Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 90 (1997)

Heft: 1

Artikel: New coalification profiles in the Molasse Basin of Western Switzerland : implications for the thermal and geodynamic evolution of the Alpine Foreland

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DOI: https://doi.org/10.5169/seals-168146

Eclogae geol. Helv. 90 (1997) 79–96
0012-9402/97/010079-18 $1.50 + 0.20/0

Eclogae Geologicae Helvetiae

New coalification profiles in the Molasse Basin of Western Switzerland: Implications for the thermal and geodynamic evolution of the Alpine Foreland

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Key words: Vitrinite reflectance profile, North Alpine Foreland Basin, Western Switzerland, erosion, thermal modelling, heat flow, geothermal gradient, lithospheric flexure

ABSTRACT

The coalification profiles of five oil wells (Chapelle, Eclépens, Essertines, Savigny and Treycovagnes) in the Western Swiss Molasse basin were determined using measurements of vitrinite reflectance (VR). The analysed sections cover essentially the Tertiary for the Chapelle and Savigny wells and the Mesozoic sediments for the other wells. VR values range from about 0.4 %Rr to 0.9 %Rr. In all wells an overall linear increase in thermal maturity was observed. Coalification gradients range from 0.17 to 0.21 %Rr/km in the Plateau Molasse. In the Subalpine Molasse, a gradient of 0.07 %Rr/km was determined for the autochthonous part of the Savigny well. The isoreflectance lines in a NW-SE profile are discordant with respect to the stratigraphy. The thermal maturity of any given formation increases towards the Alpine front. The present-day VR values represent the "frozen" maturity level prior to Miocene-Pleistocene uplift and erosion. Thermal modelling results suggest that "normal" conditions prevailed in the area of the Plateau Molasse during the Tertiary. Average paleogeothermal gradients vary between 29 and 31 °C/km and the computed paleoheat flow values range from 60 to 70 mW/m^2. Lower values were reconstructed in the Subalpine Molasse (20 °C/km and 50 mW/m^2). Modelling results demand erosion of some 2000–2600 m in the Plateau Molasse and 4300 m in the Subalpine Molasse. The level of heat flow (Tertiary and present-day) decreases towards the German Molasse Basin. This trend correlates with an increase in flexural rigidity in the same direction. The thermal activity and/or lithospheric thinning during the evolution of the Cenozoic rift system in Europe could explain to some extent these observations. However, the western Molasse Basin may have already inherited a weaker lithosphere due to greater Mesozoic extension and higher density of preexisting mechanical heterogenities (e.g. Permo-Carboniferous grabens) when compared to the German Molasse Basin.

RESUME

L'évolution verticale du pouvoir réflecteur de la vitrinite (PRV) a été déterminée dans cinq forages pétroliers du bassin molassique de Suisse occidentale (Chapelle, Eclépens, Essertines, Savigny et Treycovagnes). Les forages Chapelle et Savigny ont traversé essentiellement la Molasse tertiaire, alors que les autres sondages ont traversé surtout des séries mésozoïques. Les valeurs du PRV varient de 0.4 %Rr à 0.9 %Rr. L'évolution du PRV avec la profondeur est linéaire dans les forages analysés. Les gradients PRV obtenus ne varient guère (0.17–0.21 %Rr/km) dans la Molasse du Plateau. Une valeur de 0.07 %Rr/km a été déterminée dans la partie autochtone du forage de Savigny, implanté sur la Molasse subalpine. Dans un profil NW-SE, les courbes d'isoréflectance sont discordantes par rapport à la stratigraphie, la maturité thermique de chaque formation augmente en s'approchant du front alpin. L'état de maturité observée correspond à l'enfouissement maximal qui a précédé les soulèvements et érosions du Mio-Pleistocène. La modélisation thermique montre que le régime paléogéothermique du Plateau Suisse pendant le Tertiaire peut être considéré comme "normal". Les gradients paléogéothermiques moyens varient entre 29 et 31 °C/km et le flux de chaleur entre 60 et 70 mW/m^2. Pour la Molasse subalpine, les valeurs obtenues sont plus basses (20 °C/km et 50 mW/m^2). Nos simulations et modélisations suggèrent l'érosion d'une couche épaisse de 2000–2600 m environ dans la Molasse du Plateau et de 4300 m dans la Molasse subalpine. La diminution du flux de chaleur (actuel et tertiaire) depuis la Suisse occidentale en allant vers le bassin molassique allemand peut être corrélée avec l'augmentation de l'épaisseur élastique de la lithosphère. L'activité thermique et/ou l'amincissement lithosphérique associés à l'évolution des "rifts" cénozoïques européens pourraient expliquer, au moins en partie, cette variation géographique. Mais on pourrait aussi postuler que la lithosphère de Suisse occidentale était à l'origine plus faible à cause d'une extension lithosphérique plus importante pendant le Mésozoïque, ainsi que de la présence accentuée d'hétérogénéités mécaniques fréquentes (p. ex. graben permo-carbonifère).

Introduction

The present-day structure of the Swiss Molasse basin is the result of a geological evolution initiated in the Paleozoic. The important tectonic events which have marked this evolution are the following: i) Variscan orogeny and the subsequent formation of deep Permo-Carboniferous grabens (Thury et al. 1994), ii) Extension related to sag-basin development and thermal subsidence during the Mesozoic (Loup 1992a, b), iii) Closure of infra-Helvetic flysch basins and development of the North Alpine Foreland Basin (NAFB) as a flexural depression during the end Cretaceous-Miocene (Lihou & Allen 1996),

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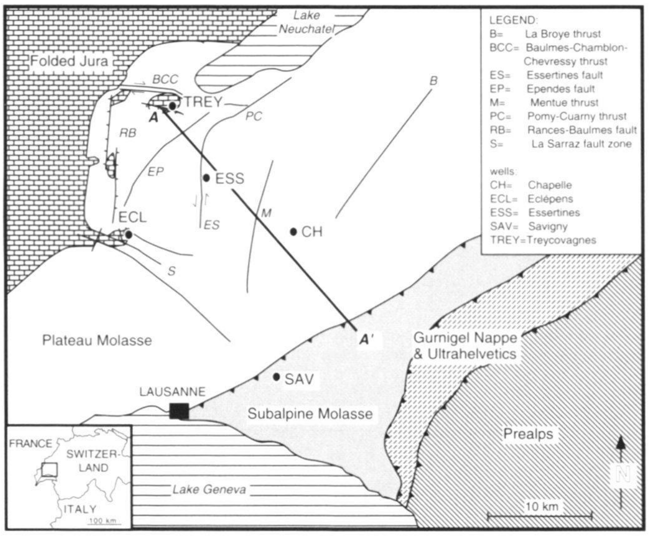

Fig. 1. Tectonic map of the western Swiss Molasse basin showing location of studied wells (modified after Jordi 1990 and Gorin et al. 1993). A-A': cross section line of Fig. 7.

and iv) Detachment of the basin, deformation of the Jura mountains and the uplift/inversion of the NAFB during the Miocene-Pliocene (Pfiffner & Erard in press).

These tectonic processes have directly influenced the thermal boundary conditions (paleoheat flow) and the basin dynamics (subsidence versus uplift/erosion). The geothermal regime in the NAFB during the Tertiary is generally characterized as hypothermal (Teichmüller & Teichmüller 1986, Sachsenhofer 1992, Schegg & Leu in press), whereas the conditions during the late Paleozoic are inferred to be hyperthermal (Kempter 1987, Diebold et al. 1991, Schegg & Leu in press). Major phases of erosion are represented by three interregional unconformities separating the sedimentary succession beneath the Molasse Basin: the late Paleozoic, the base Tertiary and the base Quaternary unconformity (see Schegg & Leu in press for a review).

Knowledge of the paleogeothermal conditions in the Swiss Molasse Basin is still rather patchy. It is mainly based on the analysis of vitrinite reflectance measurements of surface samples (Kübler et al. 1979, Schegg 1992a, 1992b, 1993, Todorov et al. 1993) and on the coalification profiles of seven wells in the eastern part: Beznau (Nagra 1984), Böttstein (Peters et al. 1986), Küsnacht (Rybach & Bodmer 1980), Riniken (Matter et al. 1987), Schafisheim (Matter et al. 1988a), Weggis (Schegg 1994), Weiach (Matter et al. 1988b) and one geothermal exploration well in the western part of the basin: Thônex (Jenny et al. 1995). Additional constraints on the thermal history come from fluid incusion data (Mullis 1987) and from clay mineralogical studies (Monnier 1982, Schegg & Leu 1996).

In this study we present five new coalification profiles from the Western Swiss Molasse Basin: Chapelle, Eclépens, Essertines, Savigny, and Treycovagnes (Fig. 1). Our purpose is to reconstruct the paleogeothermal regime in terms of the heat flow history together with estimates of the missing overburden. These results have important implications for the geodynamic evolution of the region.

Geological setting

The Tertiary North Alpine Foreland Basin is a peripheral foredeep which formed by flexural bending of the European lithosphere in response to crustal thickening in the Alpine orogen (Homewood et al. 1986; Pfiffner 1986; Allen et al. 1991). The so-called Molasse Basin is the younger, continental and shallow marine component of this foreland basin. It comprises two large coarsening and shallowing upward cycles spanning the Oligo-Miocene separated by the sub-Burdigalian unconformity (Matter et al. 1980). In Switzerland, the Molasse succession is divided into four lithostratigraphic groups (see Berger 1992 for details on the biostratigraphy), i) Lower Marine Molasse (UMM, Rupelian-Chattian); ii) Lower Freshwater Molasse (USM, Rupelian-?Burdigalian), iii) Upper Marine Molasse (OMM, Burdigalian-?Langhian), and iv) Upper Freshwater Molasse (OSM, Langhian-Serravalian).

In most places the sedimentary fill of the NAFB rests unconformably on truncated Mesozoic continental margin sediments. Within the foreland basin, the stratigraphic gap represented by the base Tertiary unconformity increases from internal to external positions (Herb 1988; Crampton & Allen 1995). The maximum gap (Oxfordian-Eocene) is reached over paleotopographic culminations such as the "Zurich High" (Büchi et al. 1965, Bachmann & Müller 1991). The Triassic-Early Cretaceous subsidence history of the Swiss Plateau was governed by lithospheric extension and thermal relaxation (Loup 1992a, b; Loup & Wildi 1994; cum biblio) related to the break-up of Pangaea (Ziegler 1987). A detailed summary of the basin evolution during the Mesozoic is given in Bachmann et al. (1987) and Bachmann & Müller (1991). Underlying the megasequence boundary defining the base of the foreland basin, Mesozoic carbonates, shales and clastic rocks are superimposed on a Hercynian basement complex with locally, deep Permo-Carboniferous grabens (Müller et al. 1984, Laubscher 1987, Diebold et al. 1991, Gorin et al. 1993).

The study area (Fig. 1), situated in the western part of the Molasse Basin, covers the region between the Lake of Neuchâtel in the north and the Lake of Geneva in the south. For a detailed introduction to the regional geology see Jordi (1955, 1990, 1993), Matter et al. (1980), Weidmann (1982), Berger (1985), Fasel (1986) and Gorin et al. (1993).

The Plateau Molasse of the study area is composed of subhorizontal USM and OMM deposits which are gently folded and locally affected by significant wrench fault zones (Fig. 1; Jordi 1990, Gorin et al. 1993). The Tertiary sediments onlap the Mesozoic floor and thin towards the external parts in the NW (Homewood et al. 1986). The Subalpine Molasse consists of a series of closely imbricated thrust slices adjacent to the Helvetic Zone and tectonically overlain, in part, by the Penninic nappes of the Prealps (Homewood et al. 1986). The Mesozoic sediments underlying the Molasse Basin have a thickness of about 2 km in the study area and are known essentially from well data (Cuarny: Althaus 1947; Eclépens: Vollmayr 1983; Essertines: Büchi et al. 1965). Additional information comes from published seismic sections (Jordi 1990, Gorin et al. 1993). The Mesozoic sequence comprises Triassic to Lower Cretaceous strata. Paleozoic sediments (Permian red-beds) have only been penetrated in the Treycovagnes well. A partially inverted Permo-Carboniferous trough has, however, been interpreted by Gorin et al. (1993) below the Subalpine Molasse.

