Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 86 (1993)

Heft: 3

Artikel: Structural configuration of the western Swiss Molasse Basin as defined by reflection seismic data

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DOI: https://doi.org/10.5169/seals-167259

Eclogae geol. Helv. 86/3: 693–716 (1993)

0012-9402/93/030693-30 $ 1.50 + 0.20/0
Birkhäuser Verlag, Basel

Structural configuration of the western Swiss Molasse Basin as defined by reflection seismic data [1)]

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ABSTRACT

In the areas of the cantons Geneva and Vaud, reflection seismic data calibrated by wells and outcrops give a good structural definition of the Molasse Basin between the Jura Mountains and the Alpine front, except for the Lake Geneva where seismic resolution is too poor.

Geological cross-sections based on representative depth-converted dip and strike lines illustrate the following threefold structural subdivision of the Molasse Basin from the northwest to the southeast:

– The Plateau Molasse consists essentially of subhorizontal Lower Freshwater Molasse (USM), which onlaps the Top Mesozoic unconformity and thins towards the Jura Mountains. It is cross-cut by wrench fault zones linking the Alps with the Jura, which often can be identified as Palaeozoic lineaments reactivated in the Early and Late Tertiary.

– The transition zone between the Plateau Molasse and Thrusted Molasse (or Subalpine Molasse) coincides with major SW-NE oriented hinge lines probably inherited from Palaeozoic lineaments. This zone corresponds in the Geneva area to the Mount Salève trend which overlies a basement high; east of Lausanne (Vaud), it is marked by an important strike-slip feature reaching the surface. These hinge zones seem to have influenced the facies developments during the Early and Middle Jurassic, the northern depositional limit of the Lower Marine Molasse (UMM) and the location of the deformation front of the Subalpine Molasse.

– The Thrusted (Subalpine) Molasse consists of a folded and thrusted complex of UMM and USM. It thickens towards the Alpine front where it overlies a deep-seated Permo-Carboniferous half-graben.

Seismic data from Western Switzerland and adjacent France demonstrate the imprint of Palaeozoic lineaments on the structural configuration of the Molasse Basin. The often postulated thin-skinned northwestward translation of the Mesozoic-Cenozoic sediments of the Molasse Basin above a regional Triassic decollement horizon during the Alpine orogeny and the folding of the Jura Mountains is not supported by the studied reflection seismic data: firstly, such a large-scale translation is not compatible with the observed fault geometries and the spatial coincidence of Palaeozoic trends and younger overlying depositional and structural features. Secondly, there are no indications of thrust faults or major halokinetic deformations at the level of the postulated detachment horizon.

The structural configuration of the Molasse Basin of Western Switzerland/France is very similar to the structural style of its Central and Eastern parts as illustrated by two published cross-sections which are also based on reflection seismic data.

RÉSUMÉ

Dans la région genevoise et le canton de Vaud, des données de réflexion sismique calibrées par des informations de puits et d'affleurements permettent de définir la configuration structurale du bassin molassique entre Jura et front alpin, sauf pour la partie sous-jacente au lac Léman où la résolution sismique est trop mauvaise.

[1)] Paper presented at the "Symposium on Swiss Molasse Basin, Bern, Nov. 22–23, 1991 (see Eclog. geol. Helv. 85/3, 1992, 772–773).

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Des sections sismiques représentatives parallèles et perpendiculaires à l'axe du bassin sont interprétées et converties en profondeur pour aboutir à des profils géologiques qui illustrent, du nord-ouest au sud-est, la subdivision suivante du bassin molassique en trois zones structurales:

– La Molasse du Plateau est formée surtout de Molasse d'eau douce inférieure (USM) subhorizontale, qui recouvre en "onlap" le Mésozoïque et s'amincit en direction du Jura. Elle est intersectée par des zones décrochantes reliant les Alpes au Jura, qui apparaissent souvent comme des linéaments paléozoïques réactivés au Paléogène et Néogène.

– La zone de transition entre la Molasse du Plateau et la Molasse charriée (ou Molasse subalpine) coincide avec d'importants linéaments d'orientation sud-ouest nord-est, probablement hérités du Paléozoïque. Dans la région genevoise, cette zone correspond à l'axe du Salève et à un point haut du socle. A l'est de Lausanne (canton de Vaud), la zone de transition se marque jusqu'en surface par une importante zone décrochante. Ces linéaments pourraient avoir eu une grande influence paléogéographique et structurale, puisqu'ils semblent coïncider avec la zone de transition plateforme-bassin au Jurassique inférieur et moyen, avec la limite nord de la Molasse marine inférieure (UMM) et avec le front de la Molasse charriée.

– La Molasse charriée consiste en un ensemble de sédiments plissés et charriés incorporant la UMM et la USM. Cet ensemble s'épaissit en direction du front alpin, où il semble coïncider en profondeur, dans les deux régions étudiées, avec un demi-graben permo-carbonifère.

Par conséquent, les données sismiques en Suisse occidentale et France voisine démontrent l'influence des linéaments paléozoïques dans la structuration du bassin molassique. L'hypothèse d'une importante translation de la couverture mésozoïque et cénozoïque sur un niveau de décollement triasique lors de l'orogène alpine ne peut pas être confirmée par les données sismiques étudiées: d'une part, cette translation n'est pas compatible avec la géométrie observée des failles et avec la coïncidence spatiale de linéaments paléozoïques et d'observations paléogéographiques et structurales dans les terrains mésozoïques et cénozoïques sus-jacents; d'autre part, il n'y a aucune indication de failles inverses ou de structures halokinétiques majeures associées au niveau postulé de décollement.

Finalement, la configuration structurale du bassin molassique en Suisse occidentale et France voisine montre beaucoup de similarités avec celle illustrée en Suisse centrale et orientale par deux profils géologiques publiés qui sont également basés sur des données de sismique réflexion.

ZUSAMMENFASSUNG

An Bohrungen und Oberflächenaufschlüssen kalibrierte reflexions-seismische Profile der Region Genf und des Kantons Waadt ermöglichen eine detaillierte tektonische Beschreibung des Molassebeckens zwischen Faltenjura und Alpen. Mit Ausnahme des Genferseebeckens ist die Qualität der seismischen Daten ausreichend um repräsentative Linien zu interpretieren, die sowohl parallel als auch senkrecht zur Streichrichtung des Molassebekkens liegen. Tiefenkonvertierte Profile illustrieren von NW nach SE folgende strukturelle Unterteilung des Molassebeckens:

– Die Mittelländische Molasse besteht hauptsächlich aus subhorizontal gelagerter USM, deren Mächtigkeit gegen den Faltenjura hin abnimmt. Die Beziehung zum mesozoischen Untergrund ist durch "onlap" gekennzeichnet. Ein wichtiges strukturelles Element in der Mittelländischen Molasse sind Blattverschiebungen, die sich von der Alpenfront bis in den Faltenjura hinein verfolgen lassen. Oft können diese Lineamente als im Paläogen und Neogen reaktivierte paläozoische Sockelstörungen identifiziert werden.

– Die Übergangszone zwischen Mittelländischer Molasse und Subalpiner Molasse entspricht SW-NE streichenden Scharnierzonen, die ererbte Sockelstrukturen überlagern. In der Transversale von Genf entspricht sie der überschobenen Antiklinale des Salève, deren Abscherung über einem Sockelsprung liegt. Östlich von Lausanne (Waadt) ist die Störungszone durch Blattverschiebungen charakterisiert, welche den gesamten mesozoischen und tertiären Schichtstapel versetzen. Diese Scharnierzone fällt mit dem Übergang zwischen Plattform- und Beckenfazies in den Sedimenten des Unteren und Mittleren Juras zusammen, und dem Auskeilen der UMM. Ausserdem scheint sie die Lokalisierung der Überschiebungsfront der Subalpinen Molasse beeinflusst zu haben.

– die Subalpine Molasse ist ein gefalteter und überschobener Komplex, bestehend aus Sedimenten der UMM und USM. Gegen die Alpenfront nimmt die Mächtigkeit dieses Sedimentkeils zu und überlagert einen Permo-Karbon Halbgraben.

Unsere Beobachtungen unterstreichen die Bedeutung paläozoischer Lineamente für die strukturelle Konfiguration des Molassebeckens. Die oft postulierte Fernschubhypothese (Laubscher 1961) kann durch unsere Daten nicht bestätigt werden, da grossräumige Horizontalverschiebungen nicht kompatibel sind mit den beobachteten Bruch Systemen und dem räumlichen Zusammentreffen von paläozoischen und jüngeren, sowohl sedimentologisch als auch tektonisch relevanten Strukturen. Das Fehlen von Überschiebungshorizonten, oder bedeutender halokinetischer Deformationen an der Basis des mesozoischen Schichtstapels, ist ein weiteres Indiz gegen grosse Horizontalverschiebungsbeträge der Mittelländischen Molasse.

Die strukturelle Konfiguration des westlichen Molassebeckens hat grosse Ähnlichkeiten mit derjenigen der Zentral- und Ostschweiz.

Introduction

The westernmost part of the Swiss Molasse Basin, addressed by this paper, covers the Canton Vaud and the greater Geneva area (Fig. 1). This basin is elongated in a SW-NE direction and its width ranges from ca. 25 to 40 km. It is limited to the northwest by the Jura Mountains and to the southeast by the frontal thrust of the Alps, represented here by the subalpine massifs and prealpine units (Fig. 1).

The general evolution of the western Molasse Basin is described in detail by Homewood et al. (1986). In the area studied, Tertiary Molasse sediments occur in: (1) a southeastern zone of closely spaced thrust faults known as the "Thrusted Molasse", "Subalpine Molasse" or "Molasse nappe" (Trümpy 1980); (2) a northwestern little deformed zone referred to as the "Plateau Molasse" or " Autochtonous Molasse" (Trümpy 1980).

This paper describes the framework of the Molasse Basin between the Alpine front and the Jura, as derived from reflection seismic data. Representative dip and strike cross-sections through the basin (Fig. 1) illustrate the spatial and structural relationship between the Molasse sediments and the underlying Mesozoic and Palaeozoic series and the basement. The analyzed seismic lines also provide a better spatial and structural definition of the major depositional units of the Molasse; in the studied area, these correspond to the Lower Marine Molasse (UMM) and the Lower Freshwater Molasse (USM, see Trümpy, 1980 and Homewood et al. 1986 for definition of these stratigraphic units). In the final section of this paper, results of our studies are compared with two published cross-sections through the central and eastern parts of the Swiss Molasse Basin.

This paper summarizes the results of initial studies which require further detailing, particularly in terms of seismostratigraphic and structural analyses.

Geological Framework and Data

Geneva area (Figs. 1 and 2)

In this area, the Molasse Basin is subdivided by the SW-NE trending Mount Salève into the northwestern Geneva basin and the southeastern Bornes Plateau:

1) The "**Geneva basin or cuvette**" extends from the most internal range of the Jura Mountains to the northwest (called "High Chain", Wildi et al. 1991) to the Mount Salève to the southeast (Joukowski & Favre 1913). To the southwest, it is limited by a major senestral wrench fault zone (the Vuache-Forens-les Bouchoux tectonic zone, Guyonnet 1988, Wildi et al 1991), along which transpressional movements have given rise to the Mount Vuache (Blondel 1984; Blondel et al. 1988) and its northerly continuation (Guyonnet 1988).

