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ORIGINAL PAPER

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Jurassic strike slip versus subduction in the Eastern Alps

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Abstract Late Jurassic formations of the Northern Calcareous Alps (NCA) contain ample evidence of synsedimentary tectonics in the form of elongate basins filled with turbidites, debris flows and slumps. Clasts are derived from the Mesozoic of the NCA; they commonly measure tens of metres in diameter and occasionally form kilometre-size bodies. These sedimentologic observations and the presumed evidence of Late Jurassic high-pressure metamorphism recently led to the hypothesis of a south-dipping Jurassic subduction zone with accretionary wedge in the southern parts of the NCA. We present new $^{40}Ar/^{39}Ar$ dates from the location of the postulated high-pressure metamorphism that bracket the age of this crystallization not earlier than 114–120 Ma. The event is therefore part of the well-documented mid-Cretaceous metamorphism of the Austro-alpine domain. Thus, there is currently no evidence of Late Jurassic high-pressure metamorphism to support the subduction hypothesis. The sediment record of the Late Jurassic deformation in the NCA, including the formation of local thrust sheets, is no conclusive evidence for subduction. All these phenomena are perfectly compatible with synsedimentary strike-slip tectonics. Large strike-slip fault zones with restraining and releasing bends and associated flower structures and pull-apart basins are a perfectly viable alternative to the subduction model for the Late Jurassic history of the NCA. However, in contrast to the Eastern Alps transect, where arguments for a Jurassic subduction are missing, a glaucophane bearing Jurassic high-pressure metamorphism in the Meliatic realm of the West Carpathians is well documented. There, the high-pressure/low-temperature slices occur between the Gemeric unit and the Silica nappe system (including the Aggtelek-Rudabanya units), which corresponds in facies with the Juvavic units in the southern part of the NCA. To solve the contrasting palaeogeographic reconstructions we propose that the upper Jurassic left lateral strike-slip system proposed here for the Eastern Alps continued eastwards and caused the eastward displacement of the Silica units into the Meliatic accretionary wedge.

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Introduction

The problem: Jurassic deformation in the Northern Calcareous Alps

The extent and tectonic setting of Jurassic deformation in the Northern Calcareous Alps (NCA) is a recurring topic of Alpine tectonics. There can be little doubt that deformation was intensive and pervasive. The Jurassic stratigraphy of the NCA abounds with evidence of syndepositional faulting, folding and low-angle thrusting.

The controversy concerns the tectonic setting of this deformation. Once again, there is general agreement that the Early Jurassic structures are largely extensional and well compatible with a setting of crustal thinning and rifting. The Late Jurassic deformation is more intensive and complex. Besides high-angle normal faults, also includes strike-slip faults, reverse faults and low-angle thrusts with displacements of several kilometres, possibly tens of kilometres. Most importantly, low-grade metamorphism of Late Jurassic age has been postulated for several areas of the NCA (Kralik et al. 1987a, b; Kralik and Schramm 1994; Spötl et al. 1998).

The opinions diverge on the tectonic setting of this Late Jurassic deformation. One school of thought assigns it to a transpressive regime on the rifted but transform-dominated, southern margin of the Penninic

Ocean (Weissert and Bernoulli 1985; Wächter 1987; Trümpy 1988; Channell et al. 1990). Another school explains it as the result of a Late Jurassic phase of subduction (Gawlick 1996; Braun 1998; Frisch and Gawlick 2001). Gawlick et al. 1999 present a rather detailed model. They postulate a subduction zone at the southeastern, Tethys-facing margin of the Austro-alpine microcontinent. With an SE dip, it is thought to have consumed the southern part of this microcontinent, scraped off part of its sediment cover and piled it up in a north-vergent stack of thrust sheets. Deeper-water sedimentation continued throughout most of this process and recorded the increasing deformation.

