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New geological observations between the Jura and the Alps in the Geneva area, as derived from reflection seismic data

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Key words: Geneva, reflection seismic, seismic stratigraphy, tectonics

ABSTRACT

A total of 350 km reflection seismic records have been interpreted in the Geneva Basin and Bornes Plateau. Using boreholes as calibration points, 10 seismic markers can be readily identified from the Cenozoic to the Palaeozoic. This interpretation allows a correlation, across the study area, of tectonic and lithological observations derived from surrounding Mesozoic and Cenozoic outcrops. In addition, seismic interpretation of a Permo-Carboniferous sedimentary sequence permits the establishment of a schematic picture of top basement. Subsequently, the potential relationship between the Palaeozoic and Mesozoic-Cenozoic structural configuration of the area is analyzed.

The tectonic framework of the Geneva area is dominated by SW-NE and NW-SE trending Permo-Carboniferous lineaments, which were rejuvenated at different stages up to the present-day:

– SW-NE lineaments coincide with the front of the subalpine massifs, prealpine units and Salève thrust, and are marked by Permo-Carboniferous half-grabens. Sedimentary and tectonic evidence indicates a multiphrase reactivation of these trends, culminating with the late Alpine orogeny. The southernmost ridge of the Jura Mountains overlies an inverted SW-NE trending Permo-Carboniferous graben. These observations suggest that the deformation of the Jura Mountains is more likely to have originated from basement shortening than from the large-scale translation across the foreland basin of the Mesozoic-Cenozoic sequence over the Triassic evaporites.

– NW-SE lineaments linking the Jura Mountains and the Alpine front: interpreted for many years as wrench fault zones in the Mesozoic outcrops around Geneva, their subsurface continuation can now be traced with certainty, particularly that of the Vuache, Cruseilles and Le Coin wrench zones. Active from Permo-Carboniferous times up to now, they often form structural highs related to flower structures at Top Mesozoic level.

Besides these basement-related lineaments, the Geneva Basin shows SW-NE trending, low-relief, anticlinal and synclinal flexures in the Cenozoic and Mesozoic sequence. These are related to the late Alpine orogeny. The anticlinal structures form the characteristic molasse hills of the Geneva landscape.

Finally, this paper illustrates the contribution of seismic stratigraphy to a better understanding of both local tectonics and sedimentary facies distribution: for example, thickness variations in the Lower and Middle Jurassic and onlaps of the molasse onto the Mesozoic demonstrate the reactivation of basement trends; the recognition on seismic sections of sedimentary facies known in Jurassic outcrops of the Jura Mountains helps to refine palaeogeographical reconstructions.

RESUME

Un total de 350 km de données de sismique réflexion a été interprété dans le bassin genevois et le Plateau des Bornes. Après calibration avec des puits pétroliers, dix réflecteurs sismiques ont pu être identifiés de manière relativement continue dans un intervalle stratigraphique allant du Cénozoïque au Paléozoïque. Cette

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interprétation permet de corréler entre elles les informations tectoniques et lithologiques provenant des différents affleurements mésozoïques et cénozoïques environnants. De plus, l'identification d'une série sédimentaire permo-carbonifère aboutit à une carte schématique d'un niveau proche du sommet du socle: cela permet d'analyser la relation structurale potentielle existant entre le Paléozoïque et le Mésozoïque-Cénozoïque.

La tectonique de la région genevoise est dominée par l'existence de linéaments permo-carbonifères orientés SW-NE et NW-SE, qui ont rejoué à différentes périodes jusqu'à l'actuel:

– Les linéaments SW-NE coïncident avec le front des massifs subalpins, des unités préalpines et du chevauchement du Salève. Ils se marquent par des demis-grabens permo-carbonifères. Des arguments sédimentaires et tectoniques montrent qu'ils ont rejoué à plusieurs reprises, en particulier pendant l'orogenèse tardi-alpine. La première chaîne du Jura semble coïncider avec un graben permo-carbonifère inversé d'orientation SW-NE. Ces observations tendent à montrer que l'origine de la formation du Jura est plus probablement liée à un racourcissement du socle qu'à une translation à travers le bassin d'avant-pays de la couverture mésozoïque-cénozoïque sur un horizon de décollement dans les évaporites du Trias.

– Les linéaments NW-SE relient le Jura au front alpin: cartographiés depuis longtemps comme failles décrochantes dans les affleurements mésozoïques autour de Genève, ils peuvent maintenant être suivis avec certitude dans la subsurface, en particulier le décrochement du Vuache, de Cruseilles et du Coin. Actifs depuis le Permo-Carbonifère jusqu'à l'actuel, ils s'expriment le plus souvent par des culminations liées à des structures en fleur au niveau du sommet du Mésozoïque.

A part ces linéaments liés au socle, on observe également dans la série mésozoïque-cénozoïque du bassin genevois des flexures anticlinales et synclinales, orientées SW-NE et de faible amplitude; elles semblent liées à l'orogenèse tardialpine. Les coteaux molassiques typiques de la cuvette genevoise correspondent à ces structures anticlinales.

Finalement, ce travail donne plusieurs exemples de la contribution de la stratigraphie sismique à une meilleure connaissance de la tectonique locale et de la distribution de certains faciès sédimentaires: les variations d'épaisseur dans le Jurassique moyen et supérieur et les onlaps de la molasse sur le Mésozoïque sont des preuves du rejeu des linéaments du socle, tandis que l'identification sur la sismique de faciès sédimentaires connus dans les affleurements du Jurassique moyen et supérieur du Jura améliore la connaissance paléogéographique de ces intervalles.

Introduction

The area covered by this study is the westernmost part of the Swiss Molasse Basin in the greater Geneva area. It is limited to the northwest by the Jura Mountains, to the west by Mount Vuache and to the southeast by the frontal thrust of the subalpine massifs (Fig. 1). The Molasse Basin is subdivided into two parts by the Salève ridge: the Geneva basin and the Bornes Plateau (Fig. 1).

Reflection seismic data in this area have been shot in French territory mainly by the petroleum industry since 1966, and in the Swiss part by the Canton of Geneva. Much of these data have been used in this study, i.e. 43 seismic profiles which total some 350 km of records (Fig. 2). Deep seismic data of the ECORS program (Guellec et al. 1990, Deville et al. 1994) shot across the investigated area do not significantly contribute to this study, because of insufficient resolution at shallow depths when compared with petroleum seismic data.

This paper presents the main results of a diploma thesis carried out at the University of Geneva (Signer 1992, Gorin & Signer 1994). Its purpose is to illustrate in more detail some of the results of Gorin et al. (1993), who presented some regional profiles based on the same seismic data set in the greater Geneva area. Special attention will be given to the structural framework, in relation to the major transcurrent tectonic accidents known in the Jura Mountains, Mount Vuache and Mount Salève (Fig. 1). Seismic stratigraphic observations in the Palaeozoic, Mesozoic and Cenozoic will also be locally highlighted.

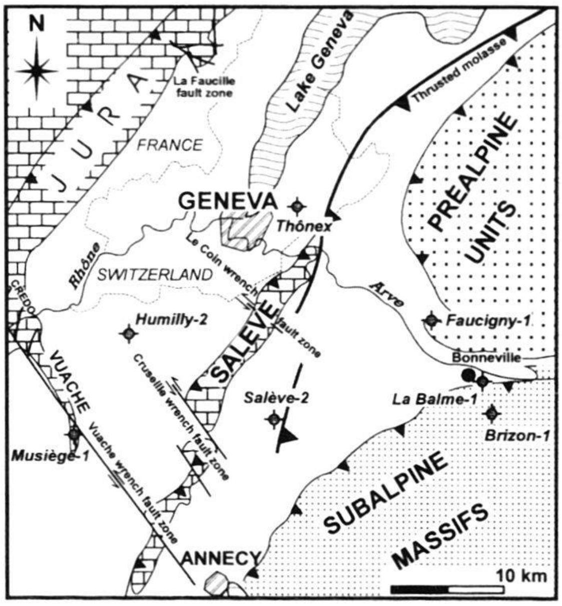


Fig. 1. Location map and tectonic framework of the greater Geneva area.

Geological framework and data (see also Gorin et al. 1993)

The area under study extends from the most internal range of the Jura Mountains in the northwest (called «High Chain», Wildi et al. 1991) to the Alpine front in the southeast (Fig. 1). Tectonically, this area is limited to the southwest by a major sinistral wrench fault zone (the Vuache-Forens-les Bouchoux tectonic zone, Wildi et al. 1991), along which transpressional movements have given rise to Mount Vuache (Blondel et al. 1988) and its northern continuation (Mount Crédo, Guyonnet 1988). Further to the east, other wrench fault zones are known from outcrops in Mount Salève and the Jura Mountains (Fig. 1). This study will attempt to confirm their continuity in the subsurface across the Bornes Plateau and the Geneva basin.

Lithological and stratigraphic control is provided both by outcrop data from the surrounding mountains and by boreholes in the Geneva basin and the Bornes Plateau (Fig. 1, 4). Data of the Permo-Carboniferous and Triassic intervals are provided by two deep wells, Humilly-2 (SNPA 1970) in the Geneva basin and Faucigny-1 (Esso Rep 1970) to the northeast of the Bornes Plateau (Fig. 2). The Mesozoic interval is well recorded from outcrops in the Jura Mountains (Charollais & Badoux 1990), in Mount Crédo (Guyonnet 1988), in Mount Vuache (Blondel 1984 und 1990), in Mount Salève (Deville 1990) and in the Bornes Massif (Charollais & Lombard 1966). The sequence has been fully penetrated by the wells Humilly-2 and Faucigny-1 and partly by the wells Brizon-1 (Eurafrep 1987; Charollais & Jamet 1990), La Balme-1 (Coparex 1990), Musiège-1 (PREPA 1962) and Thônex (drilled for geothermal exploration by the Canton of Geneva in 1993). Out of the six shallow coreholes (Gex-1 to -6) drilled by BP in 1982 near the Swiss border in the Geneva basin (Fig. 2), five reached Top Urgonian and provide a good tie for the nearby seismic profiles. In the Bornes Plateau, the well Salève-2 (PREPA 1960) also reached Top Urgonian (Fig. 2). The Tertiary molasse sequence is known both from the wells mentioned above and from outcrops in the Bornes Plateau and Geneva basin. Molasse deposits in the Bornes Plateau consist of both Lower Marine Molasse (UMM, of Early Oligocene age, Charollais 1988) and Lower Freshwater Molasse (USM, of Early to Late Oligocene age, its lower part being clearly older than that of the USM in the Geneva basin, Charollais et al. 1981, Berger et al. 1987). Molasse sediments in the Geneva basin solely contain USM and range from Late Oligocene to Early Miocene.

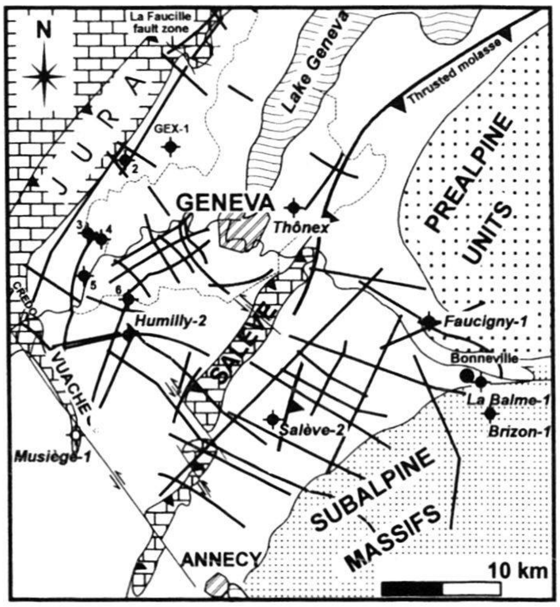


Fig. 2. Seismic and well location map.

		Seismic marker	WELL Humilly-2	WELL Faucigny
TERTIARY	Molasse		3450	4200
		TU		
LOWER CRETACEOUS	Barremian (Urgonian)		5400	6100
		THa		
	Hauterivian		4750	5800
		TVa		
	Valanginian		5900	6100
	Berriasian			
MALM	Portlandian			6200
		NTKi		
	Kimmeridgian		5100	6100
	Oxfordian			6000
		JSmc		
DOGGER	Callovian		5050	5100
		TJM		
	Bathonian		4950	4650
	Bajocian			
	Aalénian			
		NTJI		
LIAS			4450	5050
TRIASSIC	Rhétian			
		NTR		
	Keuper		Anhydrite: 5800 Salt: 4950	5500
		TRM		
	Muschelkalk		5500	6200
		TC		
	Permo-Carb.			5100

Fig. 3. Seismic interval velocities (in metres/sec.) of wells Humilly-2 and Faucigny-1 (derived from sonic logs).
Abbreviations of seismic markers stand for: TU = Top Urgonian, THa = Top Hauterivian, TVa = Top Valanginian, NTKi = Near Top Kimmeridgian, JSmc = Top argillaceous Upper Jurassic, TJM = Near Top Middle Jurassic, NTJI = Near Top Lower Jurassic, NTR = Near Top Triassic, TRM = Top Middle Triassic, TC = Top Carboniferous.

Calibration of seismic data

Seismic interval velocities were derived from the Humilly-2 and Faucigny-1 sonic logs (Fig. 3), as well as from variations in stacking velocities. Synthetic seismograms of wells Humilly-2 (Fig. 5) and Faucigny-1 (Fig. 6) were used to calibrate seismic data. Figure 5 shows the correlation between a seismic profile in the Canton of Geneva and the synthetic seismogram of Humilly-2. Calibration of reflectors is discussed below.

