

Coalification in the northern Wildhorn nappe and adjacent units, western Switzerland. Implications for tectonic burial histories

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ABSTRACT

Vitrinite reflectance of fourteen Eocene coal samples from the northern Wildhorn nappe in the Kander valley have been analyzed and compared to nine age-wise similar coals from adjacent tectonic units. The degree of coalification decreases regularly from semi-anthracite in the Kander valley to lignite in the plateau molasse. The degree of coalification in the Tertiary coals appears to be solely dependent on their tectonic history and indicates an estimated 6 km of burial by higher (Pennine) nappes for the Kander valley. The rank at this locality (low-volatile bituminous to semi-anthracite) is significantly higher than in the Border chain at Beatenberg (high-volatile A bituminous). The latter locality therefore was never buried deeper than about 4 km. A further decrease in rank is found in the subalpine flysch and molasse (high-volatile B bituminous) which in turn is significantly more mature than lignites from the folded plateau molasse at Linden. Two samples of Dogger coal from the Pennine "Préalpes médianes" are medium- to low-volatile bituminous that is intermediate between the Kander valley and Beatenberg. Their rank, however, was achieved before their final emplacement north of the Wildhorn nappe.

By comparing calculated TTI (Time-Temperature-Indices)-values for time-depth-burial curves with measured vitrinite reflectances, maximum burial temperatures were estimated for the various tectonic units. For the Wildhorn nappe, 160–180°C were obtained in the Kander valley and 100–130°C in the Border chain as a result of tectonic burial due to the thrusting by the Pennine Prealps. Sedimentary burial led to temperatures of 100–120°C in the subalpine molasse below the Border chain prior to its thrusting.

INTRODUCTION

Vitrinite reflectance studies have been applied successfully in the Alps to determine "metamorphic" zonations within its very low-grade northernmost

parts (i.e. Kübler et al., 1979; Frey et al., 1980; see Frey, 1986 for references). Due to the scarcity of coal seams in the sedimentary sequences involved, the majority of the published analyses is based on dispersed phytoclasts. Some rare coal seams, however, do exist, and the aim of this study was to determine their vitrinite reflectance and coal rank in order to compare it to the established metamorphic zonation. This zonation is mostly based on illite crystallinity and the disappearance or first appearance of index minerals such as laumontite, pumpellyite, glauconite, stilpnomelane, kaolinite and pyrophyllite. An earlier attempt of correlation between mineral zonations, illite crystallinities and coal rank, based on the yield of volatile components has been made by Frey and Niggli (1971) in the same study area.

It is well known, that illite crystallinity studies do not have a great power of resolution in the diagenesis (i.e. Kisch, 1980) and most of the mentioned index minerals (like the coals) are restricted to some particular discontinuous stratigraphic horizons. Furthermore, very few index minerals are suitable for subdivisions within the zeolite facies or diagenesis as most of them mark the transition between the diagenesis and anchimetamorphic region (Kübler et al., 1979; Frey, 1986). Vitrinite reflectance, on the other hand, has been recognized as a powerful tool for the determination of the thermal history especially within the very low-grade metamorphic region. Methods of quantification have been developed which allows the determination of organic maturation from burial histories (Karweil, 1955; Waples, 1980; Bustin et al., 1985). In this study, we attempt to determine maximum burial temperatures from vitrinite reflectance data and hypothetical burial curves.

One of the larger accessible coal occurrences in Switzerland is situated in the Kander valley and belongs to the Helvetic Wildhorn nappe. This deposit has been mined during world war II and a detailed description dates from this period (Beck, 1948). Fourteen Eocene coal samples of Beck's reference collection have been analyzed and compared to three samples from the same stratigraphic horizon but a more external position in the Border chain at Beatenberg. Two Tertiary coals from the subalpine thrust molasse (Haldemann, 1948) and one sample from the flatlying molasse north of the Border chain have also been included in this study as well as two Dogger coal samples from the Pennine Prealps.

GEOLOGIC AND TECTONIC SETTING

Eocene coals are sporadically found in the northern Wildhorn nappe at the base of the Tertiary. During late Cretaceous to Eocene times, this part of the Wildhorn nappe, like other parts of the northern Helvetic realm was exposed leading to an important stratigraphic gap and karstification of the Cretaceous substratum. In the Kander valley, the Tertiary transgression overlies either Schrätkalk or Drusbergschichten (Barremian). Coals occur at the very base

and within the lower part of the Upper Eocene Hohgant formation and are overlain by the Hohgant sandstone, Lithothamnium limestone and Globigerina marls. The thickness of the three formations together is no more than about 150 m (Steffen, 1981). These are precursors of the Helvetic flyschs but no important flysch unit is known in this part of the Wildhorn nappe. Instead, the Tertiary series of the nappe is concordantly covered by Ultrahelvetetic units 0.1–1 km in thickness and further overridden by the Pennine Prealps.

The tectonic history of the Wildhorn nappe in the vicinity of the Kander valley is complex (Adrian, 1915; Zwahlen, 1986; Burkhard, 1988). East of the lake Thun, the northernmost Wildhorn nappe is found in an external position, the Helvetic Border chain, which is thrust onto the subalpine molasse and flysch (Fig. 1, and cross section Fig. 2a). West of the lake Thun the corresponding parts of the Wildhorn nappe were left farther behind in the Kander valley (Fig. 2b). These units are folded, thrust and faulted in a complex of several thin kilometeric imbricates below the Pennine contact (Adrian, 1915). The Pennine Prealps on the other hand extend further to the north and are thrust onto the subalpine molasse. Thus, initially adjacent parts of the northern Wildhorn nappe have undergone different tectonic and burial histories east and west of lake Thun. Some prealpine klippen on top of the Wildhorn nappe