The debate about transpression versus subduction in the Austro-alpine domain gains an intriguing twist if one considers it in a broader regional context. In the late Jurassic, one finds good evidence for transpression just west of the Austro-alpine domain and equally strong evidence for subduction just east of it. Transpressive deformation is observed in the Penninic Briançonnais zone of eastern Switzerland, a series of high-angle faults and associated coarse debris fans have been convincingly interpreted as the result of Late Jurassic transpression (Schams nappes, Schmid et al. 1997, Fig. 14-6). Evidence of subduction occurs in the Meliata Zone of the Carpathians in the form of Late Jurassic, high-pressure/low-temperature metamorphism (Faryad 1995; Faryad and Henjes-Kunst 1997; Faryad and Schreyer 1996; Mello et al. 1996, 1997; Maluski et al. 1993). Still farther E, in the Caucasus, a north-dipping subduction zone seems to have operated throughout the Mesozoic (Dewey et al. 1973; Stampfli and Marchant 1997; Cavazza et al. 2004).

As concerns the NCA, a particularly crucial piece of evidence for Late Jurassic subduction S of the NCA is the postulated high-pressure metamorphism of Triassic limestones at the Pailwand in the central part of the NCA (Gawlick and Höpfer 1996). Further arguments in favour of subduction are based on the depositional facies and the Jurassic deformation patterns in the middle segment of the NCA (Gawlick 1996; Braun 1998; Gawlick et al. 1999; Frisch and Gawlick 2001).

In this report we present new geochronologic data from the Pailwand and its environs, and evaluate the evidence for Jurassic high-pressure metamorphism in the NCA. We subsequently discuss the patterns of Jurassic sedimentation and syndepositional deformation in the context of the subduction and strike-slip models of deformation. Finally, we review the implications of our findings in the context of Alpine-Carpathian tectonics.

Background on the NCA

The NCA are an entirely allochthonous fold-and-thrust belt (Fig. 1). They represent part of the sedimentary cover of the Austro-alpine basement of the Adriatic plate that was thrust northward over a stretch of ocean and its margins, i.e. over the lower Austro-alpine, the Penninic and the Helvetic domains.

The tectono-stratigraphic history of the NCA starts with Permo-Scythian red beds and evaporites deposited on the rump of the Variscan mountain belt. The Middle Triassic through Early Jurassic record consists of a passive-margin succession rich in tropical shallow-water carbonates that is becoming more open-marine and deeper with time. This trend culminates in widespread pelagic deposition in the Middle and Late Jurassic. The radiolarites and cherty pelagic limestones of this time interval can be matched one by one with coeval deposits of the central North Atlantic (Bernoulli 1972). The tectonic setting of this "oceanic stage" of deposition is a topic of this report.

From the Early Cretaceous (Barremian) we have definitive evidence of contractional tectonics with exhumation of basement and formation of nappes (Faupl and Wagreich 2000). By Late Cretaceous time, the fold-and-thrust belt was fully developed. The Late

