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Artikel: Geology of the central Jura and the molasse basin : new insight into an evaporite-based foreland fold and thrust belt = Géologie du Jura central et du bassin molassique : nouveaux aspects d'une chaîne d'avant-pays plissée et décollée sur des couches d'évaporites

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Kapitel: 2: Stratigraphy

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2. STRATIGRAPHY

2.1. INTRODUCTION

The geological interpretation of a seismic grid is based on the correlation of major seismic reflectors throughout the whole area. In sedimentary rocks, reflectors correspond to major lithological discontinuities. The stratigraphic calibration of the reflectors is done with the information obtained from the interpretation of drill hole logs. This chapter will first provide a regional overview and then present a synthetic stratigraphic column for the Neuchâtel Jura. Selected reflectors and seismic units used for the interpretation of the lines will then be presented taking into account the lithostratigraphic considerations. This chapter will also offer a series of isopach maps of the major stratigraphic units below the Molasse Basin and a rheological framework, which are both crucial for the understanding of the structures.

2.2. REGIONAL OVERVIEW

2.2.1. Introduction

The evolution of the Molasse and Jura basins during Mesozoic and Cenozoic times is here discussed in the larger geographic and tectonic context of central Europe. The following summary is not based on seismic data, but mostly on surface geology and wells, as reported in published books, guides or papers, that discuss the setting and the stratigraphic evolution of the sedimentary cover. Key references are listed below:

DIESLER (1914), HEIM (1921), JEANNET (Plate IV) in FAVRE & JEANNET (1934), GUILLAUME (1966), DEBELMAS (1974), CHAUVE (1975), AUBERT (1975), TRÜMPY (1980), DEBRAND-PASSARD *et al.* (1984), DEBRAND-PASSARD & COURBOULEIX (1984), HOMEWOOD (1986), GYGI & PERSOZ (1986, 1987), MARTIN (1987), ZIEGLER (1982, 1988, 1990), HOMEWOOD *et al.* (1989), KELLER (1989).

Formation names in quotation marks are given in French or German to avoid confusion associated with translation.

2.2.2. The basement: Paleozoic or older rocks

Paleozoic and older rocks underlie the Mesozoic strata of the Jura and the Molasse Basin. Crystalline basement crops out in the Vosges and Black Forest massifs (migmatitic gneisses), in the Serre massif and in the external Alpine massifs (Fig. 1.2). Permo-Carboniferous sediments are locally preserved in graben-like structures in all of these areas. Both kinds of rocks have been penetrated by wells underneath the Jura and the Molasse Basin.

The crystalline basement (metamorphic rocks) was formed during the Variscan (or Hercynian) orogeny. The latter is considered the product of the collision between the Gondwana and the Laurasia continents during lower Carboniferous time. Syn-kinematic granitic intrusion is associated with Variscan structures; post-kinematic granitic intrusion is related to crustal extension beginning in the upper Carboniferous. The latter corresponds to the final stage of the Hercynian orogeny, which is characterized by presumed crustal thinning along low angle normal faults and widespread strike-slip faults. Transtensional basins (pull-aparts, grabens), volcanism and hydrothermal activity is obviously the result of extension tectonics. Detrital fluvial sediments derived from high relief areas filled the basins and a luxuriant continental vegetation developed in warm climatic conditions. Coal seams result from the burial of this organic matter and Permian red sandstones and conglomerates ("Rotliegendes") overlie the coal-bearing strata. Important subsurface basins occur at the edge of the Jura: one example is the Lons-le-Saunier basin located at the western edge of the Jura (Fig. 1.2) and another basin located in the northern part of Switzerland was discovered in 1983 by the Swiss NAGRA (National Cooperative for the Storage of Radioactive Waste). Peneplanation followed the end of the Hercynian orogeny.

The basement is therefore characterized by two major unconformities: one below the Carboniferous sediments and second below the Triassic rocks.

2.2.3. Mesozoic

During the Mesozoic, an epicontinental sea developed in the area of the future Jura Mountains. Interlayered marl and limestone beds were deposited in a platform or lagoonal environment. An important facies limit (barrier or barrier reefs) appears to be located today approximately along the internal part of the Haute Chaîne Jura (TRÜMPY, 1980; PERSOZ, 1982; MOUCHET, 1995). In the Molasse Basin, more basinal facies have been recognized (PERSOZ, 1982).

Three typical stratigraphic columns of the Mesozoic formations, outcropping along the Swiss Jura, are presented on Figure 2.1. This figure shows the most important lateral changes in thickness and facies of the formations along the Swiss Jura.

2.2.3.1. Triassic

The Triassic is not exposed in the study area, except in the "Faisceaux" Jura of France. Triassic also crops out in the eastern Jura of Switzerland and it also has been drilled (Figs. 2.11 to 2.13) in the French Jura, in the Molasse Basin and in the Bresse Graben.

The stratigraphy of the Triassic layers is difficult to establish in the subsurface of the Jura and the Molasse Basin, because tectonic complications occur within these formations. As mentioned earlier (Chapter 1), the cover has been deformed over a main Triassic décollement level. Tectonic thickening, thinning and doubling of beds make it difficult to establish a detailed stratigraphy. Figure 2.2 presents a composite geological profile through the Triassic décollement level as interpreted from the well data of Schafisheim (Canton Aargau, Switzerland) (MATTER *et al.*, 1988). This area, located in the eastern Swiss Molasse Basin and a few kilometers south of the easternmost fold of the Haute Chaîne Jura, is structurally less complicated than the French Jura Plateau or the Haute Chaîne Jura. Even if the classic German Triassic and its stratigraphic framework is presented here, the area remains difficult to correlate with the limited and tectonically complicated data provided by the Jura and the Molasse Basin drill holes. The terms Keuper and Muschelkalk are not used in this work in view of the lack of reliable biostratigraphy and the tectonic considerations discussed above. Instead, we have adopted Triassic Unit 1 and Triassic Unit 2 as main subdivisions, based on seismic correlation (§2.4.3.7. and §2.4.3.8.).

At the beginning of the Mesozoic, the peneplaned basement was invaded by a marine transgression. An epicontinental shallow water sea developed with a depocenter in northern Germany (Fig. 2.3). The basin was almost completely landlocked. During times of limited connection with the Tethys, continental clastics and evaporites were deposited. During marine ingression huge lowland areas were flooded and carbonates were precipitated. The Triassic deposits in the Jura are of Germanic type and traditionally subdivided into three lithostratigraphic units (Fig. 2.4): the "Buntsandstein" consists of sandstones or conglomerates also called the "Grès bigarrés" formation; the "Muschelkalk" begins with the "Wellen-gebirge", marine sandstones, marls and dolomites and is followed by the "Anhydritgruppe" with its salt and evaporites suggesting only a restricted connection between the Germanic inland sea and the Tethys (Fig. 2.3) and terminates with the "Hauptmuschelkalk" and its marine shelly limestones; the last of the trilogy, the "Keuper", starts with the marker bed "Lettenkhole", containing lignite and dolomite and continues mainly with evaporites ("Gipskeuper") and marls. The overlying Rhaetian is represented by sandstones and marls.

The total thickness of the Triassic series (Fig. 2.5) is less than 500 m outside of the Jura fold and thrust belt and appears to increase progressively towards the center of the chain (internal Jura), reaching more than 1000 m. The formation of the Jura fold and thrust belt seems to be closely related to the thickness distribution of the Triassic layers and will be discussed later in Chapter 5.

2.2.3.2. Jurassic

Early Jurassic: Liassic

The lower Jurassic formations, like those of the Triassic, crop out in the Tabular Jura, along the northern margin of the Folded Jura and in France along the western margin of the Jura.

The Early Jurassic was characterized by a transgression. The environment was a platform or a low energy shallow basin (Fig. 2.6). The studied area is too small to be a distinct paleogeographic domain itself, although it shows influences from the Alpine (Tethys basin), Swabish and Paris basins. Several positive areas of low relief, represented by anorogenic highs (i.e. Massif Central, London-Brabant massif, Rhenish massif, Bohemian massif, ...) surround these basins. The southern part of the Molasse Basin was occupied by one of these islands called

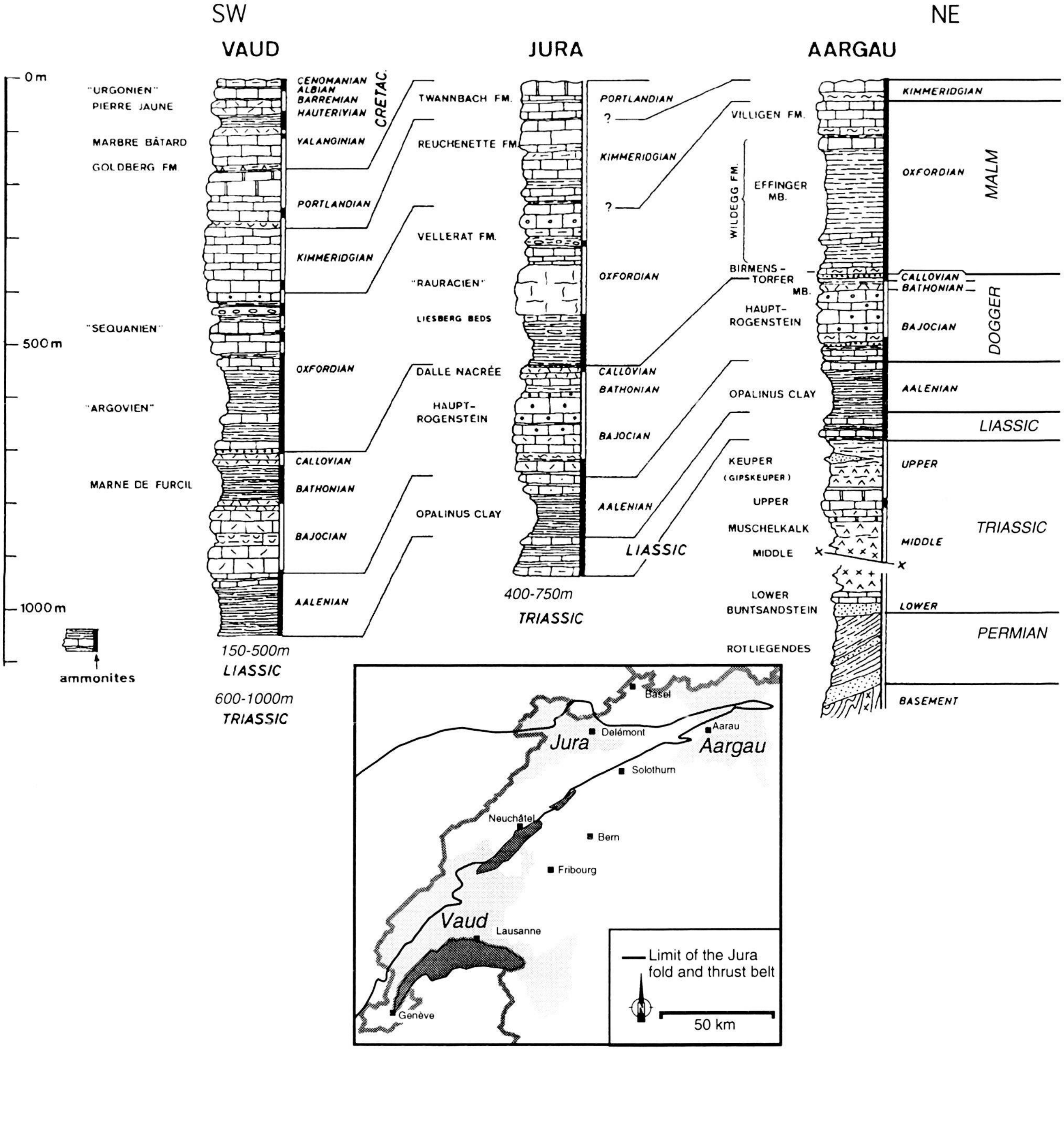
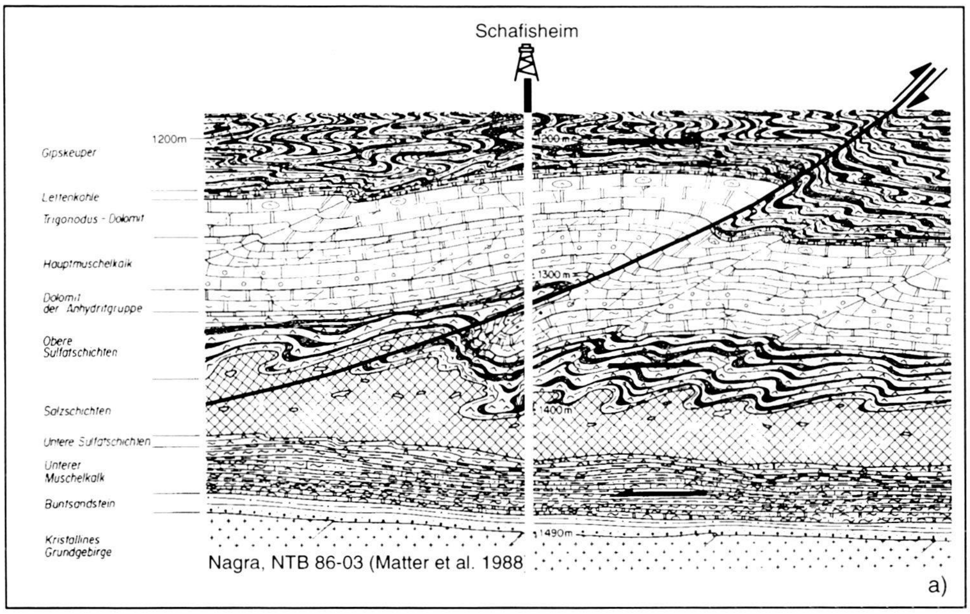


Figure 2.1: Stratigraphic sections of the Mesozoic formations in the Swiss Jura. Vaud, Jura and Aargau correspond to three Swiss Cantons, their location is given on the small adjoining map. Modified from TRÜMPY (1980).

Coupes stratigraphiques des formations mésozoïques du Jura suisse. Vaud, Jura et Aargau représentent trois cantons suisses. Modifié de TRÜMPY (1980).



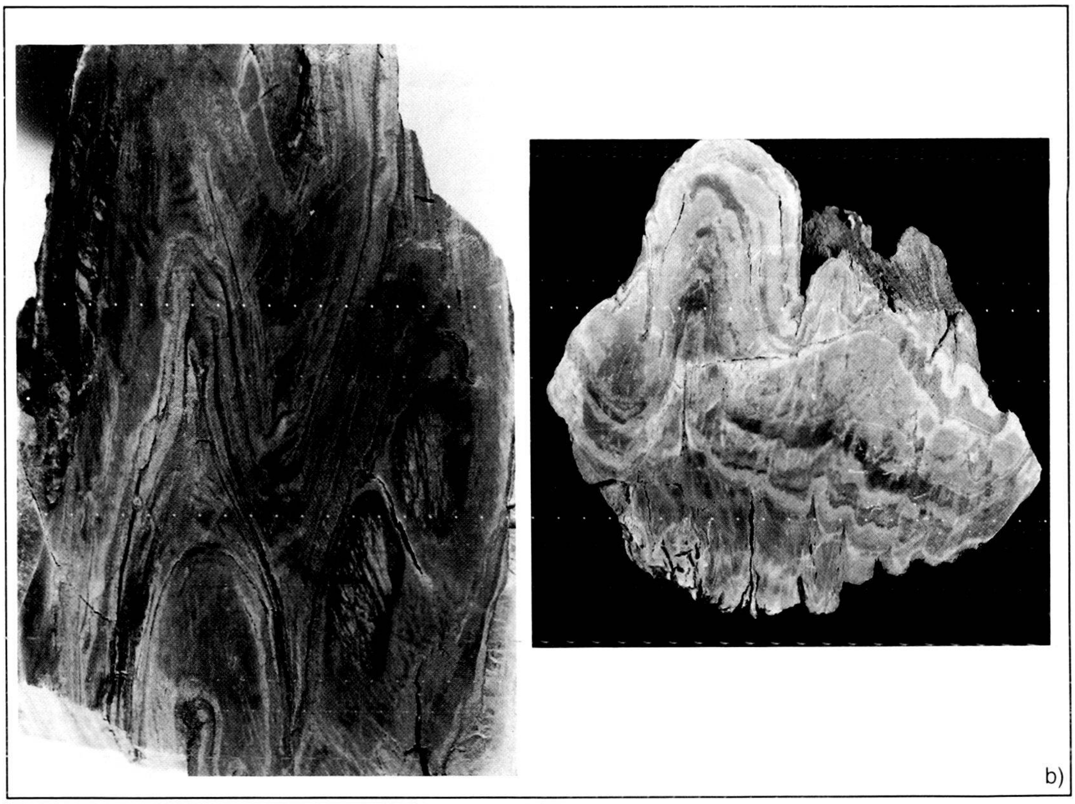


Figure 2.2a): Composite geological profile through the Triassic décollement zone. This section, based on the Schafisheim drill hole data, highlights the tectonically disturbed stratigraphy in the Triassic layers. From MATTER *et al.* (1988).

Coupe géologique à travers la zone de décollement du Trias. Ce profil, basé sur les données du forage de Schafisheim, souligne les perturbations tectoniques qui affectent la succession des couches du Trias. Tiré de MATTER et al. (1988).

Figure 2.2b): Type of folds observed in the Triassic evaporites in the Riepel quarry from Aargau Jura (645'200 m / 253'900 m, Swiss geographical reference).

Types de plis observés dans les niveaux évaporitiques du Trias de la carrière de Riepel, Jura argovien (645'200 m / 253'900 m, coordonnées géographiques suisses).

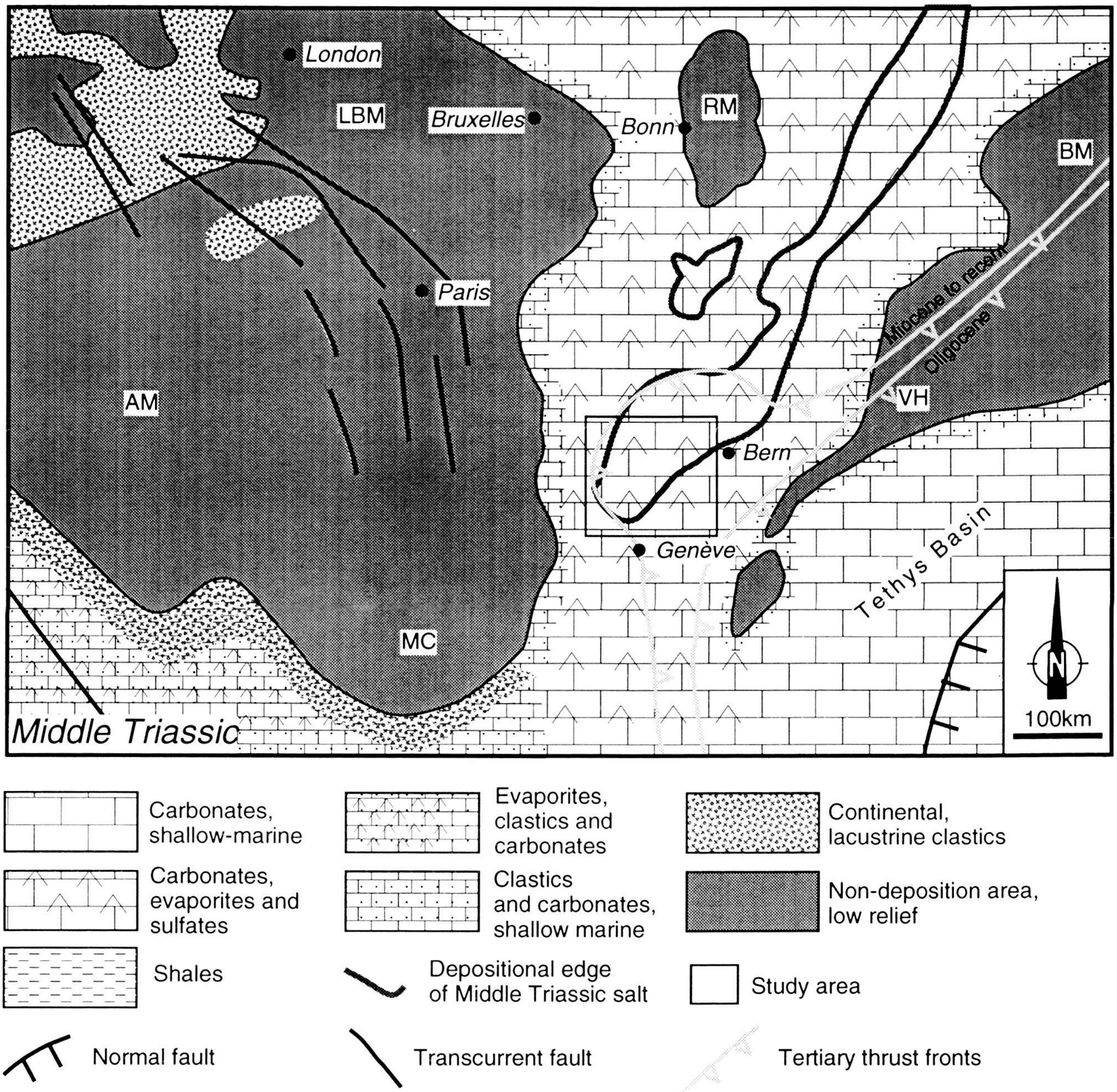


Figure 2.3: Paleogeographic map of Central Europe (not restored) in Middle Triassic times ("Muschelkalk"). AM = Armorican massif; BM = Bohemian massif; LBM = London-Brabant massif; MC = Massif Central, RM = Rhenish massif; VH = Vindelician High. Modified from ZIEGLER (1988, 1990). The square corresponds to the studied area.

Carte paléogéographique de l'Europe centrale (non reconstruite) au Trias moyen ("Muschelkalk"). AM = Massif armoricain; BM = Massif de Bohême; LBM = Massif de Londres-Brabant; MC = Massif Central, RM = Massif rhénan; VH = Seuil vindélicien. Modifiée de ZIEGLER (1988, 1990). Le carré représente la région étudiée.

