Evolution of the Lower Inn Valley Tertiary and constraints on the development of the source area

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ABSTRACT: Sedimentation in the Lower Inn Valley area began in the Priabonian on the previously folded and deeply eroded rocks of the Northern Calcareous Alps. In the area between Reith im Winkel and Rattenberg, sedimentation began in the Rupelian. The transgression is strongly overprinted by tectonic subsidence of the basin due to transtension along the sinistral Inntal Fault. The sea-level fall at the Rupelian/Egerian boundary coincided with the start of fluviatile coarse clastic sedimentation in the palaeo–Inn Valley. Upper Eocene and Oligocene deposits in the Lower Inn Valley area, and north of the Kaisergebirge, show vitrinite reflectance values that require a thick Egerian sedimentary cover. Temperature estimates from stable isotopes are in accordance with a 1500 m thick sedimentary sequence, leading to maximum temperatures of about 90 °C during the Upper Egerian and the maturation of Lattorfian bituminous marls. Subsequent tectonic activity caused uplift and a temperature drop to 60 °C in the Karpatian. Sedimentary thicknesses seem to have been controlled by rates of erosion in the Tauern Window area and adjacent regions. Strong periods of erosion from the Rupelian to Egerian and from the Pliocene to present were interrupted by slower rates in the intervening period, when several generations of ancient land surfaces (e.g. 'Augenstein' surface) evolved.

KEYWORDS: *Oligocene, maturation, tectonic evolution, uplift*

INTRODUCTION

The deposits of the Lower Inn Valley Tertiary are located in the Inn Valley between Rattenberg in the west and Kufstein in the east, and in the area between Kufstein and Reith im Winkel, north of the Kaisergebirge, farther to the east (Fig. 1). They consist of Priabonian sediments (Oberaudorf Beds), and the Lower Inn Valley Tertiary *sensu strictu*, which is of Oligocene age (Fig. 2). These are the only Priabonian to Oligocene sediments in the Northern Calcareous Alps, and are regarded to be a southern continuation of the Molasse Basin. Therefore, they are unique in providing direct evidence for the Palaeogene evolution of the Northern Calcareous Alps, which is important for the evaluation of the hydrocarbon potential of the Alpine overthrust region.

Following the Gosau depositional cycle, the Northern Calcareous Alps were subjected to extensive erosion. Pelagic Palaeocene and Eocene deposits are considered to have been present on large parts of the Eastern Alps, but have been subsequently eroded except for some small remains in the subsurface of the Lower Inn Valley Tertiary basin (Fig. 1). Therefore the Lower Inn Valley Tertiary has been deposited on deeply eroded Triassic rocks.

In this paper sedimentological and tectonic data are presented. Numerical modelling techniques are applied to reconstruct the temperature history based on burial histories and temperature sensitive parameters, coalification and isotope data.

DEPOSITIONAL HISTORY

The Oberaudorf Beds unconformably overlie deeply eroded Triassic rocks. In the Oberaudorf area, the lower part contains basal breccias, with some clasts bored by marine organisms and redeposited littoral clasts, followed by a marine to brackish deltaic succession. Sedimentation continues with fluviatile conglomerates (Hagn 1985). Between Miesberg and Aschau, basal breccias are followed by bioclastic sandstones and then littoral marls (Hagn *et al.* 1981).

In the Häring area, pre-Oligocene erosion is recorded by karstification and development of flowstones, alveolar structures and algal crusts in cavities and solution-widened joints in the subsurface, and local deposition of freshwater carbonates at the surface. The beginning of marine sedimentation seems to have been related to the rapid development of horsts and grabens resulting in a relief of about 100 m, which led to the development of fan deltas at the basin margins. These interfinger with bituminous marls that were deposited in the inner part of the basin, where they directly overlie Triassic basement rocks (Fig. 2). A detailed study of the facies distribution of the basal Häring beds has been carried out by Stingl & Krois (1991).

Between the basal unit and the bituminous marls, a coal seam is present which has been mined for many years. The coal developed in a swampy area at the margin of the basin. The high sulphur content of the coal (3.3 to 6.9%); Augustin-Gyurits & Schroll (1992) may be a result of the marine environment. On the

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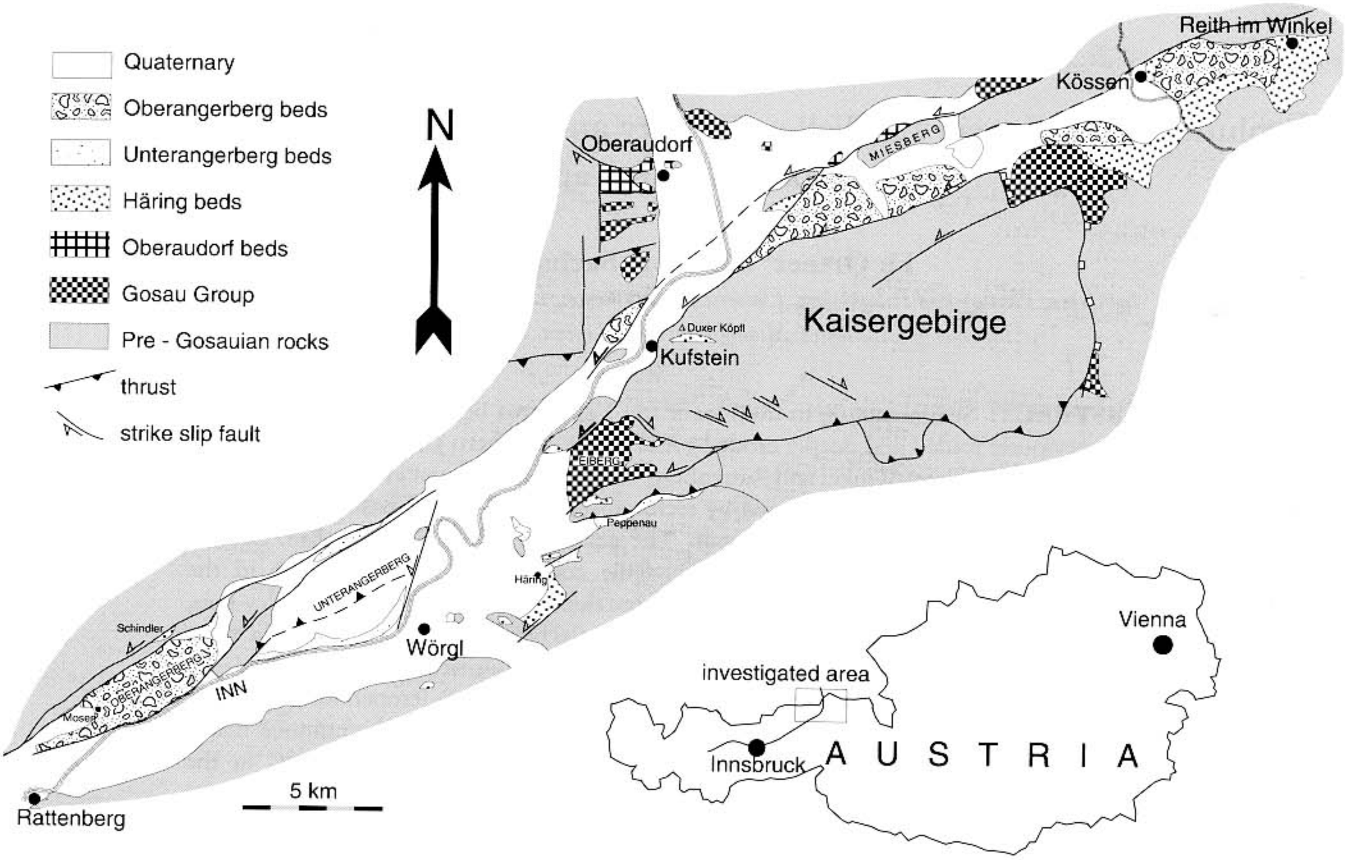