Methods

Sampling

Cuttings from the wells Chapelle, Eclépens, Essertines, Savigny and Treycovagnes were sampled for the measurement of vitrinite reflectance. Both Tertiary and Mesozoic formations have been included in order to obtain top-to-bottom coalification profiles. Chapelle and Savigny, situated in the southern part of the study area, mainly penetrated Tertiary rocks; wells in the distal part of the Molasse Basin (Eclépens, Essertines, Treycovagnes) penetrated essentially Mesozoic sediments. In the Tertiary clastics, sampling was concentrated on macroscopic coaly particles which were picked by hand. Mesozoic samples comprise dark shales and marlstones with a relatively high content of dispersed organic matter (OM). In order to obtain a suitable sample size, cuttings were collected generally over a depth interval of 20–30 m. The indicated sample depth (represented by the sample number) is, therefore, an average value.

Vitrinite reflectance (VR) measurements

Dried cuttings were mounted in epoxy resin, then ground and polished with a sequence of diamond abrasives. Random vitrinite reflectance was determined in unpolarized light at a wavelengh of 546 nm and a measuring aperture size of 5 mm using a Leitz MPV Compact microscope with an immersion objective 50*/0.85. The measurements followed the procedure described by Stach et al. (1982). The results are expressed in terms of an arithmetic mean and a standard deviation of all measurements made on each sample. Data are also presented in the form of frequency histograms, divided into 0.05% reflectance steps.

Guidelines for the interpretation of VR results

Although it is considered by many scientists as the most universally applicable tool in assessing the thermal maturity of a sample, the vitrinite reflectance technique has several limitations. In the following we list a number of limitations which are relevant to this study and present our interpretation criteria:

Properly identified vitrinites: Identification of reliable vitrinite particles is perhaps the major problem for the operator. In coal samples, readings are made on wide monomaceralic bands (ulminite B / telocollinite, see Stach et al. 1982 for details). In sedimentary rocks other than coal, vitrinite macerals are present as either autochthonous or allochthonous grains (Robert 1985). The recognition of fresh (first-cycle) humodetrinite (vitrodetrinite for higher ranks) and reworked (second-cycle) and generally more mature material is the major problem for rank determination. Problems of diagnosis may also occur for the distinction between vitrodetrinite and inertodetrinite because of the frequent lack of morphological criteria in dispersed OM (Durand et al. 1986). At elevated maturities ($Rr > 0.8\%$ inertinite can be distinguished from vitrinite by the optical anisotropy of the latter (Stach et al. 1982). Our approach was to measure all the "vitrinite-like" particles in a sample with dispersed OM. Clearly identifiable autochthonous vitrinite particles are marked as reliable values already at the microscope. Autochthonous vitrodetrinites can be recognized by their elongate form, occasionally also by their telinite cell structure (Stach et al. 1982). Rounded particles should be suspected as being reworked. The measurements often result in multi-peak reflectance histograms. When no indication of bitumen impregnation or caving (see below) is present, the lowest peak is generally interpreted as the autochthonous population, but only when the maturity values of the reliable vitrinite particles are in accordance with such an interpretation. A similar approach has been taken by Nagra (1984) and Peters et al. (1986) for the Beznau and Böttstein wells respectively.

Solid bitumen: Apart from the variation of primary vitrinite populations, secondary macerals such as morphologically similar solid bitumen can cause problems in identifying an autochthonous vitrinite population. Solid bitumen can, however, be identified relatively easily when it occurs as a pore filling. Solid bitumen reflectance values (Rb) were transformed into Rr values according to the formula of Jacob (1989): $Rr = 0.618*Rb + 0.4$.

Number of readings: The number of reflectance measurements (n) required for an adequate characterization of the mean random VR is a major concern in the petrographic analysis of dispersed OM. Barker & Pawlewicz (1992) stated that reflectance values calculated on less than 20 readings of vitrinite are potentially unreliable. However, according to the same authors, it is still a better strategy to concentrate on selecting a few high-quality characteristic vitrinite grains for analysis rather than seeking a quantity of inconsistent vitrinite grains in order to make results statistically reliable. We differentiated between reliable ($n > 20$) values and uncertain ($n < 20$) values. But the interpretation of a reliable value is not only based on the number of readings, but also on petrographic arguments (see above).

Quality of the polished surface: Inadequate polishing results in a considerable decrease of mean reflectance (Buiskool Toxopeus 1983). Samples showing bad polishing were excluded from this study. Results from inadequately polished sections were marked as questionable values (see legend in Fig. 2).

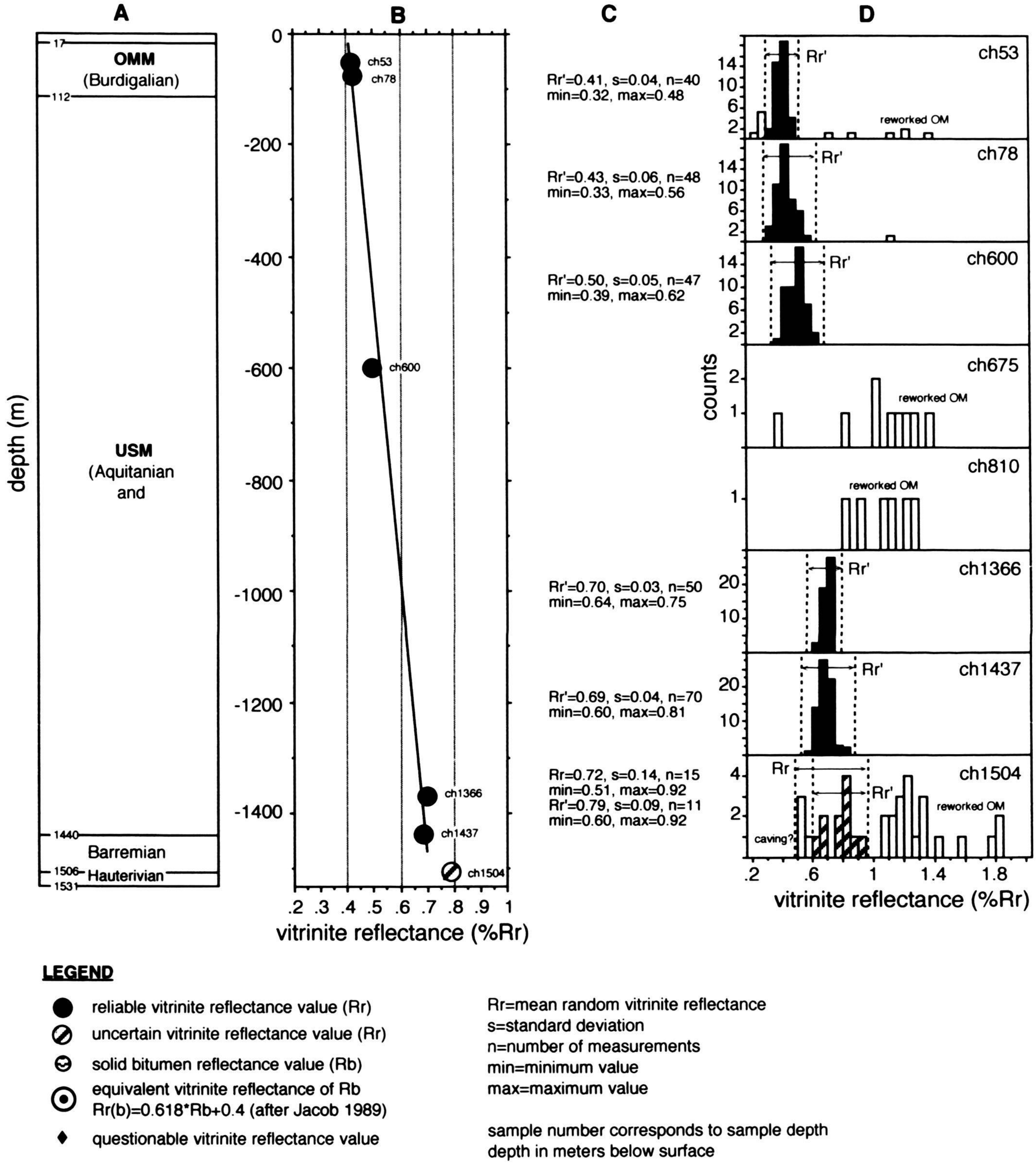

Fig. 2. Composite plot for the Chapelle well showing (A) the well stratigraphy, (B) mean vitrinite reflectance versus depth trend, (C) statistics of interpreted first-cycle vitrinite populations and (D) total reflectance histograms.

Caving: The problems associated with the identification of vitrinites in cuttings recovered from boreholes and which are contaminated by caving during drilling have been previously documented by Dow (1977). It may be difficult to detect in a single sample, but it can become quite obvious in the context of a coalification profile (e.g. low reflectance outlier).

Natural variation of VR: Buiskool Toxopeus (1983) has shown the existence of different populations of vitrinite in coals, even in the absence of reworked material. Similar observations have been made by Fang & Jianyu (1992) who stated that the initial hydrogen content of telocollinite may vary from one coal to another. For oilprone source rocks, within the oil window, vitrinite staining can produce "fluorescent" vitrinite with anomalously low reflectance.

Another interpretation criterion was the relationship of a single value with the general coalification trend. VR peaks which are clearly outside the general trend were interpreted as suspicous values. It is recognized that there is an element of circularity in this argument tending to confirm a pre-determined "trend".

Thermal modelling

The quantitative modelling of a sedimentary basin using a heat flow algorithm allows the determination of an accurate temperature history by incorporating geological factors that control temperatures and calibrating against measured thermal indicators. In this study, a one-dimensional burial history model is used to provide a framework for simulating the thermal history. The modelling was carried out using the BasinMod®1-D program (Platte River Associates 1995).

The following processes and properties are taken into account: i) subsidence history, including erosional breaks; ii) thermal boundary conditions (heat flow history at the base, variation of the sediment/water interface temperatures at the top), and iii) petrophysical properties of each lithology (thermal conductivity, heat capacity, compaction parameters). Starting with a set of primary input values, parameters which have the most direct effect on the thermal history (heat flow at the base, amount of missing section) are modified until a good fit between measured and calculated vitrinite reflectance is obtained. The relative importance of changing geodynamic scenarios is adressed during the sensitivity analysis.

Vitrinite reflectance profiles

Chapelle

A description of the lithologies and the stratigraphy of the well is given in Lemcke (1959). Two samples from the OMM, five samples from the USM and one sample from the Barremian were analysed. Apart from two USM samples with reworked vitrinite and an uncertain value at the bottom of the well, a well defined and reliable coalification profile is observed (Fig. 2). VR values range between 0.41 %Rr at the top of the well and 0.79 %Rr at the bottom. No significant coalification jump is observed at the base Tertiary unconformity. A linear regression fits the coalification trend best. The coalification gradient is 0.21 %Rr/km (0.17 log%Rr/km). The top of the oil window (0.6 %Rr) is at about 950 m.

Eclépens

A summary of the uniquely Mesozoic well stratigraphy is given by Vollmayr (1983). Three samples from the Upper Jurassic, one sample from the Middle Jurassic and four samples from the Lower Jurassic were analysed (Fig. 3). Only one reliable VR value could be measured in this well (ecl 2002). The rest of the reflectance histograms show complex patterns and the inferred VR values are uncertain. Values range between 0.49 %Rr in the Upper Jurassic to 0.76 %Rr in the Lower Jurassic. In two samples (ecl 1220, ecl 1908) solid bitumen reflectance could be measured. The equivalent VR values of these samples are slightly higher than those from the interpreted autochthonous vitrodetrinite population. The coalification gradient is 0.18 %Rr/km (0.13 log%Rr/km). The top of the oil window is situated at a depth of about 1300 m.

Essertines

A description of the lithologies and the stratigraphy of this well is given by Büchi et al. (1965). Two samples from the USM, two samples from the Lower Cretaceous, two samples from the Upper Jurassic, one from the Middle Jurassic and three samples from the Lower Jurassic were analysed. Only one reliable value (ess 315) at the top of the well was measured (Fig. 4). The thermal maturity of the sediments varies between 0.49 %Rr in a USM sample and 0.89 %Rr in sample from the Lower Jurassic. The coalification gradient is 0.19 %Rr/km (0.13 log%Rr/km). The top of the oil window is at a depth of about 900 m.

