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Coalification in Carboniferous sediments from the Lötschberg base tunnel

David J. A. Williams [1], Beda A. Hofmann [2,*] & Ian G. Glasspool [3]

Key words: coalification, vitrinite reflectance, C isotopes, Carboniferous coals.

ABSTRACT

Vitrinite reflectance (Rr), proximate analysis and carbon isotope composition ($\delta^{13}C$) have been used to characterise coal samples from two zones of Late Carboniferous sediments (Gastern and Ferden) in the Aar massif where they are penetrated by the Lötschberg base tunnel (constructed between 1999 and 2005). Samples are characterised by variable ash yields (21.7–93.9%; dry basis); those with ash yields of less than ~50% and with volatile matter content (V; dry ash-free basis) within the limits $2 < V\% \leq 8$ are anthracite. Values of Rr range from 3.89% to 5.17% and indicate coalification to the rank of anthracite and meta-anthracite in both Gastern and Ferden Carboniferous zones. Samples of anthracite and shale from the Gastern Carboniferous exhibit a relatively small range in $\delta^{13}C$ values (–24.52‰ to –23.38‰; mean: –23.86‰) and are lighter than anthracite samples from the Ferden Carboniferous (mean: –22.20‰).

The degree of coalification in the Gastern and Ferden Carboniferous zones primarily depends on the maximum rock temperature (T) attained as a result of burial heating. Vitrinite reflectance based estimates of T range from ~290°–360 °C. For a proposed palaeogeothemal gradient of 25 °C/km at the time of maximum coalification the required overburden is attributable to relatively thin autochtonous Mesozoic/Cenozoic sedimentary cover of the Aar massif and Gastern granite and deep tectonic burial beneath advancing Helvetic, Ultrahelvetic and Prealpine (Penninic) nappes in Early Oligocene to Miocene.

Introduction

Coalification in sedimentary rocks of the Helvetic zone of central Switzerland (Fig. 1) continues to be of interest. In particular, vitrinite reflectance measurements on dispersed organic matter in rocks of Mesozoic to Lower Tertiary age of the Wildhorn, Gellihorn and Doldenhorn nappes (Frey et al. 1980; Suchy et al. 1997; Árkai et al. 2002) and on Eocene coals from the northern Wildhorn nappe (Burkhard & Kalkreuth 1989) have been used in the determination of metamorphic zonation in these units and in the elucidation of their thermal and burial histories. In comparison, our knowledge of coalification in the Carboniferous rocks of the Helvetic zone is quite incomplete being limited to minimal physical (Kübler et al. 1979; their table 4) and chemical (Kündig & de Quervain 1953; their table 1) coal rank data for the Ferden Carboniferous zone (Aar massif) in which coalification is known to have reached the anthracite stage (Hügi et al. 1988).

The Ferden Carboniferous zone and a previously unknown Carboniferous zone in the Gastern granite were encountered during the construction of the Lötschberg base tunnel (LBT) between Frutigen in the Kander valley and Raron in Valais (Kellerhals & Isler 1998) (Fig. 1). Samples were obtained from areas of contact between the LBT and these zones in order to determine their degree of coalification through the use of proximate analysis (moisture, ash, volatile matter) and measurements of mean random vitrinite reflectance (Rr). In addition, anthracite and carbonaceous shale from the Gastern and Ferden Carboniferous zones and, for comparison, coals of various known ages from a number of other geological units in Switzerland were analysed for C isotopes to test for possible isotopic correlations.