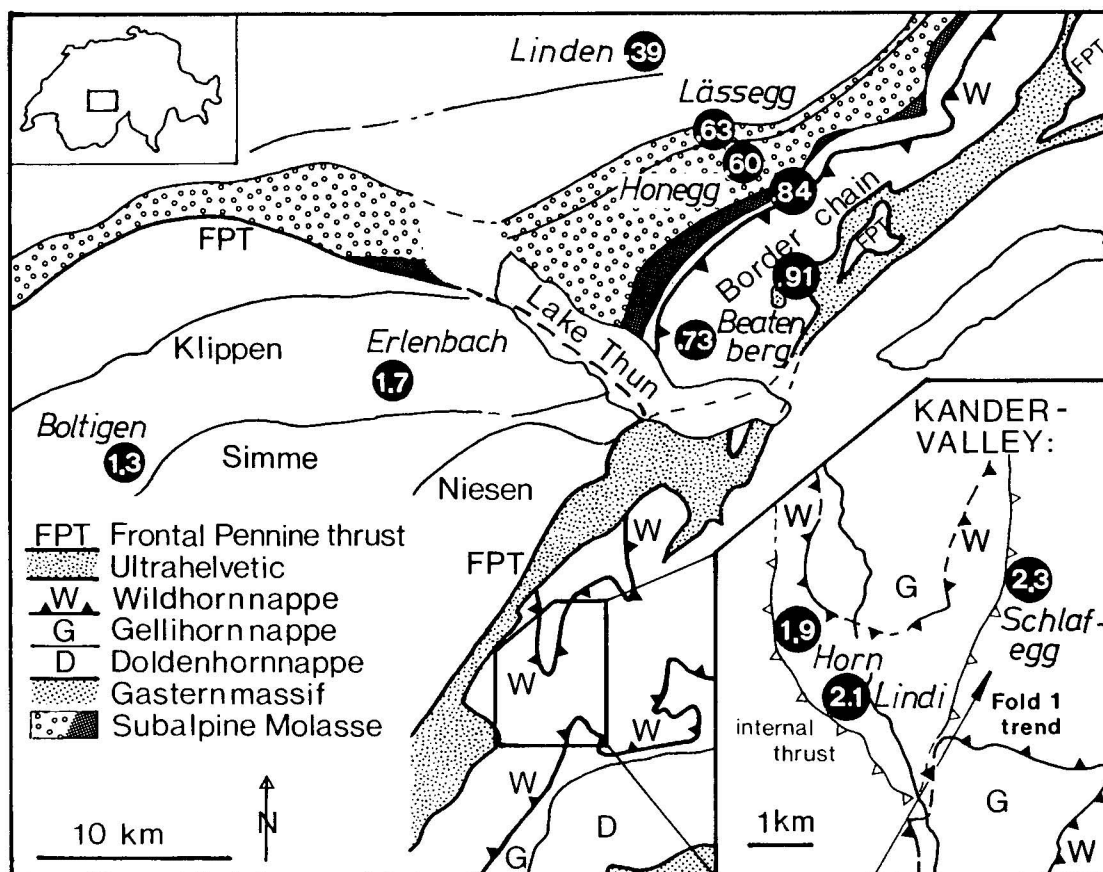


Fig. 1. Simplified tectonic map of the study area. Measured vitrinite reflectances ($\% R_{\max}$) are indicated within black dots according to Table 1.

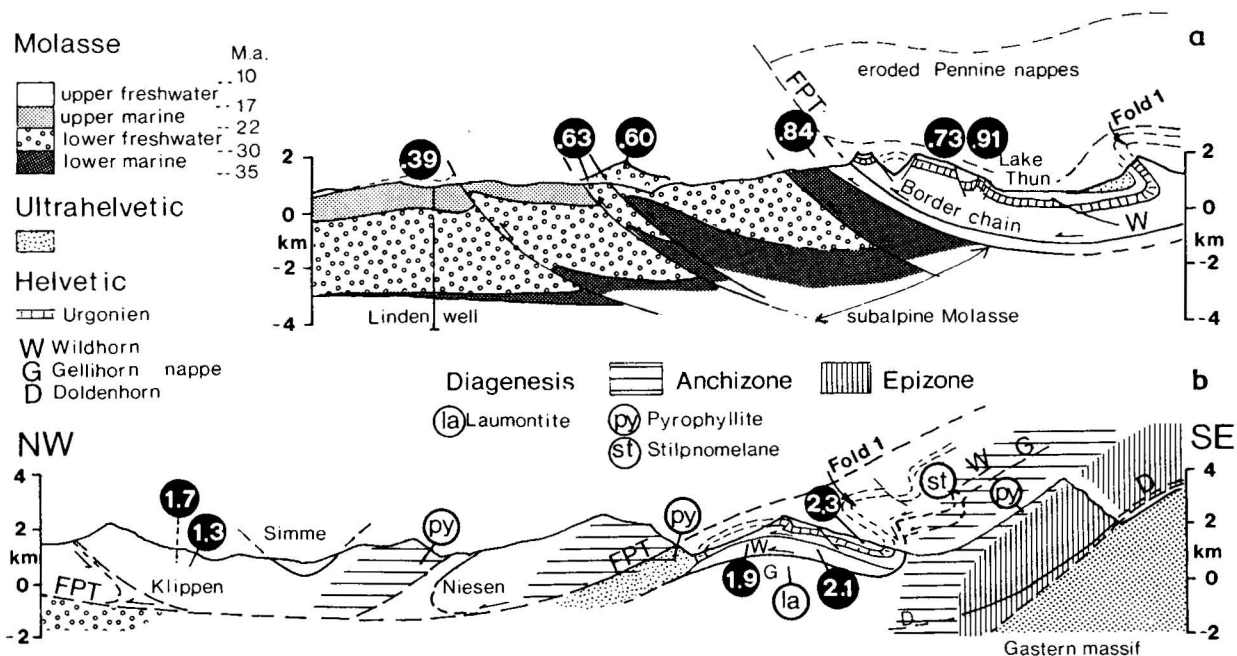


Fig. 2. Cross sections east (a) and west (b) of lake Thun. Vitrinite reflectances ($\% R_{\max}$) are compared with established metamorphic zonation which are based on illite crystallinities and the first appearance of index minerals laumontite, stilpnomelane and pyrophyllite (Frey, 1986; Burkhard, 1988).

east of lake Thun (see Fig. 1), however, testify that the lateral extension of the Pennine sheet on top of the Wildhorn nappe was far larger than seen today.