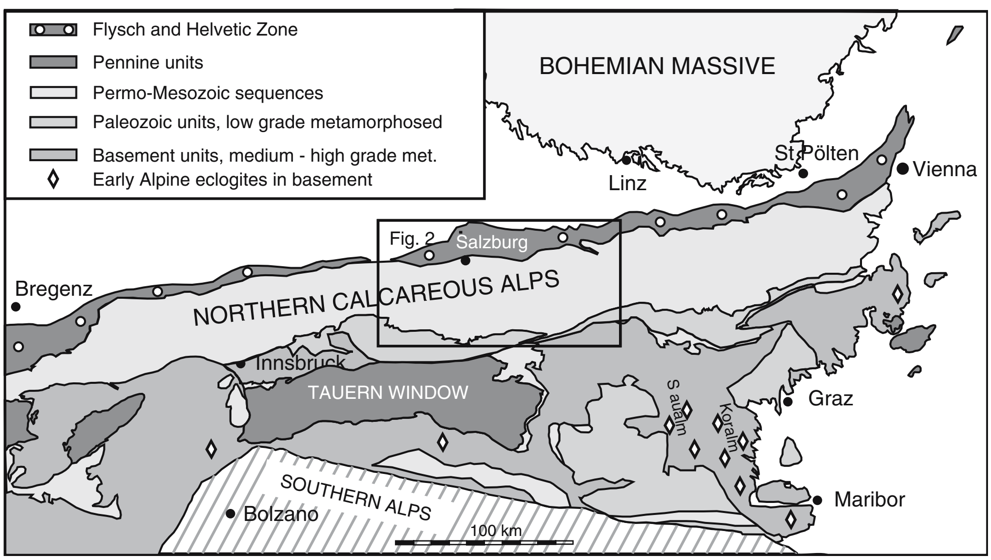

Fig. 1 Simplified geologic map of Eastern Alps, showing major tectonic zones (after numerous sources)

Cretaceous Gosau group already seals the basic nappe structures and its facies indicate pronounced relief ranging from marine troughs below carbonate compensation depth to mountainous terrestrial hinterland. The fold-and-thrust belt got its final form in the Early Tertiary when the NCA were thrust northward over the flysch troughs of the Penninic and Helvetic domains and over the southern part of the present foredeep. The older structures were dissected and re-activated in various ways during the eastward extrusion of the Eastern Alps in the Miocene (Ratschbacher et al. 1991; Frisch and Gawlick 2003).

The structure of the NCA agrees fairly well with the standard model of a fold-and-thrust belt. The sole fault rises towards the foreland and stratigraphically younger rocks dominate the external nappes, older rocks the more internal ones. However, structural style varies along strike and therefore a subdivision into western, central and eastern segment usually is applied (e.g. Plöchinger 1995). In the western and eastern segments, nappes are long and narrow, separated by south-dipping, imbricate thrust faults. In the central segment (and the southernmost parts of the eastern segment), the imbricate pattern is subdued. Nappes consist of irregularly shaped, stiff slabs of platform carbonates, separated by broad zones of intensively deformed Permo-Scythian red beds, evaporites and Triassic basin sediments (Figs. 2, 3). Opinions on the nappe architecture of the central segment differ considerably. There are two main reasons for this: (1) numerous faults dissect the stiff slabs and severely limit the lateral extent of undisturbed stratigraphic packages. (2) Permo-Scythian red beds and evaporites act as a ductile paste during deformation, facilitating horizontal and vertical displacement in variable directions. The collection of stiff blocks and ductile material in between is difficult to assemble into a coherent stack of nappes because the relationship among the various elements changes from place to place.

An important recent development is the observation that at least some tectonic klippen of basin facies and platform facies already had been emplaced in early Late Jurassic times (Mandl 1982; Schäffer and Steiger 1986; Gawlick 1996; Mandl 2000). Figure 3 shows a reconstruction of the history of thrust movements by Mandl (2000). Thrusting is assumed to have started in the south (or southeast) in the Late Jurassic and progressed