Vitrinite reflectance measurements are readily converted into maximum palaeotemperatures (T). Time-dependent (kinetic models) and time-independent (statistical correlations between Rr and T) methods have been developed (for reviews

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[1] School of Engineering, Swansea University, Swansea, UK, d.j.a.williams@swansea.ac.uk
[2] Earth Science Department, Naturhistorisches Museum der Burgergemeinde Bern, Bernastrasse 15, CH-3005, Bern, Switzerland.
[3] Department of Geology, Field Museum of Natural History, 1400 S. Lake Shore Drive, Chicago IL, 60605, USA.
*Corresponding author: Beda A. Hofmann. E-mail: beda.hofmann@geo.unibe.ch

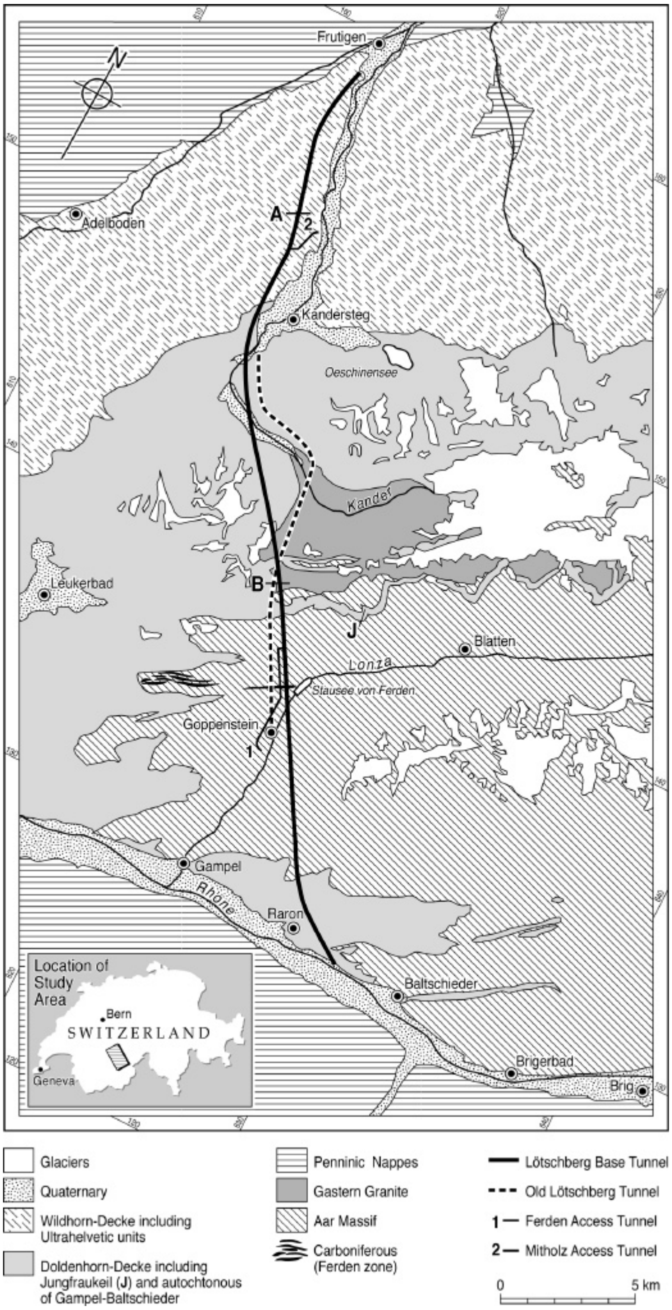

Fig. 1. Tectonic map of the study area, modified after Kellerhals and Isler (1998). The position of the profile shown in Fig. 2 is marked on the Lötschberg base tunnel axis (A-B).

see Barker & Pawlewicz 1994 and Taylor et al. 1998) of which the latter find application if vitrinite reflectance data are for sedimentary rocks with complex and poorly constrained burial and thermal histories (Laughland & Underwood 1993; Barker & Pawlewicz 1994; Uysal et al. 2000). In the present study vitrinite reflectance data are used to estimate maximum burial temperatures during the time of maximum coalification in the Ferden and Gastern Carboniferous zones. These temperatures provide additional constraints on the thermal history of this section of the Helvetic zone presently constrained by palaeothermal data derived using fluid inclusion, vitrinite reflectance and a combination of calcite-graphite and calcite-dolomite thermometry (Herwegh & Pfiffner 2005; and references therein).

