Regional geology

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4. REGIONAL GEOLOGY

4.1. INTRODUCTION

In this Chapter the lateral continuity of structures in the central Jura and the Molasse Basin is discussed, supported by regional examples. The availability of a dense seismic grid (Fig. 4.1) has given the opportunity to follow, at large scale, the structures along their strike. Interpretation of dip and especially strike seismic lines highlights some large scale continuities and/or discontinuities in the structures. Rather than presenting lengthy details of folds, thrust faults and ramps, in order to discuss the lateral continuity of the central Jura structures, we will emphasize some characteristics of the Jura and Molasse Basin anticlines and synclines. This Chapter is subdivided into regions (Neuchâtel Jura, Risoux Jura, Champagnole-Mouthe region, western Swiss Molasse Basin; for location see Figures 1.3 and 1.4), because the structures turn out different from one area to another.

4.2. NEUCHÂTEL JURA

4.2.1. *Previous studies*

Too many authors have worked on the structures of the Neuchâtel Jura to give due credit to all of them and cited here are but some of the major works that have contributed to a better understanding of the geology in Neuchâtel Canton.

During the 19th century, pioneers of Jura geology are von Buch, Thurmann, De Montmollin, Desor and Gressly. Von Buch (1867) is best known for his cross-section of 1803 from the Alps to the Jura (see comments in §1.4) and also in the Neuchâtel Jura for his drawing showing the profile and the plunge of an anticline (Chaumont). Thurmann (1836a, 1856) made a morphological map of the whole Jura and De Montmollin (1839) published the first geological map of the whole Neuchâtel Jura. Desor & Gressly (1859) presented a detailed 1:25'000 scale map. Other interesting contributions of authors working for the second Neuchâtel Academy have been recently reviewed by Schaer (1994).

Contributions on the Jura Mountains from the beginning of this century are collected in the review of Heim (1921), De Margerie (1922, 1936) and Bailey (1935). Key references for the Neuchâtel Jura are Schardt (1906), Schardt & Dubois (1903), Rickenbach (1925), Frei (1925, 1942), Thiébaud (1936), Kiraly (1969) and Meia (1969). More recently, published and unpublished works (Diploma, PhD thesis and maps deposited at the Neuchâtel University, see Tab. 1.1) have contributed to increase the knowledge of the surface and subsurface geology of the Neuchâtel Jura.

The cross-section of Schardt & Dubois (1903) (Fig. 4.2) is of particular interest for the Neuchâtel Jura, because it crosses the Creux du Van anticline and the Areuse syncline (Fig. 4.3). Beyond the fact that the Creux du Van anticline is formed over a foreland-vergent thrust, with a vertical northern limb, the top of the anticline shows an impressive steep cliff resulting from a glacier cirque development. For details about glacial deposits and the Quaternary history, the reader is referred to the appropriate literature (Ritter, 1888; Du Pasquier, 1893; Aubert, 1965; Matthey, 1971).

4.2.2. *Eastern part*

The geology of the Neuchâtel Jura is shown on the tectonic sketch of Figure 4.3. The geological units of this map have been compiled from several 1:200'000 scale tectonic sketches of 1:25'000 map sheets (see Tab. 1.1). Many tear faults appear in the eastern part, in contrast to the West. This is in part due to the different style of mapping from author to author. Many thrust faults have been added on this general map, following our interpretation of seismic lines, e.g. in front of the Chaumont anticline. At the surface, most thrust faults are capped by a veneer of Quaternary sediments and therefore it is sometimes difficult or impossible to locate them exactly in the field.

In the eastern part of the Neuchâtel Jura, the tectonic sketch highlights thrust-related anticlines with

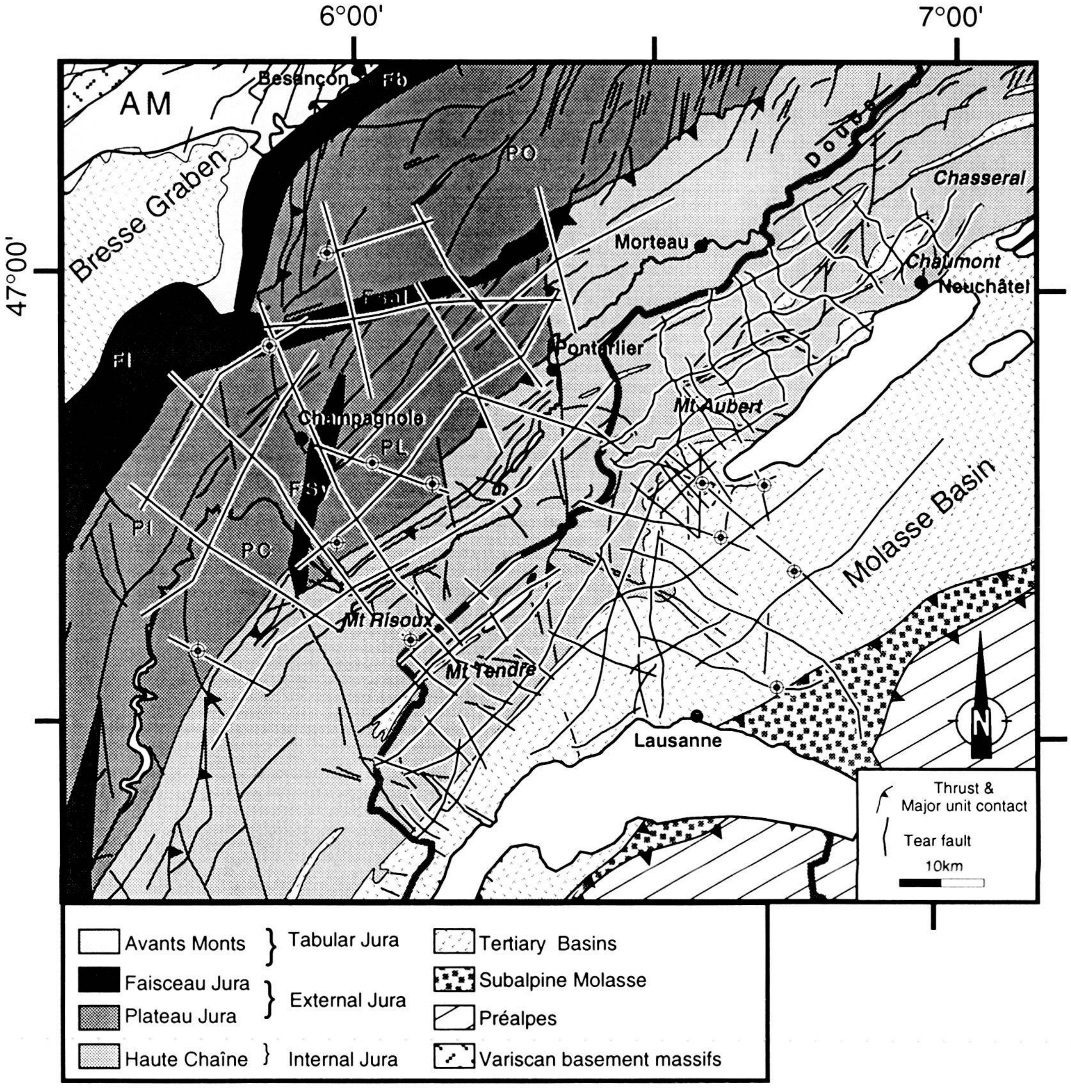


Figure 4.1: Seismic grid located on a tectonic sketch of the central Jura and the western Molasse Basin. Legend: AM = Avants-Monts; Fb = Faisceau bisontin; Fl = Faisceau lédonien; Fsal = Faisceau salinois; FSy = Faisceau de Syam; PC = Plateau de Champagnole; PL = Plateau de Levier; Pl = Plateau lédonien; PO = Plateau d'Ornans.

Grille sismique reportée sur la carte tectonique du Jura central et du Bassin molassique occidental. Légende: AM = Avants-Monts; Fb = Faisceau bisontin; Fl = Faisceau lédonien; Fsal = Faisceau salinois; FSy = Faisceau de Syam; PC = Plateau de Champagnole; PL = Plateau de Levier; Pl = Plateau lédonien; PO = Plateau d'Ornans.

a lateral continuity of about 10 km. Anticlines appear to end against tear faults (La Tourne and La Ferrière faults) and have axes oriented either ENE-WSW or NNE-SSW. The combination of both orientations results in rhomb shaped structures such as the Val de Ruz basin and the Le Locle syncline. The relationships between both trends are enhanced on the three-dimensional structural contour map representing the base of the competent upper Malm layer (top "Argovian") in the Neuchâtel Canton (Fig. 4.4a).

The rhomb shaped structure of the Val de Ruz basin, with sharp bends of more than 35°, has been analyzed at different scales by Tschanz & Sommaruga (1993) in order to better constrain the various possible models for its development. Detailed structural studies within the differently oriented portions of the anticlines show that ENE-WSE trending anticlines are formed as cylindrical folds, whereas the NNE-SSE trending anticlines are non-cylindrical, with important discrepancies of up to 30° between measurable strike (bedding and local

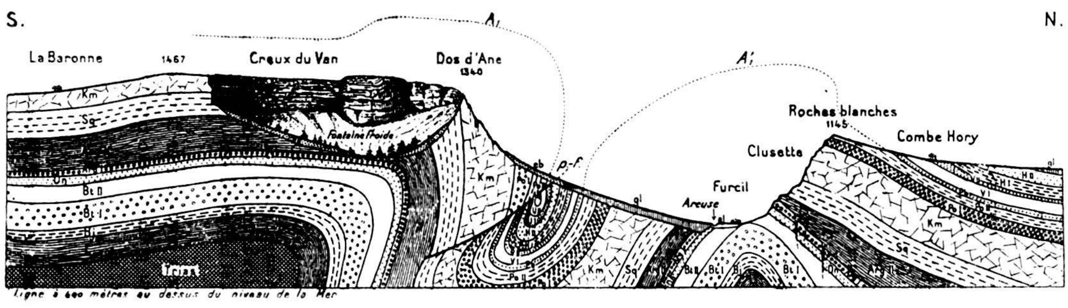


Fig. 92. — Coupe du Creux du Van et de la Vallée de l'Areuse, d'après H. SCHARDT et AUG. DUBOIS (*Eclogae Geol. Helv.*, VII, n° 5, pl. 13, Profil 1, 1903).

Échelle de l'original 1 : 15 000. Réduction à 1 : 30 000.

Légende. *Jurassique :* L. Lias; Bj. Bajocien; Bt I. Bathonien inférieur; Bt II. Bathonien supérieur; Dn. Dalle nacrée (Callovien); Arg I. Argovien inférieur (Spongitien); Arg II. Argovien supérieur; Sq. Séquanien; Km. Kimeridgien; Po I. Portlandien inférieur; Po II. Portlandien supérieur. — *Crétacique :* V I. Valangien inférieur; V II. Valangien supérieur; H I. Hauterivien inférieur; H II. Hauterivien supérieur; U I. Urgonien inférieur; U II. Urgonien supérieur. — *Tertiaire :* Aq. Aquitanien. — *Quaternaire :* gl. Moraines; al. Alluvions; eb. Eboulis.

From Schardt & Dubois 1903

Figure 4.2: Cross-section of the Creux du Van anticline and the Val de Travers (Areuse valley) syncline located in the western Neuchâtel Jura. From SCHARDT & DUBOIS (1903). For location see Figure 4.7b or Figure 4.9.

Coupe géologique de SCHARDT & DUBOIS (1903) de l'anticlinal du Creux du Van et du synclinal du Val de Travers (Gorges de l'Areuse), Jura neuchâtelois occidental (pour la localisation voir Figure 4.7b et Figure 4.9).

Figure 4.4a (page 117, top): Three-dimensional view towards the NE representing the base of Malm limestones (top of "Argovian" marls) in the Canton of Neuchâtel, based on data from a structural contour map (KIRALY, 1969). Vertical axes are in meters above sea level and horizontal axes are in kilometers (Swiss geographic coordinate grid).

Vue tridimensionnelle vers le NE, représentant la base des calcaires du Malm (toit des marnes argoviennes) dans le Canton de Neuchâtel, basée sur les données de la carte structurale de KIRALY (1969). L'axe de coordonnées vertical est exprimé en mètres au-dessus du niveau de la mer, l'axe horizontal en kilomètres (grille de référence des coordonnées géographiques suisses).

Figure 4.4b (page 117, bottom): Three-dimensional view towards the NE representing the base of Malm limestones (top of "Argovian" marls) from the Canton of Neuchâtel, the Risoux-Mt-Tendre-Pontarlier Jura area and the Molasse Basin. This three dimensional view is based on structural contour maps from KIRALY (1969, Neuchâtel area) and from AUBERT *et al.* (1979, Risoux-Mt-Tendre Pontarlier area) and from results of this work in the Molasse Basin. Vertical axes are in meters and horizontal axes are in kilometers (Swiss geographic coordinate grid). Compare the lateral continuity of the anticlines between the Neuchâtel and the Risoux-Mt-Tendre Jura.

Vue tridimensionnelle vers le NE représentant la base des calcaires du Malm (toit des marnes argoviennes) dans le Canton de Neuchâtel, dans la région jurassienne du Risoux-Mt-Tendre-Pontarlier et dans le Bassin molassique. Cette vue 3D est basée sur les données de la carte structurale de KIRALY (1969, région de Neuchâtel) et de AUBERT et al. (1979, région du Risoux-Mt-Tendre-Pontarlier). L'axe de coordonnées vertical est exprimé en mètres au-dessus du niveau de la mer, l'axe horizontal en kilomètres (grille de référence des coordonnées géographiques suisses). Comparer l'extension latérale des anticlinaux du Jura neuchâtelois et vaudois (Risoux-Mt-Tendre).

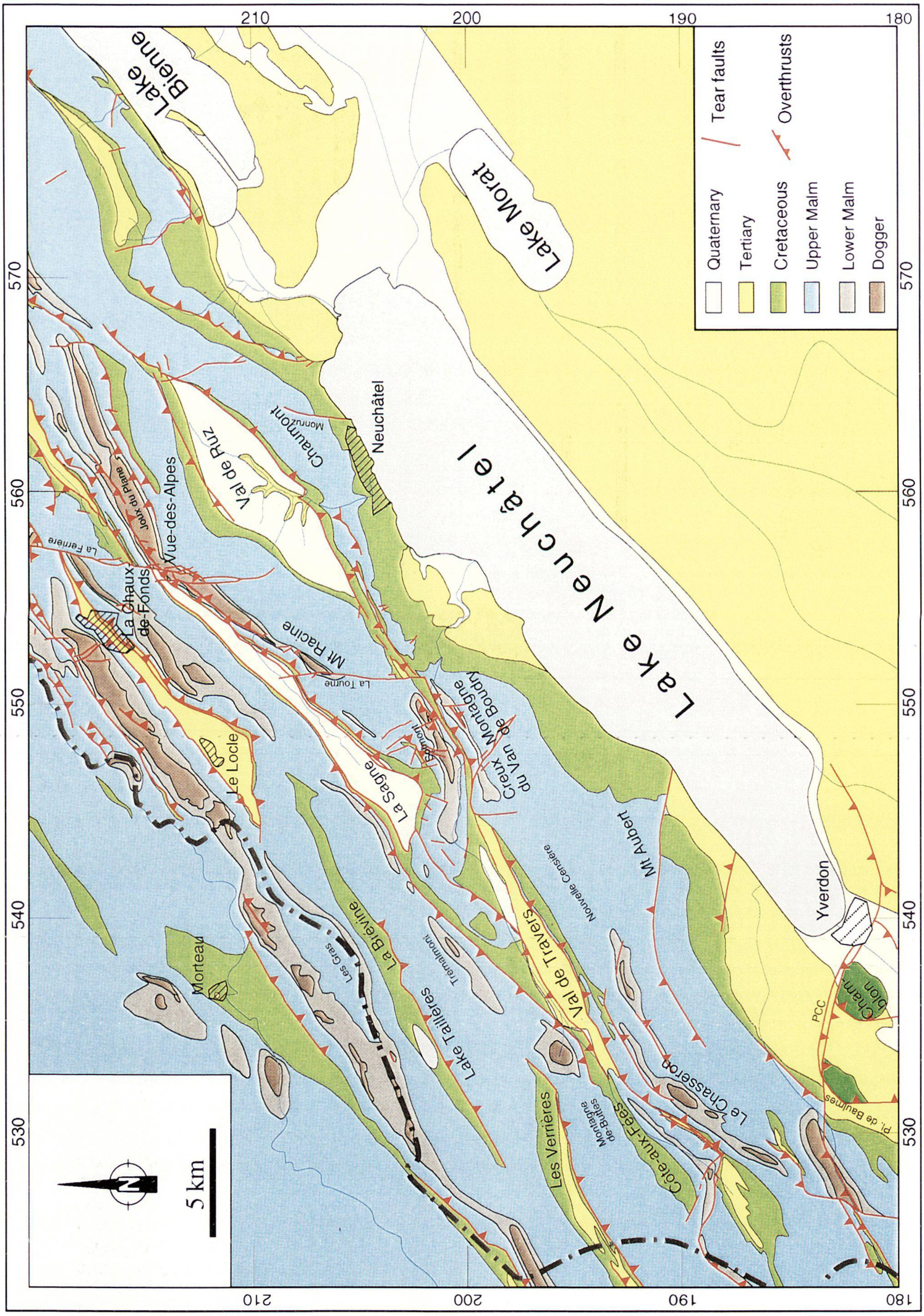


Figure 4.3: Tectonic sketch of the Neuchâtel Jura based on 1:200'000 tectonic sketches of published local maps (see texte for references).