Savigny

The initial description of the lithologies and the well stratigraphy has been presented by Lemcke (1963) and a revised interpretation (used in this study) is given in Weidmann (1988, his Fig. 3). 16 samples from the USM and one sample from the Lower Cretaceous were analysed. The sedimentary succession is characterized by the repetition of four USM thrust slices overlying an autochthonous USM series (Fig. 5). A number of samples are characterized by reworked OM and the autochthonous vitrodetrinite population is missing. In the topmost thrust sheet two reliable value from nearby shallow boreholes (Schegg 1992b) are included in the coalification profile. As the analysis of sample sav 540 yielded a questionable VR value, no coalification trend can be defined for the upper part of the well. The Aquitanian thrust sheet between 600 and 900 m suggests a negative coalification trend. The thermal maturity decreases from 0.67 %Rr at 695 m to 0.63 %Rr at 847 m depth.

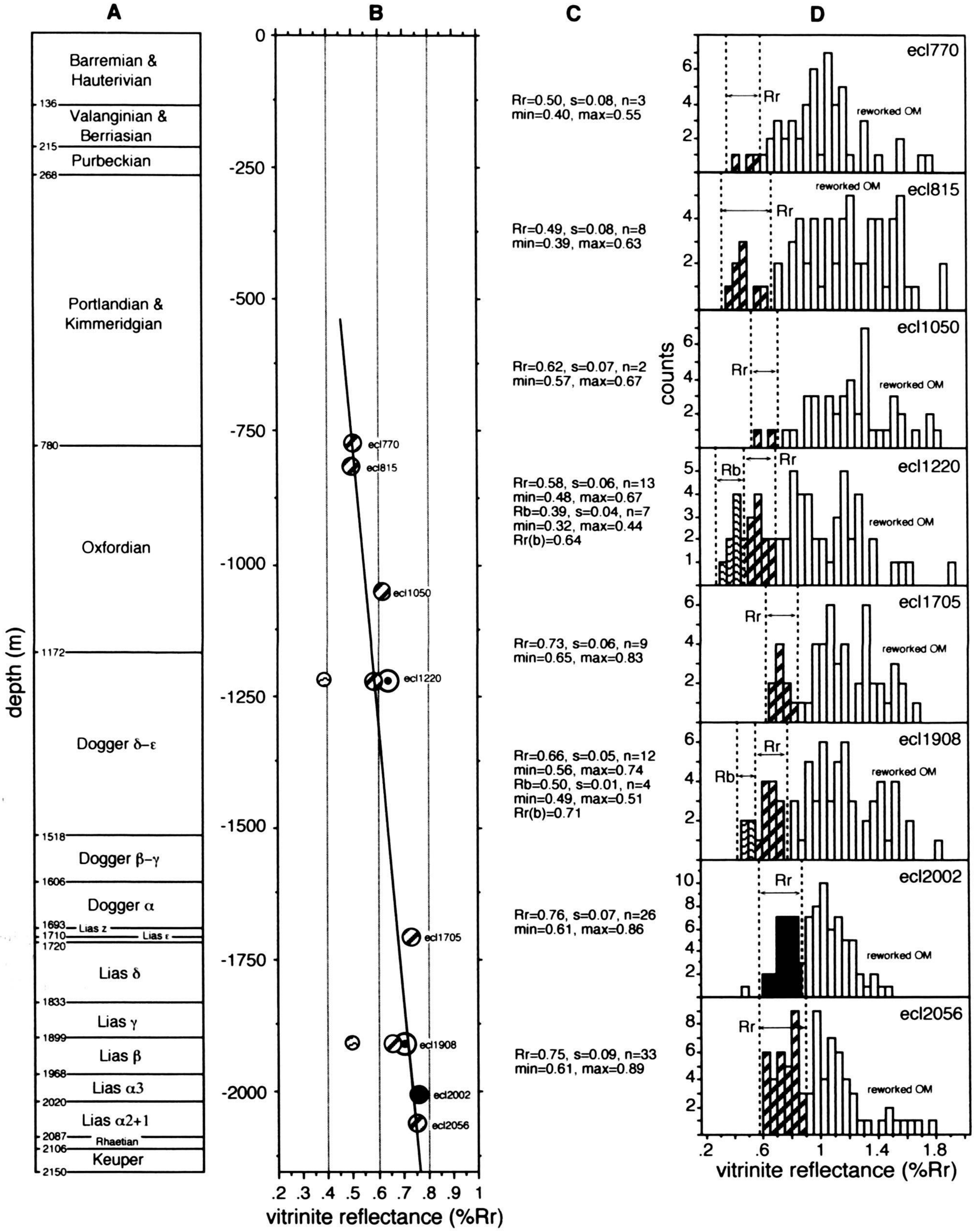

Fig. 3. Composite plot for the Eclépens well showing (A) the well stratigraphy, (B) mean vitrinite reflectance versus depth trend, (C) statistics of interpreted first-cycle vitrinite populations and (D) total reflectance histrograms. For legend see Fig. 2.

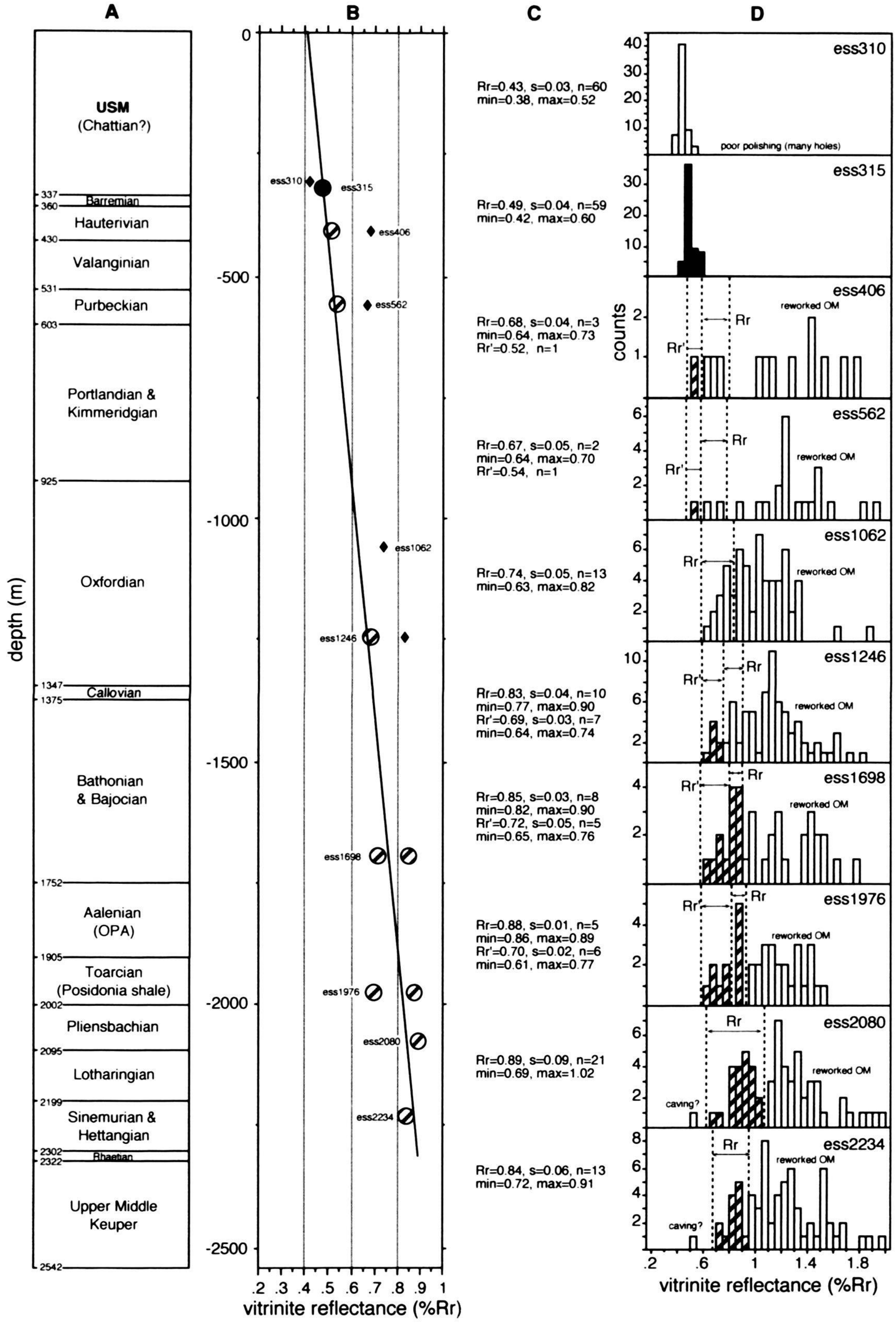

Fig. 4. Composite plot for the Essertines well showing (A) the well stratigraphy, (B) mean vitrinite reflectance versus depth trend, (C) statistics of interpreted first-cycle vitrinite populations and (D) total reflectance histograms. For legend see Fig. 2.

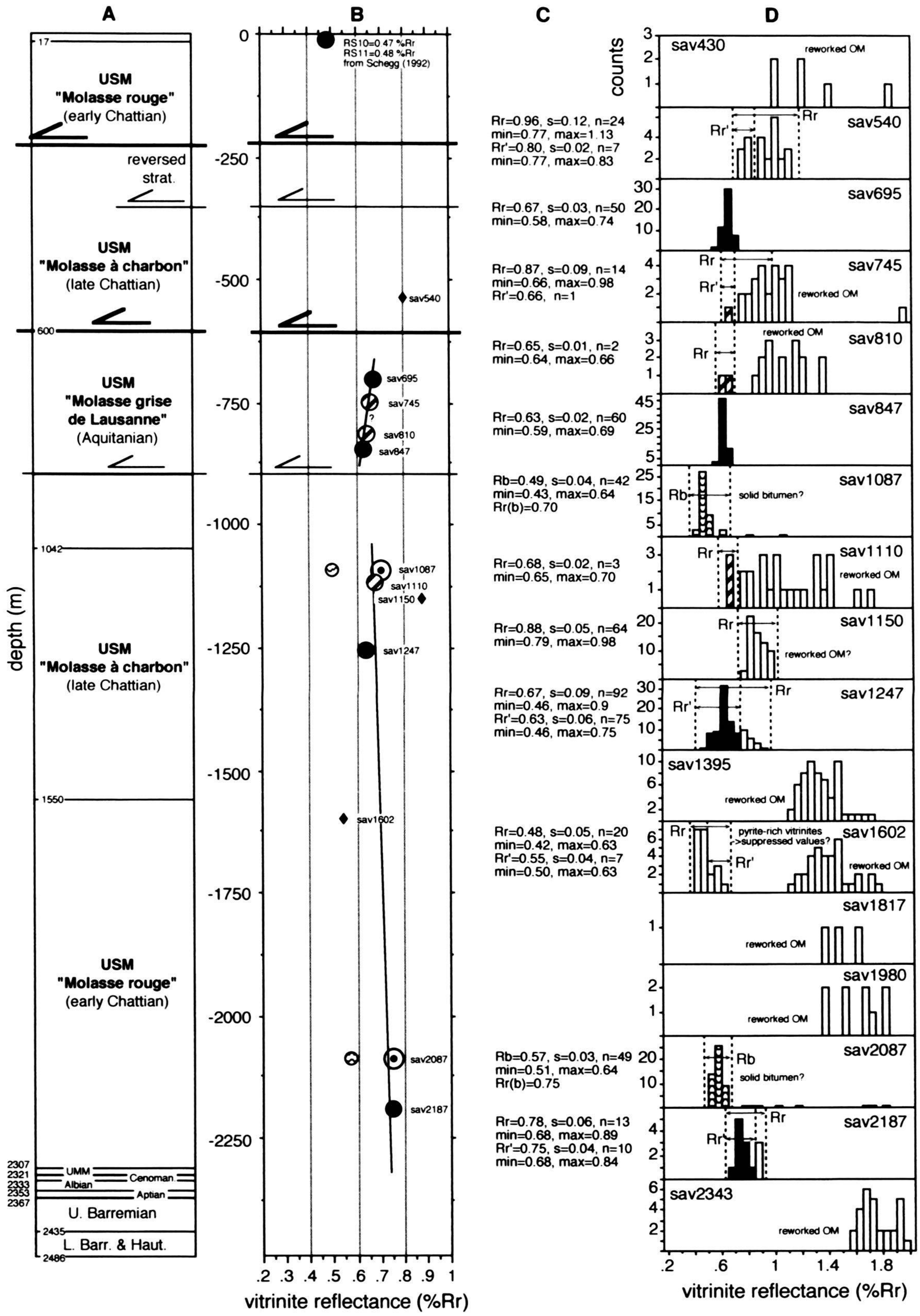

Fig. 5. Composite plot for the Savigny well showing (A) the well stratigraphy, (B) mean vitrinite reflectance versus depth trend, (C) statistics of interpreted first-cycle vitrinite populations and (D) total reflectance histograms. For legend see Fig. 2. Stratigraphic and tectonic interpretation of the well according to Weidmann (1988).