Geological setting

In the present work the tectonic nomenclature used by the BLS-Alp Transit Geologists has been adopted (Kellerhals and Isler 1998). For instance the Gastern massif is included in the Aar massif although tectonic publications frequently consider them as two distinct crystalline massifs.

The Ferden and Gastern Carboniferous zones form wedges in the crystalline basement of the Aar massif, where they make contact with the LBT and the Ferden access tunnel (Figs. 1 and 2).

In its northern section the LBT passes through Lower Tertiary sediments (flysch and Taveyannaz sandstone) and a succession of Mesozoic rocks of the Wildhorn and Doldenhorn nappes (limestone, marly limestone and slate) and the Autochton Nord (sandstone and slate) before encountering a Triassic/Carboniferous zone beneath the basal thrust plane of the Doldenhorn nappe (Fig. 2).

The Triassic sediments (sandstone, siltstone, anhydrite and shale) are succeeded in an adjoining section 15.7–16.0 km south of the Frutigen portal by sediments (sandstone, shale and coal) which have been dated to Stephanian B (Brousmiche Delcambre & Menkveld-Gfeller 2007).

South of this Carboniferous zone the LBT passes through rocks of the crystalline basement (Gastern granite and gneiss of the Aar massif) before encountering Mesozoic rocks (limestones) of the Jungfraukeil (Fig. 1) 24.42 km south of Frutigen.

The Ferden Carboniferous zone is encountered by the LBT 1.58 km (tunnel metres) south of the Jungfraukeil (Kellerhals & Isler 2004). The sediments (graphitic slate, sandstone, conglomerates and lenses of anthracite) of this zone form a thin steeply dipping wedge (80° to the south) in the gneiss of the Aar massif (Hügi et al. 1988; Kellerhals & Isler 2004). The lithology of these sediments and that of the Gastern Carboniferous zone is typical of the Late Carboniferous fluvio-lacustrine sediments of the external massifs (Aiguilles Rouges and Aar). These coal-bearing formations are thought to have been laid down in intra-montane basins isolated from each other (Trümpy 1980, Niklaus & Wetzel 1996).

Samples and Methods

Samples for proximate analysis and vitrinite reflectance measurement were from the Ferden Carboniferous zone (samples FT1-FT4; BT1-BT2) and the Gastern Carboniferous zone

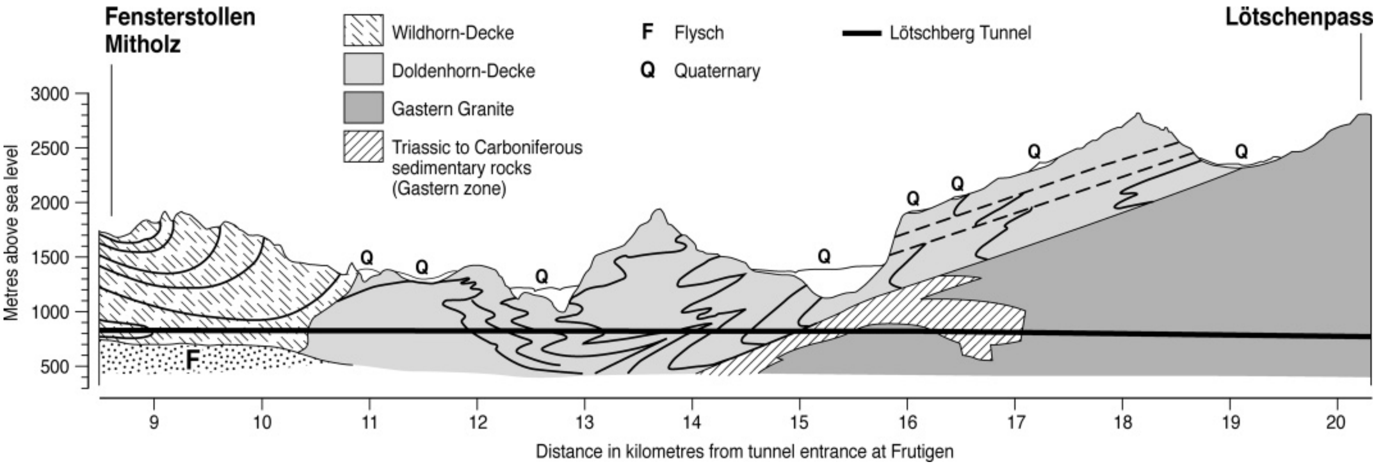

Fig. 2. Geological cross-section of the northern part of the Lötschberg base tunnel, based on web data published by the BLS-AlpTransit Geologists on November 6, 2006.

