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COALIFICATION OF DISPERSED ORGANIC MATTER IN THE DOLOMITES, ITALY: IMPLICATIONS FOR BURIAL AND THERMAL HISTORY

Robert Georg Tscherny[1,2], Ralf Littke[1,*], Carsten Büker[1,3], Sheila Nöth[1,4], Anna Kathrin Uffmann[1], Ralf Littke[1,*]

With 7 Figures and 1 Table

[1] Energy and Mineral Resources Group (EMR), Institute of Geology and Geochemistry of Petroleum and Coal, RWTH Aachen University, Lochnerstr. 4-20, 52056 Aachen
[2] present address: Chevron Energy Technology Company, 1500 Louisiana Street, Houston, TX 77002, USA
[3] present address: Shell E&P Company, 900 Louisiana Street, Houston, Texas 77587, USA
[4] present address: Schlumberger WesternGeco, 10001 Richmond Ave., Houston, TX 77042, USA
* Corresponding author: ralf.littke@emr.rwth-aachen.de

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Abstract

This study discusses the coalification pattern and regional thermal maturity evolution of the Permo-Mesozoic sediments of the Dolomite Mountains along the TRANSALP-Traverse. The overall goal of the study is to derive a well-constrained reconstruction of the thermal evolution of the central Dolomites. As part of the non-metamorphosed Southalpine retrowedge (Southern Alps) of the Neoalpine orogen, the Dolomite Mountains are ideally suited to study and quantify the thermal evolution in a complex orogenic setting. To obtain thermal maturity data, a large set of outcrop samples has been collected and vitrinite reflectance has been determined. The measured vitrinite reflectance ranges along investigated profiles in the Alta Badia between 0.5 % VR_r for Cretaceous and 0.9 % VR_r for Permian strata allowing a high-resolution analysis of the lateral and vertical coalification pattern and revealing a thermal maturity increasing with stratigraphic age within the Permo-Mesozoic strata. These observations imply a coalification prior to the Dinaric (Paleogene)- and Neoalpine(Neogene) orogeny in the Southalpine realm. In order to explain the advanced maturation even in the younger strata, deposition of later eroded Cretaceous (and possibly even Tertiary) overburden is regarded the most probable explanation. As a consequence, deposition in the Dolomitic realm persisted longer than yet was assumed. Using numerical basin modelling techniques for two pseudo-wells allowed quantifying the amount of eroded Cretaceous overburden resulting in values between 1700 and 2400 m. In this model scenario, moderate to low palaeo-heat flows are assumed and maximum temperatures were reached during the Late Cretaceous/ Paleogene.

Zusammenfassung

Die vorliegende Arbeit beschäftigt sich mit der thermischen Geschichte von Permischen und Mesozoischen Sedimenten der Dolomiten entlang der TRANSALP-Traverse. Das Ziel ist es, die thermische Geschichte des zentralen Teils der Dolomiten zu rekonstruieren. Das Gebiet befindet sich im südlichen Teil des Neoalpinen Orogens der Alpen, dessen Sedimente nicht metamorphosiert wurden. Aus diesem Grund sind die Dolomiten ein idealer Ort, um die thermische Geschichte in einem komplexen Orogen zu untersuchen. Um Reifedaten zu ermitteln, wurde ein umfangreicher Probensatz genommen und die Vitrinitreflexion gemessen. Die gemessenen Vitrinitreflexionsdaten reichen von etwa 0.5 % in kretazischen Sedimenten bei Alta Badia bis 0.9 % in einer

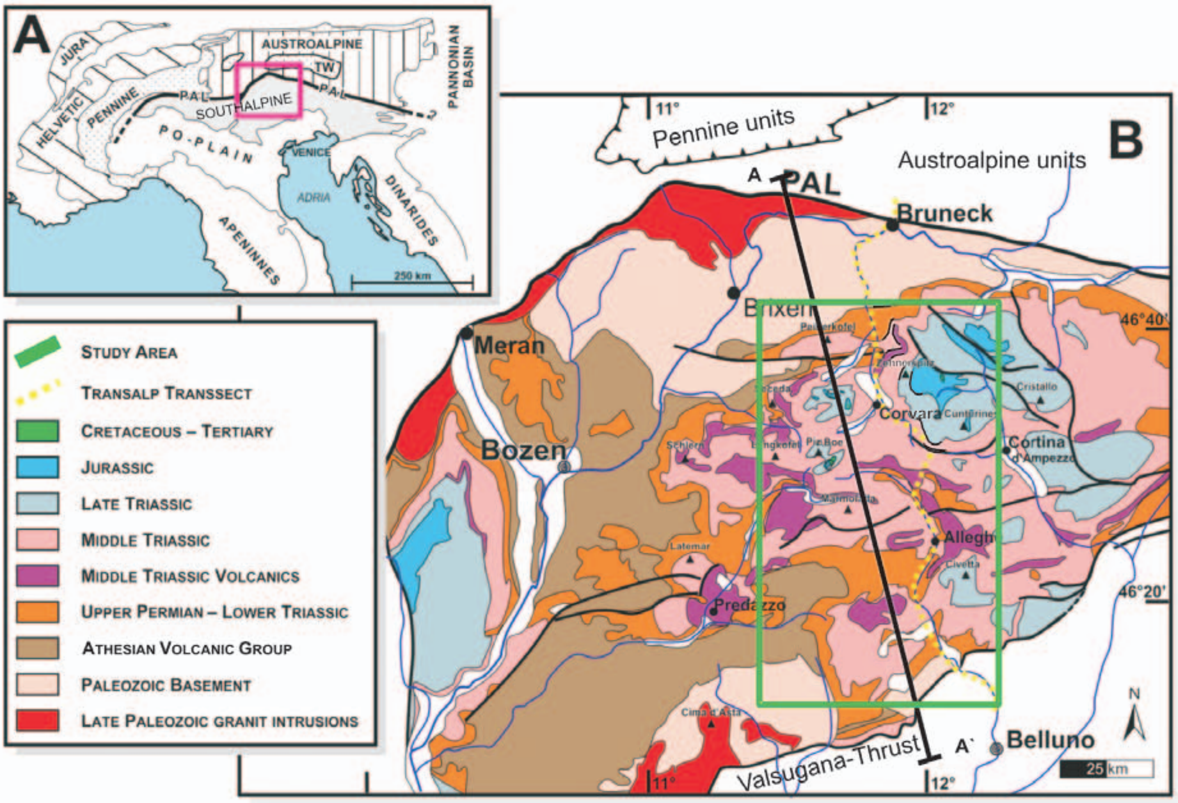

Fig. 1: A: Tectonic domains of the Alps. The square indicates the study area. Modified after Winterer and Bosellini (1981). PAL = Periadriatic Lineament, TW= Tauern Window. B: Simplified geologic map of the Dolomites. Based on Bigi et al. (1990), Brandner (1980) and own research.

Serie permischer Sedimente. Diese Daten erlauben die flächenhafte Analyse der Inkohlungsverhältnisse und zeigen eine Steigung der thermischen Reife mit dem stratigraphischen Alter der Proben. Die Untersuchungen belegen zudem, dass die Inkohlung der Sedimente im südalpinen Raum vor dem Paläogen abgeschlossen war. Eine Erklärung der erhöhten Inkohlung der jüngeren Gesteinseinheiten (Kreide) ist durch eine Überlagerung und spätere Erosion von zusätzlichen Sedimenten am wahrscheinlichsten. Folglich hat die Sedimentation im Raum der Dolomiten länger angehalten als bisher vermutet. Im Rahmen der Arbeit wurden numerische Modellierungen für zwei Lokationen durchgeführt, die Erosionsbeträge zwischen 1700 und 2400 m aufzeigen. Für die Modellierungen wurden mäßige bis niedrige Wärmeflüsse angenommen und die höchsten Temperaturen wurden in der späten Kreide bzw. im Paläogen erreicht.