In the **Molasse** interval of the Geneva Basin, seismic reflectors are usually of poor quality or fairly discontinuous, mainly because of the continental, often discontinuous nature of the USM sediments. Only locally do they show a good continuity, which may have a palaeogeographical significance (see below and Fig. 16). Near the Alpine front, a seismic sequence attributed to the UMM can be distinguished by correlation with the wells Faucigny-1 (Fig. 6) and Salève-2 (see Fig. 16, 17).

In the **Mesozoic** interval, lithological variations are expressed by a succession of well-defined reflectors (Fig. 5, 6). Top Mesozoic (= Top Urgonian) is normally a high-amplitude horizon corresponding to a high acoustic impedance between Tertiary siliciclastics and massive Urgonian limestones. The continuity of this seismic marker may locally be disturbed by karstification (Fig. 16, 17). Top Hauterivian, often less than 50 milliseconds deeper than Top Urgonian, may be difficult to interpret, because it may be obscured by

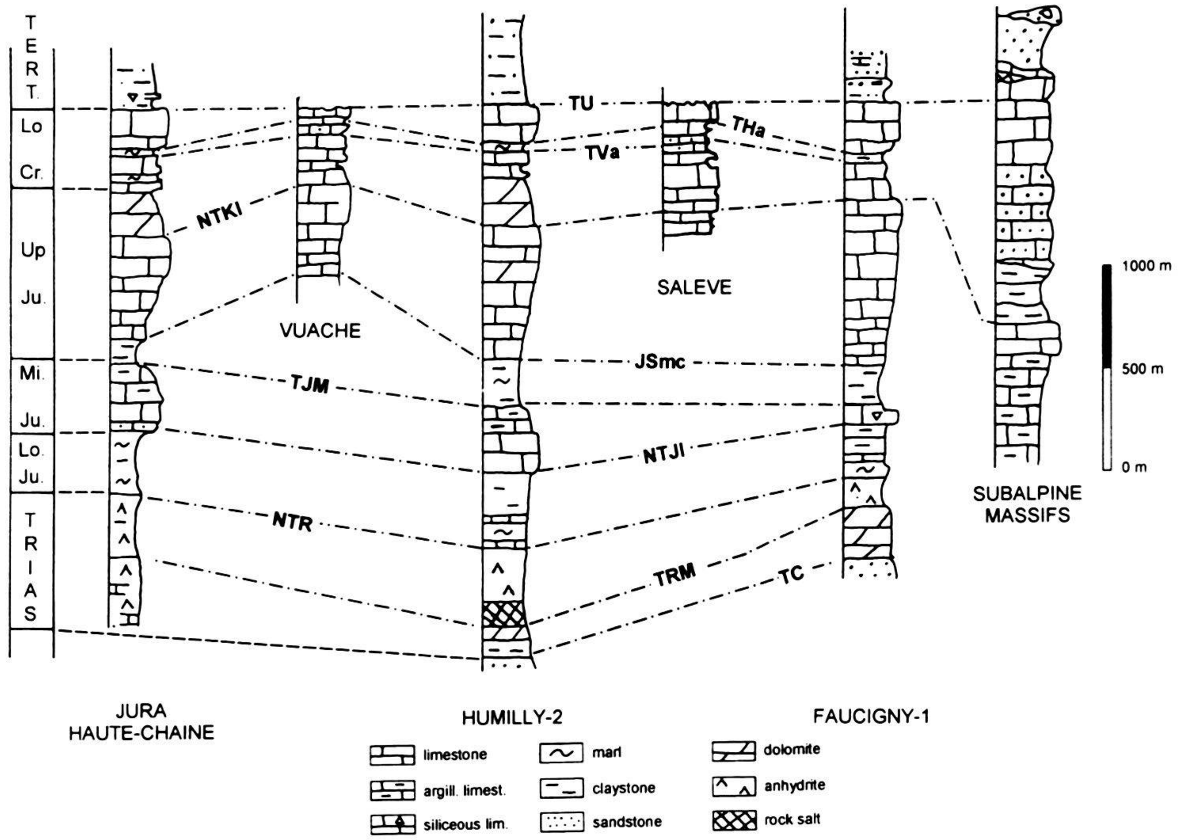


Fig. 4. Regional lithostratigraphic correlation from the Jura Mountains to the subalpine massifs. For abbreviations of seismic markers, see caption of figure 3.

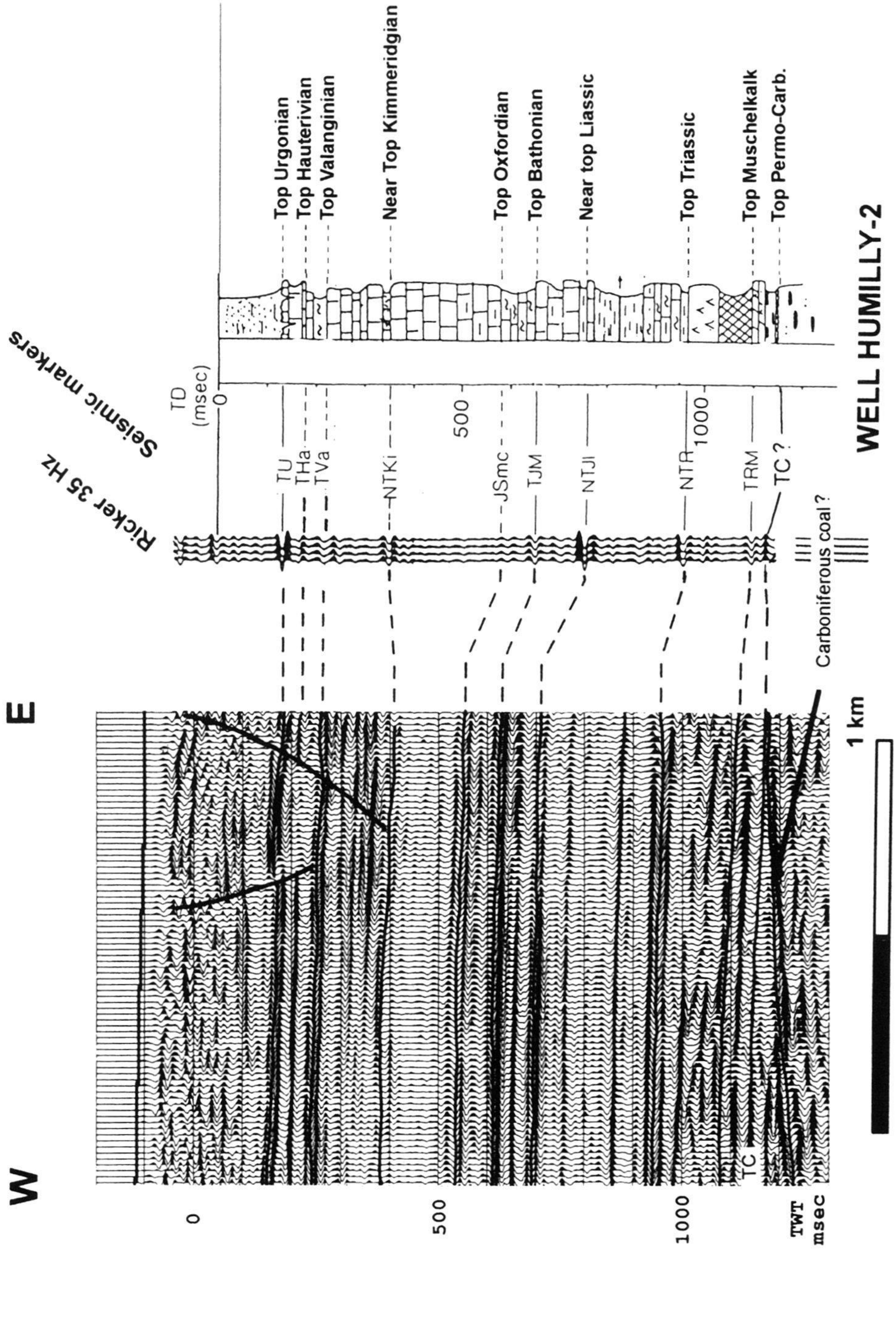
the doublet created by the strong Cenozoic-Mesozoic interface. Top Valanginian is expressed by another doublet very close to that of Top Urgonian, which originates from the interface between the "Marnes d'Hauterive" and the "Calcaire Roux" (see Blondel 1990 and Deville 1990). Consequently, more than one reflector may be interpreted in the Lower Cretaceous section, when reflector continuity is not affected by fractures and faults or by karstification at Top Urgonian level.

At the Jurassic-Cretaceous boundary, no significant density variation is noted resulting in the lack of a good seismic reflector (Fig. 5, 6). The same applies for the Kimmeridgian-Portlandian transition. In the Upper Kimmeridgian the base of a reefal limestone interval is locally reflective (near Top Kimmeridgian, Fig. 5). The seismically transparent Upper Jurassic section is interrupted by the ca. 20 milliseconds thick reflective interval of the Oxfordian "Effingerschichten" (Wildi et al. 1991) composed of an alternation of marls and lithographic limestones. Below, the Top Middle Jurassic is expressed by a high-amplitude, positive loop, which marks the sharp transition to massive Middle Jurassic limestones. The base Middle Jurassic is difficult to pick, because there is a progressive transition from sandy, micaceous Aalenian to argillaceous-marly Lower Jurassic. The Lower Jurassic consists of an argillaceous-marly upper sequence grading progressively into a marly-calcareous lower interval. This sequence is usually seismically transparent, although, locally, the top of the lower interval may be expressed by a low-amplitude reflector.

Near the top of the Triassic, a high-amplitude, positive reflector indicates the transition between Rhaetian clays and Keuper evaporites (Fig. 5). This reflector is fairly continuous, as the upper part of the Keuper consists of a relatively homogeneous anhydritic interval (Fig. 4). The seismic facies of the Keuper evaporites is characterized by discontinuous reflectors, which locally show ondulations probably related to minor halokinetic movements in the lower halite section. The base of the Keuper evaporites correspond to a continuous reflector induced by the transition to Muschelkalk dolomites. The Buntsandstein sequence is too thin to be seismically interpreted.

Both Humilly-2 and Faucigny-1 reached total depth in **Permian** sandstones characterized by a transparent seismic facies. This sequence is often underlain by an interval marked by high-amplitude, frequently discontinuous, negative reflections interpreted as coal-bearing **Carboniferous** sediments (Gorin et al. 1993). When this reflective sequence comes close to the Muschelkalk, it highlights the angular unconformity between Triassic and Permo-Carboniferous sediments (Fig. 5). Cristalline basement can be tentatively interpreted as corresponding to the transparent to chaotic seismic facies locally visible below the reflective Carboniferous. Nevertheless, this facies is often obscured by multiples and diffraction phenomena (Fig. 9 to 12). Both the tentative structural map of basement (Fig. 7) and the tentative Near Top Basement horizon on the geological cross-section of figure 8 use the base of the reflective Carboniferous sequence as a guide.

Fig. 5. Synthetic seismogram of well Humilly-2 (modified from Gorin et al. 1993) and tie of seismic reflectors with the nearest NW-SE running seismic line in Canton Geneva (see Fig. 2). For abbreviations of seismic markers, see caption of figure 3.


W
E
0
500
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TWT msec
TC
1 km
Ricker 35 Hz
Seismic markers
TD (msec)
0
500
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TU
THa
TVa
NTKi
JSmc
TJM
NTJl
NTR
TRM
TC ?
Carboniferous coal ?
Top Urgonian
Top Hauterivian
Top Valanginian
Near Top Kimmeridgian
Top Oxfordian
Top Bathonian
Near top Liassic
Top Triassic
Top Muschelkalk
Top Permo-Carb.
WELL HUMILLY-2

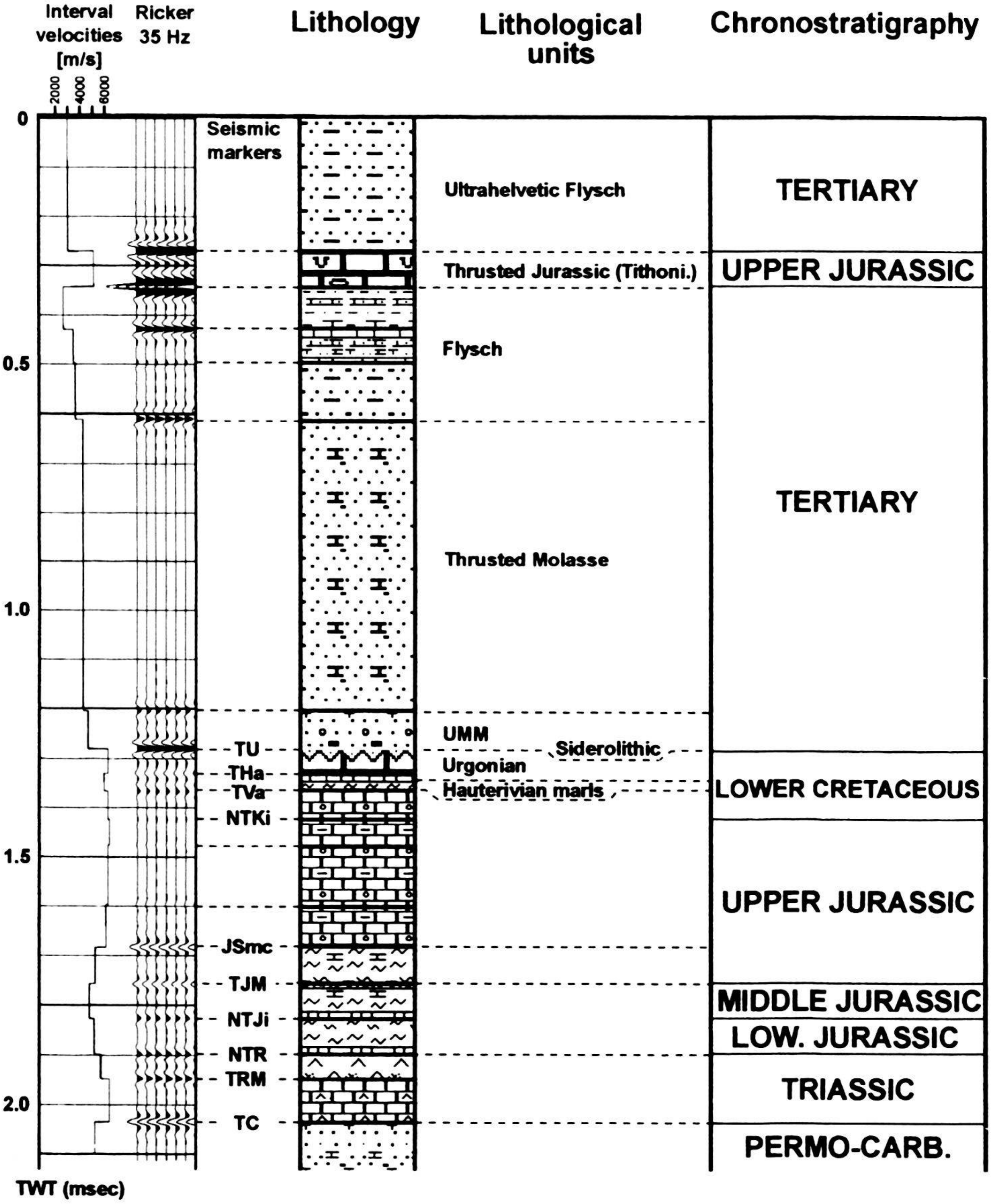


Fig. 6. Synthetic seismogram of well Faucigny-1 (based on sonic log only). For abbreviations of seismic markers, see caption of figure 3.