(samples BT3-BT6); sample locations and elevations are given in Table 3.

Proximate analysis was carried out in accordance with the methods of the British Standards Institution (1998) for volatile matter and ash content and the British Standards Institution (1999) for moisture content except that a desiccator was not used.

Samples FT1-FT4 were prepared for vitrinite reflectance measurement in accordance with ISO 7404/2 methods (International Organisation for Standardisation 1985) and measurement of mean random vitrinite reflectance followed the procedures of ISO 7404/5 (International Organisation for Standardisation 1984) except that measurements were made using a Sony XC-ST50 monochrome video camera and Leica QWin image analysis software calibrated against four reflectance standards.

Vitrinite reflectance analysis of samples BT1-BT6 was carried out by OceanGrove Geoscience, Aberdeen UK using a Leitz Ortholux microscope system equipped with a monochromatic light source ($\lambda = 546$ nm), ×50 objective lens and a photometer. This system was calibrated with two standards whose values of Rr did not overlap those for anthracitic material. However, a vitrinite reflectance measurement (Rr = 4.38, n = 46, s = 0.47) on material from sample FT1 compared well with the value obtained with the automated procedure (Tab. 1) and provided a satisfactory check on the linearity of the measuring system. The ranks (ASTM classification) of coals – other than those from the LBT – are based on published vitrinite reflectance measurements and/or V% (daf) values calculated using the chemical data (A (d), V (d)) of Kündig & de Quervain (1953) as follows:

(i) vitrinite reflectance measurements by Schegg (1992) on outcrop samples from Oron and Käpfnach in the Swiss Molasse Basin are in the range $0.43 \leq \mathrm{Rr} \leq 0.67$ which together with V% (daf) values of 52.2 and 50.7 indicate coalification to sub-bituminous rank;

(ii) the ranks of coals from the localities of Horn, Schlafegg, Lindi, Niederhorn and Boltigen are based on average values of Rmax determined by Burkhard & Kalkreuth (1989; their table 2);

(iii) the coal from Diemtigen is assumed to be of similar rank to other Dogger coal from Boltigen;

(iv) the coal sample from the Weiach borehole is from a depth of 1491 m at which the Rmax measurements of Wolf & Hagemann (1987) are in the range $0.9 \leq \mathrm{Rmax} \leq 0.98$ corresponding to coalification to high volatile bituminous rank and

(v) the V% (daf) values of 4.28 and 7.81 for coals from Dorenaz and Chandoline respectively are indicative of anthracite rank.

Carbon isotopes were determined for Carboniferous samples from the LBT and for samples of coal, shale and fossil wood of known ages (Carboniferous, lower and middle Jurassic, Eocene, Miocene) from other Swiss locations. For carbon isotope measurements, samples of a few grams of material were ground to a fine powder and leached with 10% HCl for 24 hrs at room temperature to dissolve any carbonates. Samples were then repeatedly washed with deionized water and dried. Carbon isotope measurements were performed at the Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado, USA, using a Thermo Quest EA 110 elemental analyser coupled to an Isoprime continuous flow mass spectrometer. All values are reported as $\delta^{13}C$ representing the deviation (per mil) of the $^{13}C/^{12}C$ isotopic ratio from the ratio in the Pee Dee – Belemnite standard; reproducibility averages 0.13‰. The accuracy, based on the standard deviation of 12 analyses of an atropina standard, was 0.14‰.