The coal samples of the Kander valley were taken from three different mining areas (Fig. 1, inset). Horn and Lindi west of the Kander river lie both in a complicated "Schuppen" structure, below an internal thrust of the Wildhorn nappe. These "Schuppen" are interpreted as frontal parts of the Wildhorn nappe which were overridden by the main part of the nappe (Adrian, 1915). Further east, equivalent units of the nappe are found in a more external position in the Border chain. Schlafegg east of the Kander river, on the other hand, belongs to the main part of the Wildhorn nappe above the previously mentioned internal thrust. Thus, Schlafegg has a slightly more internal origin than Horn and Lindi. In their present-day configuration however, as seen in a projected tectonic profile (Fig. 2b), Schlafegg lies only some 100 m vertically above Lindi.

In each area, coals have been mined from layer-parallel seams as well as from fault planes, where strongly tectonized coal has intruded into large open fractures. In fact some of the most interesting galleries have been excavated into such "secondary" coal deposits (Beck, 1948).

Sample preparation and analytical methods

The coals were crushed to a maximum particle size of 850 micron (20 mesh), mounted in epoxy resin, then ground and polished. Rank was determined by

measuring maximum and random vitrinite reflectances, using a Leitz MPV II microscope under standardized conditions and following the procedures outlined in the International Handbook of Coal Petrography (1971). The results are expressed in terms of an arithmetic mean (generally obtained from 50 measurements) and standard deviation. A.S.T.M. rank classes from the reflectance values were obtained by using the maximum reflectance limits for A.S.T.M. rank classes as published by Davis (1978):

		% R_{\max}	
	C	0.47-0.56	
High-volatile bituminous	B	0.57-0.70	
	A	0.71-1.09	
Medium-volatile bituminous		1.10-1.49	
Low-volatile bituminous		1.50-2.04	
Semi-anthracite		2.05-3.00	(approx.)
Anthracite		3.00	(approx.)

In a second step, 50 maximum and minimum vitrinite reflectances were determined on each sample to assess the levels of bireflectances ($R_{\max}-R_{\min}$). The reflectances of these runs were then used to estimate the optical reflectance characteristics of the coals according to the method suggested by Kilby (1988).

RESULTS AND DISCUSSION

General remarks

The results of the vitrinite reflectance measurements are summarized in Table 1. The values range from 2.50% R_{\max} (semi-anthracite) in the Wildhorn nappe of the Kander valley to 0.39% R_{random} (lignite) in the plateau molasse (Fig. 1). Bireflectances ($R_{\max}-R_{\min}$) range from 0.03 to 0.11% in the lower-rank coals (lignite-high-volatile bituminous) and from 0.17 to 0.31% in the higher-rank coals (medium-volatile bituminous-semianthracite), as recorded in Table 1. The bireflectances determined on the Swiss coals are in good agreement with data reported for coals of similar rank from France and Germany (Alpern and Lemos de Sousa, 1970; Teichmüller et al., 1979). Following the method of Kilby (1988) it appears that many of the coals have biaxial reflectance characteristics which are most likely related to their position in deformed strata (Levine and Davis, 1984; Langenberg et al., in press). The R_{\max} values estimated from the reflectance cross plots (Kilby, 1988) are on average 0.14% higher than the values obtained from standard maximum reflectance measurements. The biaxial nature of the Swiss coals will be contrasted with results obtained from Canadian coals of similar tectonic settings in a separate publication.

The following discussion will focus on the rank distribution based on stan-

TABLE 1

Sample location, geological ages and vitrinite reflectances for coals from the study area

Location	Age	Sample ^d	Pellet	Reflectance (R_{\max})			Bireflec- tance ($R_{\max}-R_{\min}$)	ASTM rank
				mean	s^a	n^b		
<i>Wildhorn nappe, Kander valley:</i>								
Schlafegg	Eocene	B3145	624/87	2.38	0.07	50	0.19	semi-anthracite
Schlafegg	Eocene	B3146	625/87	2.50	0.07	50	0.20	semi-anthracite
Schlafegg	Eocene	B3147	626/87	2.20	0.08	50	0.23	semi-anthracite
Schlafegg	Eocene	B3148	627/87	2.15	0.06	50	0.27	semi-anthracite
Schlafegg	Eocene	M7	617/87	2.28	0.07	50	0.28	semi-anthracite
Schlafegg	Eocene	M8	618/87	2.37	0.06	50	0.18	semi-anthracite
Lindi	Eocene	B3151	629/87	2.24	0.08	50	0.26	semi-anthracite
Lindi	Eocene	B3153	630/87	2.10	0.09	50	0.31	semi-anthracite
Lindi	Eocene	M4	614/87	2.00	0.04	50	0.21	low-volatile bituminous
Lindi	Eocene	M11	621/87	2.01	0.03	50	0.22	low-volatile bituminous
Lindi	Eocene	M5	615/87	2.08	0.05	50	0.22	semi-anthracite
Horn	Eocene	M6	616/87	1.99	0.05	50	0.25	low-volatile bituminous
Horn	Eocene	B3154	631/87	2.02	0.06	50	0.20	low-volatile bituminous
Horn	Eocene	B3155	632/87	1.72	0.06	50	0.17	low-volatile bituminous
<i>Wildhorn nappe, Border chain (Beatenberg):</i>								
Beatenb.	Eocene	B3150	628/87	0.73	0.04	50	0.08	high-volatile A bituminous
Sieben	Eocene	C3 ^e	222/88	0.93	0.05	25		high-volatile A bituminous
Hengste	Eocene	C4 ^e	223/88	0.89	0.02	50		high-volatile A bituminous
<i>Subalpine flysch, (below Border chain):</i>								
Schöriz	Eocene	RSH 34 ^e	221/88	0.84	0.02	50		high-volatile A bituminous
<i>Subalpine molasse (lower freshwater molasse):</i>								
Spicher.	Oligocene	M12	622/87	0.63	0.02	50	0.05	high-volatile B bituminous
Honegg	Oligocene	M13	623/87	0.60	0.02	50	0.08	high-volatile B bituminous
<i>Plateau molasse (upper freshwater molasse):</i>								
Linde	Miocene	M9	619/87	0.39 ^e	0.03	50	0.03	lignite
<i>Pennine Prealps, Klippen nappe:</i>								
Erlenbach	Dogger	M10	620/87	1.67	0.03	50	0.24	low-volatile bituminous
Boltigen	Dogger	M1	613/87	1.28	0.04	50	0.11	med. volatile bituminous

^aStandard deviation, ^bnumber of measurements, ^crandom reflectance, ^dB-numbers correspond to Beck (1948, table 6), ^esamples provided by P.Y. Jeannin.

dard maximum reflectance measurements determined in each of the tectonic units of the study area (Fig. 1) and a comparison with mineral diagenesis and metamorphism and the estimation of maximum burial temperatures using time/temperature burial curves.