Results and discussion

Structural and seismic stratigraphic observations derived from reflection seismic data are discussed below for two stratigraphical intervals, i.e. the basement and Permo-Carboniferous sequence and the Mesozoic-Cenozoic sequence. The former sequence is not as well

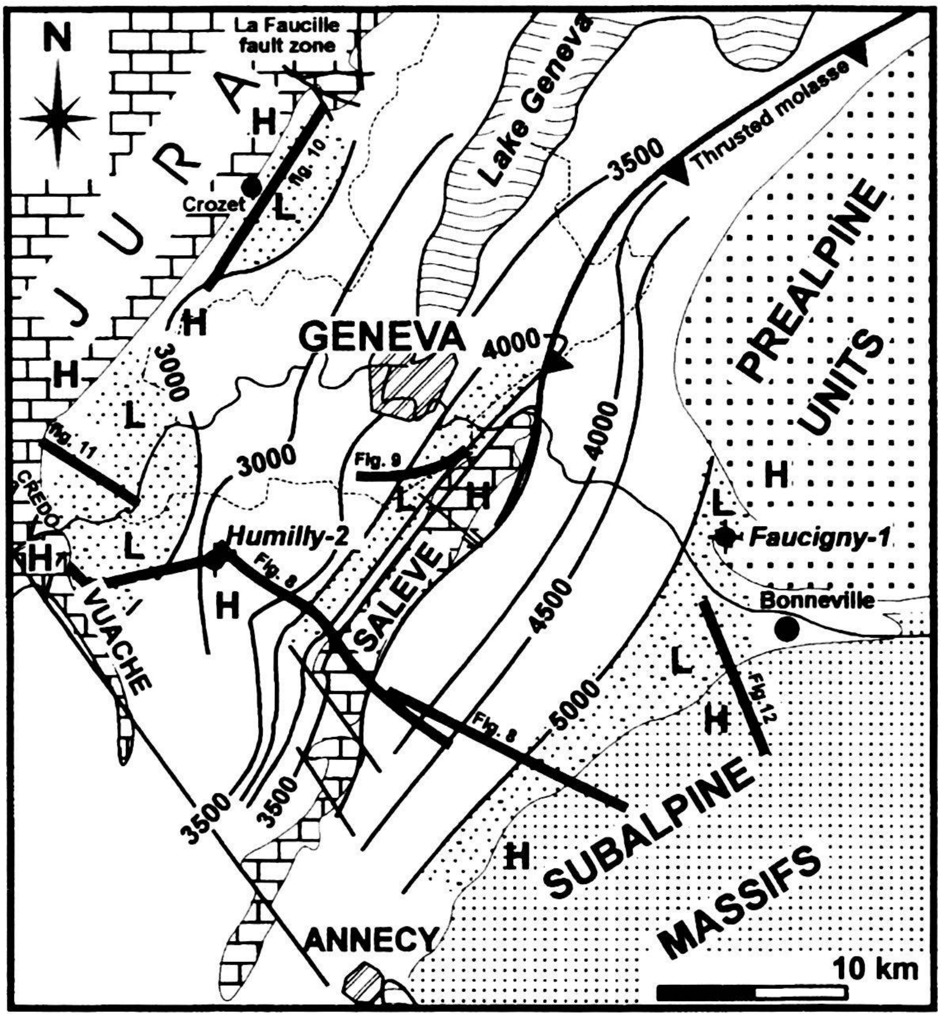


Fig. 7. Tentative structural map of basement and Permo-Carboniferous and location map of figures 8 to 12. Contours (in metres bmsl) correspond to a tentative horizon (called "Near Top Basement") drawn at the base of the reflective coal-bearing Permo-Carboniferous and depth converted using velocities of Humilly 2 and Faucigny-1. **L** and **H** indicate respectively basement lows (thick Permo-Carboniferous) and highs (thin Permo-Carboniferous). Basement lows correspond mainly to SW-NE trending Permo-Carboniferous half-grabens.

documented as the latter, because of poorer seismic resolution. Observations are illustrated by seismic sections, maps and a geological profile derived from seismic data. Seismic stratigraphic observations are very frequently local and difficult to be spatially translated onto a map, because the seismic grid is not tight enough.

Basement and Permo-Carboniferous: structural observations (see map, Fig. 7)

Figure 7 is a tentative Near Top Basement map, indicating the approximate base of the reflective coal-bearing Permo-Carboniferous (see above). Depths are tentatively derived from the velocities of Humilly-2 and Faucigny-1 and should be used only for guidance. Exact positioning of faults at this stratigraphic level is difficult and their interpretation on illustrated sections should often be considered as tentative. What is significant is the existence of structural lows and highs clearly evidenced on many sections by the position of the reflective Permo-Carboniferous sequence. Basement and Permo-Carboniferous structural configuration is further illustrated by a geological cross-section (Fig. 8, modified from Gorin et al. 1993) and by seismic profiles (Fig. 9 to 12).

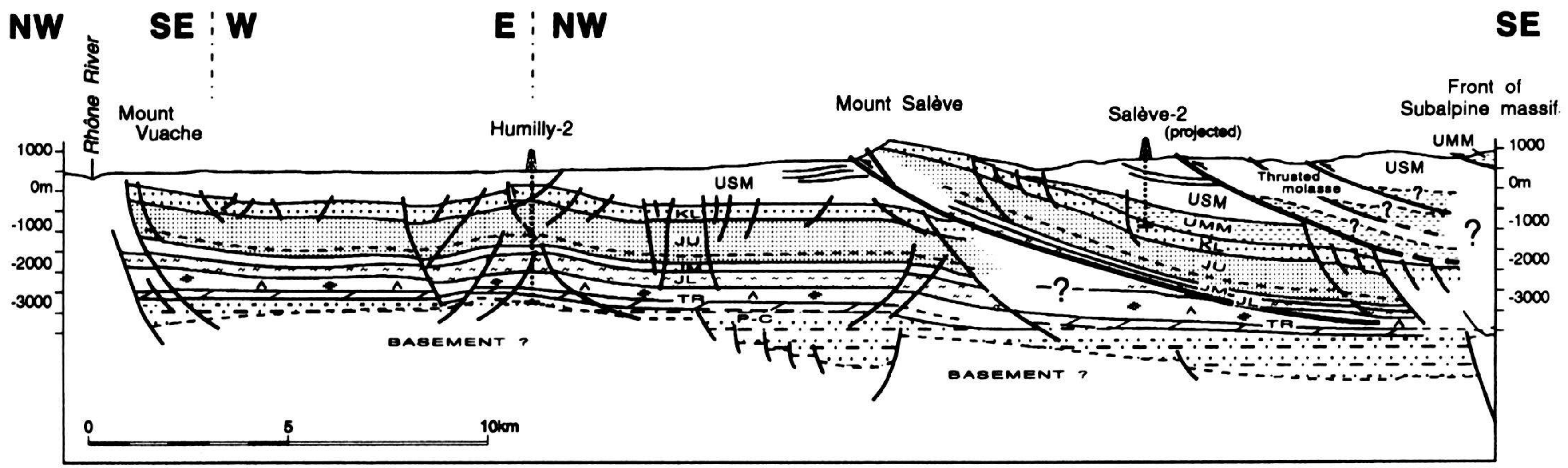


Fig. 8. Regional geological cross-section (see location on Fig. 7) derived from seismic data (modified from Gorin et al. 1993). Stratigraphic/lithological intervals as follows: P-C = Permo-Carboniferous, TR = Triassic, JL = Lower Jurassic, JM = Middle Jurassic, JU = Upper Jurassic, KL = Lower Cretaceous, UMM = Lower Marine Molasse, USM = Lower Freshwater Molasse.

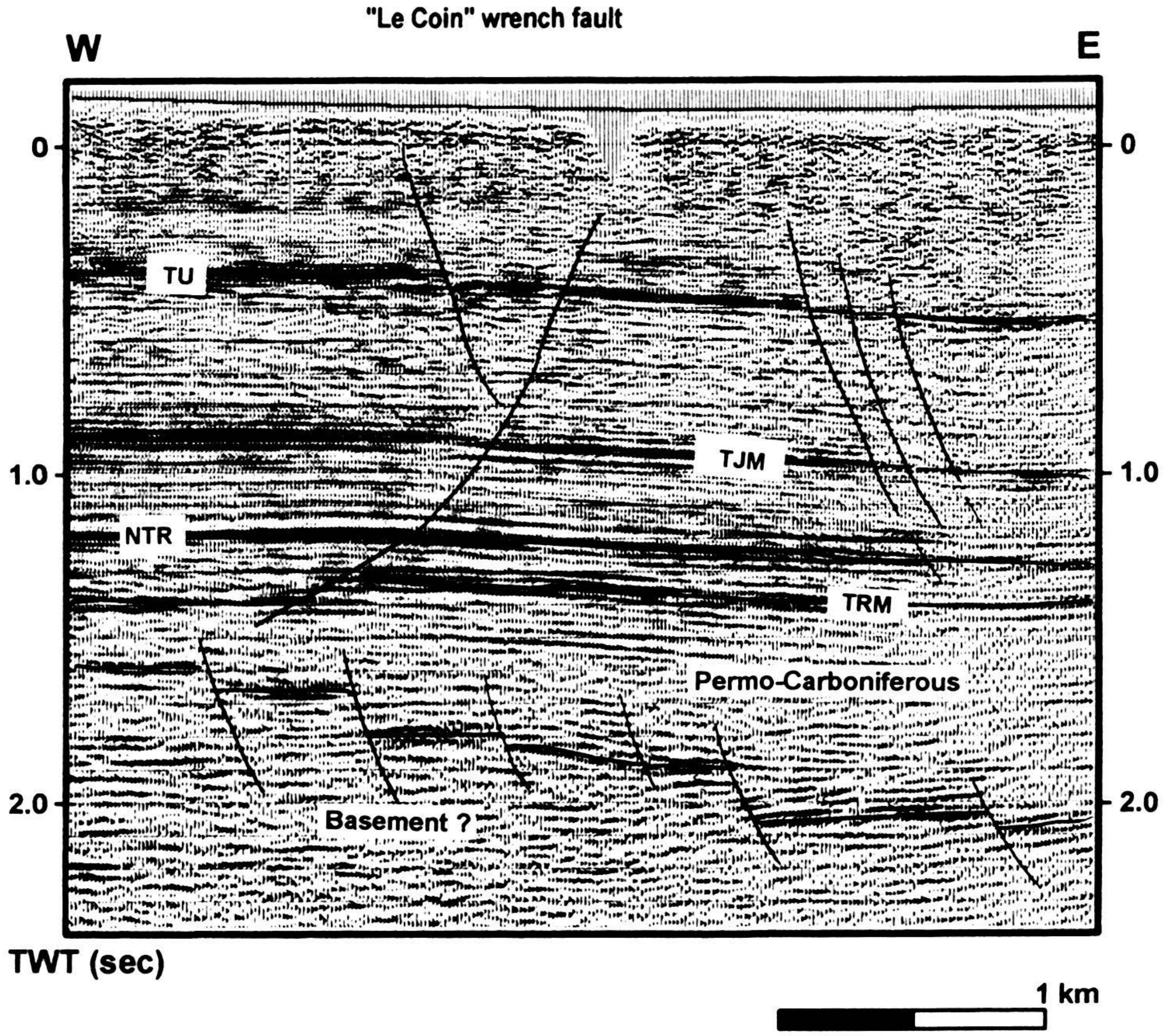


Fig. 9. Migrated seismic line in the Geneva Basin at the front of Mount Salève (see location on Fig. 7). This illustrates the subsurface continuation of "the Coin" wrench fault zone observed in Mount Salève: faulting in the Mesozoic-Cenozoic section overlies deep-seated Palaeozoic-basement faults. For abbreviations of seismic reflectors, see caption of figure 3.