Introduction

The Dolomite Mountains (Figs 1, 2) are part of the southern Alps and have been intensely studied for many decades (e.g. Dolomieu, 1791; von Richthofen, 1860; Mojsisovics, 1879; Leonardi, 1967; Doglioni, 1987; Doglioni & Bosellini, 1987; Bosellini et al., 1996; Bosellini, 1998; Castellarin et al. 1982; Castellarin & Cantelli, 2000; Tscherny, 2006). Nevertheless, the interpretation of the geotectonic and geodynamic evolution of the Dolomites is still matter of intense research and discussions (Gebrande et al., 2003). The TRANSALP-Project analysed the tectonic and orogenic processes of the collision of the Adriatic-African with the European continental plate, which finally led to the building of the Alps. This study analyses the coalification of dispersed organic particles (vitrinites) and thus provides insight into the burial, erosion and temperature history. The results might provide valuable insights into the driving geological processes and contribute essential knowledge about the geotectonic evolution and the geodynamic interpretation of the Dolomites.

For a detailed analysis of the coalification pattern and thermal maturity of the Permo-Mesozoic sediments a set of surface samples along the TransAlp line in the Dolomites was sampled. Regionally, this paper mainly deals with the central part of the Dolomites along the Alta Badia valley and the upper Cordevole valley. Vitrinite reflectance (VR_r) was measured which is the most widely-used palaeotemperature parameter for the calibration of burial and temperature histories in sedimentary basins, but also in deformed mountain belts at high levels of diagenesis (e.g. Büker et al., 1995; Nöth et al., 2001), including the Alps (Frey, 1987, Teichmüller, 1987, Rantitsch, 1997, Emmerich et al., 2008). Here, a first compilation is provided based on a thesis in German language, in which all the maturation data are tabulated (Tscherny, 2006).

Geological setting

Tectonic and structural evolution of the Dolomites

The study area comprises the central part of the Dolomites along the track of the TRANSALP traverse from the Alta Badia valley to the upper Cordevole valley (Fig. 1B). The Dolomites are a Neogene pop-up structure (Doglioni, 1987) in the eastern part of the Southern Alps in Northern Italy. The stratigraphic sequence consists of up to 4 km thick Permo-Mesozoic sedimentary rocks and unconformably overlies a Palaeozoic crystalline basement (e.g. Doglioni, 1987). Tectonic elements such as anti- and synclines, fault zones ,larger thrusts and local summit overthrusts ("Gipfelüberschiebungen" on top of the Ampezzani, Puez and Sella plateau, occur within the sedimentary succession (Ogilvie-Gordon, 1910; Castellarin, 1981; Doglioni, 1985, 1987, 1990; Sauro & Meneghel, 1995; Brandner & Keim 2011). The Dolomites are limited to the South by the southeast-vergent Valsugana Thrust and to the North by the south-vergent back-thrust of the eastern Periadriatic Lineament (PAL) (Schönborn, 1999). The Periadriatic Lineament is a major E-W striking fault system separating the Southalpine units (with the Dolomites therein) to the North from the remaining Austroalpine units (Figs 1, 2). The Southalpine represent hereby the former hinterland of the Austroalpine, both being part of the Apulian (Adriatic) micro plate separated in Jurassic time by a major transcurrent fault (Bögel & Schmidt, 1976; Winterer & Bosellini, 1981).

The present-day configuration of the Dolomites is a consequence of a complex and poly-phased history. The geologic evolution of the Dolomites was initiated in Permian times by rifting of the northern African crustal terrane (North-Gondwana) following the Hercynian orogeny of the crystalline basement (e.g. Ziegler, 1990; Schmid et al., 2004). At this time, this area represented the southern (Gondwana) continental margin of the Tethys Ocean. Permian rifting initiated block faulting, volcanic activity and caused gradual subsidence which structured the Southalpine crustal terrane and finally led to the break-up of the Apulian micro plate. In the Jurassic a passive continental margin formed at the north-eastern part of Apulia (Broglio Loriga, 1986; Hsü, 1982; Ziegler, 1990). During the time span from the Permian to the Jurassic the Dolomitic realm underwent several phases of enhanced subsidence. As response to that, prominent facies diversifications characterise the sedimentary succession. For example, Middle Triassic carbonate platforms, reefs and lagoons interfinger with interplatform basins. At the end of the Jurassic and the beginning of the Cretaceous a major re-organisation of the continental plates led to an inversion of the plate motion with an ongoing convergence of Apulia and Europe. Major changes of the convergence direction during the Cretaceous and Cenozoic are represented by Dinaric and Neoalpine orogenic phases. This convergence induced an inversion of the Dolomites with related compressional tectonics: (1) Dinaric NE-SW trending compression (Dinaric postcollisional orogeny) with summit overthrusts followed by Neoalpine N-S trending compression ("Southalpine indentation") building a SE vergent backthrust belt to the Venetian foreland (Valsugana structural system) and forming a pop-up structure (Doglioni, 1987; Castellarin & Cantelli, 2000; Castellarin et al., 1982, 2004).

Stratigraphic succession along the TRANSALP traverse

The sedimentary record along the track of the TRANSALP traverse comprises an up to 4 km thick succession beginning with the Upper Permian *Val-Gardena-Sandstone (VGS)* and ending with conglo-

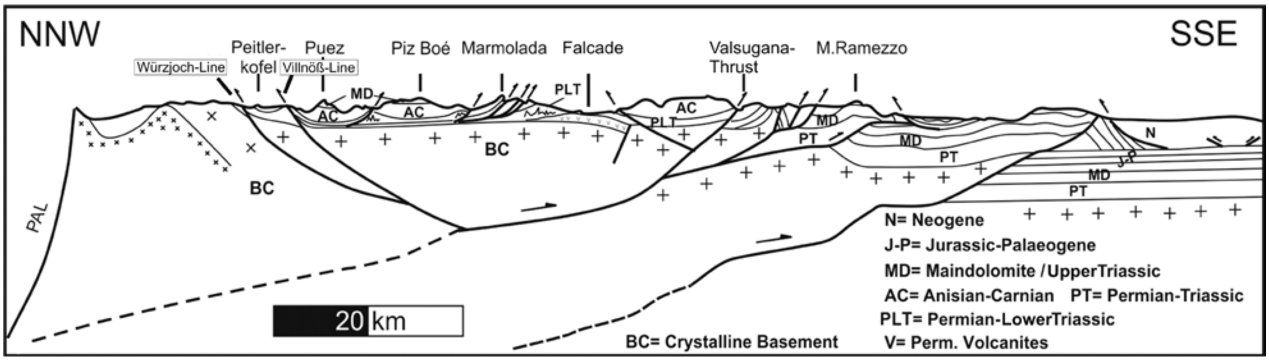

Fig. 2: Cross-section of the central part of the Dolomites modified after Castellarin et al. (1998). Position of the cross-section is shown in Fig. 1B.

merates of the Oligocene *Monte-Parei Conglomerate* (Fig. 3). This succession is described here in some detail, because the stratigraphic evolution provides the base for the conceptual geological model and the input for the numerical simulation.