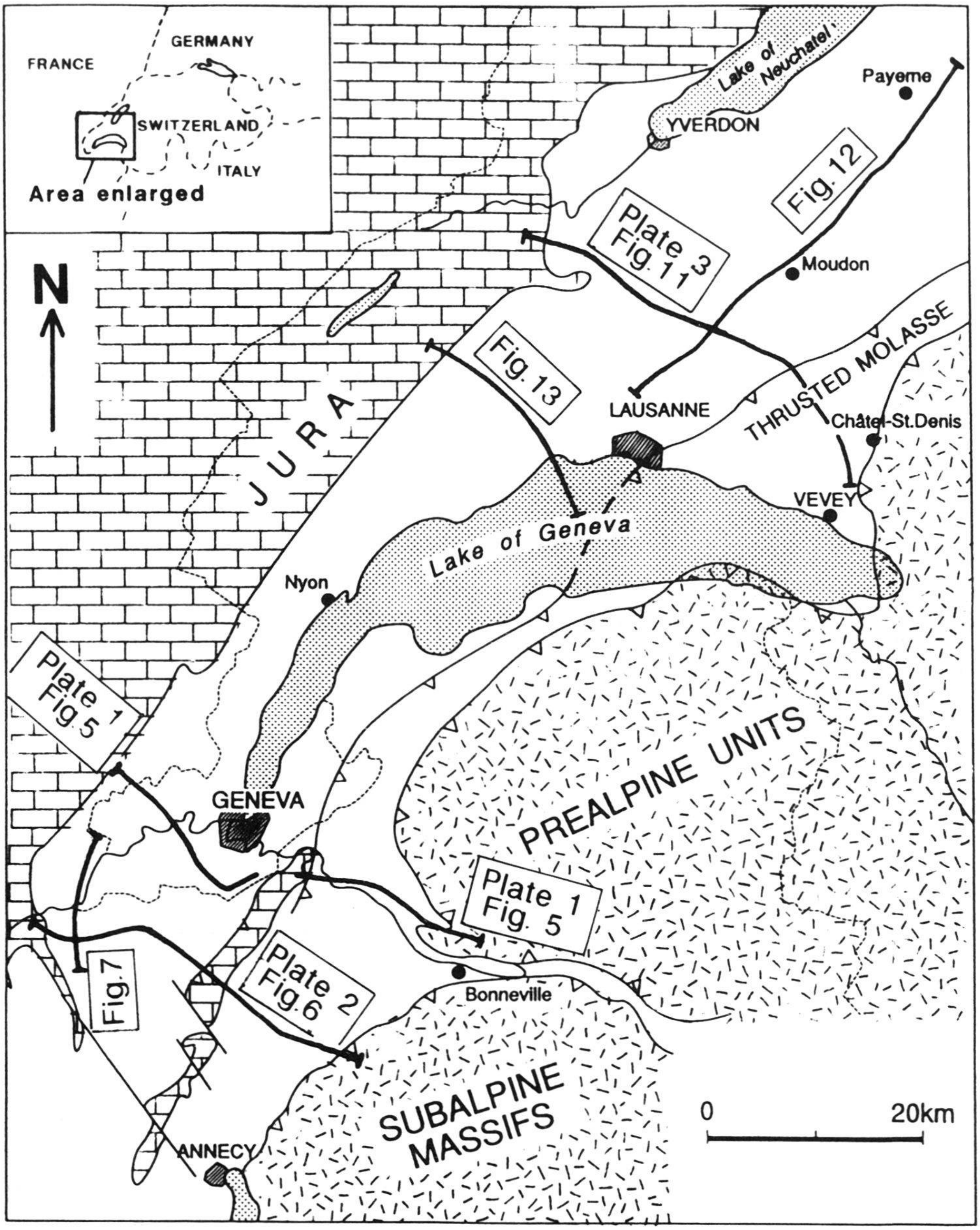


Fig. 1. General location map and structural framework

Jurassic and Cretaceous strata underlying the Molasse series in the Geneva area crop out in the adjacent Jura Mountains (Charollais & Badoux 1990), in the Mount Vuache (Blondel 1990) and in the Mount Salève (Deville 1990). The only deep subsurface control point in the Geneva cuvette is the well Humilly-2 (SNPA 1969), which bottomed in the top of the Permo-Carboniferous (Fig. 3). This provides an excellent calibration of the reflection seismic data (Fig. 4). A summary of the stratigraphic succession of the Tertiary molasse deposits in the Geneva and Haute-Savoie area is given in Charollais & Amberger (1984); these sediments are exclusively attributed to the Lower Freshwater Molasse (USM) sequence, which is subdivided into "Molasse rouge" (Berger et al. 1987) and "Molasse grise" ranging from late Early Chattian to Early Aquitanian (i.e. Late Oligocene-Early Miocene).

In the Geneva basin, some 300 km of reflection seismic data were recorded both for petroleum and geothermal exploration between 1958 and 1990. A preliminary study of some of this data was presented by Gorin & Amberger (1990) and provided a subsurface geological framework for the Geneva cuvette (Wildi et al. 1991). A more thorough geological evaluation of the available seismic data was carried out by Signer (1992). Some of this data has been used to compile figure 7 and the western part of figures 5 and 6 and of plates 1 and 2. Shallow reflection seismic data has also been shot in the westernmost part of Lake Geneva, but provide informations only down to Top Molasse (Vernet & Horn 1971).

2) The "**Bornes Plateau**" is limited by the Mount Salève and the Alpine front (Fig. 2). Stratigraphic control on the Upper Jurassic and Cretaceous series is provided by outcrops of the Mount Salève and the subalpine massifs (Charollais 1988) and by the well Faucigny-1 (Esso REP 1970), which penetrated autochtonous sediments below the prealpine nappes and bottomed in Permo-Carboniferous strata (Figs. 2 and 3). Molasse deposits are known from local outcrops and wells. Apart from Faucigny-1, the well Salève-2 (PREPA 1960) penetrated the complete molasse sequence and reached total depth in the Barremian (Fig. 2). Molasse deposits in the Bornes Plateau consist of both UMM and USM sediments. The UMM comprises the "subalpine flysch" and the "Grès de Bonneville" (Charollais & Amberger 1984), and is dated as Rupelian (i.e. Early Oligocene, Charollais 1988). The UMM crops out along some thrust planes (Charollais 1988) and was encountered in the wells Faucigny-1 and Salève-2. The USM of the Bornes Plateau is made only of "Molasse rouge" dated as Rupelian-Chattian (i.e. Early-Late Oligocene), its lower part being clearly older than that of the "Molasse rouge" in the Geneva basin (Charollais et al. 1981; Berger et al. 1987). This shows that deposition of the Molasse series commenced earlier in the Bornes Plateau close to the Alpine front, and later in time overstepped the area of the Geneva basin (Berger et al. 1987). This is compatible with the observations of Homewood et al. (1986) and Guellec et al. (1990), who demonstrated the northward migration of subsidence across the Molasse Basin in Western Switzerland and adjacent France.

About 400 km of reflection seismic data were recorded in the Bornes Plateau for petroleum exploration between 1966 and 1988. Some of these data were used to compile the eastern part of figures 5 and 6 and of plates 1 and 2. Some of the older seismic data already showed evidence of Thrusted Molasse in the Bornes Plateau and were used by Charollais (1988) to construct a cross-section extending from the Mount Salève to the Bornes Massif. On recent seismic data, thrust planes in the Molasse Basin are evident at

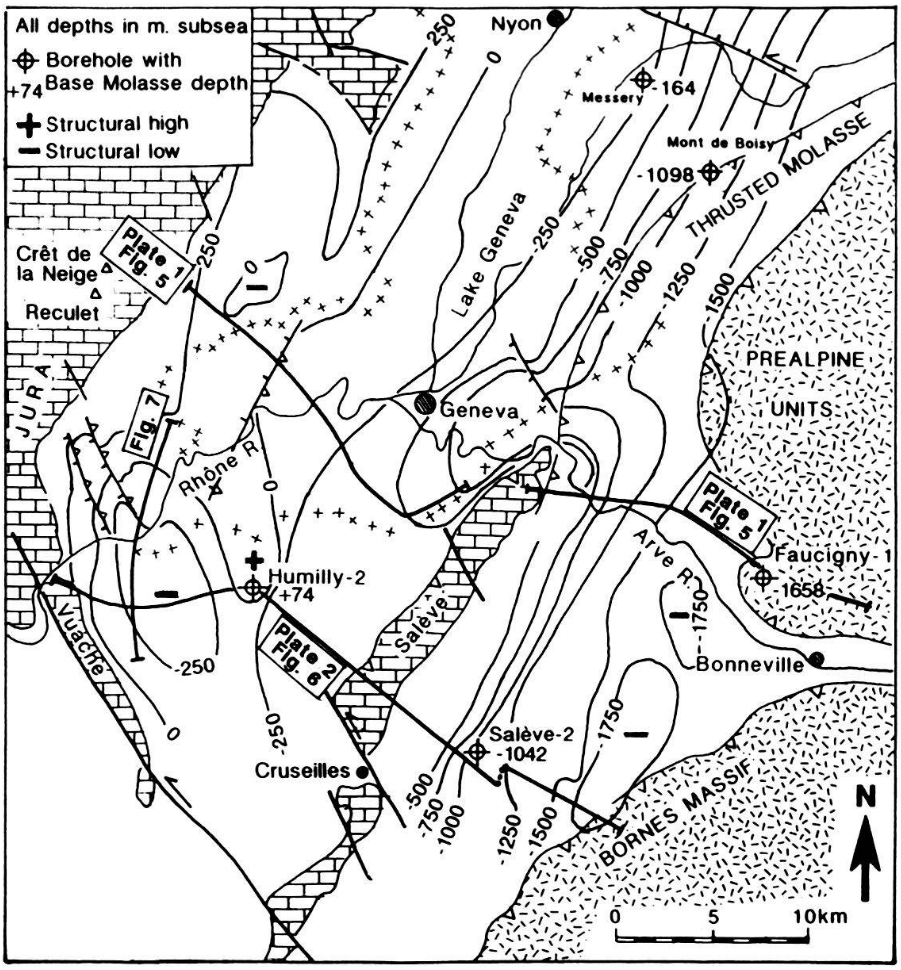


Fig. 2. Schematic Base Molasse depth map and location map in the greater Geneva area. This map connects with that of Figure 8.

the front of the Bornes Massif (Charollais & Jamet 1990). The tectonic transition zone between the Bornes Massif and the Bornes Plateau has also been studied by Huggenberger & Wildi (1991), who partly reinterpret the seismic profile shown by Charollais & Jamet (1990) and illustrate a pronounced westward downfaulting of the basement underlying the front of the Bornes Massif. Finally, the shallow part of the ECORS-ALPES II deep seismic profile provides a relatively poor-quality section that is located close to the profiles given in figure 6 and plate 2.

Vaud area (Figs. 1 and 8)

The floor of the Tertiary Molasse Basin dips from the Jura Mountains towards the Lake Geneva and the front of the prealpine units. In the Canton Vaud, pre-Tertiary stratigraphic control is provided by outcrop (see 1:25000 sheets of the Swiss Geological Atlas) and subsurface data (Bitterli 1972) in the Jura Mountains and by the wells Essertines and Treycovagnes. The well Essertines-1 (Büchi et al. 1965) was used as a tie for the reflection seismic data (Figs. 9 and 10). For the northern part of the Canton Vaud, figure 8 shows the structural interpretation that was carried out by Jordi (1990) on the