In the **Geneva Basin**, basement exhibits a general southeasterly dip, down to the front of the Salève ridge, where it underlies a SW-NE trending Permo-Carboniferous half-graben with a depth greater than 4,000 metres (Fig. 8). The basement high underlying the Salève thrusted anticline (Gorin et al. 1993) determines the southern limit of this half-graben, the transition being marked by a succession of normal faults downthrowing to the north. The wrench fault zone of "Le Coin" observed in the Mesozoic outcrops of Mount Salève (see below) appears to line up with some of these basement faults observed on seismic data at the front of the Salève (Fig. 9). Similarly, the northern continuation of Le Coin wrench zone at the foot of the Jura seems also associated with tectonic disturbances at the Permo-Carboniferous level in the Crozet area (Fig. 10).

The eastern flank of Mount Vuache overlies a normal basement fault, downthrowing to the east to form a Permo-Carboniferous half-graben (Fig. 8). This basement faulting is associated with the Vuache wrench fault zone, expressed as a flower structure in Mount Grand-Crédo to the north (Guyonnet 1988, Wildi et al. 1991, Wildi & Huggenberger 1993) and overlying an abnormally high basement-involved structure (Roure et al. 1994). The over 3,000 metres-deep Permo-Carbonierous basin associated with this basement faulting (Fig. 7) underlies the Mesozoic basin lying between the Vuache and Cruseilles wrench fault zones (see Fig. 13 and text below). Both wrench zones correspond to NW-SE trending basement highs (Fig. 7, 8), which are also expressed at Mesozoic level (see Fig. 13 and text below). East of the Grand Crédo, at the southern limit of the Jura High Chain, a northwestard thickening of the Permo-Carboniferous sequence can be observed on all studied dip lines (e.g. Fig. 11) and suggests the existence of a SW-NE trending graben (Fig. 7). This Late Palaeozoic basin, bounded southwards by basement-involved reverse faults, appears to be inverted (Fig. 11). Although none of the dip lines available continue far enough to the northwest to give structural information beneath the Jura High Chain, this basin inversion may be compared with the observations of Philippe (1994) further west: based on ECORS data, this author interprets the observed Mesozoic backthrust in the Oyonnax area as resulting from the inversion, during the Alpine compressional phase, of an underlying Permo-Carboniferous basin along a reactivated SW-NE trending Variscan fault. His profile (Fig. 18 of Philippe 1994) also suggests the existence of a Late Palaeozoic basin east of the High Chain, which would correspond to that interpreted in figure 11. Inverted Permo-Carboniferous grabens are also suspected to underlie the major Jura folds further east (Pfiffner 1994).

The structural configuration of the basement and Permo-Carboniferous underneath the **Bornes Plateau** resembles that of the Geneva basin. A SW-NE trending Permo-Carboniferous half-graben dips southeasterly towards the front of the subalpine Bornes Massif (Fig. 7, 8). The frontal thrust of this Massif overlies a major basement fault zone downthrowing to the northwest, which delineates the Permo-Carboniferous half-graben (Fig. 12, modified from Charollais & Jamet 1990). Basement rises progressively northwestwards to form the high underlying Mount Salève (Fig. 7, 8). A similar configuration is observed north of the Arve River, where a major basement fault zone downthrowing to the northwest underlies the Alpine front and opens up a Permo-Carboniferous half-graben pinching-out towards Mount Salève (see Fig. 5 and Plate 1 of Gorin et al. 1993). Less than ten kilometres north of the surface termination of the Salève, a possible continuation of this basement high may be observed in figures 16 and 17, where faults downthrow the Permo-Carboniferous to the west (see below).

Basement and Permo-Carboniferous: seismic stratigraphic observations

As mentioned above (calibration of reflectors), the only significant reflectors in this sequence are the high amplitude ones attributed to coal-bearing Carboniferous sediments, which underlie fairly transparent Permo-Carboniferous sandstones (Fig. 9 to 12). When the high-amplitude reflectors come close to the Muschelkalk, they often highlight an angular unconformity with the overlying Triassic (Fig. 5, 14, 16, 17) and indicate the presence of basement highs (see Fig. 7). Truncations of low-amplitude reflectors in the sand-

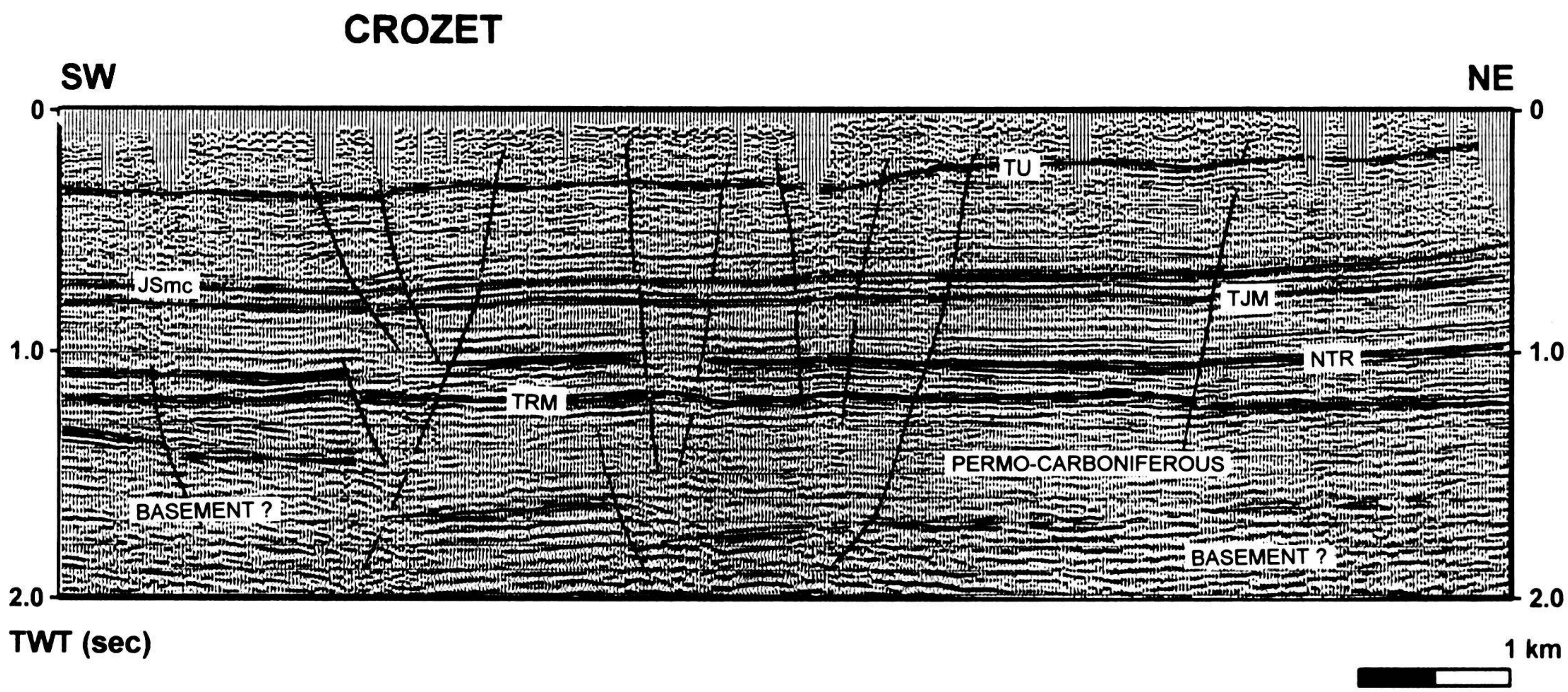


Fig. 10. Unmigrated seismic line in the Geneva Basin running subparallel to the Jura Mountains (see location on Fig. 7). Mesozoic-Cenozoic faulting in the Crozet area is interpreted as the northern continuation of "the Coin" wrench fault zone. Similarly to figure 9, these faults overlie older Palaeozoic-basement faults. For abbreviations of seismic reflectors, see caption of figure 3.

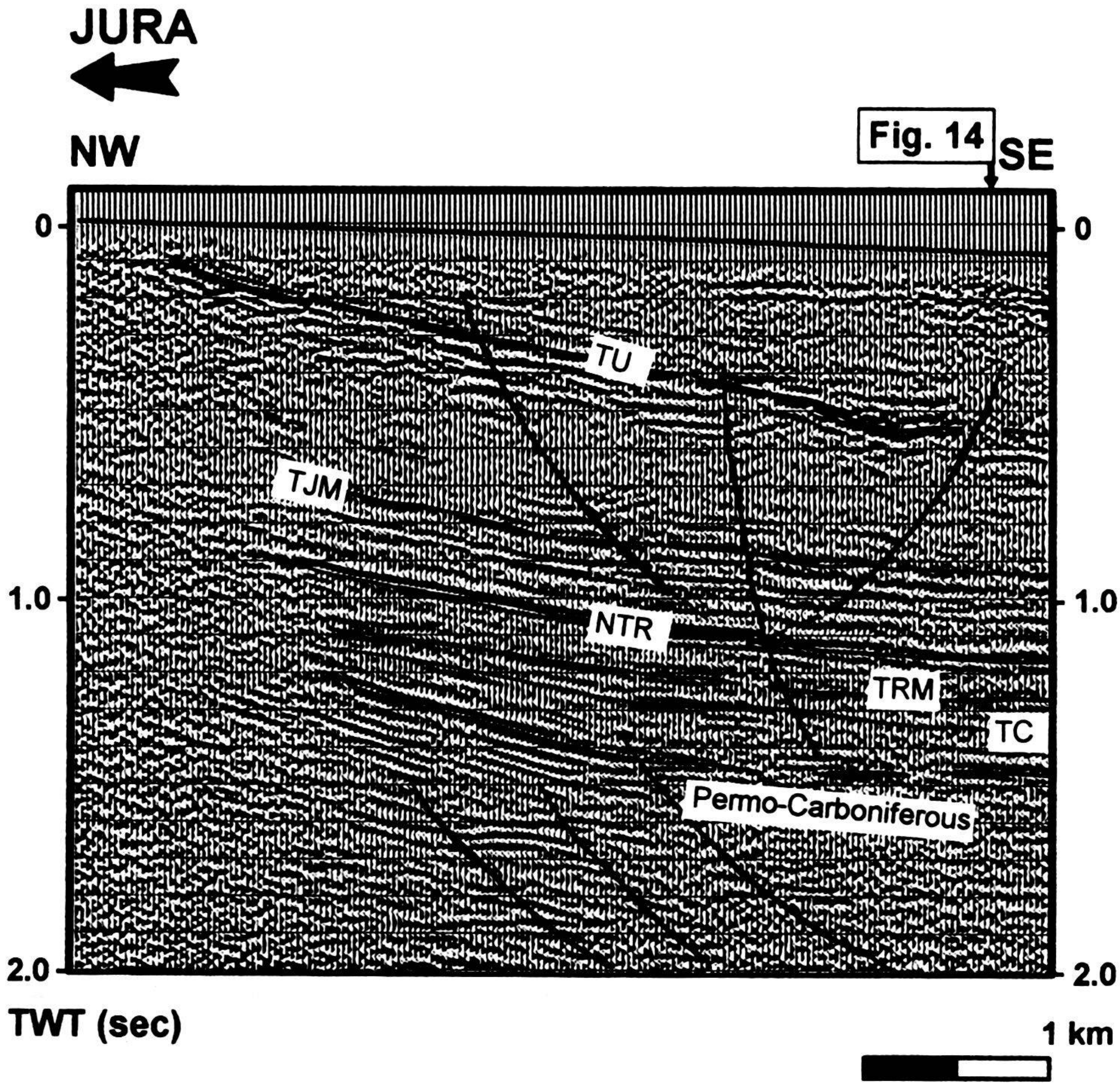


Fig. 11. Unmigrated seismic line in the western part of the Geneva Basin running northwestwards towards the foot of the Jura Mountains (see location on Fig. 7). The Permo-Carboniferous basin is affected by reverse faults and the Mesozoic-Cenozoic by backthrusting faults, both originating from the compressive late Alpine tectonic phase. Similar faulting can be observed at other locations along the Jura Mountains. For abbreviations of seismic reflectors, see caption of figure 3.

stone section may be observed (Fig. 5, 16, 17), locally permitting a more precise seismic identification of the top Permo-Carboniferous unconformity.