Fig. 1. Location of the investigated area and geological sketch.

other hand, bituminous marls with total organic carbon (TOC) contents of up to 13% are often characterized by relatively low sulphur content (0.65 to 1.65%; Table 1). This may indicate a temporary freshwater influence (Berner & Raiswell 1983). The main organic constituent of the bituminous marls, apart from allochthonous, terrigenous material, is telalginite. Bituminous marls with high proportions of telalginite are characterized by an extremely high hydrogen index (HI) with values up to 730 mgHC/gTOC (Table 1, Fig. 8). The excellent preservation of the organic matter is the result of an oxygen-deficient environment. The organic petrological methods applied do not indicate whether the telalginite is derived from (marine) Gloeocapsomorpha or (non-marine to brackish) Botryococcus related algae. Hystrichosphaeridians constitute up to 30% of the pollen assemblage and are indicative of a marine environment (Schnabel & Draxler 1976).

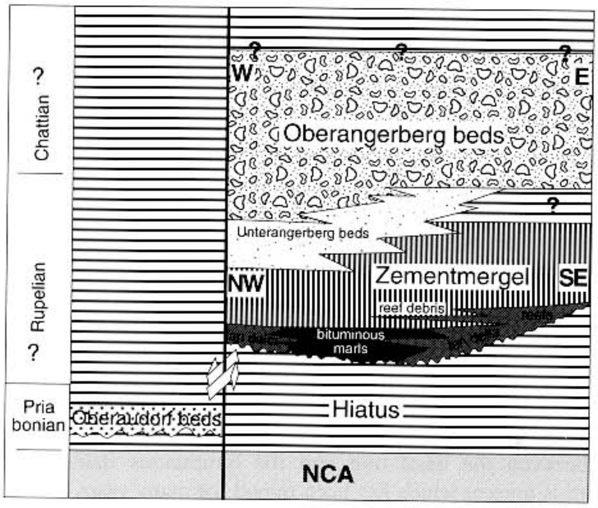


Fig. 2. Stratigraphy of the Lower Inn Valley Tertiary. In the central part of the basin it closely resembles the stratigraphy of the Molasse Basin (after Hagn *et al.* 1981). The part below the Zementmergel shows facies as seen in a NW–SE cross-section.

On the horst areas within the basin, contemporaneous Lithotamnium patch reefs, beach conglomerates and beach rocks formed. The bituminous marls grade into calcareous marls ('Zementmergel'), which in their lower part were deposited synchronously with reef growth on topographic highs. Turbidites and debris flows brought fossil-rich material into the Zementmergel Basin from the reefs. The transition from bituminous marls to calcareous marls represents the maximum subsidence event, which took the calcareous marls to a depth of about 200 m below sea-level. The breccias probably record tectonic activity resulting in subsidence. The presence of fault scarps at the basin margins is proven by blocks of Triassic rocks in the autochthonous calcareous and bituminous marls, and local scarp breccias. The upper Zementmergel were increasingly influenced by siliciclastic detritus, and finally grade into the Unterangerberg Beds.

The basin morphology is blanketed by Zementmergel and Unterangerberg Beds. The Unterangerberg beds consist of an alternation of thin turbiditic sandstones, silts and marls. They form fining and thinning-upward sequences (about 10 m thick) which are stacked in a generally coarsening-upward trend.

Table 1. *Sample characteristics of the Eocene Oberaudorf Beds and Oligocene sediments*

Sample	Locality	Lithology	Elevation (m)	Rr (%)	s.d.	T_{max} (°C)	PI	TOC (%)	HI	S_{tot} (%)
Oberaudorf										
Oberaudorf Beds										
I-14	N'Gfallermühle		620	0.47	0.03					
I-15	Oberaudorf		560	0.49	0.02	433	0.02	55.0	74	1.6
I-31	Ankerwald		725	0.49	0.02					
Rattenberg≠Kufstein										
Häring Beds										
I-16	Häring	Coal	800	0.47	0.03	424	0.04	51.3	95	4.6
I-17	Häring	Coal	790	0.53	0.04					
I-18	Häring	Coal	780	0.46	0.01	415	0.03	53.0	95	3.8
I-19	Häring	Bitum. marl	760	0.39?	0.04					
I-20	Häring	Jet		0.31?	0.02					
I-101	Häring	Bitum. marl		0.56	0.04	435	0.04	10.0	730	1.2
PAG Tunnel*	Häring	Coal	750	0.47	mean value of 13 samples					
Tiefbau IX*	Häring	Coal	241	0.54						
Tiefbau*	Häring	Coal		0.57						
Tiefbau*	Häring	Coal		0.58						
I-37	Duxer Köpfl	Coal	629	0.43	0.03					
DK 1*	Duxer Köpfl	Coal		0.46						
DK 3*	Duxer Köpfl	Coal		0.46						
I-29	Schindler	Bitum. marl	840	0.49	0.04					
I-100	Schindler	Bitum. marl		0.47	0.05	417	0.04	9.3	193	1.7
I-30	Peppenau	Bitum. coal	740	0.30?	0.02					
I-33	Peppenau	Bitum. marl	650	0.42	0.03	Phlob.: 0.50 %Rr				
I-34	Peppenau	Bitum. marl	660	0.39	0.01					
I-102	Peppenau	Bitum. marl				424	0.06	8.0	220	0.7
I-102 S	Peppenau	Bitum. marl		0.34?	0.03	432	0.06	13.0	706	1.7
Unterangerberg Beds										
I-09	Gr. W' Thal		510	0.45	0.02	416	0.06	44.0	67	1.4
I-08	Gr. W' Thal		520	0.44	0.03					
I-07	Gr. W' Thal		550	0.46	0.02	414	0.33	43.3	58	1.0
I-10	Gr. E' Thal		510	0.42	0.02	405	0.24	49.0	156	2.3
I-11	Gr. E' Achleit		510	0.57	0.02	429	0.10			
I-12	Gr. E' Steiner		570	0.48	0.03					
I-13	Gr. S' Klause		540	0.49	0.04	426	0.02	36.5	21	15.0
Oberangerberg Beds										
I-06	E' Vorhof		530	0.38	0.03	411	0.07	25.9	20	11.5
I-05	Schindler		690	0.41	0.02	411	0.04	49.0	42	4.2
I-04	N' Mosen		685	0.38	0.01	409	0.04	47.2	42	1.5
I-03	N' Mosen		620	0.43	0.02	415	0.04	41.1	94	8.2
I-02	NE' Voldöpp		525	0.47	0.03	422	0.04	18.6	16	11.1
I-01	Voldöpp		545	0.47	0.03	399	0.15	40.5	52	5.6
Kufstein–Reith im Winkl										
Basal Series										
I-38	SE' Kaltenbach		650	0.38	0.02	393	0.08			
Oberangerberg Beds										
I-21	Leitwang		600	0.38	0.04	416	0.02			
I-27	Kaiserwaldgr.		720	0.42	0.03					
I-28	Kaiserwaldgr.		740	0.40	0.02	397	0.02			
I-36	S' Durchholzen		850	0.34	0.34	376	0.02			
I-32	Mosertalbach		700	0.49	0.02					
I-22	Blindau		680	0.44	0.01					
I-26	Kaiserwaldgr.		660	0.37	0.03					
I-25	Kohlenbach		625	0.31?						
	Kohlenbach*			0.48						
W1*	Kössen			0.49						
W2*	Kössen			0.46						