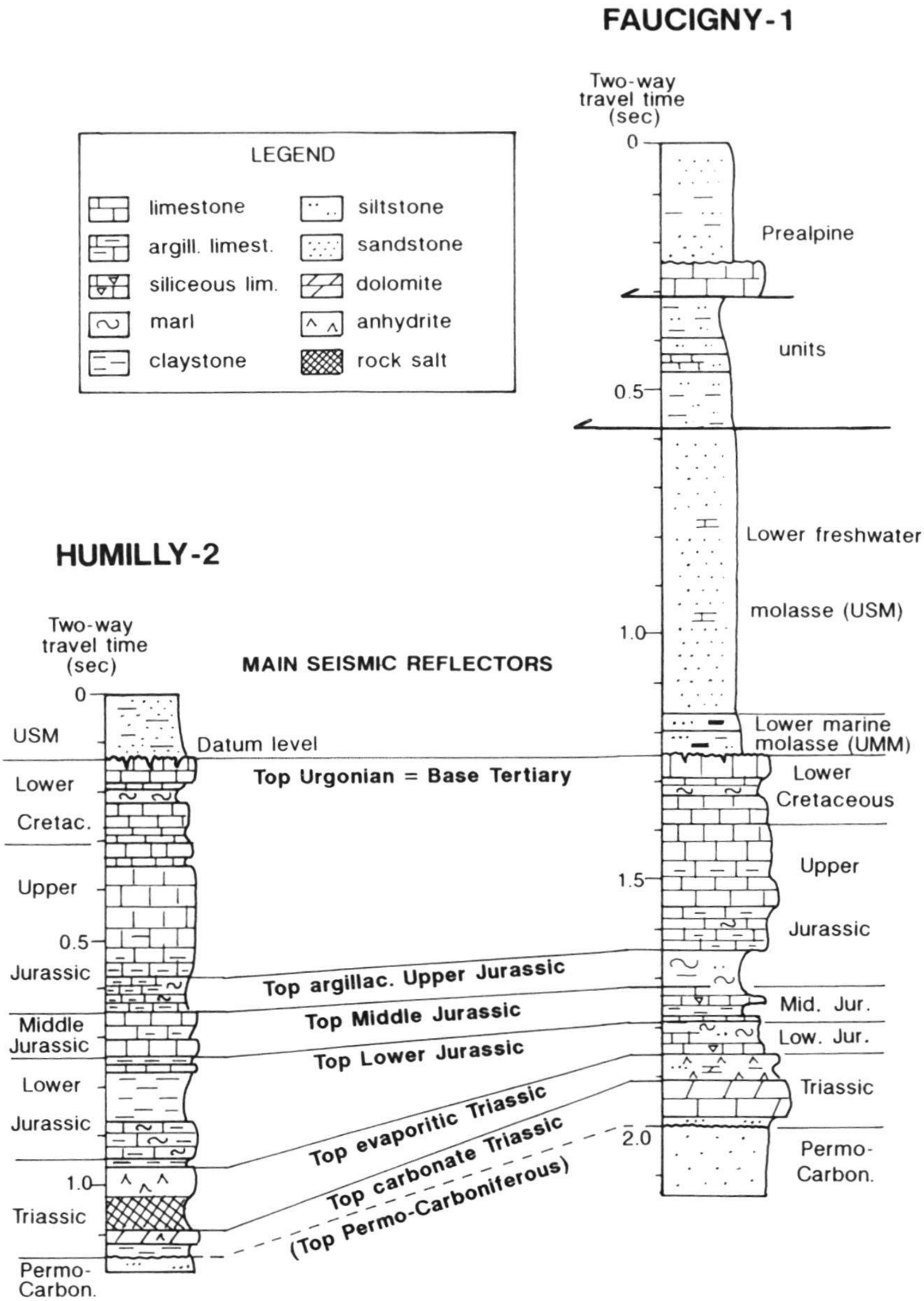


Fig. 3. Lithology and seismic reflectors in wells Humilly-2 and Faucigny-1, Geneva area. Wells are dispalyed along a time scale calibrated by sonic logs. See Fig. 2 for well location.

basis of reflection seismic data. Subsurface control on the molasse deposits is provided by wells such as Chapelle-1 (Lemcke 1959) and Savigny-1 (Lemcke 1963). These two wells together with Essertines-1 provide a north-south trending cross-section through the Molasse Basin of Canton Vaud (Fig. 9). In the molasse, three lithological units are

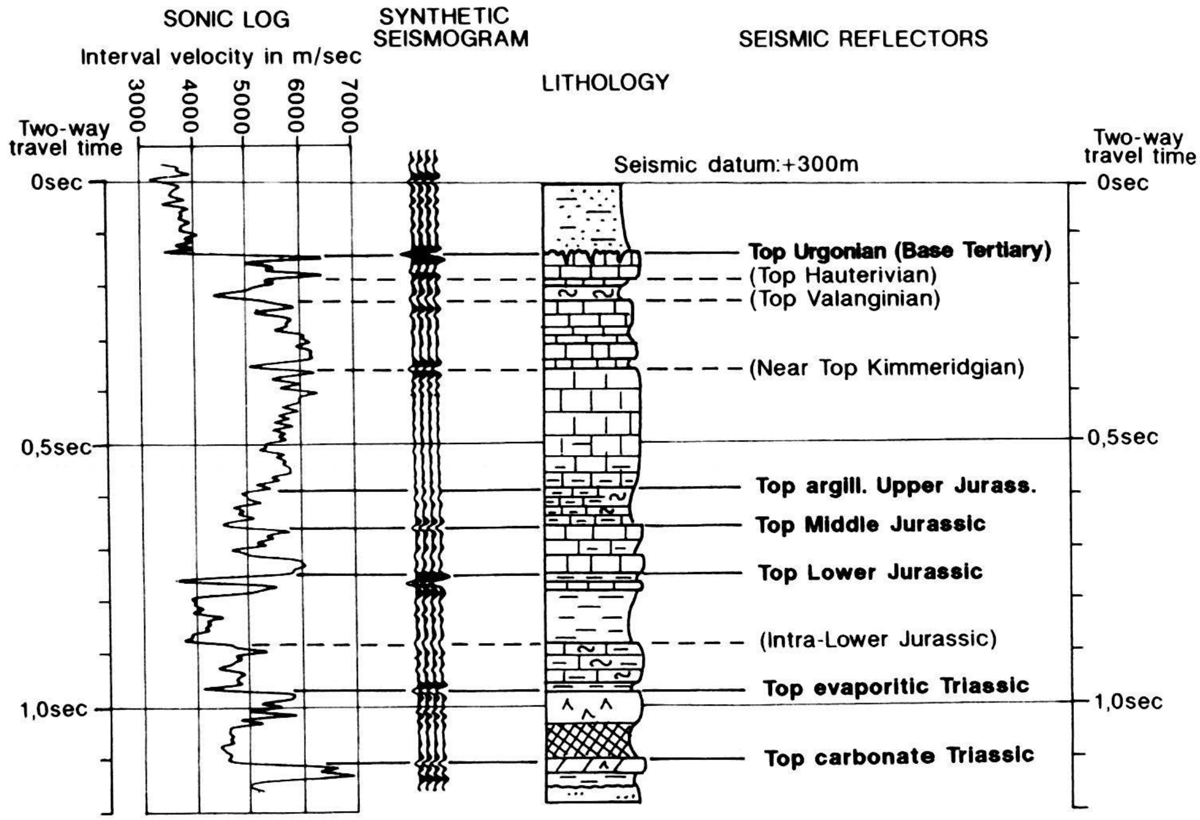


Fig. 4. Synthetic seismogram of well Humilly-2 (based on sonic log only). See Fig. 2 for well location.

encountered from bottom to top: the Lower Marine Molasse (UMM), the Lower Fresh-water molasse (USM) and the Upper Marine Molasse (OMM). These units are also known in outcrops, where they have been thoroughly studied and mapped, particularly east of Lausanne (Fasel 1986; Weidmann 1988 and 1993; Weidmann et al. 1982). UMM outcrops ("Formation de Vaulruz", Weidmann et al. 1982) are found only along the Alpine front. The "Grès de Vaulruz" are the lateral equivalent of the "Grès de Bonne-ville" in the Geneva area (Charollais 1988). The different USM units ("Molasse rouge", "Poudingues du Pélerin", "Molasse à charbon", "Molasse grise", etc...) outcrop in the Thrusted Molasse east of Lausanne, where they have been investigated in detail by Fasel (1986). The OMM is restricted to the Plateau Molasse. The geological map of the Molasse basin by Rigassi in Matter et al. (1980) provides an excellent overview of the studied area.

More than 1000 km of reflection seismic data have been acquired in Canton Vaud for hydrocarbon exploration. About 350 km of these data (older than ten years) are deposit-ed in the Geological Museum of Lausanne, where they are readily accessible to the public. Some of these data have been used to construct the schematic base Tertiary map given in figure 8 and the profiles shown in figures 11, 12 and 13 and plate 3.

Schematic structural profiles (Fig. 16.10 by D. Rigassi in Homewood et al. 1990) and regional isopach maps of the Molasse and Lower Cretaceous (Rigassi 1977) have been already illustrated for both areas.

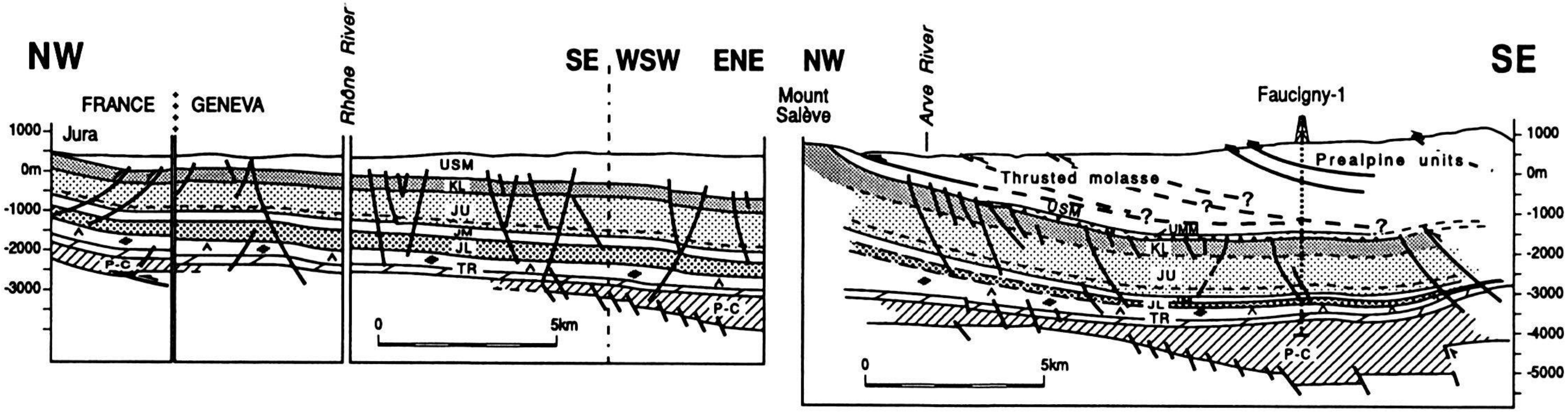


Fig. 5. Geological profile from the Alpine front to the Jura Mountains, greater Geneva area. It is based on the interpretation of the composite reflection seismic section presented in Plate 1. See Figs. 1 and 2 for location of section. P-C = Permo-Carboniferous, TR = Triassic, JL = Lower Jurassic, JM = Middle Jurassic, JU = Upper Jurassic, KL = Lower Cretaceous, UMM = Lower Marine Molasse, USM = Lower Freshwater Molasse.

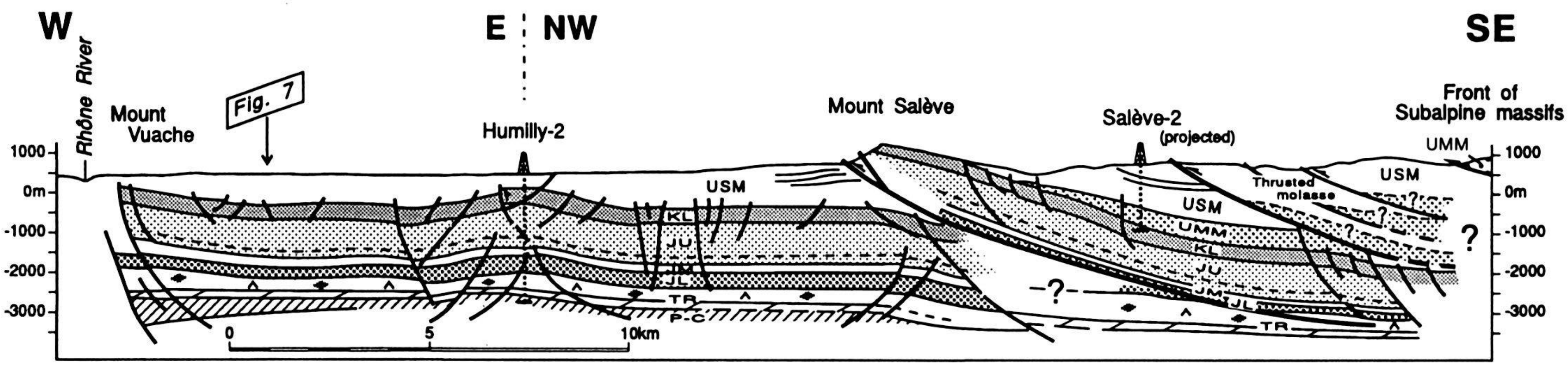


Fig. 6. Geological profile from the front of the Subalpine Massifs to Mount Vuache, crossing the Bornes Plateau and the Geneva cuvette. It is based on the interpretation of the composite reflection seismic section presented in Plate 2. See Figs. 1 and 2 for location of profile. See caption of Figure 5 for abbreviations of stratigraphic/lithological units.