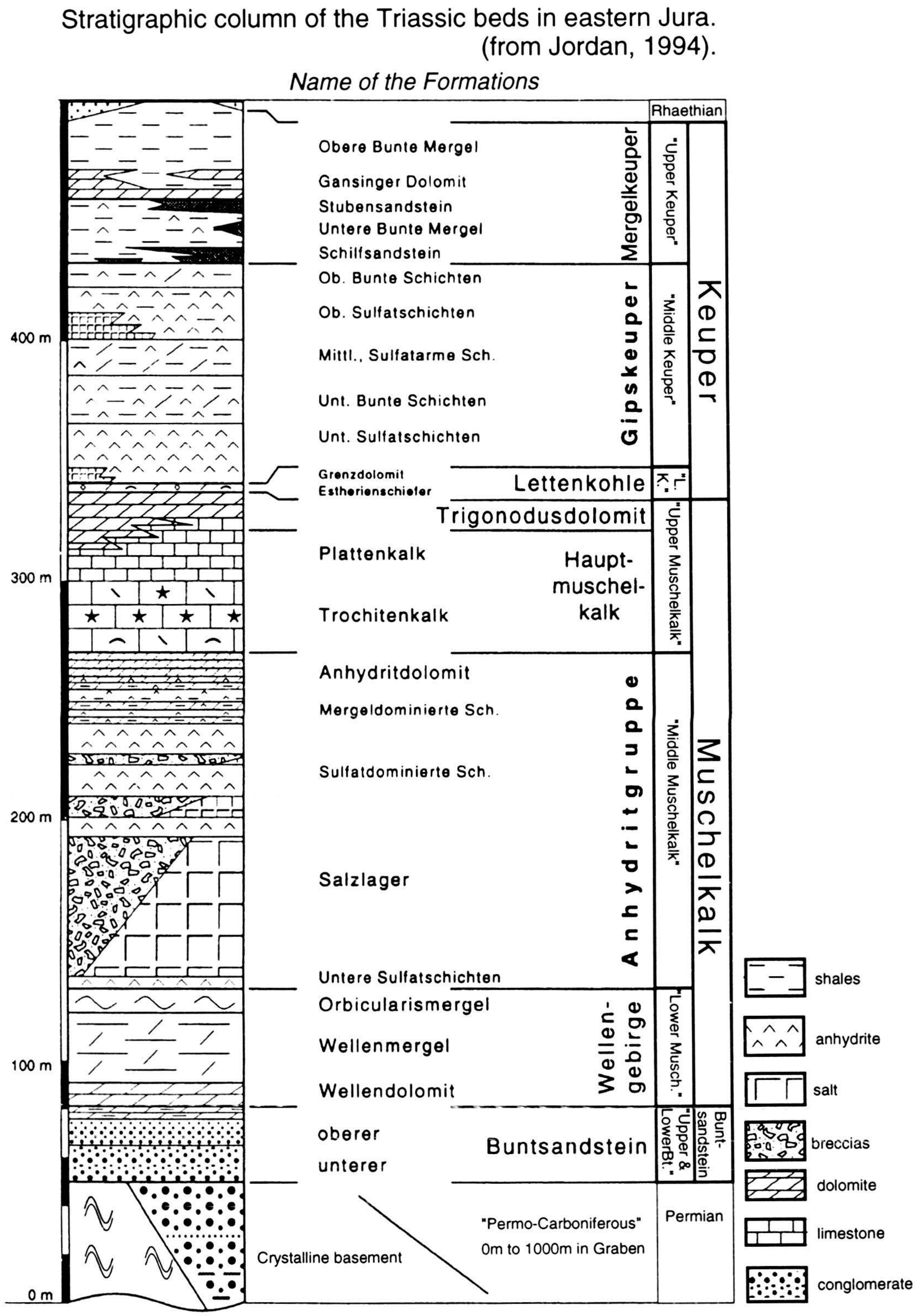


Figure 2.4: Composite stratigraphic column of the Triassic series as based on outcrops and drill hole data of the eastern Swiss Jura. Modified from JORDAN (1994).

Coupe stratigraphique des séries du Trias, reconstituée à partir des informations de la surface (affleurements) et de la subsurface (forages) de l'Est du Jura. Modifiée de JORDAN (1994).

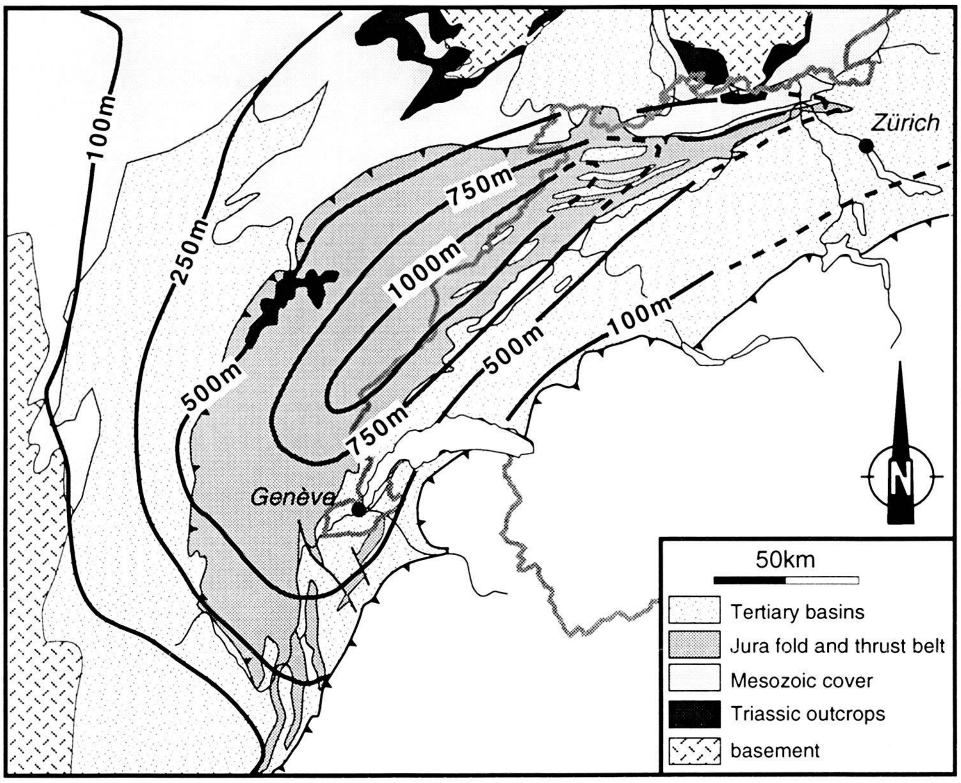


Figure 2.5: Isopachs (in meters) of the Triassic layers (minus Buntsandstein) in the Jura fold and thrust belt and adjoining areas. Thicknesses are compiled from many authors (WINNOCK *et al.*, 1967; DEBRAND-PASSARD & COURBOULEIX, 1984; BACHMANN *et al.*, 1987; BITTERLI, 1992).

Carte des isopaches (en mètres) des couches du Trias (Buntsandstein non compris) de la chaîne du Jura et des ses régions avoisinantes. Les épaisseurs sont compilées de plusieurs auteurs (WINNOCK et al., 1967; DEBRAND-PASSARD & COURBOULEIX, 1984; BACHMANN et al., 1987; BITTERLI, 1992).

the Alemannic high (Fig. 2.6). Coarse (mm size) quartz sands derived from this high occur in the Liassic series encountered in bore holes.

Middle Jurassic: Dogger

These are the oldest formations seen at outcrop throughout the Jura. By the beginning of mid-Jurassic times, the Alemannic high was flooded, but remained an area of minimal sedimentation until the late Middle Jurassic.

Lateral and vertical facies changes in the Liassic suggest differentiation of the Jura platform into different facies realms, which persisted throughout the Middle and Late Jurassic. The northwestern region was a shallow-water platform, whereas to the Southeast more muddy sedimentation prevailed in a low-energy hydrodynamic regime. The boundary between the two realms shifted repeatedly, but never corresponded to a single major shelf margin scarp; it is located along the axis Bern-Genève on the paleogeographic map of the Early Jurassic times (Fig. 2.6).

Late Jurassic: lower and upper Malm

The difference between an eastern and western domain still persisted. The boundary between the two domains shifted towards the SE during Late Jurassic times. The former Alemannic high began to subside. Sub-euxinic limestones extend beyond the Molasse Basin into the Helvetic domain (Fig. 2.7).

The Late Jurassic began with a condensed facies, represented by few centimeters of iron ooliths with Cephalopods, but was then characterized by a shallow-water platform with development of biohermal reefs. The boundary between the platform and basinal domains was marked by a discontinuous belt of patch reefs and oolitic bars. At the end of the upper Malm time, the sedimentary environment changed

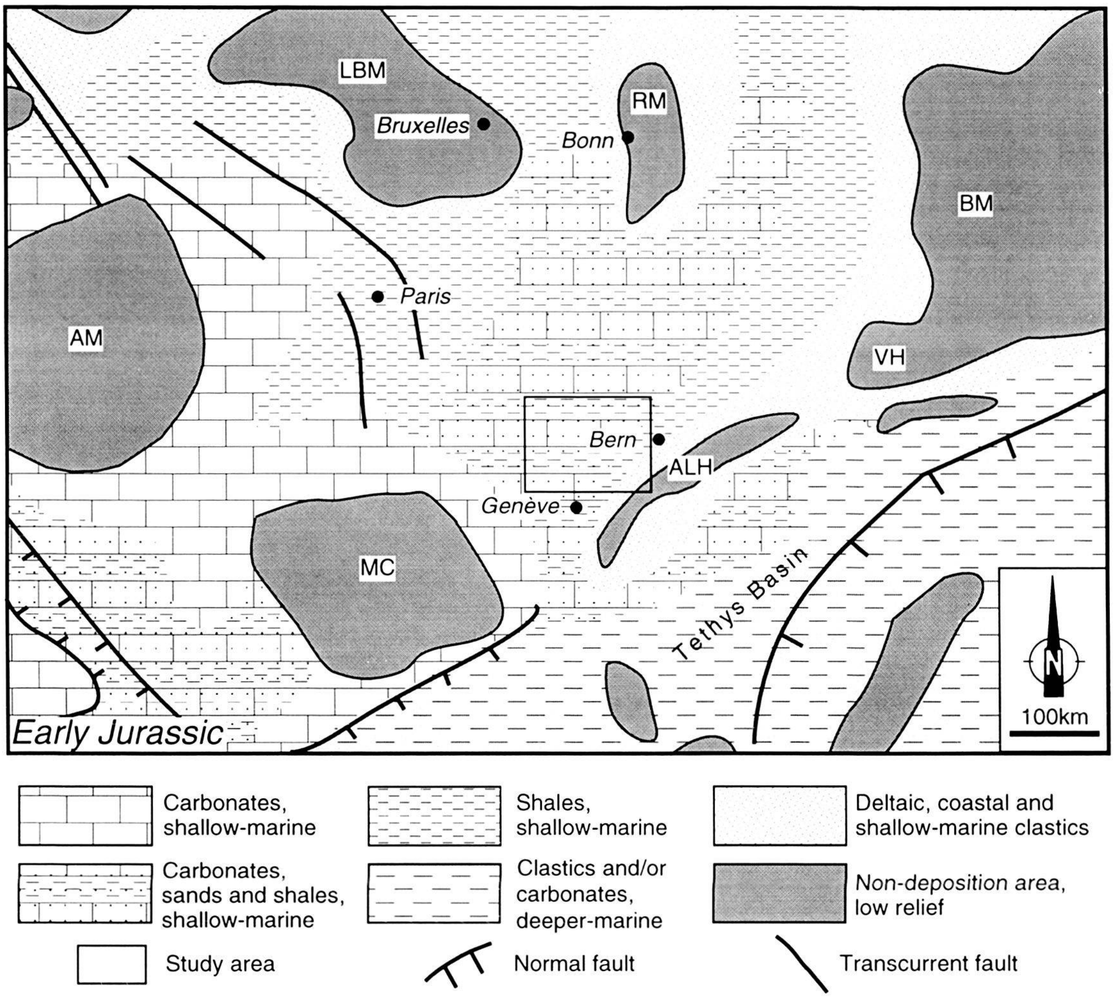


Figure 2.6: Paleogeographic map (not restored) of Central Europe in Early Jurassic times (Sinemurian - Aalenian). AM = Armorican massif; ALH = Alemannic high; BM = Bohemian massif; LBM = London-Brabant massif; MC = Massif Central, RM = Rhenish massif; VH = Vindelician High. Modified from ZIEGLER (1988, 1990). The square corresponds to the studied area.

Carte paléogéographique de l'Europe centrale (non reconstruite) au début du Jurassique (Sinémurien - Aalénien). AM = Massif armoricain; ALH = Seuil alémanique; BM = Massif de Bohême; LBM = Massif de Londres-Brabant; MC = Massif Central, RM = Massif rhénan; VH = Seuil vindélicien. Modifiée de ZIEGLER (1988, 1990). Le carré représente la région étudiée.

from a margino-littoral facies to a supratidal facies with emersion episodes, leading to a marine brackish facies. These changes occurred as the result of a widespread regression, which affected western Europe by the end of the Jurassic.

2.2.3.3. Cretaceous

The Early Cretaceous is well developed in the Haute Chaîne Jura, whereas the Late Cretaceous is discontinuous, due to Tertiary erosion. At the beginning of Cretaceous time, a new marine incursion covered the southern Jura. During the Early Cretaceous, the Jura formed a platform with sediments deposited in shallow waters (neritic environment) close to emersion conditions. A paleogeographic border was located along the internal zone of the Haute Chaîne Jura. The Early Cretaceous deposits are limestones or calcareous marls. During the Cenomanian-Turonian stage, the "Craie" (chalk) facies invaded the Jura from the Paris Basin. Detrital facies migrated progressively towards the South and the Jura became part of the Paris Basin. Late Cretaceous limestones are locally preserved in karst pockets. All Cretaceous formations thin towards N or NE and disappear totally eastward of Biel. This raises the question whether Cretaceous sediments were removed by erosion or if they were never deposited? The answer is still open (Thierry Adatte, Neuchâtel, personal communication), but it

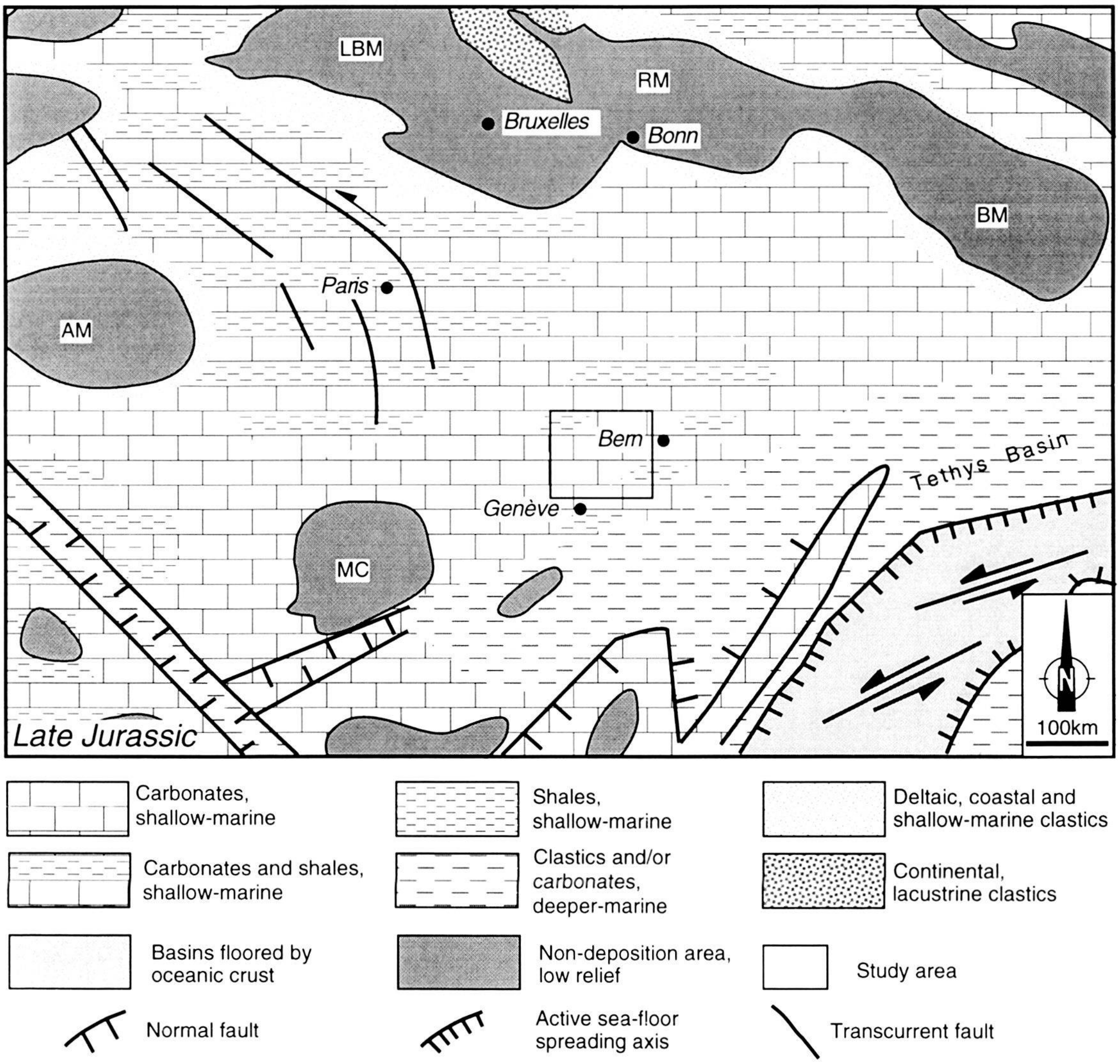


Figure 2.7: Paleogeographic map of Central Europe (not restored) in Late Jurassic times (Kimmeridgian - Tithonian). AM = Armorican massif; BM = Bohemian massif; LBM = London-Brabant massif; MC = Massif Central, RM = Rhenish massif. Modified from Ziegler (1988, 1990). The square corresponds to the studied area.

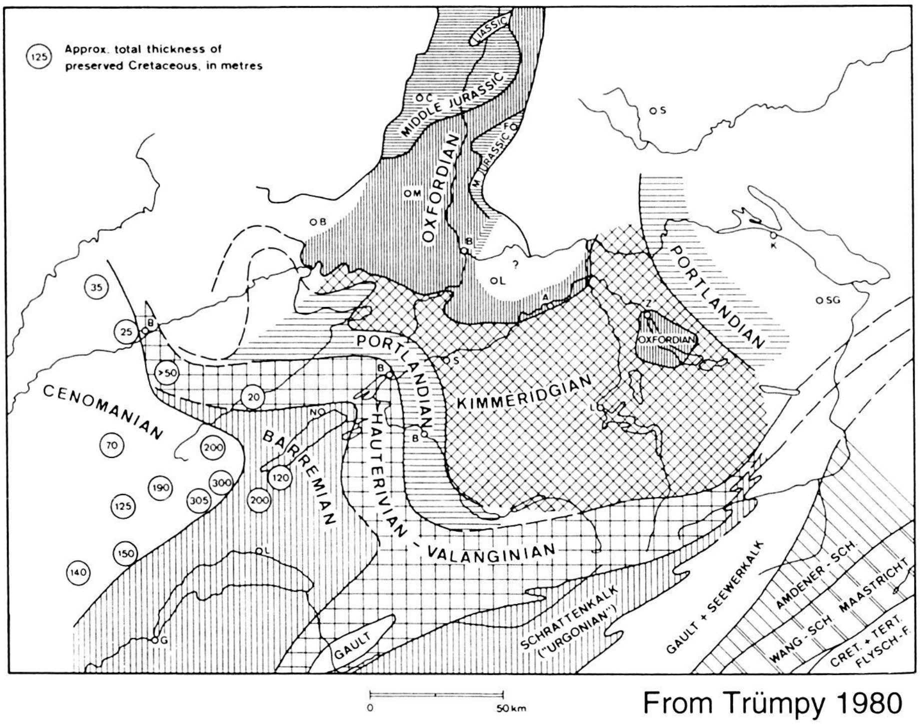
Carte paléogéographique de l'Europe centrale (non reconstruite) à la fin du Jurassique (Kimméridgien - Tithonique). AM = Massif armoricain; BM = Massif de Bohême; LBM = Massif de Londres-Brabant; MC = Massif Central, RM = Massif rhénan. Modifiée de Ziegler (1988, 1990). Le carré représente la région étudiée.

appears very likely that Cretaceous sediments were deposited in the Jura area (Pomerol, 1975; Ziegler, 1982) and subsequently eroded. The strong erosion is related to basement uplift in connection with the Oligocene Vosges-Black Forest mantle dome (Trümpy, 1980; Karner & Watts, 1983; Naef *et al.*, 1985).

2.2.4. Cenozoic: Tertiary

The Tertiary of the Molasse Basin and the Jura record the late stages of the Alpine deformation. A profound erosion surface separates various subcropping Mesozoic formations (Cretaceous, Late Jurassic and even Middle Jurassic in the East) from the onlapping Neogene (Fig. 2.8). The Eocene sediments are only known in karst pockets filled with red lateritic clays and ferrigeneous ooliths ("Bohnerz formation"). The Oligocene and Miocene successions are influenced by two major events affecting the foreland: the WNW-ESE extension of the Rhine Graben subsidence (Priabonian to Aquitanian age) and the uplift of the Black Forest - Vosges dome (Laubscher, 1992).

In the study area, the Tertiary is commonly referred to as Molasse. The Tertiary stratigraphy of the Jura and the Molasse Basin has been reviewed by Homewood *et al.* (1989), Keller (1990) and



From Trümpy 1980

Figure 2.8: Tertiary subcrop map of the Jura and the Molasse Basin. The total thickness of preserved Cretaceous (in meters) decreases towards the SE. From Trümpy (1980) with Courtesy of Shell Oil Co.

Carte paléogéographique à la base du Tertiaire. Les chiffres dans les cercles correspondent à l'épaisseur totale approximative (en mètres) des couches préservées du Crétacé. Tirée de Trümpy (1980), courtoisie de Shell Oil Co.

Berger (1992). Figure 2.9 relates the traditional nomenclature to more modern usage. The Molasse is essentially a clastic wedge prograding from the Alps towards the NW. Sediments are derived from the rising Alps, with only a minor detrital influx from the NW. Four lithostratigraphic groups are distinguished traditionally (Fig. 2.9): UMM ("Untere Meeresmolasse" = Lower marine water sediments), USM ("Untere Süsswassermolasse" = Lower freshwater Molasse), OMM ("Obere Meeresmolasse" = Upper marine water Molasse) and OSM ("Obere Süsswassermolasse" = Upper freshwater Molasse). Continental environments were represented by alluvial fans, gently sloping flood-plains with river channels and braided streams, lakes and coal swamps, whereas shallow current swept seas, paralic deltas and tidal flats represent marine to brackish environments.

Outcrops of the Lower marine Molasse group (UMM) are found in the Subalpine Molasse. The formation is represented by marine and brackish shales and sandstones. They correspond to a thick turbidite sequence at the base, followed by storm, wave and tide deposits and finally by a regressive littoral series. Along the southern rim of the Jura mountains, some thin continental deposits are time-equivalent to the UMM (Aubert, 1975). The northern limit of the marine "Rupelian" deposits lies not far north from the present day Alpine front along a line Lausanne-Lucerne. Savigny (Lemcke, 1963) is the only well in the study area yielding UMM sediments in cuttings.

During the "Chattian" - "Aquitanian" stages (USM), the sea retreated from the Molasse depression and the Alps began to rise strongly at rates of almost 1 mm/year (Trümpy, 1980). According to Berger (1992), "Chattian" and "Aquitanian" stage terms, as used locally, are imprecise chronostratigraphic terms and should be used only as "local units". A part of the USM is surely of Rupelian age (Berger, 1992). The Plateau Molasse landscape at late Oligocene times is dominated by at least seven gravel fans, at the northern margin of the Alps. Thick alluvial-fan conglomerates and sandstones were deposited grading northwards into multicolored sandstones and claystones representing meandering rivers, lakes and floodplain deposits. The USM conglomerates are derived from Mesozoic carbonates, flysch, igneous metamorphic and ophiolite clasts from Prealpine and Austroalpine nappes. In the Jura Molasse domain, the Oligocene fresh water transgression was influenced by the Rhine-Bresse graben extension and the Plateau Molasse subsidence; outcrops are isolated and some Gasteropods and Charas (algae) fossils give evidence for lacustrine facies (Aubert, 1975).