Results

Proximate analysis and vitrinite reflectance.

The results of proximate analyses and vitrinite reflectance measurements are summarised in Table 1. Samples from both Carboniferous zones are characterised by variable ash yields. The relatively high ash yield of some of the samples necessitates care in their description. Coal with more than ~50% ash is usually more correctly described in non-coal terms such as carbonaceous shale or coaly shale (see Diessel 1992). Thus, only samples FT3, BT1, BT3, BT4 and BT6 can be described as coals.

Further, the high ash content of these samples makes it likely that their analytically determined volatile content includes volatile matter evolved from minerals during the heating stage, thereby impairing the use of V%(daf) as a rank parameter. Nevertheless, the values of V% (daf) for Ferden and Gastern coals (Table 1) are within the limits for anthracite ($2 < V\% \text{ (daf)} \leq 8$; Taylor et al. 1998) and in reasonable agreement with a value of 6.4% calculated using the chemical data (A (d), V (d)) of Kündig & de Quervain (1953) for a Ferden coal sample (Ferden mine, Goltschenried).

Values of Rr range from 3.89% to 5.17%. In terms of the limits for Rr prescribed by the ASTM classification (Stach et al. 1982; their table 4A) the degree of coalification in both Carboniferous zones increases from anthracite ($2.5 < Rr \leq 5.1$) to meta-anthracite ($Rr > 5.1$) and is in accord with a value of Rmax of 5.51% for a sample from the study area (Faldum Rothorn, Swiss coordinates 621.1/135.1; Kübler et al. 1979).

Carbon isotopes

The carbon isotope compositions of samples of coal, shale and fossil wood of different ages are presented in Table 2. The $\delta^{13}C$ values vary with deposit age with average values of –25.4‰ and –24.5‰ for Miocene and Eocene samples respectively and –23.36‰ for Carboniferous samples and are (except perhaps for samples 36498, 36495,36505 and 37303) within the range expected for C_3 (Calvin cycle) plants (–27‰ to –23‰, average: ~ –24‰; Gröcke 2002). In particular $\delta^{13}C$ values for coals are within the range (–27‰ to –22‰) reported by Whiticar (1996) for other coals from Europe and USA.

Miocene samples from the Swiss Molasse Basin exhibit rather variable $\delta^{13}C$ values. In contrast there is little variation in the carbon isotopes compositions of Eocene samples although coals from the Wildhorn nappe appear to exhibit (relative to the PDB standard) a slight enrichment in ^{13}C with increasing rank (high volatile bituminous to semi-anthracite).

The $\delta^{13}C$ values for the ten samples of certain Carboniferous age range from –24.52‰ to –22.02‰. A similar range of $\delta^{13}C$ values for anthracite (–24.2‰ to –22.7‰) and bituminous coals (–24.1‰ to –23.1‰) of Late Carboniferous age from the S.Wales coalfield was obtained by Alderton et al. (2004).

Sample 30616 from the Apex tunnel is isotopically lighter than the samples of definite Carboniferous age. The geological position of this sample has been attributed to both Carboniferous (Brückner 1943) and Tertiary Flysch (Beck 1912).

Table 1. Proximate analyses and vitrinite reflectance data for samples from the study area.

Sample	M (%)	A(d) (%)	V(d) (%)	V(daf) (%)	Rr (%)	n	s
FT1	0.2	67.1	4.5	13.7	4.02	500	0.59
FT2	0.2	68.2	4.3	13.5	4.10	500	0.56
FT3	0.9	51.2	2.5	5.1	4.05	500	0.54
FT4	0.4	84.3	4.1	26.1	3.89	500	0.49
BT1	0.7	49.4	2.3	4.6	4.83	99	0.69
BT2	0.5	74.1	3.4	13.1	5.17	90	0.97
BT3	2.4	26.4	2.5	3.3	4.66	65	0.43
BT4	3.7	21.7	2.0	2.5	4.72	35	0.16
BT5	0.5	93.9	4.5	73.8	4.71	44	0.24
BT6	1.6	34.3	2.0	3.1	5.11	109	0.29

M = moisture, A = ash yield, V = volatile matter, d = dry, daf = dry, ash-free; Rr = mean random vitrinite reflectance, n = number of reflectance measurements, s = standard deviation.