Results

Geneva area

A schematic Base Molasse depth map is given in figure 2. It is a simplified version of the map presented by Signer (1992), who used most of the seismic data available. It can be tied to the north with the Base Molasse depth map of figure 8. The WNW-ESE trending wrench fault crossing Lake Geneva east of Nyon is derived from Vernet & Horn (1971). The structural configuration of the Molasse Basin is further illustrated by two dip cross-sections tied to existing wells and outcrops (plates 1 and 2, Figs. 5 and 6) and by a strike cross-section (Fig. 7), the location of which is shown in figures 1 and 2. Due to the considerable reduction of the seismic data and lateral data quality changes, some observations described below may be difficult to visualize for the reader.

Plate 1 consists of two parts: the left part crosses the Geneva basin from the Jura Mountains to Mount Salève, the right part links the eastern flank of Mount Salève with the Alpine front and crosses the Bornes Plateau. The uninterpreted data illustrates the varying quality of the different data vintages. In the Geneva basin, horizon identification was established by a direct tie of seismic lines at the well Humilly-2 (Figs. 3 and 4). From Top Urgonian down to Top carbonate Triassic, six regionally correlative reflectors were identified. Regional interpretations and ties of all available seismic data show that upper parts of the Permo-Carboniferous section are usually characterized by a fairly transparent seismic facies (sandstones?), which, at deeper levels, gives way to high amplitude reflectors, which are thought to be associated with coal-bearing Carboniferous sediments and the top of the cristalline basement. Where these high amplitude reflectors get close to the Top carbonate Triassic reflector, one can confidently assume that the Permo-Carboniferous section has become thin and the basement is located close to the base of the Mesozoic series.

The second, eastern part of plate 1 is calibrated by the well Faucigny-1 (Fig. 3) down to the base Mesozoic. The same six reflectors as in Humilly-2 can be identified, plus a

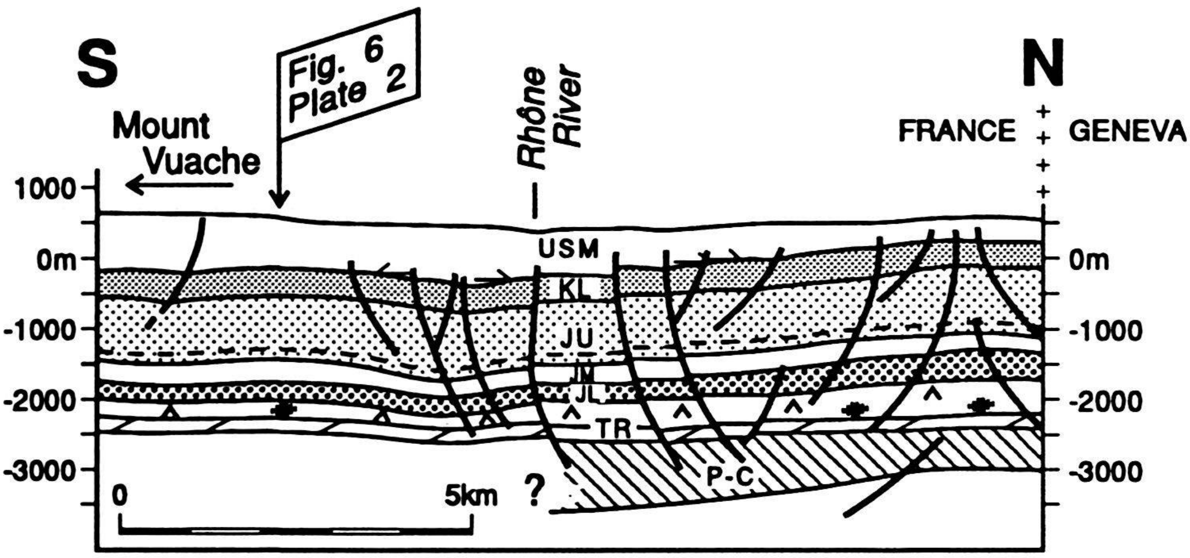


Fig. 7. Geological cross-section derived from reflection seismic data subparallel to the Jura Mountains in the Geneva cuvette. See Figs. 1 and 2 for location of section. See caption of Figure 5 for abbreviations of stratigraphic/lithological units.

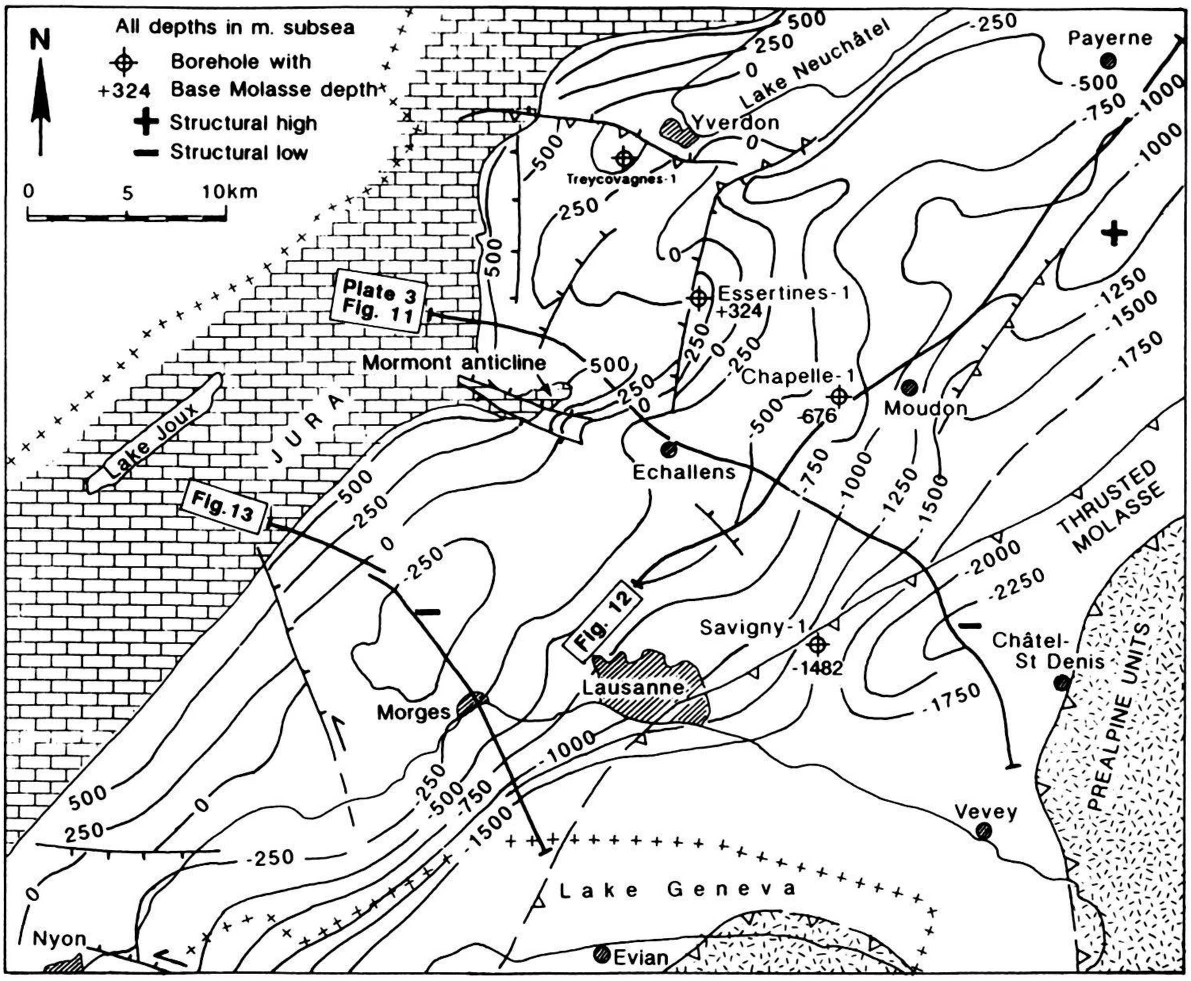


Fig. 8. Schematic Base Molasse depth map and location map in Canton Vaud area. This map connects with that of Figure 2.

Top UMM reflector. Interpretation of thrust planes in the Thrusted Molasse is conjectural, apart from the westernmost one, which has a topographical expression. The Permo-Carboniferous section has a seismic facies similar to that in the Geneva basin.

Using seismic velocities essentially derived from the wells Humilly-2 and Faucigny-1, the interpreted time section given in plate 1 has been depth converted to produce the geological profile shown in figure 5.

Plate 2 is a continuous composite line of different vintages crossing the southern part of the Geneva basin, the Mount Salève and the Bornes Plateau. Similarly to plate 1, interpretation in the Geneva basin is based on ties with the well Humilly-2: this well was drilled on a faulted structural high and the well tie is easier to visualize off the high to the southeast as shown on the interpreted data. Permo-Carboniferous reflectors are visible only close to Mount Vuache. Interpretation in the Bornes Plateau is calibrated by the well Salève-2 for the Top UMM and Top Urgonian reflectors, whereas deeper reflectors have been identified at the well Faucigny-1. In the Thrusted Molasse, the westernmost thrust is clearly visible on seismic, whereas the thrust carrying the UMM at the front of the Bornes Massif is evident in outcrop (Charollais 1988). Inbetween, the interpreted thrust planes in the molasse are hypothetical. Using seismic velocities derived from the wells Humilly-2 and Faucigny-1, the interpreted section given in plate 2 was depth converted to produce the geological profile shown in figure 6.

Figure 7 presents a geological strike cross-section derived from seismic and subparallel to the first ridge of the Jura Mountains. Reflectors are also tied to Humilly-2 down to the Triassic, whereas the Permo-Carboniferous interpretation uses the same criteria as those described above.

Vaud area

A schematic Base Molasse depth map is given in figure 8. The northeastern part is largely derived from Jordi (1990), whereas the southern part was constructed on the basis of the available reflection seismic lines. The structural configuration of the Molasse Basin is further illustrated by two dip (Plate 3, Figs. 11 and 13) and one strike (Fig. 12) cross-sections, the location of which is indicated in figure 8.

The reflection seismic line given in Plate 3 crosses the entire Molasse Basin from the Jura Mountains to very near the Alpine front north of Vevey. Five Mesozoic reflectors from Top Cretaceous down to Top evaporitic Triassic were identified at the well Essertines-1 (Fig. 10). Top carbonate Triassic is derived from seismic character by analogy with Geneva data: it can be traced at the base of the interval which displays strong discontinuous reflectors characterizing the evaporitic Triassic. At the southern end of the profile, the signature of a southward thickening Permo-Carboniferous section is confirmed by another seismic line; as in the Geneva area, the section is marked by a seismically fairly transparent facies overlying high amplitude reflectors which show a different dip from that of the Mesozoic reflectors. In the molasse interval, the Top UMM reflector has been interpreted by projecting the data of Savigny-1, where the UMM has nearly completely pinched out (Fig. 9). In the Thrusted Molasse, thrust planes can be tentatively located on the seismic data and tied to surface outcrops as shown by Fasel (1986). In particular, the interpreted "flower structure" at the front of the Thrusted Molasse can be tied with strike-slip and thrust faults observed in outcrops; it corresponds to the "Accident de la Paudèze" of Weidmann (1988).

Figure 11 is the depth-converted geological cross-section that was derived from the interpreted seismic section shown in plate 3. The available wells provided velocity data for the molasse interval, with the average velocity increasing towards the Alpine front (as in the Geneva area). For the sake of simplification, constant interval velocities derived from Essertines-1 were used for the Mesozoic series: in fact, one might expect velocities to increase slightly in the deeper part of the section underlying the Thrusted Molasse. In the Geneva area, the velocity increase of the Mesozoic section between the wells Humilly-2 (structural position in the Molasse Basin similar to that of Essertines-1) and Faucigny-1 (structural position fairly similar to that of the eastern part of figure 11) is only in the order of 10%. Therefore, by analogy, one can assume that the Mesozoic section could be about one tenth thicker than that shown in the southeastern part of figure 11. This would not significantly change the structural picture, in particular the conspicuous thinning of the Middle and Lower Jurassic section.