Mesozoic and Cenozoic: structural observations (see map, Fig. 13)

The map of figure 13 summarizes the main structural observations and interpretations presented in this chapter, which are further illustrated by seismic profiles (Fig. 14 to 17 located on Fig. 13) and schematic isopach maps (Fig. 19, 20). For the sake of clarity, no depth contours of any horizon have been added to figure 13. A depth map of the Meso-

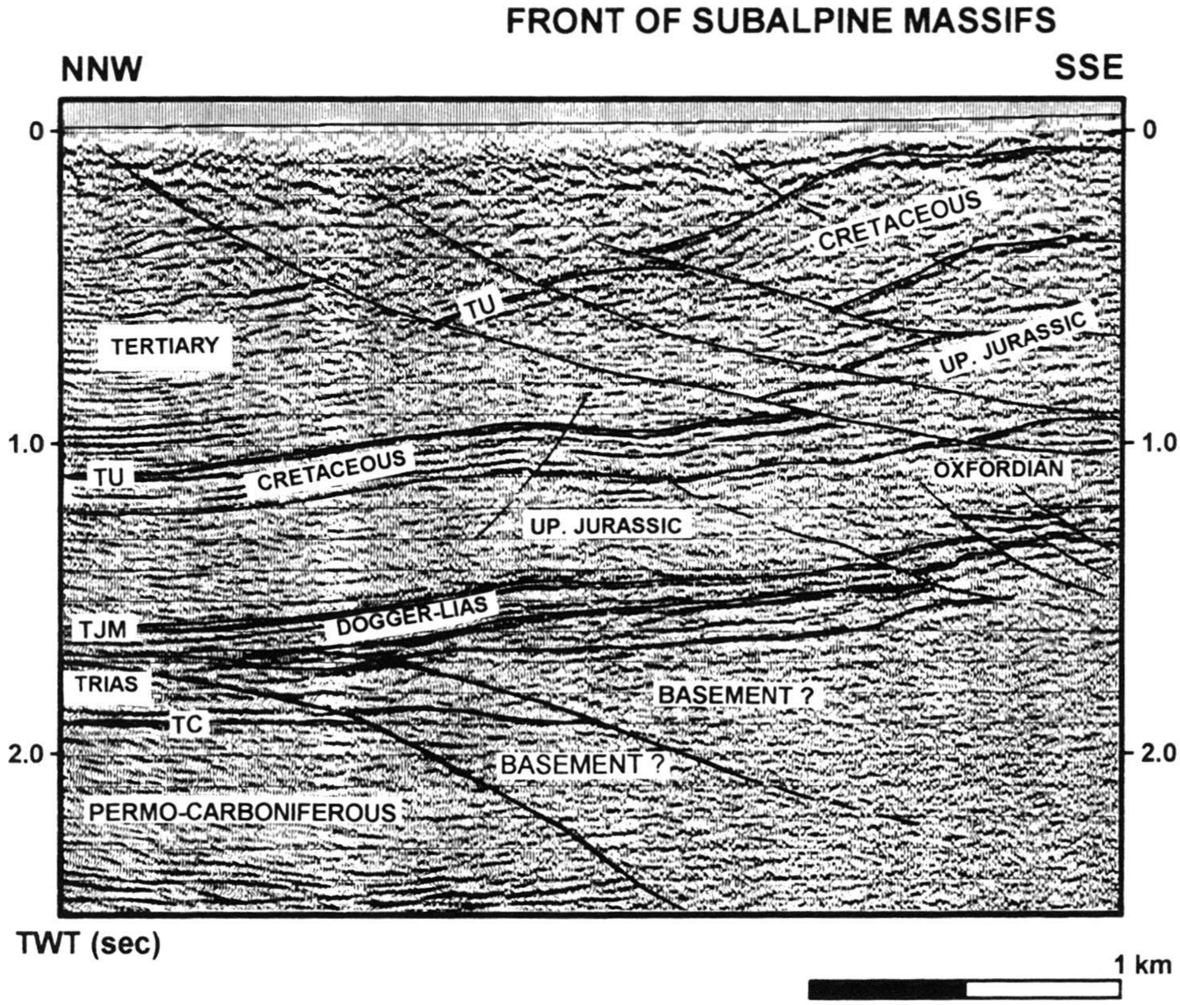
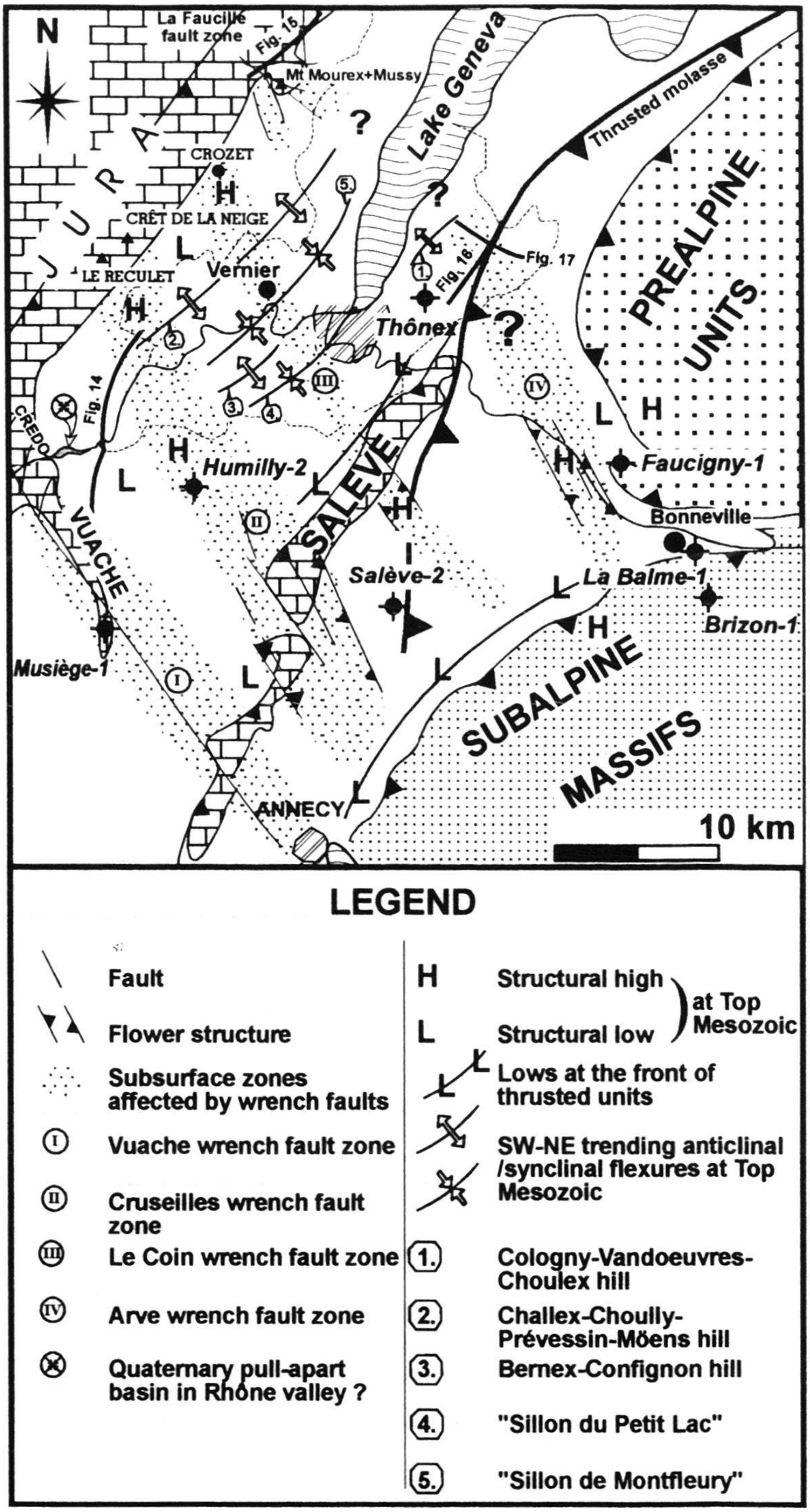


Fig. 12. Migrated seismic line at the front of the subalpine massifs (see location on Fig. 7). This is a modified interpretation of the northern part of figure 5 of Charollais & Jamet (1990). It shows the major basement normal fault (reactivated as a reverse fault during the late Alpine orogen), which opens up a Permo-Carboniferous half-graben to the north (see Fig. 7). A similar feature is observed north of the Arve river (see Fig. 5 and Plate 1 of Gorin et al. 1993). For abbreviations of seismic reflectors, see caption of figure 3.

zoic-Cenozoic interface in this area (= Top Urgonian limestone) has already been presented in figure 2 of Gorin et al. (1993): it shows that, as a whole, the Mesozoic sequence in the Geneva Basin forms essentially a monoclinal flank, which dips southeasterly from the Jura towards the Salève. A similar monocline can be observed in the Bornes Plateau dipping from the Salève outcrops towards the front of the subalpine massifs and prealpine units. At the front of the Salève and of the subalpine massifs and prealpine units, the Mesozoic forms a SW-NE trending depression (schematized by "lows" in figure 13), which overlies the Permo-Carboniferous half-grabens mentioned above (see Fig. 7). The depression in front of the Salève corresponds to the "axe négatif de Gaillard" expressed on the 1 : 50,000 gravimetric map of Poldini (1963).

In more detail, both the Mesozoic and Cenozoic sequences are in fact affected by numerous tectonic accidents largely related to wrench fault zones, which delineate local lows and highs (Fig. 13). For many years, four major sinistral NW-SE running wrench


N
La Faucille fault zone
Fig. 15
Mt Mourex+Mussy
Lake Geneva
Thrusted molasse
JURA
CROZET
H
CRÊT DE LA NEIGE
LE RECULET
Vernier
Fig. 16
Fig. 17
Thônex
PREALPINE UNITS
Fig. 14
CREDO
Humilly-2
SALEVE
Faucigny-1
Bonneville
VUACHE
Salève-2
La Balme-1
Brizon-1
Musiège-1
SUBALPINE MASSIFS
ANNECY
10 km
LEGEND
Fault
Flower structure
Subsurface zones affected by wrench faults
Vuache wrench fault zone
Cruseilles wrench fault zone
Le Coin wrench fault zone
Arve wrench fault zone
Quaternary pull-apart basin in Rhône valley ?
Structural high
Structural low
at Top Mesozoic
Lows at the front of thrusted units
SW-NE trending anticlinal /synclinal flexures at Top Mesozoic
Cologny-Vandoeuvres-Choulex hill
Challex-Choully-Prévessin-Möens hill
Bernex-Confignon hill
"Sillon du Petit Lac"
"Sillon de Montfleury"

fault zones have been traced across the Geneva Basin, based essentially on outcrop geology in the surrounding Jura, Vuache and Salève mountains (see synthetic geological map of Rigassi in Rigassi 1956 and in Jung 1982, and the tectonic map of Ruchat 1978). From west to east, seismic data contribute to a better definition of these zones in the subsurface.

The Geneva cuvette is limited to the west by the **wrench fault zone of Mount Vuache** observed in the Mesozoic outcrops. Blondel (1984) postulates that the shape and orientation of this mountain is related to basement faulting. As indicated above, seismic data (Fig. 8) show the evidence of basement faulting on the eastern flank of the Vuache.

The **second wrench fault zone is that of Cruseilles**, which clearly offsets the Salève ridge (Fig. 13). South of the Salève, seismic data in the Bornes Plateau show that this zone corresponds at top Mesozoic level to a major positive flower structure, which encompasses the wrench faults of Cruseilles, Abergement and Pommier identified in outcrop (Joukowski & Favre 1913). This high continues northwards in outcrop to form the highest point of Mount Salève ("les Pitons"). In the Geneva Basin, the Cruseilles wrench zone lines up with the Mesozoic high on which the well Humilly-2 was drilled (Fig. 13). This high is limited by reverse faults (Fig. 8). The wrench zone can be followed on seismic northwards and outcrops in the Jura High Chain, where it is expressed by the Reculet and Crêt de la Neige summits, probably the present-day surface expression of a flower structure (Fig. 13).

The Vuache and Cruseilles wrench zones delineate a NW-SE oriented depression at top Mesozoic level (Fig. 13 of this paper and Fig. 2 of Gorin et al. 1993), which bottoms at ca. –400 m bmsl, whereas top Mesozoic was reached at +74 m amsl in Humilly-2 and culminates over +1000 m amsl in Mount Vuache. In this depression, the oldest molasse sediments (of Chattian, i.e. Late Oligocene, age) are onlapping an existing topography (Fig. 14). This means that the initiation of movement along the wrench zones is older than the base of the Tertiary sequence. In fact, thickness variations in the Lower and Middle Jurassic (see below, under seismic stratigraphic observations) show that the Cruseilles-Humilly wrench zone was already active at that time. This was already highlighted in outcrops by Blondel et al. (1988). The local widening and change of orientation of the Rhône valley in this area (Fig. 13, location x) overlies this Mesozoic low. It is thought to be the surface expression of present-day localized subsidence associated with transcurrent faulting (pull-apart type). The Vuache fault zone is known to be tectonically still active (Sambeth & Pavoni 1988).

The third wrench fault zone is well documented in outcrop at **Le Coin** in Mount Salève (Joukowski & Favre 1913). South of the Salève, its continuation is indicated on seismic data by a flower structure (Fig. 13). It seems to have sinistrally offset the front of the thrusted molasse. It is also observed in the subsurface at the northern front of the

