Introduction

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1. INTRODUCTION

1.1 AIM AND SCOPE OF THE PRESENT STUDY

The Jura, together with the Molasse Basin, is generally considered a foreland fold and thrust belt representing the most external, late Miocene deformation zone of the northwestern Alps. The development of this belt is still a matter of debate. The availability of more than 1500 km of seismic lines has provided the opportunity to extend our knowledge about the subsurface stratigraphy and the geometry of the Jura and Molasse Basin folds in depth.

The geometry in depth of the Jura and Molasse Basin structures (folds, thrust faults and tear faults) provides important constraints on their development and the formation of the Alpine foreland. The main subjects addressed in this thesis are:

- the correlation between the surface geological observations and subsurface data
- the stratigraphic thickness of the buried strata
- the geometry of the folds and thrusts and their development
- the cover-basement relationship
- the structure of the basement.

Few public seismic reflection data are available to date within the Jura arc. A small seismic survey has been carried out by the NAGRA (National Cooperative for the Storage of Radioactive Waste) in the eastern Jura, whereas in the western Jura one profile has been shot by the ECORS group. The availability of recent industry seismic lines (Fig. 1.4) in the Neuchâtel Jura and older lines in the Risoux Jura, the French Jura and the western Molasse Basin has allowed infilling an important data gap for the central part of the Alpine foreland.

This manuscript is organized into six chapters, providing information and illustrations about stratigraphy and tectonics of the central Jura and the western Molasse Basin. Subsurface, as well as surface geology are presented to offer an integrated regional geologic interpretation.

Chapter 1 presents a general introduction, which exposes the aim of the study, the geological and historical setting and the methodology. Chapter 2 concerns stratigraphy. Although this thesis is focused on structure, stratigraphy is discussed because it is necessary to understand structural development for example: regional overview, outcrop and subsurface stratigraphy from well logs, seismic stratigraphic units and their correlation through the whole grid, isopach maps and rheological stratigraphy. Chapter 3 presents an overview of the structures (evaporite-related anticlines, thrust-related anticlines and tear faults), illustrated by seismic profiles. The most remarkable structures are evaporite stacks within the Triassic layers, controlling the anticline formation of the Molasse Basin and the Plateau Jura. The Haute Chaîne Jura folds, on the other hand, are leading to duplication of Mesozoic strata beneath the Haute Chaîne Jura thrust-related folds. Chapter 4 presents the regional geology of the central Jura and the western Molasse Basin, highlighted by seismic interpretation (line drawings), tectonic maps, cross-sections of specific areas and structural contour maps within the Molasse Basin. The depth to the basement map of the central Jura and Molasse Basin, derived from depth conversion of the whole seismic grid, as well as the isopach map of the Triassic beds of the Molasse Basin, will be the key for the general discussion on the formation of the Jura fold and thrust belt (Chapter 5). Chapter 6 will summarize the main conclusions of this work.

1.2. GEOLOGICAL SETTING

1.2.1. The Jura

The Jura is a small arcuate fold belt located in front of the western Alpine arc (Fig. 1.1). This chain has given its name to the Jurassic layers, because they represent the major part of the outcropping rocks in the Jura.

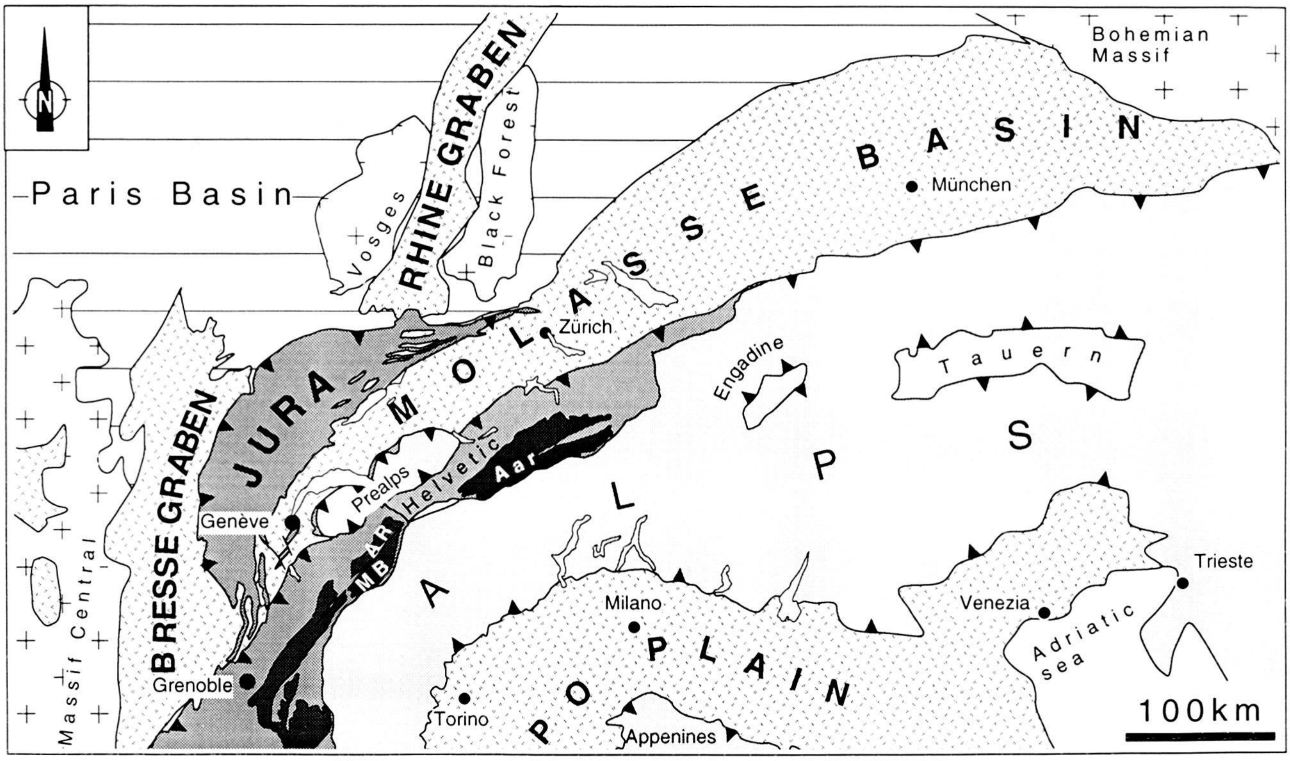


Figure 1.1: Location of the Jura arc with respect to the major Cenozoic sedimentary basins (Rhine-Bresse Grabens, Molasse Basin, Po Plain) and the Alps. Late alpine culminations and external crystalline massifs are highlighted in dark grey. AR = Aiguilles Rouges massif; MB = Mont-Blanc Massif.

Situation de l'arc jurassien par rapport aux bassins sédimentaires tertiaires avoisinants (Grabens du Rhin et de la Bresse, Bassin molassique, Plaine du Pô) et aux Alpes. Les culminations alpines tardives et les massifs cristallins externes sont soulignés en gris foncé. AR = Massif des Aiguilles Rouges; MB = Massif du Mont-Blanc.

The outer arc of the Jura is 400 km long and the inner arc 340 km. The width between both arcs varies from 0 km at the eastern end, to 65 km between Neuchâtel and Besançon (Switzerland-France). The Jura arc is surrounded by Tertiary basins of different types: to the N, the Rhine Graben, to the W the Bresse Graben and to the SSE the Molasse Basin (Fig. 1.2). The Rhine and Bresse Grabens are associated with the Oligocene, West-European rift system, whereas the Molasse Basin corresponds to an Oligo-Miocene foredeep, which developed in front of the Alpine orogen. During the Mesozoic, the Jura and Molasse Basin realm was part of the Alpine Tethys passive margin and comprises a total thickness of up to 2 km of alternating limestones and marls. Limestones of Malm age crop out in the central Jura, whereas the Cretaceous limestones (Barremian) form the crests of the western Jura anticlines. During the Oligocene and Miocene, alternating fluvial, lacustrine and marine clastic Molasse sediments were deposited. They progressively onlap the underlying Mesozoic rocks towards the Northwest. The thickness of this sedimentary wedge decreases from the South (up to 4 km) to the North (a few hundred meters). These series crop out mainly within the Molasse Basin, but they are also preserved in many Jura synclines (Val de Ruz, La Chaux-de-Fonds - Le Locle, Val de Travers, Delémont Basin, ...) (Fig. 1.3).