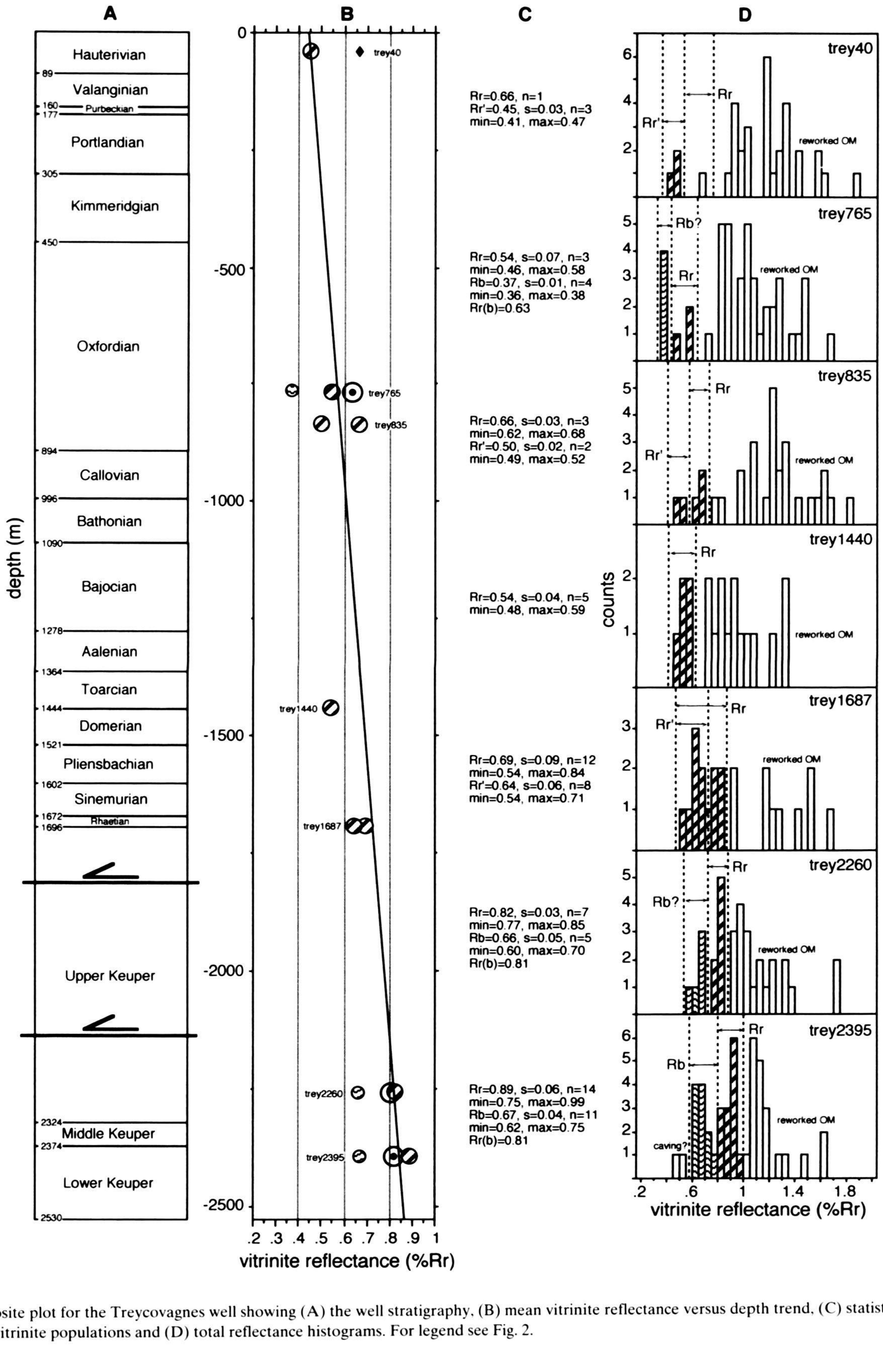

Fig. 6. Composite plot for the Treycovagnes well showing (A) the well stratigraphy, (B) mean vitrinite reflectance versus depth trend, (C) statistics of interpreted first-cycle vitrinite populations and (D) total reflectance histograms. For legend see Fig. 2.

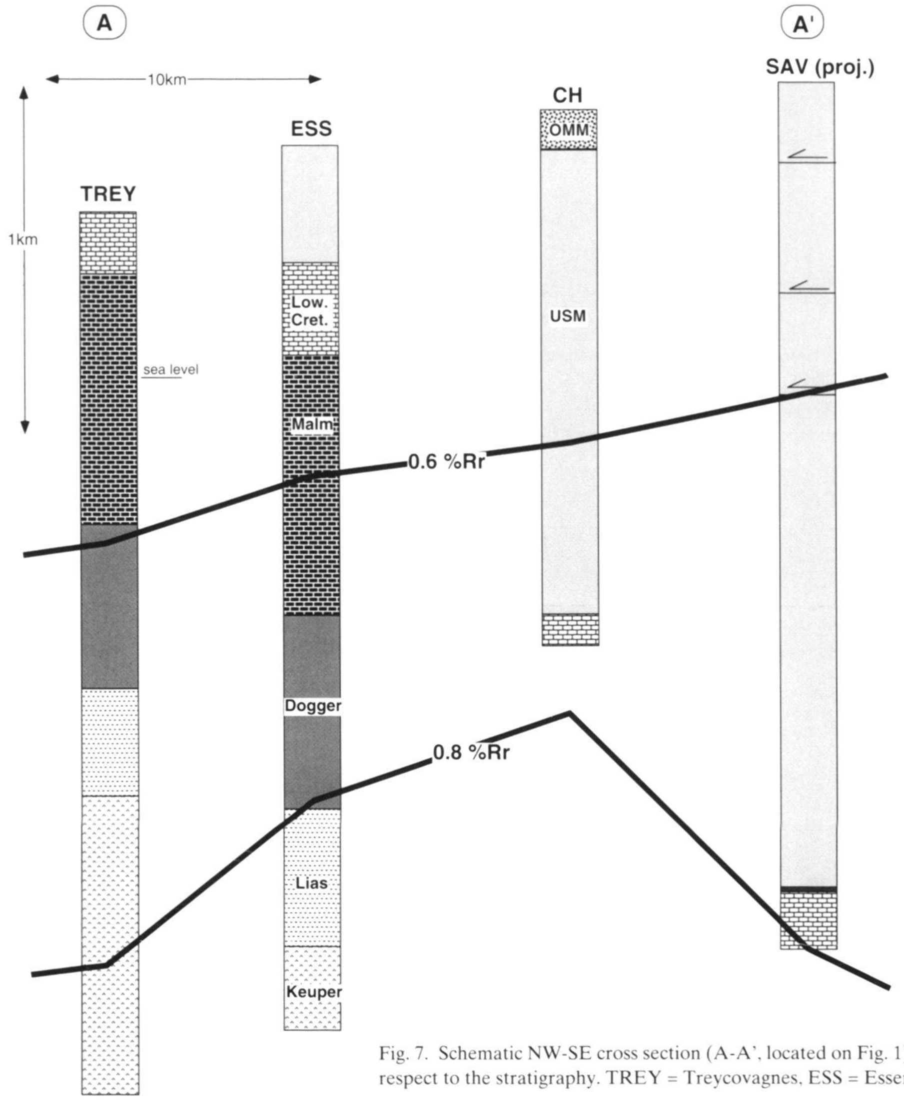

Fig. 7. Schematic NW-SE cross section (A-A', located on Fig. 1) with isoreflectance lines which are discordant with respect to the stratigraphy. TREY = Treycovagnes, ESS = Essertines, CH = Chapelle, SAV = Savigny.

VR values in the autochthonous Molasse indicate a linear increase of thermal maturity (from 0.63 %Rr at 1247 m to 0.75 %Rr at 2187 m). Taking only the autochthonous part of the profile, a coalification gradient of 0.07 %Rr/km (0.05 log%Rr/km) is calculated. The top of the oil window is situated at about 700 m.

Treycovagnes

One sample from the Lower Cretaceous, two from the Upper Jurassic, one from the Lower Jurassic and three from the Keuper were analysed. Again VR results are characterized by complex reflectance histograms (occurrence of reworked OM and solid bitumen). An overall linear increase in thermal maturity is suggested by our results (Fig. 6). VR values vary between 0.45 %Rr in a sample from the Lower Cretaceous and 0.89 %Rr in a sample from the Lower Keuper. The coalification gradient is 0.17 %Rr/km (0.12 log%Rr/km). The top of the oil window is at a depth of about 950 m.

Isoreflectance profile

A schematic NW-SE cross-section (located on Fig. 1) shows the lateral variation of VR values across the basin (Fig. 7). The top of the oil window (0.6 %Rr-isoline) is clearly discordant with respect to the present-day stratigraphy. Whereas the oil window in the Treycovagnes well is attained in the upper part of the Middle Jurassic, the same matury level in the Chapelle well can already be observed in the USM. The 0.6 %Rr-isoline is subparalell to the present-day topography. The sudden deepening of the 0.8 %Rr-isoline from Chapelle to Savigny illustrates the already observed important decrease in the coalification gradients between these two wells. The level of thermal maturity for any given stratigraphic interval increases towards the Subalpine Molasse.

Thermal modelling

Calibration data

Three different types of calibration data (porosity, present-day temperature and vitrinite reflectance) were used to constrain the models.

Apart from its role as an indicator of the state of compaction, porosity is an important factor controlling the thermal properties (e.g. thermal conductivity) of sediments. No published porosity values for the studied wells were available. For this reason averaged porosity data from the eastern part of the basin (Kälin et al. 1992, Voborny et al. 1993) were used. The fluid flow/compaction module of BasinMod was utilized to calculate porosity as a function of depth and pressure (see Platte River Associates 1995 for more details). Measured temperatures are only sensitive to thermal perturbations in the relatively recent geological past, and can therefore only be used to calibrate the modern heat flow values. The corrected bottom hole temperature (BHT) data of Vollmayr (1983) formed the basis of the heat flow derivation (heat flow = geothermal gradient * thermal conductivity). Vitrinite reflectance is regarded as one of the most reliable thermal indicators for the calibration of paleo-heat flow history (e.g. Bustin et al. 1985). Modelled thermal maturity was calculated by Platte Rivers's BasinMod® program using kinetically-based equations to calculate maturation with time and temperature, as developed by Sweeney & Burnham (1990).

Initial model

One of the most important unknowns for the reconstruction of the burial history is the estimation of the amounts of erosion at base-Tertiary and base-Quaternary unconformities. A missing section of 2000 m for the post-Molasse erosion is assumed (see Schegg & Leu in press for a discussion) composed of USM, OMM and OSM deposits for the first simulation runs. In accordance with the results of Crampton & Allen (1995) and regional observations of preserved Cretaceous thicknesses in the western part of the Molasse Basin (Schegg & Leu in press), a thickness of 400 m is taken to be a maximum value for the missing Cretaceous strata at the base-Tertiary unconformity. Modelling results (Crampton & Allen 1995) and regional observations suggest that the depth of erosion at this unconformity is relatively constant beneath the Molasse Basin.