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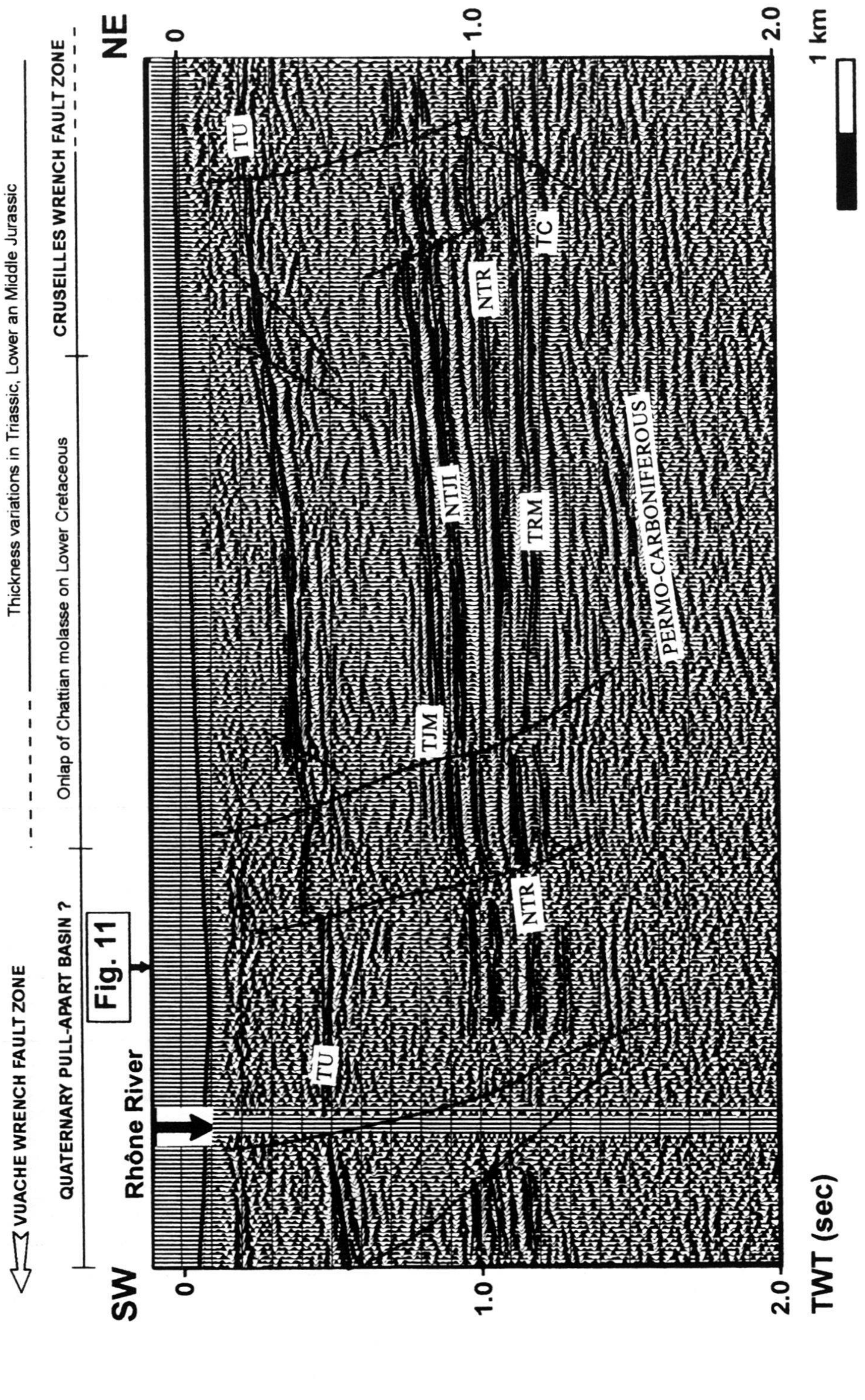
Fig. 13. Schematic Mesozoic-Cenozoic structural map and location map of figures 14 to 17. This illustrates: a) the SW-NE trending Mesozoic synclinal lows at the front of Mount Salève and of the subalpine massifs and prealpine units, overlying Permo-Carboniferous basins (see Fig. 7); b) the NNW-SSE trending wrench zones crossing the Geneva Basin and Bornes Plateau and already active in the Mesozoic (and probably in the Palaeozoic); c) the SW-NE trending, low-relief, anticlinal/synclinal flexures at Top Mesozoic related to the late Alpine tectonic phase. A schematic depth map of the Mesozoic-Cenozoic interface (= Top Urgonian) has already been presented in Gorin et al. (1993), which partly highlights a) and b).


VUACHE WRENCH FAULT ZONE
Thickness variations in Triassic, Lower an Middle Jurassic
QUATERNARY PULL-APART BASIN ?
Onlap of Chattian molasse on Lower Cretaceous
CRUSEILLES WRENCH FAULT ZONE
SW
NE
Rhône River
Fig. 11
TU
TU
NTR
NTR
TJM
NTJI
TRM
TC
PERMO-CARBONIFEROUS
0
1.0
2.0
TWT (sec)
1 km

Salève, where it is aligned with the surface faults (Fig. 9). Because of a lack of seismic data, its northward continuation across the Geneva Basin remains more hypothetical. Nevertheless, important NW-SE trending faults (up to 100 m of vertical throw) have been observed in the uppermost molasse outcrops at Vernier (Fig. 13), near the Rhône River (Rigassi 1956, Angelillo 1987). These faults are interpreted as the surface expression of the northward continuation of the Le Coin wrench fault zone, because they have the same direction. Further north, the wrench zone has been interpreted (Ruchat 1977 and 1978) as continuing in the Jura outcrops (surface faults in the Crozet area, Fig. 13). Between the Crozet and Vernier areas, seismic data subparallel to the Jura (Fig. 10) confirm this interpretation. Therefore, seismic information along the Jura and on both sides of the Salève, as well as outcrop data in the Jura and in the middle of the Geneva Basin, tend to support the interpretation of a NW-SE oriented lineament across the Geneva Basin, which coincides with the wrench fault zone observed at Le Coin in the Salève.

The **fourth wrench fault zone**, that of **the Arve**, remains more hypothetical. It can be tentatively identified on seismic data as a flower structure north-east of the Bornes Plateau, in the Arve valley, near the well Faucigny-1 (Fig. 13). As a result of insufficient seismic coverage in the Geneva Basin, it is difficult to confirm its extension further north. Previous authors (e.g. Rigassi 1956, Amberger & Ruchat 1977) have tentatively traced it across the Geneva Basin to link up with the La Faucille fault zone (Fig. 13). Southeast of La Faucille, seismic data (Fig. 15) show that the surface structures of Mont Mouret and Mont Mussy (Fig. 13) are probably the expression of wrench-related compressive tectonics in continuation with the La Faucille fault zone. Nevertheless, because of a lack of seismic data, this trend can not be traced further south towards the Lake of Geneva. On shallow reflection seismic data, Vernet & Horn (1971) have found some strike slip faults (down to top molasse) across the western end of Lake of Geneva, which they link with the Mont Mouret and La Faucille structures. On the southern side of the lake, these faults seem to coincide with the NW-SE oriented lineament suggested by Rigassi (1956) in his tectonic sketch, which is probably inferred from the abrupt northeastern surface termination of the Cologny-Vandoeuvres-Choulex hill (Fig. 13). Only two seismic lines are available in the Canton of Geneva on the southern side of the lake, in an area which should be intersected by the hypothetical Arve fault zone (Fig. 2). Both profiles (Fig. 16, 17) show a culmination at top Mesozoic level, which may be interpreted as the expression of wrench faulting. This high may also be related to a subsurface continuation of the Salève axis, which would have been sinistrally offset by the Arve accident. Seismic data (Fig. 16, 17) and the map of figure 13 show arguments for both hypotheses:

- Firstly, the southern flank of the Mesozoic high on figure 17 shows many similarities with that of the Salève observed on seismic data less than 10 km to the south (see Plate 1 and Fig. 5 of Gorin et al. 1993):

Fig. 14. Unmigrated seismic line in the northwestern part of the Geneva Basin (see location on Fig. 13). It illustrates: a) the structural low at Top Mesozoic separating the Vuache and Cruseilles wrench fault zones; b) the onlap of Chattian molasse onto the Mesozoic; c) the thickness variations in the Liassic section. For abbreviations of seismic reflectors, see caption of figure 3.

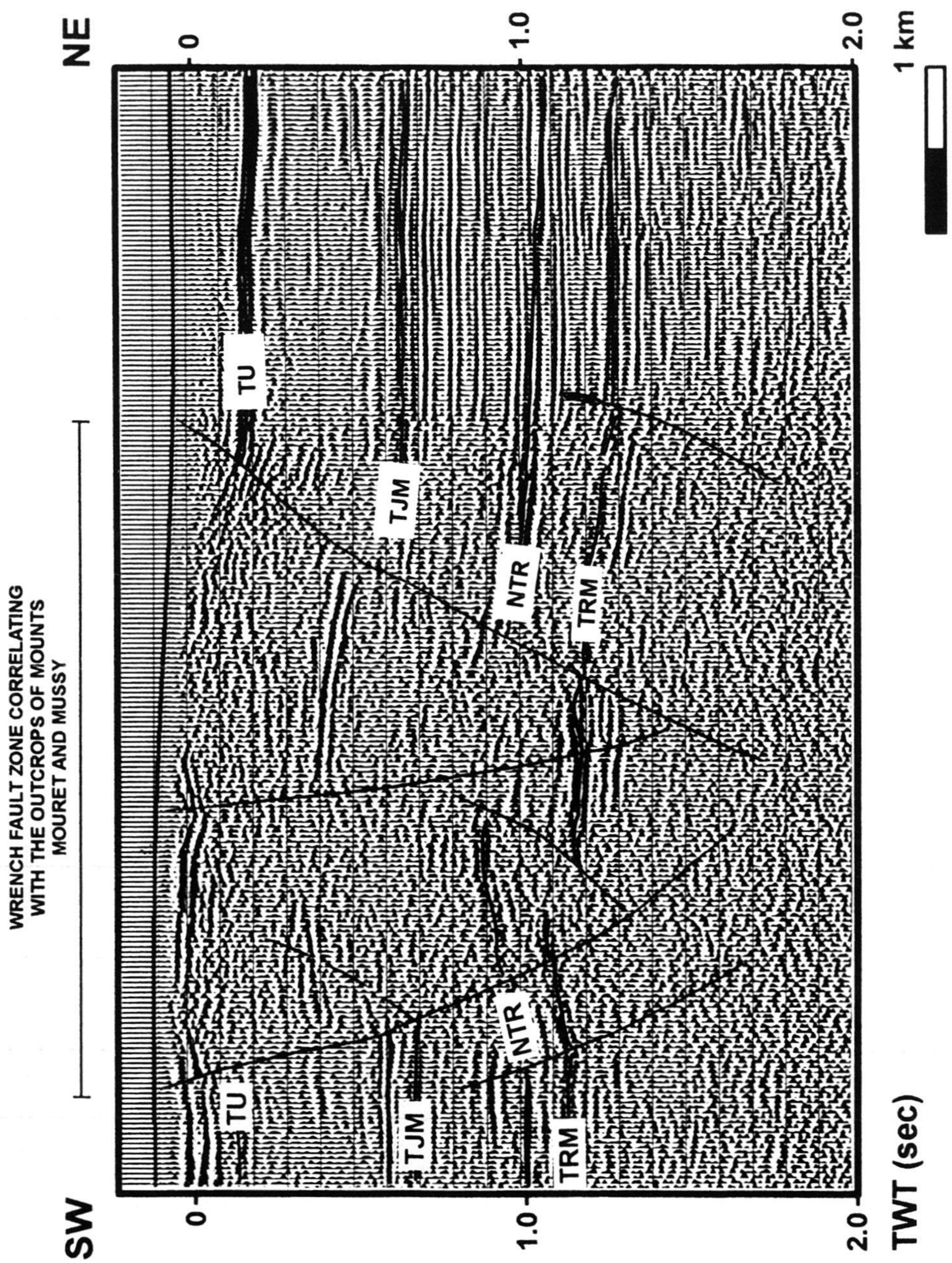


Fig. 15. Unmigrated seismic line in the northern part of the Geneva Basin running subparallel to the Jura Mountains and to Mts. Mourex and Mussy (see location on Fig. 13). It illustrates the wrench faults associated with Mts. Mourex and Mussy. For abbreviations of seismic reflectors, see caption of figure 3.

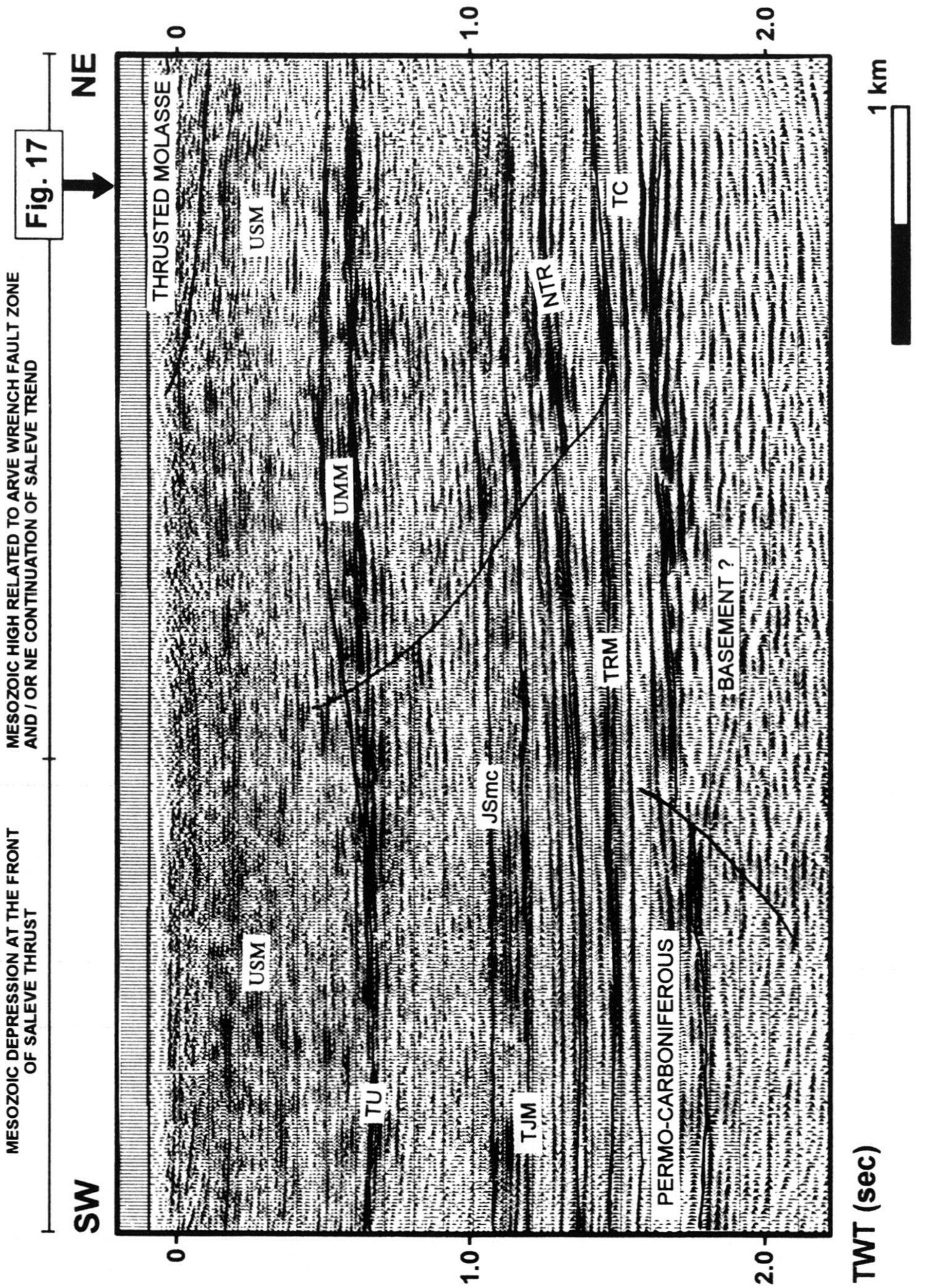
a) this flank overlies a basement high, the Permo-Carboniferous sequence becoming thicker to the west. The Pèrmo-Carboniferous fault downthrowing to the west (Fig. 16, 17) corresponds to the SW-NE basement lineament shown on figure 7.
b) this flank is marked by a noticeable southeastward thinning of the Lower and Middle Jurassic sequences. As mentioned by Gorin et al. (1993), the southward thinning of the Lower and Middle Jurassic is probably the transition from platformal (such as that encountered in Humilly-2, see Fig. 5) to more basinal facies (such as that encountered in Faucigny-1, see Fig. 6) and it might have been influenced by the rejuvenation of the Palaeozoic trend described in a). Reactivation of this trend seems to have also influenced the thickness of the Triassic (Fig. 16), although halokinesis may also have played a role.
c) The onlap and pinch-out of the Lower Marine Molasse (UMM, Fig. 16, 17) demonstrates the early tectonic activity affecting this flank, which has also probably determined the position of the front of the thrusted molasse.