The *Val-Gardena-Sandstone* is an up to 500 meter thick sequence of continental siliciclastic red beds unconformably overlying the *Athesian Volcanic Group* as well as the Palaeozoic crystalline basement. The *VGS* thus represents post-volcanic rift sediments deposited in Upper Permian times (Italian IGCP group, 1986; Massari et al., 1988, 1994). Towards the Permian-Triassic boundary, further subsidence led to the formation of up to 350 meters of evaporites and shallow water carbonates of the *Bellerophon-Fm* (Cassinis et al., 1998).

The general transgressive tendency during the Upper Permian continued in the Lower Triassic with the sedimentation of about 450 meters of full marine (shallow water) shales, marls, lime-, silt- and sandstones of the *Werfen-Fm* (Induan - Olenekian) (Mostler et al., 1982, Broglio Loriga et al., 1983) and with shallow water carbonates, e.g. the *Lower Sarldolomite*. In Middle Anisian times the western and central Dolomites underwent strong block tilting. Horst-like structures emerged partly above the sea level leading to the erosion of significant parts of the *Lower Anisian succession* and the *Werfen-Fm* (Mostler et al., 1982; Brandner, 1984; Brandner & Keim, 2011). The area further to the east shows no erosion or hiatus and remained submerged providing further accommodation space for marine sediments (*Recoaro-Fm*, *Dont-Fm* etc., with predominantly marls, interfingering with the clastic sediments of the fluvial *Voltago Conglomerate* further to the west, but shows also local carbonate platform evolution, e.g. *Upper Sarldolomite*) (Bechstädt & Brandner, 1970; Farabegoli et al., 1977; Pisa et al., 1978; Brandner, 1984). The centre of emersion with the greatest amount of erosion is the area around Colfosco - Gardena Pass in the upper Alta Badia valley where erosion truncates the complete *Werfen-Fm* and the upper part of the *Bellerophon-Fm* (Bosellini, 1965, 1968, 1982). The reason for this inversion is still matter of discussion but a magmatic intrusion into the crust related to later Ladinian volcanism (Bosellini, 1998) has been one explanation.

This inversion phase remained active only for a relative short period: On top of the erosional surface, several meters thick conglomerates of the fluvial *Richthofen-Conglomerate* (Dal Cin, 1967) were deposited. At the beginning of the Upper Anisian a general subsidence tendency of the Dolomites has been re-established. The conglomerates are overlain by a thin sequence (max. 10 meters) of marine sand- and siltstones (*Peres-Fm*, Brandner et al., 2007) and sometimes bituminous marls and bioturbated limestones of the *Morbiac-Fm*. The ongoing subsidence led to a further deepening and building of carbonate platforms on structural highs in the western Dolomites (*Contrin-Fm*) with a thickness of about 100 meters. Simultaneously, (bituminous) marls and breccias of the *Morbiac-Fm/Moena-Fm* were deposited in small, often poorly oxygenated basins separating the carbonate platforms (Masetti & Neri, 1980). In the study area the *Morbiac-Fm/Moena-Fm* shows a thickness variation between 10 and 50 meters.

In the Upper Anisian, the subsidence rate increased significantly so that the Dolomites subsided about 1000 meters within a period of 3 to 4 million years. The facies patterns of this time reflect this rapid but relative homogeneous subsidence with the

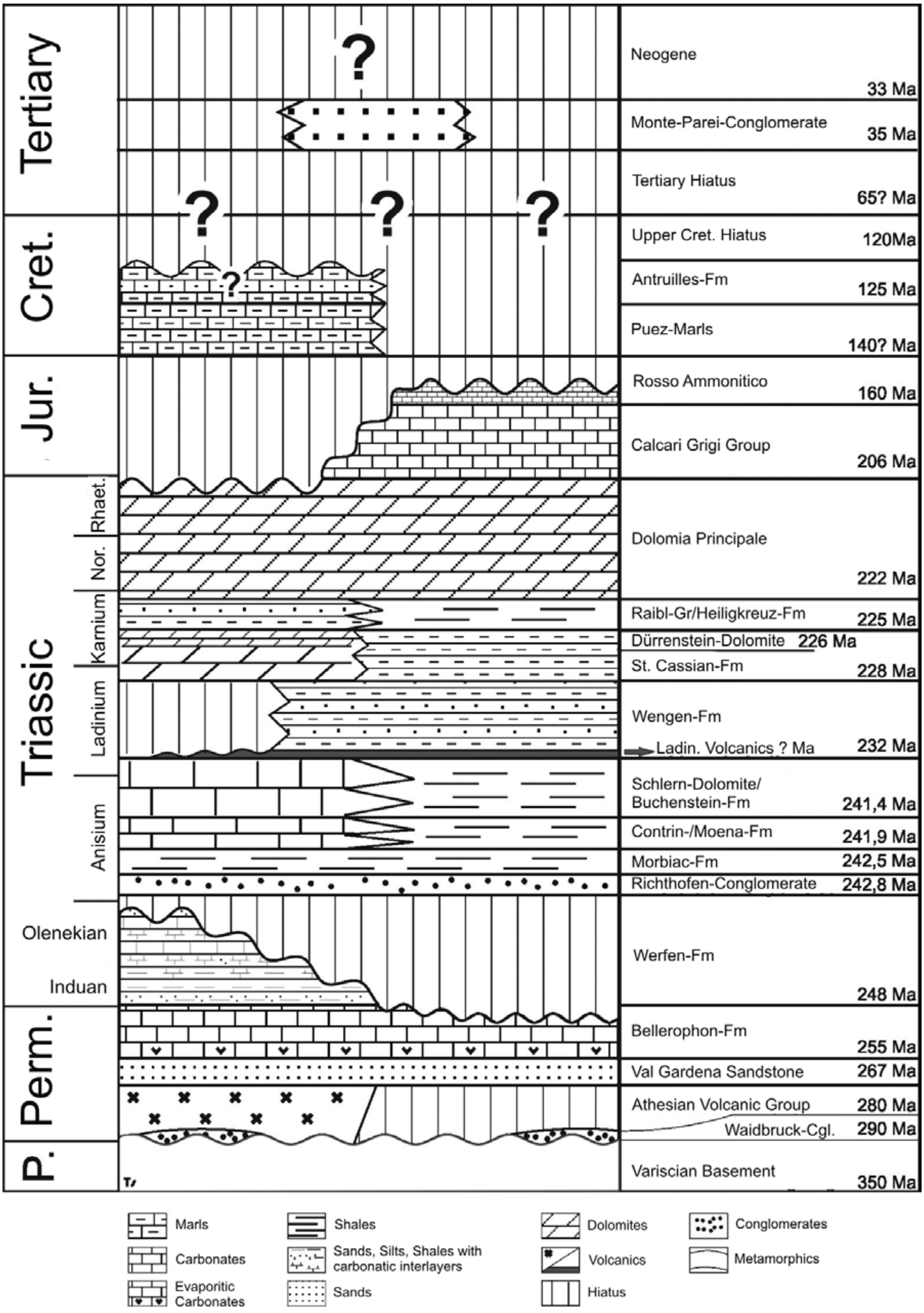

Fig. 3: Simplified stratigraphy of the dolomites including the ages used for numerical modelling. Compiled from Bosellini (1998), Bosellini et al. (2003), Brandner et al. (2007), Cassinis et al. (1998), Keim and Brandner (2001), Keim et al. (2001), Keim and Stingl (2000), Maurer (2000). Absolut ages after Gradstein and Ogg (1996).