Wildhorn nappe, Kander valley

Fourteen samples from the Kander valley were analyzed for their vitrinite reflectances. The values range from 1.72 to 2.5% R_{\max} with a mean of $2.15\% \pm 0.2$. The reflectance appears to increase from Horn (1.86 ± 0.14) to Lindi (2.09 ± 0.09) to Schlafegg (2.31 ± 0.12). This means that the coal rank increases from paleogeographically external to more internal positions within the Wildhorn nappe. Horn and Lindi are localities situated below an internal thrust of the Wildhorn nappe and are paleogeographically identical to the Border chain. The area at Schlafegg lies on the normal limb of a major syncline of the frontal Wildhorn nappe which is thrust over Horn and Lindi.

From the present-day geometry it is difficult to explain the increase in maturation from the lower to the upper parts within the Wildhorn nappe which in fact corresponds to an inverse zonation. It is therefore postulated that the internal thrusting and final emplacement of the Wildhorn nappe took place after the peak metamorphism.

Index minerals and illite crystallinities

From the numerous clay and zeolite minerals listed as indicators for sub-stages of the diagenesis by Kübler et al. (1979) a few have been searched for and found in this area; a short summary is given below (Fig. 3).

Laumontite is present in the Upper Eocene to Early Oligocene Taveyannaz sandstone which occurs below the Wildhorn nappe in the Kander valley (Kisch, 1980) and as tectonic slivers within the subalpine flysch underneath the Border chain. Laumontite is considered as a sensitive indicator of diagenesis (see Fig. 3). Its stability is probably restricted to temperatures below 200°C . At higher temperatures, laumontite disappears and pumpellyite (\pm prehnite) appears in the anchizone (i.e. Bussy and Epard, 1984). In the studied cross section (Fig. 2), the Taveyannaz sandstone formation, which contains reworked andesitic material is the only potential lithology from which to observe this transition. The first appearance of pumpellyite is found some 5 km south of the Kander valley at the top of the Gellihorn nappe (Künzi, 1975; see Frey, 1986, plate).

Glaucinite/Stilpnomelane. Glaucinite occurs frequently within Cretaceous Kieselkalk (Hauterivian) and in Tertiary sandstones. The first appearance of stilpnomelane as a reaction product of glaucinite chlorite and quartz (Frey et al., 1973) is located about 6 km south of Kandergrund within the Gellihorn

	DIAGENESIS	ANCHIZONE	EPIZONE
ILLITE			
CRYSTALLINITY 2°2θ	0.42	0.25	
SHALES:			
Smectites	—————		
Illite/smectite	—————		
Corrensite	—————		
Kaolinite	—————		
Pyrophyllite		—————	
Chloritoid			—————
META GRAYWACKES:			
Heulandite	—————		
Laumontite	—————		
Prehnite		—————	
Pumpellyite		—————	
Epidote			—————
Actinolite			—————
Glaucanite	—————		
Stilpnomelane		—————	
Biotite			—————
Temperature estimated °C	200	300	
Ro range: Kübler et al. 1979: (Rm)	2.6–2.8 %	4.0 %	
Frey 1986: (Rmax)	2.8–6.0 %	6.0 – ? %	
calculated with Lopatin (Rmax)	2.5–3.3 %	7.7 – (9.8) %	

Fig. 3. Comparison of different indicators of very low grade metamorphism according to Kübler et al. (1979) and Frey (1986). Note that vitrinite reflectances are dependent on time of exposure and temperature and vary from author to author. Calculated reflectances are based on Lopatin's calculation for 200°C and 300°C respectively, valuable for Helvetic sediments, Liassic to Tertiary in age, with sedimentary burial of less than 3 km and relatively short tectonic burial between Upper Eocene (40 Ma) and today. V-shaped tectonic burial curves for Eocene sediments give minimum values, U-shaped (10 Ma at maximum temperature) curves for Liassic sediments yield maximum values. For detailed discussion see text.

and Doldenhorn nappe (see Fig. 2b). This corresponds roughly to the limit of anchimetamorphism as determined by illite crystallinity (Künzi in Masson et al., 1980, Burkhard, 1988).

Pyrophyllite is considered the most reliable indicator for anchizonal metamorphism (Frey, 1986, 1987), and the reaction isograd kaolinite + quartz = pyrophyllite + H₂O has been mapped north of the Gastern-(Aar) massif. The cross section (Fig. 2b) shows the first appearance of pyrophyllite in the frontal Doldenhorn nappe in the Eocene Böhnerz formation (Wieland, 1976).

On the other hand, Baud (1984) and Bertherin (1980) describe pyrophyllite from the "Préalpes médianes rigides" in karstic Böhnerz deposits of Triassic age. Pyrophyllite is also known from Ultrahelvetetic Aalenien shales in the Zone des Cols (Massaad, 1973) directly below the Pennine thrust of the Prealps. Both occurrences lie north of the Kander valley and indicate clearly inverse metamorphic zonation between the Pennine Prealps and the underlying Wildhorn nappe.

Clay minerals. Many clay minerals like smectites or mixed layered illite/smectite are commonly restricted to the diagenesis (Kübler et al., 1979). The disappearance of smectites and concomitant formation of 2:1 mixed layers was observed by Monnier (1982) who introduced a division of the diagenesis in 15 drilled wells within the molasse basin. At any rate, the frontal Helvetic nappes lie not within the stability field of smectites. On the other hand, the disappearance of mixed layers with increasing metamorphic grade is gradual and difficult to quantify and so far no attempt has been made to establish zonations within the diagenesis in the frontal part of the alpine nappes by mapping the disappearance of mixed layers.