The "Burdigalian" and the "Helvetian" stages (OMM) are characterized by a marine transgression. Shallow seas flooded the Molasse Basin and rocks

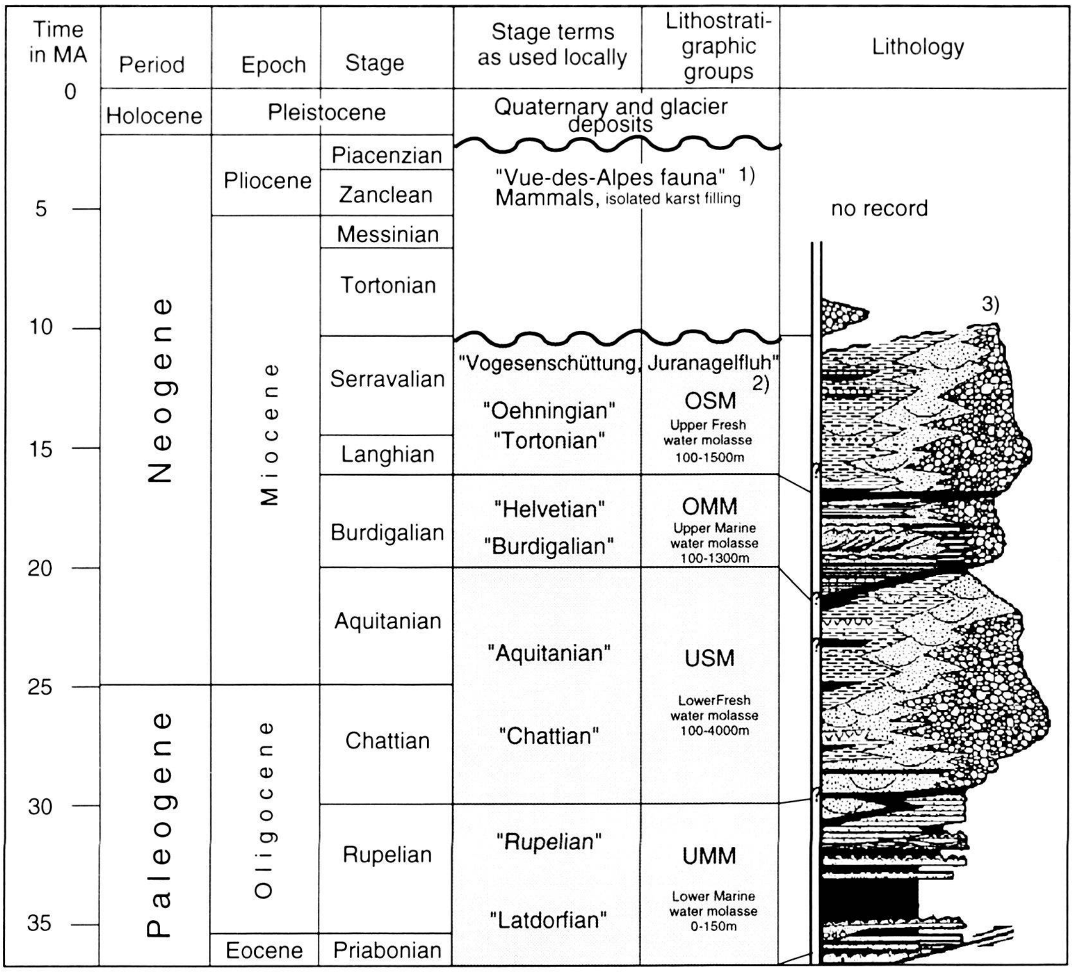


Figure 2.9: Tertiary stratigraphy and formation names as used in the Jura and the Molasse Basin. Modified from TRÜMPY (1980) and HOMEWOOD *et al.* (1989). 1) Data from BOLLIGER *et al.* (1993); 2) Data from KÄLIN (1993, 1997); 3) Lithological column from KELLER (1990).

Coupe stratigraphique et nom des formations du Tertiaire du Jura et du Bassin molassique. Modifié de TRÜMPY (1980) et HOMEWOOD et al. (1989). 1) Résultats de BOLLIGER et al. (1993); 2) Résultats de KÄLIN (1993, 1997). 3) Colonne lithologique de KELLER (1990).

consist of marine glauconitic sandstones with siliceous and calcareous grains with some thin marl layers alternating with sandstones. The transgression of the OMM is relatively well constrained by mammal ages from the underlying USM (BERGER, 1992). In the Jura Mountains, the diachronous character of the OMM-base can only be deduced from indirect correlation and from geological patterns (more detailed information on the Jura area is given by AUBERT, 1975). During these stages the Bresse-Graben subsidence stopped and basins were by then filled with Oligocene sediments.

During the "Tortonian" - "Oehningian" stages (OSM), the sea withdrew permanently, arguably not synchronously because of depocenter migration and variable relief created by alluvial fans (BERGER, 1992). Sedimentation continued in the floodplains beyond and between the gravel fans, providing fluviatile sandstones in channels and silty shales. Freshwater limestones formed in local basins. In the Neuchâtel Jura, a complete series is preserved in the Le Locle syncline (FAVRE, 1911; FAVRE *et al.*, 1937) (Figs. 1.3 and 4.3) and has a thickness of some 200 m, of which 165 m are lacustrine chalks (KÜBLER, 1962a, 1962b). The extension of this lake was small and limited to Les Verrières, La Brévine, Morteau, Le Locle and La Chaux-de-Fonds area (Fig. 4.3).

The top of the OSM is marked, in the internal part of the Molasse Basin, by an erosional boundary covered generally by Quaternary sediments, whereas in the external part (Jura Mountains, Delémont Basin) a discordance covered by conglomerates, sands and gravels ("Vogesenschüttung, Juranagelfluh", "Hipparion and Dinotherium sands", Fig. 2.9) of MN9 Mammals age (~11 M.y.) (KÄLIN, 1993) is present.

2.3. OUTCROP AND SUBSURFACE STRATIGRAPHY

2.3.1. Introduction

Facies and thickness variations cannot be presented in one single synthetic lithostratigraphic log valid for the whole region. Therefore a key area will be described first (§2.3.2.), followed by a discussion of lateral variations (§2.3.3.). The reference profile will be described in some detail, while the drill hole data and their correlation will be synthesized with respect to the seismic units described in §2.4. The key area is the Neuchâtel Jura and it has been chosen, because it presents one of the most complete profiles (from Tertiary to Aalenian rocks). Correlation and lateral variations will be based on drill hole data (Figs. 2.11 to 2.13), which show a continuous log from surface to Triassic and the basement.

The following profile and the drill hole lithostratigraphy will be described going from the youngest rocks to the oldest (i.e. from top to bottom), and will be followed stepwise on seismic lines. The key stratigraphic column is presented on Figure 2.10 and is compared with drill holes on Figure 2.12.

2.3.2. A stratigraphic column for the Neuchâtel Jura

The Tertiary Molasse is preserved in the Val de Ruz, Val de Travers and La Chaux-de-Fonds - Le Locle synclines below fluvio-glacial Quaternary sediments (Fig. 2.9). The youngest sediments are late Middle Miocene ("Oehningian", OSM) lacustrine deposits (KÜBLER, 1962a), which occur in the La Chaux-de-Fonds - Le Locle syncline. By contrast in the Val de Ruz, the youngest preserved Molasse formations are USM (lower freshwater Molasse) (MORNOD, 1970; AUBERT, 1975; MATHEY, 1976), which rest directly on the Early Cretaceous with an intermediate Eocene Laterite ("Bohnerz") formation, which fills a karst surface. In the Val de Ruz, the total thickness of Tertiary Molasse increases from 100 m in the NW (MORNOD, 1970) to about 200 m in the SE (SCHNEGG *et al.*, 1983; SCHNEGG & SOMMARUGA, 1995). In the Val de Travers, the Molasse reaches 235 m (MEIA, 1969).

The Cretaceous is of special importance for the Neuchâtel Jura because the Neocomian, Valanginian and Hauterivian stages have been defined in this area (THURMANN, 1836b; DESOR, 1854; RENEVIER, 1894). Early Cretaceous is represented by a well-layered 150-200 m thick series of limestones and marls. Cenomanian chalky limestones overlie Albian blue marls rich in Ammonites and Aptian glauconitic limestones and marls. The underlying Barremian, Hauterivian, Valanginian and Berriasian rocks consist from top to bottom (Fig. 2.10) of: the "upper Urgonian" oolitic limestones, the "lower Urgonian" spathic limestones with intercalated marls, the "Pierre jaune d'Hauterive de Neuchâtel", detrital and spathic limestones with ooliths and Echinids, the "Marnes bleues d'Hauterive" blue colored marls, the "Calcaire roux valanginien" limonitic reddish limestones and the "Marbre bâtard valanginien" oolitic limestones (REMANE, 1982). In the upper Urgonian formation, asphalt deposits have been mined in the Val de Travers from 1713 to 1986 (MEIA, 1987). The source bed of these asphalt deposits is still unknown, but the asphalt must have migrated before the deformation of the Jura (ZWEIDLER, 1985). The transition from Cretaceous to Jurassic rocks is highlighted by the 10-30 m thick Purbeckian facies (Berriasian in age), consisting of brackish marls.

In contrast to the well layered Cretaceous sequence, the underlying 350 to 400 m thick upper Malm limestones are homogeneous and massive (PERSOZ & REMANE, 1973). The Portlandian consists of 100 m of dolomites and limestones. The "Banc à Nérinées" is used as the top of the Kimmeridgian, with white massive platform limestones (150-170 m). The Sequanian represents a barrier facies, with oolitic limestones (100-120 m). The transition to the underlying Argovian marls (150-200 m) is gradational and shows a progressive decrease in layer thickness and an increase in the percentage of marly interbeds. It represents the Argovian facies sensu stricto, comprising three members (GYGI & PERSOZ, 1986): the "Couches de Geissberg" at the top, corresponding to a regional calcareous facies, the

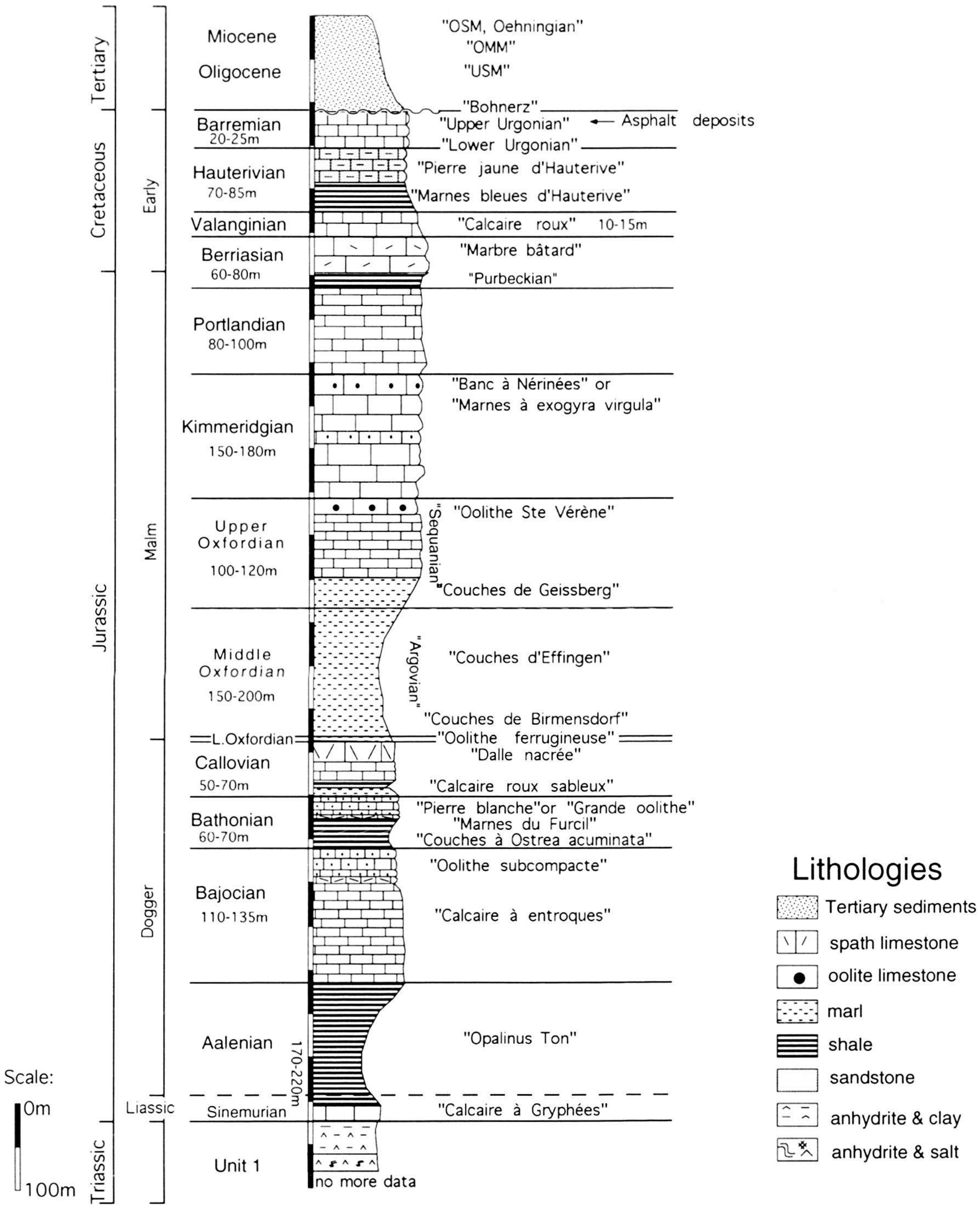


Figure 2.10: Stratigraphic profile of the Neuchâtel Jura (Val de Ruz and Val de Travers). The position of the formations mentioned in the text is given on the right hand side.

Profil stratigraphique du Jura neuchâtelois (Val de Ruz et Val de Travers). La position des formations décrites dans le texte est donnée sur le coté droit du log.

"Couches d'Effingen" consisting of marls with a wide range in carbonate content and the "Couches de Birmensdorf" composed of biostroms made of siliceous sponges and rich in Ammonites.

The Dogger is formed by at least 250 m of a well bedded coarse grained limestones subdivided into various formations: "Dalle nacrée, Calcaire roux sableux, Grande Oolithe, Marnes blanches, Oolithe subcompacte" and "Calcaire à entroques". The Aalenian black shales, corresponding to the "Opalinus Ton" of the eastern Jura, strongly contrast with the overlying Dogger limestones.

The Liassic and upper Triassic formations have been penetrated during a recent geotechnical drilling campaign near Neuchâtel (MEIA, 1992). These layers are strongly tectonized and do not allow measurement of precise stratigraphic thicknesses. The apparent thicknesses are: 160 m for the Aalenian and Liassic series and more than 100 m for the Triassic Unit 1. The Liassic is represented by bituminous shales and the "Calcaire à Gryphées" formation, whereas the Triassic consists of marls, evaporites, salt and dolomites. By comparison with the nearest well, Courtion (Fig. 2.13), the thickness of Unit 1 below the Neuchâtel Jura is expected to be of the order of 200 m of anhydrite and shales, underlain by some 60 m of dolomites. The thickness of the Triassic Unit 2 evaporites is not constrained by nearby drill holes; based on depth conversion from seismic lines, it ranges from 400 m to 1000 m.

2.3.3. *Surface and well log correlation*

2.3.3.1. Introduction

The upper 400-500 m of the stratigraphic section outcrops in the central Jura Mountains and the subsurface stratigraphy is known from wells, as shown on Figures 2.11, 2.12 and 2.13. Appendix 2 is a compilation of well data from the literature or unpublished documents in which some detailed and many summary log descriptions with elevation of tops are available. The lithostratigraphy of wells has not been reinvestigated here. Log descriptions are mainly based on cuttings and the lithological descriptions or nomenclature adopted by the different authors is not always consistent. The correlation of units and stratigraphic ages is approximate. The holes were drilled by the industry in the search of oil, gas or hot water. Most of the wells were drilled on anticlines (Risoux, Laveron, Treycovagnes, Essertines, Courtion, Hermrigen, Cuarny). Because no drill hole data exist in synclinal structures, the stratigraphic thicknesses reported from wells could be exaggerated by a few 10 to 100 m, due to thrusting, tectonic thickening and or salt flowage. This is especially true for the Triassic evaporite units.

The top Triassic is used as a datum for wells shown on Figures 2.11 to 2.13. In these figures, the thickness of the Tertiary, Cretaceous, Malm, Dogger and Liassic units corresponds to that listed in Appendix 2. However, the thickness of the Triassic Unit 1 and Unit 2 of the Triassic layers has been modified based on seismic interpretations. Details are given in subchapter 2.4.3.7. and 2.4.3.8.

Figure 2.11 is a SW-NE correlation of the lithostratigraphy of the Valempoulières, Eternoz, Buez and Buix drill holes, which are located in the external Jura. Figure 2.12 presents the Risoux, Toillon, Essavilly, Laveron drill holes and the Val de Travers and Val de Ruz profiles (Neuchâtel Jura), which are all located in the Haute Chaîne and Plateau Jura. Figure 2.13 includes Humilly 2, Treycovagnes, Essertines, Courtion and Hermrigen located in the Molasse Basin.

For previous compilations and correlations of wells in the Jura Mountains and Molasse Basin compare with BÜCHI *et al.* (1965a), WINNOCK *et al.* (1967), ZIMMERMANN *et al.* (1976), RIGASSI (1977), BÜCHI & ETHZ (1981), PERSOZ (1982), JORDAN (1992), LOUP (1992a).

2.3.3.2. Tertiary

Tertiary sediments have been encountered only in drill holes located in the Molasse Basin (Fig. 2.13). Tertiary stratigraphic subdivisions have not been distinguished, because the low resolution for this interval on seismic lines did not allow correlation of different horizons. The present-day thickness of the Tertiary strata in the project area ranges from 0 in the Jura Mountains anticlines to 2500 m in the Subalpine Molasse (South of Savigny). The wedge-shaped Tertiary sediments overlie and onlap a major erosional discordance (Fig. 2.8).

2.3.3.3. Cretaceous

The present distribution of Cretaceous outcrops (Fig. 2.14) outlines the structure of the Jura Mountains. The outcrop pattern is the result of the combined effects of Eocene erosion, Jura folding, and post- Miocene erosion. Cretaceous strata do not exist in the external and eastern Jura (Figs. 2.8 and 2.14 and see discussion §2.2.3.3.). The thickness

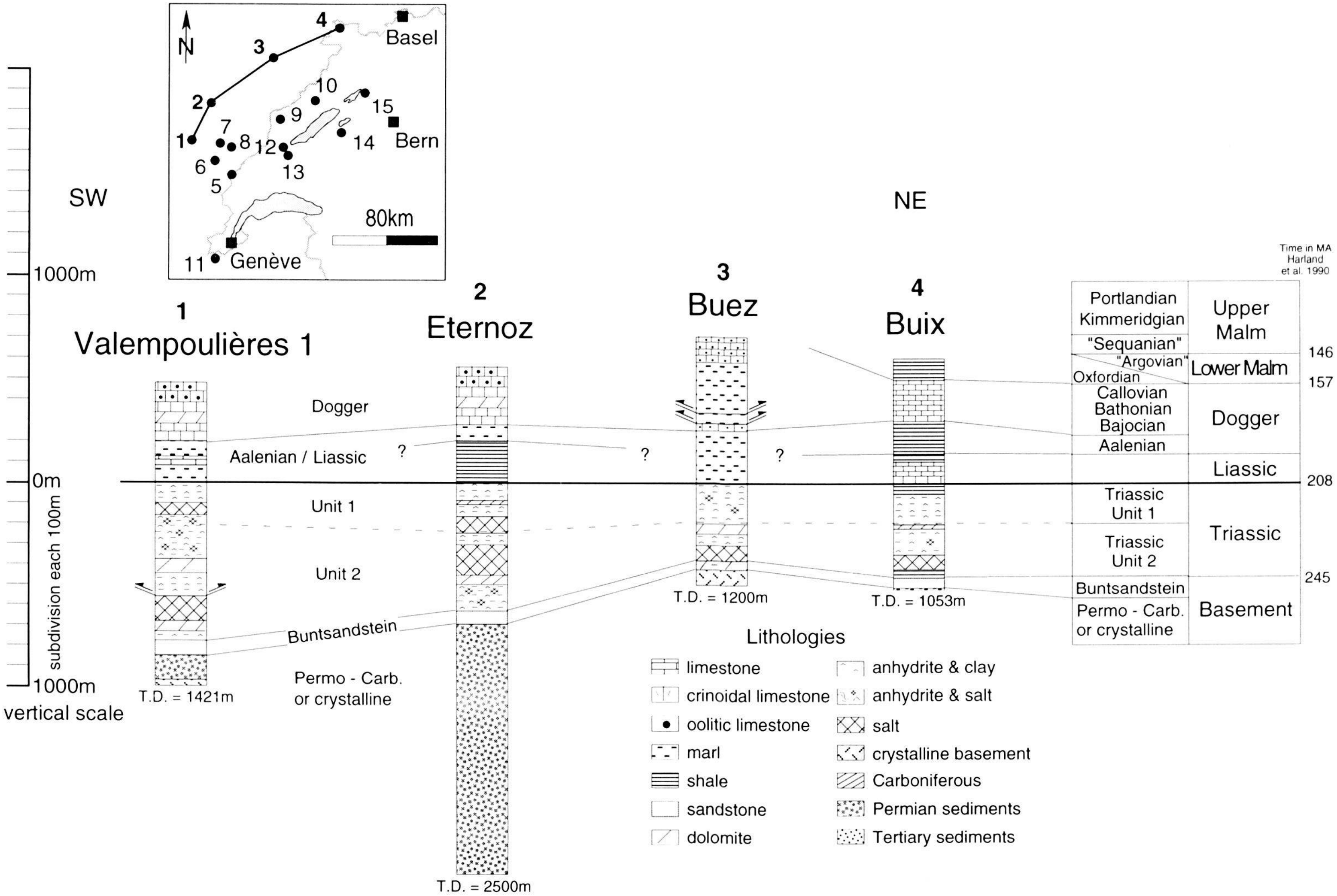


Figure 2.11: SW-NE correlation of main lithostratigraphic formations between the following wells: Valempoulières (BITTERLI, 1972), Eternoz (BRGM, 1975), Buez (BITTERLI, 1972) and Buix (SCHMIDT *et al.*, 1924). Datum plane is top of Triassic series. Plain lines represent correlation based on well data, whereas dashed lines correspond to correlation based on seismic lines. Time scale is from HARLAND *et al.* (1990).

Corrélation SW-NE des principales formations lithostratigraphiques des forages suivants: Valempoulières (BITTERLI, 1972), Eternoz (BRGM, 1975), Buez (BITTERLI, 1972) et Buix (SCHMIDT et al., 1924). Le niveau de référence correspond au toit des séries du Trias. Les lignes en trait plein correspondent aux corrélations basées sur les données de forages; les lignes en tireté correspondent aux corrélations basées sur les interprétations sismiques. L'échelle de temps est de HARLAND et al. (1990).