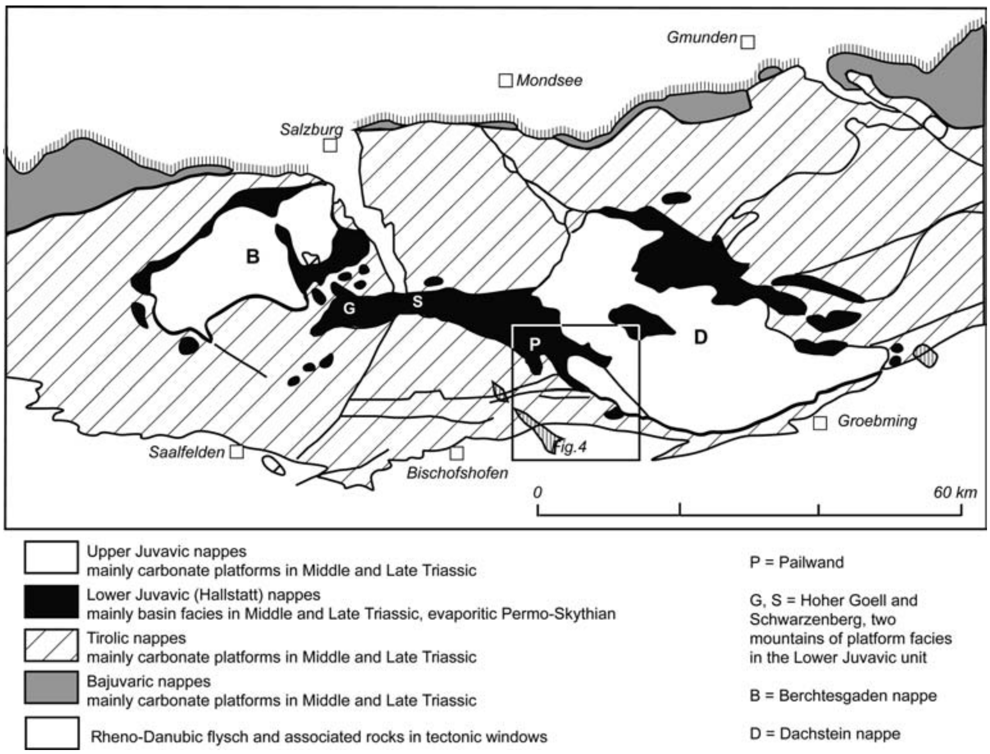

Fig. 2 Tectonic map of the central segment of the Northern Calcareous Alps (NCA); after Plöchinger (1995) modified. From bottom to top, three groups of nappes are recognized: Bajuvaric, Tirolic and Juvavic nappes. The Tirolic units dominate this segment of the NCA; at the meridian of Salzburg, the Tirolic nappes extend from the northern to the southern boundary of the NCA with Bajuvaric nappes restricted to thin slivers in the northern boundary zone. Shallow-water limestones and dolomites (1,000–2,000 m) constitute the competent element of the Tirolic nappes. Juvavic nappes form the top of the nappe stack. They consist of a lower unit, often called Hallstatt nappe(s), dominated by Triassic basin sediments, and an upper unit consisting mainly of platform limestones. The Upper Juvavic Berchtesgaden nappe overlies the Hallstatt nappe everywhere; the Dachstein nappe, on the other hand overlies some Hallstatt elements but also carries Hallstatt klippen on top. See Fig. 3 for a possible explanation of this pattern

