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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*

with 3 figures and 1 table

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Key Words: vitrinite reflectance, coalification gradient, paleogeothermal gradient, paleotemperature, organic diagenesis, erosion estimate, Alpine front, Subalpine Molasse, Switzerland.

Abstract

The 2302 m deep well Weggis is situated within the northern margin of the Subalpine Molasse, in the basal part of the Rigi alluvial fan thrust sheet (Central Switzerland). The well encountered a main thrust at a drilling depth of 780 m which dips about 27° to the southeast. Eleven samples from the Lower Freshwater Molasse (USM, Oligocene) have been analyzed to study the coalification evolution. Excluding samples with reworked vitrinite, reflectance values show only a small variation, from 0.65 %Rr in a sample taken at 900 m to 0.82 %Rr in a sample taken at 1670 m. The relatively high near surface values (0.71-0.75 %Rr) indicate the erosion of an important sedimentary overburden (>4 km). Results from this study support a pre- and syn-thrust coalification in the Subalpine Molasse. The calculated coalification gradient of the footwall is 0.14 %Rr/km and 0.08 log%Rr/km. Thermal modeling indicates that this corresponds to a paleogeothermal gradient of 20-23.5 °C/km and to paleotemperatures between 100 and 140 °C (60-70 °C higher than present-day temperatures). The amount of calculated erosion for the well Weggis (3-4.2 km), using footwall data, can be explained by the overthrusting of a thick hangingwall sequence (Rigi thrust sheet).

Zusammenfassung

Die auf 2'302 m abgeteufte Geothermie-Bohrung Weggis (LU, Zentralschweiz) befindet sich am Nordrand der Subalpinen Molasse im basalen Bereich der Überschiebungsdecke des Rigi-Schuttfächers. Die Sedimente oberhalb der in 780 m Tiefe liegenden Hauptüberschiebung (27° gegen SE einfallend) lassen sich der Unteren Süsswassermolasse (USM) und der Unteren Meeresmolasse (UMM) zuordnen. Die unterhalb der Hauptüberschiebung liegenden Serien lassen sich momentan nur informell gliedern (USM?). An 11 Spülproben wurden Vitrinit-Reflexionsmessungen (%Rr) durchgeführt. Mit der Ausnahme von zwei Proben, die durch wiederaufgearbeitetes, hochinkohltes organisches Material gekennzeichnet sind, zeigt das Inkohlungsprofil der Bohrung Weggis eine geringe Variation der Werte. Die Vitrinit-Reflexionswerte schwanken zwischen 0.65 %Rr (Spülprobe aus 900 m Tiefe) und 0.82 %Rr (Spülprobe aus 1670 m Tiefe). Die relativ hohe Reife oberflächennaher Proben (0.71-0.75 %Rr) lässt auf eine bedeutende Paläoüberdeckungsmächtigkeit (>4 km) schliessen. Die Ergebnisse dieser Studie unterstützen die Hypothese einer prä- bis syn-kinematischen Inkohlung der Subalpinen Molas-

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se. Der Inkohlungsgradient im Liegenden der Hauptüberschiebung beträgt 0.14 %Rr/km beziehungsweise 0.08 log%Rr/km. Die thermische Modellierung der Resultate für die Bohrung Weggis ergab einen tiefen paläogeothermischen Gradient (20-23.5°C/km) und maximale Paläotemperaturen zwischen 100 und 140 °C (60-70 °C höher als die heute beobachteten Bohrlochtemperaturen). Die aus "footwall"-Daten berechneten Erosionsbeträge (3-4.2 km) können durch die Überlagerung der mächtigen Rigi-Überschiebungsdecke erklärt werden.

1. Introduction

Up until now, only 2 Tertiary coalification profiles in the Swiss Molasse basin have been published: the well Küsnacht with a coalification gradient of 0.08%Rr/km and the well Hünenberg with a coalification gradient of <0.05%Rr/km (Rybach & Bodmer 1980). Additional data will be published for the well Thônex (Jenny et al. submitted) and for the well Entlebuch (Leu in prep.). Most other coalification data from the Swiss Molasse basin come from outcrop samples (Kübler et al. 1979, Burkhard & Kalkreuth 1989, Schegg 1992a, 1992b, 1993, Todorov et al. 1993, Erdelbrock 1994). Much attention has been given in the past to the diagenetic and metamorphic grade of the external part of the Alpine ranges (see references in Frey 1986). The very-low grade regional Alpine metamorphism of Central Switzerland has been studied mainly by Frey et al. (1980) and Breitschmid (1982).