Carte tectonique du Jura neuchâtelois basée sur les esquisses tectoniques, à l'échelle 1:200'000, des cartes régionales publiées (voir texte pour les références).

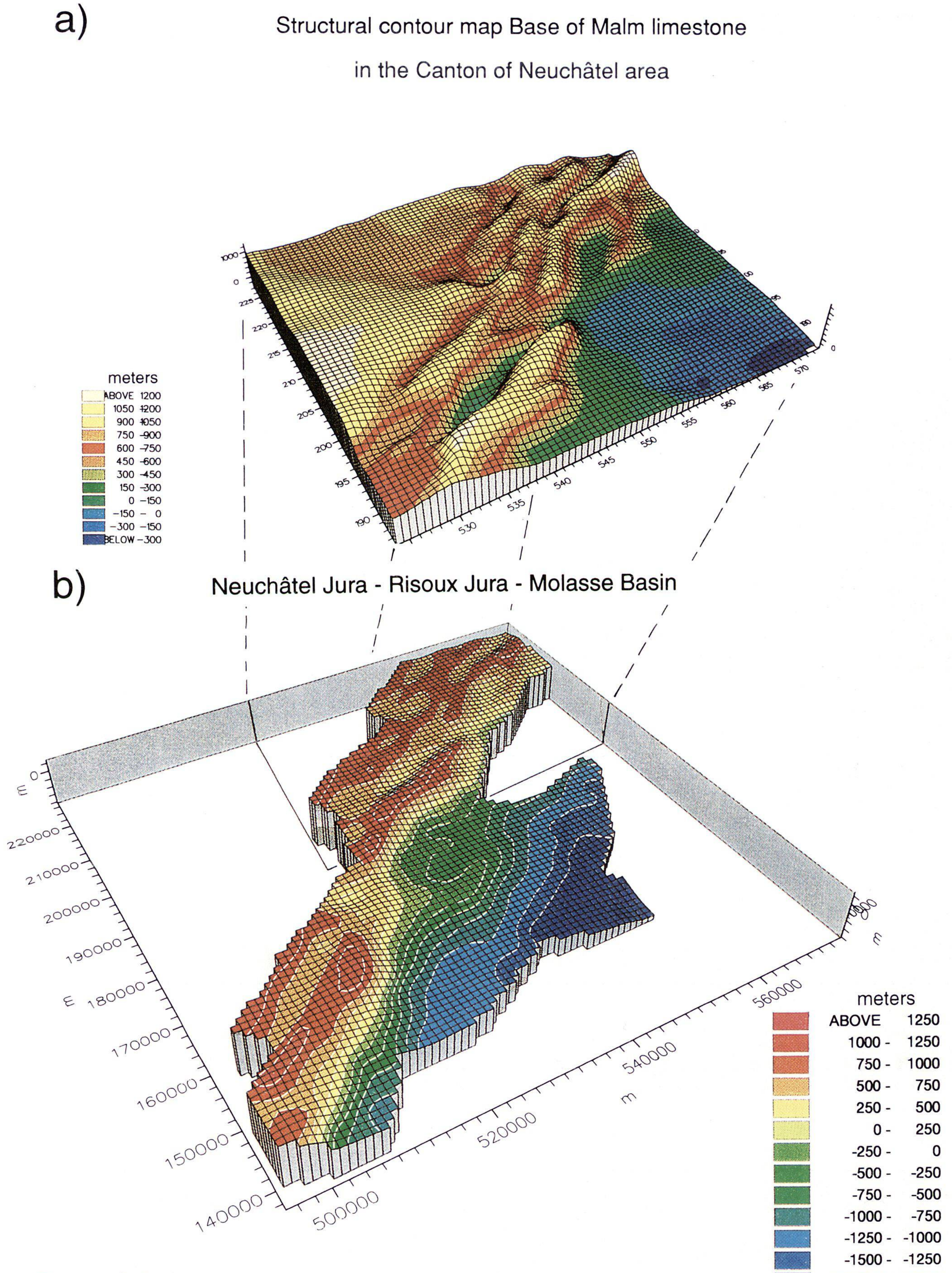

a)
Structural contour map Base of Malm limestone
in the Canton of Neuchâtel area
meters
ABOVE 1200
1050 -1200
900 -1050
750 -900
600 -750
450 -600
300 -450
150 -300
0 -150
-150 - 0
-300 -150
BELOW -300
b)
Neuchâtel Jura - Risoux Jura - Molasse Basin
meters
ABOVE 1250
1000 - 1250
750 - 1000
500 - 750
250 - 500
0 - 250
-250 - 0
-500 - -250
-750 - -500
-1000 - -750
-1250 - -1000
-1500 - -1250
BELOW -1500
220000
210000
200000
190000
180000
170000
160000
150000
140000
500000
520000
540000
560000
m

Figure 4.4

fold axes directions) and the map scale fold axes directions. The direction of map scale anticlines was determined from the geological maps of Neuchâtel and Val de Ruz at 1:25'000 scale (Bourquin *et al.*, 1968; Frei *et al.*, 1974) and a compiled structural contour map. Local anticline directions have been determined from dip and azimuth data compiled from several maps and then plotted on stereograms in order to obtain a best fit local fold (Mancktelow, 1989, Stereoplot computer software). Tschanz & Sommaruga interpret cylindrical folds as folding above a frontal ramp and non-cylindrical folds as folding above an oblique ramp, with an overall transport direction to the NNW (335°). This interpretation is corroborated by the direction of paleo-stress axes determined from fault/slickenside pairs as well as from twin strain analyses. Local maximum compression directions are invariably NNW-SSE to NW-SE oriented, regardless of the position within the rhomb shaped structure.

Strike seismic profiles within the Val de Ruz basin are of excellent quality and show strong and flat reflectors with a good lateral continuity (Section 8, and eastern part of Section 4 on Panel 3). Seismic intervals have been defined on strike Section 8 as discussed in §2.4.1 (Fig 2.15). No major structural features are recognized in those two lines. The slight bends of the basement top reflector are interpreted as velocity pull-up beneath the anticlines and pull-down beneath the Val de Ruz syncline. Due to a strong increase in thickness of Tertiary and Quaternary sediments from NNW to SSE within the syncline (Mornod, 1970; Schnegg & Sommaruga, 1995) reflectors are pulled down in the southern part of the Val de Ruz basin. On the dip seismic lines crossing the Val de Ruz basin (Sections 1, 3, 5 on Panel 1), the changes in width of the syncline are clear: on the eastern line the syncline is already broad, in the middle it is the widest (Section 3) and then it narrows towards the West, to finally end against the La Tourne tear fault. In this area, seismic data are of poor quality, probably due to the topographic effects and/or the complexity of the structures. Therefore surface geological data are required in order to obtain a clear understanding.

Three major N-S tear faults have been mapped around the Val de Ruz syncline (Fig. 4.3): the La Tourne fault in the western part, the La Ferrière fault in the northern and central part and the Monruz fault in the south-eastern part. These faults, of kilometric length, have an apparent sinistral offset of few hundred meters on the map and coincide (especially the La Ferrière fault) with the position where the mapped fold axes change direction. This suggests that these fracture zones have possibly predetermined the position of oblique and/or lateral ramps and can thus be interpreted as faults reactivated during the late Miocene folding of the Jura. Alternatively, these faults may have developed only during folding. Fault/slickenside analyses from the vicinity of tear faults indicate that these were active still after the major folding phase, since sub-horizontal striations are frequently found on faults cross-cutting vertical bedding planes (Tschanz & Sommaruga, 1993). Directions of paleo-stress axes for the past 10 Ma are indistinguishable from present day maximum horizontal stress directions.

Seismic lines do not offer any evidence for inherited or newly developed Oligocene tear faults, as suggested by Aubert (1972) and Bergerat (1987). On the seismic lines, described in Chapter 3, tear faults appear as transparent zones, thus explaining why the La Ferrière and La Tourne faults are not clearly recognizable on Sections 3 and 7, respectively.

Val de Ruz cross-section

A geological cross-section (Fig. 4.5) based on surface dip data and completed at depth with information from seismic data, has been constructed parallel to seismic Section 8 (Panel 1) in the Val de Ruz area. This cross-section has been modified from that presented by Sommaruga & Burkhard (1997). The availability of a dense seismic grid has better constrained the depth to the basement, which now lies at greater depth in this modified version (Fig. 4.5).

From SE to NW, the geological section crosses two major anticlines. These thrust-related anticlines, previously discussed in Chapter 3, formed firstly as detachment folds (or buckle folds) and then developed into fault-propagation or fold-bend folds, thus forming a complex structure e.g. La Vue des Alpes anticline (Sommaruga & Burkhard, 1997, see map of Figure 4.3). The interpretation of the seismic line (Section 8) suggests the presence of a rather smooth thrust, separating a relatively uniform dip domain with gently SSE dipping layers in the footwall, from a more strongly folded and/or faulted hangingwall. A very good correlation between SSE-vergent kink folds at the surface and SSE vergent (blind?) thrust faults at depth is observed. The southernmost of these backthrusts seems to be located above the area where the NNW thrust branches off from the basal décollement zone. Other backthrusts are unrelated to bends in the main thrust fault.

Further North, two more foreland vergent thrust faults have been postulated, based on surface geology in combination with interpretations of seismic lines. The La Chaux de Fonds syncline is located at a high elevation possibly due to a thrust fault within the Triassic beds. Further North (1 or 2 km), an anticline is related to this thrust fault.

The geological section (Fig. 4.5) crosses the La Ferrière fault which adds to the complexity of the broken up anticline near La Vue des Alpes. The extension of this fault at depth is unknown. In constructing the cross-section, this fault has been ignored, because no evidence for its presence has been found on seismic lines. If this tear fault represents a post folding feature only, its overall apparent sinistral offset of ca. 500 m should be compensated by a stretching of the section by a similar amount. On seismic Section 8, however, reflectors on either side of the supposed fault trace at depth could be correlated without major offset, suggesting that the La Ferrière fault could be a superficial tear fault.

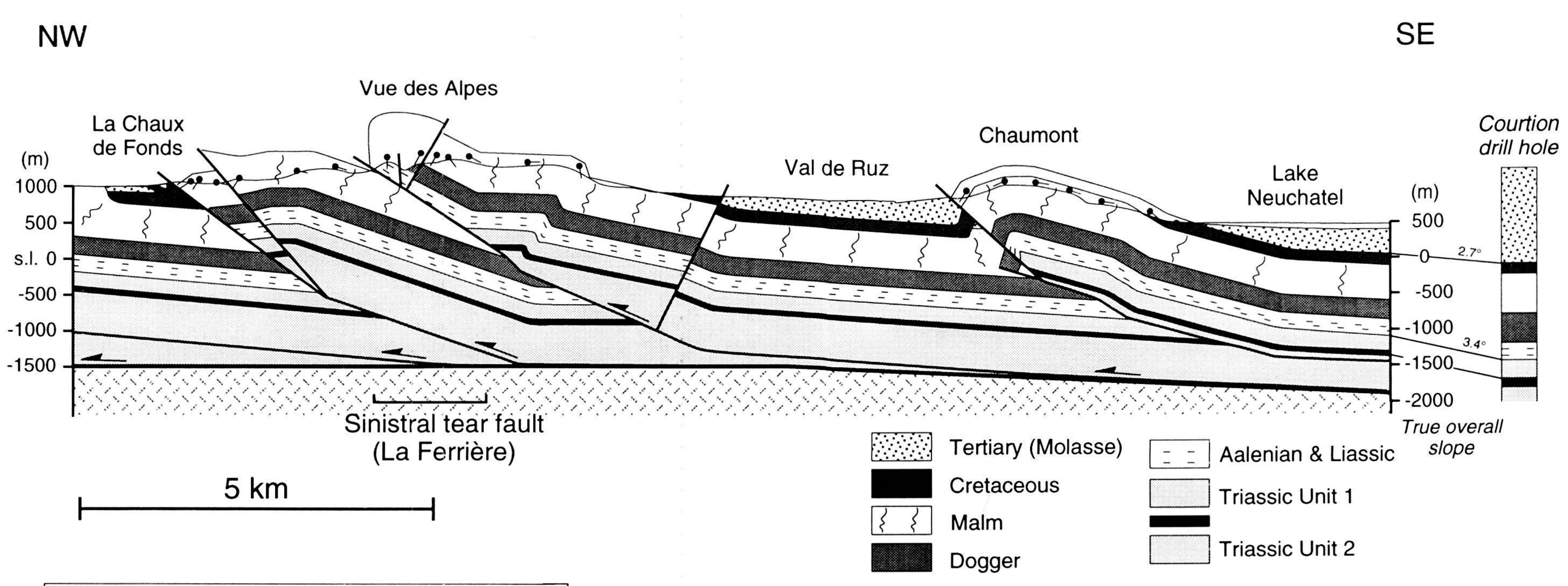
4.2.3. Western part

The western part of the Neuchâtel Jura is located between two tear faults: the La Tourne fault to the East and the Pontarlier fault to the West. In its northern part, this region is characterized by anticlines and synclines oriented NE-SW with a lateral continuity of about 15 km to 20 km e.g. the La Brévine and Morteau synclines. The central part appears much more complex, as shown on the tectonic sketch (Fig. 4.3). A detailed map analysis has been conducted in the Travers region, in order to better visualize the relations between the structures. Since no 1:25'000 scale map of this region has been published yet, a compilation (Fig. 4.7a) has been made of several unpublished maps (Schardt & Dubois, 1903; Rickenbach, 1925; Thiébaud, 1936; Frei, 1942; De Pury, 1963; Meia, 1969; Frei *et al.*, 1974; Meia, 1986; Müller, 1958).