Rr, vitrinite reflectance; PI, production index; TOC, total organic carbon contents; HI, hydrogen index (mg HC/gTOC); S_{tot}, total sulphur contents. Rr values of alginite-rich sediments and of jet, which are probably suppressed, are marked by a question mark.

* Samples from Schulz & Fuchs (1991).

Moving up the section, the depositional style changes to thick laminated calcareous marls which are interrupted by coarse-grained crossbedded conglomerates ('Höllgrabenkonglomerat'). This is the beginning of a well developed coarsening-upward sequence of conglomerates intercalated with calcareous marls, that forms the transition to the fluviatile Oberangerberg Beds. These consist of generally coarse-grained conglomerates with large-scale trough crossbedding interlayered occasionally with silty marls. Fine-grained deposits often show calcretes and soil horizons. Krois & Stingl (1991) classified the deposits as a large-scale Donjek-type braided river system. The flow direction was approximately from west to east, as shown by the generally smaller grain size towards the east. The upper parts of the Oberangerberg Beds are missing because of later erosion.

The Unterangerberg Beds are interpreted to be a prograding prodelta turbidite fan, which passes into the upper slope depositional area below the 'Höllgraben' conglomerate. The following coarsening-upward sequence shows the approach of the fluvial system of the Oberangerberg Beds.

In the Kössen/Reith im Winkel area the Unterangerberg Beds are absent (Fig. 2). The deposition of calcareous marls continued until the beginning of the deposition of the Oberangerberg conglomerates (Lindenberg 1965).

Petrographical analysis of pebbles in the Oberangerberg Beds (Moussavian 1984) shows a predominance of rocks that are not exposed near the Tertiary basin today. The basin was obviously surrounded by older Tertiary and Upper Cretaceous deposits of the Gosau Group, which were subsequently resedimented into the Tertiary basin. During the Oligocene, most of these deposits were eroded. Other pebbles from a nearby source are quartz phyllites with quartz bands, which may be derived from the nearby Greywacke and Lower Austroalpine Zone. All other crystalline and carbonate pebbles come from distant sources, whose stratigraphic and tectonic positions are not known.

The age of the deposits is generally poorly constrained. Data are available for the lower Zementmergel (NP 21; Hochuli 1978) and upper Zementmergel (Rupelian; Lühr 1962). The Oberangerberg beds have been dated as Lower Egerian (Zöbelein 1955). A sequence-stratigraphic interpretation of the Lower Inn Valley Tertiary (Krois *et al.* 1991; Fig. 3) distinguished two second-order cycles. Onlap of the basal breccias and retrogradational development of bituminous marls and calcareous marls are interpreted to be the trangressive systems tract of sequence 1. The switch from retrogradation to progradation (i. e. the beginning of turbidite sedimentation of the Unterangerberg Beds) marks the beginning of the high-stand systems tract. Sudden progradation of the deltaic/fluvial system of the Oberangerberg Beds, a low-stand systems tract, reflects the eustatic sea-level fall at the Rupelian–Lower Egerian boundary (Haq *et al.* 1988) and the beginning of sequence 2. The transgressive systems tract of sequence 1 is strongly overprinted by tectonic subsidence, as shown by facies differentiation during sedimentation of the 'Zementmergel'.

TECTONIC HISTORY

Analysis of brittle microstructures (e.g. Petit 1987) in the Tertiary sediments reveals at least part of the post-sedimentary history of the basin. Geometries of the basin formation are inferred from depositional patterns (Fig. 4). Extensional veins in Tertiary carbonates, and small normal faults in fault blocks inside the basin, record extension in a WNW–ESE direction (Fig. 5). Tertiary scarp breccias are related to E-W trending faults.

Post-sedimentary events show north–south compression passing into sinistral transpression. The Tertiary sediments were folded in a broad, generally wide E–W trending syncline. Compression caused south-vergent thrusting of horsts within the basin over Tertiary deposits (e.g. Peppenau, Unterangerberg; Fig. 1). NW–SE trending fold axes of asymmetric SE–vergent folds inside the basin might be kinematically linked to the overstep of SW–NE trending sinistral faults. Large sinistral faults ('Inn Valley Fault') cut the basin fill and reactivated older structures at the basin margins. Activity of these faults was related to the eastward extrusion of Central Alpine material during the Karpatian (Ratschbacher *et al.* 1991). Structures are overprinted by E–W compression causing small faults and folds. Still younger extensional faults trend NE–SW and commonly juxtapose the Tertiary against the Triassic basement. A transtensive set of faults trends NNW–SSE and forms small grabens.

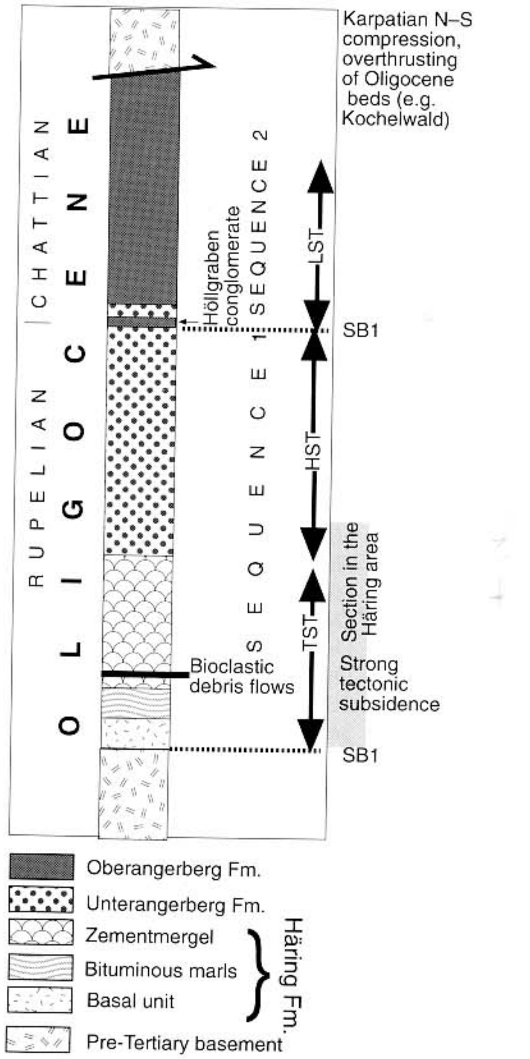


Fig. 3. Sequence-stratigraphic interpretation of the Lower Inn Valley Tertiary, after Krois *et al.* (1991).