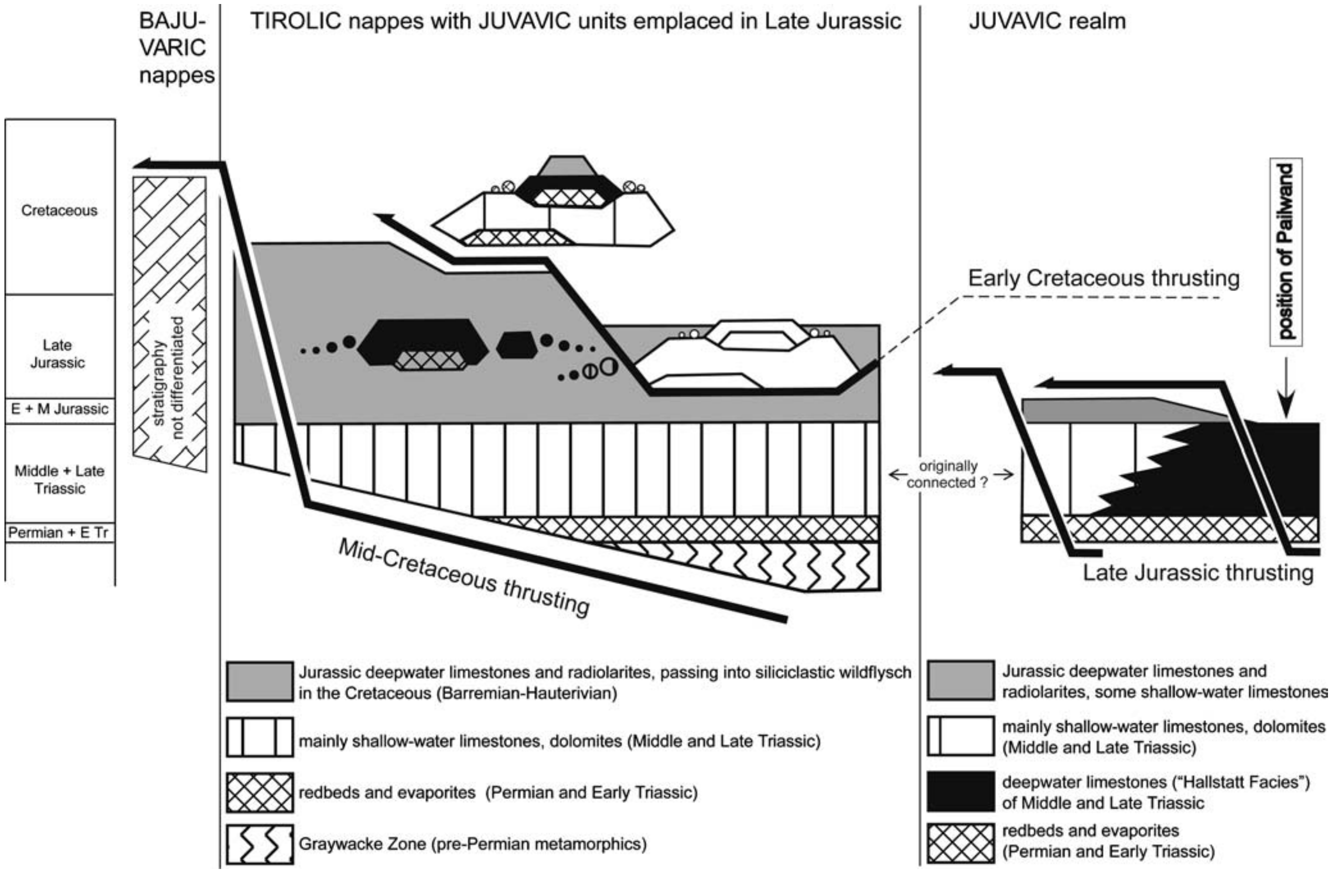

Fig. 3 Growth of the nappe stack of the central NCA and position of Pailwand in this stack, based largely on Mandl (2000). *Patterns* indicate stratigraphic supergroups reflecting major depositional stages in the history of the NCA (note age scale on *left*). *Bold lines* denote three principal phases of Jurassic-Cretaceous detachment and thrusting: (1) Late Jurassic emplacement of klippen of the Juvavic domain in a deep basin of what later became the Tirolic nappes; (2) Early Cretaceous thrusting of Juvavic klippen plus their Jurassic sedimentary cover onto more external Tirolic substrate; (3) Mid-Cretaceous thrusting of the stack of Tirolic and Juvavic nappes onto Bajuvaric nappes. (Younger phases of thrusting are not considered). We propose that the Late Jurassic thrusting probably is related to strike-slip tectonics rather than subduction and accretion

northward. Major post-Jurassic thrusting phases occurred in the Early Cretaceous (Barremian-Hauterivian), the middle Cretaceous and the Early Tertiary (the last phase not shown in Fig. 3).