The 2302 m deep well Weggis (northern shore of Lake Lucerne), which was drilled in 1992/1993, is one of the first deep geothermal wells in the Subalpine zone. A detailed description of the well is given in Greber et al. (1994). It is situated within the northern margin of the Subalpine Molasse, in the basal part of the Rigi alluvial fan thrust sheet (Fig. 1). To the south, the Helvetic border chain, a detached slab of the Drusberg nappe, is thrusted onto the Subalpine Flysch ("Border Flysch") and the Subalpine Molasse. Some Prealpine klippen overlying the Helvetic nappes south of Lake Lucerne represent small outliers of a former Penninic sheet. The well Weggis encountered a main thrust in the Molasse at a depth of 780 m which dips about 27° to the southeast. The hangingwall is formed by 580 m of Lower Freshwater Molasse (USM) and 200 m of Lower Marine Molasse (UMM). The footwall section can only informally be categorized as USM. These footwall sediments are internally thrusted.

2. Sampling and analytical method

11 samples from the Lower Freshwater Molasse (USM) have been analyzed for this study. Vitrinite reflectance results were obtained by measuring hand-picked macroscopic coaly particles from well cuttings. The coaly particles were mounted in epoxy resin, then ground and polished with different diamond sprays (6, 3, 1, 0.25 μm). Mean random vitrinite reflectance (%Rr) was determined using a Leitz MPV compact microscope under standardized conditions. The measurement procedure followed the rules outlined in the International Handbook of Coal Petrol-