Discussion

Coalification and palaeotemperatures

The geological setting of the Gastern and Ferden Carboniferous zones allows for coalification in both zones to be due to a combination of burial heating and tectonic deformation. However, the influence of the latter is not presently quantifiable and the degree of coalification is presumed, primarily, to be due to burial heating.

Herein, T is estimated using the statistical correlation of Barker (1988) where

$$\ln (Rr) = 0.0096 (T) - 1.40 \tag{1}$$

and that of Barker & Goldstein (1990) where

$$\ln (Rr) = 0.0081 (T_h) - 1.26 \tag{2}$$

and T_h is the homogenization temperature of fluid inclusions in calcite and is a good approximation of maximum palaeotemperature.

Values of T (Table 3) for sample locations in both Gastern and Ferden Carboniferous zones are estimated to be within the range ~290–360 °C. The anchizonal/epizonal conditions indicated by these temperatures are in accord with established metamorphic zonation in the northern part of the Helvetic zone of central Switzerland (Frey et al. 1980) and in the Ferden Carboniferous zone in particular (Hügi et al. 1988).

The highest palaeotemperatures (Barker & Goldstein thermometer) for both Carboniferous zones are similar to those obtained by Burkhard & Kerrich (1988; their table 2) and Herwegh & Pfiffner (2005; their table 1) for sample locations along the basal Doldenhorn thrust. The former obtained a tem-

Table 2. Carbon isotope data for coal and organic matter from Swiss geological units.

Sample	Locality	Sample description	Age	$\delta^{13}C$
Swiss Molasse Basin				
36514	Käpfnach ZH	sub-bituminous	M	–25.97
D3116	Schwarzwasser BE	silicified wood	M	–23.79
A7686	Worb BE	silicified wood	M	–25.40
B4505	Thorberg BE	silicified wood	M	–27.71
D3650	Belpberg BE	silicified wood	M	–24.20
36516	OronVD	sub-bituminous	O	–26.40
Wildhorn nappe, Kander valley				
36500	Horn BE	low-volatile bituminous	E	–24.45
36502	Schlafegg BE	semi-anthracite	E	–24.36
36571	Lindi BE	semi-anthracite	E	–24.40
Wildhorn nappe, Border chain (Beatenberg)				
36508	Niederhorn BE	high-volatile bituminous	E	–24.87
Ultrahelvetic Flysch				
33147	LBT, 680 m S Frutigen BE	flysch shale	E	–24.84
Gurnigel-Flysch (Penninic Flysch)				
A1261	Plaffeien FR	coal particles in sandstone	E	–24.13
Pennine	**Prealps, Klippen nappe**			
36498	Boltigen BE	medium-volatile bituminous	D	–22.04
36499	Diemtigen BE	medium-volatile bituminous	D	–23.89
Toarcian	**Posidonia shale, Swiss Tabular Jura**			
D3651	Gächlingen SH	coalified wood	L	–26.20
Konstanz-Frick trough				
36506	Weiach ZH	medium-volatile bituminous	C	–23.93
Salvan-Dorenaz basin, Aiguilles Rouges				
36495	Dorenaz VS	anthracite	C	–22.58
Zone Houillère, Penninic St Bernard nappe				
36496	Chandoline VS	anthracite	C	–23.47
Aar massif, Ferden Carboniferous zone				
36505	Ferden VS	anthracite	C	–22.02
37303	LBT, 24.09 km S Frutigen	anthracite	C	–22.37
Aar massif, Gastern Carboniferous zone				
	LBT, ~15.83 km S Frutigen	shale	C	–23.78
	LBT, ~15.83 km S Frutigen	shale	C	–23.38
	LBT, ~15.83 km S Frutigen	anthracite	C	–23.50
37200	LBT, ~15.827 km S Frutigen	anthracite	C	–24.10
37302	LBT, ~14.396 km S Frutigen	anthracite	C	–24.52
30616	LAT, 3.715 km S of N portal	shale	C[a]	–24.70

M = Miocene, O = Oligocene, E = Eocene, D = Dogger, L = Liassic, C = Carboniferous; a = Carboniferous or Flysch (Beck 1912; Brückner 1943). LBT: Lötschberg base tunnel; LAT: Lötschberg Apex tunnel.