The Jura and the Molasse Basin consist of folded Mesozoic and Cenozoic beds, which are detached from the pre-Triassic basement. The latter crystalline basement is never exposed in the Jura and Molasse Basin. It has, however, been penetrated by a few drill holes and laterally it crops out in the Vosges and Black Forest to the North, in the alpine external crystalline massifs to the South and in some small isolated outcrops along the northwestern external border of the Jura Mountains (Serre Massif).

At its southern termination, the Jura belt merges with the Subalpine Chains, which were folded contemporaneously. Along its western border, the Jura over-thrusts the Bresse Graben, whereas in the

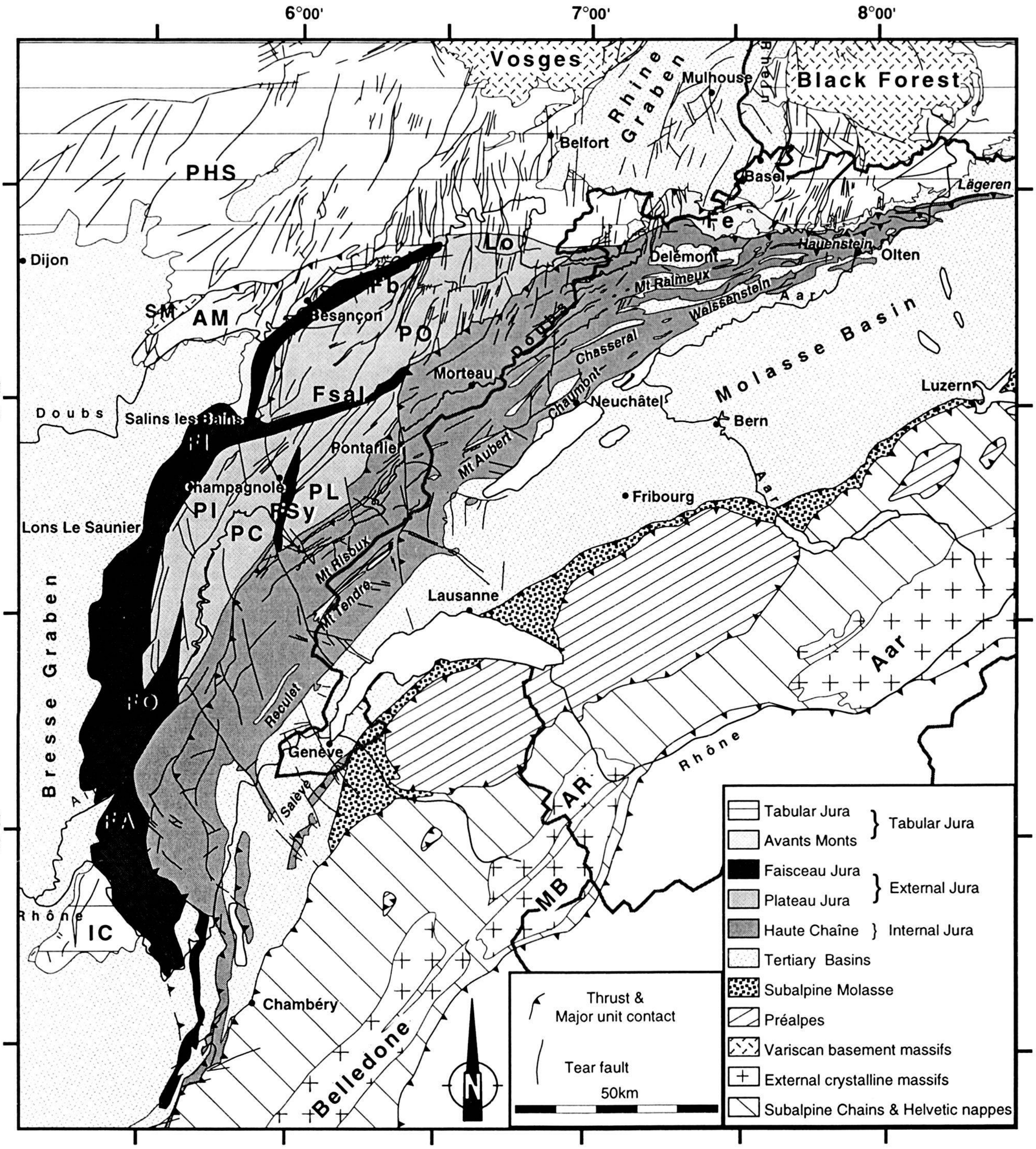


Figure 1.2: Tectonic sketch of the Jura arc with main structural units. Legend: PHS = Plateau de Haute-Saône; IC = Ile Crémieu; AM = Avants-Monts; Fe = Ferrette; FA = Faisceau d'Ambérieu; Fb = Faisceau bisontin; Fl = Faisceau lédonien; FO = Faisceau d'Orgelet; Fsal = Faisceau salinois; FSy = Faisceau de Syam; Lo = Lomont; PC = Plateau de Champagnole; PL = Plateau de Levier; Pl = Plateau lédonien; PO = Plateau d'Ornans; AR = Aiguilles Rouges; MB = Mont Blanc. Modified from Sommaruga (1995).

Carte tectonique de l'arc jurassien avec les unités structurales majeures. Légende: PHS = Plateau de Haute-Saône; IC = Ile Crémieu; AM = Avants-Monts; Fe = Ferrette; FA = Faisceau d'Ambérieu; Fb = Faisceau bisontin; Fl = Faisceau lédonien; FO = Faisceau d'Orgelet; Fsal = Faisceau salinois; FSy = Faisceau de Syam; Lo = Lomont; PC = Plateau de Champagnole; PL = Plateau de Levier; Pl = Plateau lédonien; PO = Plateau d'Ornans; AR = Aiguilles Rouges; MB = Mont Blanc. Modifiée de Sommaruga (1995).

North, it overrides the Tabular Jura. At its eastern end, the last Jura fold (Lägern) dies out within the Molasse Basin.

The Jura itself is divided into the external Jura and the internal Jura (CHAUVE *et al.*, 1980).

a) The external Jura

The external Jura (Fig. 1.2) consists of flat areas, Plateaus, limited to the North and separated from each other by the so called "Faisceaux" (from North to South: F. bisontin, F. salinois, F. lédonien, F. de Syam, F. d'Orgelet and F. d'Amberieu). These are narrow, strongly deformed fold bundles characterized by a succession of numerous small-scale imbricates and tear faults. The Plateaux (P. d'Ornans, P. lédonien, P. Champagnole and P. Levier) correspond to weakly faulted, horizontal or slightly SE dipping areas.

b) The internal Jura

The internal Jura, often called the folded Jura, "Haute Chaîne" or "Faisceau helvétique" consists of a well developed fold train representing a natural present-day northern limit to the Molasse Basin. On a large scale, deformation is characterized by major folds, thrusts and tear faults. The amplitude of the Jura folds depends on the cover thickness (800 m-2000 m) and the degree of shortening, which is highest in the internal part of the central Jura and decreases outwards. Folds are thrust-related and end laterally either with plunging axes or abruptly against tear faults. Some major sinistral tear faults cutting the whole cover are recognized; their orientation is N-S in the eastern Jura and changes gradually along the chain to a WNW-ESE direction at the western end. The outer border of the folded Jura is thrust over the Plateau Jura. At the southern border, the Mesozoic beds dip below the Oligo-Miocene sediments of the Molasse Basin.