In the initial model of the Savigny well (Subalpine Molasse), allochthonous formations have been simulated by expansion of the formation thickness during the time of thrusting. According to Burkhard (1990), the precise time of thrusting and folding within the Subalpine Molasse is difficult to determine. The most external structures appear to be formed simultaneously with folding of the Jura (Serravalian/Tortonian). We assumed that thrusting may have started at 15 Ma. Our approach, however, has its limits, as allochthonous units, with a geological and thermal history different from the autochthonous units are piled up on top of each other. Such processes cannot be handled properly by the programme. For modelling purposes, only the autochthonous part of the Savigny well is used for calibration.

Typical heat flow values for peripheral foreland basins range from 60 to 80 mW/m^2 (Allen & Allen 1990). The heat flow history for modelling was kept as simple as possible as no firm geological arguments currently exist for any major deviations from normal values during the foreland basin evolution (Beaumont et al. 1985). Therefore, the heat flow was held constant (70 mW/m^2) during the Tertiary, and was increased linearly from 5 Ma to the high present-day values (80–100 mW/m^2 in the western Molasse Basin, Bodmer & Rybach 1984).

Loup (1992a, b) analysed the tectonic subsidence of the northern Helvetic realm during the Mesozoic. The subsidence history is characterized by a long term (> 150 My) decelerating phase which started in Middle to Late Triassic times. Shorter term phases (50–60 My) are superimposed on this general trend. According to Loup (ibid.), a 2-layer stretching model (Hellinger & Sclater 1983) fits the tectonic subsidence curves best. The stretching factors in the Plateau vary between 1.03 and 1.2 for the crust and 1 and 1.35 for the subcrustal lithosphere. The mainly thermally controlled subsidence, low subsidence rates and stretching factors suggest an intracratonic rim basin rather than a classic passive margin evolution for the area of the NAFB. We used Loup's (ibid.) range of stretching factor for the Essertines well (1.2 crustal, 1.35 subcrustal) to calculate the additional heat supply due to lithospheric stretching (see Hellinger & Sclater 1983 for details). The resulting heat flow anomaly due to extension is rather modest (maximum value of 9 mW/m^2 during Late Triassic times). We added this calculated exponentially-decreasing anomaly to the assumed constant Tertiary heat flow level in order to define the Mesozoic heat flow history.

The variation of the sediment-water and sediment-air interface temperatures during the Tertiary is based on studies by Hochuli (1978) and Bodmer and Rybach (1984). Paleosurface temperatures during the Mesozoic were chosen on the basis of the global time/latitude/temperature relation of Wygrala (1989).

Thermal modelling results

The resulting final models for the burial and thermal history of the five studied wells are in good aggreement with the available calibration data. Figure 8 shows the input data and results for the Chapelle and Essertines wells. The key factors for the calibration were the level of the Tertiary heat flow and the amount of post-Molasse erosion. Changes of the heat flow during the Mesozoic have hardly any effect on the calculated present-day VR values. The calibrated values for the key pa-

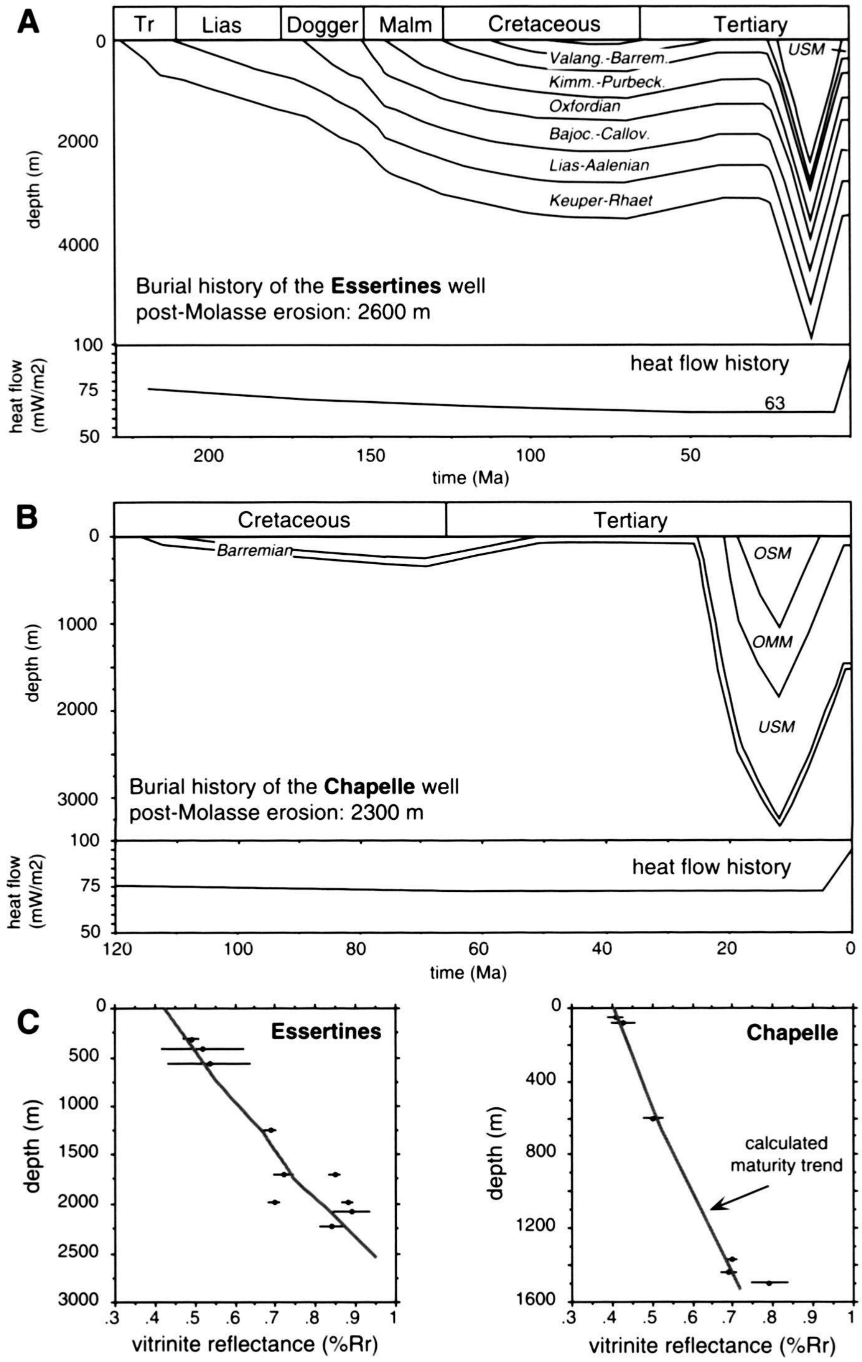

Fig. 8. Summary of basin modelling input data and results. A: Burial and heat flow history of the Essertines well. B: Burial and heat flow history of the Chapelle well. C: Comparison between measured VR values (black circles) and modelled VR trend (grey line).

rameters are summarized in Table 1. The Tertiary heat flow level for the 4 wells situated in the Plateau Molasse varies only a little (60–72 mW/m^2), but it is clearly lower in the Subalpine Molasse (Savigny well: 50 mW/m^2). In all wells the modest Tertiary heat flow had to be increased to the present-day high values (82–95 mW/m^2) in order to satisfy the measured borehole temperatures. We calculated also the average geothermal gradients at the time of maximum burial (Tab. 1). In the Plateau Molasse "normal" paleogeothermal gradients (29–32 °C/km) are obtained. In the Subalpine Molasse, a low gradient of 20 °C/km was computed. The calibrated post-Molasse erosion is moderate in the Plateau Molasse (2000–2600 m), compared with a much higher value in the Savigny well (4300 m).

Discussion of results

Vitrinite reflectance data

VR data are of quite uneven quality. The most reliable values were observed in the Tertiary samples characterized by coaly phytoclasts. The results from the dispersed OM in Mesozoic samples are generally more complex. The interpretation of the multi-peak reflectance histograms (due to reworked OM, caving, solid bitumen) is not always straightforward. This problem is well known among organic petrographers (see Robert 1985 and Mukhopadhyay 1994, and references therein). Results from this study show that a simple mean VR value with a standard deviation is often not sufficient for the correct appraisal of thermal maturity. It is helpful to base the interpretation on the evolution of reflectance histograms with depth. In other words, a single sample may often only be interpreted in the context of a top-to-bottom profile. Due to these uncertainties calculated coalification gradients should also be treated with care. This is especially the case when only few and/or unreliable data are used or when the depth range for the determination of the gradient is only a couple of hundred meters.

Despite the aforementioned limitations, results from the studied wells show a good internal consistency. Most wells (with the exception of the Savigny well) are characterized by a linear increase in thermal maturity with depth. No well defined coalification jump was observed at the base Tertiary unconformity in the Essertines well. However, given the poor quality of Cretaceous VR values in this well, this interpretation should be treated with care. The Mesozoic and Tertiary coalification gradients of wells situated in the Plateau Molasse vary only little (0.17–0.21 %Rr/km, Tab. 1). These observations suggest that both gradients have been attained during the same maturation phase.

The coalification profile of the Savigny well (Fig. 5) may be interpreted in different ways. The coalification profile could be fitted with a top-to-bottom linear trend implying a post-thrust maturation. Our description (see above) treated each tectonic unit separately, suggesting a pre- to syn-thrust maturation. Given the moderate quality of the coalification profile, it is difficult to decide between these two hypothesis. However, observations from the Subalpine Molasse of Central Switzerland (Schegg 1994) and Germany (see review in Sachsenhofer 1992) indicate that coalification jumps at the base, within and at the top of allochthonous Molasse units are a common feature. A pre- to synthrust maturation is therefore favoured in this study. The negative coalification trend in the lower hanging wall of the Savigny well (Fig. 5) could result from steady-state fluid flow where multiple aquifers are involved (Duddy et al. 1994, their Fig. 7). Potential fluid conduits might have been the thrust planes between these tectonic units.

Isoreflectance lines climb stratigraphically from external to internal (i.e. towards the Alpine front) basin positions, the thermal maturity level of any given stratigraphic interval increasing in the same direction. Results from this study strongly suggest that the main maturation phase is of Tertiary age. The iso-reflectance lines represent probably the "frozen" and tilted (during the Miocene-Pliocene uplift) maturity level at the end of deposition of Molasse sediments (about 12 Ma).

Tab. 1. Summary of coalification gradients and key factors for the thermal modelling: coalification gradients *(%Rr/km, log%Rr/km)*, Tertiary heat flow level *(Tert. HF)*, calculated average geothermal gradient during maximum burial *(°C/km (T_{max}))* and calibrated post-Molasse erosion amounts *(erosion)*.

well	*%Rr/km*	*log%Rr/km*	Tert. HF	°C/km (Tmax)	erosion
CHA	0.21	0.17	72	32	2300
ECL	0.18	0.13	65	30	2000
ESS	0.19	0.13	63	29	2600
SAV	0.07*	0.05*	50	20	4300
TREY	0.17	0.12	60	30	2600
*	only autochthonous part of the well				

Comparison of VR data with previous studies

The comparison of our results with published data from Switzerland (see references in introduction) and Germany (Teichmüller & Teichmüller 1975, 1986, Jacob & Kuckelkorn 1977, Kuckelkorn & Jacob 1977, Jacob et al. 1982) reveals the following:

i) *Thermal maturity of Tertiary sediments:* The levels of maturation in the Chapelle and Savigny (0.41–0.75 %Rr) wells are comparable to those from the Thônex (0.53–0.72 %Rr) and Weggis (0.65–0.82 %Rr) wells. A similar range of values has also been observed from surface samples in the western Swiss Molasse Basin (Schegg 1992b). In the Subalpine Molasse, a distinct increase inVR in surface samples towards the Alps is observed. Our results confirm this trend (e.g. Fig. 7). However, for the same depth level our results show much higher thermal maturities than data from the German Molasse Basin. In the Miesbach 1 well, for example, VR does not exceed 0.6 %Rr at 5738 m (Jacob & Kuckelkorn 1977), whereas the same level of maturity is already reached at about 900–1000 m in western Switzerland.

ii) *Tertiary coalification gradients:* The gradients in the western Plateau Molasse are consistent (0.21 %Rr/km Chapelle, 0.18 %Rr/km Thônex), but clearly higher than those in eastern Switzerland (0.08 %Rr/km Küsnacht, Rybach & Bodmer 1980) or in the German Molasse Basin (0.06–0.09 %Rr/km, see recent review by Sachsenhofer 1992). In the Subalpine Molasse gradients seem to be generally lower (0.07 and 0.14 %Rr/km in Savigny and Weggis respectively) than in the Plateau Molasse. A similar trend, but with much lower values (0.04 %Rr, Sachsenhofer 1992), can be observed in the German foredeep.