The Travers area is characterized by several large scale structures illustrated on the tectonic sketch of Figure 4.7b. To the North, the St-Sulpice-Trémalmont-Les Combes Derniers anticline forms a continuous, NE-SW oriented, feature with lower Malm and Dogger layers outcropping in the core. This structure grades northward into the narrow, flat bottomed La Brévine syncline. In the southern part of the area, the anticline is thrust towards the South over adjacent synclinal structures along a south-vergent fault surface. To the South, the Travers area is bordered by the NE-SW trending Nouvelle Censière-Creux du Van-Montagne de Boudry anticline. This structure is large and flat topped in the SW (Nouvelle Censière), whereas in the NE erosion allows insight in the tighter anticlinal core (Creux du Van-Montagne de Boudry). Along the southern border of the Areuse valley, the core is related to a north-vergent thrust and represented by Dogger strata. In the central portion, this anticline is cut by a conjugate set of tear faults, consisting of a N-S oriented set with sinistral offset and a NW-SE oriented set with a dextral offset. This is a typical orientation for tear faults in the central Jura. Between the two anticlines, a complex set of structures has developed. The most prominent are, to the NE, the La Sagne syncline oriented NE-SW and, to the SW, the ENE-WSW trending Val de Travers syncline. Both synclines are broad, flat bottomed and covered by Tertiary and/or Quaternary sediments. They are also overridden both from the NW and the SE by south-vergent and north-vergent thrusts respectively. Along its northern limit, the Val de Travers syncline is bordered by two small synclines oriented NE-SW and oblique to the Val de Travers, but pinches out to the East. Further to the E, the very tight Areuse syncline, like the Val de Travers syncline, is overridden to the North and the South by south-vergent and north-vergent thrusts respectively. The southern thrust (along the northern limb of the Montagne de Boudry-Creux du Van anticline) extends eastward into the N-S oriented, left-lateral La Tourne tear fault. The very narrow width of the Areuse syncline is unusual for the Neuchâtel Jura, where synclines are generally quite large, as shown by the Val de Ruz-La Sagne-Le Locle Valleys (Fig. 4.3).

Most remarkably, the Solmont anticline runs NE-SW in its eastern part, changing to a WNW-ESE orientation in its western part, where it separates the La Sagne and Val de Travers synclines. Its continuation is probably the Crêt Pellaton anticline, whose central portion is cut by a fault.

Thus between two continuous NE-SW oriented major anticlines, the southern of which is related to an foreland-vergent thrust fault and the northern to a hinterland-vergent fault, we observe a complex transfer zone, where displacement is relayed between two large en echelon synclines (La Sagne, Val de Travers). Its further noteworthy, that the La Tourne tear fault grades into a north-vergent thrust at the base of the Montagne de Boudry anticline.



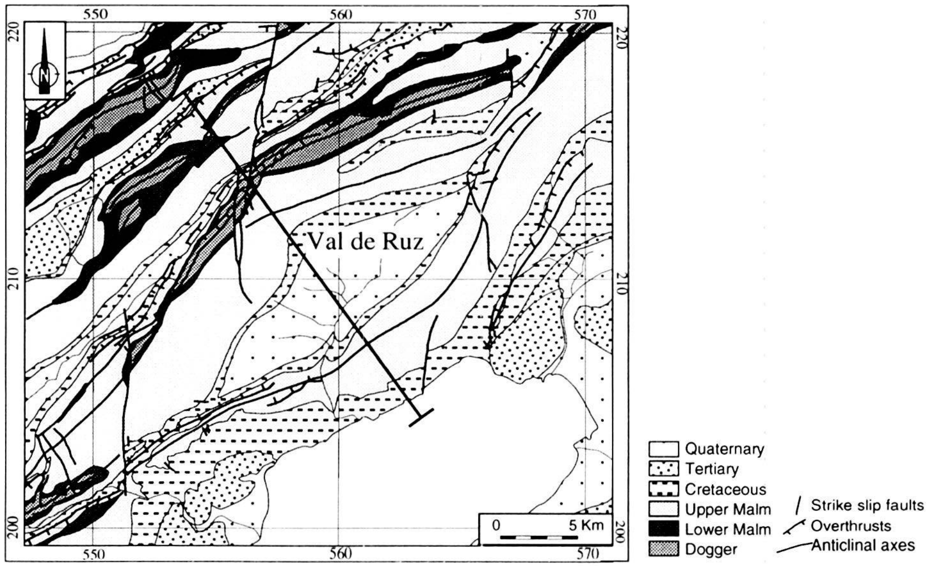
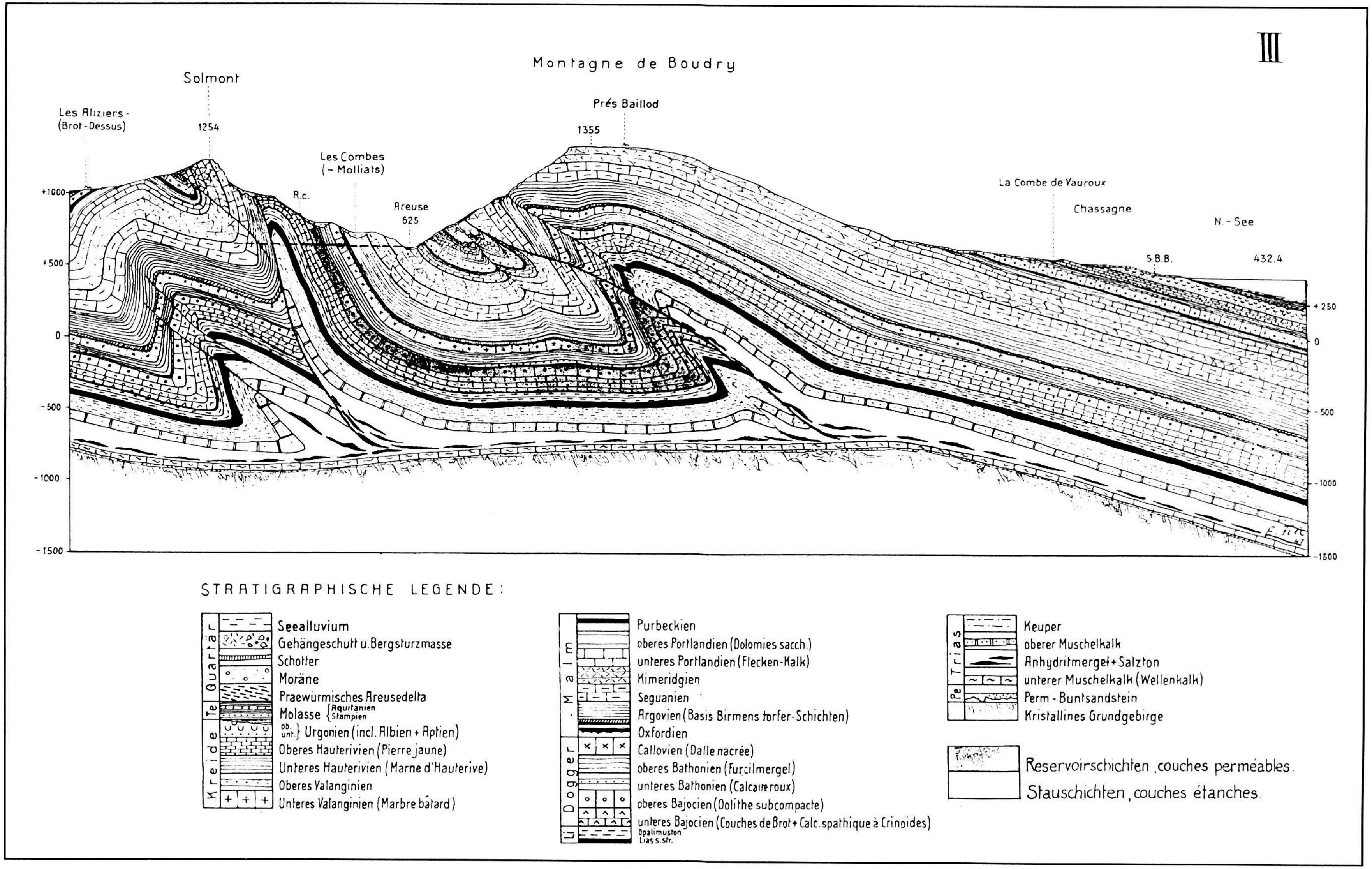


Figure 4.5: Geological cross-section based on surface data, completed at depth with information from seismic Section 3. La Ferrière tear fault is located on the cross-section. The extension of this fault at depth is unknown. During cross-section constructing, this fault has been ignored. The stratigraphy of the Val de Ruz area is correlated with the Courtion drill hole located 18 km to the SSE of the town of Neuchâtel. Modified from SOMMARUGA & BURKHARD (1997).

Coupe géologique basée sur des données de surface et complétée en profondeur avec les informations de l'interprétation du profil sismique 3. La faille de La Ferrière est localisée sur la coupe. La continuité en profondeur de cette faille étant inconnue, il n'en a pas été tenu compte pour la construction de la coupe géologique. La stratigraphie du Val de Ruz est corrélée avec les données du forage de Courtion, situé 18 km au SSE de Neuchâtel. Modifiée de SOMMARUGA & BURKHARD (1997).



From Frei 1946

Figure 4.6: Unpublished geological cross-section of Frei (1946). The section presents an anticline (Montagne de Boudry) related to a thrust fault which roots in the anhydrite layer of the "Muschelkalk" (Triassic Unit 2). Refer to text for discussion. For location see Figure 4.7b

Coupe géologique non publiée de Frei (1946). La coupe présente un anticlinal (Montagne de Boudry) en relation avec une faille de chevauchement qui s'enracine dans les couches du "Muschelkalk" (Unité 2 du Trias). Voir texte pour discussion et Figure 4.7b pour la localisation.

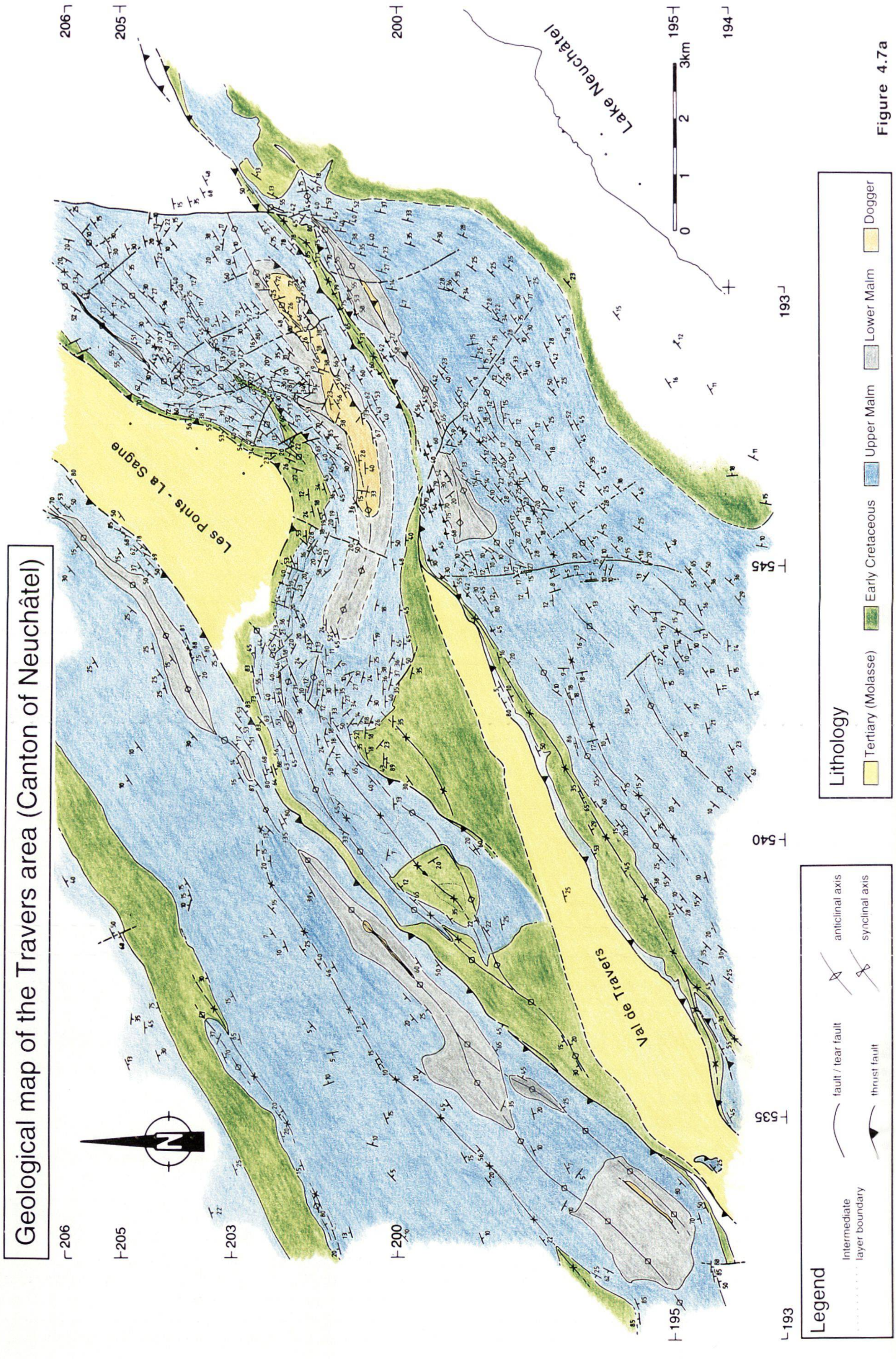

Geological map of the Travers area (Canton of Neuchâtel)
Les Ponts - La Sagne
Val de Travers
Lake Neuchâtel
0 1 2 3km
Legend
intermediate layer boundary
fault / tear fault
thrust fault
anticlinal axis
synclinal axis
Lithology
Tertiary (Molasse)
Early Cretaceous
Upper Malm
Lower Malm
Dogger

Figure 4.7a

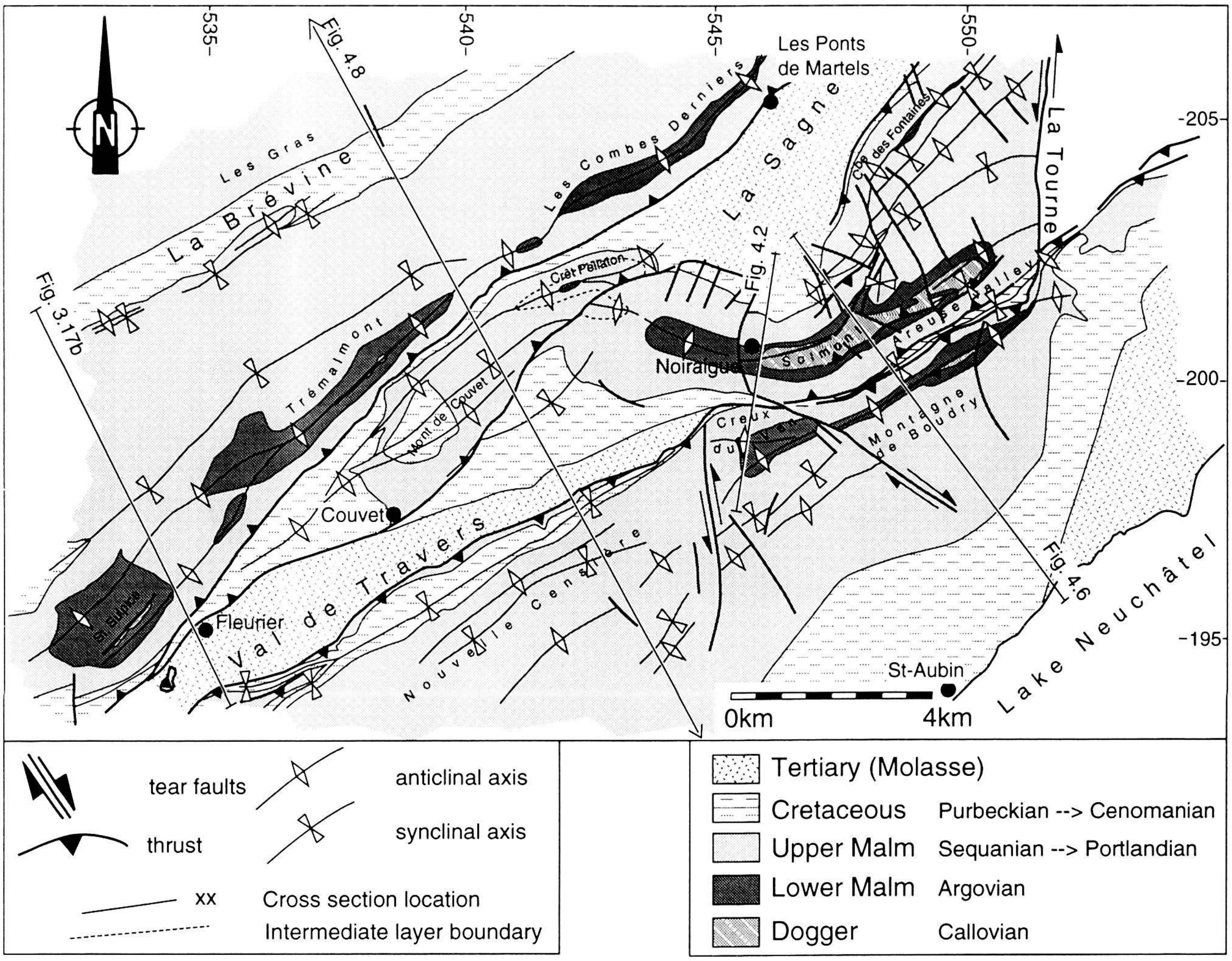


Figure 4.7b:

Tectonic sketch of the structural map of Travers presented in Figure 4.7a with location of cross-sections.