A third zone, the Tabular Jura, is often associated with the Jura. This zone is located outside of the Jura arc and represents the Mesozoic cover of the southern Black Forest and Vosges basement. The Tabular Jura represents the transition from the Rhine-Bresse Graben to the Paris Basin. Strata are subhorizontal and cut by a N-S or NE-SW Oligocene fault system. The Avant-Monts and the Ferrette areas represent the deformed cover of this Tabular Jura. At the southern end of the arc, the Ile Crémieu is the southern counterpart of the Tabular Jura.

1.2.2. The Molasse Basin

The whole Molasse Basin (sensu lato) represents a foreland basin which extends over more than 700 km, from the French Savoy in the West (Chambéry, Figs. 1.1 and 1.2) to Linz (Austria) in the East. It runs parallel to the Alpine front and widens progressively to the East, from 50 km in the Neuchâtel traverse to some 150 km in southern Germany. Sedimentation in the foreland basin was continuous from earliest Oligocene to Serravallian time and took place in alternating marine, fluvial and lacustrine environments. The thickness of this sedimentary wedge decreases from some 4 km in the South to a few hundred meters in the North.

The clastic wedge of the Molasse Basin is subdivided into three geological units, the Jura Molasse, the Plateau Molasse and the Subalpine Molasse (HOMEWOOD *et al.*, 1989).

a) The Jura Molasse

The Jura Molasse represents the northern feather edge of the Molasse Basin that has been passively involved in Jura folding and thrusting. Only isolated patches of Molasse are preserved within major synclines of the internal Jura.

b) The Plateau Molasse

The Plateau Molasse, representing the major part of the Molasse Basin, shows contrasting structural styles between the western and eastern parts.

In the western Swiss part, the structures consist of broad anticlines oriented NE-SW and tear faults trending N-S, NW-SE and WNW-ESE. The northern limit of the Plateau Molasse corresponds to an erosion limit along the most internal, high amplitude folds of the Jura belt.

In eastern Switzerland and Bavaria, surface geological outcrops show the onlap towards the North of the Tertiary wedge over the Tabular Jura (Franconian Platform) (BACHMANN *et al.*, 1987). The only known deformation is characterized by small normal faults oriented WSW-ENE, parallel to the basin and affecting the Mesozoic and Cenozoic strata (BACHMANN *et al.*, 1982).

c) The Subalpine Molasse

The Subalpine Molasse represents a narrow zone located along the southern border of the Molasse

Basin (Fig. 1.2). This zone is characterized by a stack of thrust sheets of Tertiary sediments, detached along a décollement zone within these Cenozoic layers ("Grisigen shales") (TRÜMPY, 1980). The southern limit of this zone corresponds to the Oligocene Alpine front represented by the Alpine nappe stack (Prealps, Helvetic nappes, ...) which overthrusts the Molasse sediments. The northern limit of this unit, corresponding to the transition between the Subalpine- and the Plateau Molasse, is structurally an important triangle zone (BACHMANN *et al.*, 1982; VOLLMAYR & WENDT, 1987; MÜLLER *et al.*, 1988; VOLLMAYR, 1992).

According to ALLEN *et al.* (1986), HOMEWOOD (1986) and VANN *et al.* (1986), the change in structural style along the strike of the Molasse Basin is related to the presence of a décollement zone within the Triassic evaporites. The entire Basin in the western and central parts is considered to be detached from its crystalline or Permo-Carboniferous substratum.

Figure 1.3: General geographical index map of the investigated area (cities, rivers, mountains and wells). Legend: Chl = Chapelle; Cua = Cuarny; Ess = Essertines; Her = Hermrigen; Tre = Treycovagnes; Val = Valempoulières.

Carte géographique générale de la région étudiée (villes, rivières, montagnes et forages). Légende: Chl = Chapelle; Cua = Cuarny; Ess = Essertines; Her = Hermrigen; Tre = Treycovagnes; Val = Valempoulières.

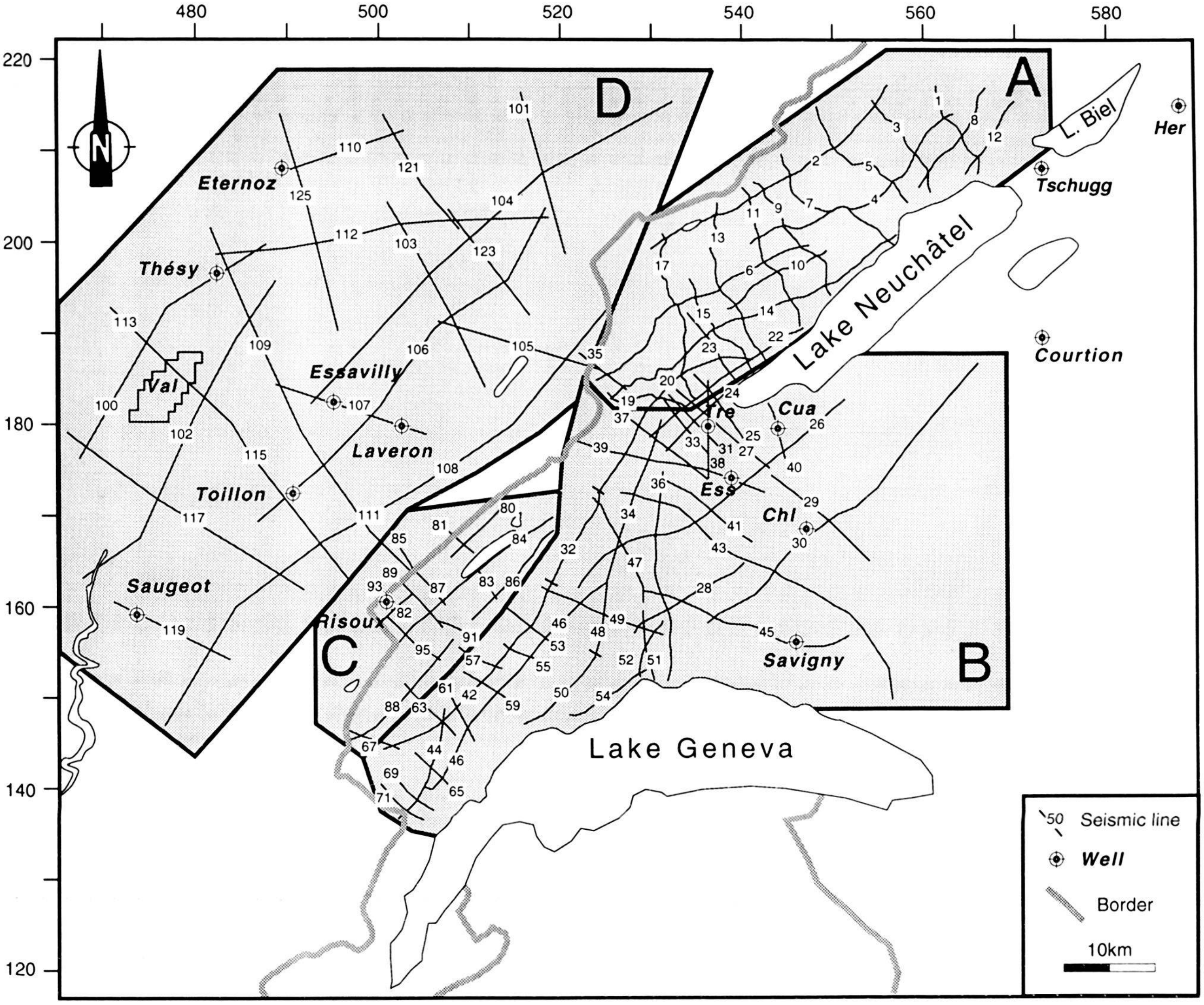


Figure 1.4: Seismic data used in this work. Location of the various sectors: A = Neuchâtel and Vaud Jura Mountains, Panels 1, 2, 3. B= Molasse Basin, Panels 4, 5, 6. C = Mt- Risoux Jura Mountains, Panels 8, 9. D = Champagnole-Mouthe Jura Mountains, Panel 10. Legend: Chl = Chapelle; Cua = Cuarny; Ess = Essertines; Her = Hermrigen; Tre = Treycovagnes; Val = Valempoulières.

