel area and to Jacques Metzger for draughting the figures. A. Schwalb and C. Beck are acknowledged for their constructive comments. This work is supported by the Swiss National Science Foundation (Grant no. 20-53543.98).

REFERENCES

Alleman, G. 1996: High-resolution seismic profiling applied to a heterogeneous area imaging and to cavity detection in Switzerland. Ph.D. thesis, Univ. of Lausanne, Switzerland.

Becker, D. 1996: Géologie de la région de Cornaux (Jura/NE) et des marnières de Cornaux et Wallenried (USM). M. Sc. thesis, Univ. of Fribourg, Switzerland .

Becker, D., Roessner, G., Picot, L. & Berger, J.-P. 2001: Early Miocene ruminants from Wallenried (USM, Aquitanian, Switzerland). Eclogae geol. Helv. 94/3, 547-563.

BERES, M. & GORIN, G.E. 2002: High-resolution seismic profiling of the Mentue delta area, southern Lake Neuchâtel (Switzerland). Proc. 8th Meeting Environm. & Engin. Geophys. Soc.-Eur. Sect., Aveiro, Portugal, Sept. 2002, 473-476.

BERES, M., SCHEIDHAUER, M. & MARILLIER, F.: Imaging Molasse and Quaternary sediments in Lake Geneva, Switzerland, with 3-D high-resolution seismic reflection methods (this volume).

BERGER, J.-P. 1996: Cartes paléogéographiques palinspastiques du bassin molassique suisse (Oligocène inférieur- Miocène moyen). N. Jb. Geol. Paläont. Abh., 202/1, 1-44.

Bureau Schopfer & Karakas 1971: Description géotechnique de quatre sondages peu profonds dans le Lac de Neuchâtel. Bureau de construction des autoroutes, Fribourg.

FINCKH, P., KELTS, K. 1976: Geophysical investigations into the nature of pre-Holocene sediments of Lake Zürich. Eclogae geol. Helv. 27/3, 289-302.

FINCKH, P., KELTS, K., & LAMBERT, A. 1984: Seismic stratigraphy and bedrock forms in perialpine lakes. Bull. Geol. Soc. Amer. 95, 1118-1128.

HOUBOLT, J. & JONKER, J. 1968: Recent sediments in the eastern part of the Lake of Geneva (Lake Léman). Geol. en Mijnb. 47/2, 131-148.

HSÜ, K.J. & KELTS, K.R. (EDS.) 1984: Quaternary geology of Lake Zürich: an interdisciplinary investigation by Deep Lake Drilling. Contrib. Sedimentol. 13, 210p.

JORDI, H.A. 1993 : Tectonique du bassin molassique et de son substratum jurassique-crétacé dans la région Orbe-Yverdon-Grandson. Bull. Soc. Vaud. Sc. Nat. 82, 279-299.

JORDI, H.A. 1996: Ältere glaziale und interglaziale Ablagerungen in der Gegend von Grandson und Les Tuileries. Bull. angew. Geol. 1/2, 145-168.

JORDI, H.A. & WILDI, W. in press: Notice explicative, carte géologique de la Suisse au 1:25'000, feuille Grandson.

MATTER, A., SÜSSTRUNK, A.E., HINZ, K. & STURM, M. 1971: Ergebnisse reflexionseismicher Untersuchungen im Thunersee. Eclogae geol. Helv. 64/3, 505-520.

MEIA, J. 1969: Géologie du Mont Aubert et de l'anticlinal Soliat-Montagne de Boudry au nord du Lac de Neuchâtel. Ph.D. thesis, Univ. of Neuchâtel, Switzerland.

MOREND, D. 2000: High-resolution seismic facies of alluvial depositional systems in the Lower Freshwater Molasse (Oligocene-early Miocene, western Swiss Molasse Basin). Terre & Environnement 23, 97p., Univ. de Genève.