Figure 12 is a geological cross-section derived from reflection seismic data, crossing at a right angle figure 11 and on strike with the Molasse Basin axis. Its interpretation is

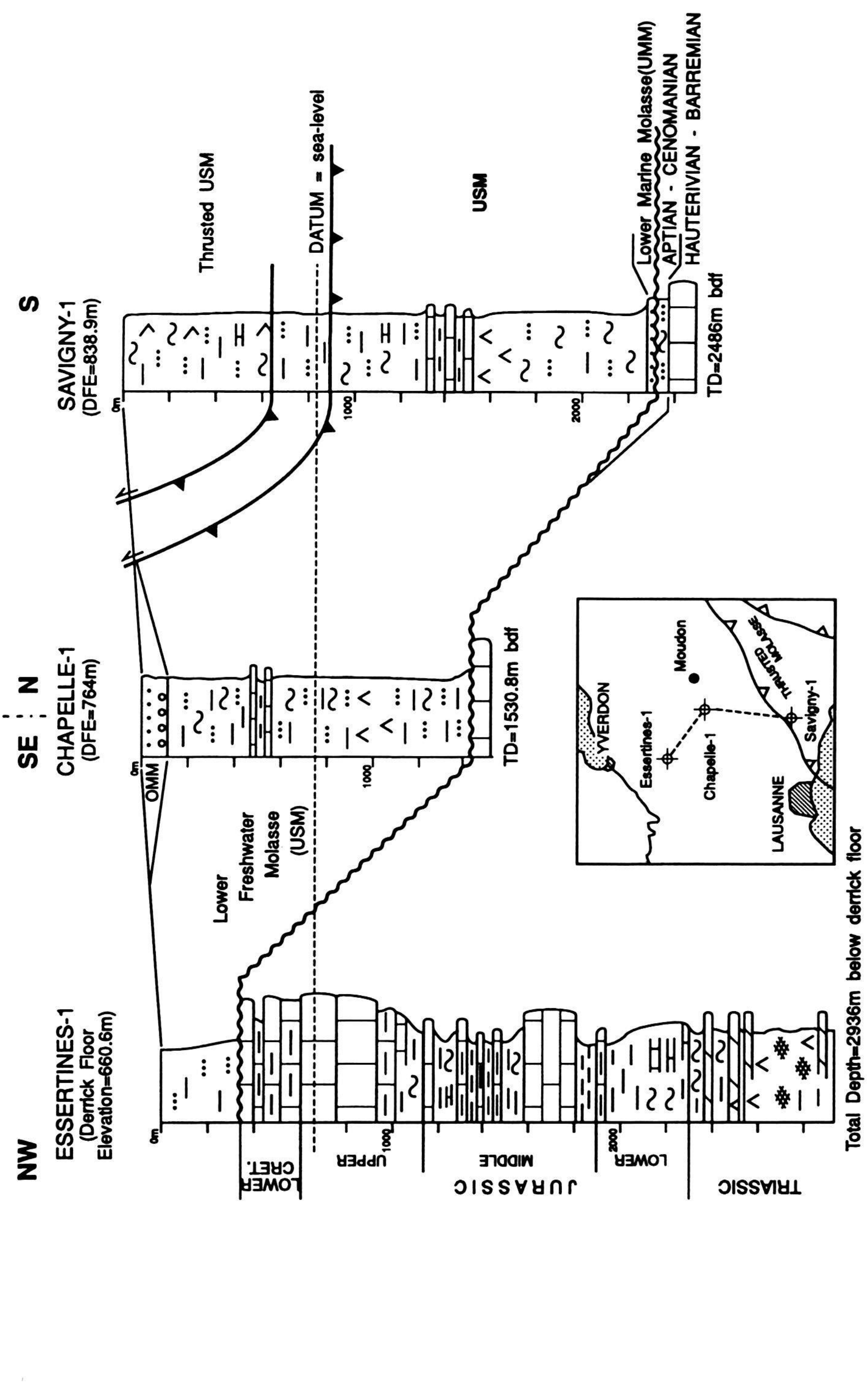


Fig. 9. Correlation of wells Essertines-1, Chapelle-1 and Savigny-1, Canton Vaud.

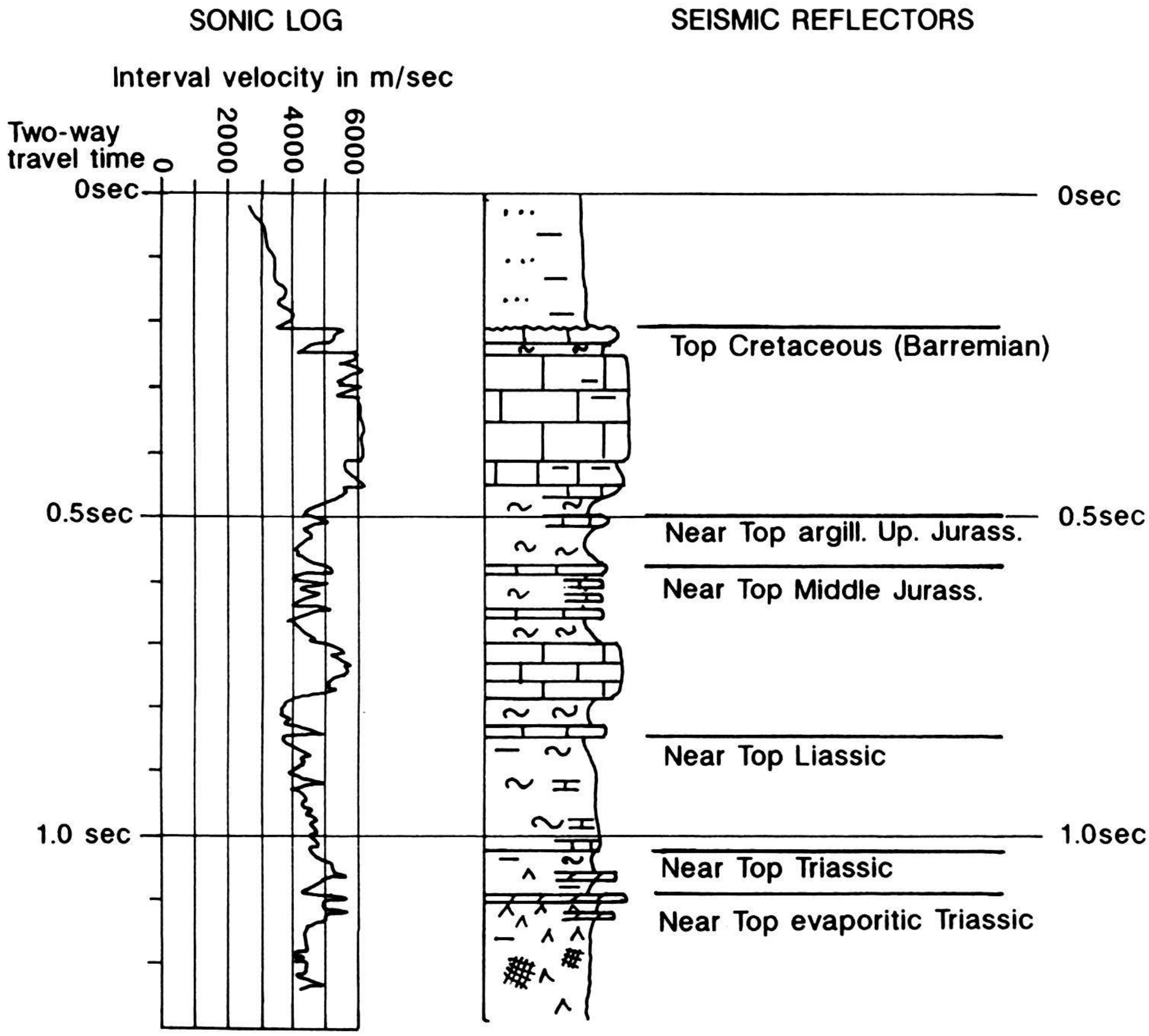


Fig. 10. Sonic log and lithology of well Essertines-1 displayed along a time scale. See Fig. 8 for well location.

based on ties with Essertines-1. Constant interval velocities derived from the wells Chapelle-1 and Essertines-1 were used for depth conversion.

Figure 13 gives a dip cross-section some 20 km southwest of figure 11, extending from the foot of the Jura Mountains to beneath Lake Geneva. It is based on a composite seismic line and the interpreted Mesozoic reflectors are tied to the well Essertines-1. Top carbonate Triassic and the Permo-Carboniferous were interpreted as in plate 3. Data quality beneath Lake Geneva is of so poor quality that no interpretation below the Upper Jurassic is possible.

Discussion

Geneva area

In the area of the Plateau Molasse, the Tertiary series rests unconformably on karstified Urgonian carbonates. Between the Jura Mountains and Mount Salève, this

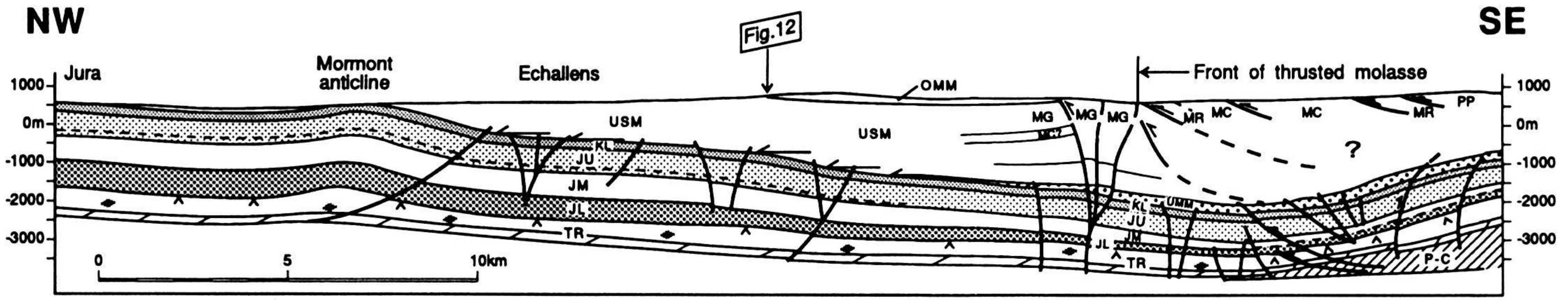


Fig. 11. Geological profile from the Alpine front to the Jura Mountains, Canton Vaud. It is based on the interpretation of the composite reflection seismic section presented on Plate 3. See Fig. 8 for location of profile. See caption of Figure 5 for abbreviations of stratigraphic/lithological units; OMM = Upper Marine Molasse; in the thrusted Lower Freshwater Molasse (USM), surface data of Fasel (1986) are integrated in the interpretation and the following stratigraphic units distinguished: MR = Molasse rouge, PP = Poudingues du Pélerin, MC = Molasse à charbon, MG = Molasse grise.