iii) *Thermal maturity of Mesozoic sediments:* VR values of Mesozoic sediments in the study area are generally higher than those measured in eastern Switzerland. In Upper Jurassic rocks for example, average VR values for the wells in

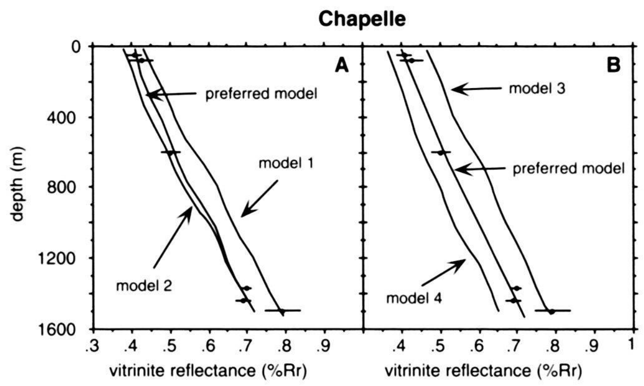

Fig. 9. Sensitivity analysis for the Chapelle well. Our preferred model assumes a Tertiary heat flow level of 72 mW/m^2 and a post-Molasse erosion of 2300 m. (A) Taking a higher Tertiary heat flow level (79 mW/m^2) results in a shift of the calculated maturity trend and a higher coalification gradient (model 1). The shift to higher values can be compensated by a lower post-Molasse erosion (1900 m: model 2). But the resulting maturity trend is still characterized by a coalification gradient which is higher than the observed. (B) Higher (2700 m: model 3) or lower (1900 m: model 4) erosion with respect to the preferred model shifts the maturity trend parallel to best-fit trend.

our study area range between 0.54 %Rr (Eclépens) and 0.69 %Rr (Essertines). In northeastern Switzerland, average maturity levels of 0.39–0.46 %Rr are observed for the same stratigraphic interval in the Nagra wells Riniken, Schafisheim and Weiach (Matter et al. 1987, 1988a, 1988b). Similar observations can be made for other Mesozoic formations.

iv) *Mesozoic coalification gradients:* The increase of VR with depth in the studied area (0.17–0.19 %Rr/km) evidences a normal paleogeothermal regime (Robert 1985). The wide range and the generally high values of coalification gradients (0.1–1.0 %Rr/km) in the Nagra wells of eastern Switzerland may be interpreted either as a statistical problem (i.e. depth ranges of only 200–300 m for wells with very high gradients, e.g. Böttstein and Beznau) or as the result of localized fault controlled thermal anomalies (Todorov et al. 1993, Schaltegger et al. 1995).

In our study area the level of thermal maturity and the coalification gradients of Mesozoic and Tertiary sediments seem to be mainly controlled by the deep Tertiary burial and subsequent uplift/erosion and by a normal paleogeothermal regime. The geothermal gradients in the German Molasse Basin during the Tertiary are much lower and post-Molasse erosion plays a minor role. Mesozoic coalification gradients are generally higher than Tertiary gradients in eastern Switzerland. However, all the data on Mesozoic gradients come from the distal part of the Molasse basin where no control on Tertiary rank gradient is available (the Tertiary section is too thin or absent). The observations may suggest that the thermal maturity and coalification gradients of Mesozoic sediments in this part of the basin have not been strongly overprinted by a Tertiary maturation phase. Mesozoic coalification gradients could still reflect a thermal event during the Mesozoic. K-Ar dating of clay minerals from Stephanian sediments in the Weiach well suggest an important Early Jurassic (183 Ma) hydrothermal activity with fluid temperatures of probably up to 210 °C (Schaltegger et al. 1995). Alternatively, the observed VR pattern can be modelled by an enhanced heat supply between Eocene and Miocene related to the Rhine Graben rifting (Todorov et al. 1993).

Discussion of the thermal modelling results

We are aware that the proposed models (i.e. the thermal and burial history) are not unique solutions, and that other geological scenarios could also fit the calibration data. Consequently, we have tested the likely outcomes of alternative scenarios.

It might be argued that the effects attributed to erosion could be explained instead by a higher heat flow. Our model runs show that as expected, the calculated coalification profile is very sensitive to heat flow value at the time of maximum burial. Higher Tertiary heat flow values result in higher coalification gradients. A relative change of 10% from the best-fit heat flow value is sufficient for a significant misfit of observed and calculated VR values (Fig. 9A, model 1), even when a higher heat flow is "compensated" by a lower post-Molasse erosion (Fig. 9A, model 2). On the other hand, changes of the heat flow history prior to the time of maximum burial are generally not relevant to the present-day heat flow values. Increase or decrease of the Tertiary erosion amount results in a shift of the maturity trend (Fig. 9B, model 3 and 4 respectively).

The calibration data of the Eclépens and Treycovagnes wells could also be fitted with a maximum burial during the Late Cretaceous, requiring about 2 km of erosion of Cretaceous rocks at the sub-Tertiary unconformity. There is, however, no viable geological concept which could explain the deposition and subsequent erosion of such an amount of Upper Cretaceous sediments (see discussions in Crampton & Allen 1995 and Schegg & Leu in press). Moreover, the internal consistency of isoreflectance lines in the study area and the 2100 m of erosion in the Chapelle well, which is clearly of Tertiary age, strongly suggest that this hypothesis can be ruled out.

Our calibrated erosion amounts are in line with results by Laubscher (1974), Lemcke (1974), Monnier (1982) and Brink et al. (1992) for the study area. A similar value (2 km) was obtained further to the west in the Thônex well (Jenny et al. 1995, Schegg & Leu 1996).

The inferred Tertiary paleogeothermal regime (29–32 °C/km, 60–72 mW/m^2) for the Plateau Molasse is in agreement with "typical" values quoted for foreland basins (60 mW/m^2: Deming & Chapman 1989, 70 mW/m^2 Allen & Allen: 1990). The modelled heat flow value in the Thônex well is only slightly lower (58 mW/m^2, Schegg & Leu 1996).

Implications for the thermal and geodynamic evolution of the NAFB

The NAFB is regarded as a typical cold foreland basin with very low coalification gradients and a low level of thermal maturity (e.g. Teichmüller & Teichmüller 1986, Sachsenhofer 1992). According to Cermak & Hurtig (1979), present heat flow values in the German Molasse Basin range between 35 and 80 mW/m^2. The present geothermal regime of the Swiss Molasse basin shows, however, a much greater variability of heat flow values (60–150 mW/m^2, Bodmer & Rybach 1984) and a generally warmer geothermal regime. In addition, the modelled paleoheat flow level during the Tertiary is significantly higher in our study area (50–70 mW/m^2) than the estimated values for the German Molasse Basin (30–50 mW/m^2, Sachsenhofer 1992). This heat flow trend correlates with a change in the effective elastic thickness (Te) from west (c. 25 km in western Switzerland) to east (c. 50 km in the German sector) proposed by Karner & Watts (1983) based on forward modelling of the Bouguer gravity anomaly. According to results of Macario et al. (1995), Te for the arcuate western portion of the Alps (Te ≈ 31 km, range 30–39 km) does not differ significantly from estimates obtained from the more linear eastern portion (Te ≈ 35 km, range 33–40 km). They determined Te from gravity and topography using the coherence method. However, estimations of Te using the present-day basement configuration (e.g. the flexural profile of the basement) lends additional support for the results of Karner & Watts (1983). According to Gutscher (1995), longer flexural wavelengths in the east indicate increasing lithospheric rigidity and elastic thickness from west (Te ≈ 23 km) to east (Te ≈ 53 km). In the eastern German Molasse Basin, Jin (1995) obtained the closest match with the basement shape by choosing an elastic thickness of 48 km.

Other fundamental differences between the German and the Swiss Molasse Basin concern the style of deformation and the amount of shortening. The German part is predominantly governed by an extensional regime, resulting in the development of synthetic and antithetic normal faults, running mainly parallel to the basin axis (Brink et al. 1992). Bachmann & Müller (1992) associated this fault pattern to bending stresses of the European lithosphere (sensu Bradley & Kidd 1991). The Swiss part of the Molasse basin is dominated by compressional deformation styles, such as folds and reverse faults (Brink et al. 1992). Signer & Gorin (1995) postulated that deformation of the Jura Mountains is more likely to have originated from basement shortening than from large-scale translation across the foreland basin of the Mesozoic-Cenozoic cover over the Triassic evaporites. This view is supported by Jouanne et al. (1995) and Pfiffner & Erard (in press) who suggest that the basement underlying the Jura mountains and the western Molasse Basin was also involved in the post-depositional shortening.

According to Watts et al. (1995), the flexural rigidity of the lithosphere is a critical factor in determining the style of lithospheric shortening: high flexural rigidities promote the initiation and development of thin-skinned fold-and thrust belts above a basal décollement: low rigidities promote thick-skinned zones of basement shortening. Observations in the Swiss part of the Molasse Basin suggest indeed that basement-involved foreland deformation and modest shortening amounts (when compared to the German Molasse basin) are related with a low flexural rigidity.

All these elements indicate that there might be a link between the paleogeothermal regime, the basin geometry and dynamics, and the deformation style in the NAFB. However, the physical meaning of one of the key factors in this respect, Te, is still difficult to assess (see review in Burov & Diament 1995). Karner & Watts (1983) suggested that there was a systematic increase of the flexural rigidity of the lithosphere with increasing thermal age at the time of loading. McNutt et al. (1988) compiled elastic thicknesses for a variety of continental environments and demonstrated a wide range of values (5–105 km). The great variability of Te indicates very different thermal structures and cannot be explained solely on the basis of thermal age (Sahagian & Holland 1993). According to these authors, the thermal structure and elastic thickness of the lithosphere are controlled by lithospheric thickening and thinning events, as well as by subsequent thermal reequilibration over time. Kusznir & Karner (1985) and Zoetemeijer et al. (1990) stressed more the temperature dependent rheology of the lithosphere. The decrease in elastic thickness may often reflect the weakening effect of elevated temperature (i.e. high heat flow) on the mechanical properties ("strength envelope") of the lithosphere. Burov & Diament (1995) proposed that the strength (i.e. effective elastic thickness) of the continental lithosphere is controlled by its thermal structure in conjunction with two other equally important complementary mechanisms: i) the strength reduction by crust – mantle decoupling and ii) by the bending stresses (related directly to the plate curvature) that result form flexure caused by the presence of the surface and subsurface loads. According to these authors, bending stresses created by major mountain belts are large enough to cause inelastic deformation (ductile flow) in the underlying plate, which in turn, leads to a 30 to 80% decrease of Te beneath such belts and less beneath the adjacent regions.

The basement of the NAFB underwent extensive deformation and metamorphism, accompanied by plutonic and volcanic activity during the Variscan orogeny, and has not changed significantly since then in terms of material components and structure (Thury et al. 1994). To our knowledge, there is no major geographical variation in the age of the lithosphere between the eastern and western part of the NAFB which could explain the observed pattern in flexural rigidity.

The modest extension (maximum stretching factor of 1.2 for the crust and 1.35 for the subcrustal lithosphere) of the European plate below the future NAFB during the Mesozoic (Loup 1992a, b) could not desequilibrate the lithosphere thermally, especially when considering that the main subsidence phases in the western NAFB took place during the Triassic or

Early Jurassic. However, it is important to note that the thickness of Mesozoic sediments decreases towards the eastern part of the NAFB (Lemcke 1974, Schegg & Leu in press). This trend may also be interpreted as one of decreasing lithospheric thinning in the same direction. Another element which has to be taken into consideration is the presence of a relatively dense network of Permo-Carboniferous troughs in the western part of the NAFB (Brink et al. 1992). These observations suggest that the western NAFB inherited already a weaker lithosphere due to greater Mesozoic extension and higher density of preexisting mechanical heterogenities.