- Secondly, if this Mesozoic high is really associated with the Salève trend, then its position is clearly sinistrally offset in relation with the Salève axis. Moreover, both the front of the thrusted molasse (Fig. 13) and the westward pinch-out of the UMM (Fig. 16, 17) are also sinistrally offset in relation with the Salève axis. These observations are arguments supporting the existence of the Arve wrench fault zone.

Apart from these major, NW-SE oriented, tectonic lineaments, the Mesozoic monocline in the Geneva Basin shows **low-relief SW-NE running anticlinal and synclinal flexures**. The anticlinal flexures often underlie the molasse hills forming the characteristic surface topography of the area: for instance, the molasse hills of Challex, Choully and Prévessin-Moëns (Fig. 13) overlie such a Mesozoic anticlinal flexure. The surface morphology of the Bernex-Confignon hill (Fig. 13) corresponds exactly to that of the underlying Mesozoic flexure which shows a gently dipping northern flank and an abrupt, fault-bounded southern flank (Fig. 18a). These Mesozoic flexures have been already outlined using gravimetry (Poldini 1963, Olivier et al. 1983). The downthrown block to the south of the Bernex-Confignon hill ("Plaine de l'Aire") overlies the negative gravimetric axis of the "sillon du Petit Lac" (Fig. 13). The same applies for the "sillon de Montfleury" (Fig. 13 and Pugin 1988), where the molasse depression overlies a low-relief, fault-induced low at Mesozoic level. Figure 17 shows that the Cologny-Vandoeuvres-Choulex hill (Fig. 13) continues northwards as a Mesozoic culmination. Consequently, seismic data show that the surface topography of the Geneva Basin is essentially reflecting that of the top molasse (Pugin 1988), which itself is the expression of deeper Mesozoic structuration. Only locally has this surface topography been significantly affected by glacial/fluvial erosion or deposition. Most of these SW-NE running anticlinal flexures are probably related to the late Alpine (Mio-Pliocene) phase of folding.

Mesozoic and Cenozoic: seismic stratigraphic observations

In the **Triassic** of the Geneva Basin, three units can normally be distinguished from base to top, using well data from Humilly-2: the first is a laterally continuous sequence corresponding essentially to the Muschelkalk dolomites, overlain by the Top Muschelkalk



MESOZOIC DEPRESSION AT THE FRONT OF SALEVE THRUST
MESOZOIC HIGH RELATED TO ARVE WRENCH FAULT ZONE AND / OR NE CONTINUATION OF SALEVE TREND
Fig. 17
SW
NE
THRUSTED MOLASSE
USM
UMM
NTR
TC
JSmc
TRM
BASEMENT ?
PERMO-CARBONIFEROUS
TU
TJM
0
1.0
2.0
TWT (sec)
1 km

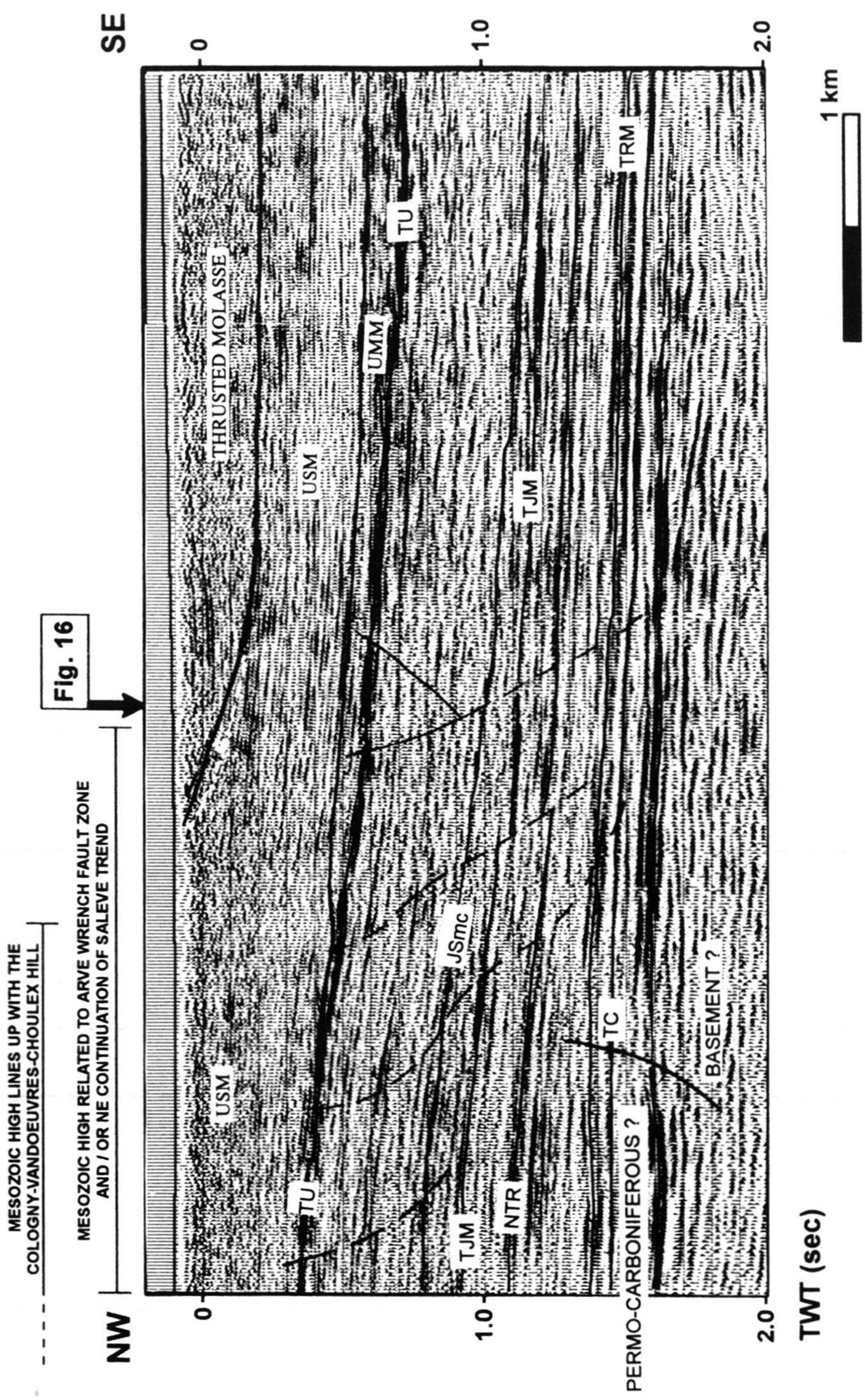
(TRM) seismic reflector. The second is a sequence characterized by discontinuous undulating reflectors of various amplitude (reflective to transparent) corresponding to the Lower Keuper sequence dominated by rock salt. The final unit is a laterally continuous reflective sequence capping the previous one, which corresponds to the Upper Keuper anhydrite and terminates with the Near Top Triassic (NTR) seismic reflector. This threefold subdivision is well illustrated in figures 5, 9 and 16. In figure 17, a thickening of the salt interval can clearly be observed.
In the **Lower and Middle Jurassic** section, seismic reflectors are quite continuous, the Middle Jurassic being the most reflective section (see Fig. 5). Consequently, it is possible to estimate the thickness variations of these two stratigraphic intervals over the studied area. Though it is difficult to draw accurate isopach maps because of the loose seismic grid, our observations allow the mapping of significant thickness variations (Fig. 19, 20). Two important trends can be observed:

- Firstly, both the Lower and Middle Jurassic thin considerably eastwards of Lake Geneva and of the Salève towards the Alpine front (see Fig. 8, 17, this paper, and Fig. 3 of Gorin et al. 1993). This thinning is thought to reflect the transition from platformal to basinal settings and may be related to a deep-seated SW-NE oriented hinge zone (Gorin et al. 1993). The offset of the lows at the northeastern end of the Salève may be another argument for the existence of the Arve wrench fault zone (Fig. 19).
- Secondly, thickness variations occur in the Geneva area close to the Vuache and Cruseilles-Humilly wrench fault zones: the Lower Jurassic, mainly its lower part (Fig. 14, 19), thins westwards of the Cruseilles-Humilly trend. The same thickness variations seem to apply for the Triassic (Fig. 14). The trend is inverted in the Dogger (Fig. 20), which is thick west of the Cruseilles-Humilly wrench zone and thins eastward. This is a strong argument for early movements along this NW-SE tectonic lineament. In the case illustrated by figure 14, the wrench zone might have been a low in the early Liassic and in the Triassic, and progressively became a positive relief during the younger part of the Liassic and the Dogger.

Middle Jurassic crinoidal limestones are well known in the nearby Jura (Metzger 1988, Neumeier 1993). Locally, seismic stratigraphic observations in this interval (Fig. 18b) demonstrate evidence of prograding sedimentary bodies. The palaeogeographical extension of this facies can therefore be extended southwards.

As mentioned above, the **Upper Jurassic** is essentially composed of massive limestones and has a fairly transparent seismic facies. The synthetic seismogram of Humilly-2 (Gorin et al. 1993) shows that the only seismic reflector which may appear is that marking the base of the reefal limestones in the Upper Kimmeridgian, which are well known

Fig. 16. SW-NE trending, migrated seismic line SE of Lake Geneva (see location on Fig. 13). This illustrates: a) The fault-related thickening of the Permo-Carboniferous to the SW; b) At Top Mesozoic (TU), the depression to the SW and the culmination to the NE; c) The westerly pinch-out of the UMM and the front of the Thrusted Molasse; d) The relative continuity of seismic reflectors in the USM possibly indicating lacustrine deposits. For abbreviations of seismic reflectors, see Fig. 3, UMM = Lower Marine Molasse, USM = Lower Freshwater Molasse.


MESOZOIC HIGH LINES UP WITH THE COLOGNY-VANDOEUVRES-CHOULEX HILL
MESOZOIC HIGH RELATED TO ARVE WRENCH FAULT ZONE AND / OR NE CONTINUATION OF SALEVE TREND
Fig. 16
NW
SE
0
1.0
2.0
TWT (sec)
1 km
THRUSTED MOLASSE
USM
UMM
TU
TRM
TJM
JSmc
NTR
TC
BASEMENT ?
PERMO-CARBONIFEROUS ?

in the Jura outcrops (Bernier 1984, Fookes 1991). Where this reflector can be interpreted, it may be locally associated with biohermal reef-like structures (Fig. 18c).

The **Lower Cretaceous** section is normally a highly reflective sequence, if it is not affected by fracturing or by intense karstification at Top Urgonian. When this is not the case, Top Hauterivian and Top Valanginian can be locally confidently interpreted (Fig. 5).

