Thermal history of the Drau Range (Eastern Alps)

Autor(en): **Rantitsch, Gerd**

Objekttyp: **Article**

Zeitschrift: **Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie**

Band (Jahr): **81 (2001)**

Heft 2

PDF erstellt am: **25.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-61687

Thermal history of the Drau Range (Eastern Alps)

by *Gerd Rantitsch*[1]

Abstract

The Drau Range represents a fragmented tectonostratigraphic unit within the Eastern Alps. Vitrinite reflectance data were measured in Scythian to Albian shales, siltstones and marls. Numerical models, calibrated on the basis of these data, are used to reconstruct the paleogeothermal conditions. The spatial pattern of coalification gives evidence for three thermal events: (1) Thermal alteration within the peripheral segments of the Drau Range (Northern Karawanken Range, eastern segment of the Gailtal Alps and the Dobratsch block and parts of the Lienz Dolomiten Range) is explained by a low heat flow of approx. 60 mW/m^2 during basinal subsidence. (2) A break in coalification across a strike-slip fault within the Lienz Dolomiten Range indicates local heating due to Oligocene magmatic activity. (3) The spatial pattern of a coalification anomaly in the central Gailtal Alps suggests highly elevated heat flow during the Miocene. This event is explained by a rise in heat flow during rapid uplift of the Tauern dome in the Early/Middle Miocene.

Keywords: Eastern Alps, Drau Range, vitrinite reflectance, basin modeling, thermal history.

1. Introduction

Low temperature metamorphism is directly related to the burial of sedimentary sequences, to the emplacement of thrust sheets (e.g. WARR and GREILING, 1996), to heating within shear zones (e.g. UNDERWOOD et al., 1999), or to the uplift of metamorphic core complexes or magmatic plutons in upper crustal levels (e.g. DUNKL and DEMÉNY, 1997; DUNKL et al., 1998; SACHSENHOFER et al., 1998). The study of very low-grade metamorphic events is therefore an important tool for paleogeographic and kinematic reconstructions. The thermal structure of fold-and-thrust-belts is usually attributed to sedimentary burial and loading beneath overriding thrust sheets (e.g. WARR and GREILING, 1996). However, within the Eastern Alps, tectonic processes subsequent to folding and thrusting (Oligocene magmatic activity and Miocene large-scale crustal extension) influenced significantly the architecture of tectonostratigraphic units (FRISCH et al., 1998, 2000). The thermal structure of the lithosphere is closely related to its tectonic evolution, therefore, it is supposed that Oligocene to Miocene tectonics influenced the thermal history of Austroalpine cover units.

The Drau Range (Fig. 1) is an important region to investigate the relationship between deformation and metamorphism. This unit exhibits a Permo-Mesozoic sedimentary facies, which is inconsistent with its present tectonic setting. Therefore, a left-lateral displacement of the Drau Range towards the east has to be assumed (BRANDNER, 1972, BECHSTÄDT, 1978; KÁZMÉR and KOVÁCS, 1985; SCHMIDT et al., 1991; HAAS et al., 1995; LEIN et al., 1997). The time of this displacement has been dated at Miocene by KÁZMÉR and KOVÁCS (1985), Middle Jurassic to Early Cretaceous by SCHMIDT et al. (1991) and Middle Cretaceous (Albian to Cenomanian) by LEIN et al. (1997). Because of identical lithostratigraphic and facial sequences the area between the western part of the Northern Calcareous Alps and western Lombardy supposedly represents the original paleogeographic position of the Drau Range during Triassic to Early Cretaceous times (BECHSTÄDT, 1978; KÁZMÉR and KOVÁCS, 1985; SCHMIDT et al., 1991; HAAS et al., 1995; LEIN et al., 1997).

Following postorogenic collapse and continental-scale wrenching of the Variscan basement in Late Carboniferous to Middle Permian times,

[1] Institut für Geowissenschaften, Montanuniversität Leoben, Peter Tunner Strasse 5, A-8700 Leoben, Austria. <rantit@unileoben.ac.at>

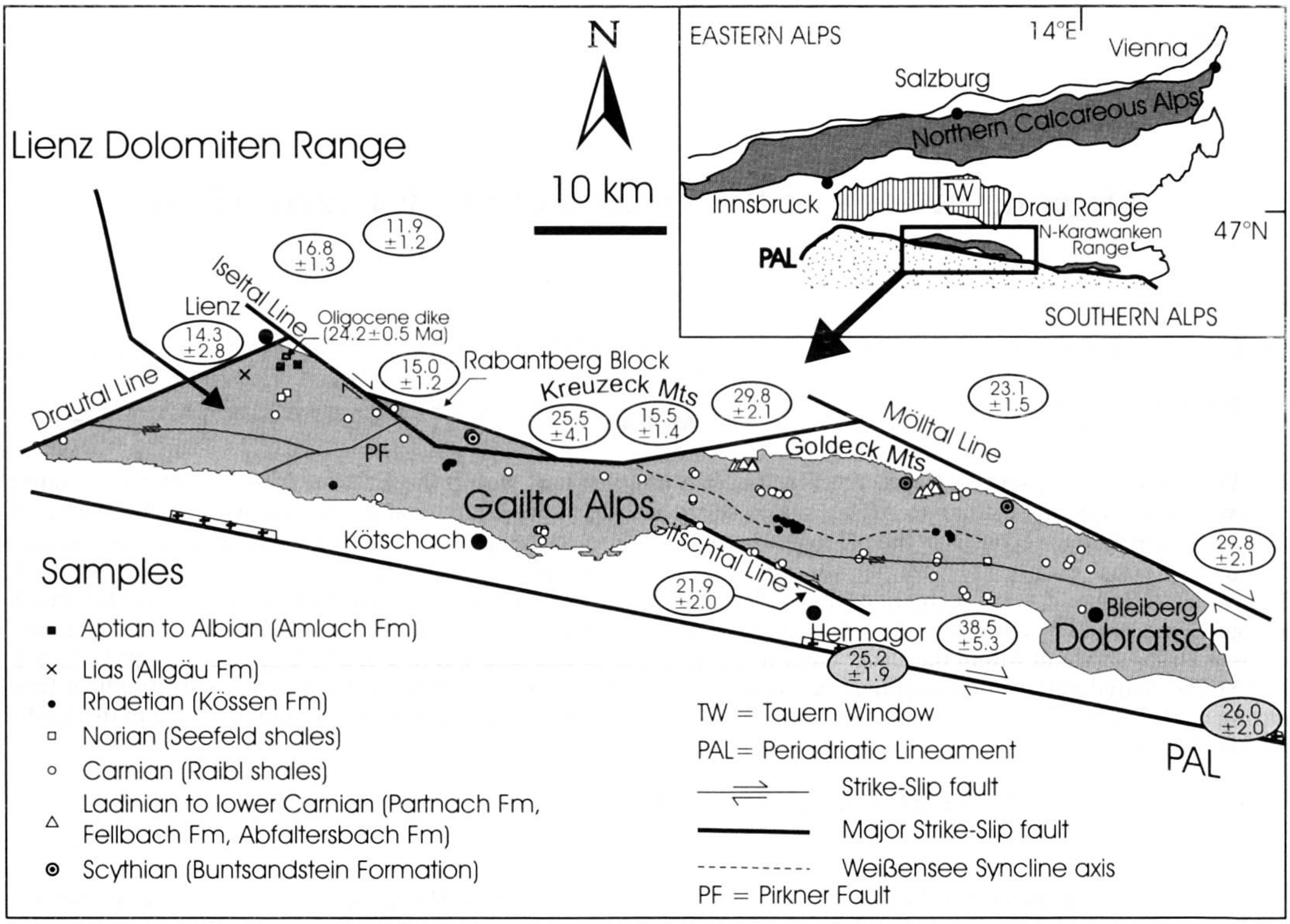

Fig. 1 Map of the study area showing the main structures and the sample locations in the Drau Range. Numbers in ovals are apatite fission-track cooling ages (Ma) from GRUNDMANN and MORTEANI (1985), STAUFENBERG (1987) and HEJL (1998). Age data of Periadriatic intrusives (cross symbols) are shaded. The K–Ar cooling age from the dike derives from DEUTSCH (1984).

Late Triassic to Middle Jurassic rifting between the Apulian and Eurasian plate created the Meliata-Hallstatt ocean (SCHMIDT et al., 1991; BERTOTTI et al., 1993; HAAS et al., 1995; CHANNELL and KOZUR, 1997; WORTMANN et al., 2001). After closure of the Meliata ocean in Late Jurassic to Early Cretaceous times (NEUBAUER, 1994; CHANNELL and KOZUR, 1997), Middle Cretaceous strike-slip faulting (POLINSKI and EISBACHER, 1992; LEIN et al., 1997) and Neogene (Early/Middle Miocene) continental escape of the Austroalpine crust towards the east (NEUBAUER, 1988; RATSCHBACHER et al., 1991; DECKER and PERESSON, 1996) dismembered the former continuous facies belt. As a result, the Drau Range represents an exotic block in its present tectonic setting (Fig. 1).

The thermal evolution of the Eastern Alps has been studied by a large number of authors (for a general reconstruction of the metamorphic events within the Permo-Mesozoic cover sequences see HOINKES et al., 1999, and FREY and FERREIRO MÄHLMANN, 1999). On the basis of the calibration of thermal basin models by organic maturity parameters (coalification of organic matter), thermal constraints (i.e. time, temperature, heat flow) have been estimated within the Austroalpine Northern Calcareous Alps (PETSCHICK, 1989; FERREIRO MÄHLMANN, 1994; FERREIRO MÄHLMANN and PETSCHICK, 1995, 1997) and in the Southalpine Carnic Alps (RANTITSCH, 1997). In this paper the regional pattern of vitrinite reflectance is used to unravel the thermal history of the Drau Range. A numerical basin model provides a new temperature calculation for the time of Mesozoic and Paleogene subsidence.

2. Geological setting

The Drau Range belongs to the southernmost part of the tectonically highest unit of the Eastern Alps (Upper Austroalpine sensu TOLLMANN, 1959). It is composed of 4 to 5 km thick Permo-Mesozoic sediments (TOLLMANN, 1977), resting transgressively and unconformably on metamorphic rocks of the

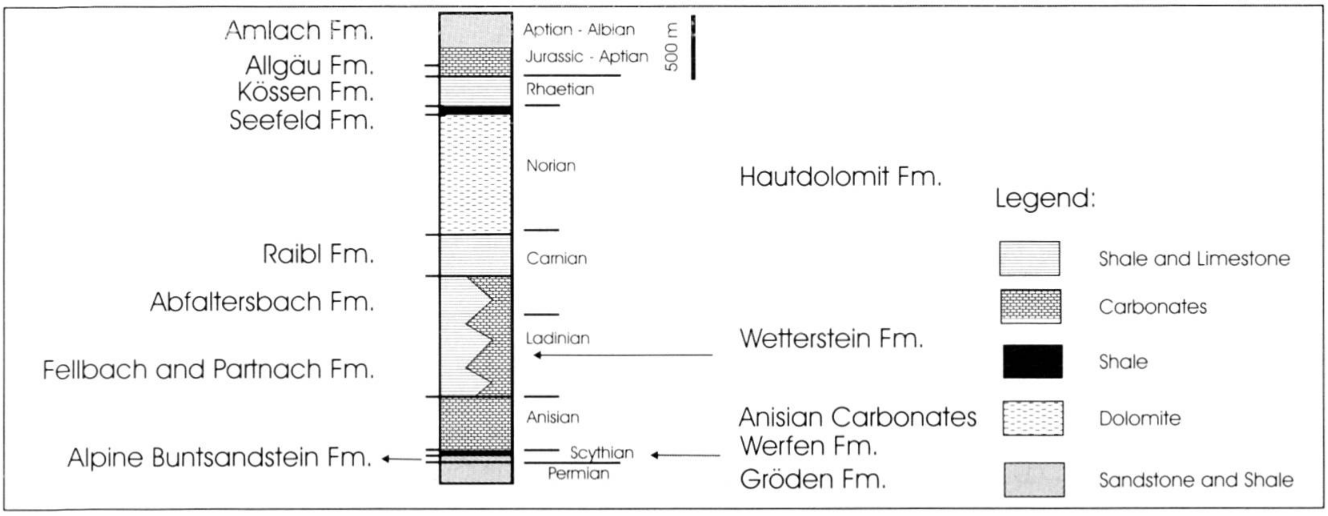

Fig. 2 Generalized stratigraphy within the Drau Range indicating the sampled stratigraphic layers in the left part of the figure.