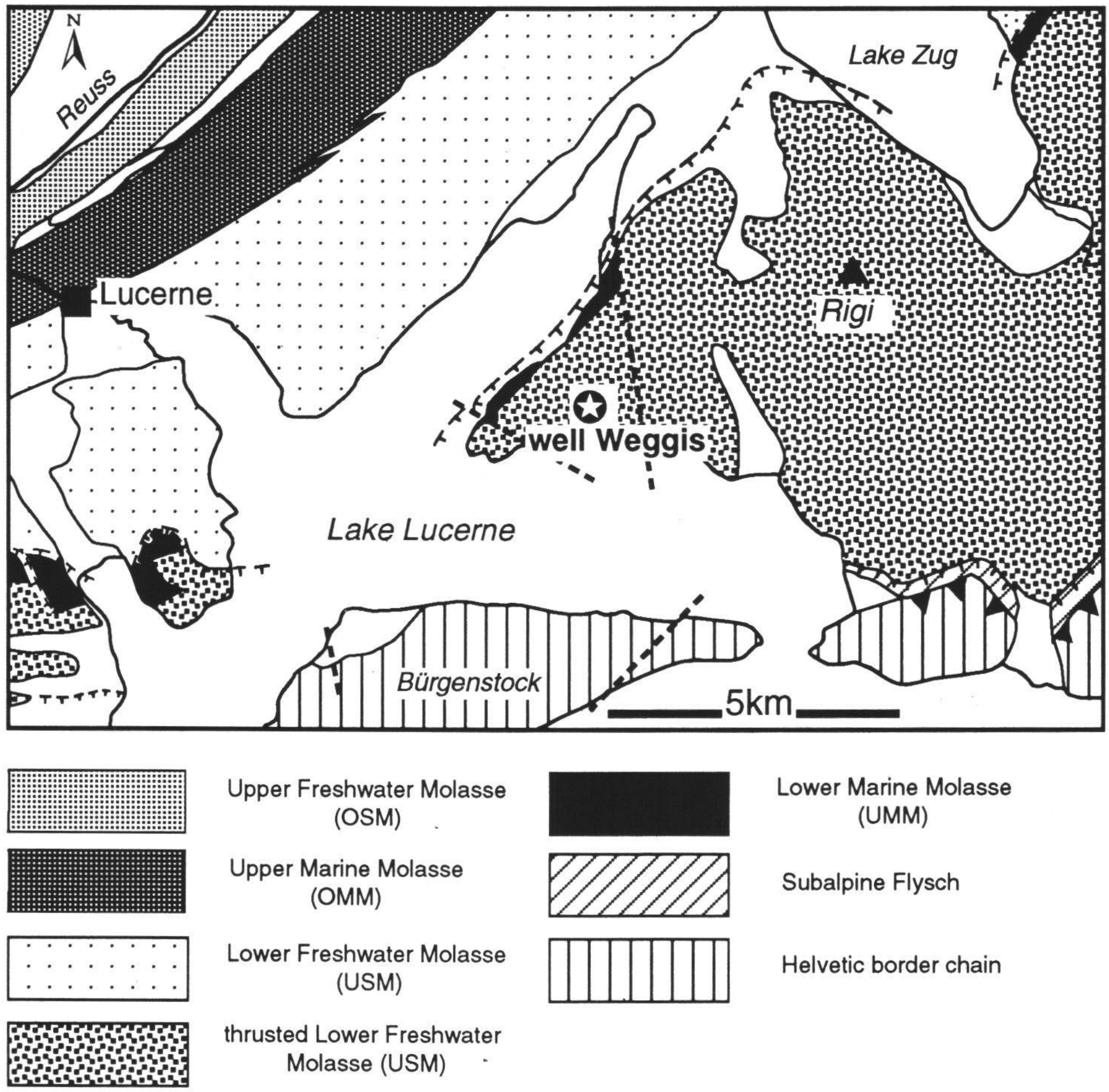

Fig.1 Simplified tectonic map of Central Switzerland showing the location of the well Weggis. Modified from Greber et al. (1994).

ogy (1971). If available, at least 50 telocollinite particles were measured for reflectance determination of a sample. A detailed discussion of the measurement technique and the limitations of the method can be found in SCHEGG (1993).
The analysis of 2 samples (We-540, We-2130) indicates reworking of organic matter which was already coalified before resedimentation. The results of these samples have, therefore, not been used for the interpretation.
BUISKOOL TOXOPEUS (1983) has shown the existence of different populations of vitrinite in coal, even in the absence of reworked material. Uncertainties are reflected in a large scattering of vitrinite reflectance histograms (e.g. bimodal histograms). For our study, only the lower mode of a bimodal histogram has been retained (->Rr').
The small size and the sometimes inadequate polishing quality of vitrinite result in lowered reflectance values. For these reasons the sample We-2000 has been excluded for the final interpretation.