Profils sismiques interprétés dans ce travail. Localisation des différents secteurs: A = Jura neuchâtelois et vaudois, Panneaux 1, 2, 3. B= Basin molassique, Panneaux 4, 5, 6. C = Région jurassienne du Mt- Risoux , Panneaux 8, 9. D = Région jurassienne de Champagnole-Mouthe, Panneau 10. Légende: Chl = Chapelle; Cua = Cuarny; Ess = Essertines; Her = Hermrigen; Tre = Treycovagnes; Val = Valempoulières.

The deformation propagated from the South into the Jura belt, whereas to the East there is as yet no evidence for a décollement zone. Thick evaporite horizons in Triassic strata are present beneath the Jura and the Swiss Molasse Basin (RIGASSI, 1977) (see also Fig. 2.5). Triassic beds progressively onlap basement to the North-East and are entirely absent beneath the Molasse Basin in Germany, where Jurassic strata lie unconformably on the basement; here, even where the Triassic is preserved, evaporite series are absent (BACHMANN *et al.*, 1987).

1.3. REGIONAL BOUNDARY CONDITIONS TO THE FORMATION OF THE JURA FOLD AND THRUST BELT

The formation of a fold and thrust belt and the nature of folding are intimately dependent on the existing boundary conditions. For the Jura belt, the major regional boundary conditions can be summarized as follows:

- the presence of Triassic evaporite beds serving as basal décollement level;

- the presence of a rigid basement dipping 1° to 3° towards the South and underlying a weak décollement level (BUXTORF, 1907);

- the rheological stratigraphy in the cover (§2.6. and Fig. 2.30): the thickness of strong competent rocks (Malm and Dogger limestones) increases from NE to SW, whereas the weak incompetent beds above the décollement decrease towards the SE;

- the small overburden and hence the weak burial depth: depths ranging from few hundreds of meters to a maximum of 2500 m in the southern Jura create low temperature conditions for the deformation of the rocks;

- the wedge shape of the whole Jura foreland: the shallow surface slope towards the NW and the basal dip towards the SE;

- the wedge shape of the Tertiary Molasse Basin: the thickness of the sediments increases strongly from the North to the South;

- the inherited Oligocene structures within the cover: the West-European rift system results in the formation of the Rhine-Bresse Grabens and also in N-S to NE-SW faults affecting the cover and the basement. These faults are especially located in the external and eastern regions of the Jura arc.

1.4. FORMATION OF THE JURA: SHORT REVIEW AND OPEN QUESTIONS

The Jura Mountains have drawn the interest of structural geologists and paleontologists since the beginning of the last century. In the early years, research was focused on stratigraphy and paleontology. Among the few early geological cross-sections that were drawn, the one of Von Buch (1806) in VON BUCH (1867) is remarkable for its time. He presented a geological section from the Aar Massif to the Serre Massif (Fig. 1.2), where the so called limestone cover rocks of the Prealps, the Molasse Basin and the Jura chain overly granite rocks. On his section, the latter crop out in the Aar and Serre Massifs, the southern and the northern borders, respectively. The major issues of the formation of the Jura are already included in this early 19th century cross-section: what are the cover-basement relationships within the Jura and the Molasse Basin and where is the Jura cover shortening compensated in the basement ?

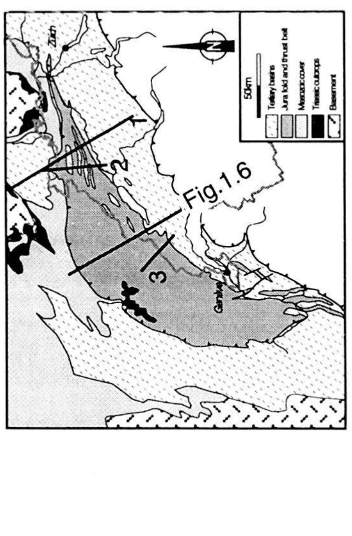
Since the beginning of this century, many authors have attempted to answer these questions. In the following sections, we will give a short review of various interpretation of the Jura formation illustrated by some published cross-sections (Fig. 1.5) and some conceptual models (Fig. 1.7) modified from BURKHARD (1990). For the Jura, two fundamentally different assumptions dominate the debate i.e. basement involved folding versus décollement of the sedimentary cover. Basement, here, includes all rocks older than the Triassic anhydrites. The viability of these models will be discussed later in the Chapter 5 together with the main results of this thesis.

For a more detailed review on the evolution of the ideas during the first 50 years of this century, the reader should refer to CAIRE (1963).

Basement involvement beneath the Jura: proponents

Many authors have argued in favor of basement involvement. They regard the Jura as an essentially autochthonous cover, which has been deformed in response to deformation in the underlying basement so that the shortening of the Jura folds is taken up in the underlying basement. AUBERT (1945) proposed disharmonic folding of the Jura cover in the Muschelkalk anhydrites due to basement slices penetrating into the cover (Fig. 1.5, section 3). This idea was inspired by the cross-sections of STAUB (1924) in the Alps. Fifteen years later, AUBERT (1959) reconsidered his theory taking into account the work of GLANGEAUD (1949) and especially new field work results in the Pontarlier strike slip fault area (Figs. 1.2 and 3.19). The latter fault, like all Jura strike slip faults, is considered in this model as deep Oligocene age strike-slip faults rooting in the basement. The contraction of the strike-slip faults of the Jura has induced some major folding in the overlying cover ("contraction du socle" theory, Fig. 1.7). Following the results of the Risoux well, with its large scale duplication of Mesozoic strata, AUBERT (1971) changed his views to conclude that the Jura cover is allochthonous.

The influence of deep seated strike-slip faults is also central to PAVONI's (1961) theory of folding related to basement involved wrench faulting (Fig. 1.7). Based on a series of experiments, Pavoni demonstrated a possible connection between the relative movement and strike of the wrench faults and the resulting fold structures. In this model, the Jura folding results from horizontal shortening oblique to the general trend of the fold axes.