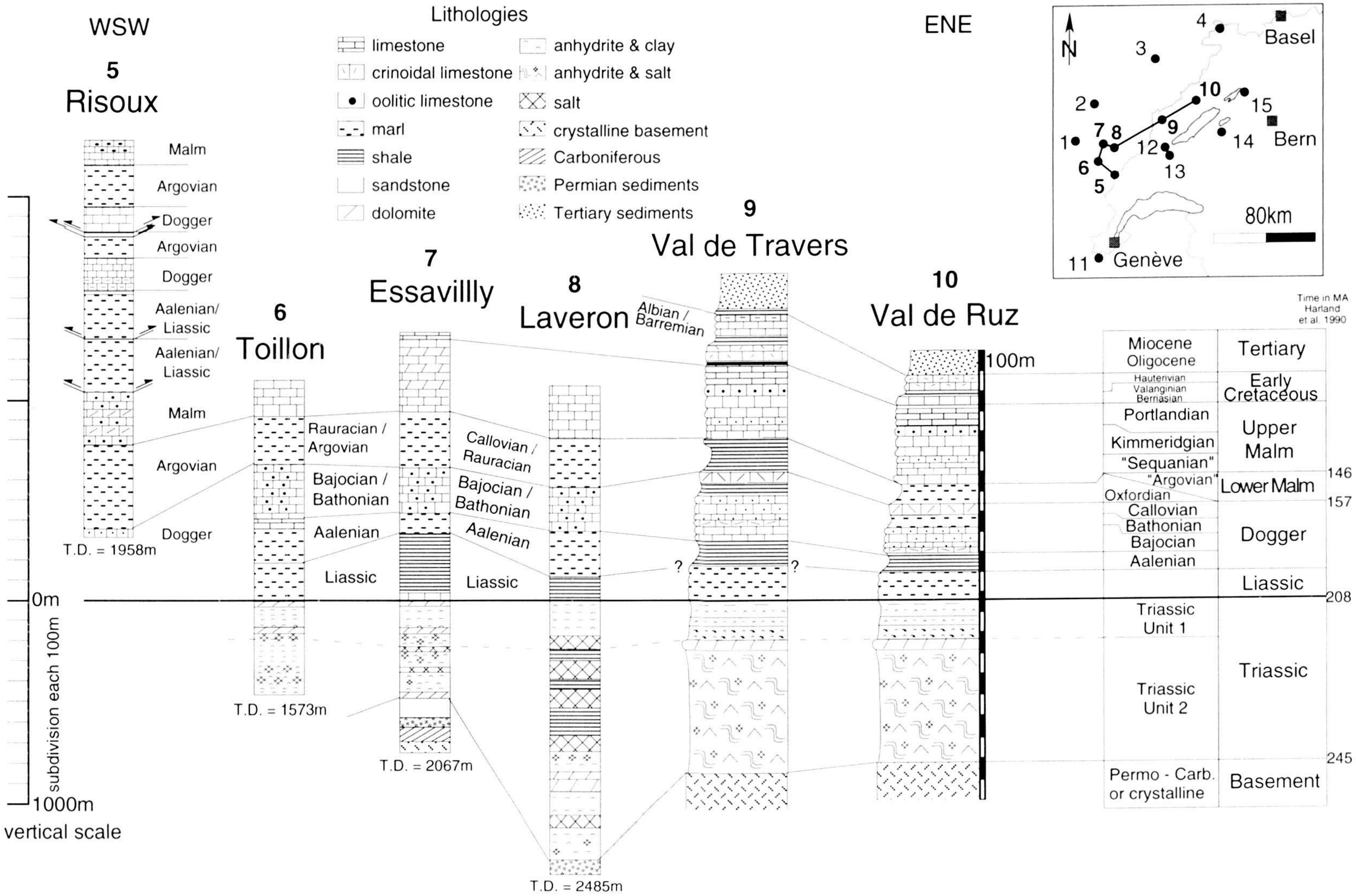


Figure 2.12: WSW-ENE correlation of main lithostratigraphic formations between the Val de Ruz and Val de Travers areas using the following wells: Risoux (WINNOCK, 1961), Toillon (BRGM, 1965a), Essavilly (BRGM, 1965a) and Laveron (BRGM, 1964). Datum plane is top of Triassic series. Plain lines represent correlation based on well data, whereas dashed lines correspond to correlation based on seismic lines.

Corrélation WSW-ENE des principales formations lithostratigraphiques entre la région du Val de Ruz et du Val de Travaers et les forages suivants: Risoux (WINNOCK, 1961), Toillon (BRGM, 1965a), Essavilly (BRGM, 1965a) et Laveron (BRGM, 1964). Le niveau de référence correspond au toit des séries du Trias. Les lignes en trait plein correspondent aux corrélations basées sur les données de forages; les lignes en tireté correspondent aux corrélations basées sur les interprétations sismiques.

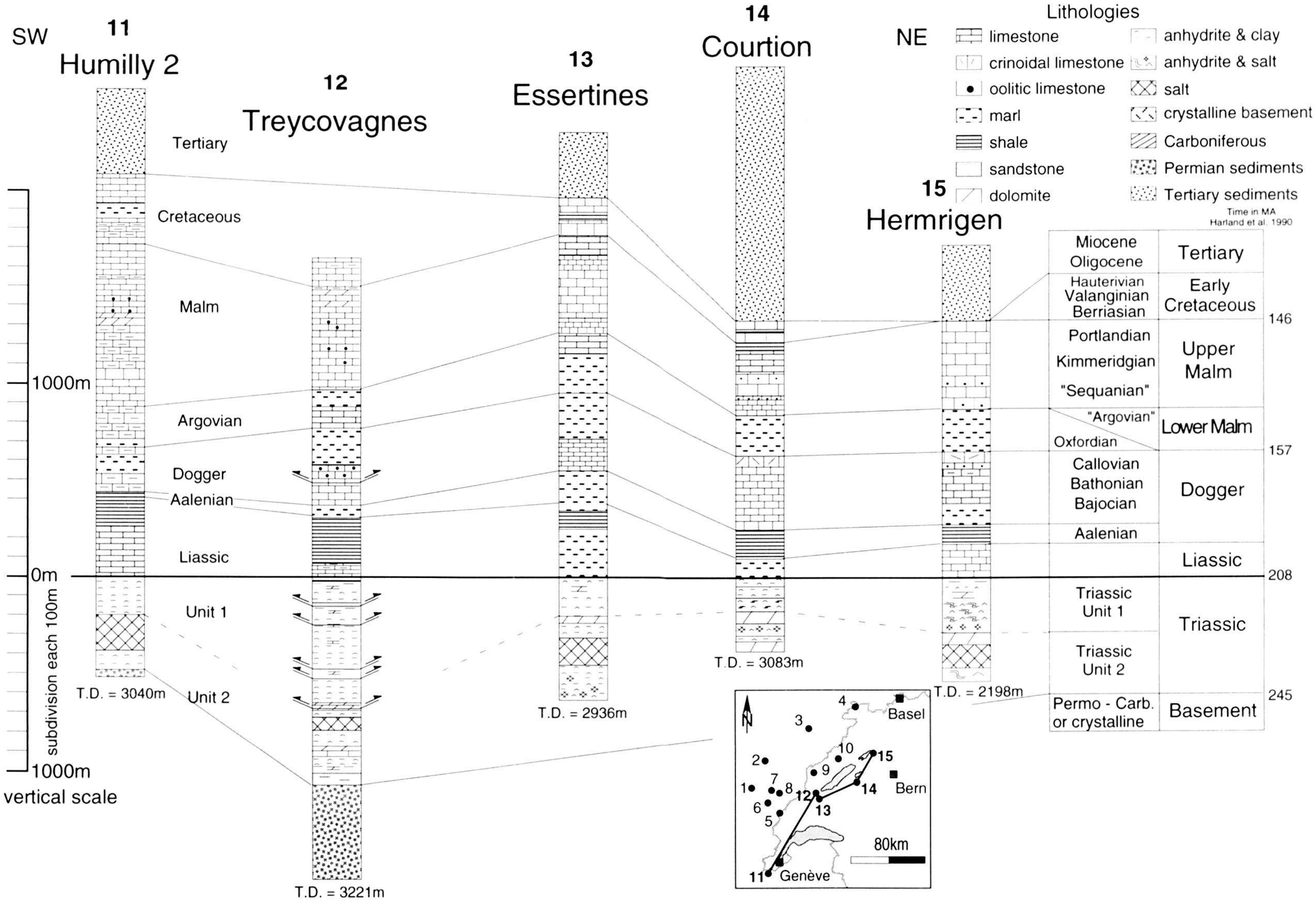
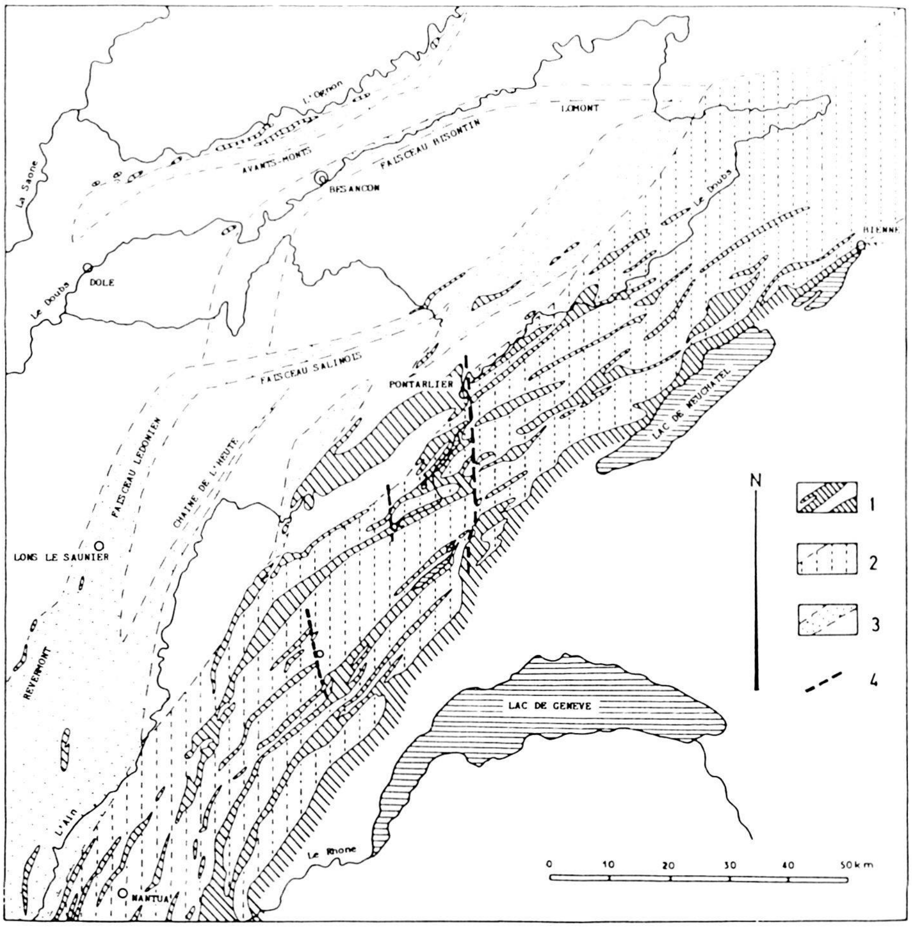


Figure 2.13: SW-NE correlation of main lithostratigraphic formations between the following wells: Humilly 2 (Persoz, 1982; Wildi *et al.*, 1991; Jenny *et al.*, 1995), Treycovagnes (Report deposited in Lausanne at the Musée géologique du Canton de Vaud), Essertines (Büchi *et al.*, 1965b), Courtion (Fischer & Luterbacher, 1963) and Hermrigen (Housse, 1982). Datum plane is top of Triassic series. Plain lines represent correlation based on wells data, whereas dashed lines correspond to correlation based on seismic lines.

Corrélation SW-NE des principales formations lithostratigraphiques des forages suivants: Humilly 2 (Persoz, 1982; Wildi et al.*, 1991; Jenny* et al.*, 1995), Treycovagnes (Rapport déposé à Lausanne au Musée géologique du Canton de Vaud), Essertines (Büchi* et al.*, 1965b), Courtion (Fischer & Luterbacher, 1963) and Hermrigen (Housse, 1982). Le niveau de référence correspond au toit des séries du Trias. Les lignes en trait plein correspondent aux corrélations basées sur les données de forages; les lignes en tireté correspondent aux corrélations basées sur les interprétations sismiques.*



From Martin 1987

Figure 2.14: Outcrop pattern of Cretaceous erosional remnants in the central Jura. 1 = Cretaceous; 2 = Haute Chaîne Jura; 3 = Faisceau Jura; 4 = Tear faults. From MARTIN (1987).

Affleurements de Crétacé dans le Jura central. 1 = Crétacé; 2 = Haute Chaîne jurassienne; 3 = Faisceau jurassien; 4 = Décrochements. Tiré de MARTIN (1987).

increases from N to S, e.g. from the French Jura (0-70 m) to Humilly (374 m) (Fig. 2.13). It shows also the wedging out of Cretaceous strata 20 km eastwards and northwards from Neuchâtel, e.g. the Hermrigen drill hole did not encounter any Cretaceous beds.

Late Cretaceous limestones are locally preserved in karst pockets. The Albian stage is only represented in the internal zone. There is a transition from the basal limestone to the top glauconitic sandstone. Albian sediments include quartzitic and shaly sands sometimes interbedded with conglomerates and biodetrital limestones. The Barremian series begins with yellow bioclastic limestones overlain with white, oolitic, biohermal limestones. During the Hauterivian stage, a shallow sea covered the whole Jura platform. The lower part consists of fossiliferous marls ("Marnes bleues d'Hauterive"), whereas the upper part is characterized by the "Pierre jaune de Neuchâtel" with its cross-bedded spathic limestone, rich in shells and glauconite. The maximum of the Early Cretaceous transgression (Valanginian stage) reached the "Faisceau salinois" area, where the "Calcaire Roux" sediments were deposited. They contain ooliths, Echinoderms and Bryozoan debris and show cross-bedded stratification. The underlying "Marbre bâtard" consists of oolitic, bioclastic and marly calcareous.

The yellow color of the Cretaceous rocks is due to post-depositional oxidation of the iron and contrasts strongly with the white Jurassic limestones.

2.3.3.4. Upper Malm

The upper Malm thins by erosional truncation in the northern Jura area e.g. in the Laveron, Toillon and Risoux wells. In the southern Jura, the thickness of the complete series is around 350-400 m, whereas in the Molasse Basin it increases from 400 m in the Northnortheast to 850 m in the Southsoutheast (Humilly).

The top of the upper Malm series consists of Portlandian limestones, representing a marginal-littoral facies. The underlying Kimmeridgian is characterized by thick beds of back-reef limestones and dolomites. A discontinuous belt of patch reefs and oolite bars represents the boundary between sedimentation domains. The Sequanian rocks consist of biohermal Spongiae limestones.

2.3.3.5. Lower Malm

The lower Malm corresponds to Oxfordian age beds represented by the "Rauracian, Argovian and Oxfordian s.s." facies. With the overlying upper Malm strata, it is partly eroded in the external regions. The rocks are marly or calcareous in the West (Humilly, Treycovagnes, Toillon, Essavilly, Laveron) and more shaly in the East (Val de Travers, Val de Ruz, Courtion).

The upper series consists generally of biohermal limestones (Rauracian facies) of upper Oxfordian age. During the middle Oxfordian stage several facies developed. Along the Haute Chaîne, the Argovian facies sensu stricto consists of interbedded marly limestones of the "Couches de Birmensdorf", Couches d'Effingen" and "Couches de Geissberg" (Fig. 2.1, Vaud and Aargau stratigraphic columns). These rocks were deposited in a starved basin of about 100 m of water depth (GYGI & PERSOZ, 1987). In the external Jura (Franche-Comté), the Argovian rocks consist of Brachiopod rich limestones replaced within the Canton Jura (Fig. 2.1) by the Rauracian facies, consisting of massive limestones, with a well preserved fauna of corals, Echinids and Gasteropods. The lower Oxfordian is condensed everywhere and consists of iron ooliths with Cephalopods. Shales were deposited only in the northwestern Jura.

As a historical note, GRESSLY (1837-41) studied Oxfordian strata in the Solothurn Jura. Detailed observations of coral bioherm and coeval fine-grained sediments (near St-Ursanne, Canton Jura) inspired him to introduce the concept of facies.

2.3.3.6. Dogger

The Dogger (Callovian, Bathonian, Bajocian stages) is the oldest formation exposed in the central and western Jura and it consists of 250-300 m thick limestones. At the top of the Dogger, the "Dalle nacrée" formation occurs almost everywhere, except in the Essavilly well, where the Callovian has been grouped with the Oxfordian layers.

The Callovian "Dalle nacrée" formation consists of biodetrital limestones deposited in a reducing high energy environment. This condensed facies extended far beyond the Swiss Molasse Plateau and even into the Helvetic domain. It corresponds to a time of increasing water depth associated with a starved basin. Eastern Swiss Jura deposits are composed of argillaceous shales. During the Bathonian, shales and crinoidal limestones were deposited in the East, giving way to oolitic and micritic limestones to the West. The upper Bajocian consists of marly shales with few layers of crinoidal limestones and iron ooliths to the Southwest, but of light colored oolitic limestones, called the "Hauptrogenstein" to the Northeast. In Bajocian strata, several Ostrea and Bryozoa hardgrounds are observed. The lower Bajocian consists of crinoidal limestones to the West (Vaud stratigraphic section, Fig. 2.1) and sandy limestones with iron ooliths to the East (Jura and Aargau sections). These beds are underlain by alternating limestone and marl horizons.

At the base of the Dogger, argillaceous beds of Aalenian age, i.e. the "Opalinus Ton" of eastern Switzerland are observed in the internal Jura (Fig. 2.1, Jura and Aargau stratigraphic columns). In the French Jura, shallow-water limestones are interbedded with ferrugineous horizons.

2.3.3.7. Aalenian - Liassic

The Aalenian - Liassic transition is poorly defined on the drill hole logs, because the rocks from Aalenian to Liassic stages show a progressive change from shales at the top to calcareous beds at the base.

From top to bottom, the Liassic series consists of: Posidonia shales and oolitic limestones, rich in nektonic and planktonic fauna (Ammonites, reptiles and fish), bituminous shales and oyster limestones, the "Calcaire à Gryphées" formation.

2.3.3.8. Triassic Unit 1

Triassic Unit 1 represents the top of the Triassic. It consists of marls and evaporites. The correlation from one well log to the other, expressed on Figures 2.11 to 2.13 by dashed lines, is based on seismic data. A good reflector can be followed between a more or less constant interval identified as Triassic Unit 1 and an underlying layer showing major thickness variations (see §2.4.3.7. and §2.4.3.8.). The Triassic is the most ductile sequence of the sedimentary cover (JORDAN, 1992), whose intense deformation results in difficulty in defining a clear stratigraphy based on cuttings.

2.3.3.9. Triassic Unit 2

The Triassic Unit 2 thickness ranges from 300 m to 1200 m. This unit is strongly influenced by evaporites and salt tectonics. Thickening and thinning are interpreted in terms of Neogene tectonics. Thickening is localized under anticlines, which trend parallel to the Jura structures. This aspect will be discussed in greater detail in Chapter 3 and 5. Repetitions or tectonic complications within the Triassic units are particularly clear in the Valempoulières and Treycovagnes wells.

2.3.3.10. Basement

Basement is defined to include all formations that occur below the sole thrust, i.e. the units which, according to the Fernschub theory, are not involved in the late Miocene deformation of the Jura and the Molasse Basin. The basement includes the Triassic "Buntsandstein" formation, downfaulted Carboniferous and Permian sediments overlying older crystalline rocks. The basement was reached in the French Jura wells (Valempoulières, Eternoz, Buez, Essavilly, Laveron) and in one recent Molasse well (Treycovagnes). In the latter, Permian conglomerates or sandstones were found. In Eternoz these clastics appear to be more than 1 km thick. Carboniferous coals have been encountered in Essavilly. To date, no Permo-Carboniferous graben, such as the one in Lons-Le-Saunier (Debrand-Passard *et al.*, 1984) or in northwestern Switzerland (Diebold *et al.*, 1991), has been identified in the studied area. Small grabens are locally visible on the seismic lines of the Molasse Basin, however (§2.4.3.9.). Such grabens have been identified also in the Geneva area in a recent paper by Signer & Gorin (1995) and in Germany (Bachmann *et al.*, 1987).

2.3.4. Conclusions

In summary, the Mesozoic stratigraphic column of the Val de Ruz area from the top of the Cretaceous to the base of Unit 2 of the Triassic appears to be about 2000 m thick, with an estimated uncertainty of about 200 m. The overall thickness increases toward the SW (Humilly, more than 2500 m).

Toward the West, the thickness of the Dogger and Malm of Neuchâtel is quite similar to that of the French Jura. However, lower Jurassic age units vary from one area to another. The lithostratigraphy of Neuchâtel is very similar to that further to the South in the Molasse Basin. For all post-Liassic formations, Persoz (1982) has shown a good correlation of whole rock and clay mineralogy, as well as lithofacies, between the Courtion well and the Val de Ruz. The thickness of the Malm and the Cretaceous beds increases regularly from Neuchâtel toward the SW. The Triassic Unit 1 sequence seems to increase slightly toward the W. The thickness of the Triassic Unit 2 changes considerably in response to "salt tectonics".

2.4. SEISMIC UNITS

Like surface studies that depend on the correct identification of lithological units and their contacts, seismic stratigraphic units require correct identification and definition. To interpret a seismic grid, however, it is not necessary to define and correlate each reflector. It is more appropriate to select seismic units bounded by robust continuous reflectors. Seismic units correlated here do not then represent sequences as defined by Mitchum & Vail (1977), i.e. a conformable succession of strata bounded above and below by unconformities. Our seismic data are not sufficiently differentiated to allow for sequence stratigraphic interpretation. As used here, a seismic unit is sandwiched between two strong reflectors (labeled from A to I). In general, these units represent an interval, characterized by a dominant lithology. The Tertiary basal foredeep unconformity is the only well visible unconformity on our seismic lines. The main reflectors used for seismic correlation are shown on Table 2.1.

Strike profiles across the study area are good to excellent and show subparallel reflectors that are most useful for the stratigraphic interpretation. The main reflectors correspond to major impedance (lithology) changes, i.e. marl/limestone or shale/limestone, as seen in the preceding sub-chapter. Dip profiles are less continuous, due to steep to vertical dips, complicated structures and rugged topography.

This sub-chapter is organized similarly to the sub-chapter on outcrop and subsurface stratigraphy. First a key area (Fig. 2.15) and also some well log data (Figs. 2.16 to 2.19) will be introduced and then lateral variations (Figs. 2.20 to 2.22) will be discussed. The key area is again the Neuchâtel Jura, more specifically the Val de Ruz syncline, because seismic intervals have been defined first on strike line 8 from this area (Fig. 1.4) (Sommaruga & Burkhard, 1997).