ISOTOPIC SIGNATURES OF CARBONATE CEMENTS

In samples of carbonate cements from Oligocene rocks and from Oligocene faults, C and O isotope ratios were measured (Fig. 6). The equations given by Anderson & Arthur (1983) were used for all temperature calculations. Presedimentary erosion and karstification of Triassic carbonates are recorded by formation of

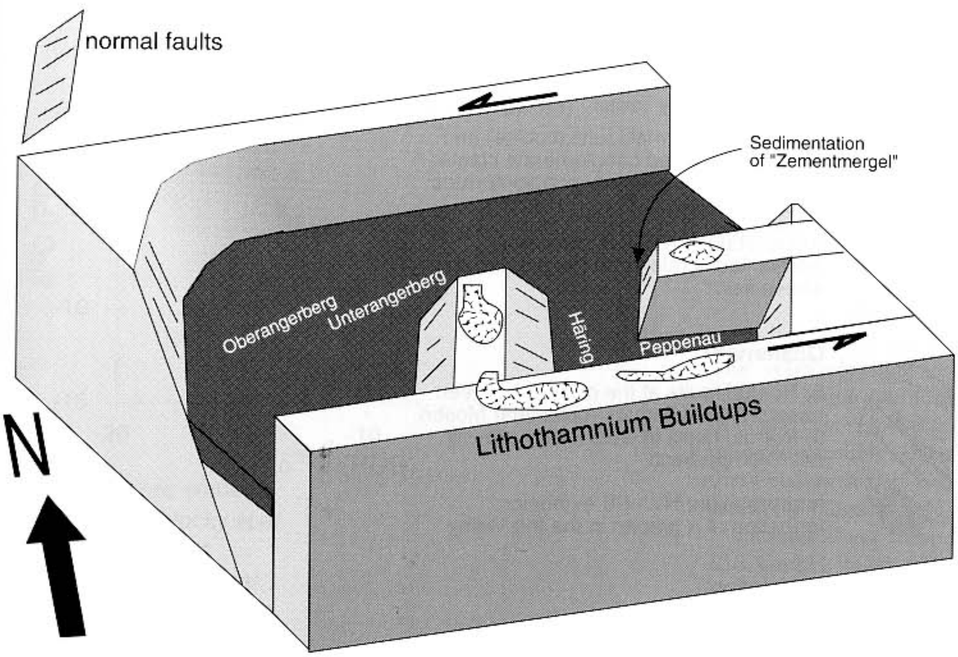


Fig. 4. Interpreted 3-D model for sedimentation of the calcareous marls (Zementmergel) in the Häring–Eiberg area. Not to scale.

flowstones, soil horizons and limnic carbonates, which yield a primary meteoric isotopic signal ($\delta^{18}O$ (SMOW) = −7). Nummulites from Tertiary carbonates on horst areas provide a primary marine signal, indicating a water temperature of 23 °C.

Normal faults in the Triassic basement of the basin show the following cement sequence: older blocky spar is partly recrystallized and overgrown by late white blocky spar. The earlier blocky spar is characterized by its brown colour and its lamination in both the exposure and hand specimen, and by slightly more negative $\delta^{13}C$ values. The cements are stained by organic material which is incorporated into the calcite. Oil migration took place during precipitation of the earlier blocky spar. The blocky spar cements, also present in extensional joints in Oligocene carbonates, have a wide range of $\delta^{18}O$ (PDB) from −3 to −19. This is interpreted to result from increasing temperatures and the mixing of marine and meteoric waters during basin subsidence and burial. Marine fluids could be derived from compaction of nearby calcareous marls, while meteoric water could infiltrate from the surface, where fluvial deposition took place from the Lower Egerian onwards. Temperatures calculated from the calcite in these veins indicate an increase from surface temperatures to a maximum of 90 °C. The composition of the fluid was then $\delta^{18}O$ (SMOW) = −6, recording an overall meteoric influence.

In the autochthonous calcareous marls, the sinistral transpressional tectonic event was associated with growth of thick saddle calcite seams and calcite fibres along the fault planes (Fig. 5). Assuming an originally marine composition for the pore fluids, which most probably originated by pressure solution and/or compaction of calcareous marls, temperatures have reached about 60 °C during the precipitation of saddle calcites in the Karpatian.

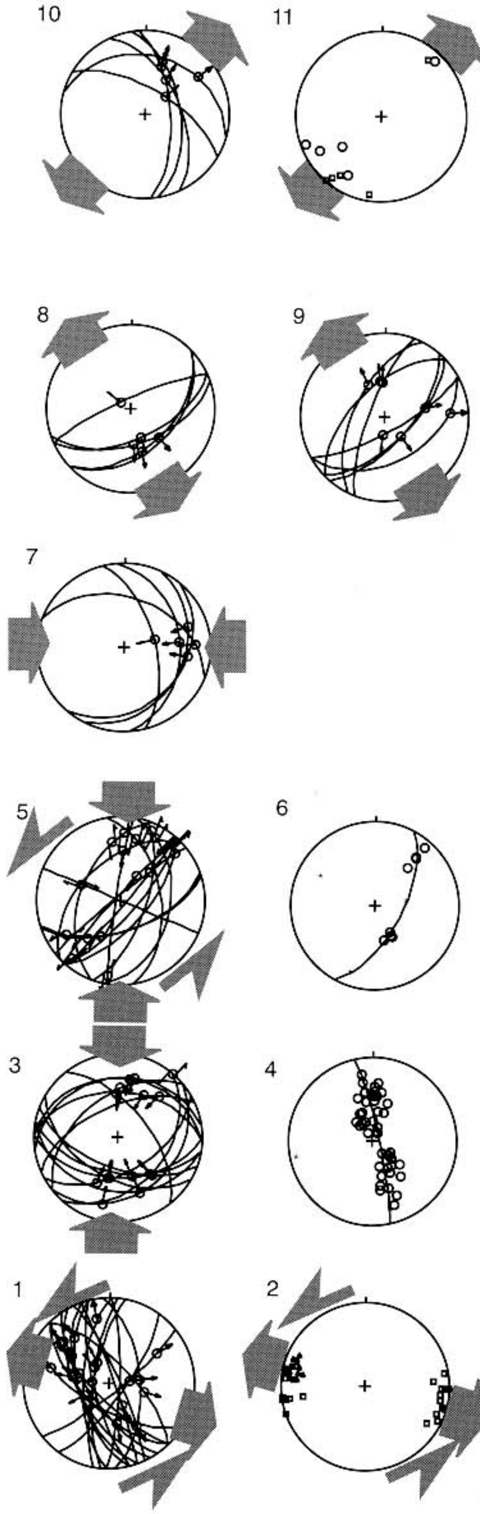
COALIFICATION PATTERN

The coalification pattern of the Lower Inn Valley Tertiary was studied using vitrinite reflectance data (% Rr) and the Rock-Eval pyrolysis parameter, T_{max}. Both parameters were measured using established procedures (Stach *et al.* 1982; Espitalié *et al.* 1977). Vitrinite reflectance values from the literature (Schulz & Fuchs 1991) were also considered. The maturity parameters of coals and bituminous marls from the Haering Beds, and of coal horizons within the Unterangerberg and Oberangerberg Beds, are summarized in Table 1. In addition, some data from the Eocene Oberaudorf Beds, which occur north of the Lower Inn Valley Tertiary, are also presented.