New $^{39}Ar/^{40}Ar$ data and their interpretation

Lithology of the investigated outcrops

In the Juvavic unit of the Pailwand two structural domains are exposed (see Figs. 4, 5). In the eastern domain, the metamorphic overprint took place at elevated anchizonal conditions. The Zlambach Formation, lithologically sensitive for low-grade metamorphic alteration, shows open folding and a weakly developed axial plane cleavage (s_1 150/85). This weak metamorphic overprint did not reach a phyllitic character. In contrast to this, the western domain is dominated by Hallstatt flaser-limestone, which developed sericite in phyllitic patches (average grain size 20–30 μm). Obviously these rocks have seen higher deformation intensity and slightly higher temperatures than the eastern domain. In this outcrop one of the most evolved metamorphic lithologies in the Juvavic units is exposed. The contact between the two domains is clearly tectonic and the schistosity developed in the Hallstatt flaser limestone is oblique (s 205/35) to the slaty cleavage of the underlying Zlambach Fm. The field observations indicate that both domains of the Pailwand were tectonically amalgamated in the last stages of deformation during which the phyllitic schistosity was formed. The samples for which minimum temperatures of about 400°C and high-pressure conditions from the phengitic micas were reported by Gawlick et al. (1999) are derived from the outcrops in the western part of Pailwand, as are our samples GW-2,3,4. These outcrops were interpreted to represent tectonic slices from a Jurassic subduction zone by Gawlick et al. 1999.

Two samples from the wider surroundings of the Pailwand klippe were analysed: One (GW-3) is a fine-grained Jurassic marble with small amounts of pelitic segregations at the eastern side of the Tennengebirge, i.e. the Tirolic unit underlying the Lammer Zone with the