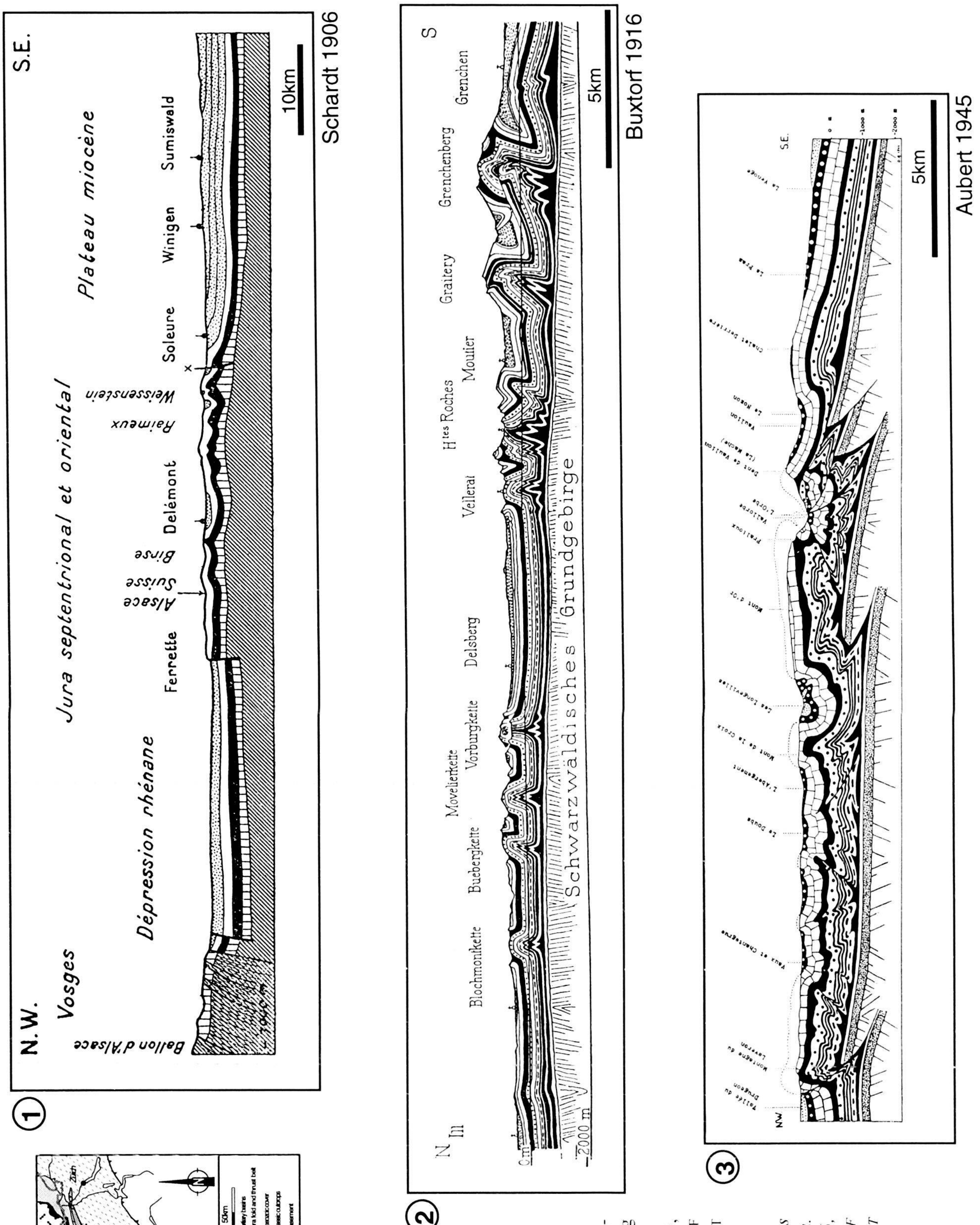


Figure 1.5: Selection of published cross-sections crossing the Jura fold and thrust belt.
1) From SCHARDT (1906, pl.VI); 2) From BUXTORF (1916); 3) From AUBERT (1945).

Coupes géologiques publiées recoupant la chaîne du Jura.
1) Tirée de SCHARDT (1906, pl.VI); 2) Tirée de BUXTORF (1916); 3) Tirée de AUBERT (1945).

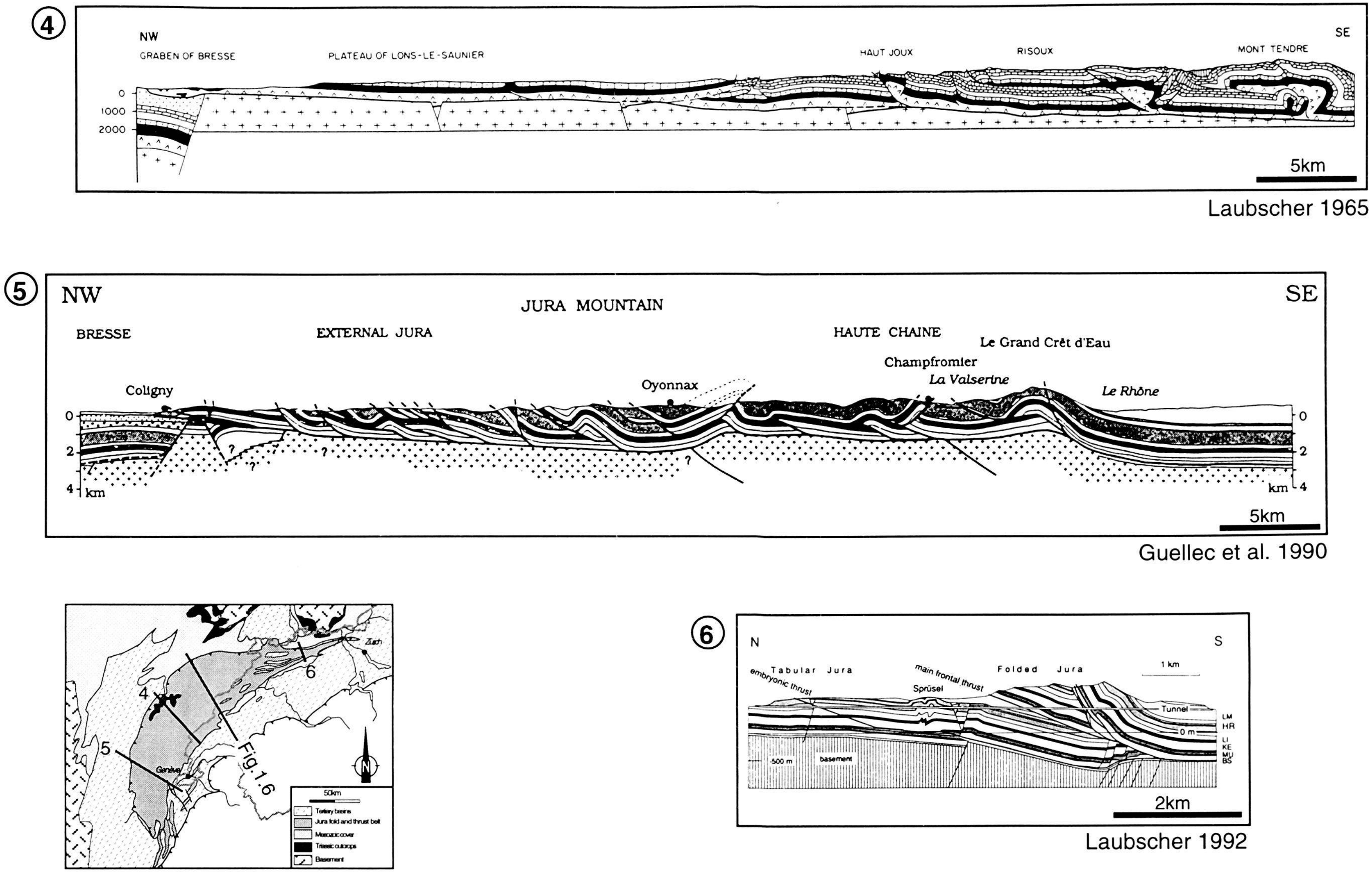


Figure 1.5: Selection of published cross-sections crossing the Jura fold and thrust belt. 4) From LAUBSCHER (1965); 5) From GUELLEC *et al.* (1990); 6) From LAUBSCHER (1992).

Coupes géologiques publiées recoupant la chaîne du Jura. 4) Tirée de LAUBSCHER *(1965); 5) Tirée de* GUELLEC *et al. (1990); 6) Tirée de* LAUBSCHER *(1992).*

Stretching in this model is essentially subhorizontal as expressed by the presence of conjugate systems of strike-slip faults. A wrench fold concept was also discussed by WEGMANN (1963), who suggested that the crystalline basement was broken by N-S trending horsts and grabens and by NE-SW trending antithetical faults. Accordingly, major tear-faults of the Jura resulted from the movement of the basement and concentrated along narrow zones. Folding resulted from more diffuse movements in the cover.