Illite crystallinity. From a great number of illite crystallinity analyses (Frey et al., 1980; Burkhard, 1988) the anchi-/epizone boundary in this profile can be placed within the Doldenhorn nappe with a fair level of confidence. The anchizone occupies only a narrow band of about 3–4 km (on a map) in the frontal parts of the Doldenhorn nappe including rear parts of the Gellihorn and Wildhorn nappes. The frontal Wildhorn nappe (Kander valley, Border chain) lies entirely within the range of diagenesis. However, there exists a slight discrepancy between different authors: Frey et al. (1980) determine anchizone conditions somewhat further to the north than Burkhard (1988). This might be merely a problem of calibration of the illite crystallinity zone boundaries and underlines the general uncertainty which exists with the definition of the diagenesis/anchizone boundary based on illite crystallinities alone.

Summary. In conclusion the northern Wildhorn nappe in the Kander valley lies within the range of diagenesis but relatively close to the anchizone region. This diagenetic part of the Wildhorn nappe is overridden by partly anchizone Prealps and Ultrahelvetic units.

Coalification and burial history

It is generally accepted, that the rank of organic matter is a function of both temperature and time. A similar degree of rank can be obtained by a long time of exposure at low temperature or alternatively by a shorter time at a relatively higher temperature (Karweil, 1955). Consequently, reflectance data are not immediately convertible into metamorphic temperatures but the time of heat exposure has to be considered as well. Due to the fact that the analyzed coals from the Kander valley are Tertiary and that no important sedimentation took place after deposition, their degree of maturation must be due to tectonic burial alone. Tectonic burial histories are far less constrained than those for sedimentary basins with an accurately established stratigraphy. While the timing of thrusting and deformation in the Helvetic nappes is relatively well constrained, depths of burial are not known and only roughly estimated from the present thickness of the different nappes and the degree of metamorphism. As the burial history of the coals from the Wildhorn nappe is comparatively short,

chances are that reflectance data allow a fairly precise determination of the maximum burial temperature. This in turn is an important piece of information which bears on the possible tectonic histories and models of this northernmost part of the Alps (Mugnier and Ménard, 1986; Burkhard, 1988).

Lopatin's method as outlined in Waples (1980) allows the calculation of an expected Time-Temperature-Index (TTI) for any sediment if its burial curve in time/temperature space is known. The conversion of TTI into vitrinite reflectance (R_0) is given by Waples (1980, table 4) and by Bustin et al. (1985, p. 16) in form of the following formula: $R_0 = -0.10528 \times \log \text{TTI} + 0.20647 \times (\log \text{TTI})^2 + 0.5011$, for TTI greater than 3. Calculated TTI (R_{max}) values in this study have been obtained by computer calculations using the continuous integral formula for TTI values given by Bustin et al. (1985, p. 16):

$$\text{TTI} = \int_{t_0}^{t_p} 2^{[T(t) - 105]/10} dt$$

where $T(t)$ is temperature ($^{\circ}\text{C}$) as a function of time (t) from time of deposition (t_0) to the present (t_p). Lopatin's method is designed to calculate rank from a known burial history in a sedimentary basin but the procedure can also be reversed. If the rank is known, different burial histories in time/temperature space can be tested until this curve matches the measured rank. Obviously, there will be an infinite number of possible burial curves which yield the desired TTI, but only few of them will be acceptable in tectonic models. This will now be examined for the case of the Wildhorn nappe.

Kander valley

Suppose that the Wildhorn nappe was covered by a thick sheet of prealpine nappes immediately after the emplacement of the ultrahelvetetic units about 40 Ma ago and that the temperature rose instantly to a level according to this new depth. Further let the uplift (cooling) be equally sharp at 0 Ma (Fig. 4, path a). This is certainly an unrealistic scenario, but it leads to the maximally possible time of exposure at a certain temperature which therefore can be assumed to be an absolute minimum temperature of burial. To obtain the measured rank of $2.09\% \pm 0.09 R_0$ temperatures must lie close to 155°C . This determination was made by trial and error, using Lopatin's method and calculating TTI (respectively R_0) for several temperatures in 10°C steps: 145, 155 and 165°C resulting in 1.86, 2.15 and 2.48% R_0 respectively.

In a second model, we assume a V-shaped burial/uplift curve where both burial and uplift are linear in time/temperature space with a peak temperature at 20 Ma (Fig. 4, path b). For peak temperatures of 175, 185 and 195°C , 1.72, 2.01 and 2.33% R_0 are obtained. Thus 190°C represents a maximum temperature in this model. This determination is independent of the time at which