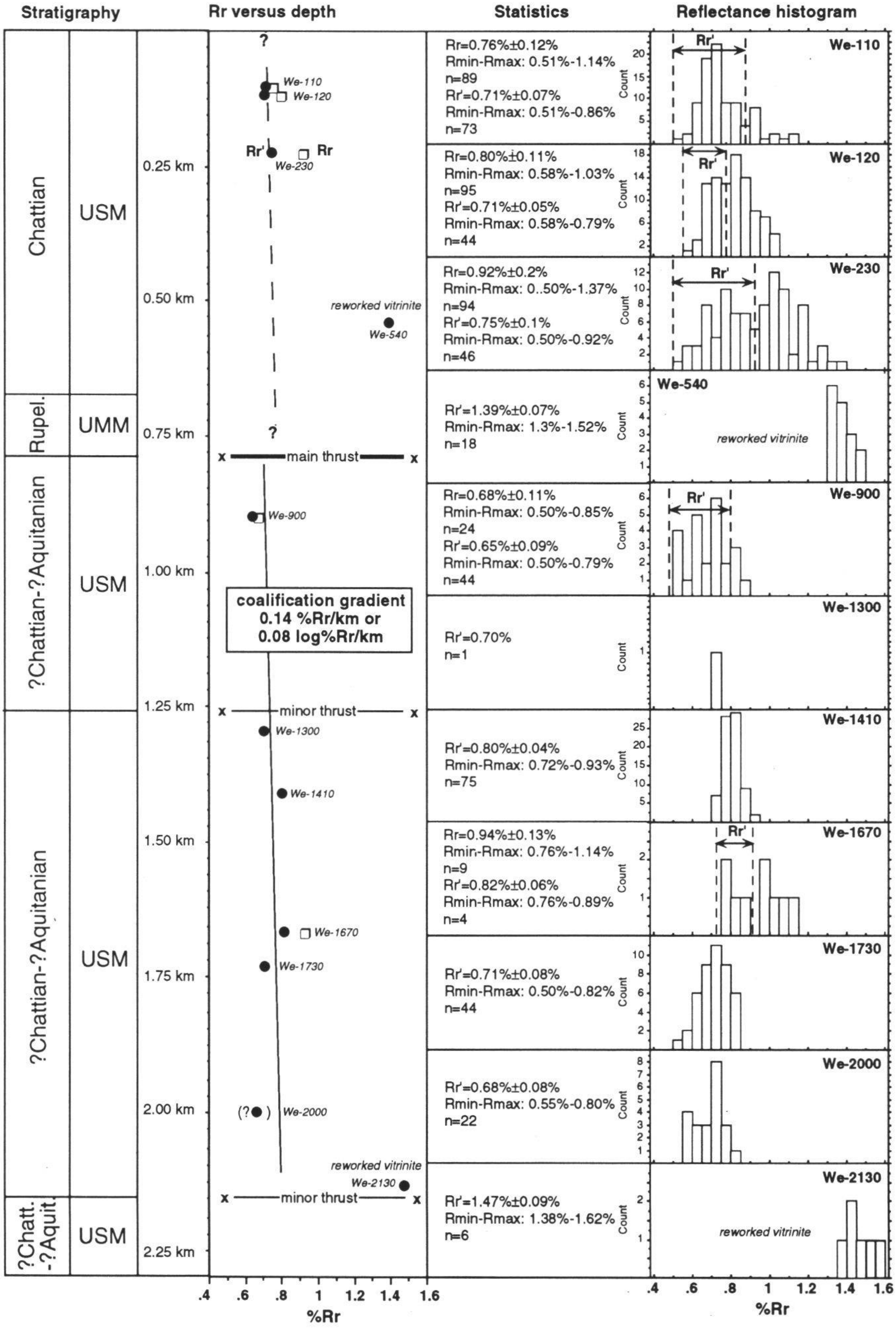

Fig. 2 Well Weggis: summary of vitrinite reflectance (Rr) results showing the simplified stratigraphy of the well, the depth versus Rr trend (indicated post-coalification thrusting is hypothetical), statistical results (Rr=mean average values with standard deviation, Rmin-Rmax=minimal and maximal values, n=number of measurement) and the reflectance histograms. Rr represents the unfiltered mean average vitrinite reflectance of a measurement and Rr' the mean average of the chosen mode of the histogram. Note that the sample number refers to the sample depth.

3. Coalification data

The results of the vitrinite reflectance measurements are summarized in figure 2. Excluding samples with reworked vitrinite (We-540, 1.39 %Rr and We-2130, 1.47 %Rr), reflectance values show only a small variation (from 0.65 %Rr in a sample taken at 900 m to 0.82 %Rr in a sample taken at 1670 m). The relatively high near surface values (0.71-0.75 %Rr) indicate the erosion of an important sedimentary section. Comparable values from outcrop samples have been found in the Subalpine Molasse north of Lake Geneva (SCHEGG 1992b). On the other hand, reflectance values from the Subalpine Molasse of Eastern Switzerland (Appenzell), despite some local anomalies, are generally lower than the near-surface values from the well Weggis (ERDELBROCK 1994).
Coalification profiles, expressed as an increase of coalification with depth, are sensitive indicators of the thermal histories of the host rocks. The well profile logarithmic reflectance gradient (log %Rr/km) and linear reflectance gradient (%Rr/km) were obtained by linear regression analysis. The independent variable has been chosen to be depth, as no uncertainty is commonly assigned to depth measurements in a well (MAJOROWICZ et al. 1990). Calculating coalification gradients (Tab. 1) with data from both the hangingwall and the footwall results in unrealistic low values (0.01 %Rr/km or 0.01 log%Rr/km) which would correspond to a paleogeothermal gradient of <2°C/km during maximum burial (Tab. 1, see also chapter 4). Thus, a post-thrust coalification which overprints the pre-coalification trends of both the hanging- and footwall can probably be ruled out. For these reasons, reflectance values from the hangingwall and the footwall have been treated separately.

There are other arguments favoring this hypothesis: FREY et al. (1980) postulated that post-metamorphic thrusting seems to be a common feature in the external part (Helvetic zone) of the Alps. The Subalpine Flysch and the Border Chain have clearly higher coal ranks (1.6-1.7%Rr) than the underlying Subalpine Molasse (BREITSCHMID 1982). This means that the coalification of these units occurred before the overthrusting onto the Subalpine Molasse.