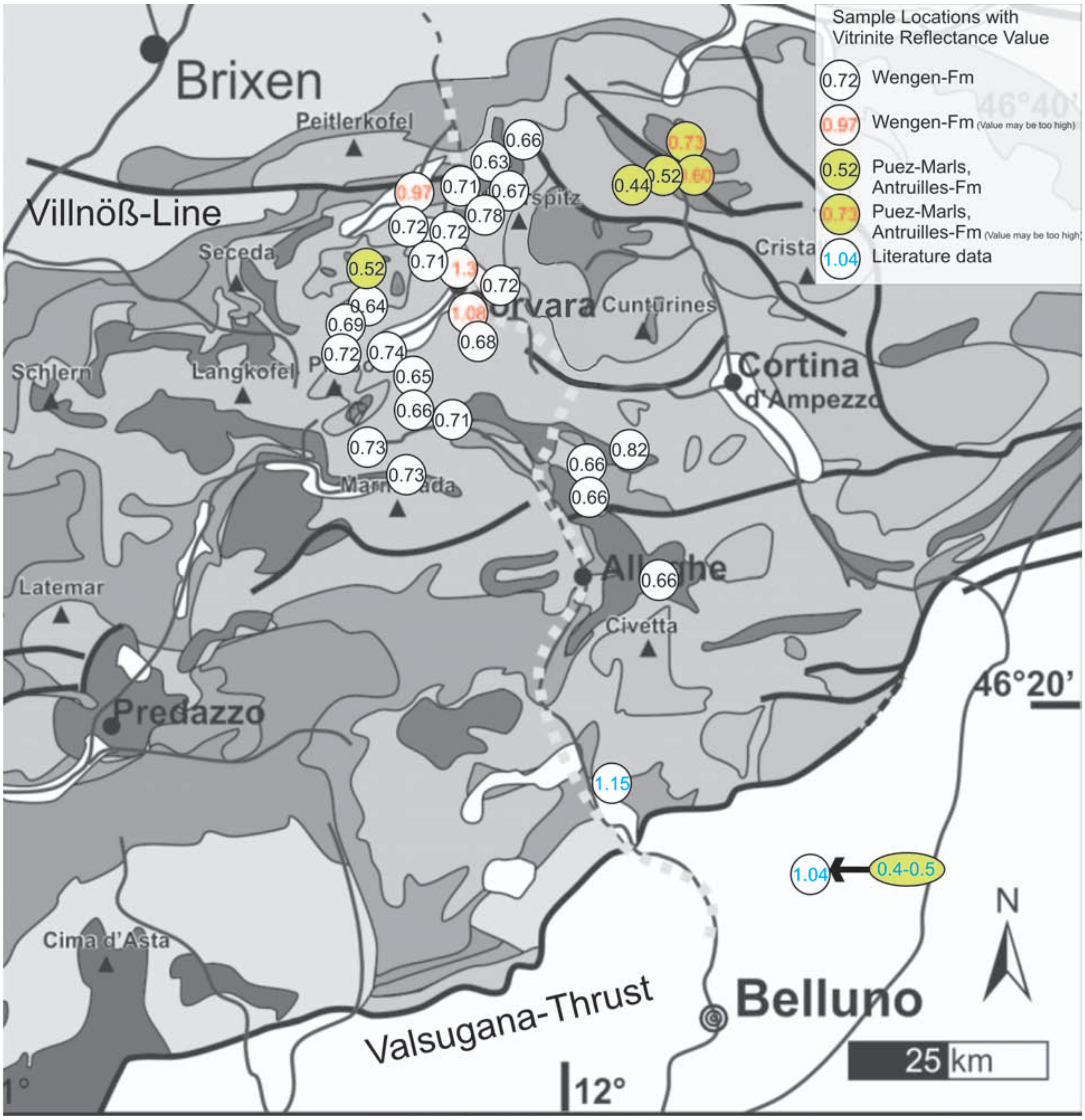

Fig. 4: Geologic map of the Dolomites with mean vitrinite reflectance data (VR_r%) of the Middle Triassic Wengen-FM and the Cretaceous Puez-Marls and Antruilles-FM. Compiled from data of this study and published data, see Tscherny (2006).

build-up of reefs of the *Schlern-Dolomite* interfingering with the coeval basinal hemipelagic sediments of the *Buchenstein-Fm* with an average thickness of 200 meters (Maurer, 2003).

In the Dolomites volcanism started again at Ladinian times, with the active centre near Monzoni and Predazzo (Bosellini et al., 1982, 1996; Castellarin et al., 1980, 1988), strongly influencing the subsequent evolution: the carbonate platforms emerged above the sea level and were covered by volcanic deposits whereas the basins in between were partly filled with submarine (pillow) lava, lavabreccias, volcanoclastic debris-flows (*Caotico Eterogeneo*), tuffs and ashes (*Fernazza Group*, Viel 1979). With diminished volcanic activity the sedimentary facies deposited in the basin areas changed to the clastic sequences of the *Wengen-Fm*. reaching thicknesses between 500 and 1000 meters. Finally, 300 meter thick marls and shales of the St. *Cassian-Fm* filled the residual basins.

In the Carnian most parts of the Dolomites emerged for a short period above the sea level with the sedimentation of about 100 meters of coastal plain sand- and siltstones, shales and marls (*Heiligkreuz-* and *Travenanzes-Fm* of the *Raibl-Group*). The basinal sediments of the *Heiligkreuz-Fm* (ca. 50 meters) are sometimes rich in organic matter and represent a local variation deposited in the Hospiz basin in the eastern Dolomites (Fanes) (Keim et al., 2001). With the onset of slow subsidence in the Upper Triassic (Norian to Rhaetian) the carbonate platform of the *Dolomia Principale* developed. In the study area it reaches a thickness between 500 and 800 meters. The Upper Triassic time of tectonic quietness continued into the Middle Jurassic with the sedimentation of about 500 meters shaly limestones of the *Calcari Grigi (Calcari Grigi Group)* on top of the Trento platform (Sauro & Meneghel, 1995; Neri et al., 2007). It is most likely that the 80 km wide submarine high of the Trento platform in the western Dolomites was already established in Rhaetian times (Stingl, 1998a).

With the opening of the Ligurian ocean (about 400 km westwards), the Southalpine became a passive margin of the Apulian microplate and the Dolomites underwent further subsidence in the Upper Jurassic and Cretaceous (Winterer & Bosellini, 1981). The gradual deepening of the Trento platform in the Upper Jurassic (Oxfordian) led to a starved sequence of *Rosso Ammonitico Veronese* (ca. 50 meters). This trend continued in the Cretaceous *(Maiolica)* but in contrast to the Jurassic the system switched to a siliciclastic dominated system. The Cretaceous deposits are preserved only in a few places in the Dolomites due to almost complete erosion during the Dinaric- and Neoalpine orogeny. Therefore, the amount of original depositional thickness is difficult to estimate. Bosellini (1998) calculated a value of approximately 200 meters using the presently remaining 150 meters of *Puez Marls* followed by 50 meter thick shales and turbiditic sandstones of the Upper Cretaceous *Antruilles-Fm* and *Ruoibes-Fm* (*Zeiss et al.*, 1991; *Stock*, 1994, 1996).

With the exception of the Oligocene *Monte Pare*i Conglomerate (Doglioni & Siorpaes, 1990; Keim & Stingl, 2000) all rocks younger than the Cretaceous have been eroded during the Dinaric- and Neoalpine orogenic phases. In the southern foreland of the Dolomites an about 2000 m thick Tertiary flysch and molasse (*Belluno Flysch* and *Belluno Molasse*) sequence gives evidence of ongoing deposition in Tertiary times (Costa et al. 1996, Stefani & Grandesso, 1991). Whether the Dolomites have also been an area of deposition during the Tertiary or not is still a matter of discussion. However, during the Neogene the ongoing isostatic compensation led to uplift and exhumation. Apatite fission track data indicate exhumation of the hanging wall of the Valsugana Thrust between 12 and 8 million years ago (Dunkl et al., 1996).