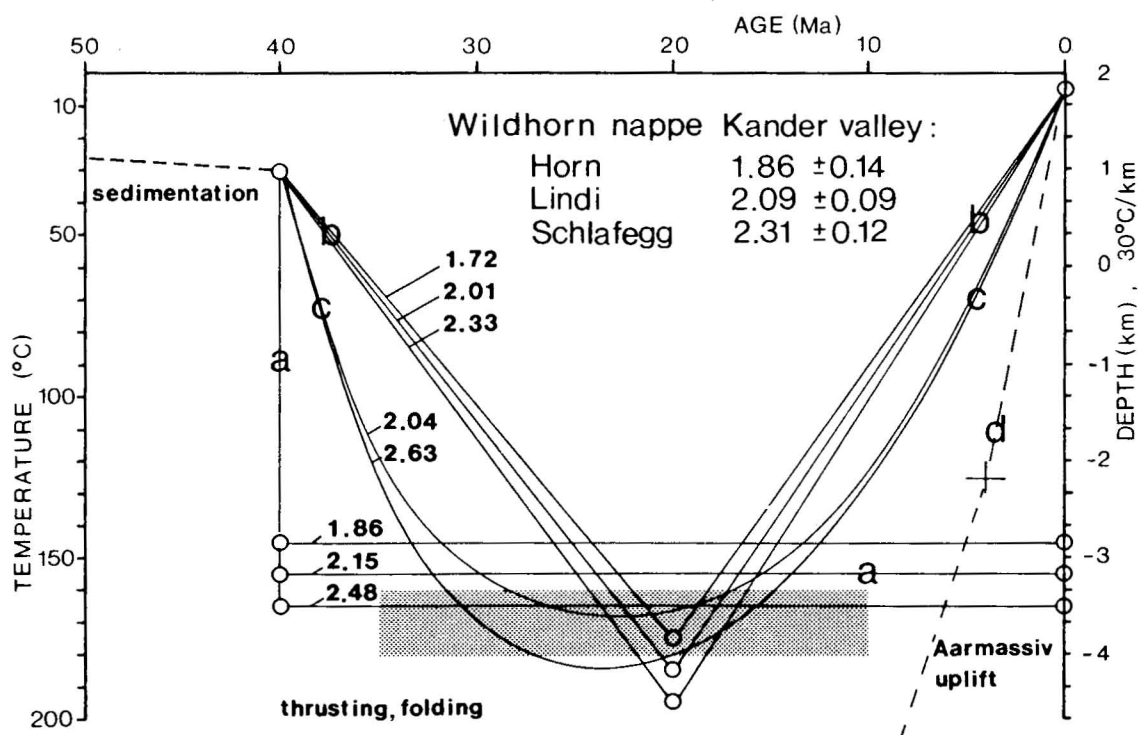


Fig. 4. Burial curves in time/temperature space for the frontal Wildhorn nappe in the Kander valley. Measured vitrinite reflectances ($\% R_{\max}$) for three mining areas Horn, Lindi and Schlafegg are compared with calculated reflectances indicated as bold numbers ($\% R_{\max}$) on corresponding burial curves (Lopatin's method). Curves a, b, c are hypothetical paths discussed in text. Curve d shows the uplift history of the Aarmassiv as determined by radiometric methods (Schaer et al., 1975; Wagner et al., 1977). Reasonable burial curves for the northern Wildhorn nappe have to pass through the stippled area. As Lopatin's calculation is only time/temperature dependent, the depth scale on the right hand side has no influence on the model but allows the estimation of tectonic burial in terms of thickness of overriding nappes. This scale is based on the present-day situation with 0°C at 2000 m and an estimated geothermal gradient of $30^{\circ}\text{C}/\text{km}$.

the peak temperature is attained as long as both burial and uplift are linear in t/T -space. Any asymmetric V-shaped curve results in the same rank as a symmetric V with the same maximum temperature.

It can be shown, that any concave U-shaped curve (without convex upward parts) (i.e. Fig. 4, path c), symmetric or asymmetric, must have its peak temperature between the two extreme models a and b in order to yield the required rank. The broader the U at the base, the lower will be the temperature at its deepest point. For instance, if half of the disposable time (20 Ma) is spent at the maximum temperature (with linear burial and uplift), 165°C is required to yield a R_0 value of 2.22%.

In summary it appears that reasonable (smooth) burial histories in t/T -space must have their peak temperatures between 160 and 180°C . In Fig. 4, the shaded area indicates the temperature/time range where reasonable burial curves will pass. Note that other burial models (Bostick, 1979; Bustin et al., 1985, fig. 9) yield slightly higher temperatures (up to 220°C) for V-shaped

burial curves with short 'effective heating times' but are similar for the U-shaped curves with close to 20 Ma of 'effective heating time'.

Assuming a normal geothermal gradient (30°C/km) a maximum tectonic cover of about 6 km is therefore needed to account for the observed rank. The total thickness of the Prealps in its thickest parts is now only about 2–3 km. Important parts of the Prealps have been eroded since Oligocene times (Simme and Breccia nappe, Trümpy and Bersier, 1954) and a tectonic thinning of the Pennine sheet cannot be excluded either. The present-day uplift rate in this section of the Kander valley is 0.5–1 mm/a (Gubler et al., 1984) which also corresponds roughly to the erosion rate of the Kander river (Jäckli, 1958). For the Aarmassiv, Schaer et al. (1975) and Wagner et al. (1977) have shown, that Miocene uplift rates determined by Rb-Sr, K-Ar and apatite fission track dating were very similar to the present-day uplift. This uplift trend for the Aarmassiv is shown in Fig. 4, path d. If an equally constant but slower uplift for the Kander valley is postulated, the uplift must have started at 12 to 6 Ma ago (for 0.5 and 1 mm/a uplift, respectively). This is surprisingly late in the tectonic evolution of the Wildhorn nappe and leaves a long time span influencing the rank. Its burial curve resembles probably rather a broad U than a sharp V (Fig. 4).

Beatenberg

Using the same procedure as outlined above, peak temperatures attained in the Border chain at Beatenberg must have been in the order of 100° to 130°C to attain vitrinite reflectances of 0.73% R_{\max} . Accordingly, only about 3–4 km of maximal overburden have to be postulated. Still, this allows for a substantial thickness of prealpine nappes which would formerly have lain on top of this most external part of the Wildhorn nappe. Only small remnants of this sheet are preserved in the Klippen syncline (Fig. 1).

Subalpine Molasse

The burial history of these coals is better constrained than that of the Helvetic nappes (Fig. 5). Deposition occurred at the base of the lower freshwater molasse (Chattian 30 Ma). The stratigraphic section above this coal in the subalpine molasse cannot be established directly because it is truncated by thrusts. From a nearby drill hole at Linden (Matter et al., 1980, fig. 8) it can be extrapolated that more than 3 km of lower fresh water molasse (Chattian and Aquitanian) and about 1 km of upper marine molasse (Burdigalian) have been accumulated after the sedimentation of these coals. These are rather under- than overestimates because the thickness of these molasse layers tends to increase considerably towards the Alps. Thrusting and uplift started at about 15 Ma (Scherrer, 1966). This thrusting was a relatively short event and probably terminated at about 10 Ma and only minor uplift/erosion of about 1 km took place since then (Lemcke, 1974). Schematic burial curves for coals from