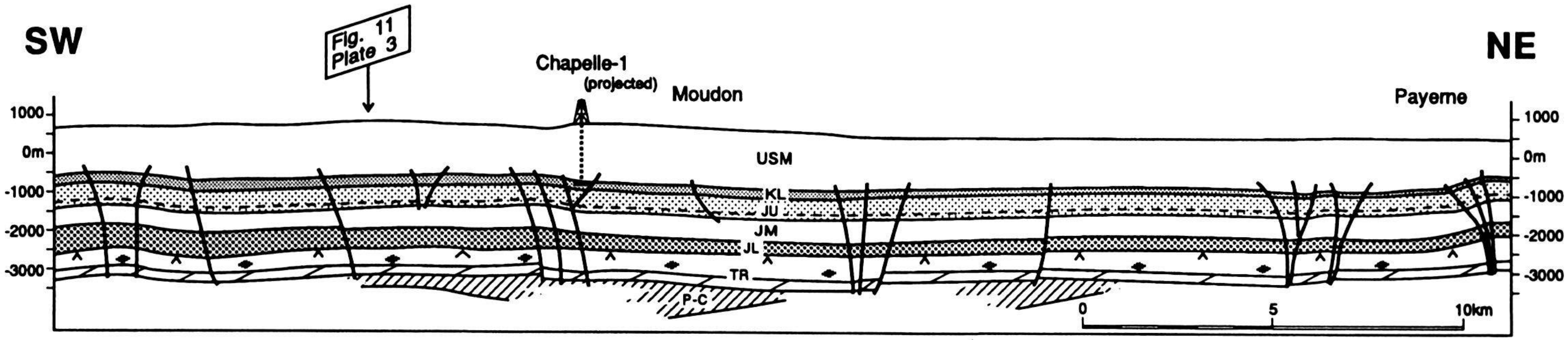


Fig. 12. Geological cross-section derived from reflection seismic data along strike of Molasse Basin, Canton Vaud. See Fig. 8 for location of section. See caption of Figure 5 for abbreviations of stratigraphic/lithological units.

unconformity has the configuration of an essentially southeasterly dipping monocline (Figs. 2 and 5). Most faults affecting this monocline have generally little vertical throw on NW-SE trending dip section (Fig. 5, Plate 1). The largest throws are observed on W-E and N-S trending strike sections (Figs. 6 and 7, Plate 2). Detailed mapping (Signer 1992) reveals that these important tectonic features correspond to NNW-SSE trending wrench fault zones subparallel to the Vuache fault zone. The well Humilly-2 is located (Figs. 2 and 6) on a structural high that is associated with such a zone, which also affects the trend of the Mount Salève structure at Cruseilles (Fig. 2) and projects northwards into the Jura High Chain, where it coincides with the Reculet and Crêt de la Neige culminations (Fig. 2). These high trends delineate structural lows such as the one separating the Vuache and the Humilly-2 wrench zones (Figs. 2, 6 and 7, Plate 2).

Initiation of these marked, basement-related, structural lineaments clearly predates the Late Tertiary phase of Jura folding, because the Chattian (i.e. Upper Oligocene) molasse can be observed to onlap on already existing topography (Fig. 7). Rigassi (1977) already highlighted the importance of pre-Middle Eocene movements along these wrench zones. Mesozoic sediments underlying the Geneva basin show overall a relatively constant thickness, except for local minor thickenings/thinnings in the evaporitic Triassic often associated with halokinesis.

Faults cutting the Base Tertiary unconformity are generally rather steep; those with the larger offsets locally appear to extend downwards into the Permo-Carboniferous series and possibly into the basement (Figs. 5, 6 and 7). The coincidence of Permo-Carboniferous structural trends with younger tectonic features suggests that the structural framework of the basin was largely determined by the rejuvenation of older lineaments. For instance, the Vuache fault zone appears to delineate a Permo-Carboniferous half-graben (Fig. 6), whereas the foothills of the Jura Mountains may also coincide with a Palaeozoic fault zone (Fig. 5). The Cruseille-Humilly-Crêt de la Neige trend overlies a basement high (Figs. 2, 6 and 7). At the front of the Salève thrust, the Geneva basin overlies a Permo-Carboniferous half-graben (Figs. 2 and 5), which corresponds to a gravity low ("axe négatif de Gaillard", Poldini 1956). The SW-NE trending thrusted Mount Salève structure appears to be superimposed on the southern margin of this Permo-Carboniferous basin and overlies a basement high (Figs. 5 and 6). In plate 2, the décollement horizon beneath Mt Salève is located in the Lower Jurassic and there seems to be no halokinetic deformation (see also Rigassi 1977); interpretation in the zone marked by a question mark is difficult, but Mesozoic reflectors may well be continuous in this interval. Nevertheless, the influence of halokinetic movements in the Triassic evaporites beneath Mt Salève can not be ruled out in Plate 1. This structural setting shows similarities with the observations of Sprecher & Müller (1986) in Northern Switzerland, where these authors observe that "a genetic relation exists between the limits of the Permo-Carboniferous basin, the normal faults bounding the southern end of this basin and the overlying thrusts which led to the formation of the Jura Mountains". Wegmann (1961) already mentioned the influence of Permo-Carboniferous trends on younger deformations in the Jura Mountains.

Seismic data show that Mount Salève and its northeastern subsurface continuation actually coincide with the front of the Thrusted Molasse (Figs. 1, 2, 5 and 6). This is in line with the interpretation of D. Rigassi (map of the Molasse Basin in Matter et al. 1980), but still has to be corrected on the 1:500000 tectonic map of Switzerland (Spicher

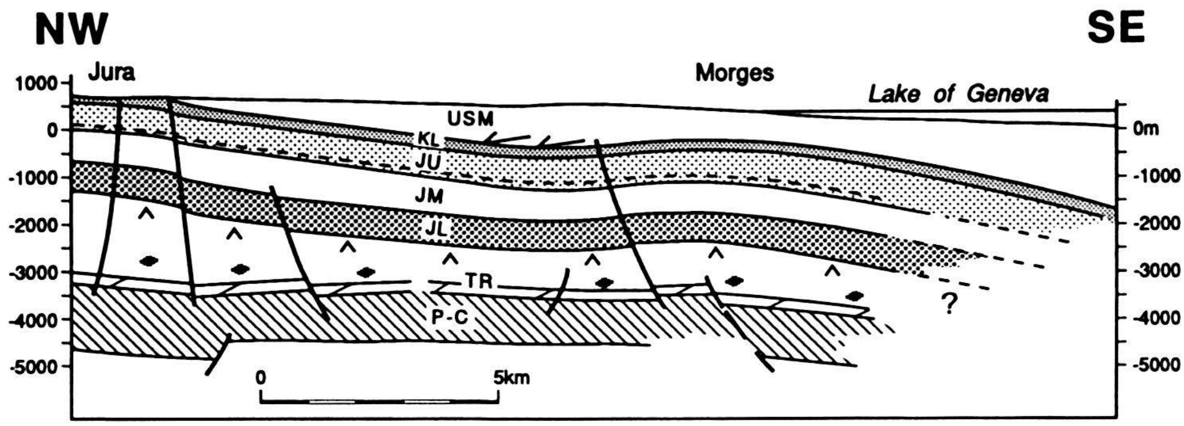


Fig. 13. Geological cross-section derived from reflection seismic data linking the Jura Mountains to Lake Geneva, Canton Vaud. See Fig. 8 for location of section. See caption of Figure 5 for abbreviations of stratigraphic/lithological units.

1980). The Salève trend also marks the western limit of the UMM, as evidenced by its seismically mappable northwestward onlap onto the top Mesozoic unconformity. Therefore, the Molasse Basin of the Bornes Plateau represents a somewhat older and deeper basin than the Geneva cuvette. This is confirmed by the observations of Berger et al. (1987) on the age of the basal USM in both basins. The major thickening of Molasse deposits towards the Alpine front (Figs. 2, 5 and 6) is directly related to the dynamics of the basin evolution involving downwarping of the foreland in response to thrust loading (Laubscher 1978). In contrast, Lower and Middle Jurassic series thin towards the south (Figs. 5 and 6): the thinning coincides with a facies change from platform carbonates to more distal and basinal clay-prone sediments, as evidenced by the wells Humilly-2 and Faucigny-1.

It is noteworthy that the deepest part of the Bornes Plateau basin coincides with an underlying deep Permo-Carboniferous half-graben (Fig. 5). Faults bounding this half-graben to the south delineate a basement high which underlies the southerly tectonic pinch-out of the molasse series beneath the Alpine front: this picture resembles that observed on seismic south of Bonneville (Charollais & Jamet 1990; Huggenberger & Wildi 1991).

Therefore, similarly to the Geneva basin, the rejuvenation of Palaeozoic lineaments seems to have influenced the configuration of the Bornes Plateau basin, both at its northwestern and southeastern margins.

Vaud area

In the area of the Plateau Molasse, the base Tertiary unconformity has the configuration of a southeasterly dipping monocline that plunges under the front of the Thrusted Molasse. An exception is the small depression north of Morges (Figs. 8 and 13). This surface is affected by relatively minor fault zones (Fig. 11). USM deposits clearly onlap this surface and thin towards the Jura Mountains. On a SW-NE trending strike section (Fig. 12), a system of wrench fault zones are evident, which penetrate the entire Mesozoic sequence. Vertical throws on these fault zones are generally small, except north of Lausanne and northeast of Payerne. Some of these fault zones may be associated with deep-seated Permo-Carboniferous fault systems. On the same section, the erosional northeasterly thinning of the Lower Cretaceous and the depositional thinning of the Lower Jurassic series is evident (see Lemcke 1974). In figure 13, the foothills of the Jura Mountains are marked by a considerable thickening of Triassic evaporites, which has been related by Bitterli (1972) to salt flowage, but also coincides with a deep-seated Palaeozoic lineament.

As in the Geneva area, the frontal zone of the Thrusted Molasse overlies a zone of major southward thinning of the Lower and Middle Jurassic section (Fig. 11). This zone appears as a major hinge line that is affected by wrench faults, which extend all the way to the surface (Fasel 1986). This disturbed area ("Accident de la Paudèze", Weidmann 1988) forms a sharp boundary between the younger Plateau Molasse basin and an older and deeper Molasse basin to the southeast. The latter is characterized by a southward expanding wedge of UMM deposits which are underlain by a southward thinning Mesozoic sequence. In contrast, the Plateau Molasse basin is characterized by a northward thinning wedge of Tertiary sediments which progressively onlaps the top Mesozoic unconformity and which, in turn, is underlain by a northward expanding sequence of Lower and Middle Jurassic. The hinge zone between the Plateau and deeper Molasse basins seems to coincide with the uplifted northern margin of a deep-seated Permo-Carboniferous half-graben.

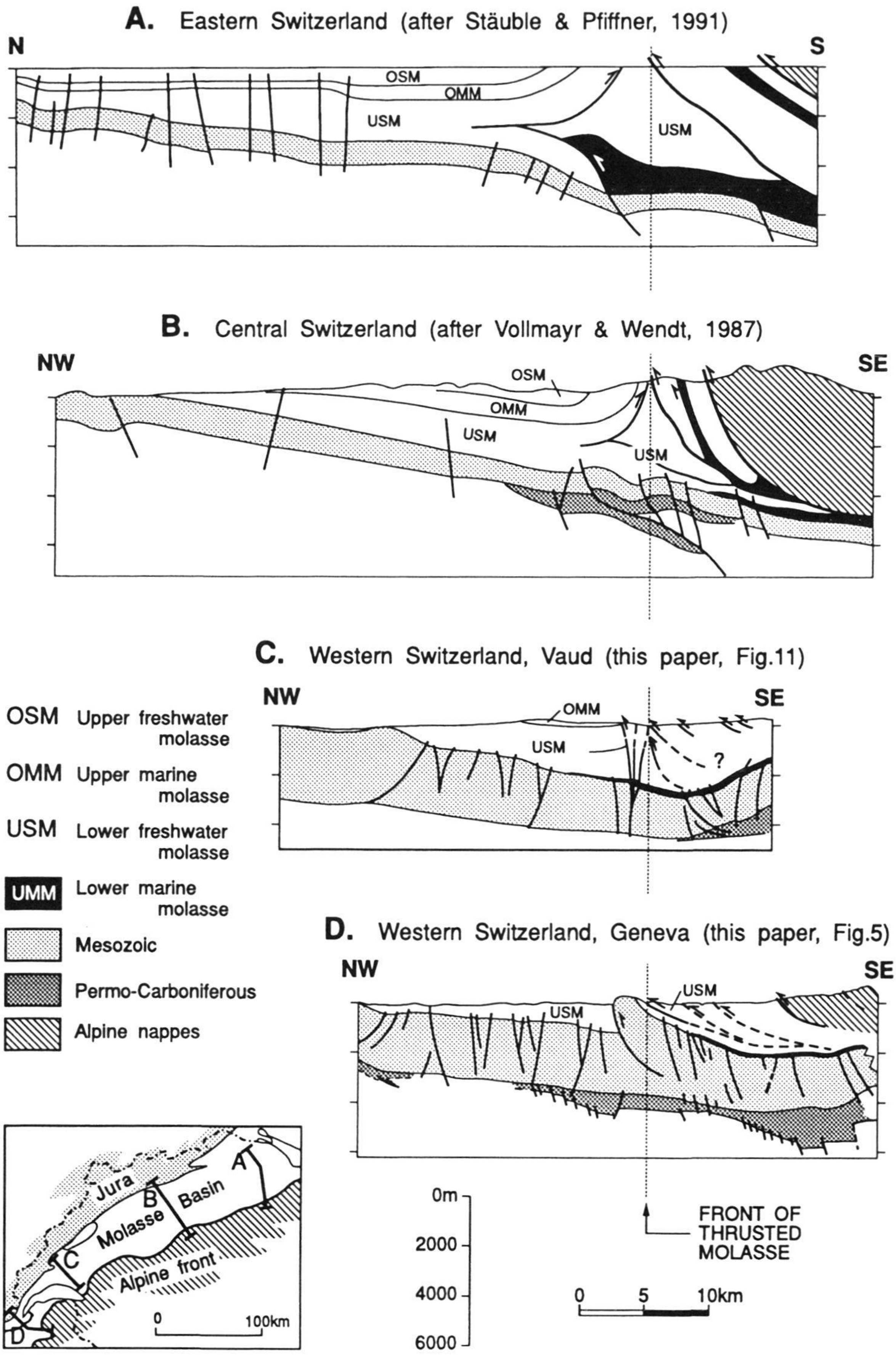
Comparisons between the Geneva and Vaud areas (Fig. 14)

The structural configuration of the Molasse Basin in both areas is similar.