Methods

Sampling and vitrinite reflectance

The analysed 159 outcrop samples range in age between Permian and Cretaceous and enclose the complete sedimentary succession of the Dolomites: *Val Gardena Sandstone (VGS)* and *Bellerophon-F*m (both Permian), *Morbiac-Fm/Moena-Fm, Buchenstein-Fm, Wengen-Fm, St. Cassian-Fm, Heiligkreuz-Fm* (basinal sequences of the Middle and Upper Triassic) and *Antruilles-Fm* (Upper Cretaceous) (Fig. 3). The random vitrinite reflectance was obtained using a Zeiss Universal micro spectrometer microscope (MPM 01K) in unpolarised light at a wavelength of 546 nm in oil immersion. The results of the vitrinite reflectance measurements are given as arithmetic mean vitrinite reflectance measured at random orientation of grains in percentage (% VR_r). The measurements followed established procedures as described by Taylor et al. (1998).

Numerical basin modelling

Numerical modelling of the thermal evolution of sedimentary sequences can provide valuable insights into and understanding of the geologic processes driving the basin evolution (e.g. Hantschel & Kauerauf, 2009; Senglaub et al., 2006). One-dimensional (1D) modelling with PetroMod software (Schlumberger) was used here to reconstruct and quantify the burial and temperature history of the Dolomites at pseudo-well locations for two profiles parallel to the TransAlp traverse in the Alta Badia valley. The transformation of the stratigraphic sequence along these profiles into so-called pseudo-wells allowed thermal modelling without "real" wells. The necessary pseudo-depth positions of geologic units were derived from the thicknesses of the units and the stratigraphic position within the succession. The pseudo-depth of the measured vitrinite reflectance data used for calibration of both pseudo-wells was calculated based on their stratigraphic position. This approach is widely

			Thermal conductivity	Radiogenic heat			Heat Capacity	Mechanical compaction		
Stratigraphy/ Name	Depositional age	Major Lithology	at 20 °C/100 °C	Uranian	Thorium	Potassium	at 20 °C/100 °C	Density	Initial Porosity	Compressibility
	(Ma)		(W/m/K)	(ppm)	(ppm)	(%)	(kcal/kg/K)	(kg/m^3)	(fraction)	(GPa-1)
Quaternary	0 – 0.2	Shale (typical)	1.64/1.69	3.7	12	2.7	0.21/0.24	2700	70	4.03 – 403.27
Monte Parei-Conglomerate	33 – 35	Sandstone_congl	3.55/3.1	1.34	3.6	1.44	0.2/0.23	2716	39	1.1 – 24.82
Upper Cret.-Hiatus	65 – 120	SandstoneSilt	2.0/2.59	1.65	4.25	1.15	0.21/0.24	2720	48	1.63 – 65.54
Antruilles-Fm	120 – 125	Sandstone (typical)	3.95/3.38	1.3	3.5	1.3	0.2/0.24	2720	41	1.15 – 27.47
Puez Marls	125 – 140	Marl	2.0/1.96	2.5	5	2	0.2/0.23	2700	50	1.98 – 77.8
Rosso Ammonitico	150 – 160	Limestone_shaly	2.66/2.45	1.54	3.2	0.7	0.2/0.23	2732	42	0.89 – 80.81
Calcari Grigi Group	160 – 206	Limestone_shaly	2.66/2.45	1.54	3.2	0.7	0.2/0.23	2732	42	0.89 – 80.81
Dolomia Principale	206 – 222	Dolomite (typical)	4.2/3.57	0.8	0.6	0.4	0.21/0.24	2790	35	1.1 – 25.23
Raibl-Group/Heiligkreuz-Fm	222 – 225	Marl	2.0/1.96	2.5	5	2	0.2/0.23	2700	50	1.98 – 77.8
Dürrenstein-Dolomite	225 – 226	Limestone (ooid grainstone)	3.0/2.69	1	1	0.2	0.2/0.23	2740	35	0.1 – 0.2
St. Cassian-Fm	226 – 228	Marl	2.0/1.96	2.5	5	2	0.2/0.23	2700	50	1.98 – 77.8
Wengen-Fm/Fernazza-Group	228 – 232	Sandstone_shaly	3.31/2.94	1.78	5.2	1.58	0.2/0.24	2716	47	1.73 – 102.63
Buchenstein-Fm	232 – 241.4	Limestone_shaly	2.66/2.45	1.54	3.2	0.7	0.2/0.23	2732	42	0.89 – 80.81
Moena-Fm	241.4 – 241.9	Shale (typical)	1.64/1.69	3.7	12	2.7	0.21/0.24	2700	70	4.03 – 403.27
Morbiac-Fm	241.9 – 242.5	Shale (typical)	1.64/1.69	3.7	12	2.7	0.21/0.24	2700	70	4.03 – 403.27
Richthofen-Conglomerate	242.5 – 242.8	Sandstone_congl	3.55/3.1	1.34	3.6	1.44	0.2/0.23	2716	39	1.1 – 24.82
Werfen-Fm	244 – 252	Shale (typical)	1.64/1.69	3.7	12	2.7	0.21/0.24	2700	70	4.03 – 403.27
Bellerophon-Fm	252 – 255	Limestone_Evap	1.73/1.81	0.51	0.51	6.55	0.18/0.21	2760	18	0.05 – 0.1
Val Gardena Sandstone	255 – 267	Sandstone (typical)	3.95/3.38	1.3	3.5	1.3	0.2/0.24	2720	41	1.15 – 27.47
Athesian Volcanic Group	290 – 350	Rhyolite	2.6/2.4	5.8	13	3.7	0.19/0.22	2500	1	0 – 0

Table 1: Petrophysical properties of applied lithologies and deposition ages for thermal modelling.

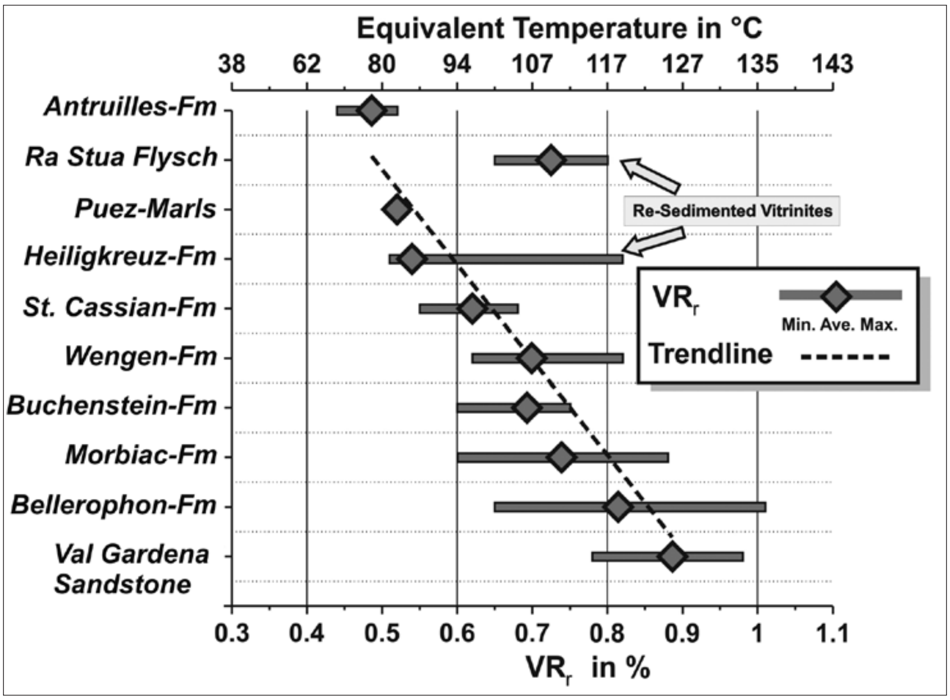

Fig. 5: Mean vitrinite reflectance values with calculated temperature after Barker & Pawlewicz (1994).

accepted for areas without well control and described in detail by Nöth et al. (2001).