Coal-bearing Haering Beds with bituminous marls extend between Kufstein in the north (Duxer Köpfl), Haering in the south and the 'Lokalität Schindler' (Stingl 1990*a*), which is situated about 15 km west of Haering. Vitrinite reflectances from these outcrops generally range from 0.40 to 0.58% Rr. The rank of the samples has therefore reached the sub-bituminous coal stage (*Glanzbraunkohlenstadium* according to the German nomenclature). T_{max} values of 415–435 °C are in good agreement with the measured Rr. Vitrinite reflectances of bituminous coals, including jet, and bituminous marls near Haering and Peppenau, between Kufstein and Haering, are significantly lower (0.30–0.35% Rr). The reflectivity of these samples is probably reduced. Suppressions of reflectance of vitrinite in alginite-rich oil shales were reported by Hutton & Cook (1980) and other authors. T_{max} of one of these samples (I-102 S : 432 °C) also indicates a sub-bituminous coal stage.

In Haering a northwestward-dipping coal seam was mined over a vertical distance of 750 m. Unfortunately no correctly located samples are available from the mine, which was closed in the early 1950s. Schulz & Fuchs (1991) supposed a slight increase in vitrinite reflectance with depth. However, the reflectance gradient cannot be estimated, because only three samples from deep parts of the former mine (Tiefbau; Table 1) were analysed and the depth of only one of these samples is known. In any case, the reflectance gradient is most probably rather low (≪0.2% Rr km).

The vitrinite reflectance of Eocene sediments north of the Lower Inn Valley Tertiary (Oberaudorf Beds) is similar to the Haering Beds (Tables 1, 2). Coalification of Unter- and Oberangerberg beds is also relatively high (0.38–0.57% Rr).



Quaternary

10) Normal faults in the basement of the Lower Inn Valley Tertiary (Eiberg Gosau)

11) Poles of normal faults (circles) and cracks in rounded conglomerate clasts (squares) of Quaternary conglomerates near Vomperbach

Interpretation: NE–SW extension; normal faults related to the present-day stress field?

Quaternary

8) Normal faults at the contact between basement and Tertiary rocks near Mosen
9) Normal faults in Quaternary gravels near Vomperbach

Interpretation: NW–SE extension; formation of a graben in the Inn Valley

?Sarmatian

7) Reverse faults in basement rocks

Interpretation: E–W compression

Karpatian

5) Sinistral oblique reverse faults in the Zementmergel; saddle calcites are present along the faults
6) Folding in the Unterangerberg Beds

Interpretation: sinistral transpression along the Inntal Fault; folding due to overstep of faults

Ottnangian / Karpatian

3) Reverse faults in the Oberangerberg Beds
4) Folding in the Oberangerberg Beds

Interpretation: N–S compression

Oligocene

1) Normal and strike-slip faults in the subsurface of the basin
2) Poles of extensional joints in Oligocene carbonates at Häring (containing late white blocky spar)

Interpretation: extensional structures due to sinistral transtension in the Inn Valley shear zone

Fig. 5. Examples of typical fault sets of the Oligocene to present tectonic history of the Unterinntal area. The relative age relationships of data-sets 7 to 10 are not clear. E–W compression has been dated by Decker *et al.*(1993) into the Sarmatian. For data-sets 8 to 11, the presence of similar fault sets in Quaternary gravels in the Inntal suggests a Quaternary age.

However, considering mean values of all the measured samples between Rattenberg and Kufstein, a slight decrease in vitrinite reflectance from the Haering (0.49) and Unterangerberg Beds (0.47) to the Oberangerberg Beds (0.42) can be recognized (Table 2). Taking into account the average thickness of the sediments, a low reflectance gradient (about 0.15–0.20% Rr km^{-1}) was calculated. Similarly, a slight increase in T$_{\max}$ values with stratigraphic age can be seen. T$_{\max}$ of the Oberaudorf Beds is 433 °C (only one sample) and decreases to 411°C in the Oberangerberg Beds (Table 2).

Vitrinite reflectances of the Oberangerberg Beds between Kufstein and Reith im Winkl are similar to those between Rattenberg and Kufstein. However, T$_{\max}$ values in the three samples studied are lower. The rank parameters of one sample from the Basal Unit indicate similar maturity compared with the Oberangerberg Beds. This is probably a result of the relatively

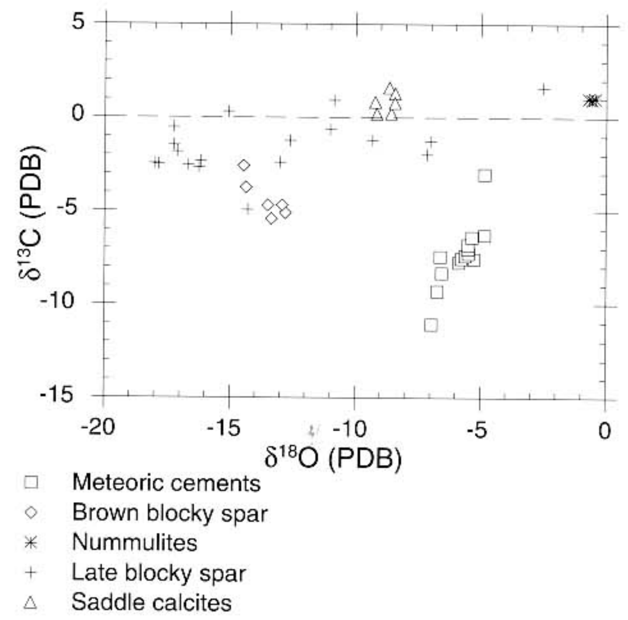


Fig. 6. Isotope data from the Lower Inn Valley Tertiary. For discussion see text.

small thickness of Calcareous Marls (Zementmergel) and the absence of Unterangerberg Beds east of Kufstein. Maturity of the Basal Unit in this area is therefore lower than the maturity of the coal horizon and the bituminous marls southwest of Kufstein. In the area between Rattenberg and Kufstein there is no obvious correlation between vitrinite reflectance of outcrop samples and present-day elevation; no significant horizontal trends are visible. Therefore predeformational coalification is likely for the main part of the basin. The interpretation that the coalification is essentially older than the compressional tectonics is in agreement with the observation that calcites associated with extensional veins show higher formation temperatures than calcites, formed during Karpatian transpression (see above). If it is correct that vitrinite reflectance increases with depth in the former Haering mine, a syndeformational coalification has to be considered in this area.