Austroalpine crystalline basement. Due to Miocene strike-slip tectonics, the Drau Range is now separated into the Northern Karawanken Range, the Dobratsch block, the Gailtal Alps, the Rabantberg block and the Lienz Dolomiten Range (Fig. 1). Stratigraphically (Fig. 2) the Drau Range displays the development of a passive continental margin, from basal Permian continental red beds to Triassic platform sediments. Subsequently Jurassic hemipelagic basin sediments and Cretaceous flysch sediments were deposited in a wide oblique-slip zone (SCHMIDT et al., 1991), leading to an initial displacement of the Drau Range from its original paleogeographic position.

Subsequent to the deposition of Scythian red beds (Alpine Buntsandstein Formation) and Anisian shallow water carbonates, Ladinian to Carnian strata of an intraplatform basin interfinger with the platform carbonates of the Wetterstein Formation. Stratigraphically higher, the mixed carbonate-siliciclastic sequence of the Raibl Group (Carnian) is overlain by lagoonal dolomites of the Hauptdolomit Formation (Norian) and basinal shales of the Kössen Formation (Rhaetian). Younger sediments are only exposed in structural synclines of the Lienz Dolomiten Range (SCHMIDT et al., 1991) and at the northern margin of the Northern Karawanken Range. They include Liassic (Hettangian) to Lower Cretaceous (Valanginian) hemipelagic basin sediments, overlain by Aptian to Albian flysch sediments (Amlach Formation; FAUPL, 1977; BLAU and SCHMIDT, 1988; BLAU and GRÜN, 1995). These flysch sediments are intruded by a 3 m thick shoshonitic dike (EXNER, 1976, see Fig. 1) with a well constrained K–Ar amphibole and biotite cooling age of 24.2 ± 0.5 Ma (Oligocene; DEUTSCH, 1984).

The internal structural architecture of the Lienz Dolomiten Range is controlled by large-scale E–W to ESE–WNW trending folds (VAN BEMMELEN, 1957, 1961; VAN BEMMELEN and MEULENKAMP, 1965) which are sheared along strike-slip and normal faults, trending in the same direction. As a result, a Miocene flower structure is exposed within the westernmost margin of the Lienz Dolomiten Range (SPERLING, 1990; SCHMIDT et al., 1993; BRANDNER and SPERLING, 1995; SCHMIDT, 1995). This structural style is also reported from the Northern Karawanken Range (POLINSKI and EISBACHER, 1992; NEMES et al., 1997). The presence of transpressional shear textures indicates that a similar structural architecture may also be exposed in the Gailtal Alps.

The polyphase tectonic history of the Drau Range shows the following chronology:

1. Pre-Oligocene (Eocene?, PRAGER, written comm. 2001) E–W trending folding of the sedimentary succession.
2. In the Lienz Dolomiten Range, an extensional tectonic setting in the Oligocene results in normal faulting of structural blocks towards the north, simultaneous with the emplacement of magmatic rocks (EXNER, 1976; DEUTSCH, 1984, 1986; VON BLANCKENBURG and DAVIES, 1995) along the Periadriatic Lineament (SPERLING, 1990; BRANDNER and SPERLING, 1995).
3. Miocene dextral shearing kinematically linked to shearing along the Periadriatic Fault (POLINSKI and EISBACHER, 1992; SPRENGER and HEINISCH, 1992; NEMES et al., 1997).

A reconstruction of the thermal history of the Alpine Mesozoic thrust belt revealed several "heating events": PETSCHICK (1989) and FERREIRO MÄHLMANN and PETSCHICK (1995, 1997) proposed in the Northern Calcareous Alps as well as in the Mittelbünden and Oberhalbstein area a (pre-tectonic) Permian to Middle Triassic diastathermal metamorphism (ROBINSON, 1987), a

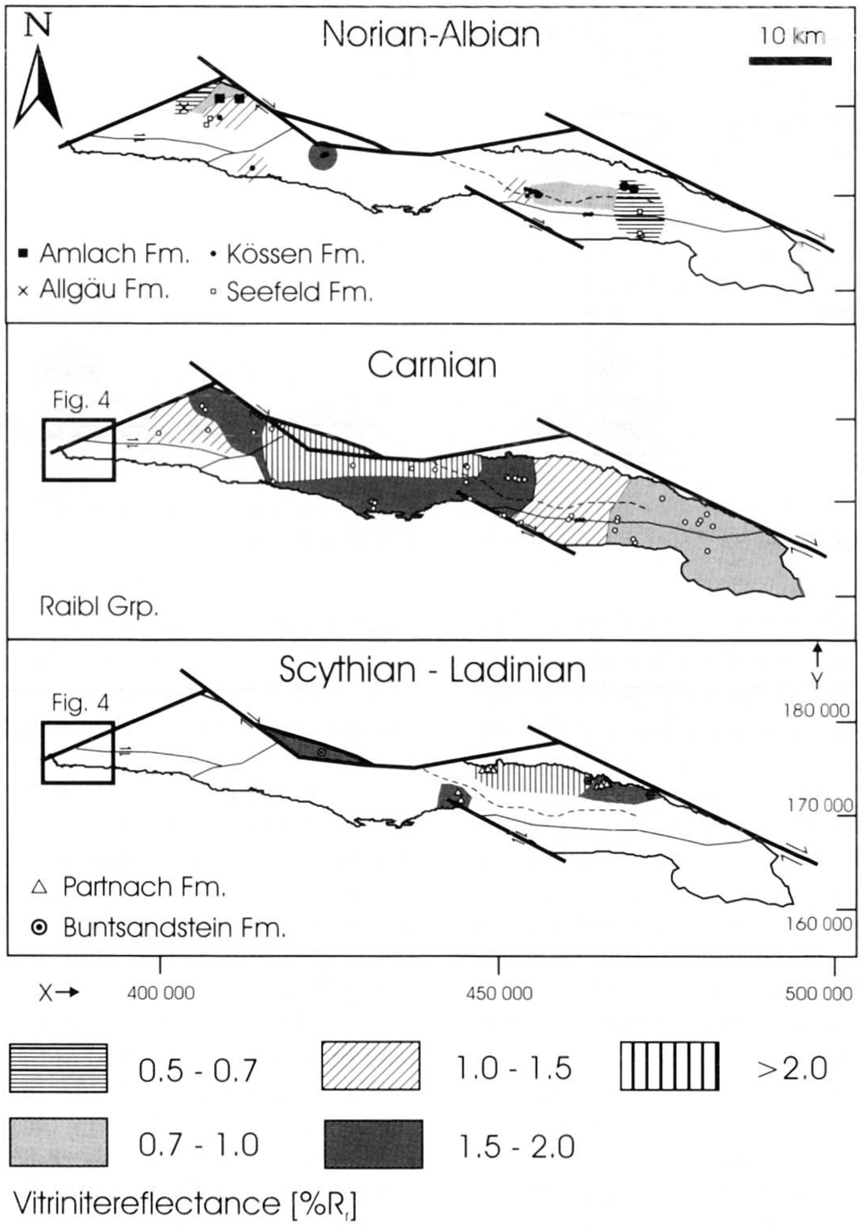

Fig. 3 Vitrinite reflectance (%R_r) in different stratigraphic layers within the Lienz Dolomiten Range, Gailtal Alps and Dobratsch block. Isocoalification areas were constructed by classifying the vitrinite reflectance values (Tab. 1) into five groups. Point symbols indicate sample localities (see Fig. 1). The coordinate system of table 1 is given for reference.

syntectonic thermal event during Early Cretaceous to Turonian times and a post-tectonic thermal event acting in the Late Paleogene to Neogene (see also HEHN-WOHNLICH, 1986; KRALIK et al., 1987; HENRICHS, 1993; KÜRMANN, 1993; KRALIK and SCHRAMM, 1994; FERREIRO MÄHLMANN, 1994, 1995, 1996; BERRA and CIRILLI, 1997). Furthermore, extremely high ranks of Conodont Alteration Indices (up to CAI 7) have been detected in the Juvavic nappe system of the Northern Calcareous Alps. These are explained by GAWLICK and KÖNIGSHOF (1993), GAWLICK et al. (1994) and GAWLICK and HÖPFER (1996) by a tectonic burial of internal parts in an accretionary wedge during Late Jurassic to Early Cretaceous closure of the Meliata-Hallstatt ocean (see also SPÖTL and HASENHÜTL, 1998).

The thermal history of the Drau Range has been previously investigated on the basis of illite crystallinity (NIEDERMAYR et al., 1984), Conodont Alteration Index (CAI, LEIN et al., 1997), and microthermometrical studies (NIEDERMAYR et al., 1984; ZEEH, 1995; ZEEH et al., 1995; RANTITSCH et al., 1999a; KAPPLER and ZEEH, 2000).