Another prerequisite for the modelling and building of pseudo-wells is a conceptual model of the geologic evolution of this part of the Dolomites. Such a conceptual model encloses a subdivision of the geologic history into a continuous sequence of events with discrete time spans representing deposition, erosion, and non-deposition, and special processes like faulting or volcanism. The most important input parameters for modelling are age, lithology and thickness of sedimentary units, petrophysical parameters (derived from lithologies, e.g. compaction behaviour, thermal conductivity, radiogenic heat production, Tab. 1), and further thermal boundary conditions (e.g., sediment-water interface temperature; basal heat flow). Palaeo-heat flow and amount of erosion are major unknowns and can be result of the modelling procedure, if reliable temperature information is available (e.g. Petmecky et al., 1999; Senglaub et al., 2006). Such calibration data are often measured vitrinite reflectance values which can be compared to calculated values based on a modelled burial and temperature history. For the latter, the EASY%Ro approach (Sweeney & Burnham, 1990) is often applied. The numerical model should finally provide an optimum fit to the measured data. A more detailed description about the concept and application of numerical basin and thermal modelling is given by Hantschel & Kauerauf (2009).

Results

Vitrinite reflectance and coalification pattern

Vitrinite reflectance (VR$_r$) was measured on dispersed organic particles from 159 outcrop samples (carbonates, marls, shales, silt- and sandstones). Results are presented as a coalification map for the Wengen Formation and the Cretaceous units (Fig. 4), whereas the basic data are available in Tscherny (2006).

The coalification for the Permian *VGS* shows a significantly increasing thermal maturity from the West (0.5 %VR$_r$; Gampen-Pass) to the East (1.5 %VR$_r$; Jesenice). Likewise, the thickness of many stratigraphic units increases from West to East and is the most likely explanation for this coalification trend (cp. e.g. Bosellini, 1998, Heissel, 1982).

The only outcrops of the Permian *VGS* along the TRANSALP traverse in the studied area are located in the northern Alta Badia valley (Fig. 1). The measured vitrinite reflectance of the Permian *VGS* from these locations ranges between 0.78 and 0.98 % VR$_r$. The lower values are from the western flank of the Alta Badia and the higher ones from the east (Tscherny, 2006). This observation fits quite well in the observed regional trend.

The vitrinite reflectance of the Upper Permian *Bellerophon-Fm* is slightly lower than in the underlying *VGS*, ranging between 0.65 and 0.82 %VR_r, but with a similar regional trend. For the southern outcrop of the Permian *Bellerophon-Fm* near Alleghe in the Cordevole valley a higher vitrinite reflectance of 1.01 %VR_r was measured. This value contradicts published data from Zattin et al. (2003). According to these authors the thermal maturity of the Upper Permian and Lower Triassic (Induan, Olenekian) ranges from 1.8 to 2.4 %VR_r. However, organic geochemical parameters (e.g. Methylphenanthrene-Index, MPI) determined by Tscherny (2006) on samples from this area support a much lower maturity. According to Radke & Welte (1983) a MPI value of 1.31 correlates with a vitrinite reflectance of about 1.16 %VR_r.

From the Middle and Upper Triassic basinal sediments, the *Morbiac-/ Moena-Fm, Buchenstein-Fm, Wengen-Fm, St. Cassian-Fm and Heiligkreuz-Fm* were sampled and measured. The results for the *Wengen-Fm* which provides the best data set are displayed as coalification map (Fig. 4). Mean vitrinite reflectance values range between 0.61 %VR_r *(Heiligkreuz-Fm)* and 0.74 %VR_r *(Morbiac-/ Moena-Fm)*. In contrast to the Permian units, the Middle/Upper Triassic sequence shows no significant lateral coalification trend. However, the data demonstrate a significantly increasing thermal maturity with stratigraphic age (Fig 5). The published data in general support the observed coalification pattern and degree of thermal maturity. Balzas & Koncz (1999) report vitrinite reflectance values between 0.67 and 1.00 % VR_r for the Middle/ Upper Triassic in the upper Alta Badia and Zattin et al. (2003) and Fantoni et al. (2001) values between 0.60 and 1.00 % VR_r for these units in the Alta Badia and Marmolada region.

The average vitrinite reflectance values for Lower Cretaceous rocks range from 0.44 to 0.73 %VR_r and for the Upper Cretaceous *Antruilles-Fm* from 0.44 to 0.52 %VR_r (Fig. 4). Most VR histograms for Cretaceous samples show a characteristic bi-modality which is typical for samples containing reworked vitrinites. The determined vitrinite reflectance of the Antruilles-Fm have more dispersed vitrinite, whereas some higher values in the other Cretaceous units (Ra Stua-Flysch) might be due to presence of resedimented vitrinite and less reliable.

In summary the mean vitrinite reflectance of the analysed outcrop samples ranges between 0.5 % VR_r for the Cretaceous Antruilles-Fm and 0.9 %VR_r for the Permian *VGS* (Fig. 5). This defines a clear coalification trend along the investigated profiles within the Permo-Mesozoic stratigraphy of the central Dolomites showing an increasing thermal maturity with increasing stratigraphic age. It can therefore be assumed that the coalification pattern mainly reflects a pre-orogenic coalification (sensu Teichmüller & Teichmüller, 1966 and Nöth et al., 2001). We also made a few measurements outside the study area discussed here (further to the south), where exceptionally high reflectance values of solid bitumen were found along faults and fractures, indicating hydrothermal effects. These hydrothermal effects, however, did not influence the studied rocks at greater distance from faults, allowing a reconstruction of temperature history (especially maximum burial temperature).

Thermal modelling

Conceptual model and input data

A conceptual model of the geologic evolution of a sedimentary basin is the basis for the numerical modelling. For the pseudo-wells along the TransAlp traverse different geological events of sedimentation or erosion were defined. Based on this conceptual model and the stratigraphic succession (Fig. 3) input data sets for the numerical modelling of the two pseudo-wells were created.

One pseudo-well (PSW-Heiligkreuzkofel) is located on the eastern flank (Fanes) and the other (PSW-Würzjoch) on the western flank (Gardenazza) of the Alta Badia valley. The input data for both pseudo-wells consist of 21 layers and around 30 events and reflect the high-resolution coalification pattern determined in this study and the local thickness variations. Layer definition comprises a depositional or erosional thickness, an absolute depositional time and a lithology definition (Tab. 1). Besides minor local thickness variations the two models differ mainly in the thickness of the eroded *Werfen-Fm*. The erosional amounts used as start value for the modelling are based on regional geologic considerations. Along the western profile (PSW-Würzjoch) the Anisian unconformity truncates almost the complete *Werfen-Fm* (350 m). The Jurassic sequence is completely missing and the Lower Cretaceous (Maiolica, *Puez-Marls)* unconformably overlies the *Dolomia Principale*. For the eastern pseudo-well (PSW-Heiligkreuzkofel) the erosion removed the upper 100 meters of the *Werfen-Fm*. The partly folded Jurassic *Calcari Grigi* is unconformably overlain by the Oligocene *Monte Parei* Conglomerate.