The map of lithospheric thickness in Central Europe, deduced from the regional dispersion of seimic surface waves (Mueller & Panza 1984), shows a broad zone of important lithospheric thinning which follows roughly the trend of the Cenozoic rift system. The western part of the NAFB lies within this zone. This observation suggests that the low elastic rigidity of the western NAFB may have been controlled by the evolving Cenozoic rift system. Other authors like Kuznir & Karner (1985) gave more emphasis to the paleogeothermal regime. They stated that the anomalous flexural rigidity in the Molasse Basin may reflect a bias introduced by thermal activity associated with either the formation of the Rhine Graben and/or major Tertiary-Quaternary volcanic activity within Europe. Results from this study indicate, indeed, relatively high paleoheat flow values (when compared to the German Molasse Basin). A prolongation of the Rhine Graben geothermal anomaly into the area of Northern Switzerland has already been postulated by Todorov et al. (1993). Similar correlations between heat flow and elastic thickness were made by Zoetemeijer et al. (1990) in the Ebro basin.

Conclusions

To conclude we would like to highlight the following points:

i) Modelled amounts for the post-Molasse erosion in the Plateau Molasse (2000–2600 m) support results from earlier studies (Laubscher 1974, Lemcke 1974, Monnier 1982, Brink et al. 1992, Jenny et al. 1995, Schegg & Leu 1996 in press).

ii) The Tertiary maturation phase has overprinted earlier (i.e. Mesozoic) phases and is associated with a "normal" geothermal regime. In the Plateau Molasse, average paleogeothermal gradients range between 29 and 32 °C/km and the paleoheat flow between 60 and 72 mW/m^2. A relatively low apparent thermal regime is observed in the Subalpine Molasse (20 °C/km).

iii) The paleogeothermal regime in our study area correlates well with the low flexural rigidity of the lithosphere in Western Switzerland (Karner & Watts 1983, Gutscher 1995). In the German Molasse Basin, low paleoheat flows are associated with a higher rigidity. The increased thermal activity and/or lithospheric thinning during the evolution of the Cenozoic rift system in Europe could explain in part the observed geographical variation in elastic thickness. Another important factor to explain the variation of lithospheric strength is the heritage of an already weakened lithosphere (Permo-Carboniferous grabens, more lithospheric stretching during the Mesozoic) in the Swiss part of the NAFB.

Acknowledgments

This study was funded by the Swiss National Foundation for Scientific Research (SNFSR project N°2000–037585.93/1, W. Wildi). The work has been finished during the tenure of a fellowship (SNSFR: bourse de relève) at the University of Oxford. We are indebted to P. Lahusen from Swisspetrol/SEAG for authorizing the sampling of the wells and to ESSO (Switzerland) and SHELL (Switzerland) for authorizing the publication of stratigraphic information. For critical review, practical support and helpful contributions we would like to thank the following: H.A. Jordi, R. Sachsenhofer, M. Weidmann and W. Wildi.

REFERENCES

ALLEN, P.A. & ALLEN, J.R. 1990: Basin analysis: principles and applications. Blackwell Scientific Publication, London.

ALLEN, P.A., CRAMPTON, S.L. & SINCLAIR, H.D. 1991: The inception and early evolution of the North Alpine Foreland Basin, Switzerland. Basin Research 3, 143–163.

ALTHAUS, H.E. 1947: Erdölgeologische Untersuchungen in der Schweiz. – 1. Die ölführende Molasse zwischen Genfer und Neuenburger See. – 2. Über geologische Untersuchungen im Gebiet der ölführenden Molasse im Kanton Genf. Beitr. Geol. Schweiz, geotech. Ser. 26/1, 1–43.

BACHMANN, G.H. & MÜLLER, M. 1991: The Molasse basin, Germany: evolution of a classic petroliferous foreland basin. In: Generation, Accumulation and Production of Europe's Hydrocarbons (Ed. by SPENCER, A.M.). Spec. Publ. European Assoc. Petroleum Geoscientists 1, 263–276.

– & – 1992: Sedimentary and structural evolution of the German Molasse Basin. Eclogae geol. Helv. 85, 519–530.

BACHMANN, G.H., MÜLLER, M. & WEGGEN, K. 1987: Evolution of the Molasse Basin (Germany, Switzerland). Tectonophysics 137, 77–92.

BACHMANN, G.H., DOHR, G. & MÜLLER, M. 1982: Exploration in a classic thrust belt and its foreland: Bavarian Alps, Germany. Bull. amer. Assoc. Petroleum Geol. 66, 2529–2542.

BARKER, C.E. & PAWLEWICZ, M.J. 1992: An estimate of the minimum number of measurements needed to constrain the mean random vitrinite reflectance of disseminated organic matter. Abstr. Ninth Annu. Meeting Soc. Org. Petrol., University Park, Pennsylvania, 10–11.

BEAUMONT, C., BOUTILIER, R., MACKENZIE, A.S. & RULLKÖTTER, J. 1985: Isomerization and aromatization of hydrocarbons and the paleothermometry and burial history of Alberta foreland basin. Bull. amer. Assoc. Petroleum Geol. 69, 546–566.

BERGER, J.-P. 1985: La transgression de la Molasse marine supérieure (OMM) en Suisse occidentale. Münchn. Geowiss. Abh., Reihe A, Geol. Pläont. 5.

– 1992: Correlative chart of the European Oligocene and Miocene: Application to the Swiss Molasse basin. Eclogae geol. Helv. 85, 573–609.

BODMER, P. & RYBACH, L. 1984: Geothermal map of Switzerland (Heat flow density). Beitr. Geol. Schweiz, geophys. Ser. 22.

BRADLEY, D.C. & KIDD, W.S.F. 1991: Flexural extension of the upper continental crust in collisional foredeeps. Bull. Geol. Soc. Amer. 103, 1416–1438.

BRINK, H.-J., BURRI, P., LUNDE, A. & WINHARD, H. 1992: Hydrocarbon habitat and potential of Swiss and German Molasse Basin: A comparison. Eclogae geol. Helv. 85, 715–732.

BÜCHI, U.P., LEMCKE, K., WIENER, G. & ZIMDARS, J. 1965: Geologische Ergebnisse der Erdölexploration auf das Mesozoikum im Untergrund des schweizerischen Molassebeckens. Bull. Ver. schweiz. Petroleum-Geol. u. -Ing. 32/82, 7–38.

Buiskool Toxopeus, J.M.A. 1983: Selection Criteria for the Use of Vitrinite Reflectance as a Maturity Tool. In: Petroleum Geochemistry and Exploration of Europe (Ed. by Brooks, J.). Spec. Publ. geol. Soc. London 12, 295–307.

Burkhard, M. 1990: Aspects of the large-scale Miocene deformation in the most external part of the Swiss Alps (Subalpine Molasse to Jura fold belt). Eclogae goel. Helv. 83, 559–583.

Burov, E.B. & Diament, M. 1995: The effective elastic thickness (Te) of continental lithosphere: What does it really mean? J. geophys. Res. 100, 3905–3927.

Bustin, R.M., Barnes, M.A. & Barnes, W.C. 1985: Diagenesis 10. Quantification and modelling of organic diagenesis. Geosci. Canada 12, 4–21.

Cermák, V. & Hurtig, E. 1979: Heat flow map of Europe. In: Terrestrial heat flow in Europe (Ed. by Cermák, V. & Rybach, L.). Springer Verlag, Heidelberg–Berlin–New York.

Crampton, S.L. & Allen, P.A. 1995: Recognition of forebulge unconformities associated with early stage foreland basin development: example from the North Alpine Foreland Basin. Bull. amer. Assoc. Petroleum Geol. 79, 1495–1514.

Deming, D. & Chapman, D.S. 1989: Thermal histories and hydrocarbon generation: An example from the Utah-Wyoming thrust belt. Bull. amer. Assoc. Petroleum Geol. 73, 1455–1471.

Diebold, P., Naef, H. & Ammann, M. 1991: Zur Tektonik der zentralen Nordchweiz. Interpretation aufgrund regionaler Seimik, Oberflächengeologie und Tiefbohrungen. Nagra tech. Ber. 90–04, Wettingen.

Dow, W.G. 1977: Application of oil-correlation and source-rock data to exploration in Williston Basin. Bull. amer. Assoc. Petroleum Geol. 58, 1253–1262.

Duddy, I.R., Green, P.F., Bray, R.J. & Hegarty, K.A. 1994: Recognition of the thermal effects of fluid flow in sedimentary basins. In: Geofluids: Origin, migration and evolution of fluids in sedimentary basins (Ed. by Parnell, J.). Geol. Soc. Spec. Publ., 78, 325–345.

Durand, B., Alpern, B., Pittion, J.L. & Pradier, B. 1986: Reflectance of vitrinite as a control of thermal history of sediments. In: Thermal Modelling in Sedimentary Basins (Ed. by Burrus, J.). Ed. Technip, Paris, 441–474.

Fang, H. & Jianyu, C. 1992: The cause and mechanism of vitrinite reflectance anomalies. J. Petrol. Geol. 15, 419–434.

Fasel, J.-M. 1986: Sédimentologie de la Molasse d'Eau douce Subalpine entre le Léman et la Gruyère. Thèse no. 907, Univ. de Fribourg (Suisse), unpubl.

Gorin, G., Signer, C. & Amberger, G. 1993: Structural configuration of the western Swiss Molasse Basin as defined by reflection seismic data. Eclogae geol. Helv. 86, 693–716.

Gutscher, M.-A. 1995: Crustal structure and dynamics in the Rhine Graben and the Alpine foreland. Geophys. J. Int. 122, 617–636.

Hellinger, J.H., Sclater, J.G. 1983: Some comments on two-layer extensional models for the evolution of sedimentary basins. J. geophys. Res. 88, 8251–8269.

Herb, R. 1988: Eocaene Paläogeographie and Paläotektonik des Helvetikums. Eclogae geol. Helv. 81, 611–657.

Hochuli, P.A. 1978: Palynologische Untersuchungen im Oligozän und Untermiozän der Zentralen und Westlichen Paratethys. Beitr. Paläont. Österr. 4, 1–132.

Homewood, P., Allen, P.A. & Williams, G.D. 1986: Dynamics of the Molasse Basin of western Switzerland. Spec. Publ. int. Ass. Sediment. 8, 199–217.

Jacob, H. 1989: Classification, structure, genesis and practical importance of natural solid oil bitumen ("migrabitumen"). Int. J. Coal. Geol. 11, 65–79.

Jacob, H. & Kuckelkorn, K. 1977: Das Inkohlungsprofil der Bohrung Miesbach 1 und seine erdölgeologische Interpretation. Erdöl-Erdgas-Z. 93, 115–124.

Jacob, H., Kuckelkorn, K. & Müller, M. 1982: Inkohlung und Tektonik im Bereich der gefalteten Molasse. Insbesondere am Beispiel der Bohrung Staffelsee 1. Erdöl u. Kohle-Erdgas-Petrochemie vereinigt mit Brennstoffchemie 35, 510–518.

Jenny, J., Burri, J.-P., Muralt, R., Pugin, A., Schegg, R., Ungemach, P., Vuataz, F.-D. & Wernli, R. 1995: Le forage géothermique de Thônex (Canton de Genève): Aspects stratigraphiques, tectoniques, diagénétiques, géophysiques et hydrogéologiques. Eclogae geol. Helv. 88, 365–396.

Jin, J. 1995: Dynamic stratigraphic analysis and modeling in the south-eastern Molasse basin. Tüb. geowiss. Arb., Reihe A, 24.

Jordi, H.A. 1955: Geologie der Umgebung von Yverdon (Jurafuss und mittelländische Molasse). Beitr. Geol. Schweiz (N.F.) 99.

– 1990: Tektonisch-strukturelle Übersicht Westschweizerisches Molassebecken. Bull. Ver. schweiz. Petroleum-Geol. u. -Ing. 56/130, 1–11.

– 1993: Tectonique du bassin molassique et son substratum jurassique-crétacé dans la région Orbe-Yverdon-Grandson. Bull. Soc. vaud. Sci. nat. 82, 279–299.

Jouanne, F., Ménard, G. & Darmendrail, X. 1995: Present-day vertical displacements in the north-western Alps and southern Jura Mountains: Data from leveling comparisons. Tectonics 14, 606–616.

Kälin, B., Rybach, L. & Kempter, E.H.K. 1992: Rates of Deposition, Uplift and Erosion in the Swiss Molasse Basin, Estimated from Sonic- and Density-Logs. Bull. Ver. schweiz. Petroleum-Geol. u. -Ing. 58/133, 9–22.