Anchizonal illite crystallinities in Permo-Scythian strata (NIEDERMAYR et al., 1984) as well as CAI values between 1.5 and 2.5 in Middle to Late Triassic carbonates (LEIN et al., 1997) are interpreted by NIEDERMAYR et al. (1984) and LEIN et al. (1997) by burial heating of the sedimentary

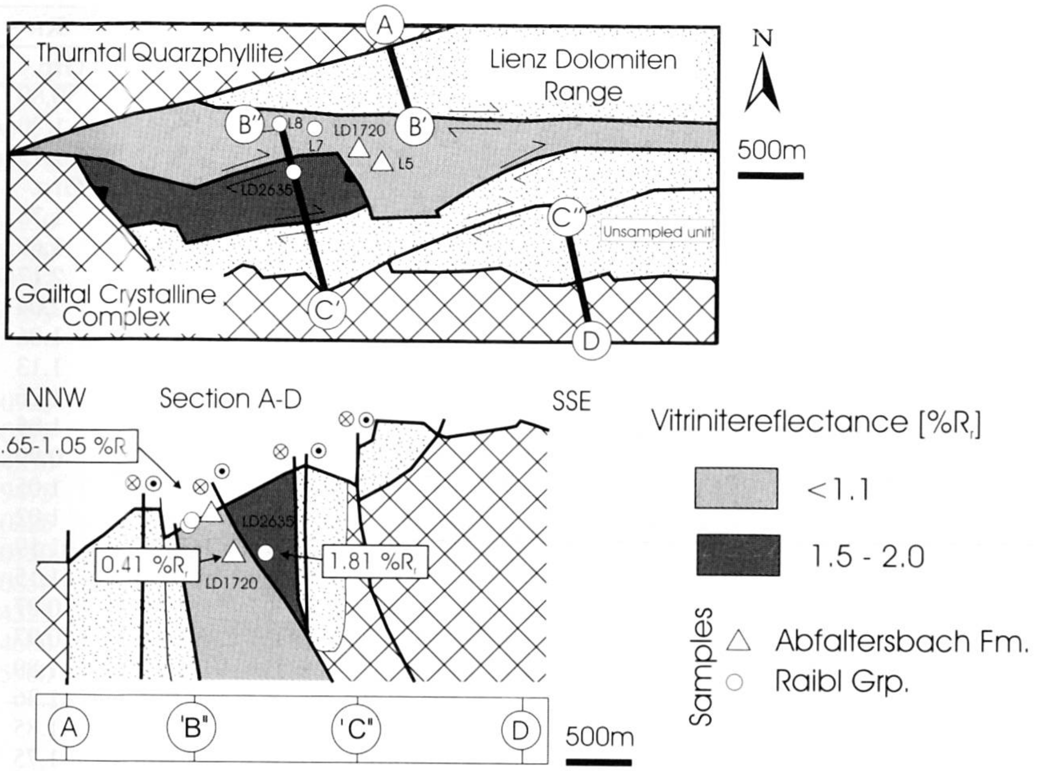

Fig. 4 Coalification within the westernmost segment of the Lienz Dolomiten Range in the structural map and the section of SPERLING (1990). Two samples derive from the Strassen-Amlach hydroelectric power tunnel. Section A–B'–B"–C'–C"–D is segmented into three section lines. Note that there is a marked break in coalification across a strike slip fault. Coalification in Carnian strata is higher than in stratigraphical deeper (Ladinian) strata.

sequence during or slightly after emplacement of the Drau Range in its present position. Fluid inclusions have been studied in quartz fissures crosscutting Permo-Scythian red beds (NIEDERMAYR et al., 1984), in carbonate cements within Carnian carbonates (ZEEH et al., 1995), in ore minerals of the Bleiberg-type Pb-Zn mineralizations (ZEEH and BECHSTÄDT, 1994; RANTITSCH et al., 1999a), and in authigenic quartz hosted in Norian dolomites (RANTITSCH et al., 1999a). NIEDERMAYR et al. (1984) reported microthermometrical data of aqueous fluid inclusions hosted in quartz fissures crosscutting Permo-Scythian red beds. They are all trapped along healed fractures (secondary inclusions). Due to the lack of CO_2, CH_4 or higher hydrocarbons, these fluids are attributed to the water-zone in the fluid zonation of MULLIS (1979) by NIEDERMAYR et al. (1984). Minimum trapping temperatures of 270 °C are assumed in analogy to the Swiss Alps. ZEEH et al. (1995) presented microthermometrical data of late stage fluid inclusions entrapped simultaneously with the precipitation of carbonate cements (calcite and dolomite) and fluorites within Carnian carbonates (Wetterstein Formation). Accepting the cement stratigraphy of ZEEH et al. (1995), cement precipitated during the Miocene (KAPPLER and ZEEH, 2000), thus indicating fluid entrapment after the time of maximum subsidence. Trapping temperatures of 125 to 278 °C were estimated by ZEEH et al. (1995) based on a pressure correction of 30 MPa. Hydrocarbons in ore minerals of Bleiberg-type Pb-Zn minerals and in authigenic quartz embedded in dolomites of the Norian Hauptdolomit Formation of the Lienz Dolomiten Range have been analyzed by microthermometrical methods, bulk-sample gas chromatography and fluorescence microscopy (RANTITSCH et al., 1999a). Microthermometrical data of hydrocarbon and aqueous fluid inclusions and the molecular composition of the hydrocarbons indicate trapping at 120 to 130 °C and 20 to 25 MPa.

In the Austroalpine-Southalpine realm there is clear geochronological evidence of a two-stage thermal history during Oligocene to Miocene times. Apatite fission track dating in the area between the Penninic Tauern window and the Periadriatic Lineament reveals ages in two clusters around 31–25 Ma (Oligocene) and 19–15 Ma (Early/Middle Miocene) respectively (GRUNDMANN and MORTEANI, 1985, STAUFENBERG, 1987; HEJL, 1998, see Fig. 1). In the absence of a regional metamorphic event between 15–31 Ma in the Austroalpine basement, these cooling ages are related to the emplacement of Oligocene intrusives along the Periadriatic Lineament (VON BLANCK-

Tab. 1 Measured vitrinite reflectance values in 131 locations of the Drau Range (x, y = coordinates in the Austrian M31 Gauß-Krüger coordinate system, see Fig. 1, Fm = sampled formation, Rr = vitrinite reflection, sd = standard deviation, N = number of measurements). Two samples derive from the Strassen-Amlach hydroelectric power tunnel (marked by a star symbol, the tunnel position is indicated by the sample code). Samples within the Northern Karawanken Range are marked by a circle (°) symbol.

Sample	x	y	Fm	Rr	sd	N
			Amlach Fm.			
LD200	412244	184162		1.32	0.17	50
LD201	411739	184027		1.47	0.13	50
LD202	411579	184112		1.26	0.12	50
LD203	410699	183943		1.29	0.15	50
LD204	410289	183833		0.91	0.12	50
LD205	410179	184015		4.53	0.59	50
LD206	410154	184025		0.93	0.14	50
LD206A	411289	184267		1.17	0.21	50
LD207	411834	184232		1.19	0.12	50
			Allgäu Fm.			
L6	404159	183636		0.59	0.13	57
			Kössen Fm.			
DR107	451275	172325		1.03	0.10	38
DR109	451750	172300		0.99	0.11	10
DR110	451850	172375		0.98	0.21	49
Dr110-1	451855	172370		0.93	0.12	38
DR1121	451500	172525		1.41	0.23	20
DR1122	451500	172550		0.94	0.27	10
DR114	451250	172825		0.95	0.15	43
DR115	450950	172850		0.93	0.12	30
DR117	450425	172975		1.09	0.28	10
DR118	450100	172175		1.06	0.20	17
DR119	449800	173250		1.21	0.19	13
DR125	422675	177875		2.20	0.40	75
DR126	422525	177775		1.73	0.15	49
DR128	422075	177625		1.53	0.27	31
DR130	422200	177500		1.71	0.14	32
DR147	464560	171590		0.59	0.12	65
DR148	464540	171640		0.63	0.14	22
DR151	412600	176000		1.45	0.18	90
DR56	422375	177875		1.66	0.30	17
L3	408160	183500		1.33	0.17	10
			Seefeld Fm.			
LD11	409300	182125		1.09	0.17	48
LD10	409300	182000		1.25	0.15	60
WH1	468127	170177		0.58	0.11	34
WH2	468130	170180		0.58	0.12	20
WH3	468132	170177		0.55	0.11	15
Wind1-2	468797	166438		0.60	0.10	27
Wind2	468531	166319		0.47	0.10	28
Wind3	468286	166284		0.61	0.11	25
Wind4	468047	166567		0.47	0.11	66
			Raibl Grp.			
BB5	474115	165624		0.84	0.15	42
D11	463525	169975		0.94	0.23	26
D12	463450	168700		0.94	0.19	20
D2	472500	169925		0.71	0.12	27
D3	470750	170875		0.94	0.10	39
D4	470875	171025		0.75	0.15	18

Sample	x	y	Fm	Rr	sd	N
			Raibl Grp.			
D5	471300	171250		0.80	0.13	36
Dr142	449600	175450		1.80	0.22	21
Dr143	449750	175450		1.75	0.23	49
			Raibl Grp.			
Dr144	450825	175250		1.78	0.22	26
Dr145	450025	175250		1.69	0.25	50
DR152	434725	176710		2.17	0.17	21
DR153	438480	176450		2.04	0.17	16
DR20	451325	168525		1.06	0.20	24
Dr202	456388	170201		1.13	0.18	64
Dr204	456953	170581		1.26	0.16	24
Dr205	465462	167181		1.05	0.23	36
Dr207	465677	167334		0.99	0.19	40
Dr208	466121	166483		1.05	0.19	50
DR22	451757	168665		1.02	0.14	12
DR24	451902	168775		1.19	0.22	28
DR25	451900	168775		1.15	0.15	30
DR26	451900	168777		0.87	0.14	29
DR27	451875	168850		0.97	0.17	31
DR50	429825	172200		1.89	0.10	69
DR51	429875	172175		1.36	0.25	25
DR52	429925	172200		1.85	0.19	23
DR54	430400	172025		1.75	0.14	32
DR55	430175	171300		1.27	0.20	50
DR57	447725	170450		1.51	0.39	31
DR59	443375	172575		1.26	0.12	27
DR60	442800	174650		1.47	0.29	29
DR63	442875	177050		2.70	0.28	22
DR64	442975	176875		2.40	0.23	14
DR72	445025	177025		2.40	0.47	27
L7	389840	179625		1.05	0.16	32
L8	389546	179525		0.65	0.12	120
LD15	408575	183275		1.55	0.25	10
LD2635*	390040	179125		1.81	0.12	40
H16	415628	179651		1.72	0.19	50
K14	407051	180283		1.37	0.15	44
K3	418568	179512		1.99	0.22	34
K8	417818	179713		2.10	0.21	20
LuOb10	416296	174982		2.11	0.27	50
LuOb40	416300	174980		1.82	0.15	14
H16	415628	179651		1.72	0.19	50
L1	389586	179495		0.86	0.11	40
K14	407728	179268		1.37	0.15	44
G24a	400542	180381		1.26	0.17	22
			Partnach Fm.			
DR100	463564	175496		1.67	0.32	41
DR104	461925	175300		1.94	0.35	20
DR105	462050	175300		1.95	0.35	15
DR1062	462490	175440		1.94	0.33	10
DR121	447875	177625		2.12	0.31	12
DR122	446275	177500		2.85	0.24	12
DR1231	446700	177550		2.39	0.44	27
DR1232	446700	177525		2.53	0.39	14
DR1233	446725	177513		2.47	0.22	10
DR1241	447125	177600		1.96	0.35	27
DR1243	447163	177613		1.95	0.30	23
			Partnach Fm.			
Dr200	443549	173793		1.66	0.32	25
Dr201	443680	172838		1.49	0.24	100
Kü003	460355	175216		1.75	0.12	33

Tab. 1 (cont.)

Sample	x	y	Fm	Rr	sd	N
		Abfaltersbach Fm.				
L5	390978	178925		0.73	0.14	50
LD1720*	390370	179235		0.41	0.10	59
		Buntsandstein Fm.				
DR30	424150	179975		1.90	0.20	11
DR32	424350	179825		1.90	0.12	43
Kü001	470392	173603		1.79	0.17	65
Kü005	461899	176388		2.81	0.25	100
		Raibl Grp.				
NK16°	540725	151575		0.89	0.24	12
NK17°	540875	151560		0.92	0.18	15
NK3°	544250	154700		0.85	0.16	25
NK30°	519475	150875		0.86	0.13	24
NK34°	560325	152875		0.69	0.10	26
NK35°	560150	152750		0.83	0.09	14
NK36°	560850	154375		0.90	0.13	16
NK5°	544325	154625		0.86	0.18	20
NK7°	544600	154300		0.80	0.10	41
NK8°	545960	151850		0.72	0.16	11

ENBURG and DAVIES, 1995) and to the Miocene exhumation of the Eastern Alps in the context of tectonic denudation of the Tauern dome (FRISCH et al., 1998, 2000).