The Plateau Molasse consists mainly of USM, thickening towards the southeast. Its Mesozoic substratum forms a monocline gently dipping southeastwards, which is progressively onlapped by the USM in a northwestward direction. This substratum is affected by significant wrench fault zones, which often display the configuration of flower structures (Figs. 6, 7 and 12). Such zones have already been described as cross-cutting the entire Molasse Basin (Rigassi in Matter et al. 1980). In the Geneva area, seismic data confirm the general NNW-SSE to N-S directions of these lineaments and demonstrate that their initiation predates the deposition of the Chattian (i.e. Late Oligocene) USM. One may possibly see here the imprint of an earlier Oligocene tectonic activity associated with the Rhine and Bresse grabens (Burkhard 1990); Rigassi (1977) also highlights the evidence of pre-Middle Eocene strike-slip movements along these basement faults. In both areas, some wrench zones appear as rejuvenated Permo-Carboniferous trends which are rooted in the basement. In the Geneva basin, local thickness variations in the Jurassic across some of these faults are another proof of rejuvenation (Signer 1992). Although the seismic resolution in the Molasse interval is often rather poor, some lines in the Geneva area show that these faults intersect the entire Tertiary interval (e.g. at the Humilly location, fig. 6): these strike-slip trends were therefore reactivated during the Miocene folding of the Jura Mountains, as postulated by Burkhard (1990).

Major SW-NE trending hinge zones seem to delineate the front of the Thrusted Molasse: in the Geneva area, this zone is marked by the Salève trend, and in Vaud by

Fig. 14. Regional cross-sections across the Swiss Molasse Basin based on reflection seismic data in Western Switzerland (this paper), Central Switzerland (Vollmayr & Wendt 1987) and Eastern Switzerland (Stäuble & Pfiffner 1991).


A. Eastern Switzerland (after Stäuble & Pfiffner, 1991)
N
S
OSM
OMM
USM
USM
B. Central Switzerland (after Vollmayr & Wendt, 1987)
NW
SE
OSM
OMM
USM
USM
C. Western Switzerland, Vaud (this paper, Fig.11)
NW
SE
OMM
USM
?
D. Western Switzerland, Geneva (this paper, Fig.5)
NW
SE
USM
USM
OSM Upper freshwater molasse
OMM Upper marine molasse
USM Lower freshwater molasse
UMM Lower marine molasse
Mesozoic
Permo-Carboniferous
Alpine nappes
Jura
Molasse
Basin
Alpine front
A
B
C
D
0
100km
0m
2000
4000
6000
FRONT OF THRUSTED MOLASSE
0
5
10km

a wrench zone which extends to the surface. These zones more or less coincide with the westward depositional pinch-out of the UMM and with the considerable southeastward thinning of the Lower and Middle Jurassic interval. In both areas, the hinge zones coincide with the uplifted northern margin of a deep-seated Permo-Carboniferous half-graben. These observations suggest that old SW-NE trending basement lineaments were rejuvenated at different times: they may have determined the Early and Middle Jurassic subsidence pattern, were reactivated in the Early Tertiary and defined the northern edge of the incipient UMM basin, and, finally, during the late Tertiary influenced the location of the Thrusted Molasse front. In the Thrusted Molasse domain, thickening of the Molasse sediments coincides in both areas with a thickening Permo-Carboniferous half-graben and, again, this may be the effect of Tertiary rejuvenation of Palaeozoic lineaments. Also in Northern Switzerland, reactivated older trends appear to have controlled the northern margin of the Molasse Basin (Sprecher & Müller 1986; Kempter 1992).

Although the purpose of this paper is not to embark on a general discussion of the Alpine foreland development, some of our seismic-based observations seem to contradict the hypothesis that the entire sedimentary sequence of the Molasse Basin was translated northwards by a few tens of kilometres during the folding of the Jura Mountains along a detachment level in the evaporitic Triassic series ("Fernschub" hypothesis of Laubscher 1961; Homewood et al. 1986; Burkhard 1990; Guellec et al. 1990). In the Geneva area, the incipient Salève trend, limiting the UMM basin to the west, predates UMM deposition and coincides with a basement high. On all seismic lines examined across the Plateau Molasse in Geneva and Vaud, there are absolutely no indications of north-verging thrust faults at the base of the thick Jurassic carbonate interval. It is mechanically difficult to conceive how such a mass of competent sediments may "glide" for tens of kilometres over an anisotropic surface without giving rise to compressional events or significant, halokinetically-induced deformations. Moreover, in both areas, steeply dipping faults, cutting through the entire Mesozoic sequence, are rooted in the Permo-Carboniferous sediments and possibly in the basement. Therefore, on this point, our interpretation tends to support the concept presented by Ziegler (1982, Fig. 26) for Central Switzerland. Other authors (e.g. Wegmann 1960 and 1961; Pavoni 1967 and Rigassi 1977) have used data from the Jura Mountains to argue against the "Fernschub" hypothesis.

Comparisons with Central and Eastern Switzerland (Fig. 14)

Schematic structural cross-sections across the Molasse Basin in Western, Central and Eastern Switzerland have been compiled by Rigassi (Fig. 16.10 in Homewood et al. 1990), some of which being probably partly based on informations derived from reflection seismic data. Nevertheless, for Central and Eastern Switzerland, only two detailed regional cross-sections based on reflection seismic profiles have been published in the past. These are given in figure 14 together with two of the cross-sections presented in this paper. Figure 14B shows a profile published by Vollmayr & Wendt (1987). It is calibrated by wells in the Molasse Basin and represents the latest update of cross-sections originally published by Trümpy (1980, Fig. 8) and Ziegler (1982, Fig. 26). Figure 14A gives the cross-section through Eastern Switzerland published by Stäuble & Pfiffner (1991). The tectonic evolution of the foreland basin in this area has been presented by Pfiffner (1986, Fig. 4).

All four cross-sections shown in figure 14 are in so far similar as they show a relatively undisturbed Plateau Molasse in the north, consisting mainly of northward onlapping USM, and a tectonically complex Thrusted Molasse in the south. The frontal zone of this Thrusted Molasse coincides more or less with the northern limit of the UMM basin, which overlies a much thinner Mesozoic interval than the USM further north. On all cross-sections, the boundary between the Plateau and Thrusted Molasse appears to coincide with a zone of important tectonic disturbances in the basement, which involves Permo-Carboniferous sediments in Central and Western Switzerland. In Eastern Switzerland (Pfiffner 1986, Fig. 4), basement faulting appears to delineate the northern limit of UMM deposits and the frontal zone of the Thrusted Molasse. Finally, as in Western Switzerland, there seems to be absolutely no indication of thrusting or halokinetic disturbances in the basal Mesozoic sequence underlying the Plateau Molasse in Central Switzerland (Vollmayr & Wendt 1987, Fig. 6). This seems to contradict the hypothesis of Burkhard (1990, Fig. 3) who postulates in the same area a major displacement of the Mesozoic cover over a decollement horizon in the Triassic.

Conclusions

Results of reflection seismic interpretations in the Cantons Geneva and Vaud have improved the understanding of the structural configuration of the Molasse Basin. Three major structural zones can be distinguished from the Jura Mountains in the north to the Alpine front in the south:

– The **Plateau Molasse** consists mainly of flat-lying USM onlapping northwards the erosional surface of the Mesozoic substratum, which gently dips towards the southeast. Therefore, basal USM sediments become older towards the Alpine front. The Plateau Molasse is cross-cut by important wrench fault trends, which often appear as rejuvenated Palaeozoic lineaments. In the Geneva area, some of these trends were already structured as marked, NNW-SSE oriented highs prior to the deposition of the Molasse series.

– **The transition zone between Plateau Molasse and Thrusted Molasse** seems to coincide with major SW-NE trending hinge lines. In the Geneva area, it is marked by the Mount Salève thrusted anticline, which overlies a basement high. East of Lausanne, it is characterized by a major wrench fault zone which affects the entire Mesozoic and Cenozoic series. These hinge zones are probably associated with Palaeozoic lineaments which were rejuvenated at different periods of time: during the Early and Middle Jurassic, they may have determined the regional subsidence and facies patterns; during the Early Tertiary, they delineated the northern termination of UMM deposits and during the Late Tertiary, they influenced the location of the Thrusted Molasse front. The spatial coincidence of these diachronous events in the foreland basin speaks against the hypothesis of a large-scale translation of the Mesozoic-Cenozoic cover over a Triassic decollement horizon during the Alpine orogeny. The absence of thrust faults as well as of halokinetic deformations at the base of the carbonate Mesozoic cover underlying the Plateau Molasse, and the presence of steep faults cutting the entire Mesozoic sequence and rooting apparently in the Permo-Carboniferous or the basement speak against the "Fernschub" hypothesis of Laubscher (1961).

– The **Thrusted Molasse**, which pinches out underneath the Alpine nappes, is marked by complex folding and thrusting involving USM and UMM. The Molasse Basin deepens up towards the Alpine front, where it overlies in both areas a thick Permo-Carboniferous half-graben.

These observations in Western Switzerland highlight the influence of Palaeozoic lineaments on the structural configuration of the Molasse Basin.

Comparison with the scarce published structural cross-sections derived from reflection seismic in the Molasse Basin of Central and Eastern Switzerland points to many similarities with the threefold structural subdivision established in Western Switzerland. Additional reflection seismic data are required to assess the validity of the "Fernschub" hypothesis or to refute its applicability to the deformation of the Molasse Basin.

Acknowledgements

The authors thank the following Institution and oil companies for authorizing the publication of the reflection seismic data illustrated in plates 1, 2 and 3: the Canton of Geneva (Pl. 1), Esso Rep (Pl. 1 &2), Société Nationale Elf Aquitaine (Production) (Pl. 1 and 2), Triton France (Pl. 2), RWE-DEA (Pl. 2), Coparex (Pl. 1) and Swisspetrol Holding SA (Pl. 3). The authors are indebted to P. A. Ziegler and E. H. K. Kempter for their very thorough review and to M. Weidmann for his critical comments. Their thanks also go to J. Metzger (Univ. of Geneva) for draughting part of the figures and to A. Baud (Geological Museum, Lausanne) for kindly providing the seismic data open to the public in Canton Vaud.