Bituminous marls are excellent sources for oil, with TOC values up to 13% and HI values up to 730 mgHC/gTOC. T_{max} (Fig. 7), vitrinite reflectance and the production index indicate that coals and bituminous marls within the Haering Beds are generally immature. However, the occurrence of solid bitumen in underlying Triassic carbonates (e.g. Grattenbergl, SE Haering) proves that some early hydrocarbons have already been generated.

SIMULATION

The relatively high coalification and the low coalification gradients require a thick uppermost Oligocene and/or lowermost Miocene cover above the Northern Calcareous Alps. Numerical modelling techniques were applied to estimate the thickness of these sediments, to evaluate coalification temperatures, and to assess the Oligocene/Miocene heat flow.

The modelling was performed using the PDI-1D software of IES GmbH, Jülich (Wygrala 1989). For the calculations it was assumed that coalification is predeformational. Input data included the present thickness of distinct stratigraphic units (events), estimates of erosion, lithotypes (and their physical properties), as well as the temperaure at the sediment–water interface, and heat-flow data. The age assignment follows Steininger *et al.* (1988/89) for Oligocene sediments and Steininger *et al.* (1990) for the Miocene. Difficulties arose from the fact that no samples from deep boreholes are available. The only geological information was from the Haering mine and from outcrops. All data were incorporated into a synthetic well, which should be representative of the area between Rattenberg and Kufstein. The reconstructed heat-flow histories were calibrated with vitrinite reflectance data. Because the exact position of samples from the Ober- and Unterangerberg beds within the stratigraphic column was often difficult to determine, the mean values and standard deviations of vitrinite reflectance for the upper part of the Haering Beds (coal seam and bituminous marls) and for the Unter- and Oberangerberg beds (Table 2) were plotted. Calculation of vitrinite reflectance followed the `Easy Ro` approach of Sweeney & Burnham (1990). Input data for the most probable model of the area southwest of Kufstein are presented in Table 3, and physical properties of the lithotypes used are presented in Table 4.

Table 2. *Thickness, vitrinite reflectance and T_{max} for samples of Eocene Oberaudorf Beds and Oigocene sediments*

Formation	Present thickness (m)	Rr (%)	s.d.	Samples	T_{max} (°C)	s.d.	No. of samples
Oberaudorf–Walchsee							
Oberaudorf Beds		0.48	0.01	3	433		
Rattenberg–Kufstein							
Oberangerberg Beds	200	0.42	0.04	6	411	8	6
Unterangerberg Beds	120	0.47	0.05	7	418	10	5
Zementmergel	200						
Basal Unit and bituminous marls	55	0.49	0.06	13	425	8	5
Kufstein–Reith im Winkl							
Oberangerberg Beds	200	0.43	0.05	10	396	20	3
Zementmergel	120						
Basal Unit	135	0.38		1	393		1

Rr, vitrinite reflectance.
Samples with suppressed vitrinite reflectance are not considered.

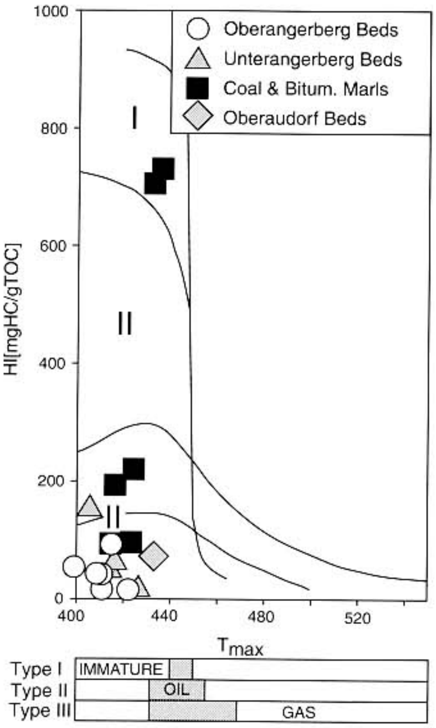


Fig. 7. Crossplots of T_{max} versus hydrogen index (HI). All studied samples are immature. Note extremely high HI values of alginite-rich bituminous marls.

A good fit between measured and calculated vitrinite reflectance data in the area southwest of Kufstein is obtained with the following model (Table 3, Fig. 8a). Sedimentation in the Lower Inn Valley continued until the end of the Egerian (22 Ma) and about 1300 m of thick fluvial and marine(?) sediments were deposited on top of the Oberangerberg Beds. After a short period of non-deposition, uplift resulted in erosion of these thick sediments. Heat flow during Oligocene and Miocene times was about 70 mW m^{-2}. This is slightly higher than the present average value for continental crust. The calculated maximum temperature for the basal Tertiary sequence is about 90 °C. This value fits excellently with the temperature derived from isotopic investigations. The post-Oligocene erosion history cannot be reconstructed in detail. However, the Karpatian temperature indicated by isotope data can easily be explained by erosion of 550 m of sediments before or during the Karpatian.

Uncertainties result from the lack of knowledge about the lithology and physical properties of the eroded rocks, the small depth interval with calibration data, and their large standard deviations. To account for these uncertainties, sensitivity analyses were performed.

In the original simulation, 800 m of thick shaly sandstones were deposited during late Egerian times and heat flow was 70 mW m^{-2}. For the sensitivity analyses we assumed that (1) conglomerates or (2) shales and sandstones were deposited during the late Egerian. Higher proportions of fine-clastic sediments are highly improbable. The results are similar. A good fit between measured and calculated vitrinite reflectance values is achieved for (1) 1000 m of thick conglomerates (total eroded thickness: 1500 m) and a heat flow of 67 mW m^{-2} and (2) for 700 m of thick shales and sandstones (total eroded thickness: 1200 m) and a heat flow of 71 mW m^{-2}. Therefore, in this case the different lithologies had relatively little influence on the simulation results.

The authors are aware that the postulation of a 1300 m thick Egerian cover on top of the Oberangerberg Beds seems quite provocative and may have consequences for our understanding of the Tertiary subsidence history of the Northern Calcareous Alps. Therefore, and because of the uncertainties that arise from the fact that the reflectance data are from a relatively small depth interval, an attempt was made to model vitrinite reflectance with a thinner overburden and higher heat flow. Figure 8b shows the simulation results considering erosion of only 600 m of sediments and an Oligocene heat flow of 115 mW m^{-2}. With this model the fit between calculated and measured reflectance data is poorer. However, the calculated data are still within the standard deviation of the measured data. This model also predicts a maximum temperature of 90 °C. In order to model the Karpatian temperature (60 °C), a decrease in heat flow and/or significant erosion were assumed.