3. Samples and Methods

More than 150 outcrop samples (shales, siltstones and marls) were collected from eight stratigraphic layers of the Permo-Mesozoic basin fill (Fig. 2). The sample localities are indicated in figures 1, 3 and 4 (see table 1 for their coordinates). Vitrinite reflectance has become the most widely applied parameter for quantitatively estimation of the thermal maturity of sedimentary rocks. Principles and techniques of vitrinite reflectance were originally developed for use on coal, and have been modified for use on organic matter dispersed in sedimentary rocks. In this study, vitrinite reflectance was performed in polished whole rock samples cut perpendicular to the bedding, by measurement of mean random reflectance (%R_r) in non-polarized light of 546 nm wavelength in dispersed organic matter following standard techniques (STACH et al., 1982; TAYLOR et al., 1998). Only samples without optical evidence for oxidation are used.

PDI-1D™ software of IES, Jülich (WYGRALA, 1988; LITTKE et al., 1994) was used to model paleo-heat flow during burial heating before folding of the Drau Range. Physical properties of the implicated lithotypes used for modeling are presented in table 2. Surface information on average thickness and lithology (TOLLMANN, 1977: Tab. 24; SPERLING, 1990; BLAU and GRÜN, 1995; BRANDNER and SPERLING, 1995) was used (Tab. 3) to reconstruct the subsidence history of the Drau Range. The measured range of vitrinite reflectance is considered to be representative for the entire stratigraphic thickness of the sampled layer because no exact biostratigraphic ages of the samples are available. Temperatures at the sediment-water interface were calculated by the algorithm from paleogeographic latitudes, paleoclimatic information, and water depths (Tab. 3). The definition of age was performed on the basis of the timescale of HARLAND (1990). For the calculation of vitrinite reflectance, the kinetic EASY%Ro method of SWEENEY and BURNHAM (1990) was applied. Temperature and time are considered to

Tab. 2 Physical properties of lithotypes used for thermal modeling. The thermal conductivities are given as rock matrix conductivities, which are recalculated continuously by the algorithm depending on temperature. Bulk rock thermal conductivities are calculated based on the state of compaction and porosity during burial, assuming complete water saturation.

Lithotype	Initial porosity	Density (kg/m²)	Compressibility (Pa⁻¹)		Thermal Conductivity (W/m*K)		Heat Capacity (cal/g*K)		Permeability at porosity of	
			Min.	Max.	20 °C	100 °C	20 °C	100 °C	5%	75%
Sandstones+Conglomerates	0.35	2663	330	10	2.93	2.63	0.184	0.217	–3.50	0.00
Siltstone	0.56	2672	8000	10	2.14	2.03	0.201	0.242	–5.00	0.00
Marly Limestone	0.46	2707	500	20	2.63	2.41	0.201	0.235	–4.50	9.00
Limestone+Sandstone	0.45	2695	700	20	2.93	2.62	0.190	0.219	–3.50	11.50
Marl	0.55	2687	2000	20	2.23	2.11	0.208	0.248	–5.00	0.00
Limestone	0.42	2710	300	25	2.83	2.56	0.195	0.223	–4.00	13.00
Limestone+Shale	0.50	2700	700	25	2.51	2.31	0.203	0.237	–4.50	9.00
Shale	0.65	2680	60000	10	1.98	1.91	0.213	0.258	–5.50	–1.00
Dolomite	0.48	2836	450	20	3.81	3.21	0.202	0.229	–2.00	15.00
Sandstone	0.42	2660	500	10	3.12	2.64	0.178	0.209	–2.00	0.00

Tab. 3 Input of the basic geological data (SWI Temp = temperature at the sediment-water interface) for modeling of time and burial history of the peripheral parts of the Drau Range (Northern Karawanken Range, eastern area of the Gailtal Alps and Dobratsch block, westernmost area of the Lienz Dolomiten Range).

Time (Ma)	Stratigraphy	Formation	Thickness (m)	Lithology	Depositional Environment	Recent Porosity (%)	Water Depth (m)	SWI Temp. (°C)
0-1.6	Quaternary		50	Sandstone+Conglomerates	Terrestric	34	0	13
1.6-50	Quaternary-Eocene	Erosion	-1430	Siltstone	Platform	45	15	24
50-97	Eocene-Cenomanian	Gosau	900	Marly Limestone	Platform	45	15	24
97-112	Albian -Aptian	Amlacher Fm.	900	Limestone+Sandstone	Platform	18	100	26
112-135	Aptian-Valanginian	Fleckenmergel Fm.	20	Marl	Platform	16	100	25
135-152	Valanginian-Thitonian	Biancon	20	Limestone	Platform	19	100	24
152-195	Kimmeridgian-Pliensbachian	Rotkalk Fm.	20	Limestone	Deep Water	19	750	11
195-208	Sinemurian-Hettangian	Allgäu Fm.	50	Limestone	Basinal	19	100	21
208-212	Rhaetian-Norian	Kössen Fm.	300	Limestone+Shale	Shallow Marine	15	15	24
212-215	U.Norian	Seefeld Fm.	80	Shale	Platform	12	10	24
215-223	Norian	Hauptdolomit Fm.	800	Dolomite	Platform	16	100	23
223-227	U. Carnian	Raibl Grp.	400	Limestone+Shale	Platform	9	100	26
227-238	Carnian-Ladinian	Partnach Fm, Wetterstein Fm.	1200	Limestone	Platform	7	100	26
238-241	Anisian	Muschelkalk Fm.	800	Limestone	Shallow Marine	5	30	27
241-242	Scythian	Werfen Fm.	100	Shale	Shallow Marine	5	30	28
242-243	Scythian	Alp. Buntsandstein Fm.	200	Sandstone	Terrestric	7	0	28

be the prime factors responsible for vitrinite maturation. In the used algorithm heat enters at the base of the decompacted stratigraphic succession and is transferred conductively by contact according to temperature gradients. Only forced (i.e. compaction induced) convection is directly taken into account. Effects of free convective fluid flow systems are not simulated. Models were calibrated by modifying heat flow and the thickness of eroded sediments until a satisfactory fit between measured and calculated vitrinite reflectances was obtained.

4. Results

The measured vitrinite reflectance values are presented in table 1. Due to the widespread exposure of the Carnian Raibl Group, organic maturation of Raibl shales provides the best marker to evaluate the spatial distribution of organic metamorphism. In this stratigraphic level a peak in organic maturation with vitrinite reflectance values up to 2.7 $\%R_r$ is exposed at the northern margin of the Gailtal Alps (Fig. 3). From there vitrinite reflectance decreases gradually. The coalification pattern within Carnian strata cross-cuts internal fold axes (e.g. the Weißensee syncline axis, see Fig. 3) and strike-slip faults that separate the Gailtal Alps from the adjacent tectonic units (Rabantberg block, Dobratsch block and Lienz Dolomiten Range, see Fig. 3). The decrease in vitrinite reflectance towards the east and west is also reflected in the coalification patterns of the Partnach, Seefeld, Kössen (see also BECHTEL et al., 2001) and Amlach Formations (see Fig. 3). These data are in accordance with illite crystallinity data from Scythian sediments (NIEDERMAYR et al., 1984) and Conodont Alteration Index data observed within Middle Triassic carbonates (LEIN et al., 1997).

One sample from a hornfels contact, surrounding a 3 m thick Oligocene dike in the Aptian to Albian Amlach Formation (LD 205, see Tab. 1) contains anisotropic coke-like particles with a vitrinite reflectance of 4.53 $\%R_r$. Reflectance values between 0.91 $\%R_r$ and 1.47 $\%R_r$ were measured at vertical distances of more than 80 m from this dike. There is no spatial correlation between vitrinite reflectance and lateral distance to the dike. In contrast, the local pattern of organic maturation shows an eastward increase towards the central parts of the vitrinite reflectance anomaly (see Fig. 3). Therefore these samples are located within the area of the coalification anomaly.

There is a break in vitrinite reflectance across an E–W trending dextral strike-slip fault in the flower structure of the western Lienz Dolomiten Range (Fig. 4). This fault displaces Ladinian to lower Carnian basinal carbonates in the north from platform carbonates of the same age in the south (SPERLING, 1990; SPERLING and BRANDNER, 1995, Fig. 4).

Vitrinite reflectance of Carnian shales within the Northern Karawanken Range is characterized by values between 0.7 $\%R_r$ and 0.9 $\%R_r$ (see Tab. 1), corresponding to reflectance values at the eastern end of the Gailtal Alps.

5. Discussion

Within the eastern parts of the Gailtal Alps and within the Dobratsch block there is a clear top-to-bottom increase in reflectance from 0.6 $\%R_r$ in Rhaetian and Norian strata to 1.0 $\%R_r$ in Carnian strata and to 1.8 $\%R_r$ in Scythian strata (see Figs 3 and 5). Obviously, this gradient is related to a burial heating before folding. Coalification in all Carnian samples of the Northern Karawanken Range and in one Liassic sample of the Lienz Dolomiten Range is compatible with the observed trend. Therefore, it is assumed that the reflectance trend of the eastern parts of the Gailtal Alps approximates the stratigraphic rank behaviour in Northern Karawanken Range and in parts of the Lienz Dolomiten Range.

A disconformity in vitrinite reflectance across a shear zone of a Miocene flower structure within the Lienz Dolomiten Range (Fig. 4) points to a thermal event prior to Miocene shearing. If a local variation in the stratigraphic thickness of post-Carnian sediments is negated, strong thermal alteration of Carnian sediments (1.8 $\%R_r$, Fig. 4) gives evidence for a thermal overprint exceeding the burial overprint before folding. A high rank of vitrinite reflectance on both sides of the shear zone is expected if shear stress influenced organic maturation (e.g. SUCHY et al., 1997). This is not observed, therefore, a possible effect of shear heating is excluded.