Esquisse tectonique de la carte structurale de Travers, présentée dans la Figure 4.7a. Localisation de plusieurs coupes présentées dans ce travail.

Figure 4.7a (page 122):

Structural map of the Travers region. This map is a compilation and interpretation of several published or unpublished geological maps. See text for references. Small dots (SE Les Ponts-La Sagne valley and Lake Neuchâtel) correspond to end points of three unpublished cross-sections by Frei (1946).

Carte structurale de la région de Travers. Cette carte est une compilation et une interprétation de diverses cartes géologiques publiées ou non publiées. Voir le texte pour les références. Les petits points (au SE de la vallée Les Ponts-La Sagne et dans le lac de Neuchâtel) correspondent à la fin de la trace de trois coupes géologiques non publiées de Frei (1946).

Thus, fold and thrust appear to be contemporaneous with the tear fault, at least in this specific case. Inspection of the tectonic sketch of the Neuchâtel Jura (Fig. 4.3) shows that transfer zones such as that of the Travers area are common in e.g. the Le Locle-La Brévine area or the NW of lake Biel region. However, the Travers area presents the best outcrops.

Unfortunately the seismic line crossing the Creux du Van and Solmont anticlines (Section 9, Panel 2) is of poor quality, probably due to the steep topography and the karstification of the Jurassic limestones. The geology of the Travers area has been illustrated since the beginning of the century in cross-sections by Schardt & Dubois (1903) (Fig. 4.2) and Frei (1946) (Fig. 4.6). The first section oriented N-S, crosses the western part of the Solmont anticline, the Areuse syncline and the Creux du Van anticline. On this section, the latter appears related to a thrust fault, whereas the Solmont anticline does not. The unpublished cross-section by Frei (Fig. 4.6) shows a modern structural concept, in that anticlines are related to thrust faults which root in the Middle Triassic evaporite décollement zone. The top of the basement is flat, showing a minor bend beneath the southern limb of the Montagne de Boudry anticline. Its depth is much shallower than the depth to the top basement presented in the maps of Chapter 5. The results of the seismic interpretation from the western Val de Travers area have shown that the Dogger, Liassic and especially Triassic layers are much thicker than predicted from surface geology.

The structure of the western region of the Travers area (Fig. 4.7b) is illustrated by two seismic lines (Sections 11 and 13 on Panel 2, for location see also Figure 4.3) and by two geological cross-sections (Figs. 3.17b and 4.8). The cross-section of Figure 4.8, running from Lake Neuchâtel to Morteau (for location see Figures 4.3 and 4.9), is based on surface geological data and completed at depth with information from seismic lines. From SE to NW, this section crosses different types of structure: the Mt Aubert dextral tear fault system, the periclinal end of the Mt Aubert anticline, the Nouvelle Censière anticline, the Val de Travers syncline, the Mont de Couvet anticline, the Trémalmont anticline, the Brévine syncline, the Les Gras anticline and the Morteau syncline. All the large scale anticlines are thrust-related structures. The broad Nouvelle Censière thrust-related anticline has already been discussed in Chapter 3. From the interpretation of the seismic lines, duplication of the Jura cover beneath the anticline can be demonstrated.

Dips of 35° towards the South are observed in the northern portion of the Val de Travers syncline, whereas the central portion dips gently to the S, extending far below the broad Nouvelle Censière. The Mont de Couvet area presents, at surface, two short wavelength anticlines related to a hinterland-vergent thrust fault (the southernmost of which corresponds to the Corridor aux Loups anticline). Seismic lines (Sections 11 and 13) in this region present at depth a rather broad anticline, with thickening within the Triassic layers. Both these anticlines and the steeper northern portion of the Val de Travers syncline are related to an important change in thickness of the Triassic series, which appears to originate at the point of development of a complex imbricate thrust fault system linked to the Mont de Couvet thrust fault. Further North, the Trémalmont anticline is related to a backthrust of the broad north-vergent Les Gras anticline that steps up over a ramp and flat thrust surface. This anticline also shows duplication of the Mesozoic cover series.

The Triassic series is less important below the meridional portions of the Nouvelle Censière and Les Gras anticlines. The thickness of these layers increases toward the North of these structures, especially beneath the Val de Travers and the Mont de Couvet, suggesting "flow" of the evaporites under the weight of the overriding broad anticlines.

Thickness changes are also noticeable in Dogger - Liassic strata in the hangingwall of the Nouvelle Censière thrust-anticline, as well as south of the Mont Aubert tear fault; these are thicker compared to those in the footwall, indicating that strata thicken toward the South, in general agreement with the trend of Middle Jurassic facies.

It must be emphasized that the northwestern part of the Neuchâtel Jura is characterized by synclines, that have a higher topographic elevation (e.g. La Brévine, Le Locle-La Chaux-de-Fonds, La Sagne synclines) compared to the southern synclines e.g. Val de Ruz and Val de Travers. This is well shown on the cross-sections of Figure 3.17 and Figure 4.5. Strike seismic Section 2, running parallel to La Brévine syncline, shows a succession of very strong flat reflectors, usefully constraining the seismic stratigraphy. At depth, duplication of the Triassic stratigraphy is observed, explaining the high elevation of the Jurassic, Cretaceous and Tertiary strata. The total thickness of Triassic is around 1000 m. In terms of balancing, the duplication of the Triassic beds represents an important shortening which must

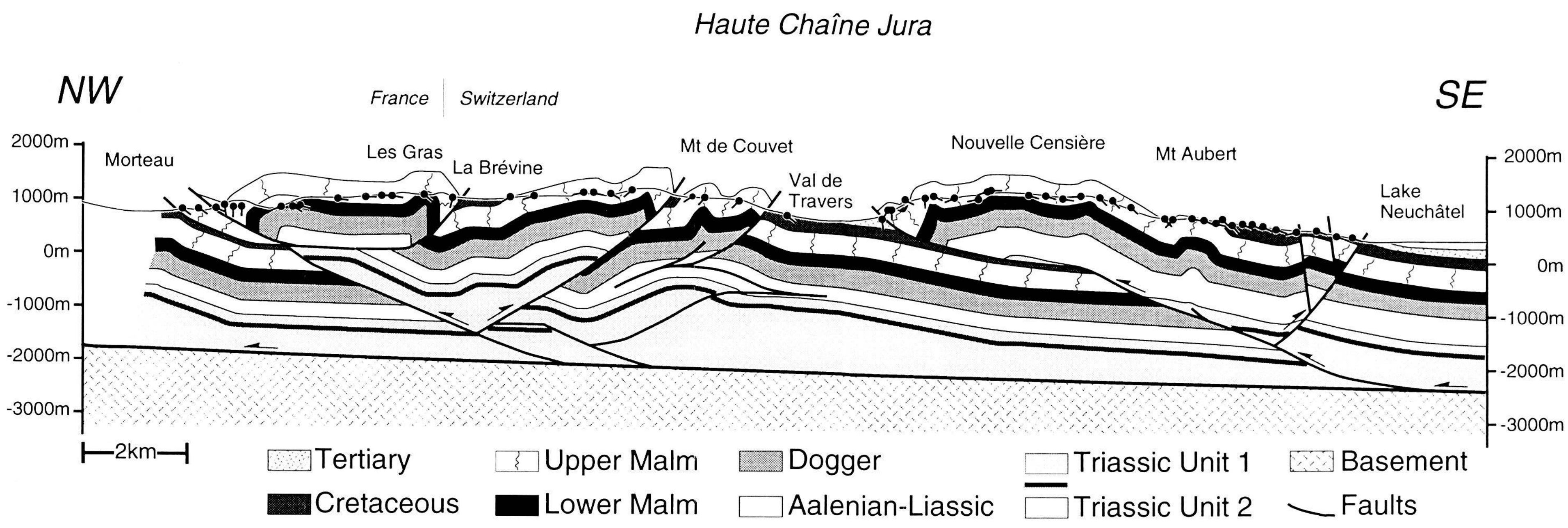


Figure 4.8: Geological cross-section from lake Neuchâtel to Morteau based on surface data and completed at depth with information from seismic Sections 11 and 13. For location see Figure 4.7b and Figure 4.9.

Coupe géologique allant du lac de Neuchâtel à Morteau, basée sur les données de la surface et complétée en profondeur par les informations des profils sismiques 11 et 13. Pour la localisation voir Figure 4.7b et Figure 4.9.

be present in higher Mesozoic rocks and has to be compensated beneath anticlines.

4.3. RISOUX JURA

The following paragraphs discuss the regional geology of the Risoux (sensu lato) area, which consists of the Mont-Risoux (sensu stricto) anticline, the Vallée de Joux syncline and the Mont-Tendre anticline.

4.3.1. Previous studies

The Risoux region located in the Haute Chaîne Jura along the Swiss-French border (Figs. 1.3 and 4.1) has been the subject of many papers. During the last century, the Mt-Risoux anticline was considered to be a simple anticline, because of the apparent lateral continuity of the structures seen at surface. At the beginning of this century, the excavation of the Mont d'Or railway tunnel, located at the eastern end of the Mt-Risoux chain, revealed some unexpected structural complexities (Collot, 1913) (see also cross-section 3 in Fig. 1.5). Some fifty years later, the Risoux well results (Winnock, 1961) showed a major thrust fault separating an upper series, ranging from Malm limestone ("Sequanian-Rauracian" facies) down to Liassic marls in the hangingwall, from a second series, ranging from Malm limestone ("Sequanian-Rauracian" facies) to Bathonian limestone in the footwall. The drill hole log data presented in Figure 2.12 and Figure 2.19 were the first formal proof of tectonic duplication of the Mesozoic cover beneath Jura anticlines. These unexpected results have considerably increased, not only, the understanding of the internal structure of the Haute Chaîne Jura anticlines, but were a major step forward in the tectonics of the Jura fold and thrust belt. The older hypothesis suggesting the Mt-Risoux anticline as "... *masse inerte à peine ébranlée par la poussée orogénique* ..." (Aubert, 1959) was reconsidered by Winnock (1961), Laubscher (1961, 1965) and later again by Aubert (1971). These authors stress the presence of a basal décollement level in the Triassic as postulated much earlier by Buxtorf (1916).

Since the discovery of the tectonic duplication of the Mesozoic cover within the Risoux well, the Risoux area has become a classical region for structural studies in the Jura. Several authors have attempted to explain the geometry and especially the vergence (either foreland or hinterland) of the main overthrust in relation to the anticline using field evidence. For a short review the reader can refer to the paper by Wildi & Huggenberger (1993) and for details see Collot (1913), Aubert (1941, 1945), Winnock (1961), Rigassi (1962), Laubscher (1965), Aubert (1971), Bitterli (1972), Rigassi (1977), Chauve *et al.* (1980), Martin (1987), Philippe (1995).

From this literature, we have singled out the cross-section by Laubscher (1965) presented in Figure 1.5 (cross-section 4) and also that of Bitterli (1972). Laubscher's section crosses two Haute Chaîne anticlines, the Mt-Tendre and the Mt-Risoux, then the whole Plateau Jura domain to end in the Bresse Graben area. The shortening within the Mt-Risoux anticline equals 10 km and the total shortening of the sedimentary cover along the whole section amounts to 25-30 km. The latter agrees with the estimate made using his rotational model of the Jura cover (Laubscher, 1965). Before Laubscher's work, the shortening of the Mesozoic cover was always underestimated. Moreover this section shows a more or less flat basement top, dipping few degrees towards the South.

The geological cross-section of Bitterli has been constructed using surface geology data and subsurface information. In 1972 some seismic lines had already been shot in the Champagnole-Mouthe area (Shellrex concession, Fig. 1.4), located North of the Risoux area. Bitterli completed the northern part of the Mt-Risoux - Mt-Tendre section at depth using these seismic data.

4.3.2. Interpretation

At the surface the Mt-Risoux (sensu stricto) chain shows a large anticline oriented NE-SW, a classical trend for a Jura anticline. It is limited towards the North by the NE-SW oriented Mouthe syncline (the Doubs valley), towards the South by the Vallée de Joux syncline, to the West by the Morez fault and towards the East by the Pontarlier fault. This anticline extends over some 30 km laterally (Fig. 4.1 and Fig. 3.20a).

The Mt-Tendre anticline, located south of the Vallée de Joux syncline (Fig. 4.4b), has a lateral extent of over 25 km and ends westward at the Morez fault and eastward at the Pontarlier fault. The lateral continuity of the Mt-Risoux and Mt-Tendre anticlines across the Morez and Pontarlier faults are not discussed in this work, because more surface geological data are necessary. Recently, PHILIPPE (1995, PhD thesis) proposes an extension of these anticlines beyond the Morez and Pontarlier faults and considers latter faults to be secondary tear faults, where fold axes are offset as passive markers (§3.3.).

The NE-SW trend of the Mt-Tendre anticline axis, sub-parallel to the Mt-Risoux anticline, is emphasized on the three-dimensional view of Figure 4.4b, of the base of the Malm limestones. In the Risoux area the structures are parallel and aligned along one axial trend. This contrasts with the Neuchâtel Jura, where, as explained in preceding paragraphs, the NNE-SSW or ENE-WSW orientation of the anticlines results in a rhomb shaped form in the synclines.

The lateral continuity of the Risoux Jura area is also well shown on the strike profiles running along the northern limb of the Mt-Tendre anticline (Section 86, Panel 8) and the southern limb of the Mt-Risoux anticline (Section 82-80, Panel 8). These sections do not show any lateral discontinuities, except for some zones with poor seismic data quality. They are most valuable in helping to constrain the seismic stratigraphy of the dip sections, which are of poorer data quality. Moreover, these sections highlight the duplication of part of the Jurassic cover, the Dogger and Malm layers.

Four dip profiles crossing the Mt-Risoux and the Mt-Tendre anticlines are presented on Panel 9. Unfortunately, no profile crosses the entire Mt-Tendre anticlinal structure. Seismic interpretation shows that the Mt-Tendre anticline is related to a foreland vergent thrust fault that soles out in Triassic Unit 2. The thrust ramp emerges in the Vallée de Joux syncline. The Mt-Risoux anticline is also related to a major north-vergent ramp which roots in Triassic Unit 2. This ramp breaks surface in the Mouthe syncline. A major shallow dipping backthrust is associated with the frontal ramp. This thrust represents a flat of 4 km in Liassic marls that ends in the Vallée de Joux syncline. The geometrical relationships between thrust faults, syncline and anticline beneath the Vallée de Joux are not clear on the seismic lines, due to poor quality. The shortening within the Mt-Risoux and Mt-Tendre anticlines is more than kilometric, in agreement with estimates by LAUBSCHER (1965).

The interpretation of seismic lines clearly highlights (Panel 9) that the Risoux Jura (sensu lato) is characterized by a succession of two different anticlines, the Mt-Risoux (sensu stricto) and the Mt-Tendre anticline located in the northern and in the southern part, respectively. This structural view has already been expressed by LAUBSCHER (1965) (Fig. 1.5) and PHILIPPE (1995). Other authors, such as AUBERT (1971) and WILDI & HUGGENBERGER (1993) have considered the Risoux (sensu lato, i.e. Mt-Risoux and Mt-Tendre anticlines) as a single thrust sheet rooting in the Triassic evaporite layers further to the South at the border of the Haute Chaîne Jura and Molasse Basin. Their hypothesis suggests shortening of up to 20 km for the Risoux area alone.