Investigations by Jacob *et al.* (1982) indicated generally low Oligocene/Miocene heat flows and a southward decrease in heat flow within the southernmost Molasse (Allochthonous Molasse) north of the study area. Extremely high Oligocene/Egerian heat flows in the Inn Valley area are therefore unlikely. Nevertheless ,the possibility that heat flow might have been elevated along the Inn Valley Fault cannot be ruled out totally. Duddy *et al.* (1994) emphasized that the flow of hot fluids in shallow aquifers causes 'normal' geothermal and reflectance gradients below and extremely raised gradients above the aquifer. If the sediments

Table 3. *Input data-set for modelling of temperature and burial history for the area between Rattenberg and Kufstein*

Nr.	Name	End (Ma)	Begin (Ma)	Thickness (m)	Lithology	Recent porosity (%)	Water depth (m)	SWI temp. (°C)	Heat flow (mW m^{-2})
12	Erode 6	0.0	11.0	–9999	Conglomerate	35	0	14	70
11	Erode 7	11.0	16.5	–9999	Sand, shaly	48	0	16	70
10	Karpatian (E. 7)	16.5	17.2	–450	Sand, shaly	48	0	18	70
9	Erode 7	17.2	21.5	–50	Sand, shaly	48	0	18	70
8	Hiatus	21.5	22.0	0	Sand, shaly	48	0	18	70
7	Egerian 3	22.0	25.5	800	Sand, shaly	32	30	18	70
6	Egerian 2	25.5	28.0	500	Conglomerate	22	5	19	70
5	Oberangerb. B.	28.0	29.3	200	Conglomerate	18	5	19	70
4	Unterangerb. B.	29.3	31.0	120	Shale and sand	17	150	17	70
3	Calcareous Shales	31.0	35.5	200	Marl	15	200	18	70
2	Bituminous marls	35.5	36.0	15	Marl	14	30	18	70
1	Basal Unit	36.0	36.4	40	Conglomerate	16	30	18	70

Table 4. *Physical properties of Lithotypes used by the simulation software*

Lithotype	Initial porosity (%)	Density (kg m^{-3})	Compressibility (Pa^{-1})		Thermal conductivity (W/m × K)		Heat capacity (cal/g × K)		Permeability[1] at porosity of	
			Min.	Max.	20 °C	100 °C	20 °C	100 °C	5%	75%
Conglomerate	35	2663	10	330	2.93	2.63	0.184	0.217	–3.5	0
Sand,shaly	48	2666	10	1400	2.78	2.37	0.19	0.226	–4	0
Shale and sand	52	2669	10	2800	2.65	2.38	0.197	0.236	–4	3
Marl	47	2687	10	940	2.23	2.11	0.208	0.248	–5	–0.89
Water	0	1160	1	2	0.6	0.68	0.999	1.008	1	1

[1] For permeability values, –5 = 10^{-5} md.

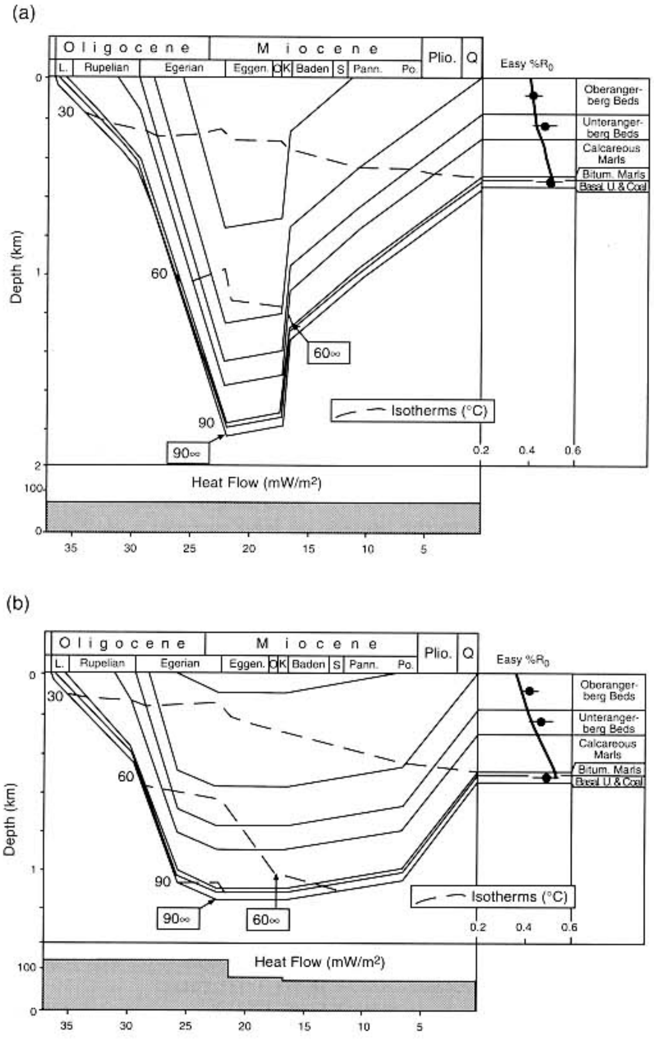


Fig. 8. Burial and temperature histories and heat flow models of the region between Rattenberg and Kufstein. Calculated (Easy %Ro) and measured vitrinite reflectance values are plotted versus depth. (**a**) A good fit between measured and calculated values is achieved with a heat flow of 70 mW m^{-2} and a total eroded thickness of 1300 m. (**b**) The fit is significantly poorer assuming an Egerian heat flow of 120 mW m^{-2} and only 600 m total eroded thickness. Temperatures derived from isotopic studies are shown in boxes.

above the aquifer are eroded, this may result in the overestimation of uplift. However, in the present case, a continuous aquifer between Rattenberg and Kufstein with 60–70 °C hot fluids at the top of the Oberangerberg Beds seems improbable.

On the other hand, extremely thick Egerian (Chattian and Aquitanian) sediments are known from the Allochthonous Molasse. A total thickness of Egerian sediments of the order of 1500 m in the Lower Inn Valley Tertiary, which formed the southern continuation of the Molasse Basin, is therefore possible, and a scenario with erosion of significantly more than 1000 m (1500 m?) of sediments is favoured.

SYNTHESIS

The evidence described above produces a possible scenario of Upper Eocene–Oligocene deposition in the Lower Inn Valley area. The Gosau depositional cycle lasted until the Lower Lutetian (pelagic calcareous marls) and was terminated by Middle Eocene compressional tectonics and associated uplift and erosion. The cause of relatively widespread limnic to shallow marine sedimentation of Priabonian age in the northern part of the Northern Calcareous Alps (Oberaudorf Beds; Hagn 1985) is not known, as the deposits are bordered by faults on all sides and the primary basin geometry is not known. However, this part of the Northern Calcareous Alps had already been eroded down to the Triassic by the Upper Eocene.