Organic maturation in the central part of the Drau Range is characterized by a concentrically shaped coalification anomaly. Within the central part of the reflectance maximum, Scythian to Rhaetian stratigraphic levels display vitrinite reflectance values (1.9 $\%R_r$ in Scythian strata, 2.0 to

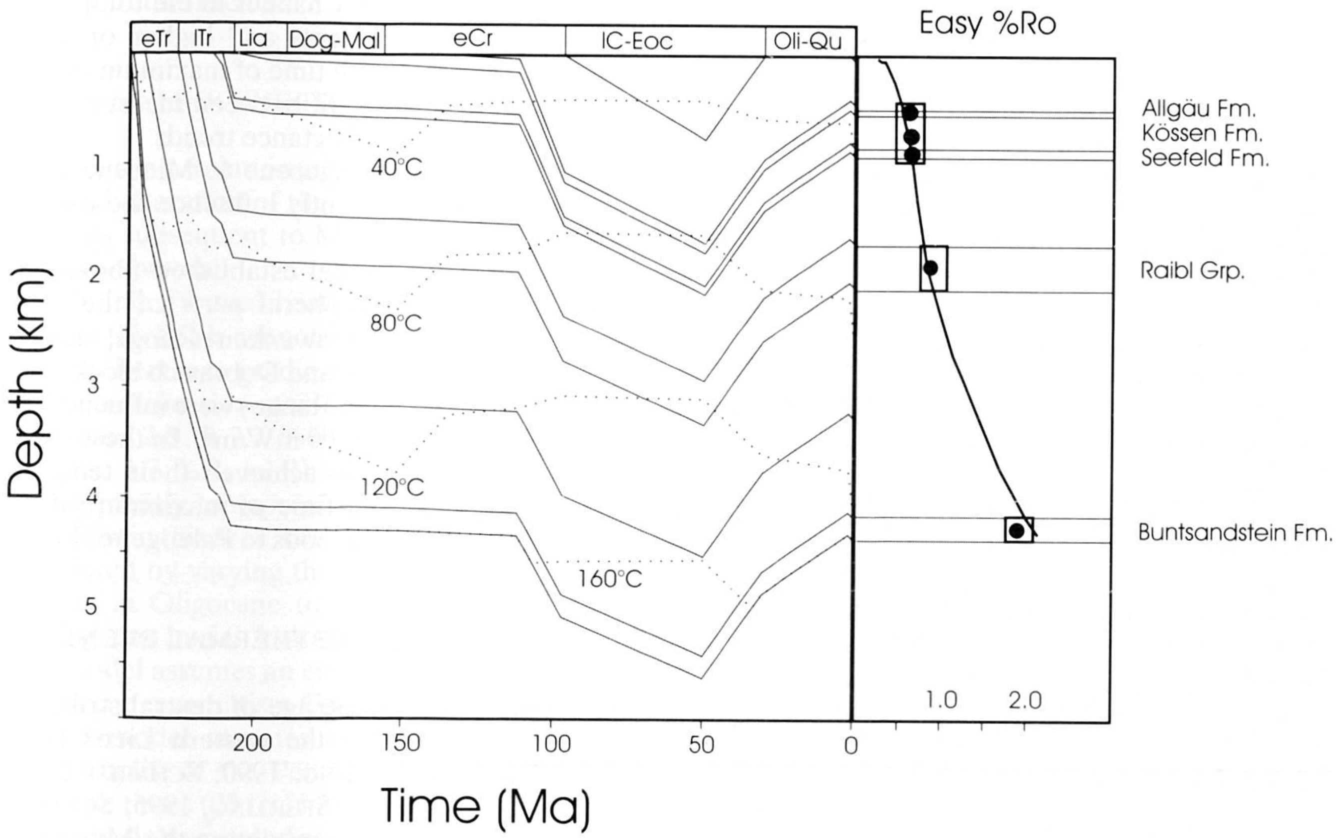

Fig. 5 Burial history, temperature history and heat flow model of the peripheral parts of the Drau Range (Northern Karawanken Range, eastern area of the Gailtal Alps and Dobratsch block, parts of the Lienz Dolomiten Range) based on an assumed heat flow of 60 mW/m². Dashed curves are iso-temperature lines. In the right part of the figure measured (dots) and calculated vitrinite reflectances (line) calculated on the basis of burial and temperature history using the EASY%Ro method are plotted versus depth.

2.7 %R_r in Carnian strata and 1.5% to 1.7 %R_r in Rhaetian strata; Fig. 3) which are incompatible with a top-to-bottom increase of the thermal overprint. The coalification pattern cross-cuts internal structural elements. Therefore, a thermal overprint subsequent to folding has to be assumed and a synsedimentary diastathermal metamorphism (ROBINSON, 1987) is excluded. This zonation cuts the strike-slip fault separating the Dobratsch block from the Gailtal Alps, it cuts the Iseltal Line which is interpreted as a dextral strike-slip fault acting in the Early Miocene as a Riedel shear of the Periadriatic fault system (SPRENGER and HEINISCH, 1992), and it cuts the Pirkner fault. The Pirkner fault is interpreted as a normal fault which was reactivated as a reverse fault during Oligocene time (PRAGER, written comm. 2000). Thus, there is evidence for a Miocene event of strong heating.

In summary, the coalification data give evidence of two thermal events (pre-Miocene and Miocene), overprinting the syn-depositional thermal alteration which was achieved during subsidence of the basin fill. These events are discussed separately in the following sections.

5.1. THERMAL ALTERATION DURING CRETACEOUS TO EOCENE SUBSIDENCE

Thermal alteration during Cretaceous to Eocene subsidence is still preserved outside the area of the reflectance maximum. To constrain the heat flow and subsidence history in this region, a numerical 1-D model was established by fitting the observed coalification data within the peripheral parts of the Drau Range (Northern Karawanken Range, eastern area of the Gailtal Alps and Dobratsch block, parts of the Lienz Dolomiten Range, Figs 3 and 5) with the calculated coalification trend. The resulting model is presented in figure 5.

In this model (see tables 2 and 3 for the input parameters), a pile of 1400 m Late Cretaceous to Eocene sediments is added on top of the exposed stratigraphic succession, and a heat flow of 60 mW/m² is applied. The additional thickness is obtained by adding of 530 m Aptian to Albian flysch sediments and 900 m of Cenomanian to Eocene Gosau type sediments which were eroded during regional uplift in the Oligocene and Miocene (VON GOSEN, 1989 and references therein). The assumed bulk thickness is supported by a paleogeographic relationship of the Lienz Dolomiten Range with the Southalpine Lombardian basin (TOLLMANN, 1977; SCHMIDT et al., 1991; BRANDNER and SPERLING, 1995) and the Transdanubian Mountains of the Pannonian realm (SCHMIDT et al., 1991). In this regions CLAYTON and KONCZ (1994) and GREBER et al. (1997) used similar model assumptions for a successful thermal modeling of the Mesozoic basin fill. Late Santonian to Eocene Gosau sediments are exposed in the north of the Drau Range within the Krappfeld Gosau basin (TOLLMANN, 1977, NEUMANN, 1989; WILLINGSHOFER et al., 1999). The estimated amount of eroded thickness is also in accordance with a rough estimate of surface erosion in the Austroalpine tectonic unit south of the Tauern window in the order of 1 km (KUHLEMANN et al., 2001).

Sensitivity analyses demonstrate the reliability of these assumptions:

(1) For numerical simulations of basin evolution, the exact thickness of existing and eroded sequences are very important. In this study, modeled vitrinite reflectance in Late Triassic to Early Jurassic strata depends mainly on the amount of eroded thickness on top of the exposed sequence. Consequently, the observed vitrinite reflectance values of about 0.6 %R_r within Late Triassic to Early Jurassic strata can only be explained by the assumed loading. If no additional overburden is assumed it is impossible to achieve a fit of the calculated vitrinite reflectance values with the observed ones (Fig. 6 a). Changes in the total thickness of eroded sediments and higher or lower heat flow values for the time of maximum subsidence result in a worse fit between measured and calculated vitrinite reflectance trends.

(2) Varying the Oligocene to Miocene uplift path does not significantly influence the calibration.

Accepting the model established above it is obvious that the peripheral parts of the Drau Range (Northern Karawanken Range, eastern area of the Gailtal Alps and Dobratsch block, parts of the Lienz Dolomiten Range) were influenced by low heat flow (approx. 60 mW/m²). In these areas, all stratigraphic layers achieved their temperature maximum at the time of maximum subsidence in the Late Cretaceous to Paleogene (Fig. 5).

5.2. PRE-MIOCENE THERMAL EVENT

Accepting the Miocene age of dextral strike-slip faults exposed within the western Lienz Dolomiten Range (SPERLING, 1990; SCHMIDT et al., 1993; BRANDNER and SPERLING, 1995; SCHMIDT, 1995), a thermal event predating the Miocene is preserved in a displaced structural block of a genetically related flower structure. This block is characterized by strong thermal alteration (1.8 %R_r) of Carnian sediments (Fig. 4). According to the model established above, it is not possible to explain such a high thermal alteration by basinal subsidence.

Remarkably high vitrinite reflectance values in the contact zone of an Oligocene dike demonstrates that magmatism provides a plausible explanation for this observation. In the hornfels sample maximum paleotemperatures of 550 to 600 °C are estimated using the measured vitrinite reflectance of 4.53 %R_r and the diagram of BOSTICK (1973; see also BAUER et al., 1997). Therefore, it seems most likely that Oligocene syncollisional magmatism along the Periadriatic Lineament above the subducted Penninic plate (VON BLANCKENBURG and DAVIES, 1995) could cause a thermal overprint. The assumption of high heat flow during Oligocene times in this region fits well in a reconstruction of the heat flow pattern at the southern margin of the Eastern Alps by SACHSENHOFER (2001, see also SACHSENHOFER, 1992). Also, the widespread distribution of Oligocene apatite fission track ages in the vicinity of the Drau Range (GRUNDMANN and MORTEANI, 1985; GRUNDMANN, 1987; STAUFENBERG, 1987; von BLANCKENBURG and DAVIES, 1995; HEJL, 1997, 1998; FRISCH et al., 1998, see Fig. 1) indicates that magmatism significantly influenced the thermal history of this region.

5.3. MIOCENE THERMAL EVENT

Crosscutting relationships clearly demonstrate thermal alteration of the central part of the Gailtal Alps subsequent to Miocene strike-slip faulting (see above).

Modeling burial heating by varying the total eroded thickness cannot explain the observed vitrinite reflectance gradient within the central part of the coalification maximum (1.9 %R_r in Scythian strata, 2.0 to 2.7 %R_r in Carnian strata, and 1.5% to 1.7 %R_r in Rhaetian strata; see Fig. 3). Consequently, to approximate a possible range of heat flow in this area, two alternative models were calculated by varying the post-tectonic heat flow density in Oligocene to Miocene times and assuming the burial history described above. The first model assumes an enhanced heat flow due to Oligocene magmatism (35 to 23 Ma), whereas the second model assumes an enhanced heat flow during uplift of the Penninic Tauern Window in Miocene times (23 to 15 Ma). Application of both single models revealed no accordance between all measured and calculated vitrinite reflectance (Figs 6b and c). In the used algorithm heat enters from the base of the stratigraphic succession. These results imply that the principle assumptions of the models do not appear to be realistic. Therefore, in order to explain thermal maturation in all stratigraphic layers, an increase of the effective stratigraphic thickness due to tilting of the sequence prior to heating or a lateral dissipating heat flow has to be assumed. Because of lack of calibration data no definitive estimation of paleoheat flow within the area of the coalification anomaly can be made. Nevertheless, the simulation results suggest strongly enhanced heat flow during post-tectonic coalification (Figs 6b, c).

Most probably, rapid exhumation of the Penninic Tauern dome during the Miocene (FÜGENSCHUH, 1995; GENSER et al., 1996 and references therein) provided the heat source for this alteration. This explanation is supported by the regional heat flow pattern in the area of the rising Tauern dome and by Miocene cooling ages in the surrounding metamorphic basement. It has been demonstrated by SACHSENHOFER (1992, 1994), FÜGENSCHUH (1995) and SACHSENHOFER et al. (1998, 2000) that heat flow was extremely high during Early/Middle Miocene uplift of metamorphic core complexes (Tauern and Rechnitz Window, Pohorje/Kozjak area). This results from rapid uplift of hot basement rocks (e.g. GENSER et al., 1996; DUNKL and DEMÉNY, 1997; DUNKL et al., 1998). A map for the Early/Middle Miocene times (SACHSENHOFER, 2001) demonstrates a circular zonation of an increase in heat flow to more than 150 mW/m^2 towards the center of the rising Tauern dome. In the palinspastic reconstruction of the Eastern Alps of FRISCH et al. (1998) it is obvious that during this time (Ottnangian to Early Badenian) the northern margin of the Drau Range was situated just south of the rising Tauern dome. Advection of heat during periods of rapid exhumation results in the elevation of isotherms and thus in an increase of near-surface geothermal gradients (KOONS, 1987; FÜGENSCHUH, 1995; GENSER et al., 1996; DUNKL and DEMÉNY, 1997; MANCKTELOW and GRASEMANN, 1997; DUNKL et al., 1998; SACHSENHOFER et al., 1998). Therefore, advective heat transport during extremely rapid cooling of Penninic rocks (~200 °C/Ma, FÜGENSCHUH et al., 1997), which is accompanied by convective heat loss due to fluid circulation (e.g. POHL and BELOCKY, 1994; RANTITSCH et al., 1999b; RANTITSCH, submitted), could cause an increasing heat flow within the crystalline basement of the Drau Range and high organic maturation of Triassic sediments in the Gailtal Alps. Evidence for hydrothermal activity in the basement is given by the presence of small vein type gold, silver, copper, lead, zinc, antimony and mercury mineralization within the Kreuzeck- and Goldeck- Crystalline Complexes north of the Drau Range (Fig. 1).