As only 3 closely-spaced reflectance values could be measured in the hangingwall, calculation of the coalification gradient has been restricted to the footwall section. Given the small number of samples in the footwall, the computed coalification gradients (as well as erosion estimates and calculated paleogeothermal gradients in chapter 4) have to be taken as a first approximation. Taking all samples in the footwall (data set 1 in Tab. 1), the increase of %Rr with depth (0.05 %Rr/km or 0.03 log%Rr/km, Tab. 1) is comparable with those found in the Bavarian Molasse (0.03-0.09 %Rr/km, TEICHMÜLLER & TEICHMÜLLER 1986) or in the Swiss Molasse (<0.05-0.08 %Rr/km, RYBACH & BODMER 1980). A higher value (0.14 %Rr/km or 0.08 log%Rr/km, Fig. 2, Tab. 1) is obtained when excluding the lowermost sample (data set 2 in Tab. 1, see chapter 2 for discussion). This figure is in line with the coalification gradient of the well Thônex in the western part of the Swiss Molasse basin (0.18 %Rr/km or 0.13 log%Rr/km, Jenny et al., submitted).

	coalification gradient		paleogeothermal gradient			
calculation method			Easy%Ro	Barker		
	%Rr/km	*log%Rr/km*	*°C/km*	*°C/km*		
all data*	0.01	0.01	0.3	1.5		
data set 1*	0.05	0.03	5.9	8.1		
data set 2*	**0.14**	**0.08**	**20.2**	**23.5**		
	eroded section			**max. overburden**		
calculation method	Easy%Ro	Barker	log%Rr	Easy%Ro	Barker	log%Rr
	km	*km*	*km*	*km*	*km*	*km*
all data*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
data set 1*	17	11	15	17.8	11.8	15.8
data set 2*	**4.2**	**3**	**4.1**	**5**	**3.8**	**4.9**
* samples with reworked vitrinites excluded						
data set 1=data below main thrust (at 780m)						
data set 2=data below main thrust (at 780m); sample We-2000 excluded						
n.d.=not determined						
Easy%Ro=max. paleotemperature calculated with the maturation model of Sweeney and Burnham (1990)						
Barker=max. paleotemperature calculated with the Tmax-Rr correlation of Barker & Goldstein (1990)						
log%Rr=eroded section estimated by extrapolating of coalification gradients to a surface value (Dow 1977)						

Tab. 1 Well Weggis: summary of interpretation results.

4. Implications of the results on eroded section estimates and the paleogeothermal gradient

The rate of increase of vitrinite reflectance with depth is not constant but varies with present-day and/or paleogeothermal gradients (TEICHMÜLLER & TEICHMÜLLER 1986). The intercept of the logarithmic coalification gradient with zero coalification is commonly inferred to represent an estimate of the eroded thickness (DOW 1977). According to MAJOROWICZ et al. (1990), the zero coalification = 0.25 %Rr is a more reasonable assumption than either the 0.15 %Rr employed by ENGLAND & BUSTIN (1986) or that of 0.18 %Rr used by HACQUEBARD (1977), if the reflectance of peat is considered. Using the data set 1 (Tab. 1), e.g. the 0.03 log%Rr/km coalification gradient, 15 km of eroded section results. This value is geologically not viable and shows that linear regression by least square methods is accompanied by large uncertainties, especially when computing with a low number of scattered reflectance values. An estimate of 4.1 km has been obtained with the data set 2 (Tab. 1). Taking the present-day thickness of the hangingwall (800m) into account, a maximum overburden thickness of 4.9 km has to be postulated.

Thermal modeling with the EASY%Ro model of SWEENEY & BURNHAM (1990) enables the calculation of mean vitrinite reflectance values for a given stratigraphic level if the time-temperature history is known. Taking a simplified V-shaped temperature history (e.g. BURKHARD & KALKREUTH 1989) for the near-surface samples in the hangingwall (0.71-0.75 %Rr) of the well Weggis, a maximum burial temperature between 120-125°C can be calculated for the observed maturity values (see Schegg 1992b for further explanations). Assuming a paleogeothermal gradient of 25°C/km and a paleosurface temperature of 15°C, an erosion amount of >4 km and a former hangingwall thickness of about 5 km are obtained. The maximum present-day thickness of the Rigi thrust sheet is 3.5 km (GREBER et al. 1994).