Both the Mt-Risoux and the Mt-Tendre anticlines ride above important kilometric thrust faults, leading to a duplication of the entire Mesozoic series (Panel 8 and 9). In a recent publication, based on surface geology data, WILDI & HUGGENBERGER (1993) did not attempt to fill the core of the Risoux anticlines and invoked "volume cachés" (= hidden volumes) between the surface geology and top basement.

Seismic Section 87-85-111 (Panel 9) differs from previous interpretations in identifying an important backthrust associated with the Mt-Risoux anticline.

4.4. THE CHAMPAGNOLE-MOUTHE REGION

4.4.1. General comments

The Champagnole-Mouthe region, as discussed hereafter, extends beyond these two towns as represented on Figure 1.4 (sector D). The Champagnole-Mouthe (sensu lato) name has been chosen for this region, following the name of the seismic survey. This region is located in the Plateau and Faisceau Jura (see Chapter 1). These Plateaux represent large scale flat zones, whereas the "Faisceaux" correspond to strongly deformed zones. The main geological units of the Champagnole-Mouthe region (sensu lato) are (Figs. 1.2 and 4.1.):

- in the North, the "Faisceau bisontin" oriented NE-SW in its northern part and N-S in its southern part (between Besançon and Salins-les-Bains). The Lomont anticline in the northern part forms the link between the external and internal Jura.

- in the central part, the "Faisceau salinois" is oriented ENE-WSW and the "Faisceau de Syam" is

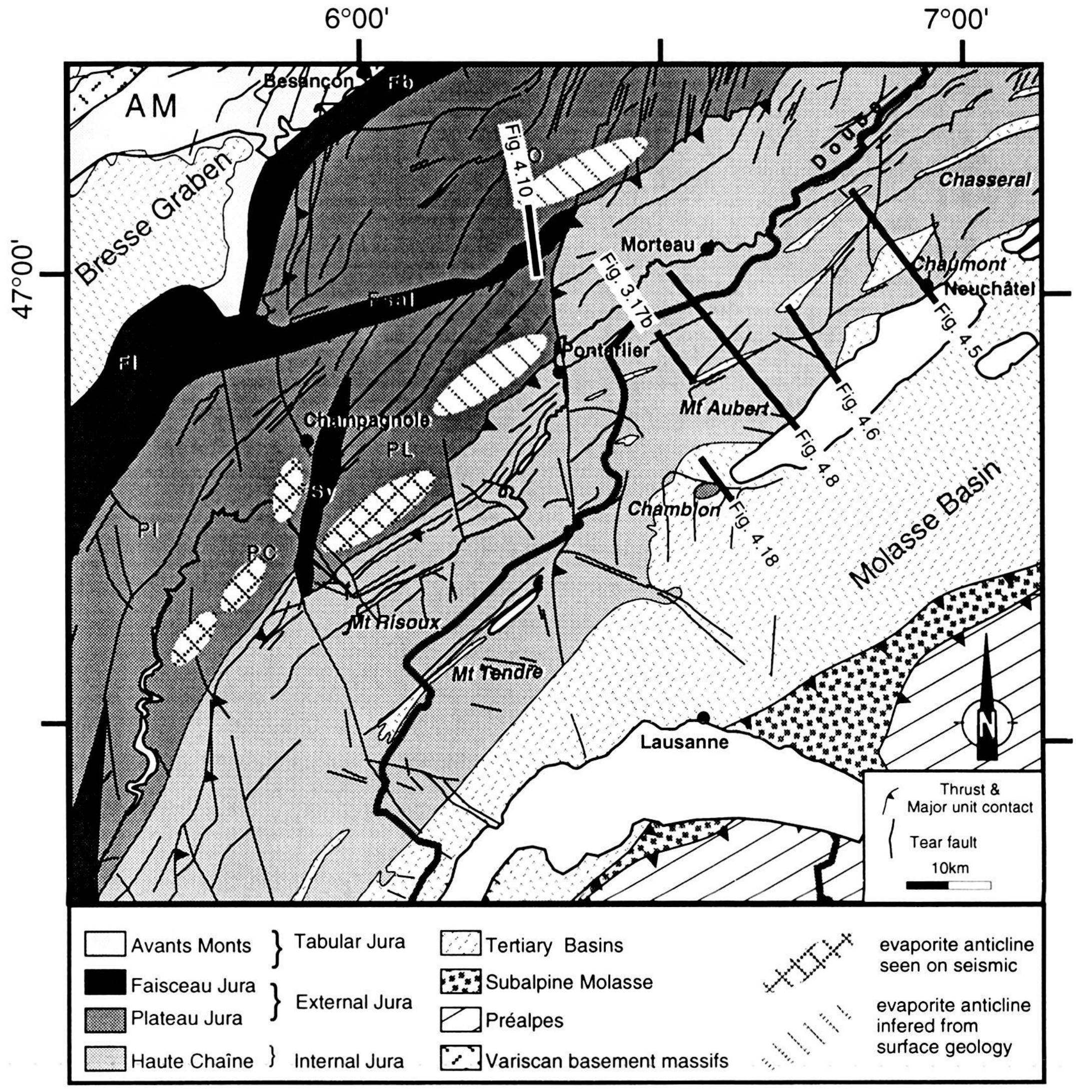


Figure 4.9: Tectonic sketch of the Jura and Molasse Basin with location of the evaporite-related anticlines of the external Jura. Geological cross-sections presented in this work are also located in this Figure. Legend: AM = Avants-Monts; Fb = Faisceau bisontin; Fl = Faisceau lédonien; Fsal = Faisceau salinois; FSy = Faisceau de Syam; PC = Plateau de Champagnole; PL = Plateau de Levier; Pl = Plateau lédonien; PO = Plateau d'Ornans.

Carte tectonique du Jura central et du Bassin molassique occidental montrant la situation des anticlinaux en relation avec les évaporites. Les coupes géologiques présentées dans ce travail sont aussi localisées sur cette figure. Légende: AM = Avants-Monts; Fb = Faisceau bisontin; Fl = Faisceau lédonien; Fsal = Faisceau salinois; FSy = Faisceau de Syam; PC = Plateau de Champagnole; PL = Plateau de Levier; Pl = Plateau lédonien; PO = Plateau d'Ornans.

oriented NNE-SSW. The latter separates two Plateaux, the "Plateau de Levier" to the East and the "Plateau de Champagnole" to the West, whereas the "Faisceaux bisontins, salinois" and the Haute-Chaîne limit the Plateau d'Ornans". The "Faisceau lédonien", corresponding to the outmost northwestern Jura unit, overthrusts the Bresse Graben by a few kilometers (5-7 km) (LIENHARDT, 1962). This important thrust does not outcrop, but has been encountered in many wells (LIENHARDT, 1962; CHAUVE *et al.*, 1988).

- in the southern part, the "Faisceau d'Orgelet and d'Ambérieu" folded and faulted units are directly linked to the Haute Chaîne Jura. No Plateau exists in this region.

4.4.2. Previous studies

The lack of published work on the external part of the Jura, in comparison with the internal part, is due to the scarce geological outcrops in this flat region.

In the northern part, the geological structures of the "Faisceau salinois and bisontin" have been studied by KILIAN (1893), GLANGEAUD (1947), GLANGEAUD & MATTAUER (1955), DREYFUSS (1960), CHAUVE *et al.* (1980; 1988), MARTIN *et al.* (1986). Martin *et al.* suggest a polyphase context for the "Faisceau salinois" formation, resulting in a kilometric translation of the cover towards the NW, concluding that the cover thus needs to be detached in the Triassic evaporites. They also postulate the reactivation of earlier Paleozoic and Oligocene faults.

At outcrop scale, the flat lying series of the Plateau areas show slight deformation: faults and striae, tensions cracks and stylolites witness a N-S to NW-SE oriented compression. These tectonic features have been studied along the whole external Jura, including the Champagnole-Mouthe area, by PLESSMANN (1972, stylolites), SOPENA & SOULAS (1973, faults and striae), BERGERAT (1987, faults and striae), LE PICHON *et al.* (1988), TSCHANZ (1990, calcite twins, stylolites, faults and striae), PHILIPPE (1995). Most of these authors infer two to three main tectonic events which are summarized in the paper of HOMBERG *et al.* (1994): 1) N-S Eocene compression; 2) Oligocene extension (WNW-ESE); 3) NW-SE Mio-Pliocene compression. These phases are recognized at large scale from the opening of the Central European Graben system (Rhine-Bresse-Rhône-Limagne) and their timing is constrained by sediments found in these grabens and from volcanic events (BECKER, 1985). Outcrop scale paleo-stress measurements cover the Jura and adjoining platforms. The third phase results in reactivation of Paleogene structures. The interpretation of these paleo-stress results is unclear, since the present day orientation of the maximum horizontal stress in the Jura Mountains is N-S in the northern Jura and NNE-SSW in the southern Jura (BECKER, 1987, 1989). Deviation of these data from the uniform NW-SE trend of the central and western European stress field (BECKER & WERNER, 1995) suggests care as required in interpreting paleo-stress results from the Jura.

4.4.3. Interpretation

Seismic lines crossing the external Jura have highlighted some important features, especially beneath the Plateau Jura. In the southern region of the "Plateau de Levier" and "Plateau de Champagnole" seismic lines show broad anticlines related to evaporite stacking (Panel 10 and Fig. 4.1), whose geometry has already been described in Chapter 3. The seismic interpretation indicates important thickening in the Triassic Unit 2. The Laveron well (Fig. 2.12) encountered up to 1400 m of Triassic strata. The location of the thick zones within the Triassic Unit 2 has been mapped on Figure 4.9, which shows two zones of aligned isopach thicks. The first, oriented NE-SW, is located in front of the Risoux area (Haute Chaîne Jura), between the "Faisceau de Syam" and the Mouthe tear fault and the second, oriented NNE-SSW, located in the Champagnole Plateau, in front of the Haute Chaîne anticline, stops against the south-western border of the "Faisceau de Syam". Apparently evaporite-anticlines are located in front of the Haute Chaîne anticlines and many stop against a tear fault or a Faisceau zone, e.g. Sections 107, 117 on Panel 10 and Section 111 on Panel 9. Unfortunately seismic lines show transparent zone across tear faults and Faisceau zones and as a result it is impossible to observe the precise relationship between evaporite-anticlines, Faisceaux and tear faults. In the northern area of the Plateaux, the quality of seismic lines does not allow interpretation of any features.

In the Faisceau zones, because of very poor seismic data quality, surface geology remains the best constraint. Along the deep cut of the Loue river, strata seen in the cliffs represent the transition from the "Faisceau salinois" to the "Plateau d'Ornans". DREYFUSS (1960) and later AUBERT *et al.* (1980) have drawn a cross-section showing the relationship between the different outcrops. Based on these surface geological data, a new cross-section has been constructed, including the entire stratigraphic succession down to the basement (Fig. 4.10, location on Figure 4.9). This geological section indicates a kilometric shortening in the cover. The south dipping Malm layers in the footwall and to the North of the main thrust (see cross-section from Dreyfuss) most likely correspond to thickening within the Triassic layers. The overload of the hangingwall to the South may induce evaporite flow toward the North. Similarly, such flowage possibly contributed to enhance the evaporite stack in the footwall of the Mt-Risoux anticline (see Section 111 on Panel 9).

The same relationship between the footwall Cretaceous layers and the faulted Jurassic hangingwall layers in the cross-section of Hautepierre (Fig. 4.10) has been well described along the southern border of the Verrières syncline by MARTIN *et al.* (1991).

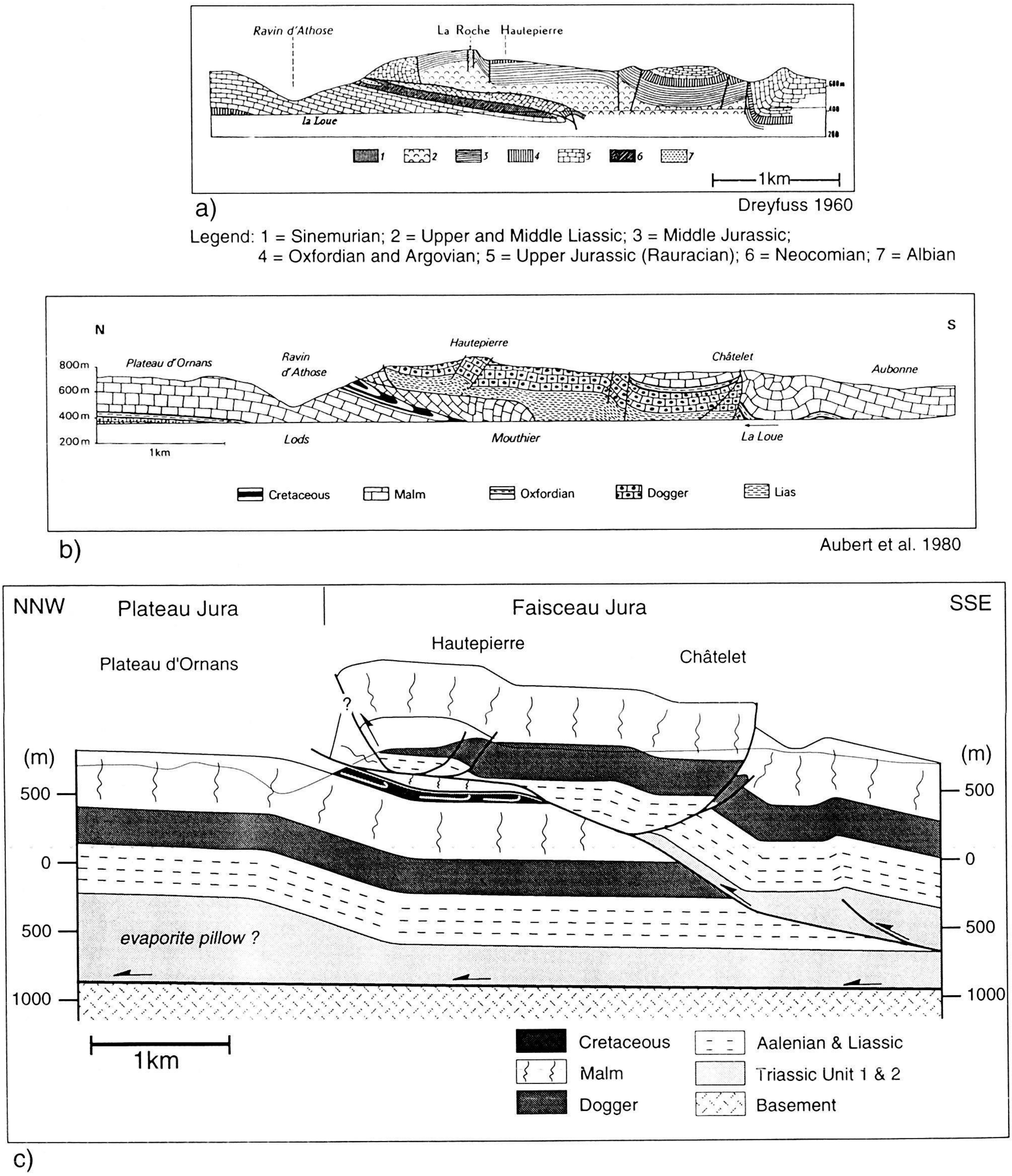


Figure 4.10: Geological cross-sections of the transition from Faisceau Jura (Faisceau salinois) to Plateau Jura (Plateau d'Ornans). For location see Figure 4.9.
a) Surface geological cross-section made by DREYFUSS (1960).
b) Surface geological cross-section made by AUBERT *et al.* in TRÜMPY (1980).
c) Deep cross-section based on surface data from Dreyfuss and Aubert *et al.* and subsurface interpretation of seismic lines. The section shows a thrust-related anticline in the Faisceau Jura and an evaporite-anticline or a pillow at the front of the high amplitude anticline.