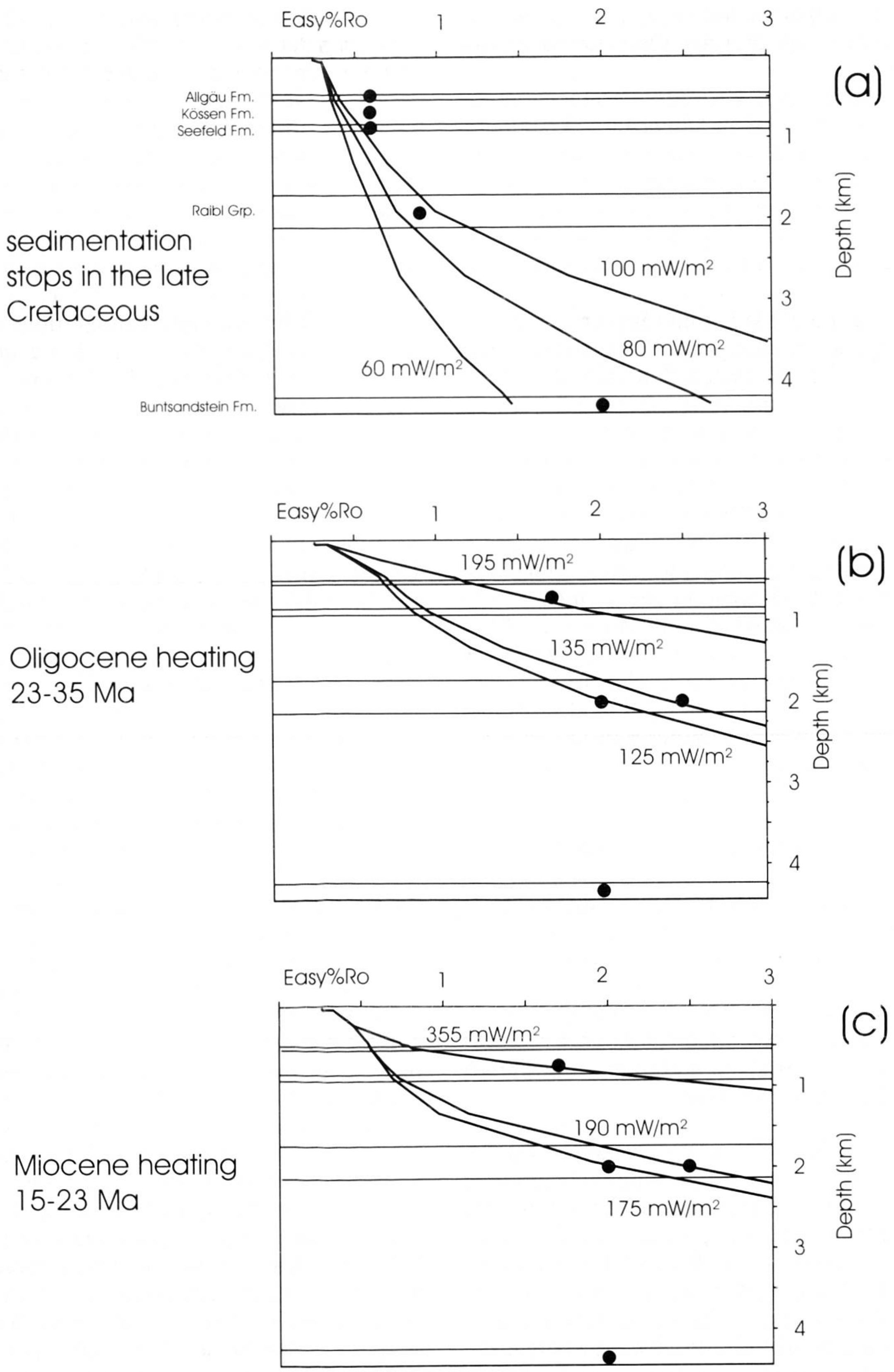

Fig. 6 Measured (dots) and calculated vitrinite reflectances (line) calculated on the basis of burial and temperature history using the EASY%Ro method within the peripheral parts of the Drau Range (Northern Karawanken Range, eastern area of the Gailtal Alps and Dobratsch block, parts of the Lienz Dolomiten Range) are plotted versus depth (a) No additional overburden on top of the exposed stratigraphic sequence is assumed. Varying the heat flow density at the time of maximum subsidence (Cretaceous) no fit of the calculated coalification trend with the observed vitrinite reflectance values can be achieved. (b) Modeling of elevated heat flow in the central part of the coalification anomaly in Oligocene times (30–23Ma) assuming the burial history of figure 5. (c) Modeling of elevated heat flow in the central part of the coalification anomaly in Miocene times (23–15 Ma) assuming the burial history of figure 5.

These are explained by post-Eocene fluid circulation (FEITZINGER et al., 1995; MALI, 1996).

In the crystalline basement between the Tauern Window and the Periadriatic Lineament there are numerous geothermometric evidences of Early/Middle Tertiary cooling of hot basement units (GRUNDMANN and MORTEANI, 1985; GRUNDMANN, 1987; STAUFENBERG, 1987; HEJL, 1997, 1998; LÄUFER et al., 1997; FRISCH et al., 1998, 2000, see Fig. 1). Apatite fission track ages around 17 Ma (ca. Early/Middle Miocene boundary) are reported from the southern margin of the Tauern Window (GRUNDMANN and MORTEANI, 1985; GRUNDMANN, 1987; STAUFENBERG, 1987). They are related to cooling of Austroalpine basement units below 110 °C in the cover of the rising dome. Similar ages are found in the crystalline basement north of the observed coalification anomaly (STAUFENBERG, 1987; DUNKL, pers. comm. 1999, Fig. 1). These data provide further evidence for a Miocene cooling event.

Fluid inclusion data of NIEDERMAYR et al. (1984), ZEEH et al. (1995) and RANTITSCH et al. (1999a) indicate fluid flow during basinal subsidence and uplift in the Late Cretaceous to Eocene and retrograde hyperthermal fluid activity in the Neogene. Based on the established thermal basin model, heat transfer is supposed to be conductive at the time of maximum subsidence, whereas convective heat flow characterizes the circulation of retrograde fluid. A new evaluation of fluid inclusion data (RANTITSCH, submitted) demonstrates that trapping temperatures of aqueous fluid inclusions in quartz fissures, cross-cutting Permo-Scythian sediments, and those in fluorites of the Carnian Wetterstein Formation (125 to 215 °C in quartz, 115 to 180 °C in fluorite) can be used as estimates of the burial temperatures (190 °C in the Permo-Scythian, 130 to 160 °C in the Carnian, see Fig. 5). In contrast, trapping temperatures of hydrocarbon-bearing fluid inclusions hosted in authigenic quartz of the Norian Hauptdolomit Formation (120 to 130 °C) and aqueous fluid inclusions in deep burial carbonate cements (150 to 300 °C) exceed the basinal isotherms (100 to 120 °C in the Norian, 130 to 160 °C in the Carnian, see Fig. 5), These data indicate convective heat loss due to fluid circulation. If BARKER's (1983) equation for hydrothermal systems is employed for the highest vitrinite reflectance value measured within the coalification anomaly (2.7 $\%R_r$), a paleotemperature close to 270 °C is estimated. This temperature may be related to high fluid inclusion homogenization temperatures (150 to 300 °C), measured in late-stage carbonate cements (ZEEH et al., 1995).

6. Conclusions

The following conclusions can be summarized on the basis of this study:

(1) Vitrinite reflectance values in Scythian to Albian sediments of the peripheral segments of the Drau Range (Northern Karawanken Range, eastern segment of the Gailtal Alps and Dobratsch block, parts of the Lienz Dolomiten Range) are explained by a relatively low heat flow of approx. 60 mW/m^2 during basinal subsidence.

(2) In the Lienz Dolomiten Range a break in coalification indicates a local pre-Miocene thermal event, attributed to Oligocene magmatic activity along the Periadriatic Lineament. This magmatic activity is related to slab breakoff of the subducted Penninic plate (VON BLANCKENBURG and DAVIES, 1995).

(3) A vitrinite reflectance anomaly in the Gailtal Alps gives evidence for strong heating during or after tectonic activity along strike-slip faults, bordering the internal structural units of the Drau Range. This heat flow maximum can be best explained by advective heat transport during rise of the metamorphic Tauern dome in the Early/Middle Miocene. This model explains Miocene (~17 Ma) apatite fission track ages in the surrounding crystalline basement.

Acknowledgements

This study was financially supported by the Austrian Science Fund (FWF) due to grant P10277. Particular thanks are devoted to B. Russegger for many vitrinite reflectance data, to R. Brandner and C. Prager for sample material, to R. Sachsenhofer for many fruitful discussions, and to O.A.R. Thalhammer for correcting the English. Constructive comments of M. Burkhard, M. Engi, W. Frisch, C. Prager, C. Spötl and an anonymous reviewer on an earlier version of this manuscript are gratefully acknowledged.

References

BARKER, C.E. (1983): Influence of time on metamorphism of sedimentary organic matter in liquid-dominated geothermal systems, western North America. Geology 11, 384–388.

BAUER, W., HAGEMANN, H.W., POSCHER, G., SACHSENHOFER, R.F. and SPAETH, G. (1997): Permian coals from Western Dronning Maud Land – Composition, Environment, and the influence of Jurassic magmatism on their maturity. The Antarctic Region: Geological Evolution and Processes 1997, 945–951.

BECHSTÄDT, T. (1978): Faziesanalyse permischer und triadischer Sedimente des Drauzuges als Hinweis auf eine großräumige Lateralverschiebung innerhalb des Ostalpins. Jb. Geol. B.-A. 121, 1–121.

BECHTEL, A., GRATZER, R. and RANTITSCH, G. (2001): Upper Triassic (Rhaetian) mudstones (Kössen Formation) within the central Gailtal Alps (Eastern Alps, Austria) as potential hydrocarbon source rocks. N. Jb. Geol. Paläont. Abh. in print.

BERRA, F. and CIRILLI, S. (1997) Preservation and thermal alteration of organic matter in the Ortles and Quattervals nappes (Upper Austroalpine, North-Eastern Lombardy, Italy): Preliminary results and implications for regional geology. Eclogae geol. Helv. 90, 325–336.

BERTOTTI, G., PICOTTI, V., BERNOULLI, D. and CASTELLARIN, A. (1993): From rifting to drifting: tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. Sedimentary Geology 86, 53–76.