The availability of seismic reflection and well log data induced some authors (ZIEGLER, 1982; GORIN *et al.,* 1993) to further develop arguments in favor of an autochthonous cover. ZIEGLER (1982) argues that seismic reflection data show that the Molasse Basin is transected by a set of basement-involving normal and wrench-faults. These faults die out in the Oligocene or Miocene sediments and were active during the folding of the Jura fold and thrust belt. On the seismic lines, basement appears much deeper in the hinterland part of the Jura than below the Molasse Basin. Based on these data, ZIEGLER (1982, Fig. 26) suggests, that "... *the southern margin of the Jura belt is associated with a major basement imbrication along which the bulk of the shortening evident in the Jura-thrust belt is taken up. ... The configuration of the Molasse Basin implies that the postulated basement imbrication is carried out by a gently southeast-dipping thrust fault that possibly soles out within the crust. ...*". This thick-skinned allochthonous model suggests that the folding of the Jura belt was associated with crustal delaminations (Fig. 1.7). Recently, GORIN *et al.* (1993) have published structural interpretations of industry seismic lines from the western Swiss Molasse Basin. According to these authors the "... *foothills of the Jura Mountains are marked by a considerable thickening of the Triassic evaporites, which has been related by BITTERLI (1972) to salt flowage, but also coincides with a deep-seated Paleozoic lineament. ...*". These lineaments would have been active during that time and reactivated several times until the present day. Gorin *et al.* then argued that the geometry of these faults did not permit the translation of the cover and therefore the latter is autochthonous.

PFIFFNER *et al.* (1997a) have also suggested recently that the presence of inverted Permo-Carboniferous grabens argues in favor of a thick-skin deformation. A first detachment would be located within the Triassic evaporites and a second detachment horizon would be present within the basement. An inverted Permo-Carboniferous graben has been interpreted on one seismic reflection line in the central Molasse Basin (Hermrigen) (Fig. 1.3) and another one has been postulated in order to balance a geological cross-section in the central Jura (Chasseral anticline) (KÜHNI, 1993) (Fig. 1.7). This model agrees with that of GUELLEC *et al.* (1990) based on a ECORS deep seismic line as well as surface and subsurface data, who propose a shallow décollement in the Triassic evaporites layers and a deeper one within the basement (Fig. 1.5, section 5). According to them, "... *basement shortening is often required to account for the late deformation of the overlying but allochthonous sedimentary cover.*"

A similar interpretation of the Jura in terms of "thick-skinned" tectonics is given by JOUANNE *et al.* (1994) based on the comparisons of triangulations and present day vertical uplift rates (JOUANNE & MÉNARD, 1994).

Basement involvement beneath the Jura: opponents

Many other authors have explained the formation of the Jura belt as folded above a main décollement level within Triassic evaporite series. This hypothesis supposes an allochthonous cover and no basement involvement. For these authors, the discussion centres around the question of where the shortening of Jura and Molasse Basin cover is compensated in the basement ? The review presented here is based on a discussion by BURKHARD (1990) with the addition of some new references.

BUXTORF (1907) was among the first to interpret the Jura fold and thrust belt as an allochthonous cover deformation, resulting from a distant Alpine push (= "Fernschub" in German) transmitted through Mesozoic and Cenozoic strata of the Molasse Basin. The cover would be detached from the basement in the Triassic anhydrite beds. BUXTORF (1907; 1916) based his hypothesis on the observation of Triassic rocks in railway tunnel cut through anticlines (Fig. 1.5, section 2). The earlier section of SCHARDT (1906), shows that the Jura as an allochthonous cover folded over a slightly warped basement, stating a décollement zone between the cover and the basement (SCHARDT, 1906, 1908).

Gravity sliding for the whole Jura belt was proposed as early as 1892 by REYER (1892) and later more clearly expressed by LUGEON (1941, p. 9) for whom, the Jura resulted from the lateral migration of the evaporite layers from the Molasse Basin,

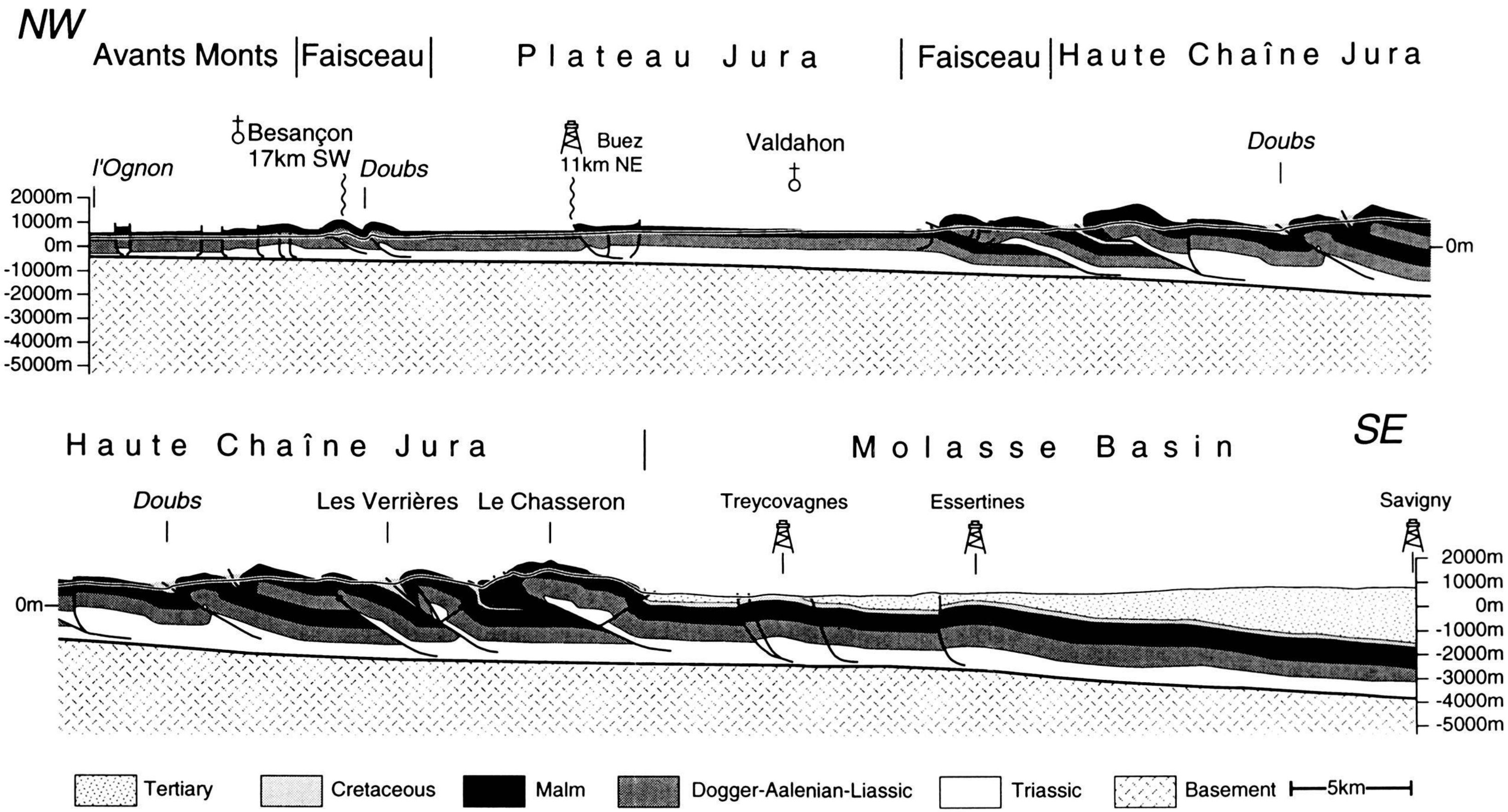


Figure 1.6: Line length balanced cross-section across the Jura and the Molasse Basin. This figure corresponds to the enlargement of the northern part of the large scale cross-section in Plate 9. For location, see geological map of Figure 1.5.