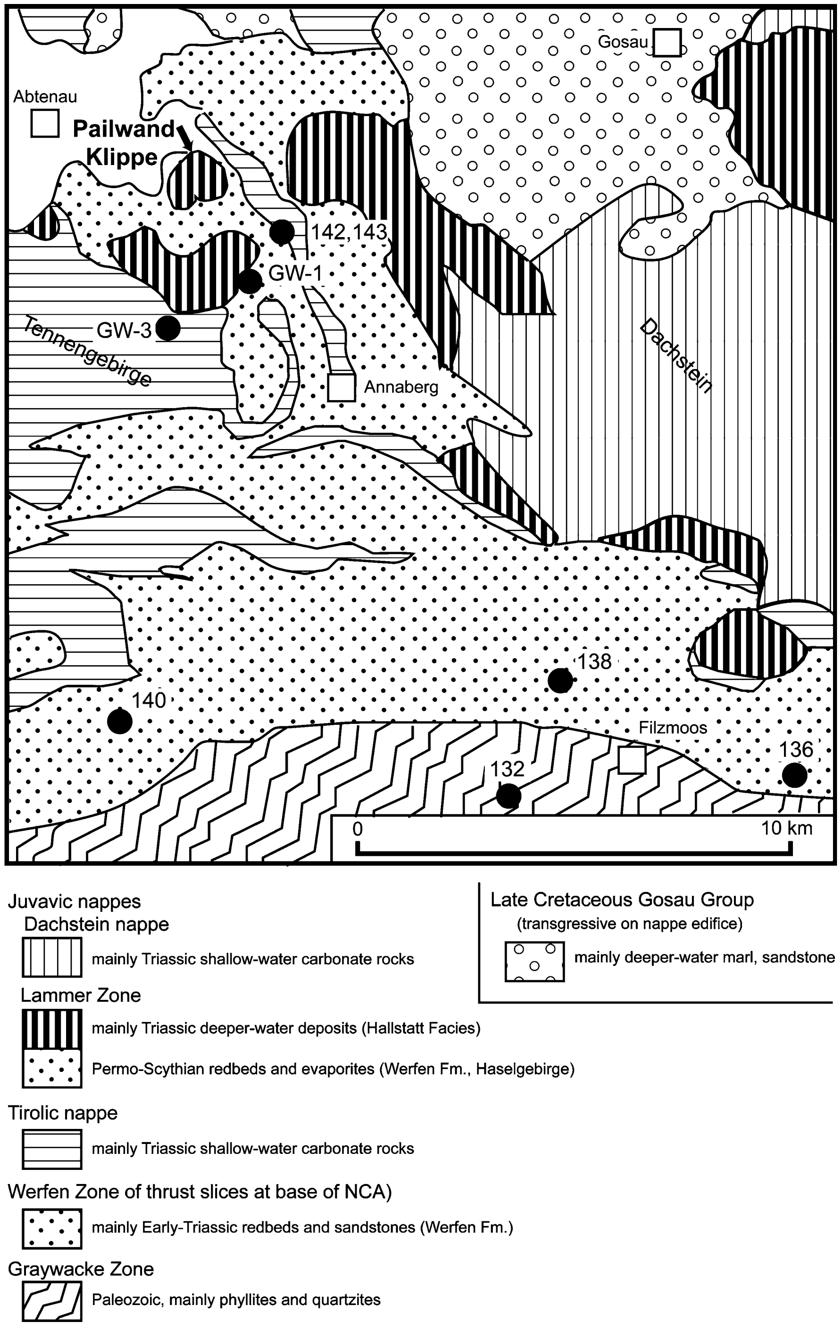

Fig. 4 Geologic overview of the surroundings of the Pailwand klippe in the central NCA. Location of samples from Werfen Fm. and Paleozoic phyllites are indicated by *black dots* and *numbers*

Pailwand klippe. The other sample (GW-1) is from the Werfen Formation of the Lammer Zone itself.

For a better understanding of the timing of the regional metamorphism, a series of illites and sericites from fine-grained lithologies of the Werfen Formation and the topmost parts of the Graywacke Zone collected in road cuts from Abtenau, Annaberg, St. Martin, Filzmoos have also been investigated with the Ar/Ar method. Tectonically these samples belong to the Lammer Zone, the Werfen Schuppen Zone and the Graywacke Zone (Mandl et al. 1987; Rossner 1972).

Analytical procedure The geochronological investigations were performed in the Ar-laboratory of the Institute for Geological Sciences, Vienna University. In the meantime the equipment was transferred and is continuing as Central European Ar-Laboratory (CEAL) at the Geological Institute of Slovak Academy of Science, Bratislava. Fine fractions (<2 μm, 2–6 μm, 6–11 μm) from pelite rich samples (see sample localities in Figs. 4, 5) have been investigated and dated by the $^{39}Ar/^{40}Ar$ incremental heating technique after treating the calcareous samples with acetic acid. All samples are illite-rich, some with minor amounts of chlorite. We thank H-J. Gawlick for testing the mineralogical composition with XRD. The analytical procedure is the same as described in Frimmel and Frank (1996).