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Manuscript received 18 November 1992
Revision accepted 25 May 1993

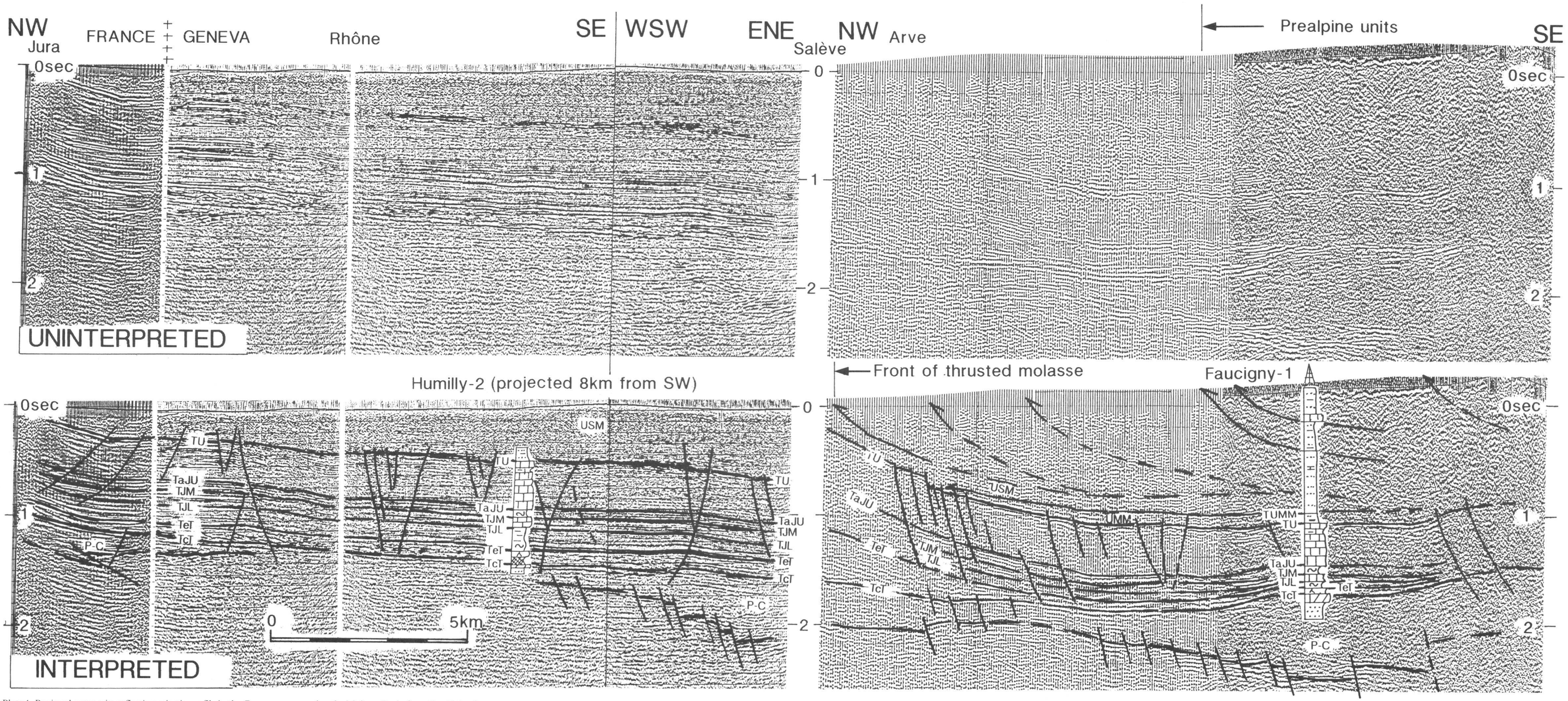

Plate 1. Regional composite reflection seismic profile in the Geneva area crossing the Molasse Basin from the Alpine front to the Jura Mountains. See Figs. 1 and 2 for location of profile and Fig. 5 for geological cross-section.
Seismic reflectors are tied with the wells Humilly-2 and Faucigny-1 (Figs. 3 and 4). They are abbreviated as follows: TcT = Top carbonate Triassic, TeT = Top evaporitic Triassic, TJL = Top Lower Jurassic, TJM = Top Middle Jurassic, TaJU = Top argillaceous Upper Jurassic, TU = Top Urgonian, TUMM = Top Lower Marine Molasse. The following abbreviations stand for sedimentary units: P-C = Permo-Carboniferous, UMM = Lower Marine Molasse, USM = Lower Freshwater Molasse.

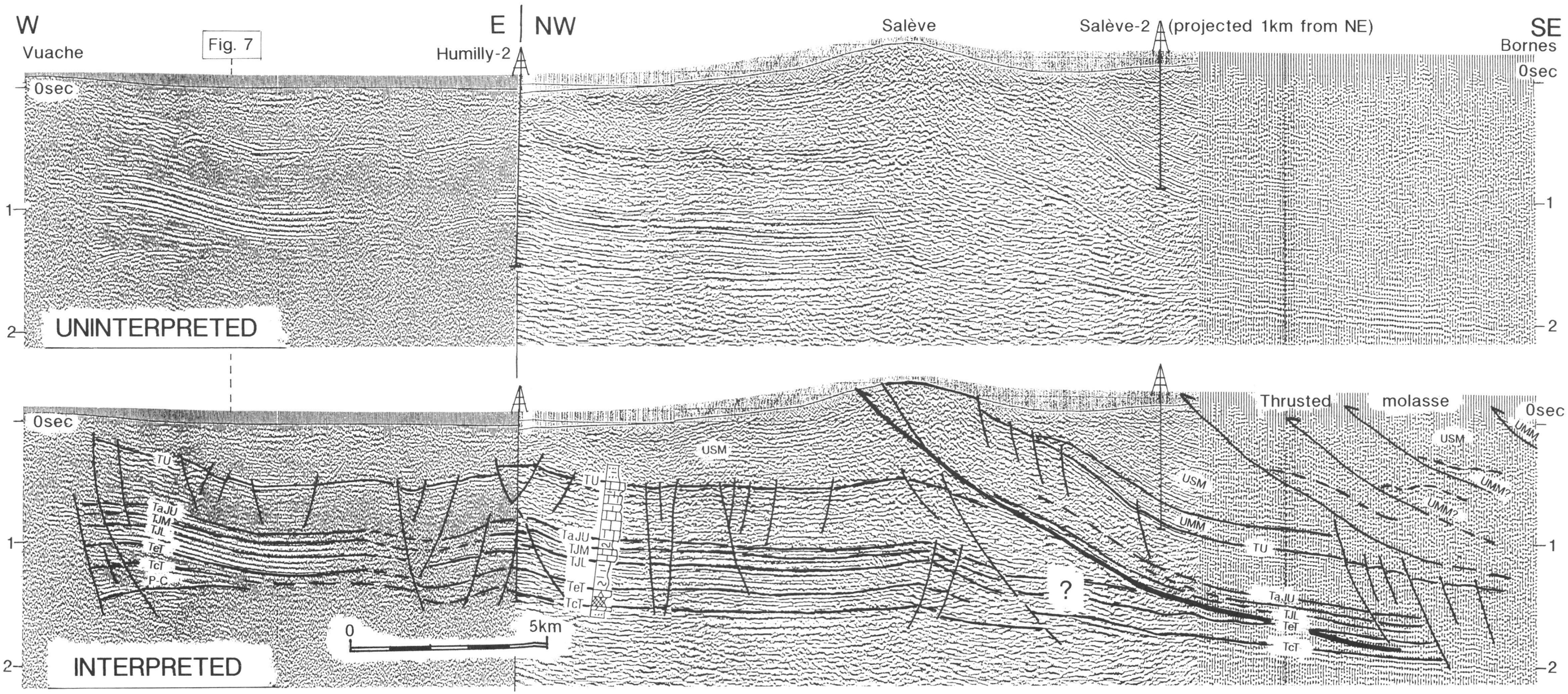

Plate 2. Regional composite reflection seismic profile in the Geneva area crossing the Molasse Basin from the front of the Subalpine Massifs to Mount Vuache. See Figs. 1 and 2 for location of profile and Fig. 6 for geological cross-section. Same abbreviations as on Plate 1. Reflectors are tied with the wells Humilly-2 and Salève-2.

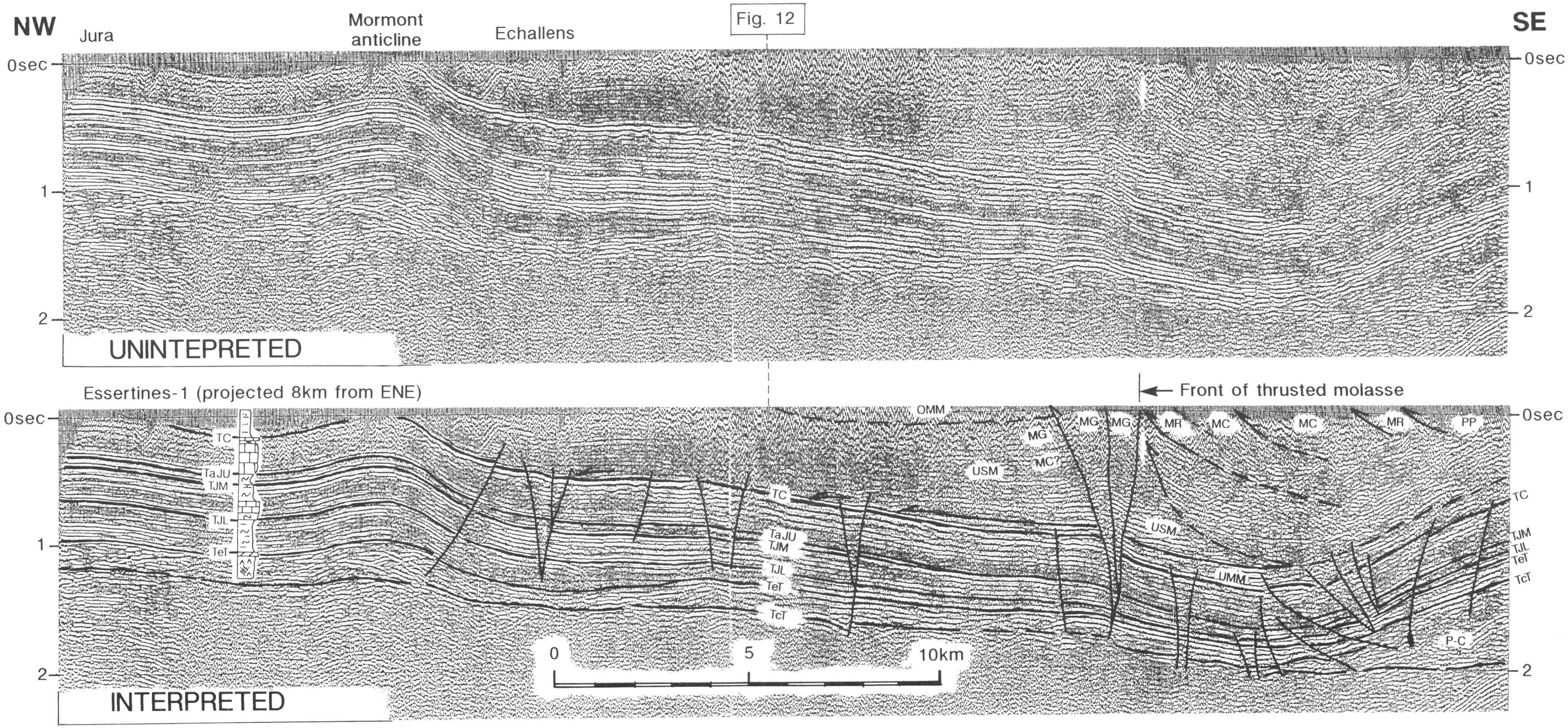

Plate 3. Reflection seismic profile in Canton Vaud crossing the Molasse Basin from the Alpine front to the Jura Mountains. See Fig. 8 for location of profile and Fig. 11 for geological cross-section.
Seismic reflectors are tied with the well Essertines-1 (Fig. 10) and abbbreviated as follows: TeT = Top evaporitic Triassic, TJL = Top Lower Jurassic, TJM = Top Middle Jurassic, TaJU = Top argillaceous Upper Jurassic, TC = Top Cretaceous. The reflector TcT = Top carbonate Triassic is interpreted by analogy with the Geneva area. The following abbreviations stand for sedimentary units: P-C = Permo-Carboniferous, UMM = Lower Marine Molasse, USM = Lower Freshwater Molasse, OMM = Upper Marine Molasse. In the thrusted USM, surface data of Fasel (1986) are integrated in the interpretation and the following stratigraphic units distinguished: MR = Molasse rouge, PP = Poudingues du Pélerin, MC = Molasse à charbon, MG = Molasse grise.