Coupe équilibrée à travers le Jura et le Bassin molassique. Cette figure correspond à l'agrandissement de la partie septentrionale de la coupe à grande échelle de la Planche 9. Pour la localisation, voir la carte géologique de la Figure 1.5.

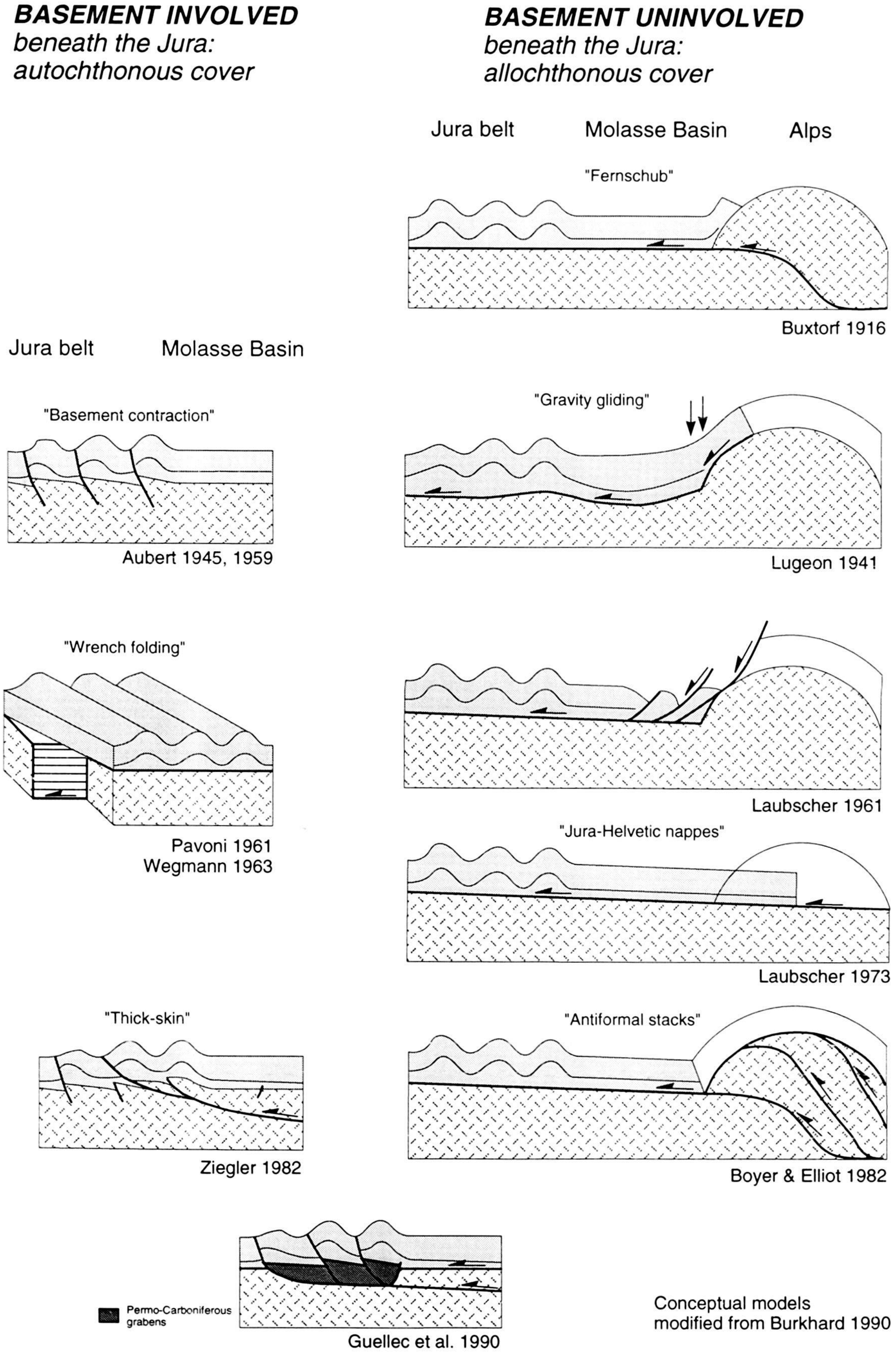


Figure 1.7: Review of conceptual models of the formation of the Jura fold and thrust. Modified from Burkhard (1990).

Présentation de plusieurs modèles conceptuels expliquant la formation de la chaîne plissée du Jura. Modifié de Burkhard (1990).

under a vertical loading stress (Fig. 1.7). The first model of LAUBSCHER (1961, 1965) also suggested that gravity sliding played an important role (Fig. 1.7). The Mesozoic cover together with the overlying Tertiary Molasse is folded and thrusted towards the NW from 2 to 25 km and rotated 8° around its northern tip, above a main décollement horizon located within the Triassic evaporite beds (Fig. 1.5, section 4). This model assumed a smooth underlying basement dipping 2° to 3° towards the South. Later, LAUBSCHER (1973b) presented a kinematic model of the Jura-Helvetic system, where the main Jura décollement level was connected to the basal Helvetic thrust; as a result the uplift of the external crystalline massifs would postdate the formation of the Jura thrust and fold belt. BURKHARD (1990) referring to fission track data from the Alps (SCHAER *et al.*, 1975; HURFORD, 1986) argues that "... *the uplift of the Central Alps must have started at the Early Miocene time, when the Molasse Basin was still subsiding. .... This means that during the thrusting of the Jura, there existed already an Aar massif culmination that had about half its present amplitude* ...". Consequently, the Jura basal thrust must root below or in the front of the external crystalline massifs (BOYER & ELLIOTT, 1982) and it cannot connect with the basal Helvetic thrusts (Fig. 1.7).

Recently, several seismic reflection lines have been shot and a series of drill holes have been made in the northeastern Swiss Jura by the NAGRA (Cooperative for the Storage of Radioactive Waste) (DIEBOLD *et al.*, 1991). This work has led to the discovery of an important Permo-Carboniferous trough. In addition the basement top seems to be affected by E-W trending normal faults with throws of some tens of meters. However, these faults are not important enough to impede a basal detachment within the thick Triassic beds (LAUBSCHER, 1992) (Fig. 1.5, section 6).

1.5. SOURCES OF DATA

Surface geological information, reflection seismic data and wells provide the data sets for this research.

1.5.1. Surface geological data

The surface geology data consist of a large number of published and unpublished geological maps, near-surface cross-sections and lithostratigraphic logs. In Switzerland, the studied area is more or less covered by 1:25'000 scale geological maps published by the Swiss Geological and Hydrological Survey and in France by 1:50'000 scale maps published by the French BRGM (Bureau de recherches géologiques et minières). Several unpublished original maps and cross-sections (diploma, PhD theses and private contracts) deposited at the Geology Department of Neuchâtel University, have been very useful for understanding structures. All maps used in this investigation are listed in Table 1.1.

1.5.2. Subsurface data

Industry seismic reflection surveys were conducted in the study area between 1970 and 1988 by different companies: British Petroleum (sector A in Figure 1.4), Shell Switzerland (sector B et C), Société anonyme des Hydrocarbures (sector B) and Shellrex (sector D). This subsurface data set consists of more than 1500 km of migrated or unmigrated seismic profiles and lithology- and velocity-logs of some twenty wells. The parameters (acquisition and processing) of the seismic set are more or less consistent, depending on each survey and especially on the date of exploration (Tab. 1.2). The Neuchâtel Jura and French Jura data sets were provided directly by the oil companies. Most of the industry seismic lines and well data from the Canton Vaud area are deposited at the Musée de Géologie at Lausanne, who kindly gave access to this information. The data sets include a migrated or unmigrated stack copy on paper.