Maximum paleotemperature estimates for different samples in a well enable reconstruction of paleotemperature gradients at the time of peak temperature. Further, their extrapolation to a paleosurface temperature is also useful in attaining the amount of erosion (see DUDDY et al. 1991 for a detailed discussion). There are different approaches to estimate maximum paleotemperatures:

i) According to BARKER & GOLDSTEin (1990), homogenization temperatures (Th) of fluid inclusions in calcite record temperatures close to the maximum reached by the rock. Strong correlation (r=0.93) between Th and Rr in 46 diverse geologic systems allowed them to establish the following equation: ln(Rr)=0.00811*Th-1.26.

ii) The EASY%Ro-model of SWEENEY & BURNHAM (1990) has already been mentioned in the previous paragraphs. The method is based on a given time/temperature history. Different temperature histories can be tested until this curve matches the measured rank. It is assumed that maximum burial temperatures have been reached at maximum burial depth. For the well Weggis, the maximum burial depth of the footwall is probably associated with the emplacement of the Rigi fan thrust sheet. According to BURKHARD (1990), the precise time of thrusting and folding within the Subalpine Molasse is difficult to determine. The most external structures, in particular the triangle zones in Bavaria, Eastern and Central Switzerland appear to be formed simultaneously with folding of the Jura (Serravalian/Tortonian). The more internal thrust slices of the Subalpine Molasse are truncated at their top by either Subalpine Molasse-, Helvetic- or Pennine-thrusts and thrusting may have occurred as early as the Middle Oligocene (BURKHARD 1990). According to GREBER et al. (1994), the youngest sediments in the footwall may be of Aquitanian age. The thrusting of the Rigi fan would consequently be younger. For modeling purposes we took an age of 20 my for the start of thrusting and 15 my for the start of uplift.

The present thermal conditions of the Swiss Molasse basin indicate a low geothermal regime on a basin-wide scale. According to RYBACH (1984) and RYBACH et al. (1987), average geothermal gradients gradually decrease from >35°C/km close to the Rhine Graben in the North to <25°C/km towards the Alps. Results from GREBER et al. (1994) for the well Weggis indicate, however, a higher present-day geothermal gradient within the Alpine front (29.5°C/km). Results from thermal modeling suggest (Fig. 3) that calculated maximum paleotemperatures (100-140°C) are 60-70°C higher than present-day temperatures and that the corresponding paleogeothermal gradient is lower than the present-one: 20°C/km (method EASY%Ro) and 23.5°C/km (method BARKER & GOLDSTEIN 1990).