BLAU, J. and GRÜN, B. (1995): Jura und Kreide in der Amlacher Wiesen-Mulde (Nördliche Lienzer Dolomiten. In: HAUSER, C. (ed.): Geologie von Osttirol. Arbeitstagung 1995 der Geologischen Bundesanstalt. Geologische Bundesanstalt Wien, 43–66.

BLAU, J. and SCHMIDT, Th. (1988): Tektonisch kontrollierte Sedimentation im Unterlias der Lienzer Dolomiten (Österreich, Osttirol, Kärnten). Mitt. Ges. Geol. Bergbaustud. Österr. 34/35, 185–207.

BOSTICK N.H. (1973): Time as a factor in thermal metamorphism of phytoclasts (coaly particles). Compte Rendu 7. Congrès International des Stratigraphie et de Geólogie du Carbonifère 2, 183–193.

BRANDNER, R. (1972): "Südalpines" Anis in den Lienzer Dolomiten (Drauzug) (ein Beitrag zur alpin-dinarischen Grenze). Mitt. Ges. Geol. Bergbaustud. 21, 143–162.

BRANDNER, R. and SPERLING, M. (1995): Zur "Terrane"-Geschichte der Lienzer Dolomiten (Drauzug) aus stratigraphischer und struktureller Sicht. In: HAUSER, C. (ed.): Geologie von Osttirol. Arbeitstagung 1995 der Geologischen Bundesanstalt. Geologische Bundesanstalt Wien, 23–35.

CHANNEL, J.E.T. and KOZUR, H.W. (1997): How many oceans? Meliata, Vardar, and Pindos oceans in Mesozoic Alpine paleogeography. Geology 25, 183–186.

CLAYTON, J.L. and KONCZ, I. (1994): Petroleum Geochemistry of the Zala Basin, Hungary. Am. Assoc. Pet. Geol. Bull. 78, 1–22.

DECKER, K. and PERRESSON, H. (1996): Tertiary kinematics in the Alpine-Carpathian-Pannonian system: links between thrusting, transform faulting and crustal extension. In: WESSELY, G. and LIEB, W. (eds): Oil and gas in Alpidic thrustbelts and basins of Central and Eastern Europe. European Association of Geoscientists and Engineers Spec. Publ. 5. Geological Society London, 69–77.

DEUTSCH, A. (1984): Young Alpine dykes south of the Tauern Window (Austria): a K–Ar and Sr isotope study. Contrib. Mineral. Petrol. 85, 45–57.

DEUTSCH, A. (1986): Geochemie oligozäner shoshonitischer Ganggesteine aus der Kreuzeckgruppe (Kärnten/Osttirol). Mitt. Ges. Geol. Bergbaustud. Österr. 32, 105–124.

DUNKL, I. and DEMÉNY, A. (1997): Exhumation of the Rechnitz Window at the border of Eastern Alps and Pannonian basin during Neogene extension. Tectonophysics 272, 197–211.

DUNKL, I., GRASEMANN, B. and FRISCH, W. (1998): Thermal effects of exhumation of a metamorphic core complex on hanging wall syn-rift sediments: an example from the Rechnitz Window, Eastern Alps. Tectonophysics 297, 31–50.

EXNER, C. (1976): Die geologische Position der Magmatite des periadriatischen Lineamentes. Verh. Geol. Bundesanst. Wien 1976, 3–64.

FAUPL P. (1977): Sedimentologische Studien im Kreideflysch der Lienzer Dolomiten. Österr. Akad. Wiss. math.-natw. Kl., Anz. 113, 131–134.

FEITZINGER, G., PAAR, W.H., TARKIAN, M., RECHE, R., WEINZIERL, O., PROCHASKA, W. and HOLZER, H. (1995): Vein type Ag–(Au)–Pb, Zn, Cu–(W, Sn) mineralizations in the Southern Kreuzeck Mountains, Carinthia Province, Austria. Mineralogy and Petrology 53, 307–332.

FERREIRO MÄHLMANN, R. (1994): Zur Bestimmung von Diagenesehöhe und beginnender Metamorphose-Temperaturgeschichte und Tektogenese des Austroalpins und Südpenninikums in Vorarlberg und Mittelbünden. Frankfurter geowiss. Arb. Serie C 14, 1–498.

FERREIRO MÄHLMANN, R. (1995): Das Diagenese-Metamorphose-Muster von Vitrinitreflexion und Illit-"Kristallinität" in Mittelbünden und im Oberhalbstein. Teil 1: Bezüge zur Stockwerktektonik. Schweiz. Mineral. Petrogr. Mitt. 75, 85–122.

FERREIRO MÄHLMANN, R. (1996): Das Diagenese-Metamorphose-Muster von Vitrinitreflexion und Illit-"Kristallinität" in Mittelbünden und im Oberhalbstein. Teil 2: Korrelation kohlenpetrographischer und mineralogischer Parameter. Schweiz. Mineral. Petrogr. Mitt. 76, 23–46.

FERREIRO MÄHLMANN, R. and PETSCHICK, R. (1995): Illit-Kristallinität, Vitrinitreflexion und Maturitätsmodellierung: Tektonische Fallstudien aus der Lechtal- und Silvrettadecke. In: AMANN, G., HANDLER, R., KURZ, W. and STEYRER, H.P. (eds): 6. Symposium Tektonik-Strukturgeologie-Kristallingeologie. Erweiterte Kurzfassungen, 112–115.

FERREIRO MÄHLMANN, R., PETSCHICK, R. (1997): The coalification map of the Alps between the rivers Inn, Isar and Rhein (Austria and Switzerland). Electronic Geology 2, 83–84.

FREY, M. and FERREIRO MÄHLMANN, R. (1999): Alpine metamorphism of the Central Alps). Schweiz. Mineral. Petrogr. Mitt. 79, 135–154.

FRISCH, W., KUHLEMANN, J., DUNKL, I. and BRÜGEL, A. (1998): Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion. Tectonophysics 297, 1–15.

FRISCH, W., DUNKL, I. and KUHLEMANN, J. (2000): Post-collisional orogen-parallel large-scale extension in the Eastern Alps. Tectonophysics 327, 239–265.

FÜGENSCHUH, B. (1995): Thermal and kinematic history of the Brenner area (Eastern Alps, Tyrol). Dr. nat. sci. Thesis, ETH Zürich, 226 pp.

FÜGENSCHUH, B., SEWARD, D. and MANCKTELOW, N. (1997): Exhumation in a convergent orogen: the western Tauern window. Terra Nova 9, 213–217.

GAWLICK, H.-J., KRYSTYN, L. and LEIN, R. (1994): Conodont colour alteration indices: Paleo-temperatures and metamorphism in the Northern Calcareous Alps – a general view. Geol. Rundsch. 83, 660–664.

GAWLICK, H.-J. and HÖPFER, N. (1996): Die mittel- bis früh-oberjurassische Hochdruckmetamorphose der Hallstätter Kalke (Trias) der Pailwand – ein Schlüssel zum Verständnis der frühen Geschichte der Nördlichen Kalkalpen. Schriftenr. Dt. Geol. Ges. 1, 30–32.

GAWLICK, H-J. and KÖNIGSHOF, P. (1993): Diagenese, niedrig- und mitteltemperierte Metamorphose in den südlichen Salzburger Kalkalpen – Paläotemperaturabschätzung auf der Grundlage von Conodont-Color-Alteration-Index-(CAI-) Daten. Jb. Geol. B.-A. 136, 39–48.

GENSER, J., VAN WEES, J.D., CLOETINGH, S. and NEUBAUER, F. (1996): Eastern Alpine tectono-metamorphic evolution: Constraints from two-dimensional P-T-t modeling. Tectonics 15, 584–604.

GREBER, E., LEU, W., BERNOULLI, D., SCHUMACHER, M.E. and WYSS, R. (1997): Hydrocarbon provinces in the Swiss Southern Alps – a gas geochemistry and basin modelling study. Marine and Petroleum Geology 14, 3–25.

GRUNDMANN, G. (1987): Hebungsraten im Tauernfenster, abgeleitet aus Spaltspurendatierungen von Apatiten. Mitt. Österr. Miner. Ges. 132, 103–116.

GRUNDMANN, G. and MORTEANI, G. (1985): The young uplift and thermal history of the Central Eastern Alps (Austria/Italy), evidence from apatite fission track ages. Jb. Geol. B.-A. 128, 197–216.

HAAS, J., KOVÁCS, S., KRYSTYN, L. and LEIN, R. (1995): Significance of Late Permian–Triassic facies zones in terrane reconstructions in the Alpine-North Pannonian domain. Tectonophysics 242, 19–40.

HARLAND, W.B. (1990): A geological time scale. Cambridge University Press Cambridge, 263 pp.

HEHN-WOHNLICH, A. (1986): Inkohlungsuntersuchungen in den Kalkalpen und den nördlichen Vorzonen. Dr. Thesis, Univ. Berlin, 55 pp.

HEJL, E. (1997): 'Cold spots' during the Cenozoic evolution of the Eastern Alps: thermochronological interpretation of apatite fission-track data. Tectonophysics 272, 159–173.

HEJL, E. (1998): Über die känozoische Abkühlung und Denudation der Zentralalpen östlich der Hohen Tauern – eine Apatit-Spaltspurenanalyse. Mitt. Österr. Geol. Ges. 89, 179–199.

HENRICHS, C. (1993): Sedimentpetrographische Untersuchungen zur Hochdiagenese in der Kössen-Formation (Obere Trias) der westlichen Ostalpen und angrenzender Südalpengebiete. Bochumer geol. u. geotechn. Arb. 40, 1–206.

HOINKES, G., KOLLER, F., RANTITSCH, G., DACHS, E., HÖCK, V., NEUBAUER, F. and SCHUSTER, R. (1999): Alpine metamorphism of the Eastern Alps. Schweiz. Mineral. Petrogr. Mitt. 79, 155–181.

KAPPLER, P. and ZEEH, S. (2000): Relationship between fluid flow and faulting in the Alpine realm (Austria, Germany, Italy). Sedimentary Geology 131, 147–162.

KÁZMÉR, M. and KOVÁCS, S. (1985): Permian-Paleogene paleogeography along the eastern part of the Insubric-Periadriatic Lineament system: evidence for continental escape of the Bakony-Drauzug Unit. Acta Geol. Hung. 28, 69–82.

KOONS, P.O. (1987): Some thermal and mechanical consequences of rapid uplift: an example from the Southern Alps, New Zealand. Earth Planet. Sci. Lett. 86, 307–319.

KRALIK, M., KRUMM, H. and SCHRAMM, J.-M. (1987): Low grade and very low grade metamorphism in the Northern Calcareous Alps and in the Greywacke Zone: illite-crystallinity data and isotopic ages. In: FLÜGEL, H.W. and FAUPL, P. (eds): Geodynamics of the Eastern Alps. Deuticke Wien, 164–178.

KRALIK, M. and SCHRAMM, J.-M. (1994): Illit-Wachstum: Übergang Diagenese-Metamorphose im Karbonat- und Tongesteinen der nördlichen Kalkalpen: Mineralogie und Isotopengeologie (Rb–Sr, K–Ar und C–O). Jb. Geol. B.-A. 137, 105–137.

KUHLEMANN, J., FRISCH, W., DUNKL, I. and SZÉKELY, B. (2001): Quantifying tectonic versus erosive denudation by the sediment budget: the Miocene core complexes of the Alps. Tectonophysics 330, 1–23.

KÜRMANN, H. (1993): Zur Hochdiagenese und Anchimetamorphose in Permotrias-Sedimenten des Austroalpins westlich der Tauern. Bochumer geol. u. geotechn. Arb. 41, 1–328.