Appendix 1 presents an inventory of seismic lines with the renumbering adopted in this thesis. In this new line numbering scheme (see Tab. 1.2 thesis numbering and sector), even numbers denote strike lines (NE-SW), whereas odd numbers denote dip lines (NW-SE). For a wider area, SWISSPETROL (1992) and BITTERLI (1972) present a general location map with a seismic grid and survey names from the Jura arc and the Molasse Basin.

Data from some twenty drill holes could be used for calibration of the seismic lines. These data include lithology and velocity logs (Appendix 2) coming essentially from the literature or provided by the Musée de Géologie in Lausanne.

1.6. METHODOLOGY

This subchapter present a short view of the important steps involved in the elaboration of this research.

Title	Location	Scale	Authors
Val de Ruz	NE, CH	1: 25'000	Bourquin et al. (1968)
Bieler See	BE, NE, CH	1: 25'000	Schär (1971)
Neuchâtel	NE, CH	1: 25'000	Frei et al. (1974)
Le Locle- La Chaux-de-Fonds	NE, CH	1: 25'000	Rollier & Favre (1910)
Chaumont (East sector)	NE, CH	1: 5'000	Schaer (1956)
Chaumont (West sector)	NE, CH	1: 5'000	Margot (1962)
Le Pâquier	NE, CH	1: 25'000	Aragno (1994)
Mont Amin Kette	NE, CH	1: 5'000	Baer (1959)
Biaufond-...-Saint-Imier	NE, JU, CH	1: 25'000	Bourquin & Suter (1946)
Les Verrières	NE, CH	1: 25'000	Mühlethaler (1930)
Val de Travers	NE, CH	1: 25'000	Rickenbach (1925)
Travers	NE, CH	1: 25'000	Thiébaud (1936)
Solmont	NE, CH	1: 25'000	Frei (1942)
Les Gorges de l'Areuse	NE, CH	1: 15'000	Schardt & Dubois (1903)
Les Gorges de l'Areuse	NE, CH	1: 25'000	Meia (1986)
Creux du Van	NE, CH	1: 10'000	Müller (1958)
Ponts-de-Martel	NE, CH	1: 5'000	De Pury (1963)
La Tourne	NE, CH	1: 5'000	Schwaar (1959)
Mt-Aubert	VD, NE, CH	1: 25'000	Meia (1969)
Les Gorges de La Vaux	VD, CH	1: 5'000	Dessoulavy (1952)
Ste-Croix	VD, CH	1: 25'000	Rigassi & Jaccard (1995)
Yverdon	VD, CH	1: 25'000	Jordi (1994)
Orbe	VD, CH	1: 25'000	Aubert & Dreyfuss (1963)
Cossonay	VD, CH	1: 25'000	Custer & Aubert (1935)
Jorat	VD, CH	1: 25'000	Bersier (1952)
Morges	VD, CH	1: 25'000	Vernet (1972)
Lausanne	VD, CH	1: 25'000	Weidmann (1988)
Châtel-St.-Denis	VD, FR, CH	1: 25'000	Weidmann (1992)
Marchairuz	VD, CH	1: 25'000	Falconnier (1950)
Vallée de Joux	VD, CH	1: 25'000	Aubert (1941)
Baume-Les-Dames	F	1:50'000	BRGM (1972)
Chalon-sur-Sâone	F	1: 250'000	BRGM (1987a)
Champagnole	F	1: 50'000	BRGM (1965a)
Dijon	F	1: 250'000	BRGM (1989)
Dôle	F	1:50'000	BRGM (1979)
Lons-Le-Saunier	F	1:50'000	BRGM (1966)
Morez-Bois d'Amont	F	1:50'000	BRGM (1968a)
Morteau	F	1: 50'000	BRGM (1968b)
Mouthe	F	1: 50'000	BRGM (1964)
Ornans	F	1: 50'000	BRGM (1963)
Poligny	F	1:50'000	BRGM (1981)
Pontarlier	F	1: 50'000	BRGM (1969)
Quingey	F	1:50'000	BRGM (1975)
Salins-Les-Bains	F	1:50'000	BRGM (1967)
Thonon-Les-Bains	F	1: 250'000	BRGM (1987b)
Vercel	F	1: 50'000	BRGM (1965b)

Table 1.1: List of geological maps from the studied area. Cantons: NE = Neuchâtel; BE = Bern; VD = Vaud; FR = Fribourg. Countries: CH = Switzerland; F = France.

Liste des cartes géologiques utilisées dans cette étude. Cantons: NE = Neuchâtel; BE = Bern; VD = Vaud; FR = Fribourg. Pays: CH = Suisse; F = France.

- Compilation of existing data

A large amount of data on the Central Jura and Molasse Basin exists, but few of these are easily accessible. Tools for documenting this study include: geological maps, dip data, cross-sections, drill hole data and seismic reflection lines. Different petroleum companies have shot thousands of kilometers of seismic reflection lines and drilled many wells in the project area. Many of them are neither published nor in the public domain. However, upon request BP and SHELL oil companies kindly provided many useful seismic lines and drill logs.

- Field work

Field work was conducted in order to collect additional dip data for the cross-sections.

- Seismic interpretation

More than 1500 km of seismic lines were interpreted for this work (Fig. 1.4). Surface data from geological maps of the central Jura and additional data collected in the field have been integrated with seismic profiles and well logs. Knowledge about stratigraphy is essential for seismic interpretation. As first step drill hole logs were therefore compiled. Based on wells, seismic stratigraphic units have been defined and correlated through the whole seismic grid, with jump correlations if necessary, because good data in synclines are often interrupted by bad data across anticlines and tear faults. Due to the good quality of strike lines, mainly shot along synclines, it was possible to constrain the stratigraphic column at depth. This has been especially important for unexposed Triassic formations. Each intersection of the seismic profiles was checked to obtain an internally consistent interpretation.

- Depth conversion and contour maps

Seismic time lines (two way time in seconds) were converted to depth (meters), in order to construct contour and isopach maps. Seismic velocities were constrained by nearby drill hole velocities. In the Jura itself, a simple velocity model was used for depth conversion, whereas in the Molasse Basin region, powerlaw or linear functions, dependent on depth were used (Appendices 3).

- Cross-sections

One line length balanced cross-section across the whole Jura and Molasse Basin (Fig. 1.6 and Plate 9) and two more regional cross-sections across the Neuchâtel Jura (Val de Ruz: Fig. 4.5; Val de Travers: Fig. 4.8) were drawn. These sections are based on the depth conversions of the nearest seismic lines and constructed using modern concepts of structural geology (WOODWARD *et al.*, 1989).

Survey	Year	Migration	Quantity	Sector	Lenght	Source	D. P.	Thesis numbering
British Petroleum	1988	yes	17	A	300km	vibroseis	500m	1-19
Shell Switzerland	1973-1978		11	B	450km	vibroseis	500m	20-
SADH *)	1972-1979		34	B	200km	vibroseis	500m	-71
Shell Switzerland	1972-1974	yes	14	C	100km	vibroseis	500m	80-95
Shellrex	1970-1974	mostly	20	D	600km	vibroseis	800m	100-125

Table 1.2: Seismic data parameters for each survey. For sectors, see Figure 1.4. D.P. = Datum Plane. *) SADH = Société anonyme des Hydrocarbures.

*Paramètres sismiques caractérisant chaque campagne sismique. Pour les secteurs, voir Figure 1.4. D.P. = Niveau de référence sismique. *) SADH = Société anonyme des Hydrocarbures.*