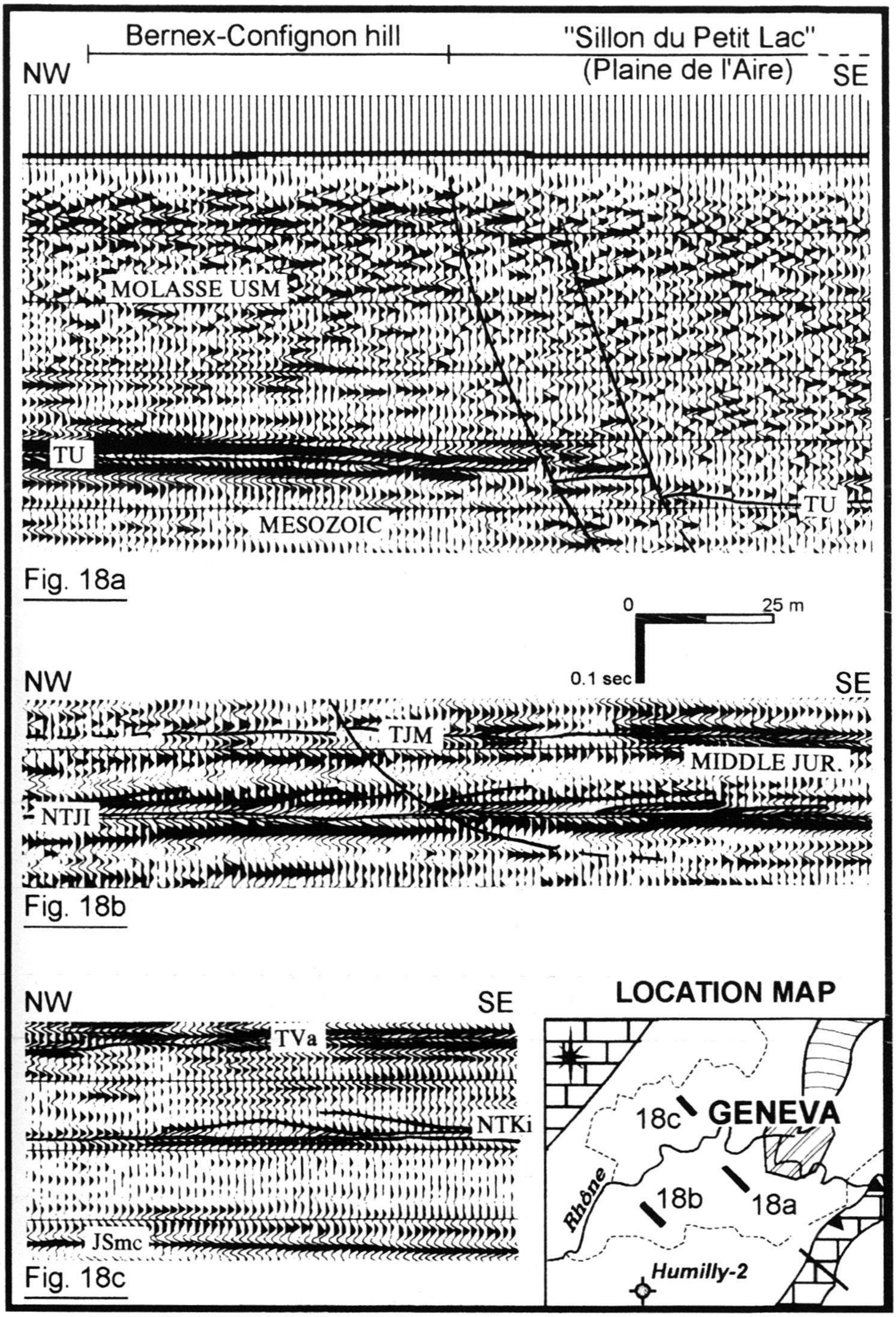
In the **Molasse** interval, the Lower Marine Molasse (UMM) has been deposited only close to the Alpine front, in the Bornes Plateau and north of the Arve River. In the Bornes Plateau, it onlaps and wedges out against a pre-existing Salève topography (Fig. 8). A similar onlap and pinch-out can be observed north of the Salève surface termination (Fig. 17): the lowermost molasse sediments on this profile may be correlated with the UMM encountered in Faucigny-1 (Fig. 6), where it consists of "subalpine flysch" and "Grès de Bonneville", which locally outcrop as thrusted molasse in the Bornes Plateau (Charollais & Amberger 1984). The "Grès de Bonneville" contain coal beds, which may explain the high amplitude, discontinuous reflectors locally present in the UMM (Fig. 17). The entire molasse sequence deposited in the Geneva Basin consists of younger Lower Freshwater Molasse (USM), which onlaps northwestwards the eroded Lower Cretaceous surface. Onlaps of the USM onto the top Mesozoic surface in the depression located between the Vuache and Cruseilles-Humilly lineaments (Fig. 14) demonstrate the pre-Oligocene age of this structuration (see also Gorin et al. 1993). In most of the Geneva basin, seismic reflectors in the USM show a poor continuity due to their continental origin. They appear laterally much more continuous in the frontal depression of the Salève (Fig. 16) and in the deeper part of the foreland basin in and north of the Bornes Plateau (Fig. 17 of this paper, and Plate 2 of Gorin et al. 1993). This may be an indication that these parts of the USM basin were covered for a long period of time by a large-size freshwater body.

Conclusions

Interpretation of all available seismic data in the greater Geneva area allows the correlation of the tectonic and lithological observations derived both from surface geology (mainly the Mesozoic outcrops in the Jura, Salève, Vuache and subalpine massifs) and from borehole data (mainly the wells Humilly-2 and Faucigny-1 which reached the Palaeozoic).

In many locations, a Permo-Carboniferous sedimentary sequence can be identified: its base is often highlighted by a reflective sequence interpreted as Carboniferous coals. Although the exact location of faults at this stratigraphic level may often be conjectural, the position of the reflective sequence with respect to the Triassic permits to distinguish significant basement highs and lows. This interpretation contributes to the production of

Fig. 17. NW-SE trending, migrated seismic line SE of Lake Geneva (see location on Fig. 13). This illustrates: a) the fault-related thickening of the Permo-Carboniferous to the NW; b) the thinning of the Middle-Lower Jurassic (interval TJM-NTR) to the SE; c) the culmination at Top Mesozoic to the NW; d) the pinch-out of the UMM onto the Mesozoic flank and the front of the Thrusted Molasse. For abbreviations of seismic reflectors, see figure 3, UMM = Lower Marine Molasse, USM = Lower Freshwater Molasse.


Bernex-Confignon hill
"Sillon du Petit Lac"
(Plaine de l'Aire)
NW
SE
MOLASSE USM
TU
MESOZOIC
TU
Fig. 18a
0
25 m
0.1 sec
NW
SE
TJM
MIDDLE JUR.
NTJI
Fig. 18b
NW
SE
TVa
NTKi
JSmc
Fig. 18c
LOCATION MAP
18c
GENEVA
Rhône
18b
18a
Humilly-2

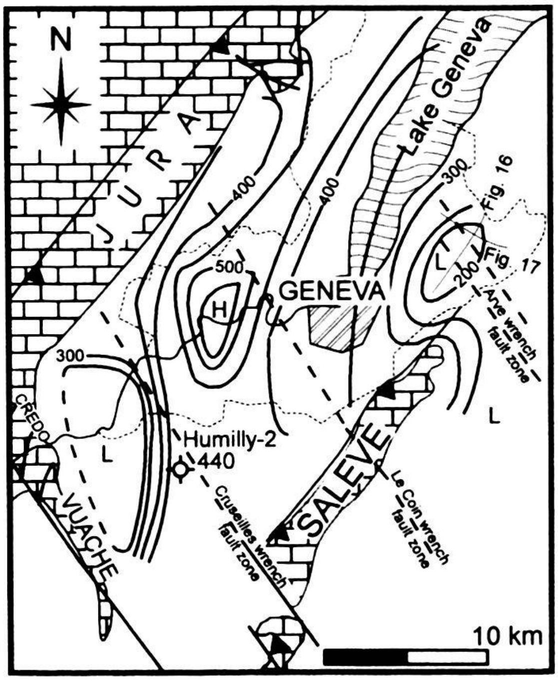


Fig. 19. Schematic isopach map (in metres) of the Lower Jurassic in the Geneva Basin. The thinning east of Lake Geneva and the Salève is thought to correspond to the transition from platform to basin (see Gorin et al. 1993). The sinistral offset of this thinning may be the imprint of the Arve wrench fault zone. Thickness variations in the western part of the Geneva Basin show the imprint of the Vuache and Cruseilles wrench fault zones.

a schematic tectonic picture of top basement. Consequently, it is possible to analyze the potential relationship between the Palaeozoic (Fig. 7) and Mesozoic-Cenozoic (Fig. 13) structural configuration of the area.

The tectonic framework of the Geneva region is dominated by SW-NE and NW-SE trending Permo-Carboniferous lineaments, which have been rejuvenated at different stages up to the present-day, thereby influencing both the sedimentation and the structural history:

- **SW-NE running lineaments** are observed at the front of the subalpine massifs, prealpine units and Salève thrust, and at the southern edge of the Jura Mountains. In the first three locations, northward downfaulting of basement has created Permo-Carboniferous half-grabens (Fig. 7) which are overlain by structural lows at Top Mesozoic level, filled by thick molasse deposits (Fig. 8, 14). At the Alpine front, the compressive Alpine tectonic phase reactivated these basement faults as reverse faults, thereby creating basement highs (Fig. 7, 14). The basement high underlying the Salève has probably been reactivated at different periods of time since the Palaeozoic: it seems to be associated with the major southward thinning of the Lower and Middle Jurassic.

Fig. 18. **a)** Seismic expression of the Bernex-Confignon molasse hill and of the adjacent "plaine de l'Aire", which overlies the negative gravimetric axis called "Sillon du Petit Lac". The molasse hill is underlain by a low-relief culmination at top Mesozoic (TU = Top Urgonian reflector) which is downfaulted to the SE to form a low underneath the "Plaine de l'Aire".
b) Seismic expression of westward progradation in the Middle Jurassic crinoidal limestone. TJM = Top Middle Jurassic reflector, NTJI = Near Top Lower Jurassic reflector.
c) Seismic expression of biohermal reefs (?) in the Upper Kimmeridgian. TVa = Top Valanginian reflector, NTKi = Near Top Kimmeridgian reflector, JSmc = Top argillaceous Oxfordian reflector.

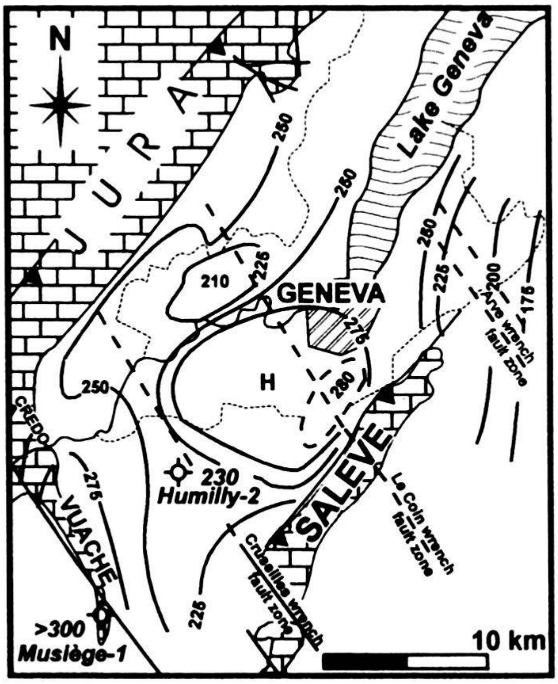


Fig. 20. Schematic isopach map (in metres) of the Middle Jurassic in the Geneva Basin. The major thinning east of Lake Geneva and the Salève is thought to correspond to the transition from platform to basin (see Gorin et al. 1993). Thickness variations in the western part of the Geneva Basin show the imprint of the Cruseilles wrench fault zone.

It also marks the western limit of the UMM basin and has probably determined the position of the thrusted molasse front. Finally, north of the Geneva basin, the Jura High Chain seems to overlie an inverted Permo-Carboniferous graben.

As already discussed in Gorin et al. (1993), this vertical and spatial coincidence of Palaeozoic and Mesozoic/Cenozoic sedimentary and structural features is an argument against the large-scale northward translation across the foreland of the Mesozoic-Cenozoic sequence along a detachment level in the evaporitic Triassic, which has been postulated to explain the observed shortening in the Jura Mountains ("Fernschub" hypothesis of Laubscher 1961). Moreover, the dissection of the Triassic evaporite horizon, which results from the renewed activity of these SW-NE trending faults, and the disappearance of the Triassic rock salt towards the Alpine front (see Faucigny-1) are other arguments against the "Fernschub" hypothesis. These observations are in line with those of Pfiffner (1994) further east in the Molasse Basin: they support this author's hypothesis that the topmost basement underlying the Jura Mountains and the western Molasse Basin was also involved in the deformation, which was possibly controlled by the geometry of the Permo-Carboniferous grabens. Compensation of this basement shortening should be rooted beneath the external cristalline massifs.

- **NW-SE running lineaments**, intersecting the SW-NE trends described above, have been mapped and interpreted for many years as wrench fault zones in the Mesozoic outcrops surrounding Geneva. Seismic data confirm the subsurface continuation of these zones across the Geneva Basin and the Bornes Plateau, particularly that of the Vuache, Cruseilles and Le Coin (Fig. 13). Their seismic expression is often marked by flower structures (Fig. 15), which delineate structural highs and bordering lows (Fig. 13). These wrench zones have been active from Permo-Carboniferous times (Fig. 7) throughout the Jurassic (see thickness variations in the Middle and Lower

Jurassic, Fig. 19, 20) and the Cenozoic (see onlap of Upper Oligocene molasse onto the Mesozoic, Fig. 14) up to the present-day (see localized pull-apart basin in the Rhône valley, Fig. 13, 14).
The existence of the fourth wrench fault zone, that of the Arve, is supported by various local subsurface observations, particularly south of Lake Geneva, but some extra seismic data would be required across and north of the Lake to confirm its northward continuation towards La Faucille fault zone (Fig. 13).

Independantly from these two types of basement-related lineaments, the Geneva Basin displays **SW-NE trending, low-relief, anticlinal and synclinal flexures affecting both the Mesozoic and Cenozoic intervals** (Fig. 13), which are related to the late Alpine orogeny. The anticlinal flexures correspond to the molasse hills characteristic of the Geneva Basin topography.

Finally, the quality of seismic markers allows a good **seismic stratigraphic control** across the study area. Despite the relatively loose seismic grid, schematic isopach maps can be established and help to demonstrate the influence of structural lineaments on sedimentation (Lower and Middle Jurassic, Fig. 19, 20). Onlaps of molasse sediments onto the dipping erosional Top Mesozoic surface illustrate the existence of pre-Oligocene palaeoreliefs (e.g. Fig. 14). Seismic observations of prograding Middle Jurassic grainstones and of Kimmeridgian reefal bioherms in the Geneva Basin (Fig. 18) lead to a better knowledge of the southward distribution of these facies known so far only in the outcrops of the Jura Mountains.

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