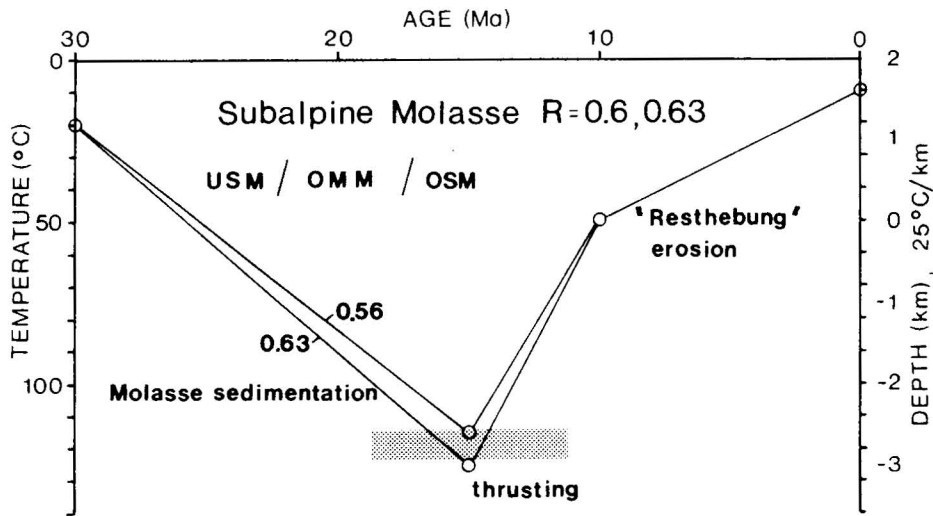


Fig. 5. Burial curves for the Subalpine Molasse, same principle as Fig. 4. Coal deposition at about 30 Ma at the base of the lower freshwater molasse (USM) is followed by rapid sedimentation of some km of USM, upper marine molasse (OMM) and upper freshwater molasse (OSM). Thrusting, subsequent uplift and erosion started at ca. 15 Ma. The depth scale to the right is constructed with 0°C at 2000 m and a geothermal gradient of $25^{\circ}\text{C}/\text{km}$ which corresponds to present-day conditions for this part of the Alps.

this stratigraphic interval are constructed in Fig. 5. Peak temperatures between 115 and 125°C are required to yield the observed vitrinite reflectance of 0.6 – 0.63% R_0 . Recently, geothermal gradients in this area were determined from deep drill holes (Linden 1 and Entlebuch 1) at around $25^{\circ}\text{C}/\text{km}$ (Rybach et al., 1986). This gradient and an estimated burial of 5 km at approximately 15 Ma, followed by a rapid uplift could well account for the observed rank of 0.6 – 0.63% R_{max} .

Plateau Molasse

Coalification in the (folded) plateau molasse (Miocene) at Linden near Ob-erdiesbach is too weak to allow a temperature estimation with Lopatin's method. Burial of this horizon was probably never more than 1 km (Matter et al., 1980, fig. 8), and led to an expected TTI value of less than 1 which corresponds to the observed coalification stage of lignite ($R_{\text{random}} = 0.39\%$). This is further in good agreement with Monnier (1982, fig. 13) who found the onset of a potential oil generation at 2.7 km depth in the Linden 1 well as defined by the disappearance of smectites and the concomitant appearance of 2:1 mixed layers. According to Waples (1980) the onset of oil generation corresponds to a TTI value of 15 ($R_0 = 0.65\%$) but other authors place this limit already at $\text{TTI} = 7$ ($R_0 = 0.55\%$). Calculated vitrinite reflectance data for this drill hole are shown in Fig. 6. It can be seen that the situation is compatible with the known ages and thicknesses of sediments, a geothermal gradient close to the present-day gradient of $26.6^{\circ}\text{C}/\text{km}$ (Rybach et al., 1987) and a postulated uplift ("Resthebung") of about 1 km since the Late Miocene (Lemcke, 1974).

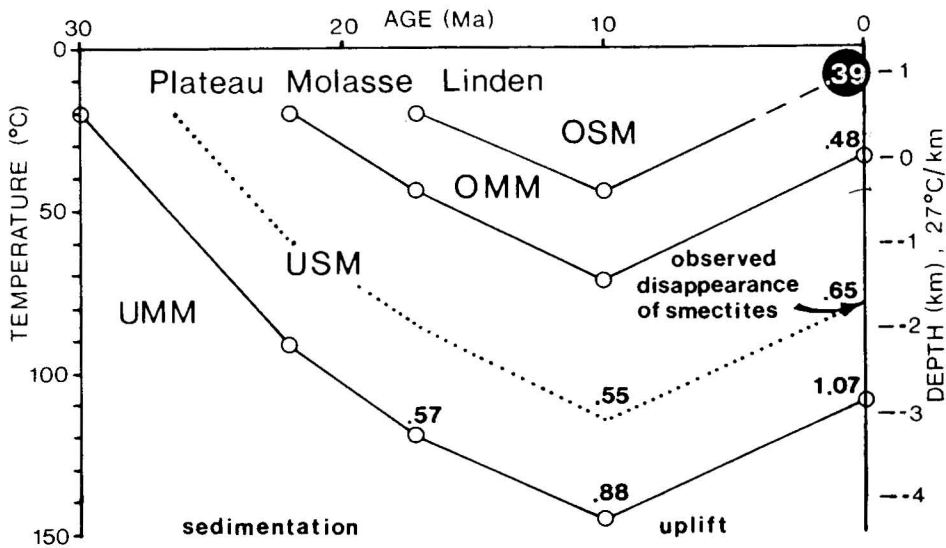


Fig. 6. Schematic burial history of the Plateau Molasse at the Linden 1 well. UMM=lower marine molasse, USM=lower freshwater molasse, OMM=upper marine molasse, OSM=upper freshwater molasse. Calculated vitrinite reflectances ($\% R_{\max}$, bold numbers) for different stratigraphic intervals are compared with one measured vitrinite reflectance at the surface and the disappearance of smectites at 2.7 km below surface (Monnier, 1982). This limit is interpreted as “onset of oil generation” usually correlated with reflectances of 0.55 to 0.65.