Coupes géologiques montrant la transition entre le Faisceau salinois et le Plateau d'Ornans. Pour la localisation, voir Figure 4.9.
a) Coupe géologique de surface dessinée par DREYFUSS (1960).
b) Coupe géologique de surface dessinée par AUBERT et al. dans TRÜMPY (1980).
c) Coupe géologique dessinée à partir des données de la surface de Dreyfuss et Aubert et al. et des interprétations des profils sismiques. La coupe montre dans le Faisceau jurassien un anticlinal en relation avec un chevauchement. Dans le Plateau jurassien, on observe un anticlinal d'évaporites ou un coussin d'évaporites au front d'un anticlinal de grande amplitude.

4.5. THE WESTERN MOLASSE BASIN

4.5.1. Previous studies

Research on the stratigraphy and the sedimentology in the western Molasse Basin has a long history. Lithostratigraphic logs (e.g. Fig. 2.9) have been established since the beginning of the century and detailed stratigraphic correlations along the Molasse Basin are not so straightforward, due to the lateral changes of facies and especially to the scarcity of outcrops (references concerning the stratigraphy of the western Molasse Basin have been cited in Chapter 2).

Few structural studies of the Molasse Basin have been published, due to the scarcity and poor quality of outcrops and the extensive cover by ground moraine. Furthermore, the gentle dip of the bedding requires careful collection of much data to map structures. During World War II, many Molasse areas were precisely mapped for oil exploration, resulting in detailed structural maps (ALTHAUS & RICKENBACH, 1947, 1952; SCHUPPLI, 1950), which show the main anticline and syncline structures and the major tear faults.

Recently, the availability of modern industry seismic lines has allowed elucidation of the stratigraphy and the structures beneath the Tertiary sediments. Structural interpretations and a contour map of the base of the Molasse sediments have been presented by JORDI (1990, 1993) for the Yverdon-Lake Morat region, by GORIN *et al.* (1993) for the Lausanne and Geneva Cantons region and by SIGNER & GORIN (1995) for the Geneva area. All these interpretations show that the Plateau Molasse consists of a weakly deformed Tertiary clastic wedge thinning towards the Jura belt and onlapping the top Mesozoic strata towards the N-NW.

4.5.2. Interpretations and contour maps

Surface geological maps from the Plateau- and Subalpine Molasse (ALTHAUS & RICKENBACH, 1947; SCHUPPLI, 1950; BERSIER, 1952; VERNET, 1972; WEIDMANN, 1988, 1992; JORDI, 1994) give an overview of the major structures that involve the Cenozoic and Mesozoic strata i.e. tear faults, broad folds and thrust sheets. These features have also been recognized in the subsurface and are interpreted on Panels 4, 5, 6. Seismic lines are mostly located in the Plateau Molasse, except for two lines, Sections 43 and 45, which extend into the Subalpine Molasse, because of their greater length.

In the Molasse Basin, Cenozoic strata are onlapping the Mesozoic beds. On most strike lines, they appear strictly parallel. In some dip lines, located in the southern Molasse Basin e.g. Section 43 on Panel 5, Tertiary sediments onlap clearly onto the underlying strata. Onlaps have been observed mostly on south dipping limbs of structures. The interpretation of these onlaps is discussed in Chapter 3 and Chapter 5.

At a large scale, the Mesozoic strata of the Plateau Molasse dip to the SE, as demonstrated by subcrop contour maps of the top of the Cretaceous, upper Malm, "Argovian", Dogger, Triassic Unit 1 and Triassic Unit 2 layers (Figs. 4.11 to 4.17) within the western Molasse Basin. These contours maps are based on depth conversion of the seismic lines and have been calibrated by well log data. Seismic velocities used for each seismic unit are presented in Appendices 3. Contours have been calculated by computer, using a bilinear interpolation method. Tear faults, as known from geological maps and surface data, as well as seismic interpretation, have been imposed as discontinuities in the contour calculations. As a result small zones due to insufficient data density (blank zones in the maps) appear during contouring in the vicinity of these faults. Furthermore, minor closed contours may in some cases also represent contouring artifacts. Despite these contouring artifacts, the complete original computer contoured maps are presented here, because they clearly and objectively show large scale regional trends.

All these maps highlight a hinterland-dipping Mesozoic monocline with a NE-SW structural trend, except along the south-western and northern edges which are unfortunately not well constrained by data and are crossed by several faults. Cretaceous, upper Malm and Triassic Unit 1 depth maps clearly show a depression located between the two major tear faults (on the West Pontarlier fault, on the East La Sarraz fault). This structural low has already been noted by GORIN *et al.* (1993) on their schematic Base Molasse map. This depression is located exactly above a thin thickness of Triassic Unit 2 beds (compare Figure 4.11 and Figure 3.6) and therefore seems to be related to it. Other thinning or alternatively thickening shown on the isopach map of Triassic Unit 2 beds (Fig. 2.29, Fig. 3.6) does not seem to have any direct impact for the overlying unit maps. Of course the spacing (200 m) of the depth intervals in Figures 4.11 to 4.17 is too large to resolve structures involving 100, 150 or even 200 m thickness changes.

Isopach maps of Triassic Unit 2 are presented in Figures 2.29 and 3.6. The first figure (Fig. 2.29) has been contoured automatically by computer and the second (Fig. 3.6) has been contoured by hand, but based on the same data set. Both maps highlight elongated or elliptical thickening or thinning of Triassic Unit 2 along a NE-SW trend, parallel to the general trend of the Jura fold belt. The maximal thickness coincides with the most internal Jura anticlines. Some major sinistral tear faults oriented NNW-SSE (Pontarlier fault) to N-S (Yverdon-Treycovagnes area) and the conjugate dextral system WNW-ESE (La Sarraz fault) cross-cut and offset these pillows. In the hand contoured map, computer artifacts have been neglected to produce better lateral continuity of structures and the position of geological surface structures has also been taken into account. Furthermore, the

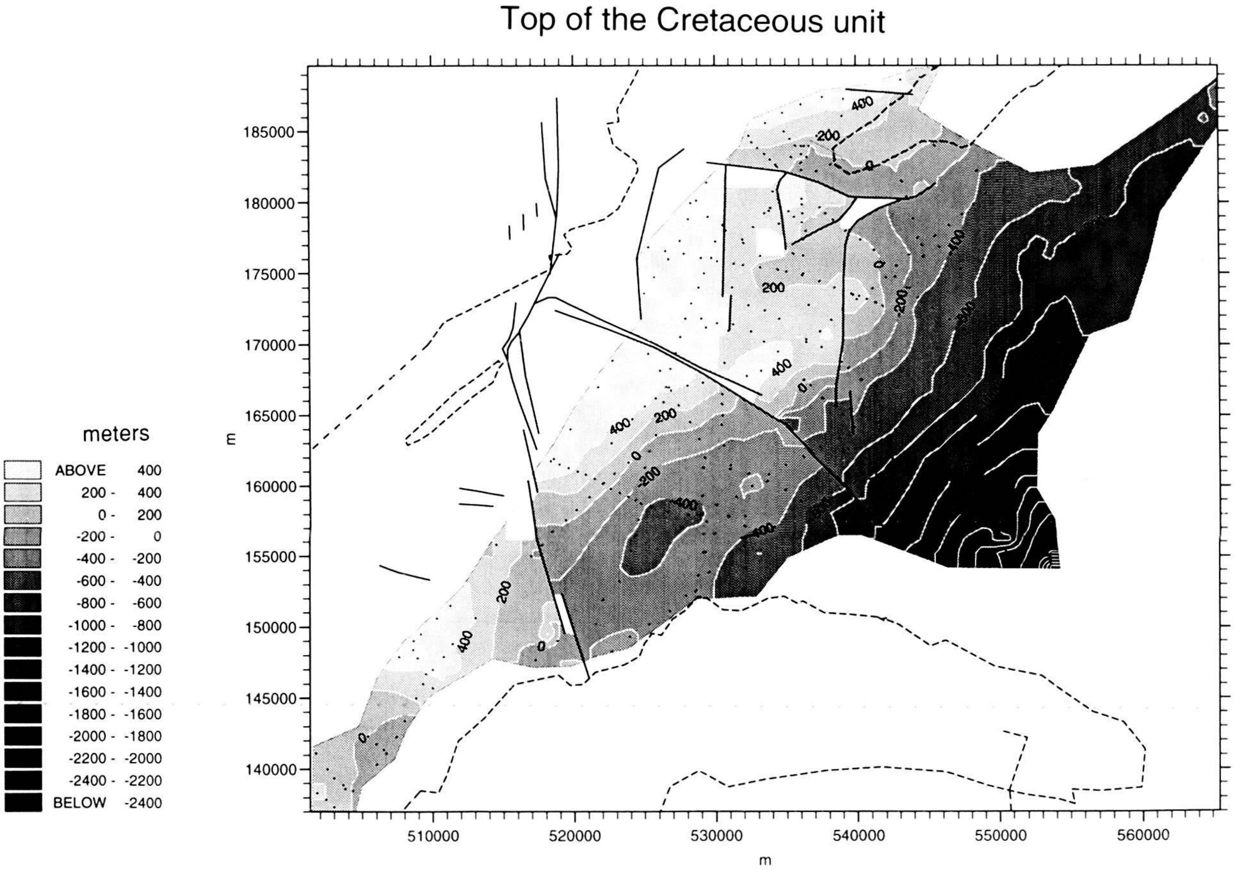


Figure 4.11: Contour map of the top Cretaceous unit in the western Molasse Basin. Depths are in meters. Black dots are shotpoints used for depth control of contour map. Note that blank areas and tight closed circles are computer-related artefacts in areas of sparse control. Numbers on the side and bottom are in meters, that relate to the Swiss national geographical coordinate system. Lakes Geneva and Neuchâtel are outlined for general reference.

Carte structurale des contours du toit des couches du Crétacé dans le Bassin molassique occidental (profondeurs en mètres). Les points noirs représentent la position géographique des points de tir, utilisés pour le contrôle des profondeurs de la carte de contours. Les zones vides et les petits cercles fermés sont des artefacts, dus au programme de contourage, dans des régions où la densité des données est faible. Les coordonnées géographiques (en mètres) se réfèrent à la grille suisse. Les lacs Léman et de Neuchâtel permettent une localisation générale de la carte.

Figure 4.12 (page 133, top): Contour map of the top upper Malm unit in the western Molasse Basin. Depths are in meters. For explanation see legend of Figure 4.11.

Carte structurale des contours du toit des couches du Malm supérieur dans le Bassin molassique occidental (profondeurs en mètres). Pour les explications, voir la légende de la Figure 4.11.

Figure 4.13 (page 133, bottom): Contour map of the top "Argovian" unit (lower Malm) in the western Molasse Basin. Depths are in meters. For explanation see legend of Figure 4.11.

Carte structurale des contours du toit des couches de l'"Argovien" (Malm inférieur) dans le Bassin molassique occidental (profondeurs en mètres). Pour les explications, voir la légende de la Figure 4.11.

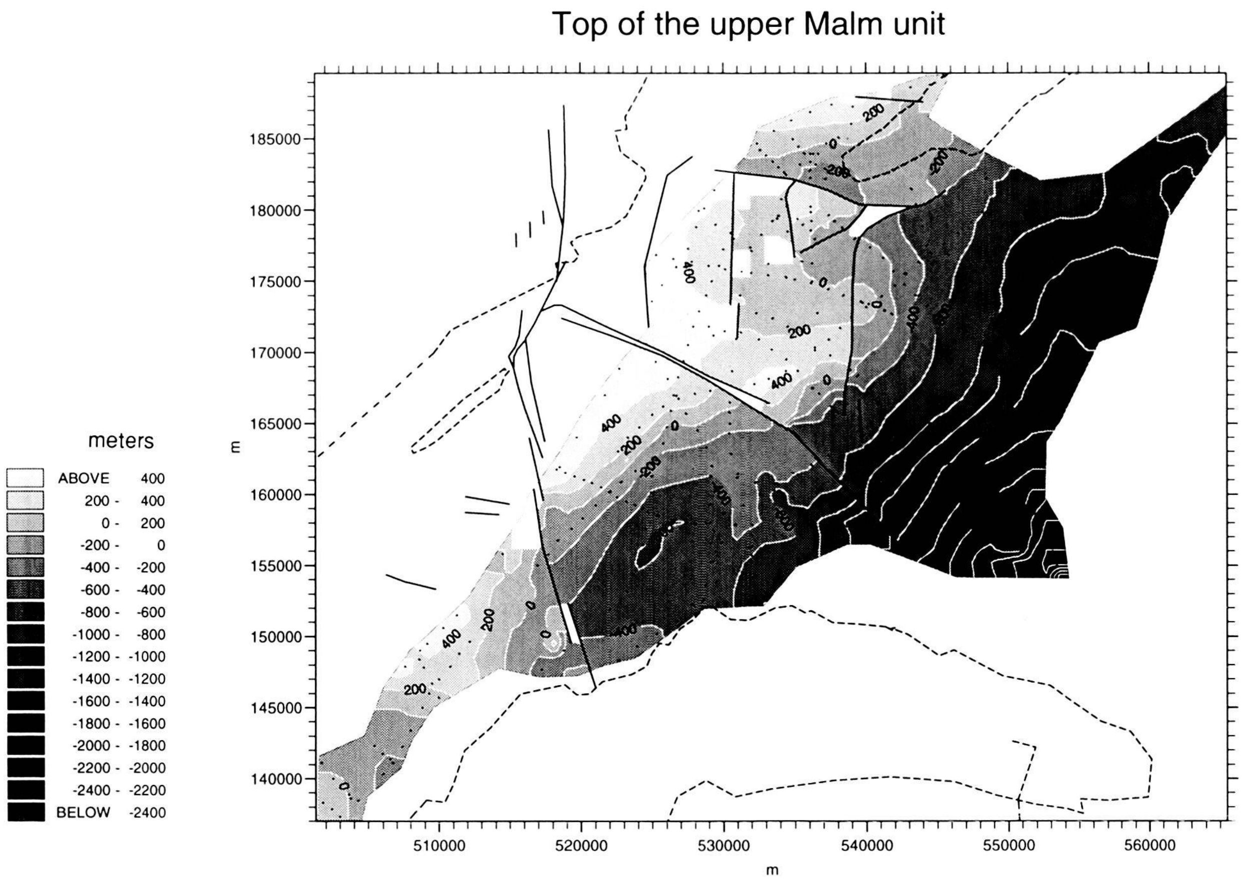


Figure 4.12

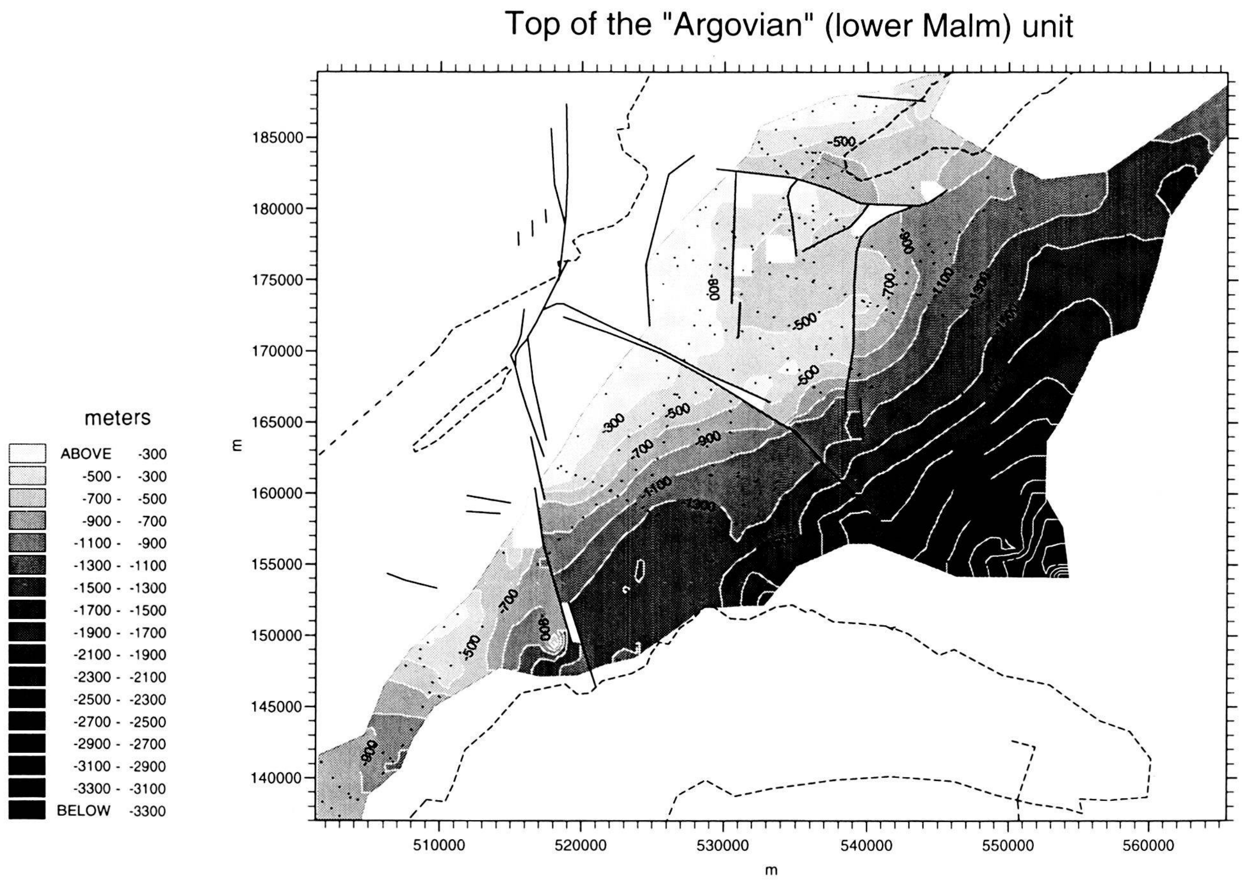


Figure 4.13

contour intervals are closer (each 50 m). The broad folds from the Plateau Molasse, observed on these maps, are due to tectonic thickening of evaporites, salt and clays within the Triassic Unit 2 (see discussion in Chapter 3).