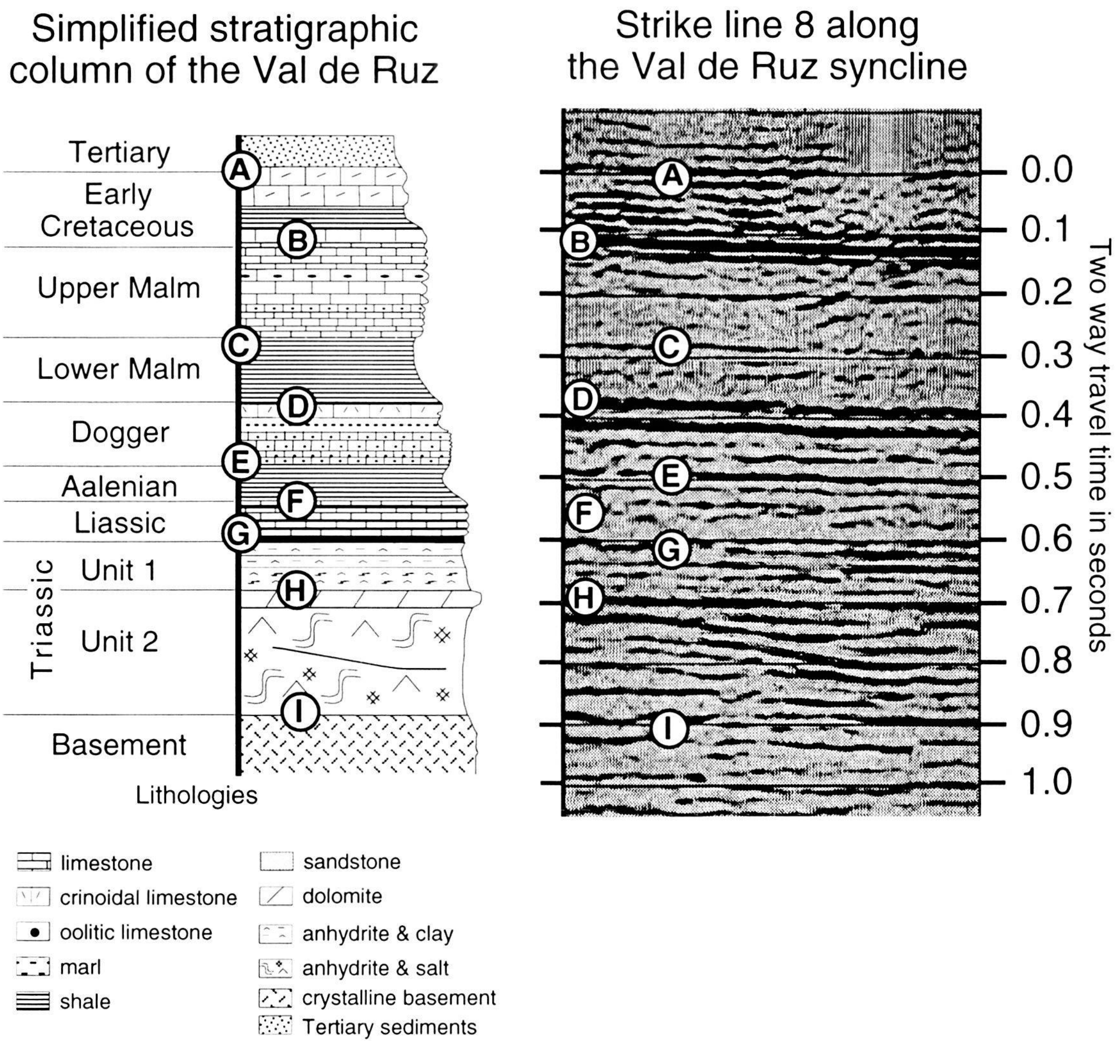


Figure 2.15: Correlation of seismic reflectors (line 8, vertical scale in seconds, TWT) with simplified stratigraphic column of the Val de Ruz. For oblique reflectors in Triassic Units, see discusions in §3.4. Legend for the letters A, B, C, ... is explained in Table 2.1.

Corrélation entre les réflecteurs sismiques (ligne 8, échelle verticale en secondes, temps double) et une colonne stratigraphique simplifiée du Val de Ruz. Concernant les réflecteurs obliques dans les unités du Trias, voir §3.4. La signification des lettres A, B, C, ...est expliquée dans le Tableau 2.1.

2.4.1. Neuchâtel (Val de Ruz) seismic line

Figure 2.15 illustrates the calibration of the seismic reflectors followed throughout the whole area. The calibration is based on stratigraphic thicknesses and lithologies known from the surface and from nearby wells. The stratigraphic column of the Val de Ruz shown in Figure 2.15 is a simplified version of that in Figure 2.10.

The Tertiary Molasse is preserved within many synclines and often buried underneath a thick fluvio-glacial Quaternary cover. The important unconformity between the top Cretaceous and the base of the Tertiary (A) is not easily recognized on the seismic section shown in Figure 2.15. The Early Cretaceous beds between reflectors A and B consist of interbedded limestones ("Pierre jaune d'Hauterive", "Marbre bâtard") and marls ("Marnes bleues d'Hauterive"). The underlying, 350 to 400 m thick, upper Malm limestones form a homogeneous, massive bed. The strong reflector B corresponds to the top of the upper Malm limestones, which are transparent on seismic profiles. The transition from pure, massive limestones to the underlying, increasingly marly sediments of the "Argovian" (lower Malm), appears as weak reflector C. The strong reflector D is one of the most prominent marker horizons in the region and corresponds to the "Dalle

Labelling of the major seismic reflectors

This work	Naef & Diebold (Nagra Bulletin 1990)
A Top Cretaceous	A Base Tertiary
B Top upper Malm	
C Top lower Malm, Argovian	C within Malm
D Top Dogger	D Base Malm
E Top Aalenian	
	G within "Opalinus Ton"
F Top Liassic	H Top Liassic
G Top Triassic Unit 1	
H Top Triassic Unit 2	M Top Hauptmuschelkalk
I Top Basement	P Top Permian
	Q Carboniferous

Table 2.1: Labeling of major seismic reflectors used in this work and correlation with the NAGRA tops (NAEF & DIEBOLD, 1990).

Numérotation par une lettre des réflecteurs sismiques importants et comparaison avec la numérotation de la CEDRA (NAEF & DIEBOLD, 1990).

nacrée" formation, the top of the Dogger series, comprising some 250 m of well layered coarse grained limestones. The Aalenian black shales corresponding to the "Opalinus Ton" (shales), contrast strongly with the overlying Dogger limestones. Thus, strong reflector E corresponds to the top Aalenian (base Dogger), in contrast to the weaker top Liassic F reflector. Between 0.6 and 0.65 s TWT, a series of layered reflectors is interpreted as Liassic limestones. The top of the Triassic Units is reflector G and corresponds to the transition from the early Liassic "Calcaire à gryphées" formation to the underlying anhydrite and shales. Below reflector G, a strong, continuous reflector H most probably corresponds to the top of Triassic Unit 2, which may be the "Hauptmuschelkalk" dolomite or the "Lettenkohle" formation. Below this formation, oblique reflectors, between 0.73 and 0.85 s TWT, constitute a most remarkable feature on several strike lines. Their interpretation will be discussed later. The top basement (I) is not as a strong continuous reflector on this profile. Reflectors below I may represent Permo-Carboniferous; however, the deeper reflectors (below 1 s) are, almost certainly, multiples.

2.4.2. Seismic lines and well log data

Figures 2.16 (Essertines) and 2.17 (Treycovagnes) present the correlation between the seismic line, the sonic log and the lithology. The availability of a scale in meters and in seconds for both wells allows direct correlation of the lithology log (in meters) and the seismic line (in seconds).

At the Essertines well location on the seismic line, good reflectors correspond to contrasts of lithology that are also highlighted by the sonic log (Fig. 2.16). Five good reflectors are observed: 1) within the Cretaceous; 2) C, top Argovian; 3) D, top Dogger; 4) F, top Liassic and 5) H, top Triassic Unit 2. The Jurassic interval is represented by a well bedded sequence, whereas both Triassic units consist of discontinuous reflectors.

The Treycovagnes well log is characterized by multiple duplication of the stratigraphy (Fig. 2.17) within the Aalenian and the Triassic. The Dogger and the Triassic Unit 1 intervals show the best reflectors, whereas the Cretaceous, the Malm and the Triassic Unit 2 intervals are transparent zones, due to uniform lithology.

The figures of the Courtion (Fig. 2.18) and Risoux (Fig. 2.19) well logs present a correlation between the sonic log and the lithology data. These logs are useful in terms of lithology and especially seismic velocities, which were used to depth convert the lines and are presented in Appendices 3.

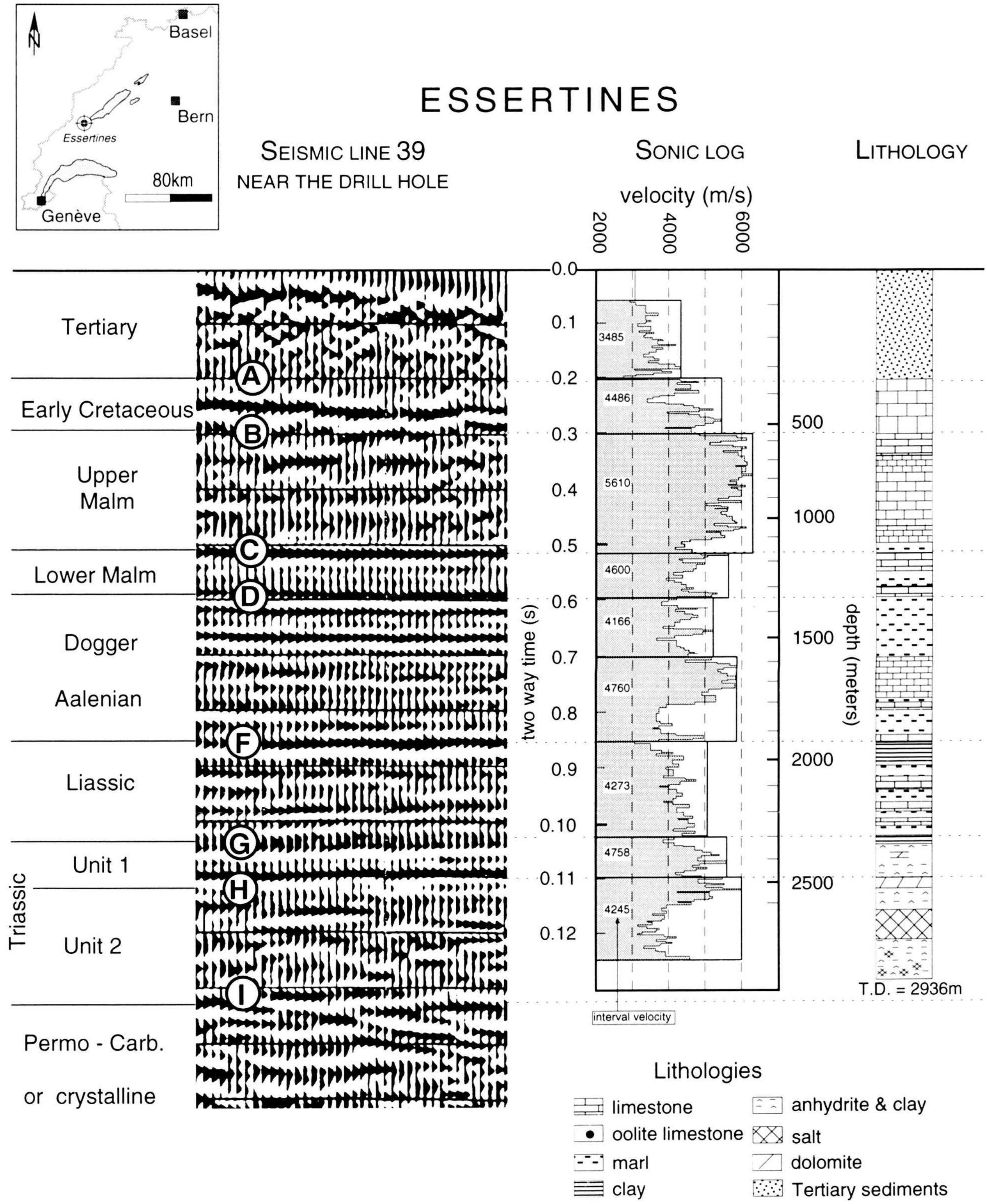


Figure 2.16: Correlation between the Essertines (BÜCHI *et al.*, 1965b) well lithology, the sonic log (GORIN *et al.*, 1993) and a nearby seismic line.

Corrélation entre le litholog du forage d'Essertines (BÜCHI et al., 1965b), le log sonique (GORIN et al., 1993) et un profil sismique voisin.

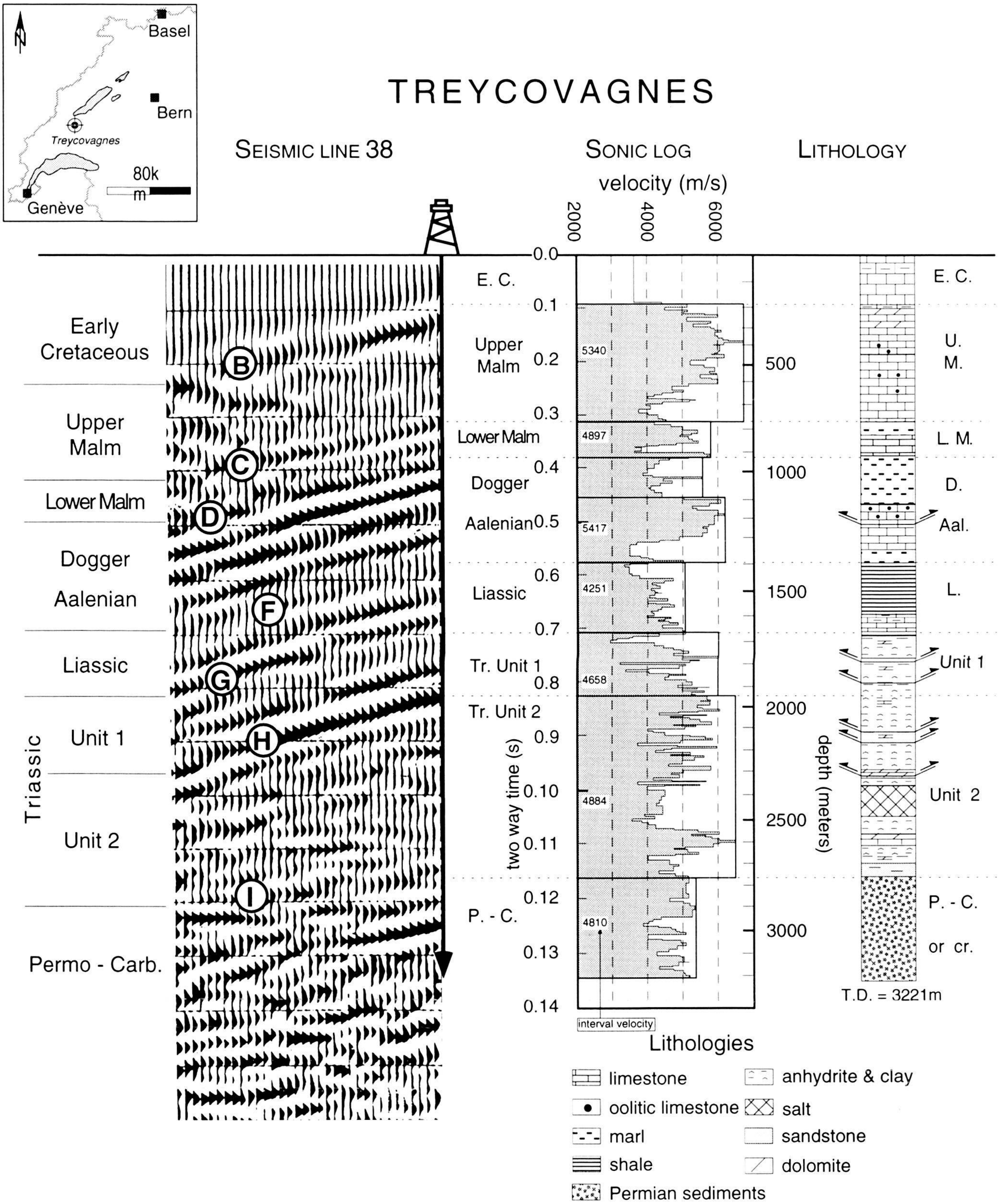


Figure 2.17: Correlation between the Treycovagnes well lithology (SCHEGG *et al.*, 1997), the sonic log (report deposited in Lausanne at the Musée géologique du Canton de Vaud) and a nearby seismic line.

Corrélation entre le litholog du forage de Treycovagnes (SCHEGG et al., 1997), le log sonique (rapport déposé à Lausanne au Musée géologique du Canton de Vaud) et un profil sismique voisin.

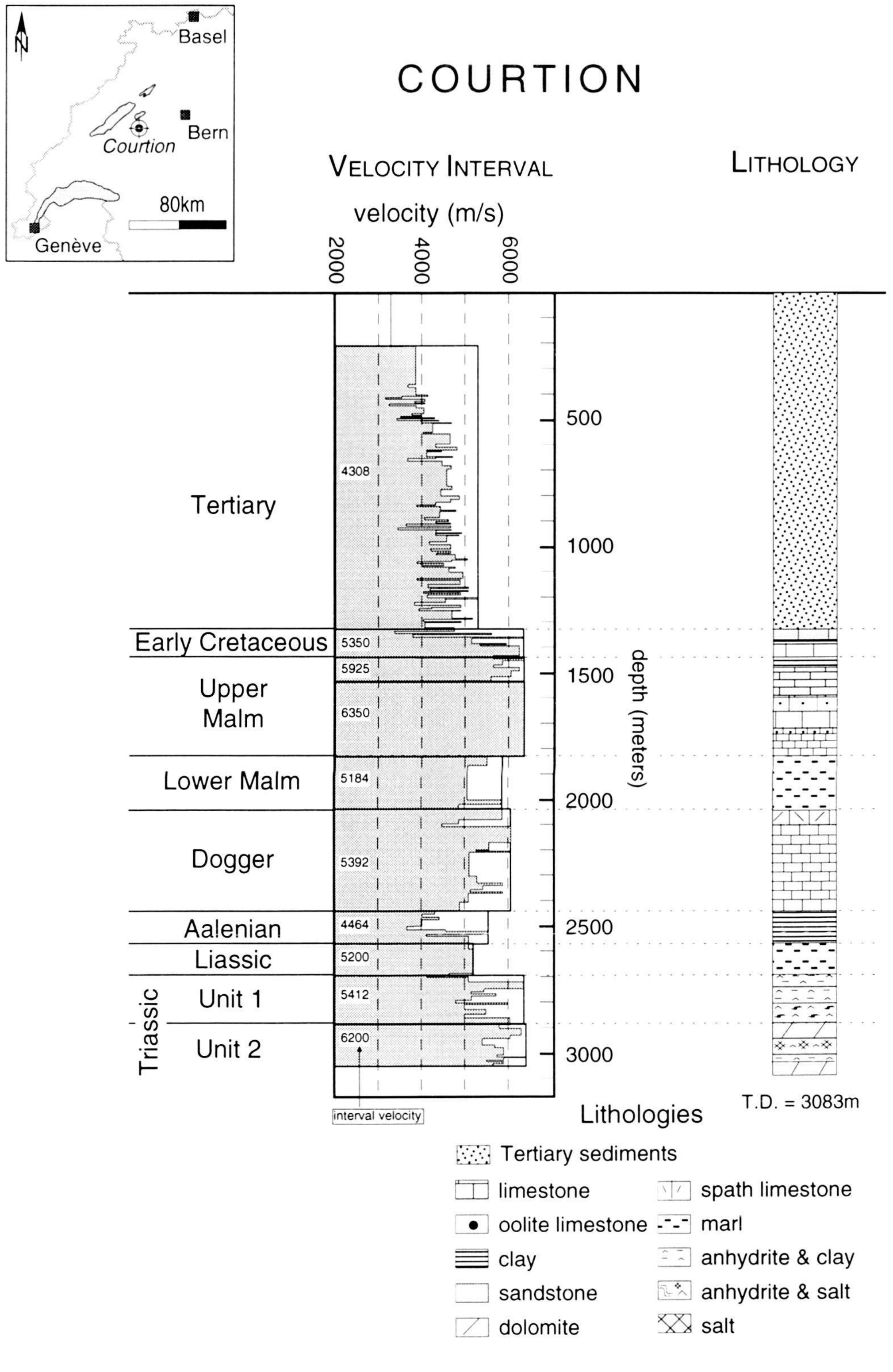


Figure 2.18: Correlation between the Courtion well lithology (FISCHER & LUTERBACHER, 1963) and the sonic log.

Corrélation entre le litholog (FISCHER & LUTERBACHER, 1963) et le log sonique du forage de Courtion.

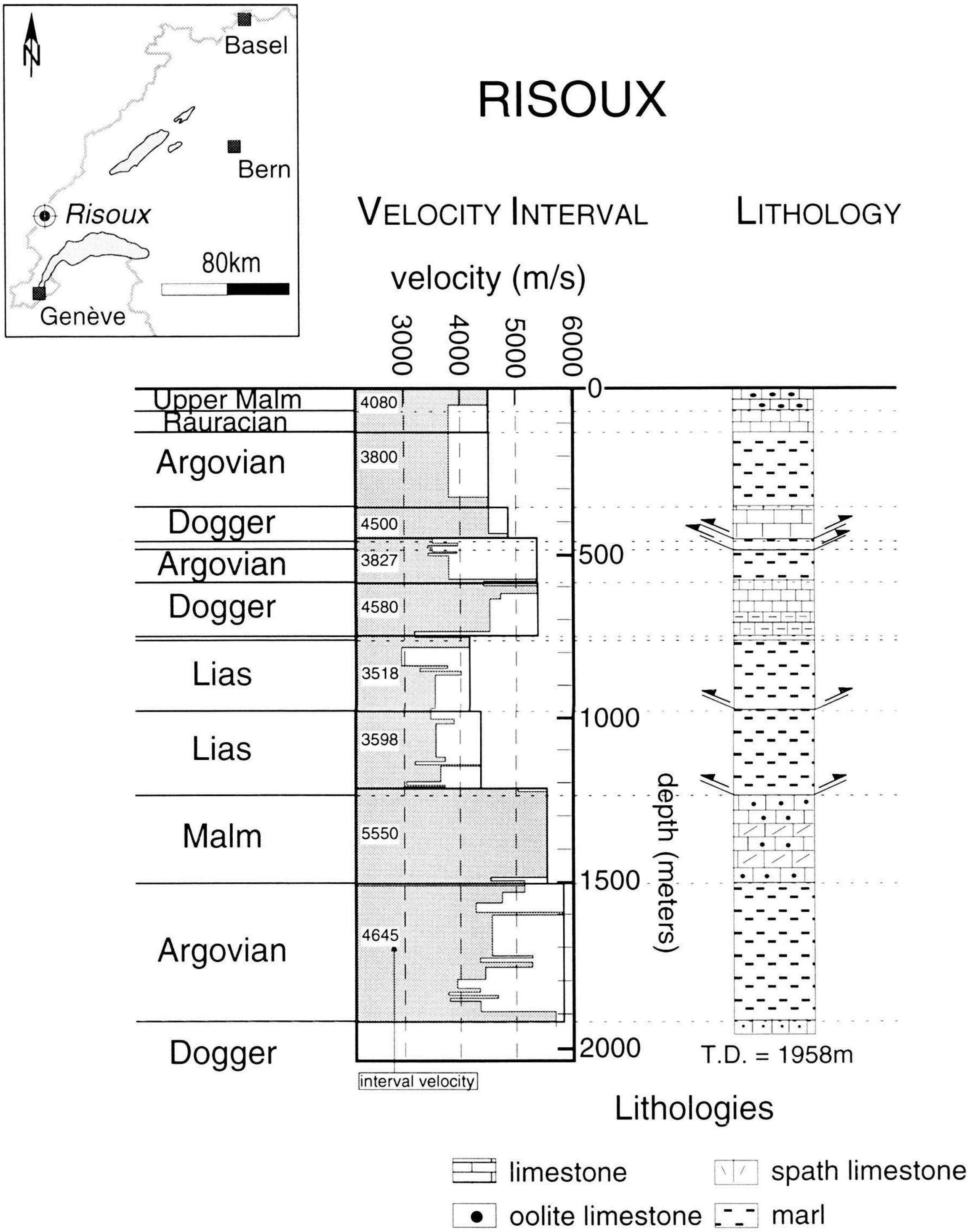


Figure 2.19: Correlation between the Risoux well lithology (WINNOCK, 1961) and the sonic log.