LÄUFER, A.L., FRISCH, W., STEINITZ, G. and LOESCHKE, J. (1997): Exhumed fault-bounded Alpine blocks along the Periadriatic lineament: the Eder unit (Carnic Alps, Austria). Geol. Rundsch. 86, 612–626.

LEIN, R., GAWLICK, H.J. and KRYSTYN, L. (1997): Paläogeographie, Tektonik und Herkunft des Drauzuges – Eine Diskussion auf der Basis von Fazies- und Conodont Colour Alteration Index (CAI)-Untersuchungen. Zentralblatt für Geologie und Paläoontologie Teil I 1996, 471–483.

LITTKE, R., BÜKER, C., LÜCKGE, A., SACHSENHOFER, R.F. and WELTE, D.H. (1994): A new evaluation of paleo-heat flows and eroded thicknesses for the Carboniferous Ruhr basin, western Germany. International Journal of Coal Geology 26, 155–183.

MALI, H. (1996): Bildungsbedingungen von Quecksilber- und Antimonlagerstätten im Ostalpin (Österreich). Dr. mont. sci. thesis University of Leoben, 215 pp.

MANCKTELOW, N.S. and GRASEMANN, B. (1997): Time-dependent effects of heat advection and topography on cooling histories during erosion. Tectonophysics 270, 167–195.

MULLIS, J. (1979): The system methane-water as a geological thermometer and barometer from the external part of the Central Alps. Bulletin de Minéralogie 102, 526–536.

NEMES, F. (1996): Kinematics of the Periadriatic Fault in the Eastern Alps. Evidence from structural analysis, fission track dating and basin modelling. Dr. nat. sci. Thesis University of Salzburg, 225 pp.

NEMES, F., NEUBAUER, F., CLOETINGH, S. and GENSER, J. (1997): The Klagenfurt Basin in the Eastern Alps: an intra-orogenic decoupled flexural basin? Tectonophysics 282, 189–203.

NEUBAUER, F. (1988): Bau und Entwicklungsgeschichte des Rennfeld- Mugel- und des Gleinalm-Kristallins (Ostalpen). Abh. Geol. B.-A. 42, 1–137.

NEUBAUER, F. (1994): Kontinentkollision in den Ostalpen. Geowissenschaften 12, 136–140.

NEUMANN, H.-H. (1989): Die Oberkreide des Krappfeldes. Arbeitstagung 1989 der Geologischen Bundesanstalt, Geologische Bundesanstalt Wien, 70–80.

NIEDERMAYR, G., MULLIS, J., NIEDERMAYR, E. and SCHRAMM, J.M. (1984): Zur Anchimetamorphose permo-skythischer Sedimentgesteine im westlichen Drauzug, Kärnten-Osttirol (Österreich). Geol Rundsch. 73, 207–221.

PETSCHICK, R. (1989): Zur Wärmegeschichte im Kalkalpin Bayerns und Nordtirols (Inkohlung und Illitkristallinität). Frankfurter geowiss. Arb. Serie C 10, 1–259.

POHL, W. and BELOCKY, R. (1994): Alpidic metamorphic fluids and metallogenesis in the Eastern Alps. Mitt. Österr. Geol. Ges. 86, 141–152.

POLINSKI, R.K. and EISBACHER, G.H. (1992): Deformation partitioning during polyphase oblique convergence in the Karawanken Mountains, southeastern Alps. J. Struct. Geol. 14, 1203–1213.

RANTITSCH, G. (1997): Thermal history of the Carnic Alps (Southern Alps, Austria) and its paleogeographic implications. Tectonophysics 272, 213–232.

RANTITSCH, G. (submitted): A new evaluation of fluid inclusion data based on thermal basin modeling for the Drau Range, Eastern Alps. Mitt. Österr. Geol. Ges.

RANTITSCH, G., JOCHUM, J., SACHSENHOFER, R.F., RUSSEGGER, B., SCHROLL, E. and HORSFIELD, B. (1999a): Hydrocarbon-bearing fluid inclusions in the Drau Range (Eastern Alps, Austria): Implications for the genesis of the Bleiberg Pb-Zn deposit. Mineralogy and Petrology 65, 141–159.

RANTITSCH, G., MALI, H. and SACHSENHOFER, R.F. (1999b): Hydrothermal mineralization during syn-collisional magmatism (Tertiary) in the Eastern Alps. Strasbourg, J. Conf. Abs. 4, 468.

RATSCHBACHER, L., FRISCH, W., LINZER, H.G. and MERLE, O. (1991): Lateral extrusion in the Eastern Alps. Part 2. Structural analysis. Tectonics 10, 257–271.

ROBINSON, D. (1987): Transition from diagenesis to metamorphism in extensional and collision settings. Geology 15, 866–869.

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

SACHSENHOFER, R.F. (1994): Petroleum generation and migration in the Styrian Basin (Pannonian Basin system, Austria: an integrated geochemical and numerical modeling study. Mar. Pet. Geol. 11, 684–701.

SACHSENHOFER, R.F. (2001): Syn- and post-collisional heat flow in the Cenozoic Eastern Alps. Int. J. Earth Sciences, in print.

SACHSENHOFER, R.F., DUNKL, I., HASENHÜTTL, C. and JELEN, B. (1998): Miocene thermal history of the southwestern margin of the Styrian Basin: vitrinite reflectance and fission-track data from the Pohorje/Kozjak area (Slovenia). Tectonophysics 297, 17–29.

SCHMIDT, Th. (1995): Zur Tektonik der Lienzer Dolomiten. In: HAUSER, C. (ed): Geologie von Osttirol. Arbeitstagung 1995 der Geologischen Bundesanstalt. Geologische Bundesanstalt Wien, 37–42.

SCHMIDT, Th., BLAU, J. and KÁZMÉR, M. (1991): Large-scale strike-slip displacement of the Drauzug and the Transdanubian Mountains in early Alpine history: evidence from Permo-Mesozoic facies belts. Tectonophysics 200, 213–232.

SCHMIDT, Th., BLAU, J., GRÖSSER, J.R. and HEINISCH, H. (1993): Die Lienzer Dolomiten als integraler Bestandteil der dextralen Periadriatischen Scherzone. Jb. Geol. B.-A. 136, 223–232.

SPERLING, M. (1990): Stratigraphie und Strukturgeologie der westlichen Lienzer Dolomiten (Drauzug, Osttirol). Dipl. nat. sci. Thesis, Univ. of Innsbruck, 142 pp.

SPÖTL, C. and HASENHÜTTL, C. (1998): Thermal history of the evaporitic Haselgebirge mélange in the Northern Calcareous Alps (Austria). Geol. Rundsch. 87, 449–460.

SPRENGER, W. and HEINISCH, H. (1992): Late Oligocene to recent brittle transpressive deformation along the Periadriatic Lineament in the Lesach Valley (Eastern Alps): remote sensing and paleo-stress analysis. Annales Tectonicae VI, 134–149.

STACH, E., MACKOWSKY, M.Th., TEICHMÜLLER, M., TAYLOR, G.H., CHANDRA, D. and TEICHMÜLLER, R. (1982): Stach's Textbook of Coal Petrology. 3rd ed. Borntraeger Berlin, 535 pp.

STAUFENBERG, H. (1987): Apatite fission-track evidence for postmetamorphic uplift and cooling history of the eastern Tauern Window and the surrounding Austroalpine (Central Eastern Alps, Austria). Jb. Geol. B.-A. 130, 571–586.

SUCHY, V., FREY, M. and WOLF, M. (1997): Vitrinite reflectance and shear-induced graphitization in orogenic belts: A case study from the Kandersteg area, Helvetic Alps, Switzerland. International Journal of Coal Geology 34, 1–20.

SWEENEY, J.J., BURNHAM, A.K. (1990): Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. Am. Assoc. Pet. Geol. Bull. 74, 1559–1570.

TAYLOR, G.H., TEICHMÜLLER, M., DAVI, A., DIESSEL, C.F.K., LITTKE, R. and ROBERT, P. (1998): Organic petrology. Borntraeger Berlin, 704 pp.

TOLLMANN, A. (1959): Der Deckenbau der Ostalpen auf Grund der Neuuntersuchung des zentral alpinen Mesozoikums. Mitt. Ges. Geol. Bergbaustud. 10, 3–62.

TOLLMANN, A. (1977): Geologie von Österreich. Band 1. Die Zentralalpen. Deuticke Wien, 766 pp.

UNDERWOOD, M.B., SHELTON, K.L., MCLAUGHLIN, R.J., LOUGHLAND, M.M. and SOLOMON, R.M. (1999): Middle Miocene paleotemperature anomalies within the Franciscan Complex of northern California: Thermo-tectonic responses near the Mendocino triple junction. Geol. Soc. America Bull. 111, 1448–1467.

VAN BEMMELEN, R. (1957): Beitrag zur Geologie der westlichen Gailtaler Alpen (Kärnten, Österreich). Erster Teil. Jb. Geol. B.-A. 100, 179–212.

VAN BEMMELEN, R. (1961): Beitrag zur Geologie der westlichen Gailtaler Alpen (Kärnten, Österreich). Zweiter Teil. Jb. Geol. B.-A. 104, 213–237.

VAN BEMMELEN, R. and MEULENKAMP, J. (1965): Beiträge zur Geologie des Drauzuges. 3. Teil: Die Lienzer Dolomiten. Jb. Geol. B.-A. 108, 213–268.

VON BLANCKENBURG, F. and DAVIES, J.H. (1995): Slab breakoff: A model for syncollisional magmatism and tectonics in the Alps. Tectonics 14, 120–131.

VON GOSEN, W. (1989): Gefügeentwicklung, Metamorphosen und Bewegungen der ostalpinen Baueinheiten zwischen Nockgebiet und Karawanken (Österreich). Geotekt. Forsch. 72, 1–247.

WARR, L.N. and GREILING, R.O. (1996): Thrust-related very low grade metamorphism in the marginal belt of an orogenic wedge, Scandinavian Caledonides. Tectonics 15, 1213–1229.

WILLINGSHOFER, E., NEUBAUER, F. and CLOETINGH, S. (1999): The significance of Gosau-type basins for the Late Cretaceous tectonic history of the Alpine-Carpathian belt. Phys. Chem. Earth (A) 24, 687–695.

WORTMANN, U.G., WEISSERT, H., FUNK, H. and HAUCK, J. (2001): Alpine plate kinematics revisited: The Adria problem. Tectonics 20, 134–147.

WYGRALA, B.P. (1988): Integrated computer-aided basin modeling applied to analysis of hydrocarbon generation history in a Northern Italian oil field. Org. Geochem. 13, 187–197.

ZEEH, S. (1995): Complex replacement of saddle dolomite by fluorite within zebra dolomite. Mineralium Deposita 30, 469–475.

ZEEH, S. and BECHSTÄDT, T. (1994): Carbonate-hosted Pb-Zn mineralization at Bleiberg-Kreuth (Austria): Compilation of data and new aspects. In: FONTBOTÉ, L. and BONI, M. (eds): Sediment-hosted Zn-Pb ores. Spec. Publ. Soc. Geol. applied to Mineral. Deposits 10, 271–296.

ZEEH, S., BECHSTÄDT, T., MCKENZIE, J. and RICHTER, D.K. (1995): Diagenetic evolution of the Carnian Wetterstein platforms of the Eastern Alps. Sedimentology 42, 199–222.

Manuscript received August 16, 2000; revision accepted June 8, 2001.