MOREND, D., PUGIN, A. & GORIN, G.E. 2002: High-resolution seismic imaging of outcrop-scale channels and an incised-valley system within the fluvial-dominated Lower Freshwater Molasse (Aquitanian, western Swiss Molasse Basin). Sediment. Geol. 149, 245-264.

MOSCARIELLO, A., PUGIN, A., WILDI, W., BECK, C., CHAPRON, E., DE BATIST, M., GIRARDCLOS, S., RACHOUD-SCHNEIDER, A.M., SIGNER, C. & VAN CLAUWENBERGHE, T. 1998: Déglaciation würmienne dans des conditions lacustres à la terminaison occidentale du bassin lémanique (Suisse occidentale et France). Eclogae geol. Helv. 91/2, 185-202.

PYTHON, BERGER, J.-P. & PLANCHEREL, R. 1999: Notice explicative, carte géologique de la Suisse au 1:25'000, feuille 1185 Fribourg, 54 p.

PUGIN, A. 1988: Carte des isohypses de la base des sédiments du Quaternaire en Suisse occidentale, avec quelques commentaires. Rapport géologique no. 3, Service hydrologique et géologique national, Berne, 20p.

PUGIN, A., PULLAN, S.E., BURNS, R.A., DOUMA, M. & GOOD, R.L. 1999a: High-resolution, multichannel, marine seismic surveying using small airgun source. Extended Abstract, SAGEEP Meeting, Oakland CA, 255-264.

PUGIN, A., PULLAN, S.E. & SHARPE, D.R. 1999B: Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario. Can. J. Earth Sci. 36, 409-432.

SCHWALB, A. 1992: Die Sedimente des Lac de Neuchâtel (Schweiz): Rekonstruktion spät-und postglazialer Klima- und Umweltveränderungen. Ph.D. thesis, Univ. of Neuchâtel, Switzerland.

SCHWALB, A., HADORN, P., THEW, N. & STRAUB, F. 1998: Evidence for Late Glacial and Holocene environmental changes from subfossil assemblages in sediments of Lake Neuchâtel, Switzerland. Palaeogeogr., Palaeoclim., Palaeoecol. 140, 307-323.

SCHWALB, A., LISTER, G.S. & KELTS, K. 1994: Ostracode carbonate $d^{18}O$- and $d^{13}C$-signatures of hydrological and climatic changes affecting Lake Neuchâtel, Switzerland, since the latest Pleistocene. J. Paleolimnol. 11, 3-17.

SOMMARUGA, A. 1997: Geology of the Central Jura and the Molasse Basin: new insight into an evaporite-based foreland fold and thrust belt. Mém. Soc. Neuchâtel. Sci. Nat. 12, 176p.

TRÜMPY, R. 1980 : Geology of Switzerland, a guide-book. Swiss Geol. Comm., Wepf & Co., Basle-New York, 104p.

VAN RENSBERGEN, P., DE BATIST, M., BECK, C. & CHAPRON, E. 1999: High-resolution seismic stratigraphy of glacial to interglacial fill of a deep glacigenic lake: Lake Le Bourget, Northwestern Alps, France. Sediment. Geol. 128, 99-129.

VAN RENSBERGEN, P., DE BATIST, M., BECK, C. & MANALT, F. 1998: High-resolution seismic stratigraphy of late Quaternary fill of Lake Annecy (northwestern Alps): evolution from glacial to interglacial sedimentary processes. Sediment. Geol. 117, 71-96.

VERNET, J.-P. & HORN, R. 1971: Etudes sédimentologique et structurale de la partie occidentale du lac Léman par la méthode sismique à réflexion continue. Eclogae geol. Helv. 64/2, 291-317.

VERNET, J.-P., HORN, R., BADOUX, E. & SCOLARI, G. 1974: Etude structurale du Léman par sismique réflexion continue. Eclogae geol. Helv. 67/3, 515-529.

Communication submitted October 17 - 18, 2001
Manuscript accepted November 11, 2002