Table 3. Palaeotemperature estimations for the Ferden and Gastern carboniferous zones.

Sample	Location (Swiss Nat. Coords.)	Elevation (m)	Rr	T (°C) Eqn. 1	T (°C) Eqn. 2
FT1–FT4[a]	623.988/137.016 to 623.986/137.021	890	4.02	291	327
BT1–BT2	624.105/137.070	740	5.00	313	354
BT3–BT5	619.624/143.808	816	4.70	307	347
BT6	618.720/145.060	827	5.11	316	357

[a]) Samples FT1–FT4 were from the Carboniferous in the Ferden access tunnel between these coordinates.

perature of 340 °C using calcite – dolomite thermometry for a Gasterntal location (sample 53a; 620.9/143.9) and the latter, using a combination of calcite – graphite and calcite – dolomite thermometry, obtained temperatures between ~330 °C (sample K-14WB; 618.8/145.0) above and close to the Gastern Carboniferous and ~380 °C for the deepest Jungfraukeil (sample Jung-986; 623.550/138.800) near the Ferden Carboniferous layer. However, the apparent average increase in T (from N to S) of ~6 °C/km along the Doldenhorn basal thrust estimated by Herwegh & Pfiffner (2005; their fig. 9) is not evident in the present vitrinite based palaeotemperatures (Table 3) which suggest similar burial depths and heating conditions in both Carboniferous zones during the time of maximum coalification.

The burial history of the Gastern and Ferden Carboniferous sediments is complex involving sedimentary burial of long duration beneath the Mesozoic sedimentary cover of the Gastern granite and Aar massif and tectonic burial beneath Helvetic, Ultrahelvetic and Prealpine (Penninic) nappes which moved forward in a northwesterly direction during Early Oligocene to Miocene. It is assumed that the Ultrahelvetic and Prealpine nappes were – at least for part of their journey – passively transported on top of the Wildhorn nappe (Masson et al. 1980; Ramsay 1981; Burkhard 1988).

The thickness of transported sediments of the Helvetic nappes (Wildhorn, Gellihorn, Doldenhorn) is estimated to be 4–6 km (Burkhard 1988). Estimates of the thickness of sediments forming the Prealpine nappes vary. According to Burkhard & Kalkreuth (1989) the degree of coalification in Eocene coals from the Wildhorn nappe indicates 6 km of burial of the Wildhorn nappe by Penninic nappes for the Kander Valley. More generally, thicknesses of between 5 km and 10 km have been given by Burkhard and Kerrich (1988) and a probable total thickness of ~10 km has been suggested by Kirschner et al. (1999).

During Early Oligocene the Ferden coal deposits were buried beneath the Mesozoic/Cenozoic sediments of the proto-Doldenhorn nappe; their thickness is estimated to have been ~2 km (Burkhard 1988; his fig. 3c). During the interval ~38–30 Ma further burial occurred with the thrusting and emplacement of the Wildhorn and Gellihorn nappes and the overriding Ultrahelvetic and Penninic nappes. Assuming T = 360 °C requires (assuming a palaeosurface temperature of 15 °C and a normal geothermal gradient of 25 °C/km) a tectonic burial depth of ~12 km at the time of maximum coalification. This tectonic cover is postulated to be made up of a thickness of 3 km of sediments of the Wildhorn and Gellihorn nappes and a thickness of 9 km of sediments of the Ultrahelvetic and Penninic nappes.