The Subalpine Molasse is characterized by a stack of thrust sheets of Tertiary sediments detached along an incompetent décollement zone at the base of the Oligocene layers ("Grisigen shales" formation or "Schistes à Meletta" formation; TRÜMPY, 1980). Unfortunately, seismic resolution is really poor within the Molasse and therefore does not allow clear observation of these structures. Nevertheless, foreland-vergent thrust faults have been recognized on seismic lines crossing the Subalpine Molasse (Sections 43 and 45 on Panel 5; Plates 6 and 7). Beneath the Subalpine Molasse, the Mesozoic layers present small thrust faults. Furthermore, seismic Section 43 (on Panel 5)

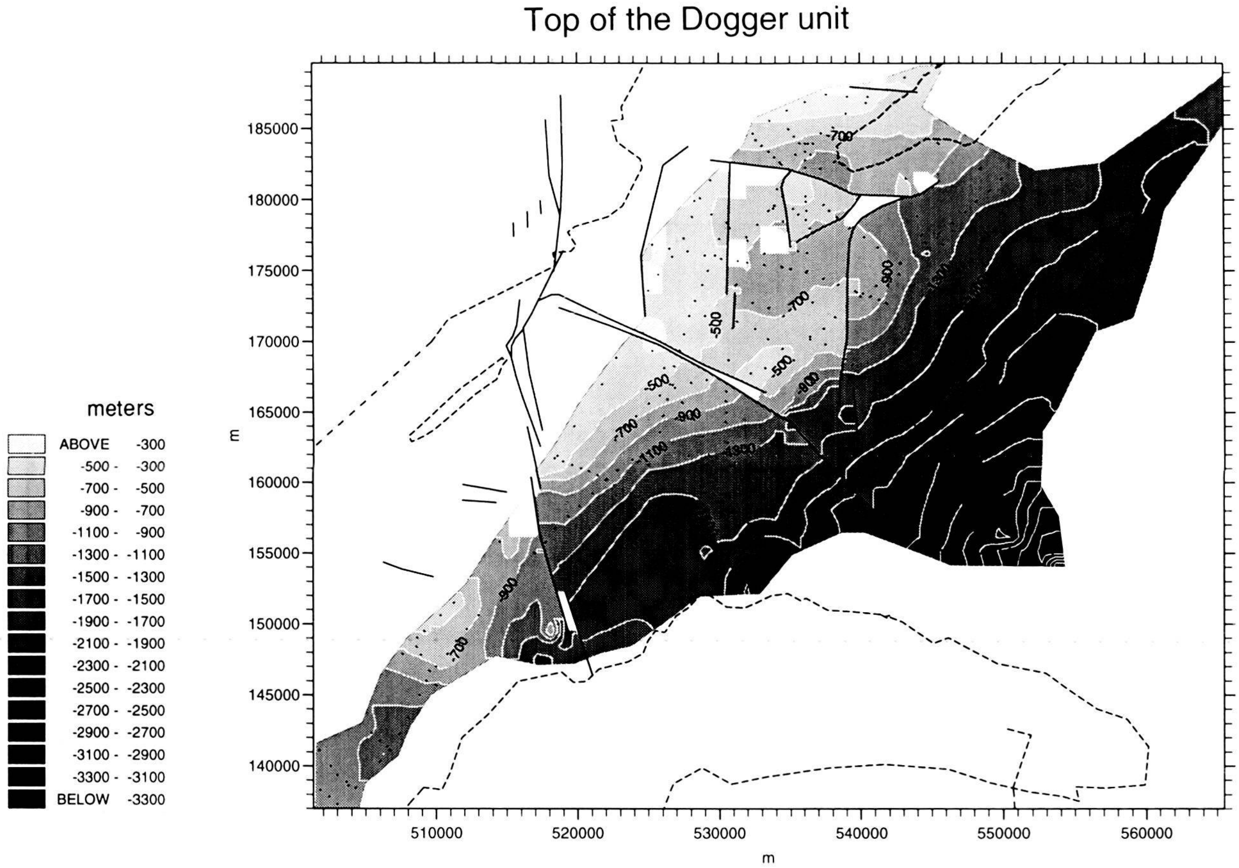


Figure 4.14: Contour map of the top Dogger unit in the western Molasse Basin. Depths are in meters. For explanation see legend of Figure 4.11.

Carte structurale des contours du toit des couches du Dogger dans le Bassin molassique occidental (profondeurs en mètres). Pour les explications, voir la légende de la Figure 4.11.

Figure 4.15 (page 135, top): Contour map of the top of the Liassic unit from the western Molasse Basin. Depths are in meters. For explanation see legend of Figure 4.11.

Carte structurale des contours du toit des couches du Lias dans le Bassin molassique occidental (profondeurs en mètres). Pour les explications, voir la légende de la Figure 4.11.

Figure 4.16 (page 135, bottom): Contour map of the top Triassic Unit 1 in the western Molasse Basin. Depths are in meters. For explanation see legend of Figure 4.11.

Carte structurale des contours du toit des couches de l'Unité 1 du Trias dans le Bassin molassique occidental (profondeurs en mètres). Pour les explications, voir la légende de la Figure 4.11.

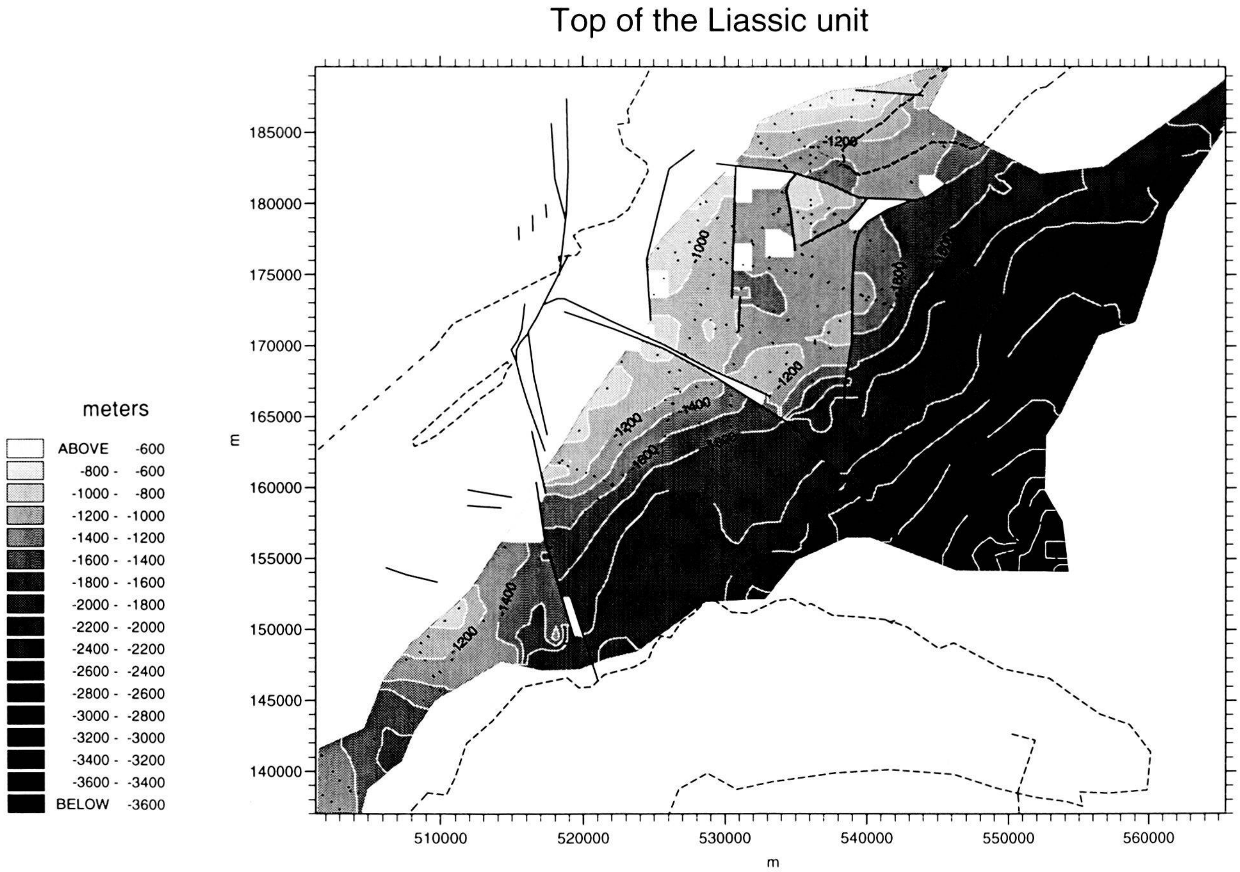


Figure 4.15

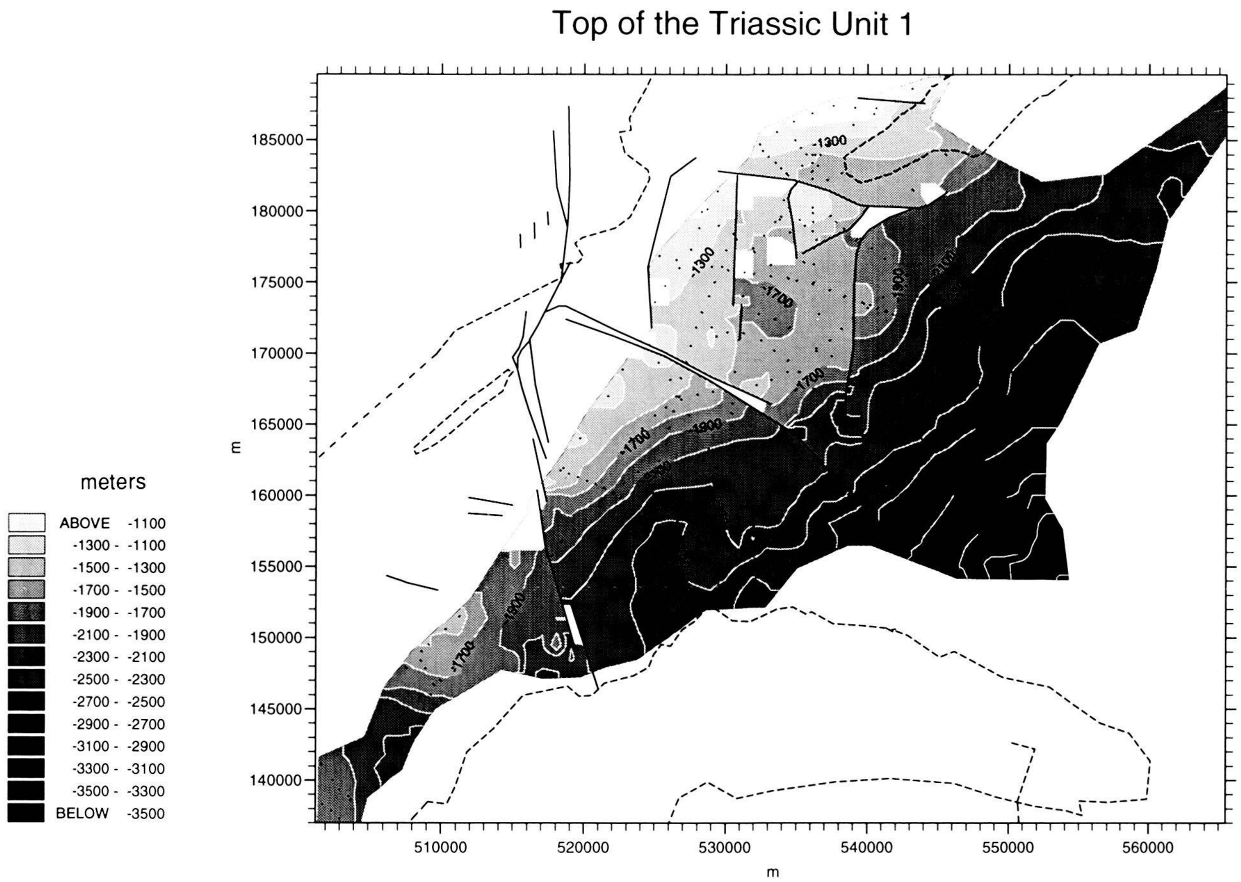


Figure 4.16

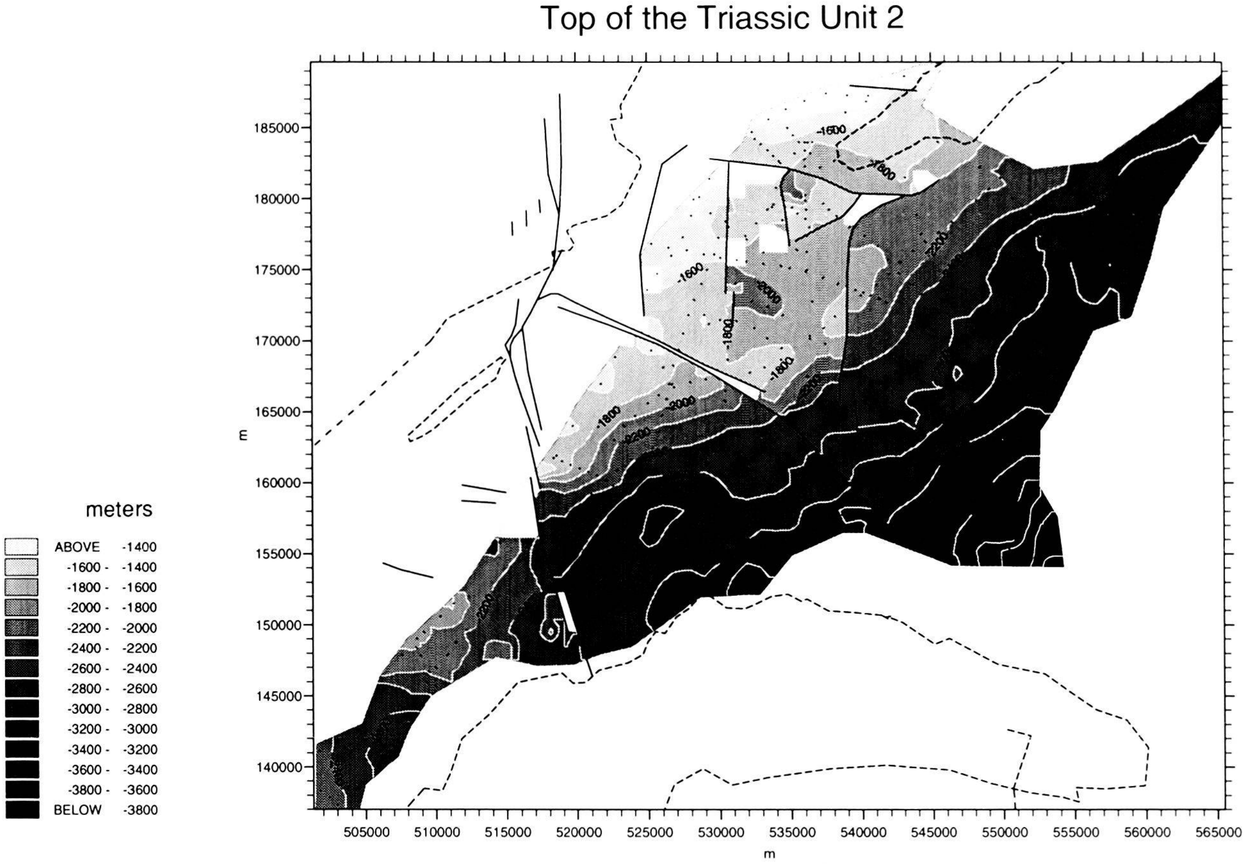


Figure 4.17: Contour map of the top Triassic Unit 2 in the western Molasse Basin. Depths are in meters. For explanation see legend of Figure 4.11.