Karner, G.D. & Watts, A.B. 1983: Gravity anomalies and flexure of the lithosphere at mountain ranges. J. geophys. Res. 88, 10449–10477.

Kempter, E.H.K. 1987: Fossile Maturität, Paläogradienten und Schichtlücken in der Bohrung Weiach im Lichte von Modellrechnungen der thermischen Maturität. Eclogae geol. Helv. 80, 543–552.

Kübler, B., Pittion, J.-L., Héroux, Y., Charollais, J. & Weidmann, M. 1979: Sur le pouvoir réflecteur de la vitrinite dans quelques roches du Jura, de la Molasse et des Nappes préalpines, helvétiques et penniques (Suisse occidentale et Haute-Savoie). Eclogae geol. Helv. 72, 347–373.

Kuckelkorn, K. & Jacob, H. 1977: Inkohlungsgradienten im Alpenvorland. Erdöl und Kohle, Erdgas, Petrochemie Compendium 77/78, 331–338.

Kusznir, N. & Karner, G. 1985: Dependence of the flexural rigidity of the continental lithosphere on rheology and temperature. Nature 316, 138–142.

Laubscher, H.P. 1974: Basement uplift and decollement in the Molasse Basin. Eclogae geol. Helv. 67, 531–537.

– 1987: Die tektonische Entwicklung der Nordschweiz. Eclogae geol. Helv. 80, 287–303.

Lemcke, K. 1959: Das Profil der Bohrung Chapelle 1. Bull. Ver. schweiz. Petroleum-Geol. u. -Ing. 26/70, 25–29.

– 1963: Die Ergebnisse der Bohrung Savigny 1 bei Lausanne. Bull. Ver. schweiz. Petroleum-Geol. u. -Ing. 30/78, 4–11.

– 1974: Vertikalbewegungen des vormesozoischen Sockels im nördlichen Alpenvorland vom Perm bis zur Gegenwart. Eclogae geol. Helv. 67, 121–133.

Lihou, J.C. & Allen, P.A. 1996: Importance of inherited rift margin structures in the early North Alpine Foreland Basin, Switzerland. Basin Research, in press.

Loup, B. 1992a: Evolution de la partie septentrionale du domaine helvétique en Suisse occidentale au Trias et au Lias: contrôle par subsidence thermique et variations du niveau marin. Publ. du Dépt. Géol. et Paléont. 12, Université de Genève.

– 1992b: Mesozoic subsidence and stretching models of the lithosphere in Switzerland (Jura, Swiss Plateau and Helvetic realm). Eclogae geol. Helv. 85, 541–572.

Loup, B. & Wildi, W. 1994: Subsidence analysis in the Paris Basin: a key to Northwest European intracontinental basins? Basin Res. 6, 159–177.

Macario, A., Malinverno, A. & Haxby, W.F. 1995: On the robustness of elastic thickness estimates obtained using the coherence method. J. geophys. Res. 100, 15163–15172.

Matter, A., Homewood, P., Caron, C., Rigassi, D., VanStuijvenberg, J., Weidmann, M. & Winkler, W. 1980: Flysch and Molasse of Western and Central Switzerland. In: Geology of Switzerland: A Guide Book. Part B: Geological Excursions (Ed. by Trümpy, R.). Schweiz. Geol. Komm., Wepf & Co. Publishers, Basel–New York, 261–293.

Matter, A., Peters, T., Isenschmid, C., Bläsi, H.-R. & Ziegler, H.-J. 1987: Sondierbohrung Riniken – Geologie, Textband. Nagra tech. Ber. 86-02, Wettingen.

Matter, A., Peters, T., Bläsi, H.-R., Schenker, F. & Weiss, H.-P. 1988a:

Sondierbohrung Schafisheim – Geologie, Textband. Nagra tech. Ber. 86-03, Wettingen.

MATTER, A., PETERS, T., BLÄSI, H.-R., MEYER, J., ISCHI, H. & MEYER, C. 1988b: Sondierbohrung Weiach – Geologie, Textband. Nagra tech. Ber. 86-01, Wettingen.

MCNUTT, M.K., DIAMENT, M. & KUGAN, M.G. 1988: Variations of elastic plate thickness at continental thrust belts. J. geophys. Res. 93, 8825–8838.

MONNIER, F. 1982: Thermal diagenesis in the Swiss molasse basin: implications for oil generation. Canad. J. Earth Sci. 19, 328–342.

MUELLER, S. & PANZA, G.F. 1984: The lithosphere-asthenosphere system in Europe. In: First EGT workshop – The northern segment (Ed by GALSON, D.A. & MUELLER, S.). European Science Foundation, Strasbourg, 93–112.

MUKHOPADHYAY, P.K. 1994: Vitrinite reflectance as maturity parameter. Petrographic and molecular characterization and its applications to basin modeling. In: Vitrinite reflectance as a maturity parameter (Ed. by MUKHOPADHYAY, P.K. & DOW, W.G.). Amer. chem. Soc. Symp. Ser. 570, 1–24.

MÜLLER, W.H., HUBER, M., ISLER, A. & KLEBOTH, P. 1984: Erläuterungen zur Geologischen Karte der zentralen Nordostschweiz 1 : 100 000. Nagra tech. Ber. 84–25, Wettingen.

MULLIS, J. 1987: Fluideinschluss-Untersuchungen in den Nagra-Bohrungen der Nordschweiz. Eclogae geol. Helv. 80, 553–568.

NAGRA 1984: Die Kernbohrung Beznau. Beitr. Geol. Schweiz, geotech. Ser. 66.

PETERS, TJ., MATTER, A., BLÄSI, H.-R. & GAUTSCHI, A. 1986: Sondierbohrung Böttstein -Geologie, Textband und Beilagenband. Nagra tech. Ber. 85-02, Wettingen.

PFIFFNER, O.A. 1986: Evolution of the north Alpine foreland basin in the Central Alps. Spec. Publ. int. Assoc. Sediment. 8, 219–228.

PFIFFNER, O.A. & ERARD, P.F. IN PRESS: Two cross sections through the Swiss Molasse Basin. In: Deep structure of the Swiss Alps: Results from NFP/PNR 20 (Ed. by PFIFFNER, O.A., STECK, A., HEITZMANN, P. & LEHNER, P.). Birkhäuser, Basel.

PLATTE RIVER ASSOCIATE 1995: BasinMod® 1D for Windows™, Document Version 5.0. 2000 West 120th Avenue, Suite 10, Denver, CO 80234, USA.

ROBERT, P. 1985: Histoire géothermique et diagenèse organique. Bull. Centres Rech. Expl.-Prod. Elf-Aquitaine, Mém. 8, Pau.

RYBACH, L. & BODMER, P. 1980: Die geothermischen Verhältnisse der Schweizer Geotraverse im Abschnitt Basel-Luzern. Eclogae geol. Helv. 73, 501–512.

SACHSENHOFER, R.F. 1992: Coalification and thermal histories of Tertiary basins in relation to late Alpidic evolution of the Eastern Alps. Geol. Rdsch. 81, 291–308.

SAHAGIAN, D.L. & HOLLAND, S.M. 1993: On the thermo-mechanical evolution of continental lithosphere. J. geophys. Res. 98, 8261–8274.

SCHALTEGGER, U., ZWINGMANN, H., CLAUER, N., LARQUÉ, P. & STILLE, P. 1995: K-Ar dating of a Mesozoic activity in Carboniferous to Triassic clay minerals of northern Switzerland. Schweiz. mineral. petrogr. Mitt. 75, 163–176.

SCHEGG, R. 1992a.: Coalification, shale diagenesis and thermal modelling in the Alpine Foreland basin: the Western Molasse basin (Switzerland/France) Org. Geochemistry 18, 289–300.

– 1992b: Thermal maturity of the Swiss Molasse Basin: Indications for paleogeothermal anomalies? Eclogae geol. Helv. 85, 745–764.

– 1993: Thermal maturity and history of sediments in the North Alpine Foreland Basin (Switzerland, France). Publ. Dépt. Géol. et Paléont. 15, Université de Genève.

– 1994: The coalification profile of the well Weggis (Subalpine Molasse, Central Switzerland): Implications for erosion estimates and the paleogeothermal regime in the external part of the Alps. Bull. Ver. schweiz. Petroleum-Geol. u. -Ing. 61/139, 57–67.

SCHEGG, R. & LEU, W. 1996: Clay mineral diagenesis and thermal history of the Thônex well, western Swiss Molasse Basin. Clays and Clay Min 44, 693–705.

– (IN PRESS): Analysis of erosion events in the North Alpine Foreland Basin of Switzerland. In: Basin Modelling: Practical Applications. (Ed. by DÜPPENBECKER, S. & ILLIFFE, J.E.) Spec. Publ. geol. Soc. London.

SIGNER, C. & GORIN, G.E. 1995: New geological observations between the Jura and the Alps in the Geneva area, as derived from reflection seimic data. Eclogae geol. Helv. 88, 235–265.

STACH, E., MACKOWSKY, M.-TH., TEICHMÜLLER, M. & R., TAYLOR, G.H. & CHANDRA, D. 1982: Stach's textbook of coal petrology. 3. ed., Gebrüder Borntrãger, Berlin–Stuttgart.

SWEENEY, J.J. & BURNHAM, A.K. 1990: Evaluation of a Simple Model of Vitrinite Reflectance Based on Chemical Kinetics. Bull. amer. Assoc. Petroleum Geol. 74, 1559–1570.

TEICHMÜLLER, M. & TEICHMÜLLER, R. 1975: Inkohlungsuntersuchungen in der Molasse des Alpenvorlands. Geologica bavar. 73, 123–142.

TEICHMÜLLER, R. & TEICHMÜLLER, M. 1986: Relations between coalification and palaeogeothermics in Variscan and Alpidic foredeeps of western Euope. In: Paleogeothermics (Ed. by BUNTEBARTH, G. & STEGENA, L.). Lecture Notes in Earth Sciences 5, 53–78.

THURY, M., GAUTSCHI, A., MAZUREK, M., MÜLLER, W.H., NAEF, H., PEARSON, F.J., VOMVORIS, S. & WILSON, W. 1994: Geology and hydrogeology of the crystalline basement of Northern Switzerland. Nagra tech. Ber. 93–01, Wettingen.

TODOROV, I., SCHEGG, R. & WILDI, W. 1993: Thermal maturity of Mesozoic and Cenozoic sediments in the south of the Rhine Graben and the Eastern Jura (Switzerland). Ecloge geol. Helv. 86, 667–692.

VOBORNY, O., ADANK, P., HÜRLIMANN, W. & THOMPSON, B.M. 1993: Hydrogeologische Modellierung im Opalinus-Ton und in der Unteren Süsswasser-Molasse der Nordostschweiz. Nagra tech. Ber. 90–14, Wettingen.

VOLLMAYR, T. 1983: Temperaturmessungen in Erdölbohrungen der Schweiz. Bull. Ver. schweiz. Petroleum-Geol. u. Ing. 49/116, 15–27.

WATTS, A.B., LAMB, S.H., FAIRHEAD, J.D. & DEWEY, J.F. 1995: Lithospheric flexure and bending of the Central Andes. Earth planet. Sci. Letters 134, 9–21.

WEIDMANN, M. 1982: Situation et description des coupes visitées en 1978. Doc. Lab. Géol. Fac. Sci. Lyon H.S. 7, 11–24.

– 1988: Atlas géol. Suisse 1 : 25000: Feuille 1243 Lausanne. Notice explicative. Service hydrol. et géol. nat., Berne.

WYGRALA, B.P. 1989: Integrated stdy of an oil field in the southern Po Basin, northern Italy. Ber. Kernforschungsanlage Jülich 2313.

ZIEGLER, P.A. 1987: Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine foreland – a geodynamic model. Tectonophysics 137, 389–420.

ZOETEMEIJER, R., DESEGAULX, S., CLOETINGH, S., ROURE, F. & MORETTI, I. 1990: Lithospheric dynamics and tectonic-stratigraphic evolution of the Ebro Basin. J. geophys. Res. 95, 2701–2711.

Manuscript received June 11, 1996
Revision accepted September 12, 1996