The present thickness of autochtonous (Mesozoic) cover (Autochton Nord) of the Gastern Carboniferous zone is ~200 m (Kellerhals & Isler 1998) and notwithstanding any (reasonable) adjustment of this thickness to account for erosion, it is likely that the rank of Gastern coals is mainly due to deep tectonic burial.

Staircase $^{40}Ar/^{39}Ar$ time spectra (Kirschner et al. 1996; Kirschner et al. 2003) provide time limits (~32–15 Ma) for the beginning and ending of deformation of the Doldenhorn nappe which was thrusted beneath the Wildhorn and Gellihorn nappes. During this interval the depth of tectonic burial of the Gastern coal deposits reached a maximum and coalification reached meta-anthracite rank.

Assuming a sedimentary burial depth of 1 km and again assuming T = 360 °C and a palaeosurface temperature of 15 °C requires (for a geothermal gradient of 25 °C/km) a tectonic burial depth of 13 km at the time of maximum coalification. At this time the thickness of the sediments of the Wildhorn, Gellihorn and Doldenhorn nappes is assumed to be the upper value (6 km) of Burkhard (1988) with the remaining tectonic cover being composed of a thickness of 7 km of sediments of the Ultrahelvetic and Penninic nappes.

It is of interest to note that the thicknesses of Penninic sediments required by the present burial depth/geothermal gradient interpretation of coalification for Carboniferous sediments from the LBT are in accord with those predicted by the Oligocene palinspastic reconstruction of the Helvetic and Lower Penninic domains of the Alps by Crespo-Blanc et al. (1995).

Carbon isotopic compositions

The variability exhibited by the $\delta^{13}C$ values for coals (Table 2) is a characteristic feature of these materials and has been attributed to differences in primary plant assemblages and palaeoclimate (Hoefs 2004) and, to a much lesser extent, to deposit age and the process of coalification (Whiticar 1996).

According to the calculations of Whiticar (1996) positive shift in $\delta^{13}C$ with increasing rank (lignite to anthracite) is unlikely to exceed 1‰. It is possible therefore, that the apparent increase in $\delta^{13}C$ values (–24.87‰ to –24.40‰: Table 2) for Eocene coals of high volatile bituminous to semi-anthracite rank from the localities of Lindi, Horn and Niederhorn – which are palaeogeographically identical (Burkhard & Kalkreuth 1989) – may be due to the process of coalification. However, the limited nature of the data precludes a firm conclusion.

The $\delta^{13}C$ values for samples of shale and anthracite from the Gastern Carboniferous zone appear to be consistent with their Carboniferous age. World wide averages of $\delta^{13}C$ for terrestrial organic matter are –23.6‰ to –23.8‰ for the Stephanian to Westphalian (Strauss & Peters-Kottig 2003), close to the measured values. However, the agreement with the measured values for an anthracite from the Salvan-Dorenaz basin (the sedimentary fill of which has been dated as Westphalian-Stephanian by Capuzzo & Bussy 2000) and for anthracite from the Ferden Carboniferous (presumably of similar Late Carboniferous age) is less good. It is to be noted that the two Ferden samples are heavier than Carboniferous coals from other locations (Table 2); in particular they are at least 1‰ heavier than the heaviest Gastern sample (–23.38‰) and the mean is heavier by 1.66‰. These differences in carbon isotope compositions of coals of similar (Late Carboniferous) ages and degree of coalification can be attributed to differences in precursor plant material and consequential differences in maceral content (for example see Rimmer et al. 2006).

Conclusions

Proximate analyses and measurements of mean random vitrinite reflectance indicate coalification to anthracite and meta-anthracite rank in Carboniferous sediments from the LBT. These ranks evince anchizonal/epizonal conditions in the Gastern and Ferden Carboniferous zones in accord with established metamorphic zonation in the northern part of the Helvetic zone of central Switzerland. Coalification in these zones can be satisfactorily explained by a depth of burial/geothermal gradient model. Values of $\delta^{13}C$ for Gastern coals are consistent with their Carboniferous age.

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