Corrélation entre le litholog du forage du Risoux (WINNOCK, 1961) et le log sonique.

2.4.3. Correlation across the seismic grid: "jump correlation"

2.4.3.1. Definition of "jump correlation"

Seismic jump correlation methods have to be used in the interpretation of the profiles, because typically good data in synclines are interrupted by poor data areas underneath anticlines. The stratigraphy of adjacent synclines could be confidently correlated by juxtaposing and matching the best reflectors between adjacent synclines. Thus the major reflectors A to I were all traced and tied to the better quality strike lines. In general thickness variations were negligible from one syncline to another, as is supported by the outcrop data. Three figures (Figs. 2.20 to 2.22) illustrate seismic jump correlations. Note seismic segments, but reflectors can still be traced easily using neighboring lines. Figure 2.20 shows the West-East correlation of seismic units through the Haute Chaîne and Plateau Jura lines. Figure 2.21 shows the Southwest-Northeast correlation of seismic units through the Plateau Molasse and Figure 2.22 presents North-South dip comparisons from the Neuchâtel folded Jura to the Subalpine Molasse.

2.4.3.2. Tertiary unit

The Tertiary unit is mainly present in the Molasse Basin and in some Jura synclines (Fig. 2.20, line 6, 4 and close to Tschugg). The onlap of Tertiary sediments to the underlying Mesozoic layers (Fig. 2.22 line 45) corresponds to the basal foredeep unconformity (BALLY, 1989), which is best visible on lines 45 and 43. The age of the onlapping sediments becomes younger from the South to the North, as explained in §2.2.4. Unfortunately no Molasse-interval subdivision could be distinguished.

2.4.3.3. Cretaceous unit: from reflector A to B

The base Tertiary or top Cretaceous layer is highlighted by reflector A (white reflector). For more convenience, the black reflector has been chosen for the correlations. This missmatch may represent an offset of 0.04 s. The Cretaceous unit is a well layered sequence of marls and limestones, especially in the Molasse Basin.

2.4.3.4. Upper Malm unit: from reflector B to C

The massive platform limestone of the upper Malm is typically devoid of reflectors. To the SW, the lower part of the unit is more reflective (Line 46), due to the appearance of well-bedded limestones. Reflector B, the top of the Malm, may correspond either to the Purbeckian brackish facies or to the Portlandian limestones. TWT isopachs increase considerably towards SW and S, as shown on Figure 2.22.

2.4.3.5. Lower Malm (Argovian): from reflector C to D

Argovian and Rauracian units have been highlighted in gray in Figures 2.20 to 2.22. This sequence is bounded by two strong reflectors, C at the top and D at the base. In the Jura, the sequence is unreflective where it corresponds to marls, but is more reflective to the Southwest, where the marly facies becomes intercalated with limestones. TWT isopachs are constant on Northeast-Southwest profiles, but thin southsouthwestward to disappear on section 45 and then 43; seismic line 45 clearly confirms this change. A stratigraphical log (TRÜMPY, 1980) of the autochtonous cover of the Aiguilles Rouges unit (the adjacent unit paleogeographically) shows well developed upper Malm layers and no lower Malm strata and is in agreement with the disappearance of the Argovian as seen on seismic lines.

2.4.3.6. Dogger-Aalenian-Liassic unit: from reflector D to G

The strong reflector D characterized by considerable lateral continuity throughout the seismic grid, corresponds to the top of the Dogger series, the "Dalle nacrée" formation. The Dogger is represented by two, three, or in places, four strong reflectors. The underlying transparent zone of the Aalenian contrasts with the Liassic reflective zone. This contrast is due to facies differences, between the Aalenian "Opalinus Ton" beds (shales) and the Liassic limestones. The top Liassic is a good reflector only within the Molasse Basin. The time interval thickness of this unit increases towards the Southwest (Fig. 2.21) and decreases toward the South (Fig. 2.22). The southern part of the Molasse Basin corresponds to an island (Alemannic high) during the Lower Jurassic, which explains the decrease in sediment thickness.

2.4.3.7. Triassic Unit 1: from reflector G to H

The strength of reflector G, marking the top of the Triassic beds, is due to the contrast between the early Liassic "Calcaire à Gryphées" formation and the Triassic evaporites or Rhaetian marls. Triassic Unit 1, highlighted in gray in Figures 2.20 to 2.22, is well layered with regular and continuous reflections and contrasts strongly with the underlying unit. The correlation of the base of this unit is based only on seismic interpretation.

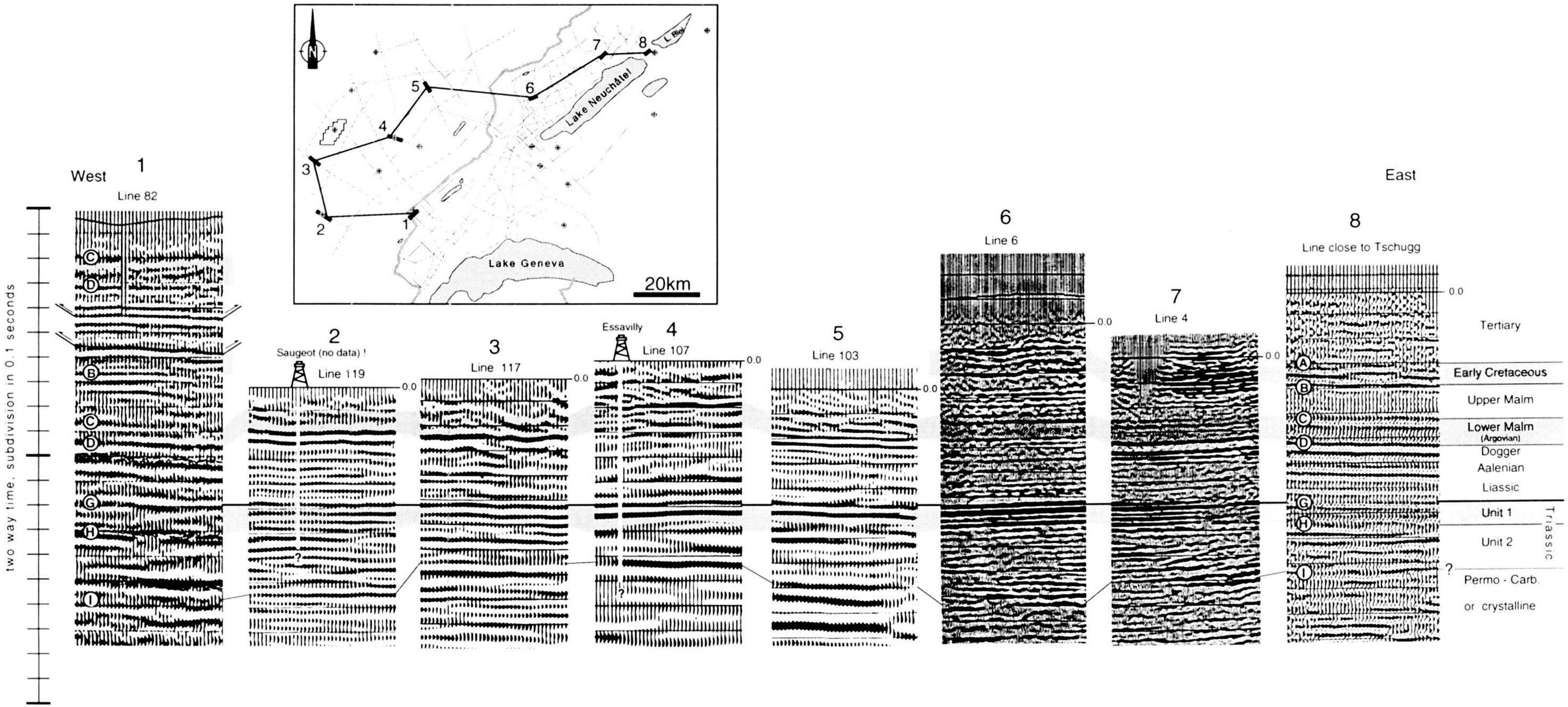
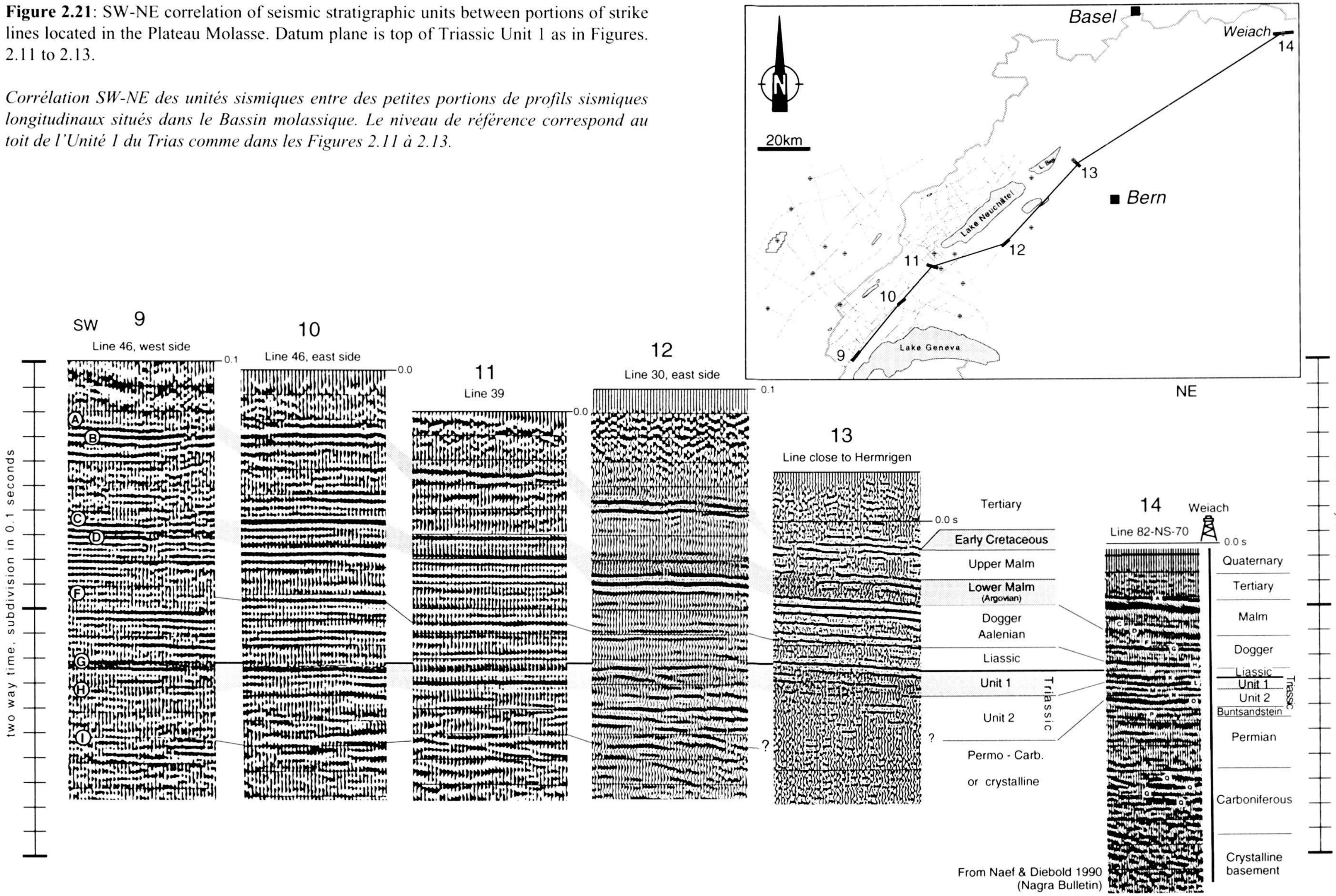


Figure 2.20: W-E correlation of seismic stratigraphic units between small portions of strike lines located in the Plateau Jura and the folded Jura. Datum plane is top of Triassic Unit 1 as in Figures 2.11 to 2.13.

Corrélation W-E des unités sismiques entre des petites portions de profils sismiques longitudinaux situés dans les Plateaux jurassiens et le Jura plissé. Le niveau de référence correspond au toit de l'Unité 1 du Trias comme dans les Figures 2.11 à 2.13.

Figure 2.21: SW-NE correlation of seismic stratigraphic units between portions of strike lines located in the Plateau Molasse. Datum plane is top of Triassic Unit 1 as in Figures. 2.11 to 2.13.

Corrélation SW-NE des unités sismiques entre des petites portions de profils sismiques longitudinaux situés dans le Bassin molassique. Le niveau de référence correspond au toit de l'Unité 1 du Trias comme dans les Figures 2.11 à 2.13.



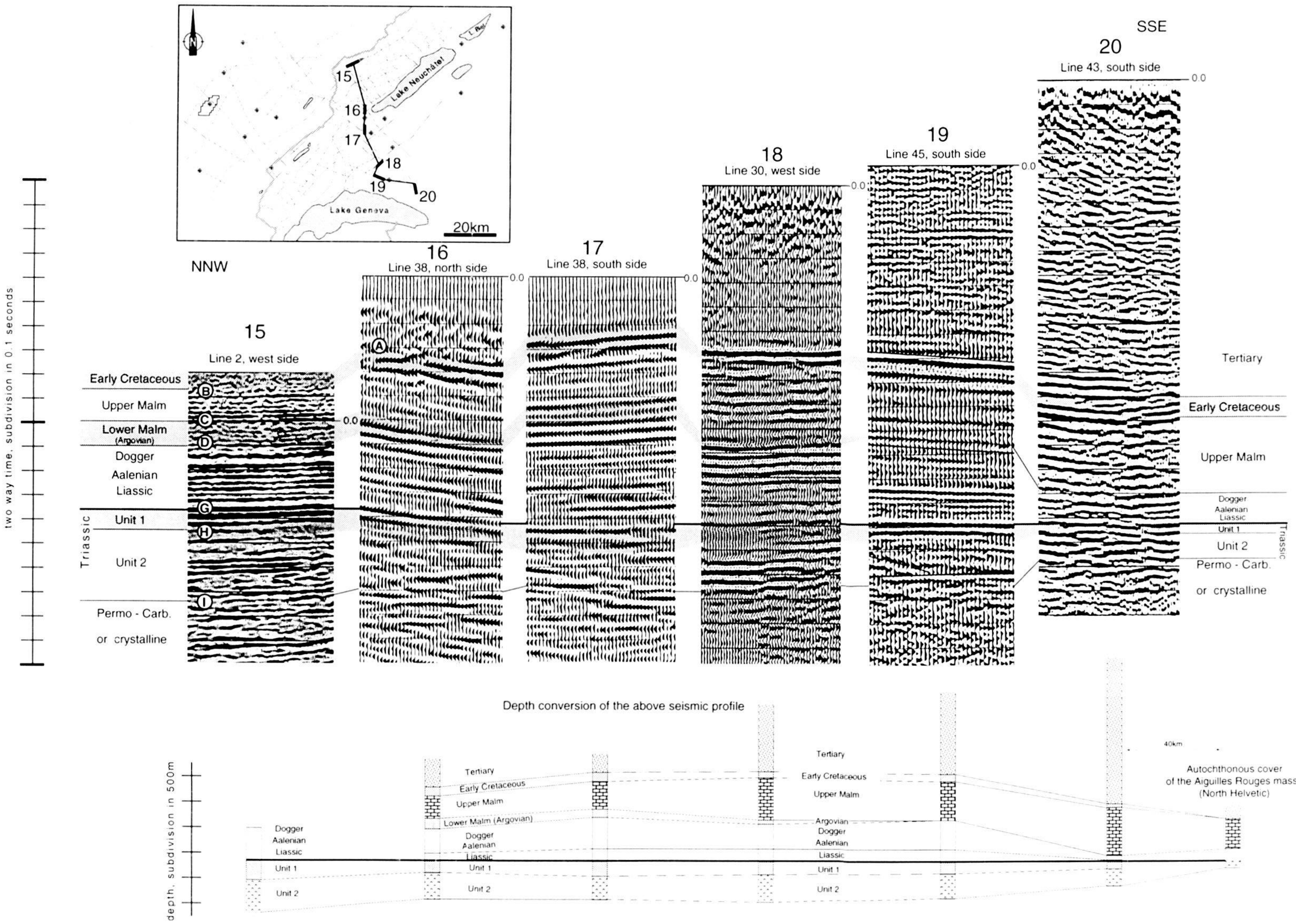


Figure 2.22: NNW-SSE correlation of seismic stratigraphic units between portions of lines located in the folded Jura and Molasse Basin. Correlation of depth converted seismic units underlie the seismic lines. Datum plane is top of Triassic Unit 1 as in Figures 2.11 to 2.13. The stratigraphic thickness of the southern part of the Molasse Basin is compared to the autochthonous cover of the Aiguilles Rouges massifs (Trümpy, 1980).

Corrélation NNW-SSE des unités sismiques entre des petites portions de profils sismiques situés dans le Jura plissé et le Bassin molassique. Le niveau de référence correspond au toit de l'Unité 1 du Trias comme dans les Figures 2.11 à 2.13. L'épaisseur de la partie méridional du Bassin molassique est comparée directement à celle de la couverture autochtone du massif des Aiguilles Rouges (Trümpy, 1980).

2.4.3.8. Triassic Unit 2: from reflector H to I

Reflector H defines the top of Triassic Unit 2. In the East, it may represent the "Hauptmuschelkalk dolomite" formation, while toward the West, it corresponds to the "Lettenkohle" beds. This sequence shows discontinuous and oblique reflectors, especially visible on lines 30, 39, 6, 119, Tschugg, 2 and 38. The origin of these reflections is not obvious and will be discussed later (Chapter 3). This unit is clearly differentiated from the Triassic Unit 1 and has led to the correlation (dashed lines on Figures 2.20 to 2.22) of the top of Triassic Unit 2.

The time interval varies strongly from one line to another, depending on the structural position: thickening is observed in anticlines and thinning in synclines.

2.4.3.9. Basement: from I reflector to downward

The top of the basement corresponds to the base of the last strong reflection, that contrasts with the unreflective crystalline basement below (Naef & Diebold, 1990). Occasionally however, reflections are present below I. These are either multiples (line 103, 117) or Permo-Carboniferous sediments (Fig. 2.23). Identifiable Permo-Carboniferous sediments are characterized by discontinuous strong reflectors, that contrast with the unreflective crystalline basement.

2.5. ISOPACH MAPS

2.5.1. Introduction

A series of isopach maps for individual Mesozoic units has been constructed for the western Molasse Basin (Figs. 2.24 to 2.29). Isopach maps are a powerful tool to depict even slight lateral thickness variations. Such changes are interesting for the analysis of subsidence mechanisms as well as for rheological considerations. The subsidence has been analyzed in detail (Loup, 1992a, 1992b) for the western Molasse Basin and Helvetic realm. His study was based on well logs and stratigraphic profiles which were corrected for compaction, depositional water depth and eustatic sea level changes. The maps presented here cannot compete with Loup's analysis as far as time resolution and accuracy in subsidence rates are concerned, but is complementary, however. Based on a large seismic grid with continuous profiles, this analysis has the advantage of a wide spatial resolution with the potential to reveal subsidence trends, synsedimentary faults and also anomalies not penetrated by wells.

Isopach maps presented herein are based on the depth conversion of the interpreted seismic lines and calibrated by wells. Only data below the datum plane (D.P.) of 500 m a.s.l. have been included in the contour maps, which do not extend to the folded and thrusted Jura. The velocities assigned to each seismic unit are described in Appendices 3. Contouring has been performed by computer, using the Uniras/Unimap package. The chosen bi-linear interpolation (to a uniform grid 1 km by 1 km) between individual points (with a spacing of 1 to 2 km along seismic profiles) results in a conservative extrapolation in areas with no data. Major tear faults, as known from surface mapping, have been introduced as discontinuities. Contouring is performed independently on either side of such faults. The advantage of this automatic contouring are no "observer-bias" and the capability to treat large data sets very rapidly. Disadvantages are interpolation artifacts in areas with little data coverage, e.g. close to faults or region borders, as well as crooked contour lines around isolated data points (an interpreter might have smoothed them out or else reviewed the basic data input). Blank holes appear where data density was insufficient for contouring. Actual data points are superimposed on the contours together with the tear faults.

2.5.2. Isopachs of the upper Malm unit

These isopachs represent the depth converted interval from reflector B to C (see §2.4.3.4.). The isopach map of the upper Malm layer (Fig. 2.24) confirms a progressive increase in thickness from N to S. No abrupt changes are visible on this map. The thickness of the complete unit is around 350-400 m in the southern Jura, whereas in the Molasse Basin it increases from 400 m in the Northnortheast to 850 m in the Southsoutheast (Humilly). Some contour intervals are offset by tear faults, whose sense of offset is consistent with field observation of sinistral N-S tear faults and dextral WNW-ESE tear faults.

2.5.3. Isopachs of the "Argovian" unit (lower Malm)

This isopach is the depth conversion of the "Argovian" seismic unit between reflector C and D (see §2.4.3.5.). The thickness ranges from 150 to 300 m and decreases gently from the Northwest to the Southeast and is close to zero near Savigny (southeastern edge) (Fig. 2.25). This decrease is well expressed also on the dip transect of Figure 2.22. No major changes across tear faults are noticeable.