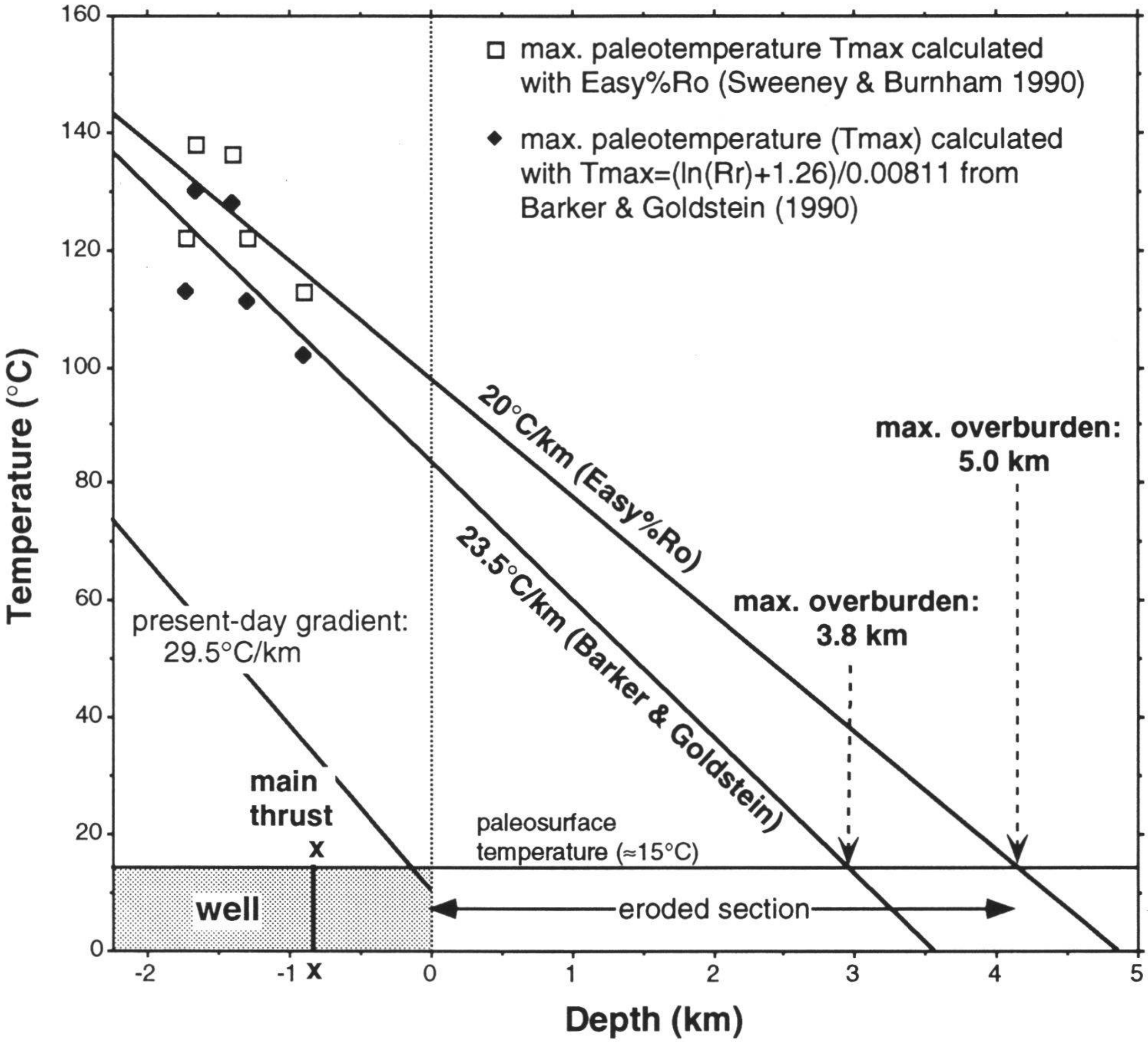

Fig. 3 Well Weggis: Comparison between present-day geothermal gradient and calculated paleogeothermal gradient. Estimate of eroded section by extrapolation of paleogeothermal gradient to a paleosurface temperature.

In accordance with these results, fluid inclusion data from outcrops of the Helvetic border chain indicate minimum formation temperatures of about 120°C (FREY et al. 1980). Low paleogeothermal gradients have also been postulated for the Bavarian Molasse basin (TEICHMÜLLER & TEICHMÜLLER 1986). These authors interpreted the observed decrease of coalification gradients (0.09 to 0.03 %Rr/km) in boreholes of the Bavarian Molasse towards the South as caused by a decrease of the geothermal gradient (from 30 to 20°C/km) in the same direction.

Extrapolating this paleogeothermal gradient (Fig. 3) to a paleosurface temperature of 15°C results in an eroded section of 4.2 km (EASY%Ro) and 3.0 km (BARKER & GOLDSTEIN). The corresponding maximum overburden of the footwall is 5.0 km (EASY%Ro) and 3.8 km (Barker & Goldstein 1990).
A high former overburden is indicated by the high degree of compaction for these sediments as confirmed by geophysical well logging (GREBER et al. 1994). The

maximum observed thickness of the Rigi thrust sheet (hangingwall) is about 3.5 km (GREBER et al. 1994). The amount of calculated erosion for the well Weggis (3-4.2 km) can, therefore, be explained by the former overburden of the Rigi thrust sheet.

5. Conclusions

The results from this study can be summarized as follows:
i) The coalification study in the well Weggis indicates a rather low paleogeothermal average gradient (20-23.5°C/km using only data from the footwall). These results support those of other authors (RYBACH 1984, TEICHMÜLLER & TEICHMÜLLER 1986).
ii) Maturation of the footwall is probably due to the burial under a thick (4-5 km) thrust sheet (Rigi thrust sheet). Maturation of the hangingwall is associated with normal sedimentary burial (pre-thrust coalification). Our results indicate that there is no important post-thrust overprinting of the whole profile.

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