Palaeo-heat flow is beside the erosional amounts the most important, variable modelling parameter. Only for times of maximum temperature, palaeo-heat flow is a direct modelling result. For the first simulation runs, a simple palaeo-heat flow model derived from the basic geodynamic and crustal evolution of the Dolomitic realm was applied. It is unknown to what extent Permian volcanism influenced the heat flow regime, but the sedimentary rocks were at that time either not deposited or at very shallow depth and therefore not affected or only locally affected. Highest heat flow values might have been reached in Jurassic times (about 160 million years before present) when also oceanic crust was formed in the Ligurian ocean. In the best fit model, we assumed 60 mW/m^2 for this period. Thereafter, heat flow decreased up to the present-day values of about 30-35 mW/m^2 (cp. IHFC, 1993; 41 mW/m^2 was measured at well Sedico 1, pers. com. Dr. R. Fantoni, ENI Agip). In some publications higher heat flows are assumed. Fantoni & Scotti (2003) favour a range between 85 and 105 mW/m^2 for the Southalpine and Zattin et al. (2003) use 100 mW/m^2 for a model in the southern Dolomites.

Thermal modelling results and discussion

The best fit of calculated and measured vitrinite reflectance was reached for both simulated pseudo-wells with an 1700 to 2400 m thick Upper Cretaceous and Palaeocene sequence that was eroded prior to summit overthrusting in the Oligocene (Figs 6A, 7A). The additional overburden for PSW-Heiligkreuzkofel represents 200 m *Puez-Marls* and *Antruilles-Fm* and a 1500 m thick Upper Cretaceous sequence.

The calculated vitrinite reflectance gradients of 0.01-0.02 %VR$_r$ / 100 m reflect an overall cool geothermal field during maximum burial. The "best fit" palaeo-heat flow model is characterised by a peak of 55 mW/m^2 in Jurassic times (160 million years ago) which is followed by a decrease to the present-day value of about 30 mW/m^2. Similar, low heat flow also occurred at times of maximum burial during the latest Cretaceous and early Tertiary (35 and 30 mW/m^2). The burial history of PSW-Heiligkreuzkofel is characterised by deposition and burial until the Palaeocene followed by erosion of the Palaeocene/Cretaceous sequence during the Eocene/Oligocene. This evolution is strongly indicated by the deposition of the Oligocene Monte Parei conglomerate situated unconformably on top of the folded Jurassic sequence. Therefore, the erosion of the additional overburden has to be part of the Dinaric orogeny. The burial history of PSW-Würzjoch is similar, but the Anisian unconformity cuts deeper into the stratigraphy and the Jurassic, if deposited, was eroded completely prior to the deposition of the Cretaceous and Palaeocene. After the erosion of the major Cretaceous deposits this region was overthrusted during the Dinaric orogeny. Both models reveal a similar palaeo-heat flow trend with different thickness of eroded sediment (Figs. 6 and 7). It should be noted that other authors proposed for the Cretaceous time a condensed sedimentation of a maximum of 200 meters (cp. Bosellini, 1998 and Stingl, 1998b). Such a low thickness is, however, in conflict with the enhanced thermal maturity of these uppermost units. This result implies sedimentation followed by erosion of about 1700 m of Cretaceous units. Thus the area subsided and provided accommodation space, possibly for a siliciclastic turbiditic depositional system. The sedimentary pattern of the preserved Cretaceous deposits (the *Puez-Marls* to the *Antruilles-Fm*) supports such a deepening of the Trento platform. Furthermore, the regional geology of the southern foreland reveals the presence of about 700 m of Upper Cretaceous sediments and 1100 m of Palaeocene to Eocene *Belluno-Flysch*. As an alternative, burial could also be due to a combination of sedimentation and overthrusting by a nappe followed by erosion of these units. Whether the deep burial was partly due to such tectonic processes cannot be resolved by this study.

The evolution of vitrinite reflectance and temperature over time is shown in Figures 6B, 6C, 7B and 7C for the mid of the Werfen Fm and the Puez Marls, respectively. The model results indicate high temperatures in the Werfen Fm already during the Late Triassic and Jurassic. Peak temperatures and present-day maturity were reached during the early Tertiary.

Figures 6D and 7D visualize the calibration of the two models. In both cases, a good fit between measured and calculated vitrinite reflectance can be achieved (compare dots and black line in the figures). Assumption of a lower eroded thickness (by 700 m) in combination with a slightly higher heat flow leads to the blue curves. The fit is even worse, if no eroded thickness at a uniform, high heat flow of 60 mW/