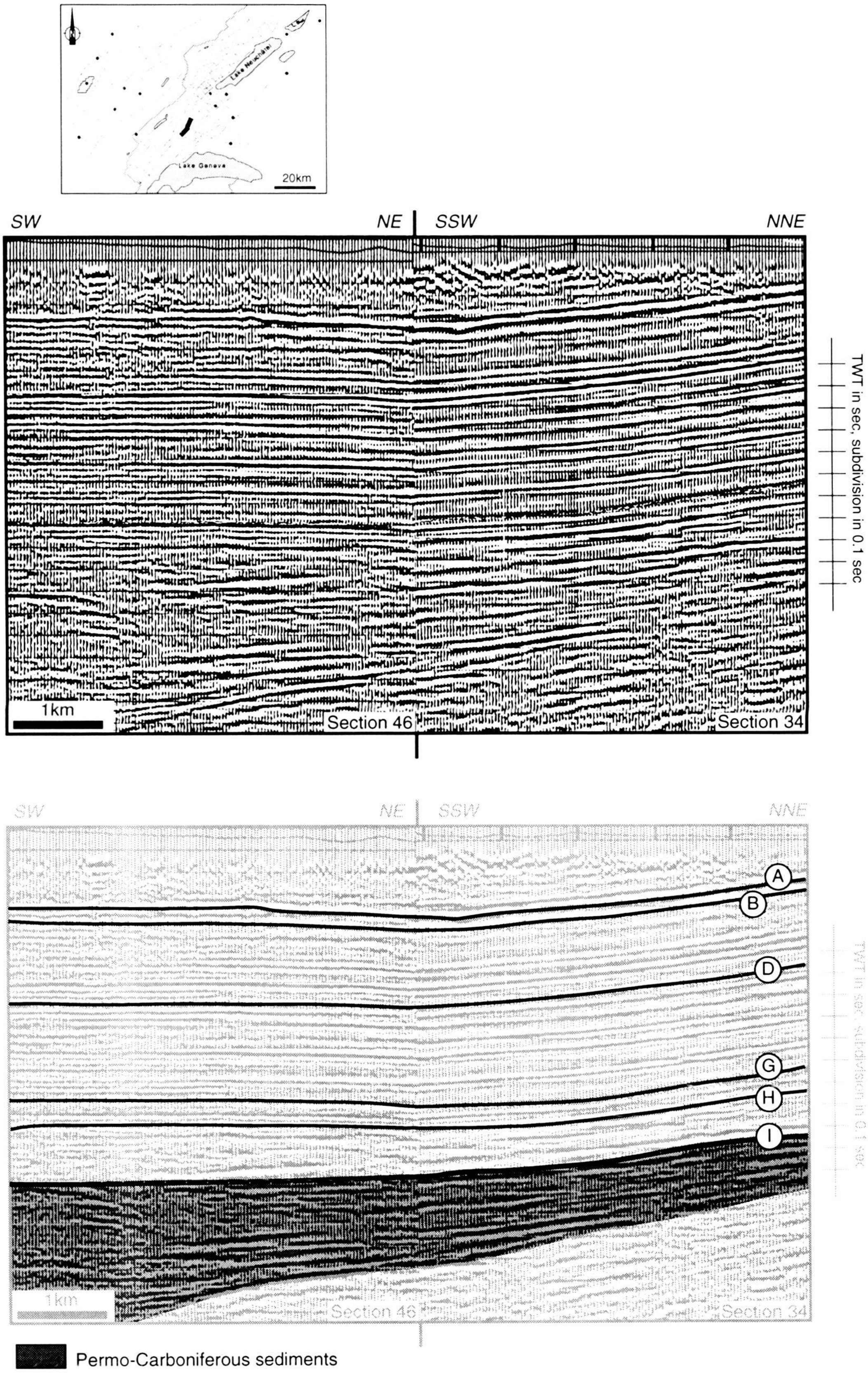


Figure 2.23: Seismic section (intersection between lines 46 and 34) showing Permo-Carboniferous sediments under the Mesozoic cover. Letters A to I label the reflectors (see Tab. 2.1).

Profil sismique (intersection entre les lignes 46 et 34) montrant des sédiments Permo-Carbonifères sous la couverture mésozoïque. Les lettres de A à I soulignent des réflecteurs importants (voir Tab. 2.1).

2.5.4. Isopachs of the Dogger unit

The isopachs of the Dogger unit (including the Aalenian unit), between reflectors D and F, are shown in Figure 2.26. In the Molasse Basin, the Dogger thickness is maximum along the W-E trending zone Treycovagnes - Essertines - Courtion (600 m) and decreases towards the SW (Humilly, 200 m). The same trends can also be seen on Dogger subsidence rate maps presented by LOUP (1992a). Abrupt changes are observable on the Treycovagnes-Essertines transects (see also Figure 4.18). These changes may be explained by a facies change either related or not to a synsedimentary normal fault. The Treycovagnes-Yverdon area will be discussed and illustrated in Chapter 4 (Regional geology of the Yverdon area, Fig. 4.18).

2.5.5. Isopachs of the Liassic unit

These isopachs represent the depth converted interval from reflectors F to G. The thickness increases from 200 m (Neuchâtel Jura) to 500 m (Essertines, Humilly) (Fig. 2.27). Changes observable on the Treycovagnes-Essertines or Essavilly-Laveron transects (see Appendix 2 for well data) can be explained either by tectonic thickening of these ductile beds during the Miocene deformation (e.g. in the Laveron area), or by facies changes (Yverdon area).

Isopach map of the upper Malm unit

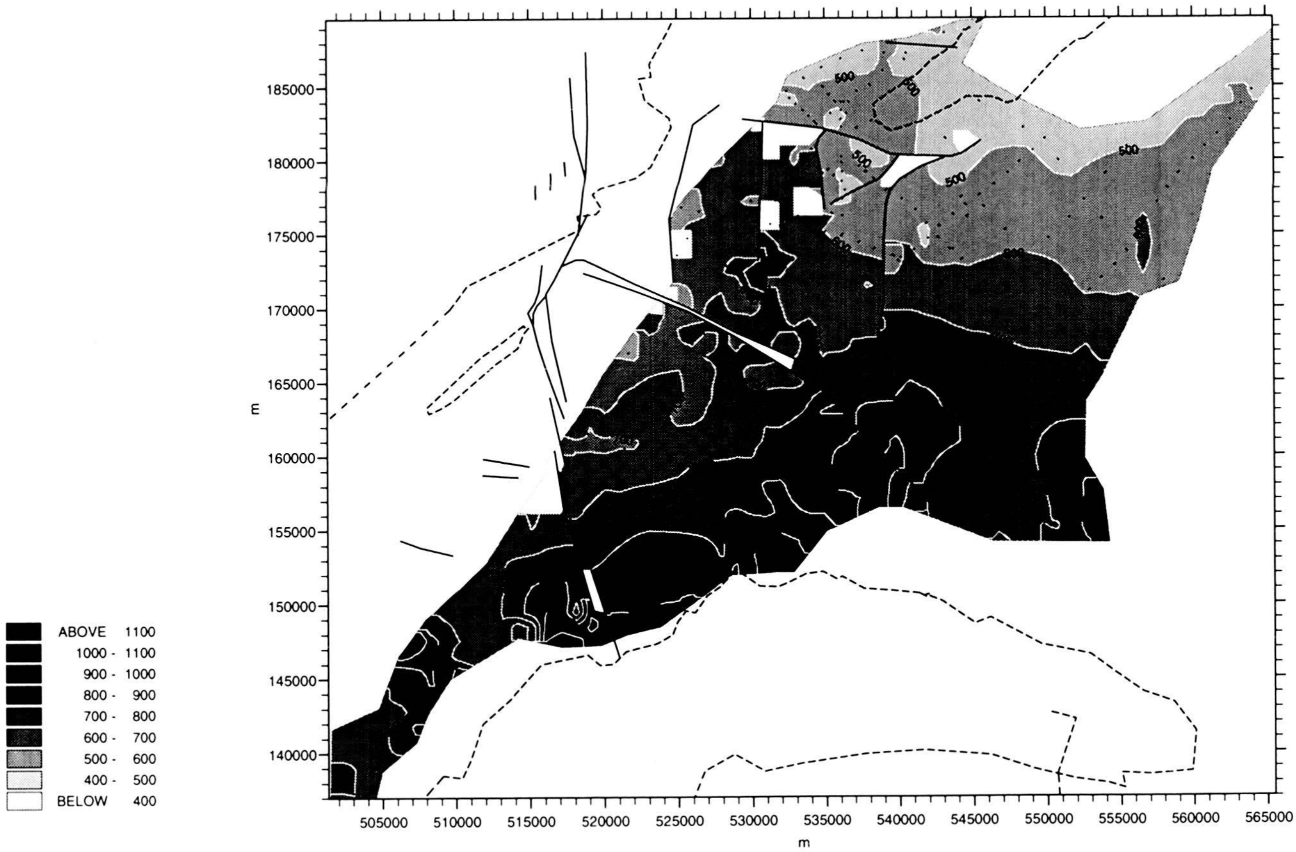


Figure 2.24: Isopach map of the upper Malm unit of the western Molasse Basin. Thickness is in meter. Black dots are shotpoints used for depth control of contour map. Note that blank areas and tight closed circles are computer-related artefacts in areas of sparse control. Numbers on the side and bottom are in meters, that relate to the national Swiss geographical coordinate system. Lakes Geneva and Neuchâtel are outlined for general reference.

Carte des isopaches (en mètres) des couches du Malm supérieur du Bassin molassique occidental. 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.

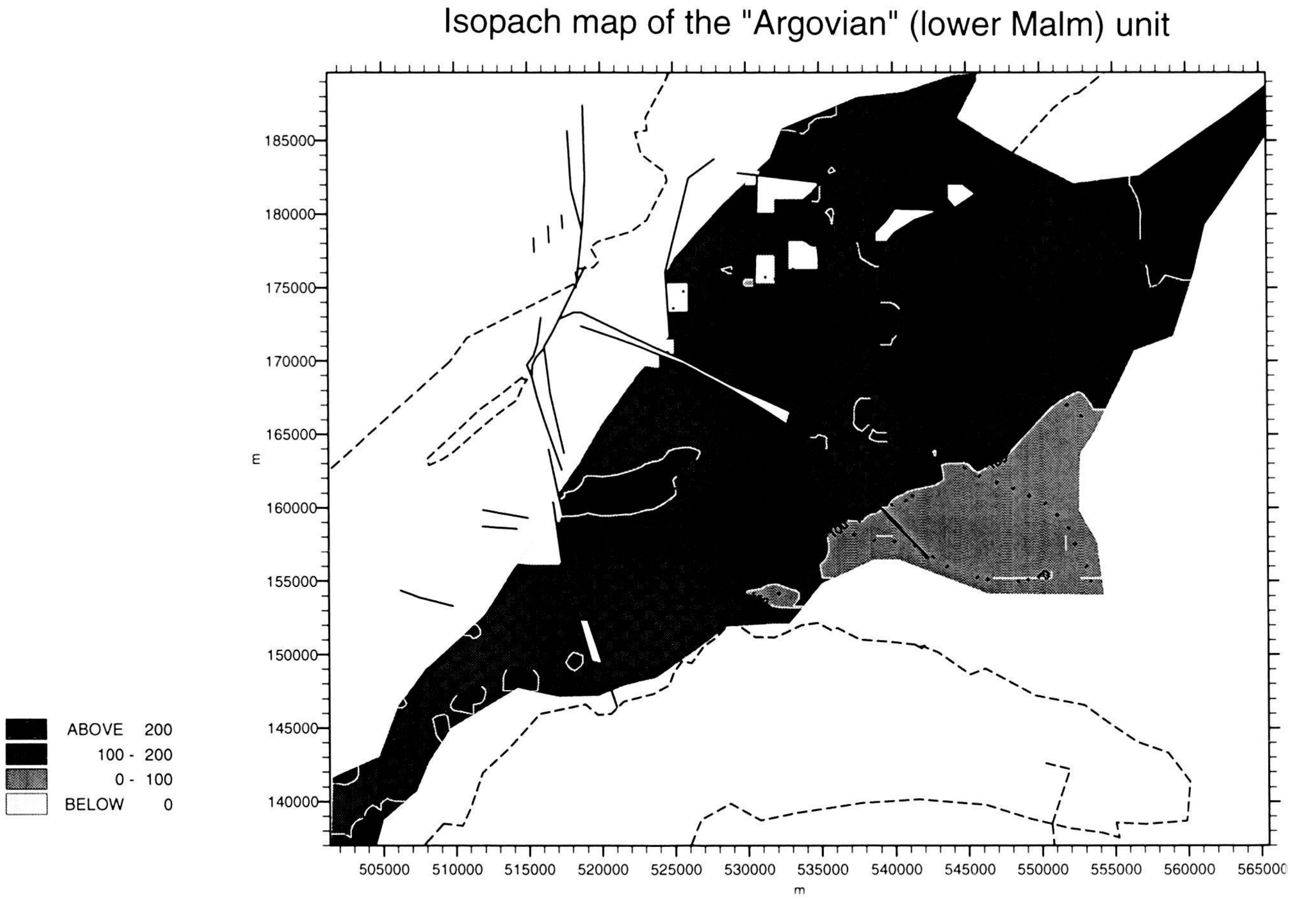


Figure 2.25: Isopach map of the "Argovian" unit (lower Malm) of the western Molasse Basin. Thickness is in meter. For explanation see legend of Figure 2.24.

Carte des isopaches (en mètres) des couches de l'"Argovien" (Malm inférieur) du Bassin molassique occidental. Pour les explications, voir la légende de la Figure 2.24.

Figure 2.26 (page 67, top): Isopach map of the Dogger-Aalenian unit of the western Molasse Basin. Thickness is in meter. For explanation see legend of Figure 2.24.

Carte des isopaches (en mètres) des couches du Dogger-Aalénien du Bassin molassique occidental. Pour les explications, voir la légende de la Figure 2.24.

Figure 2.27 (page 67, bottom): Isopach map of the Liassic unit of the western Molasse Basin. Thickness is in meter. For explanation see legend of Figure 2.24.

Carte des isopaches (en mètres) des couches du Lias du Bassin molassique occidental. Pour les explications, voir la légende de la Figure 2.24.

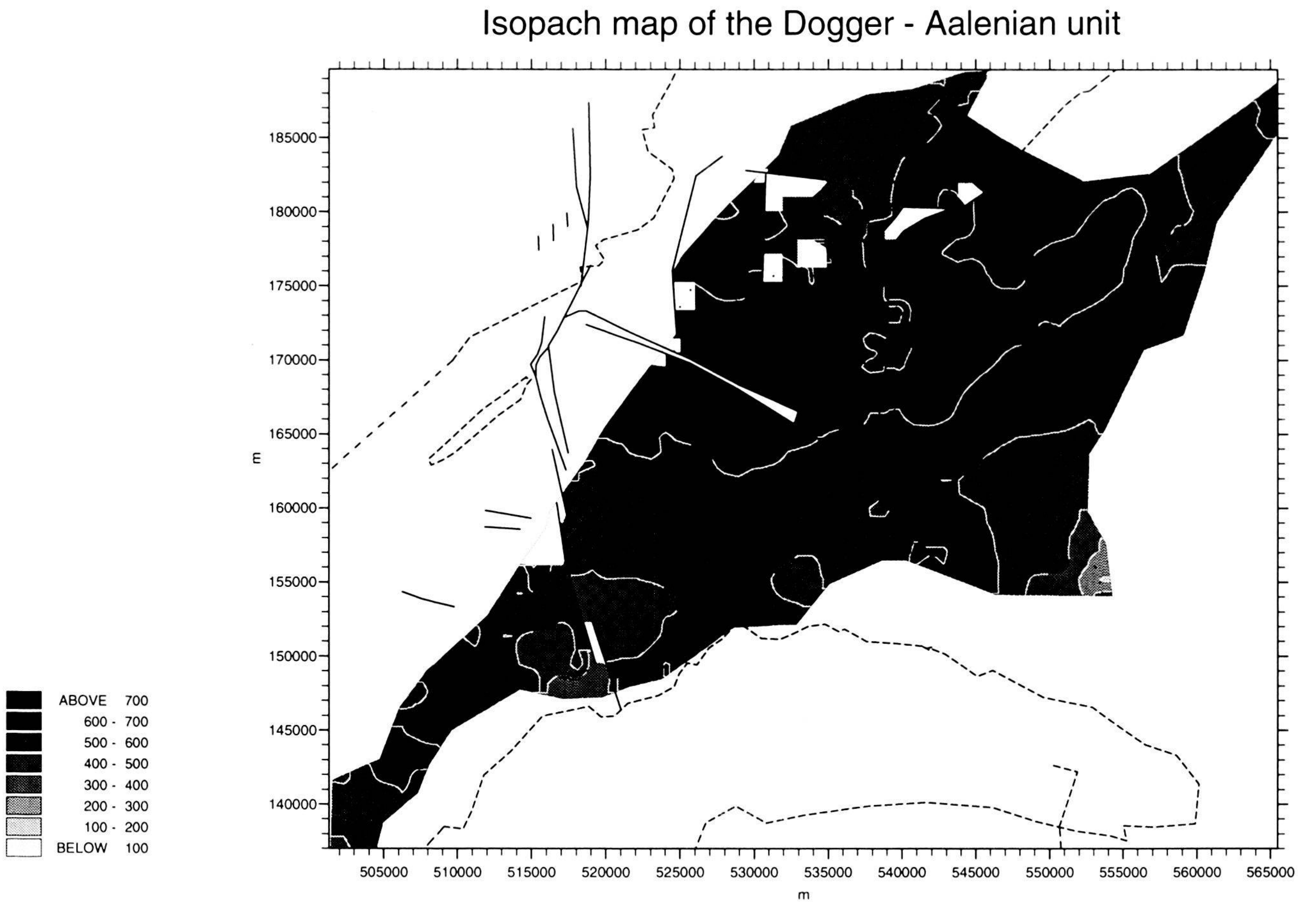


Figure 2.26

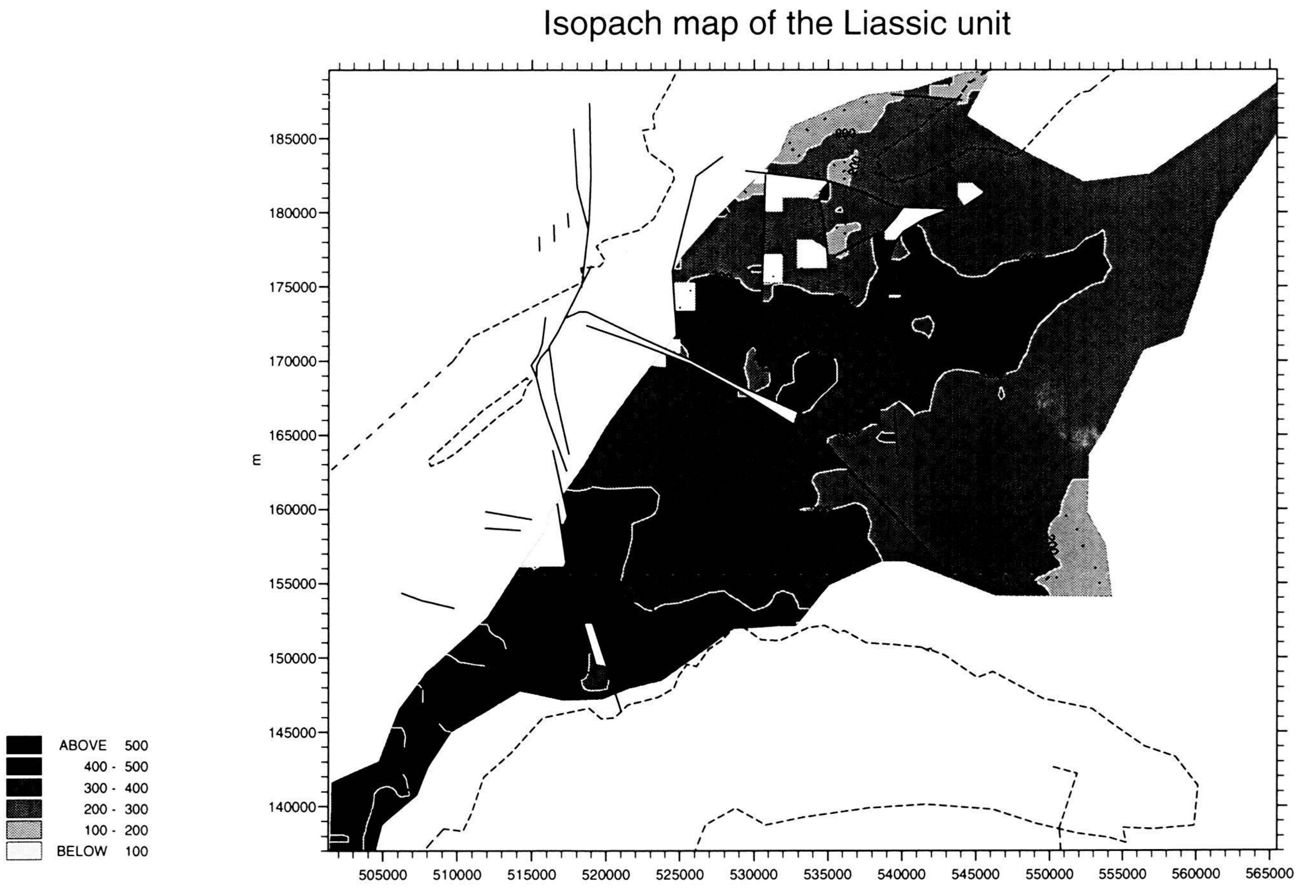


Figure 2.27

2.5.6. Isopachs of the Triassic Unit 1

These isopachs represent the depth converted interval from reflector G to H (see §2.4.3.7.). The thickness of Triassic Unit 1 ranges from 400 m to 200 m, decreasing progressively toward the ESE (Fig. 2.28). The well thicknesses do not match with this map, because of the new correlation based on our seismic interpretation (for more details see §2.4.3.7. and §2.4.3.8.).

2.5.7. Isopachs of the Triassic Unit 2

These isopachs consist of the depth converted interval from reflector H to I (see §2.4.3.8). The thickness varies considerably and ranges from 300 m to 1200 m (Fig. 2.29). In addition to a general trend of thickening towards the NW, this isopach map shows a conspicuous series of lows and highs, which alternate on the 10 km scale with a weak NE-SW trend, parallel to the Jura folds further to the North. A hand contoured version of this map is presented in Chapter 3 (Fig. 3.6). The highs are interpreted in terms of stacks of evaporites, clays and salt and will be discussed in detail in Chapter 3.

2.5.8. Summary

Thicknesses of individual stratigraphic intervals have been mapped from the interpretation of seismic lines and allow assessment of some gross regional trends in the Mesozoic subsidence pattern.

During the Triassic, more than 1000 meters of tectonically thickened sediments were accumulated in the area of the future Jura arc, whereas some 60 km further south, in the North Helvetic domain, less than 50 m of sediments were deposited in the same time span. Despite this considerable lateral variation, no evidence for synsedimentary faults has been detected. Important lateral thickness variations in the Triassic on the scale of about 10 km are related to Miocene deformation and material redistribution within this weak layer, which served as the major décollement horizon for Jura tectonics.

During Liassic and Jurassic times, lateral variations in subsidence were significant, but less important than during the Triassic. Depocenters shifted in an irregular manner over the study area, but no persistent trends were found. Some small abrupt thickness changes in the Yverdon region may be the result of synsedimentary faults, but direct evidence is obscured by Miocene tear faults.

Throughout the Mesozoic, the studied area was a slowly subsiding region intermediate between the Paris basin to the NW and the Alpine Tethys to the South. According to LOUP (1992b), the subsidence was polyphase and cannot easily be described in terms of a single Mesozoic event. Modeling the subsidence curves yields stretching factors for Triassic, Liassic and Late Jurassic rifting events on the order of 1.05 to 1.20. Subsidence ceased during the upper Cretaceous.

Figure 2.28 (page 69, top): Isopach map of the Triassic Unit 1 of the western Molasse Basin. Thickness is in meter. For explanation see legend of Figure 2.24.

Carte des isopaches (en mètres) des couches de l'Unité 1 du Trias du Bassin molassique occidental. Pour les explications, voir la légende de la Figure 2.24.

Figure 2.29 (page 69, bottom): Isopach map of the Triassic Unit 2 of the western Molasse Basin. Thickness is in meter. For explanation see legend of Figure 2.24.

Carte des isopaches (en mètres) des couches de l'Unité 2 du Trias du Bassin molassique occidental. Pour les explications, voir la légende de la Figure 2.24.