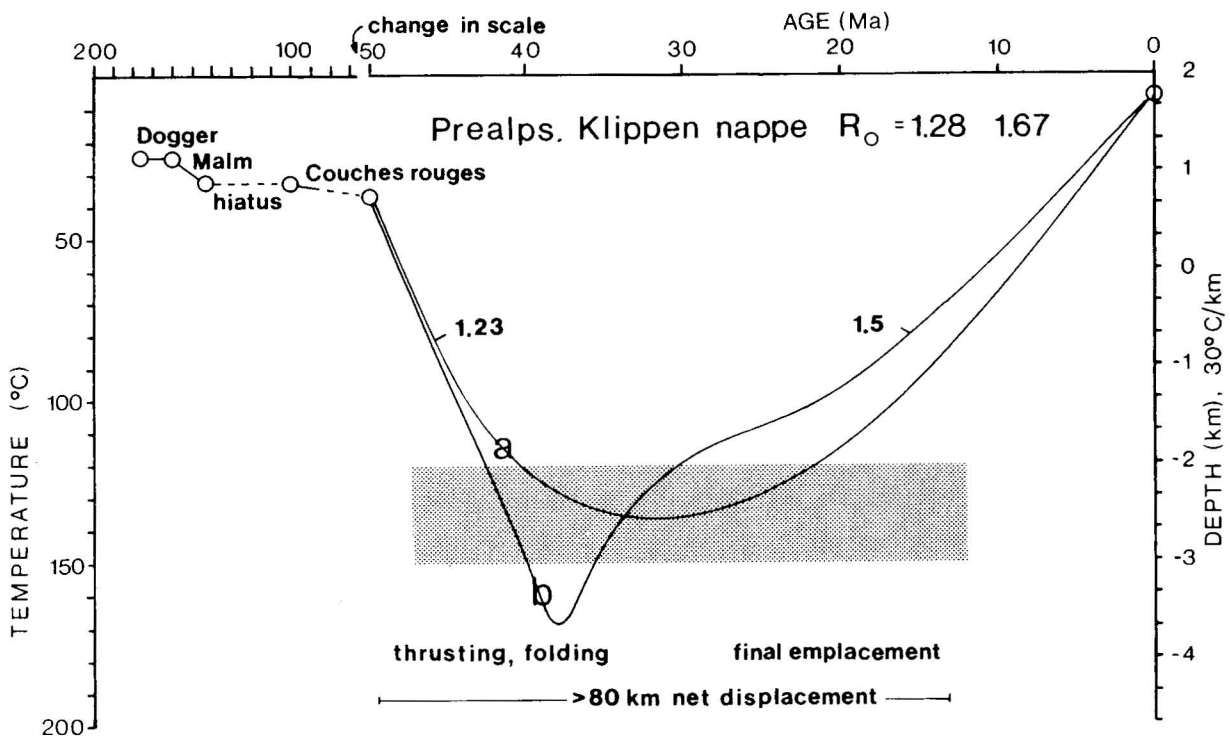


Fig. 7. Burial curves for the Pennine Klippen nappe at Boltigen and Erlenbach. Coal deposition took place in the Mytilus Dogger and is followed by slow sedimentation of some hundred meters of Malm, immersion and erosion? during lower Cretaceous times, and sedimentation of 200–300 m of “Couches rouges” and flysch. Tectonic burial started in Upper Eocene times, final emplacement on molasse at about 15 Ma is followed by uplift and erosion. For detailed discussion see text.

Pennine Klippen nappe

The geological history of these coals is more complicated as they are much older and potentially, their rank could be due to both sedimentary and tectonic burial. Coals from the Klippen nappe occur within the *Mytilus* Dogger beds and are overlain by Malm and "Couche Rouges". The thickness of the latter two measures only about 300 m together and unless a very high paleogeothermal gradient is postulated, the long time span between deposition and the onset of tectonic burial has virtually no influence on the calculated rank. On the other hand the tectonic history of these far travelled units is much more complex, longer and less constrained than for the Helvetic nappes. The youngest flyschs found in parts of the prealpine Klippen nappe are Middle to Upper Eocene (Matter et al., 1980, fig. 2). Assuming again simple scenarios with a starting point for the burial at 50 Ma, peak temperatures of 120–150°C (Boltigen) and 130–150°C (Erlenbach) were obtained, resulting in vitrinite reflectances of 1.28 and 1.67% R_{\max} respectively (Fig. 7, path a). Slightly higher temperatures (170°C) are obtained with the assumption of partly convex burial curves (i.e. Fig. 7, path b).

Within the Prealps, an increase in metamorphic grade from the front to its rear parts is known from the literature. Anchizonal conditions are encountered in the internal "Préalpes médianes" (Baud, 1984), and Dortmann (1982) found an increase in vitrinite reflectance from 3 to 5% R_{\max} within the Niesen nappe. For more details see Mosar (1988). The anchizonal metamorphism of the Niesen- and rear parts of the Klippen nappe is overlying the diagenetic Wildhorn nappe which in the Kander valley was never buried deeper than 6 km. This inverted zonation shows, that considerable transport of the Prealps must have taken place after the deepest burial of its lower units. If one considers the age of the youngest flyschs on the Helvetic nappes as the time limit for thrusting of the Pennine nappes over the Helvetics, the peak temperature in the Prealps must have been reached before early Oligocene (approximately 35 Ma).

CONCLUSION

Vitrinite reflectance data are in good agreement with the established metamorphic zonation in the northern Helvetic nappes. The general trend of increasing paleotemperatures from the outer toward the inner zones of the Alps is confirmed. Detailed zonation is possible even in the diagenesis to a degree of resolution which is not attained with any other method. Transported metamorphism is evident for the Pennine Prealps where anchi-metamorphic rocks are thrust over diagenetic Helvetic units. Inverse zonations as revealed by vitrinite reflectance exist also within the Helvetic Wildhorn nappe in the Kander valley. Slightly more "metamorphic" internal parts of the nappe override the external "Schuppen" after the peak of metamorphism. By modelling possible tectonic burial histories, maximum burial temperatures can be deter-

mined to within $\pm 10^\circ\text{C}$ using Lopatin's method. Such determinations are precious pieces of information for the reconstruction of the tectonic evolution of the northern parts of the Alps.

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