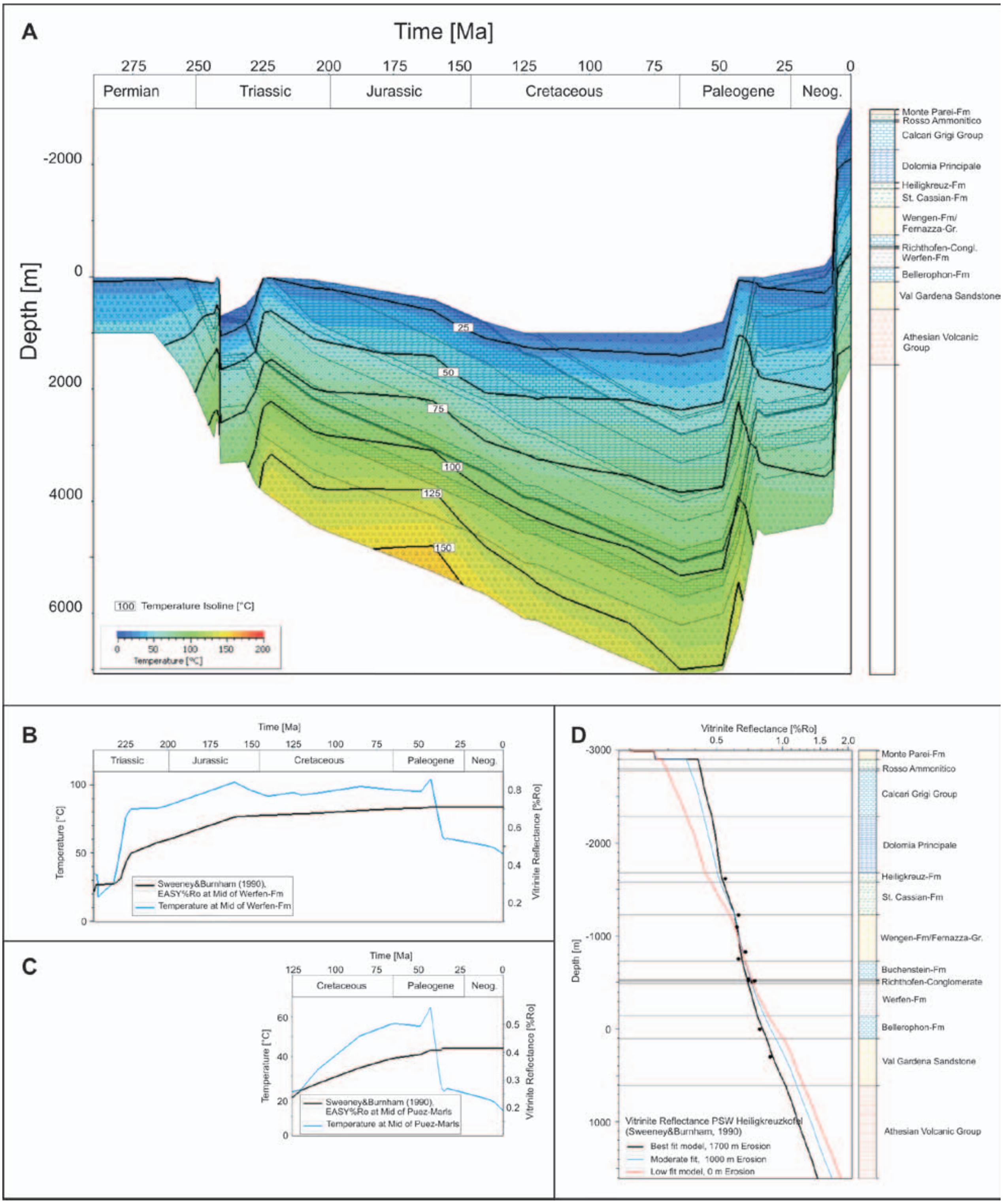

Fig. 6: Burial and temperature history (A) east of Alta Badia valley (Heiligkreuzkofel model), temperature and vitrinite reflectance evolution of the mid of Werfen Formation (B) and Puez Marls (C) and comparison of measured (dots) and calculated (lines) vitrinite reflectance (D). Black line: best fit; blue line: erosion reduced by 700 m, heat flow enhanced by 5 mW/m^2; red line: 0 m erosion and constant heat flow of 60 mW/m^2.

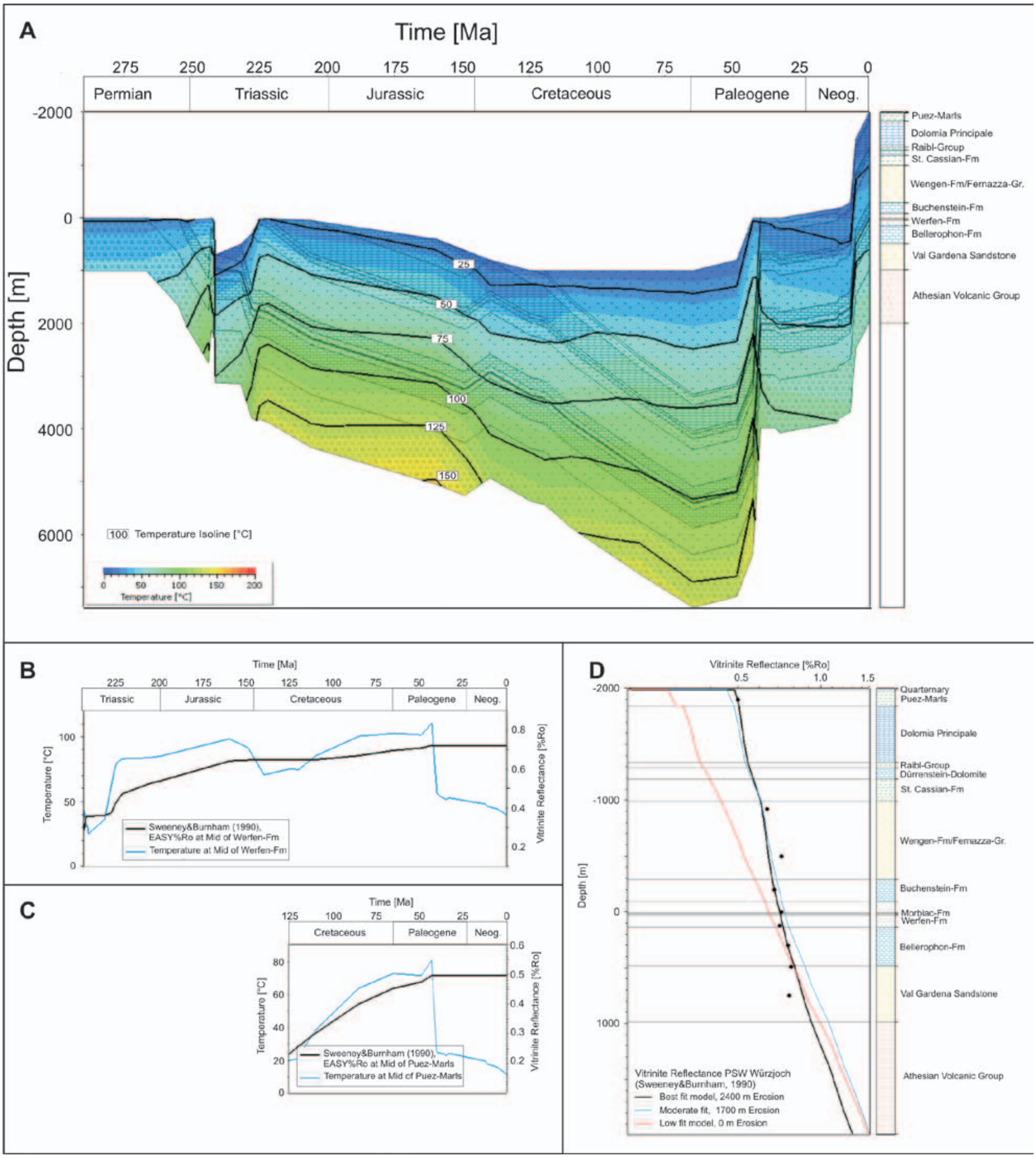

Fig. 7: Burial and temperature history (A) west of Alta Badia valley (Würzjoch model), temperature and vitrinite reflectance evolution of the mid of Werfen Formation (B) and Puez Marls (C) and comparison of measured (dots) and calculated (lines) vitrinite reflectance (D). Black line: best fit; blue line: erosion reduced by 700 m, heat flow enhanced by 5 mW/m^2; red line: 0 m erosion and constant heat flow of 60 mW/m^2.

m^2 is assumed (red lines in Figures 6D, 7D). Thus the data clearly indicate significant erosion both east and west of Alta Badia valley.

Conclusions

The analysis of the coalification pattern of the Permo-Mesozoic sedimentary succession of the Dolomites provides a basis for a constrained and quantitative analysis of basin evolution using numerical basin modelling techniques. This study deepens the current knowledge on the thermal maturity of the Dolomites. Especially for the Middle Triassic it provides a constrained high-resolution picture of the coalification pattern and relates this to the geodynamic evolution of the Dolomitic realm. The application of numerical basin modelling techniques enabled to quantify the burial and temperature history of the Dolomite Mountains. The results of this study can be highlighted with the following points:

Our data reveal an increasing thermal maturity with increasing stratigraphic age. Along the investigated profiles the observed mean vitrinite reflectance ranges between 0.5 % VR_r for the Cretaceous *Antruilles-Fm* and 0.9 %VR_r for the Permian *VGS*. This can be best explained by a coalification prior to the Dinaric- and Neoalpine orogeny.

Vitrinite reflectance values of about 0.5 %VR_r for the Cretaceous implies a substantial subsidence and burial of these Cretaceous units which will have occurred during the Late Cretaceous/Early Tertiary, i.e. prior to Alpine orogeny. This overburden is now eroded.

Based on the numerical modelling of two pseudowells the amount of Tertiary erosion probably ranged between 1700 m and 2400 m. As consequence, the deposition in the Dolomitic realm persisted longer than up to now known during the Cretaceous and possibly even earliest Tertiary. However, based on the results presented here, it cannot be excluded that part of the deep burial is due to tectonic overthrusting and later erosion of this nappe.

Deepest burial and maximum temperatures probably date into Palaeocene and Eocene times with concurrent heat flows between 35 and 30 mW/m^2. The observed coalification gradients (0.01 to 0.02%VR_r / 100 m) indicate a quite low heat flow regime during times of maximum temperatures and maximum burial.

The deposition of thick Triassic as well as Cretaceous and Paleogene strata has probably overprinted any thermal effects of the Permian and Ladinian volcanism on the oldest sedimentary rocks.

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