Motion on the sinistral strike slip-fault of the Inn Valley is postulated to have caused the tectonic movements recorded in the Lower Oligocene beds. A first pulse of motion on the Inntal Fault system is dated to the lowest Oligocene by basin formation, and was contemporaneous with widespread sinistral shearing in the Alpine wedge (Neubauer 1994; Behrmann 1990). At the same time, the sea transgressed to the southwest onto the Northern Calcareous Alps to form a relatively narrow marine inlet, with fan deltas entering the basin from the north and the south. Subsequently, a large fluvial system prograded from the SW towards the NE, and the Unterangerberg prodelta passed into the fluvial system of the Oberangerberg Beds. This process was enhanced by a eustatic sea-level fall at the Rupelian/ Lower Egerian boundary (Haq *et al.* 1988). Therefore, in the east younger equivalents of the 'Zementmergel' are directly overlain by Oberangerberg Beds.

The gravel of the Oberangerberg Beds must have been derived from the SW, as young sediments of the northernmost part of the Northern Calcareous Alps had already been eroded by the Upper Eocene (see above). Clasts from the Gosau Group form a major constituent of the 'Höllgraben' conglomerate. A large fluvial system and its distributaries, covering large parts of the present

Tauern Window, Lower Austroalpine, Greywacke Zone and the Mesozoic Cover of the Ötztal crystalline zone, ran parallel to the orogen. It eroded these units and the Gosau deposits of Upper Cretaceous to Lower Eocene age farther to the south. Andesitic and dacitic clasts can be compared to Lower Egerian dykes in the area north of the Periadriatic Line (Mair *et al.* 1992) and prove the source area extended to the Oligocene intrusives (cw. Skeries & Troll 1991). To the north the sedimention area ended at a thrust ridge along the active Alpine basal thrust zone. There, rocks from the Northern Calcareous Alps and the Flysch Zone were redeposited into the Molasse Basin (Hagn & Moussavian 1980). Denudation of the uplifting area north of the Periadriadic Line provided debris for rapid sedimentation of a 1500 m thick sequence, and was the reason for the very low observed heat flow.

L. Wagner (pers. comm.) postulated a marine connection from the Molasse Basin to the Gardasee area in the Late Egerian. Hagn (1985) found pebbles of shallow-water marine sandstones of Ottnangian age. Intensive shortening and uplift in the depositional area began in the Ottnangian, when debris from the Northern Calcareous Alps started to dominate in conglomerates in the Chiemgau Molasse, which is probably the fan of the palaeo–Inn river into the Molasse Basin (Skeries & Troll 1991). During the Karpatian, N–S compression changed into sinistral transpression along the Inn Valley Fault. Southvergent thrusts developed into oblique thrusts (e.g. thrusts of horsts within the basin onto Tertiary sediments). The sinistral transpression was related to extrusion of the Central Eastern Alps to the east (Ratschbacher *et al.* 1991). Because of uplift of the depositional, area temperatures dropped to 60 °C at the base of the Tertiary. Thrusting in the Molasse Basin, and therefore the driving force for the extrusion, also terminated at the end of the Karpatian (Wagner *et al.* 1986).

Whereas temperatures decreased during Miocene times in the Lower Inn Valley Tertiary as a result of erosion and/or decreasing heat flows, heat flow and temperatures increased along the eastern margin of the Penninic Tauern Window. Significantly elevated Karpatian to Middle Miocene heat flows are indicated by the coalification patterns of the Ennstal Tertiary and the Noric Depression, and are associated with the rapid Miocene uplift of the Tauern Window (Sachsenhofer 1992). It is important to note that coalification gradients in Oligocene (?) and Miocene sediments along the eastern margin of the Tauern Window (e.g. about 0.6% Rr km^{-1} in the Tamsweg Basin) are significantly higher than in the Lower Inn Valley Tertiary. Obviously, coalification in the Inn Valley Tertiary, 25 km north of the Tauern Window, was not affected by the rapid Miocene uplift of the Tauern Window.

Very little data are available for the history of the area between the Middle Miocene and the Quaternary. Sedimentation of 'Augenstein' gravels including gravels with bean ore and quartz pebbles, both often with polished surfaces, on ancient land surfaces (Mutschlechner 1953, 1992; Pichler 1962) points to littoral or fluvial reworking of older gravels and redeposition of the material into karst voids. Most deposits show mixtures of varying amounts of exotic crystalline clasts with locally derived limestones (Pichler 1962; Stingl 1990*b*). All the evidence suggests that the Augenstein gravels neighbouring the Inn Valley are redeposited remains of the Egerian Oberangerberg fluviatile system or its distributaries (cw. Tollmann 1968). Between Innsbruck and Kufstein, Augenstein deposits are only present south of the Inn Valley. This is in accordance with an SW–NE trending fluviatile system parallel to the orogen, as the gravels could not be transported across the system.

The most important aspect of post-Early Miocene evolution of the Inn Valley area is the formation of the present-day topography by (?Quaternary) NW–SE extension. The Tertiary deposits were downthrusted some 100 m along Inn Valley parallel faults as reconstructed by seismic investigations (Heissel 1951). This resulted in a graben structure in the Inn Valley. This tectonic activity might be the reason for the overdeepened Inn Valley, with about 1400 m of Quaternary (and Tertiary?) fill (Poscher 1993). It might be related to late uplift of the Tauern Window area (Senftl & Exner 1973) and associated gravity-driven sliding of the Northern Calcareous Alps into the Molasse Basin.

CONCLUSIONS

The evolution of the Lower Inn Valley Tertiary was characterized by strike-slip tectonics along the Inn Valley line, eustatic sea-level changes, and uplift and erosion in the source area. Transgressional events were responsible for sedimentation of the Oberaudorf Beds and basal Häring Beds. Sinistral shearing caused facies differentiation and subsidence of grabens. Strong uplift of the source area, the Austroalpine units above the present-day Tauern Window, and the Mesozoic cover of the Ötztal crystalline rocks during the Oligocene, caused progradation of coarse clastic sedimentation (Unterangerberg and Oberangerberg beds). Stüwe & Sandiford (1994) estimate 15–20 km of exhumation in the Tauern Window area prior to 20 Ma. This corresponds to the occurrence of crystalline material in the Molasse Basin in the Baustein Beds and the Lower Süßwassermolasse, which ended in the uppermost Egerian. The effect was rapid burial of the basal Lower Inn Valley Tertiary under a thick fluviatile cover, which led to peak temperatures and maturation of the bituminous marls during the Egerian. Thrusting and sinistral transpression during the Karpatian caused uplift and erosion in the depositional area, and ended the maturation of hydrocarbons.

During the post-Egerian evolution a set of ancient land surfaces was preserved. Denudation was much slower, and sediment thicknesses never became significant except in some Karpatian strike-slip basins in Eastern Austria (e.g. Ennstal Tertiary, Noric Depression). During the Pliocene or Pleistocene erosion accelerated. The rate of uplift is at present at about 1 mm a^{-1} (Senftl & Exner 1973). According to Sakaguchi (1973), from the Pliocene to the present no land surfaces were formed, but there has been widespread coarse clastic sedimentation including crystalline pebbles. Different climatic conditions might be the explanation for the preservation of ancient land surfaces, as geochronological data indicate rather uniform uplift rates during Oligocene to Miocene history (e.g. Selverstone 1988 for the western Tauern Window).

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