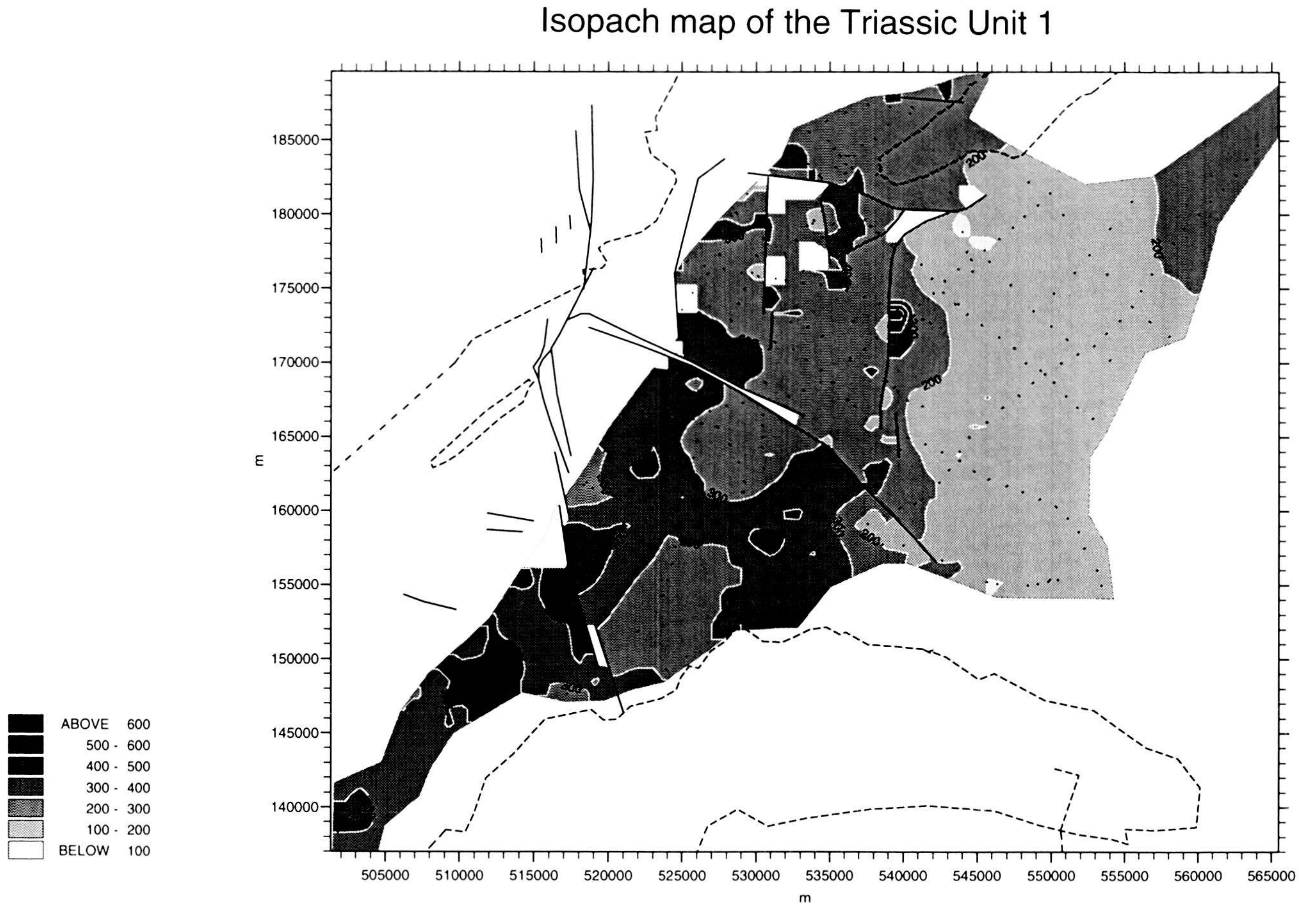


Figure 2.28

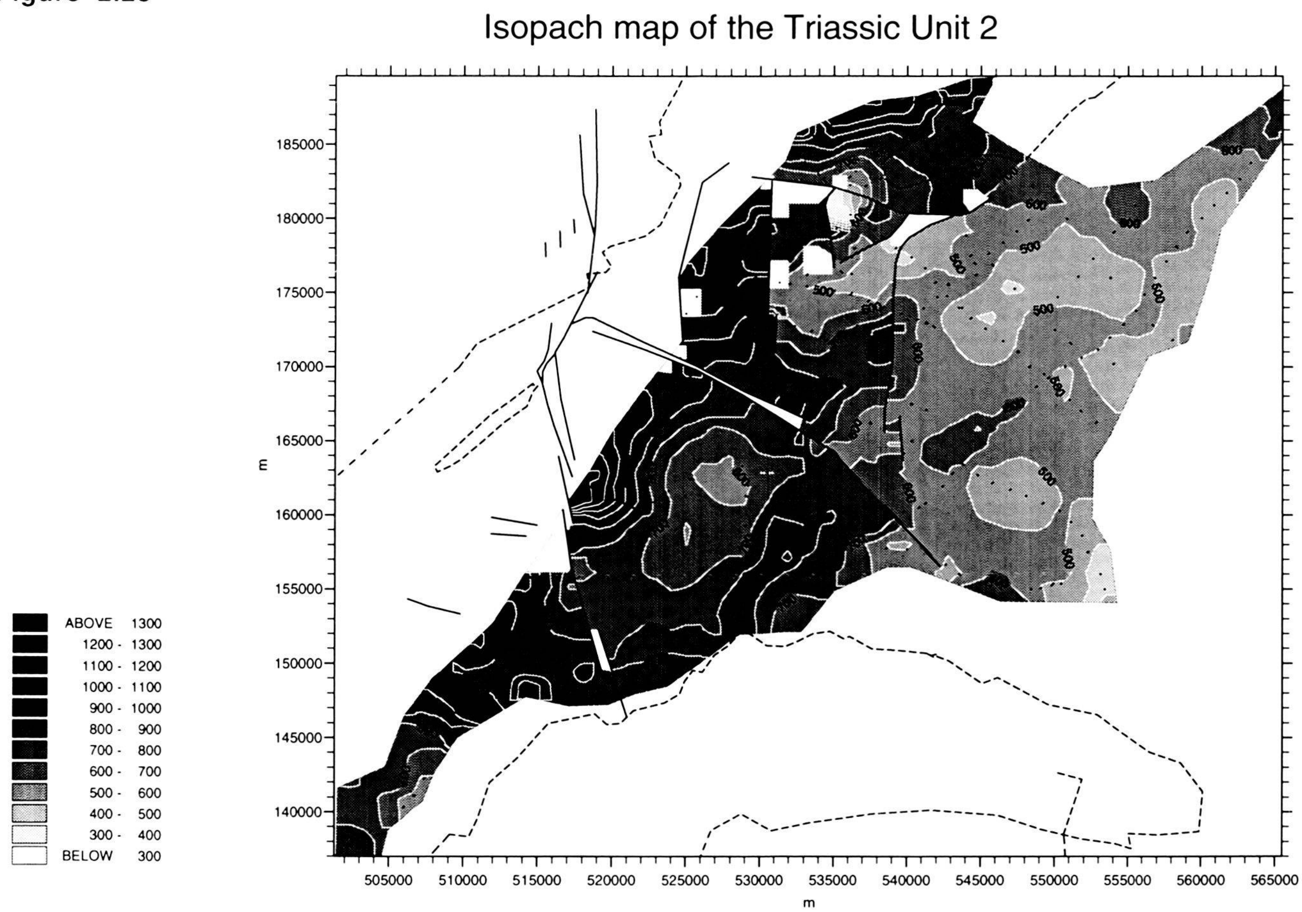


Figure 2.29

2.6. RHEOLOGICAL STRATIGRAPHY

2.6.1. General comments

The stratigraphic thickness and lateral continuity of competent and incompetent formations within the stratigraphic column plays a key role in the tectonic evolution of foreland fold and thrust belts. The rheology of individual layers is primarily dependent on the mineralogical composition of the rock, the texture and the deformation temperature. In the case of a sedimentary cover consisting of alternating competent and incompetent beds, the relative thickness of these layers also plays an important role in the style of deformation (RAMSAY, 1967). Variations in any of these parameters across a foreland area will strongly influence the tectonic and structural style.

Given a maximum total thickness of less than 1.5 km of Mesozoic and Cenozoic cover rocks in the northern Jura, increasing to 2 km in the central Jura and to more than 3 km at the southern rim of the Molasse Basin, maximum temperatures at the base of the cover series can be estimated to be between 60°C and 130°C respectively (JORDAN, 1992). Under these very low temperature conditions, the relative competence of the sediments present in the stratigraphic column increases by orders of magnitude in the following estimated order (from weakest to strongest): salt, gypsum, anhydrite, shale, marl, Molasse sandstone, limestone, dolomite (NÜESCH, 1991; TWISS & MOORES, 1992; JORDAN, 1994). Although the entire area lies in the low temperature field, a slight southward temperature increase is important insofar, because the rheology of gypsum and anhydrite are very sensitive in this temperature range (OLGAARD & DELL'ANGELO, 1991).

2.6.2. Rheological behavior of rocks from the Jura

The following rheological behavior of individual layers in the Jura can be expected and has been confirmed by detailed structural observations from outcrops and experiments:

2.6.2.1. Salt

Laboratory data (CARTER & HANSEN, 1983) indicate that pure rock salt is by far the most ductile lithology at low temperature. For reasonable geological strain rates, salt will deform plastically by dislocation - glide and - climb, as well as pressure solution mechanisms. This behavior has been confirmed by observation in samples of the Schafisheim drill cores (MATTER *et al.*, 1988; JORDAN & NÜESCH, 1989a). Experimental work (CARTER & HANSEN, 1983) on halite, with a similar grain size to the Jura halite, yields very low shear strengths, especially in the presence of pore fluids. In the Jura, pure salt thicknesses are generally thin and vary between 20 m and 300 m in the Laveron drill hole (Figs. 2.11 to 2.13; see also JORDAN, 1992).

In terms of rheology, salt behavior will be the same for a 10 m or a 100 m thick salt layer. There seems to be little or no justification for trying to establish some critical minimum thickness of salt (JENYON, 1986). The difference will reside in the shape and the size of the features resulting from thinning or thickening. Thus a very thin salt layer will probably act as a lubricant between floor and roof sequences, once thrust or décollement movement has been initiated.

2.6.2.2. Gypsum / Anhydrite

At the depth of the main Jura décollement, gypsum is expected to be transformed into anhydrite (HEARD & RUBEY, 1966). This transition is important for the rheological behavior, since anhydrite is somewhat stronger than gypsum. The transformation of gypsum to anhydrite involves dewatering, a reaction which in turn, could have weakened the associated clay rich rocks by creating higher than hydrostatic fluid pressures. Outcrops of Triassic gypsum/anhydrite series show compelling evidence for the ductile behavior of anhydrite layers during Jura deformation (Fig. 2.2b).

Deformation within the anhydrite shear zones from the eastern Jura has been studied by JORDAN (1994). Even at moderate temperatures and shallow depths, anhydrite is in an intracrystalline glide deformation regime in combination with grain boundary migration. Fluids are responsible for the early onset of grain boundary migration and therefore for the weakening of the anhydrite (fluid enhanced flow). Highly deformed anhydrite tectonites show evidence for diffusion and grain boundary gliding processes (OLGAARD & DELL'ANGELO, 1991).

Fluids seem to have been omnipresent in the Triassic evaporites during the deformation of the Jura belt. This appears to be reasonably correlated with the experimental results of HEARD & RUBEY (1966) on the dehydration of the gypsum transformed to anhydrite and water and other experiments on clays (JORDAN & NÜESCH, 1989b). Dehydration increases fluid pressure and decreases the rock strength.

During an initial stage, strain was mainly accommodated by ductile flow of anhydrite, while at a later subsurface stage, main shear deformation changed into new-grown gypsum and finally into fault breccias. Comparable behavior has been observed in Triassic imbrications outcropping in the northeastern Jura (JORDAN *et al.*, 1990).

2.6.2.3. Shales / shaly Marls

It is commonly accepted, that shales are efficient décollement horizons. Their competence, however is strongly dependent on porosity, fluid pressure and anisotropy. Dry, compacted shales, at low temperature, may be almost as strong as limestone, whereas wet, overpressured shales can be weaker than evaporites.

Experimental results confirm the existence of a regime of low-strength pervasive cataclastic-type deformation in shales not known in other rock types (JORDAN & NÜESCH, 1989b). Such a deformation regime is explained by the ability of clay minerals to adsorb and to retain water. This interlayer water decreases the strength of clay and hence that of shales significantly.

Observations on the naturally deformed shale layers of the eastern Jura show that deformation is generally friction controlled. Shales interbedded with evaporites on the other hand show plastic deformation behavior, interpreted as controlled by sulfate lubrication (JORDAN & NÜESCH, 1989b). Therefore, in the Jura, deformation of the Opalinus shales (Aalenian layers of the eastern Jura, Fig. 2.30) is predominantly brittle, due to the lack of lubricant, whereas in the Triassic evaporites the deformation is dominantly plastic.

In the Jura, shale interlayers within the evaporites result in two types of deformation, depending on burial depth. The domains of deformation are separated by the inversion of relative competence of shale and anhydrite and the onset of gypsification (JORDAN & NÜESCH, 1989b). In deeper domains, strain is focused on slickensides, which are often coated with sulfate that acts as a lubricant. Anhydrite is ductily deformed and shale interlayers are boudinaged. In shallower domains, and especially in domains with significant exposure to water, strain becomes pervasive and very low strength ductile shale-gypsum tectonites are formed. The deformation is characterized by boudinaged brittle anhydrite layers within highly ductile shale-gypsum cataclasites. Such tectonites are restricted to areas of little overburden and to domains of significant water content.

2.6.2.4. Limestones

At low temperature, dry limestones are very strong compared to the above mentioned lithologies, because intracrystalline deformation mechanisms are not operative below temperatures of about 200 °C (RUTTER, 1974). From this, an entirely brittle behavior would be expected for a limestone succession. In the presence of water, however, pressure solution and recrystallization play an important role (GRATIER, 1984). This mechanism impairs some apparent macroscopic plasticity to the rock, although in terms of rheological behavior, limestones at low temperature must be regarded rather as brittle than ductile.

2.6.3. Rheological profiles for the central and eastern Jura

The more theoretical considerations discussed above, together with outcrop observations and data from seismic lines, allow construction of a composite rheological stratigraphic profile (Fig. 2.30). The Jurassic and Cretaceous stratigraphic columns from Vaud, Jura and Aargau are taken from TRÜMPY (1980). The Neuchâtel stratigraphic log and the Triassic log are compiled from the literature and from subsurface data respectively. In the four sections, three degrees of competence have been distinguished : 1) strong (limestone dominated); 2) weak (shale and marl dominated); 3) very weak (evaporite dominated).

The main incompetent formations are the Lower Cretaceous shales ("Marnes bleues d'Hauterive" in the Neuchâtel Jura), the "Purbeckian" formation at the transition of Malm to Cretaceous strata, the Lower Malm marls ("Argovian" formation in the northwestern part of the Swiss Jura), the Aalenian shales ("Opalinuston") and the evaporitic levels of the Triassic Unit 1 and Unit 2. Based on interpretation of seismic lines and on well data, Triassic Unit 2 appears as the most ductile zone or weakest zone of the whole stratigraphic column in the central Jura and the western Swiss Molasse Basin. Field observations (eastern Jura) and core sample observations

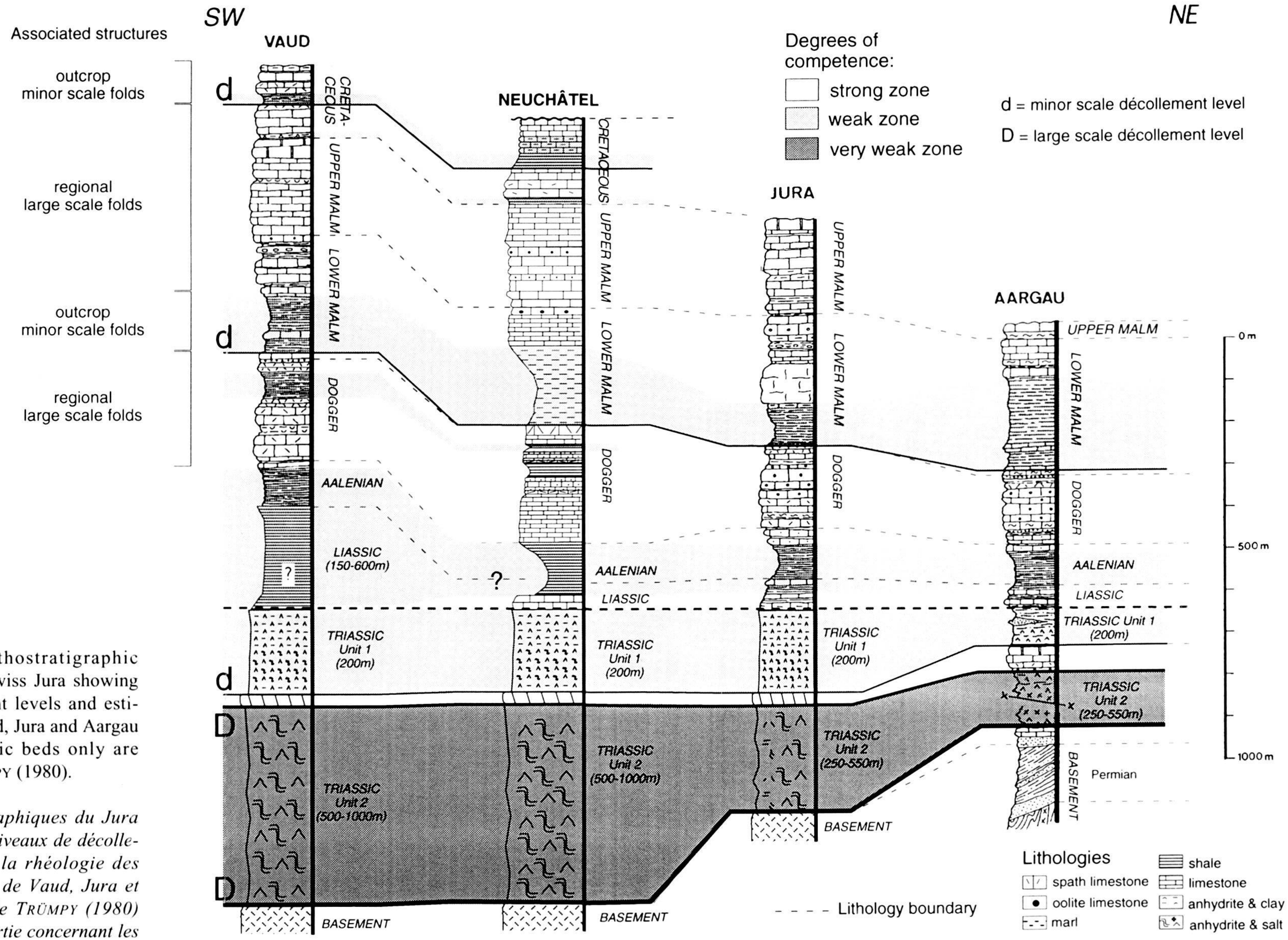


Figure 2.30: Lithostratigraphic columns from the Swiss Jura showing potential décollement levels and estimated rheology. Vaud, Jura and Aargau columns for Jurassic beds only are modified from TRÜMPY (1980).

Profils lithostratigraphiques du Jura suisse montrant les niveaux de décollements potentiels et la rhéologie des couches. Les profils de Vaud, Jura et Aargau sont tirés de TRÜMPY (1980) seulement pour la partie concernant les couches du Jurassique.

show several shear zones and ductile deformation in the Triassic evaporites (WEBER *et al.*, 1986; JORDAN & NÜESCH, 1989a; JORDAN *et al.*, 1990; HAUBER, 1993; JORDAN, 1994). The mineralogical composition of this unit consists of anhydrite, gypsum, salt, clay, calcite and dolomite. Salt has been recognized in all wells, but pure rock salt thicknesses are difficult to establish. There were variations of rheological behavior of the individual layers during compressional deformation, ranging from low strength viscous flow within pure halite and anhydrite layers, to rigid behavior or high-strength cataclastic flow in pure shales, marls and carbonates (JORDAN & NÜESCH, 1989a). The shear zones tend to be localized in pure halite and anhydrite layers.

The rigid layers are the upper Malm limestones (especially in the West) and the Dogger bioclastic limestones. The net thickness of these layers determines the wavelength of the first order folds. The ratio between competent and incompetent layers in the Mesozoic cover decreases from SW toward NE i.e. from 2:1 in the southern Jura to 1:2 in the eastern Jura, passing through 1:1 in the central Jura. The total cover thickness has a major influence on the structural relief which also decreases from SW to NE.

Major and minor potential décollement levels are indicated in Figure 2.30 with thick and thin black lines respectively. Minor décollement horizons include Triassic Unit 1 evaporites, Aalenian black shales, Argovian marls and lower Cretaceous marls. Deformation and structures resulting from minor décollement along these levels is discussed in §3.2.3.4. Among these, the most important in the Neuchâtel and Vaud Jura is the lower Cretaceous horizon. A strong decoupling level within the Cretaceous is observed in many outcrops (DROXLER, 1978; MARTIN *et al.*, 1991), where a strong disharmony in folding style is observed between the large folds of the Malm and small scale folds in the Cretaceous. The latter are too small to be resolved on seismic lines. The same may be true for the slightly disharmonic folding observed within the Argovian (PFIFFNER, 1990) (see Figure 3.17). However, only one case has been found on the examined seismic lines (Section 71, Fig. 3.2), where the Argovian acts as a significant décollement level for the overlying fold.

The major décollement zone is located in the Triassic Unit 2. This appears clearly from the interpretation of seismic lines. This zone is bound both by a roof décollement and a basal décollement and the style of deformation within this zone is very different from the underlying rigid basement and from the overlying Triassic Unit 1 and especially the Jurassic layers. HARRISON & BALLY (1988), in the salt-based Melville Island fold and thrust belt, preferred to define the whole interval as a ductile zone, (although the processes are not truly plastic at microscopic scale), instead of a décollement zone, because the term décollement refers to a single weak plane. In this work we will interchangeably use ductile zone or décollement zone, keeping in mind that this décollement is represented by a thick zone and not by one single weak plane. The envelope of the ductile zone corresponds to the décollement level. Previously SCHARDT (1908) expressed this very same idea: "*... Il serait plus juste de parler d'une zone de glissement. Il est en effet peu probable que la poussée venant des Alpes ait produit un glissement sur un plan déterminé; mais ce sont certainement les couches marneuses dans leur ensemble qui ont servi de lits mobiles en se déformant dans toute leur masse. ...*".

The presence of a weak continuous basal décollement horizon or zone is a primary condition for the development of any foreland fold and thrust belt. In the case of the Jura arc, the original paleogeographical extent of Triassic evaporite series (Fig. 2.5), with salt, gypsum and/or anhydrite and clays, seems to be responsible for the shape of the external and lateral limits of the fold thrust belt. These outer limits are interpreted mainly as due to the disappearance of a suitable basal décollement horizon, i.e. the Triassic evaporites. Note that in Bavaria (Germany), where no Triassic evaporites exist, there is no lateral equivalent to the Jura and the Alpine deformation front remains tens of kilometers further back at the southern border of the Molasse Basin (BACHMANN *et al.*, 1987; LEMCKE, 1988; BURKHARD, 1990).