Carte structurale des contours du toit des couches de l'Unité 2 du Trias dans le Bassin molassique occidental (profondeurs en mètres). Pour les explications, voir la légende de la Figure 4.11.

shows Cenozoic and Mesozoic foreland dipping reflectors in its southernmost part. The latter may be interpreted to be linked, through a simple, bend to the south dipping reflectors further to the North in the Molasse Basin. The interpretation of this bend is difficult and is clearly related to a structure underlying the Triassic strata. One interpretation involves a slice of basement, related to a thrust fault rooting in the basement. This thrust fault may step up from the basement into the basal Triassic evaporites and then evolves as the main decoupling zone for the Jura fold and thrust belt (MOSAR *et al.*, 1996). Another hypothesis could be that of GORIN *et al.* (1993), who proposed an inverted Permo-Carboniferous graben and a third suggestion could be a thick evaporite pillow. All these interpretations have profound implications for the formation of the Jura foreland fold and thrust belt, which will be discussed in Chapter 5. It should also be noted, that these structures occur at the end of a non migrated line that runs obliquely to the direction of local structures, cautioning against overinterpretations.

4.5.3. The Yverdon - Treycovagnes area

4.5.3.1. Previous studies

The Yverdon-les-Bains area has attracted much attention, because of hot water springs. During the 1970's, Shell conducted a seismic survey (Swisspetrol) and drilled a well (Treycovagnes, see Appendix 2) for oil exploration (Figs. 1.4 and 4.1). Besides the wells drilled by oil industry during the 1940's (Cuarny, see Appendix 2), the 1960's (Essertines) and 1970's (Treycovagnes), many shallow holes were made recently for geothermal purposes or for mineral water production (BURGER & GOHRAN, 1986).

The area has been the subject of several geological studies: the earliest were based on surface geology (RENEVIER, 1854; JORDI, 1955) and later studies were based on surface geology observations and subsurface interpretations of seismic lines and wells (JORDI, 1990, 1993, 1994, 1995).

The recent investigation of the Yverdon area for hydrogeological purposes (CHYN, 1995; MURALT *et al.*, 1997) has led to a new detailed interpretation of seismic lines in this region which is presented below.

4.5.3.2. Geological setting

The Yverdon-Treycovagnes area extends along the foot of the internal Jura, at the southern end of Lake Neuchâtel (Fig. 4.3). The region is dissected by two conjugate sets of tear faults that trend N-S (sinistral) and W-E to WNW-ESE (dextral). A complex dextral fault zone, the Pipechat-Chamblon-Chevressy fault zone (PCC, see Figure 4.3) (JORDI, 1993) with at least two distinct faults (North and South fault), is joined by several southward trending sinistral faults: one along the western border of Mont de Chamblon and a second from the Plaine de Baulmes towards the South. All these faults also have a reverse compressional component and are transpressive faults. The areas located SE of the junctions of the sinistral with the dextral faults consequently form NW-pointing "indenters". They are either uplifted above NW-vergent thrust faults (e.g. Chamblon) or depressed below SE-vergent backthrusts. Near Yverdon, major water sources are all located along these faults.

4.5.3.3. Interpretation

The interpreted seismic lines (see Figure 4.1 for the seismic grid) were depth converted according to velocities presented in Appendices 3. Compilation and correlation of all data led to a well supported structural model of the Yverdon area (Fig. 4.19), except for the faulted zone along the dextral transpressive PCC-fault. Seismic reflectors within this zone are blurred and the sparse surface data have had to be projected laterally over large distances and downwards across décollement horizons.

On all seismic lines crossing the PCC-fault, the reflectors dip gently south outside the faulted zone. Within the faulted zone, reflectors dip gently south on the westernmost line (Section 38 on Panel 6) and are subhorizontal on the next line to the East (Section 24, see Figure 1.4 for location). On both lines the reflectors within the fault zone are well displayed and thus the south-dipping faults on either side are constrained. Section 25, the next line to the east, cuts the fault zone at a highly oblique angle. The faulted zone is blurred, but a gentle northward dip of some Cretaceous-Malm reflectors can be inferred nonetheless. Since both faults have a compressional component and the hangingwall as well as footwall of the whole fault zone are clearly displayed, the inter-fault zone can be established with some confidence, once its general dip direction is known. The resulting structure (Fig. 4.18) is a fault-related fold with two faults breaking through the frontal limb. A third thrust fault is inferred at depth to account for the gentle northern dip of the strata immediately to the north of the faulted zone.

Seismic and drill hole data show thickness changes of various strata across the PCC fault zone. The Dogger sequence decreases from 420 m in the South to 290 m in the North (Fig. 4.18). This may be due to a Jurassic normal fault, reactivated during the Jura folding in late Miocene-Pliocene time. Reactivated faults often show tortuous geometries in detail, so local complexities must be expected. Such an inherited fault could also have influenced the orientation of the younger fault zone presently observed. Further, tectonic thickening of the ductile beds during the Miocene deformation cannot be excluded. In any case two different regions which were not juxtaposed during Jurassic sedimentation time, are today juxtaposed.

The interpretation and the depth conversion of the seismic lines discussed above have led to a structural model of the top of the Dogger unit. Figure 4.19 represents a structural contour map of the Dogger in the Yverdon-Treycovagnes area. This figure highlights the structure of the Chamblon area, which appears to form a NW-pointing indenter uplifted above a NW vergent-thrust fault. The vergence of the structures along the PCC fault changes further towards the East, where the northern side is uplifted above a steep southeast vergent thrust fault (Fig. 4.19).

In conclusion, the Chamblon hill (Yverdon-Treycovagnes area) shows a north-vergent fault-related fold with two to three faults breaking through the frontal limb. The thrust faults sole out in the Triassic décollement zone, but there are also suggestions that the Alpine faults reactivate earlier, possibly Liassic normal faults.

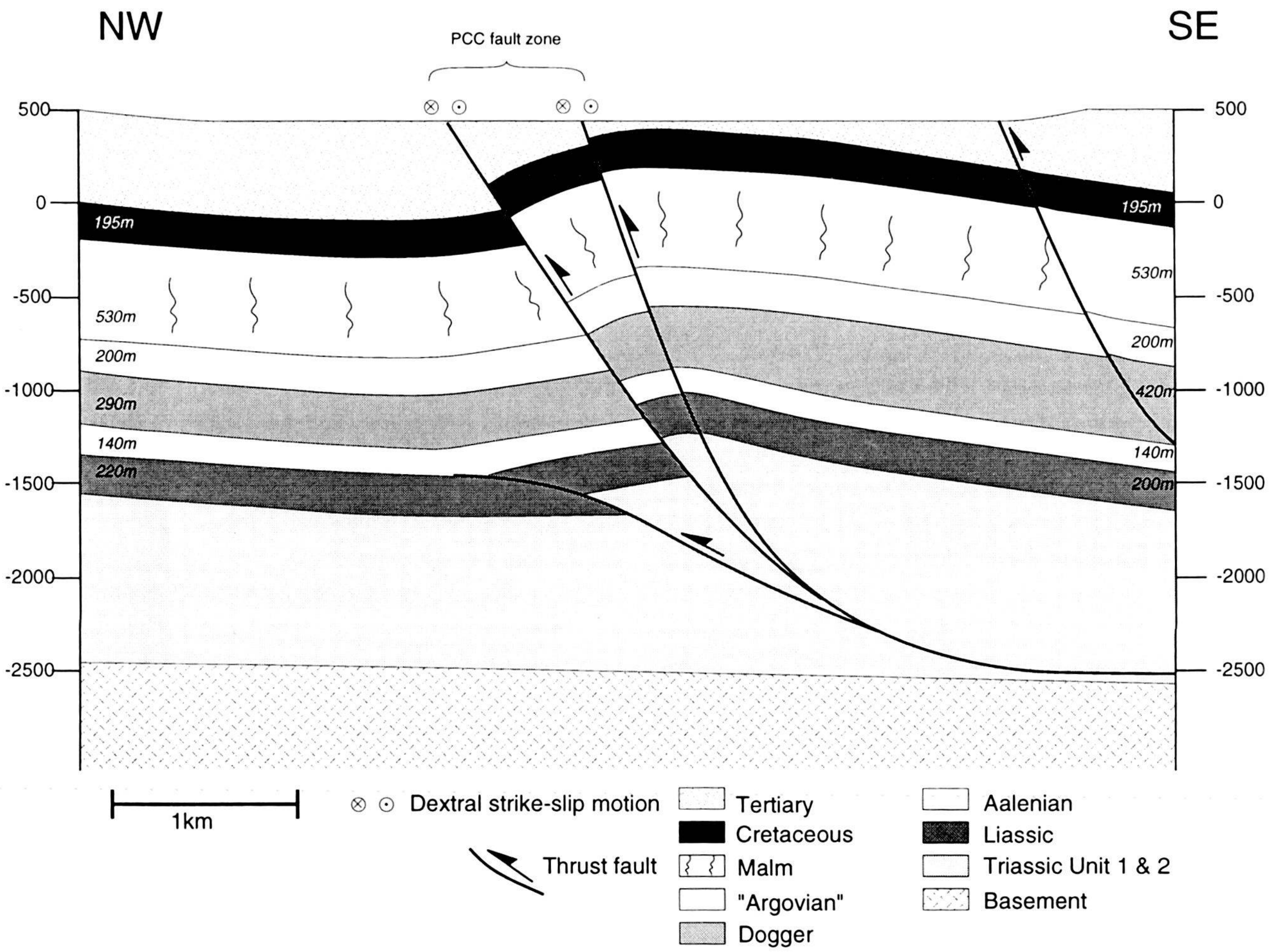


Figure 4.18: Geological cross-section oriented NW-SE based on surface geological data and completed at depth with information from seismic Section 25, Section 27 (Panel 5) and Section 38 (Panel 6). This geological section crosses the Chamblon hill (for location see Figs. 4.3 and 4.9). Modified from MURALT *et al.* (1997).

Coupe géologique orientée NW-SE construite à partir des données de la surface et complétée en profondeur par les informations des profils sismiques 25, 27 (Panneau 5) et 38 (Panneau 6). Cette coupe traverse la colline du Mont de Chamblon (pour localisation voir Figs. 4.3 et. 4.9). Modifiée de MURALT et al. (1997).

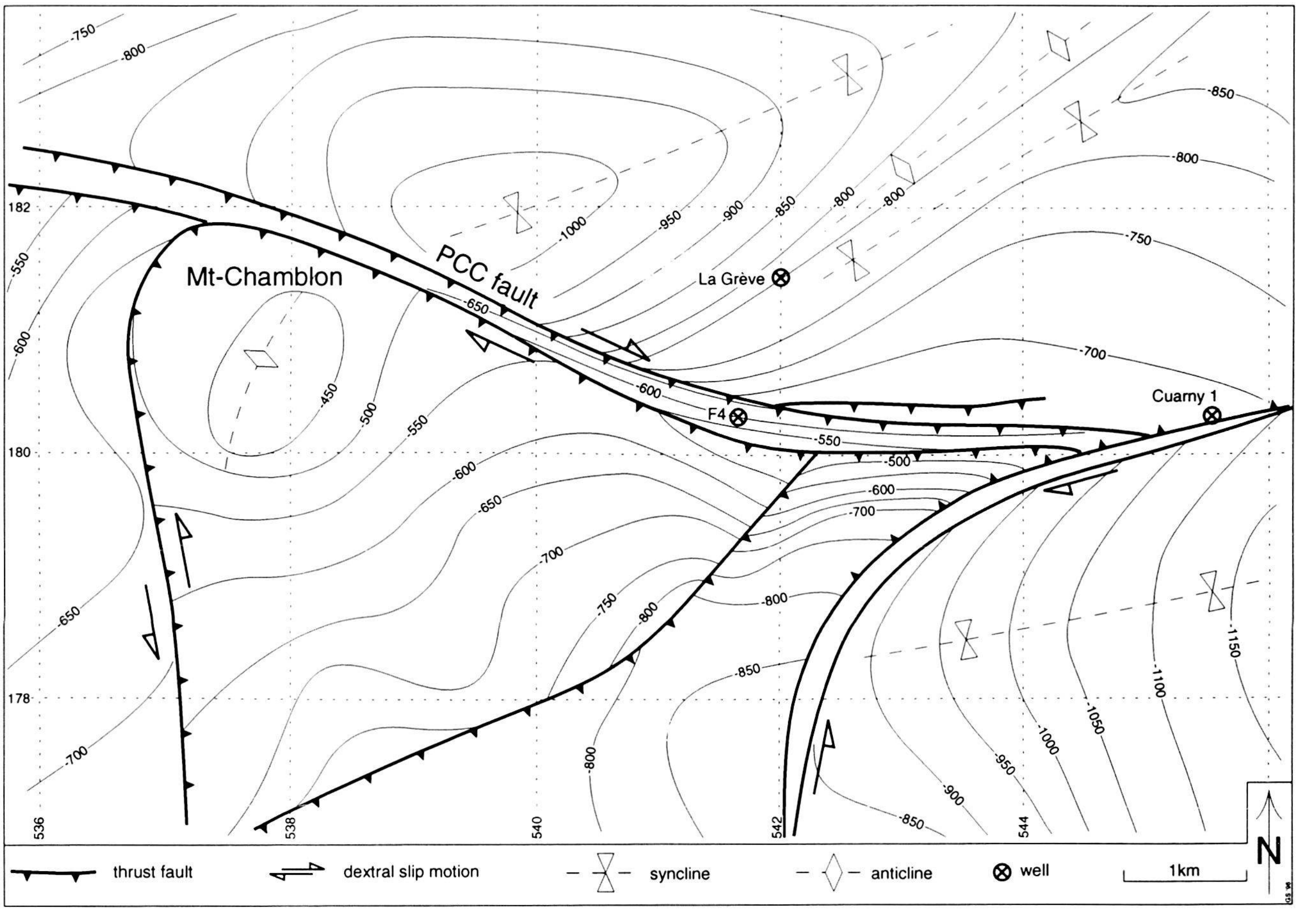


Figure 4.19: Contour map of the top Dogger in the Yverdon-Treycovagnes area, western Molasse Basin. Depths are in meters, below sea level. Numbers on the side and bottom are in kilometers that relate to the Swiss national geographical coordinate system. Modified from MURALT *et al.* (1997).

Carte structurale des contours du toit des couches Dogger dans la région d'Yverdon-Treycovagnes, Bassin molassique occidental (profondeurs en mètres, en-dessous du niveau de la mer). Les coordonnées géographiques (en kilomètres) se réfèrent à la grille suisse. Modifiée de MURALT *et al. (1997).*