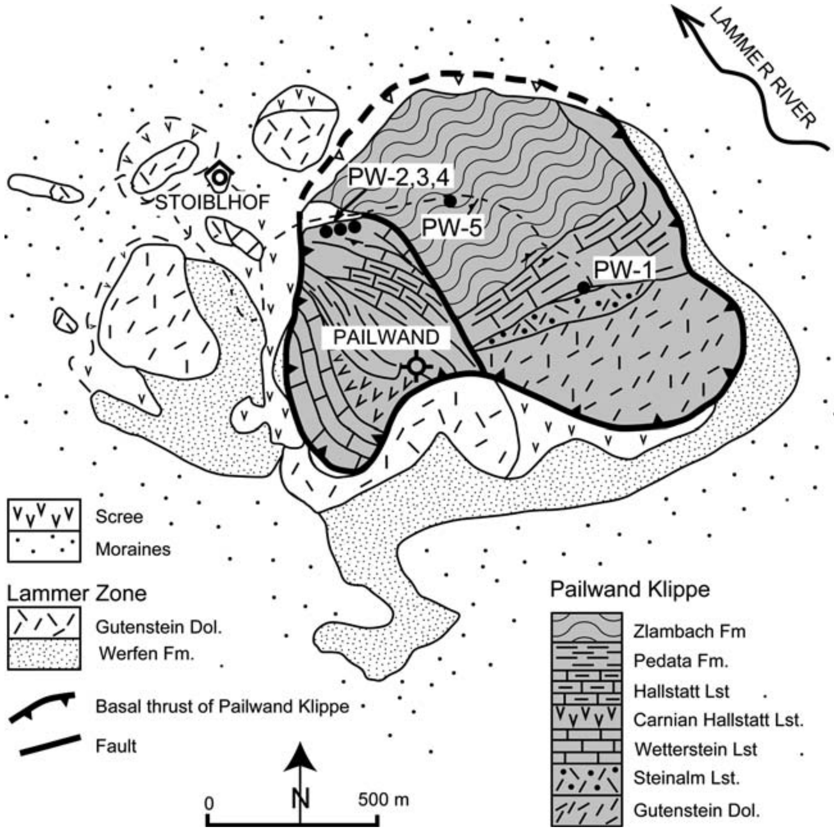

Fig. 5 Geologic map of Pailwand and sample locations. Geology after Hamilton (1981), modified. Note that the mappable substrate of the Pailwand klippe consists of Triassic rocks of the (Lower Juvavic) Lammer Zone; there is no field evidence that the klippe is embedded in Jurassic Strubberg Beds

Data from the Pailwand area

Here we present data from the eastern part of Tennengebirge close to Gwechenberg Alm (GW-1,3) and from the Pailwand SE of Abtenau. Apart from GW-3, all samples are derived from complexes that have been tectonically emplaced on the Tennengebirge, traditionally considered a southern part of the Tirolic realm. The samples are discussed from S to N.

The Ar release spectra are given in Figs. 6 and 7, followed by age summaries in Fig. 8. A prominent and common feature is the strongly discordant age patterns with old relicts from the cores at highest temperatures (approximately 5% of the total gas released). In most cases they can be interpreted as detrital relicts. The first 80–90% of the released gas shows either rejuvenation staircases (mainly from Werfen Formation, e.g. sample GW-1) or inhomogeneous and variable release spectra, often with negative staircase patterns. The release spectra exhibit a more homogeneous plateau-type pattern only in case of PW-5 and PW-3. From these observations we can deduce that all samples belong to a low-temperature range not exceeding 420°C. Temperatures were in most cases distinctly lower than this range above which Ar equilibration can be expected given the grain sizes investigated. The differences between the < 2 μm, 2–6 μm and 6–11 μm fractions are generally small, but show systematic variations of two kinds: (1) In samples with a distinct detrital component coarser fractions normally have somewhat higher ages and more pronounced relictic detrital domains compared with finer fractions, which are more affected by rejuvenation. (2) When excess ^{40}Ar is present it is more dominant in the fine fractions.

The Ar/Ar analyses yielded the following results. All fractions from sample GW-1, taken from the Werfen Fm. from the Lammer Zone (Fig. 4) shows staircase patterns with a range of 159–217 Ma (detrital domains omitted) in the 6–11 μm fraction and a considerable younger time range of 140–190 Ma in the < 2 μm fraction. Rejuvenation is obviously much more effective in the smaller grains. The absence of a distinct plateau suggests that even in the < 2 μm fraction no geologically meaningful equilibrium was reached. We also consider the youngest age information from this sample as an incompletely rejuvenated age pattern. One should bear in mind that in detrital lithologies, such as the Werfen formation, the rejuvenating event may be younger than the youngest step age obtained. The distinctly older ages from the core (276 Ma, 248 Ma, 230 Ma) are obviously derived from small relicts of detrital muscovites; either overgrown or from mechanical fragments produced during sample preparation. The real age of the oldest domains in these grains can be assumed to exceed the numerical ages obtained because gas from the relics is mixed with Ar from the younger domains.

Sample GW-3 is a thin layer of light-green shale, locally occurring in a fine grained, whitish marble from the

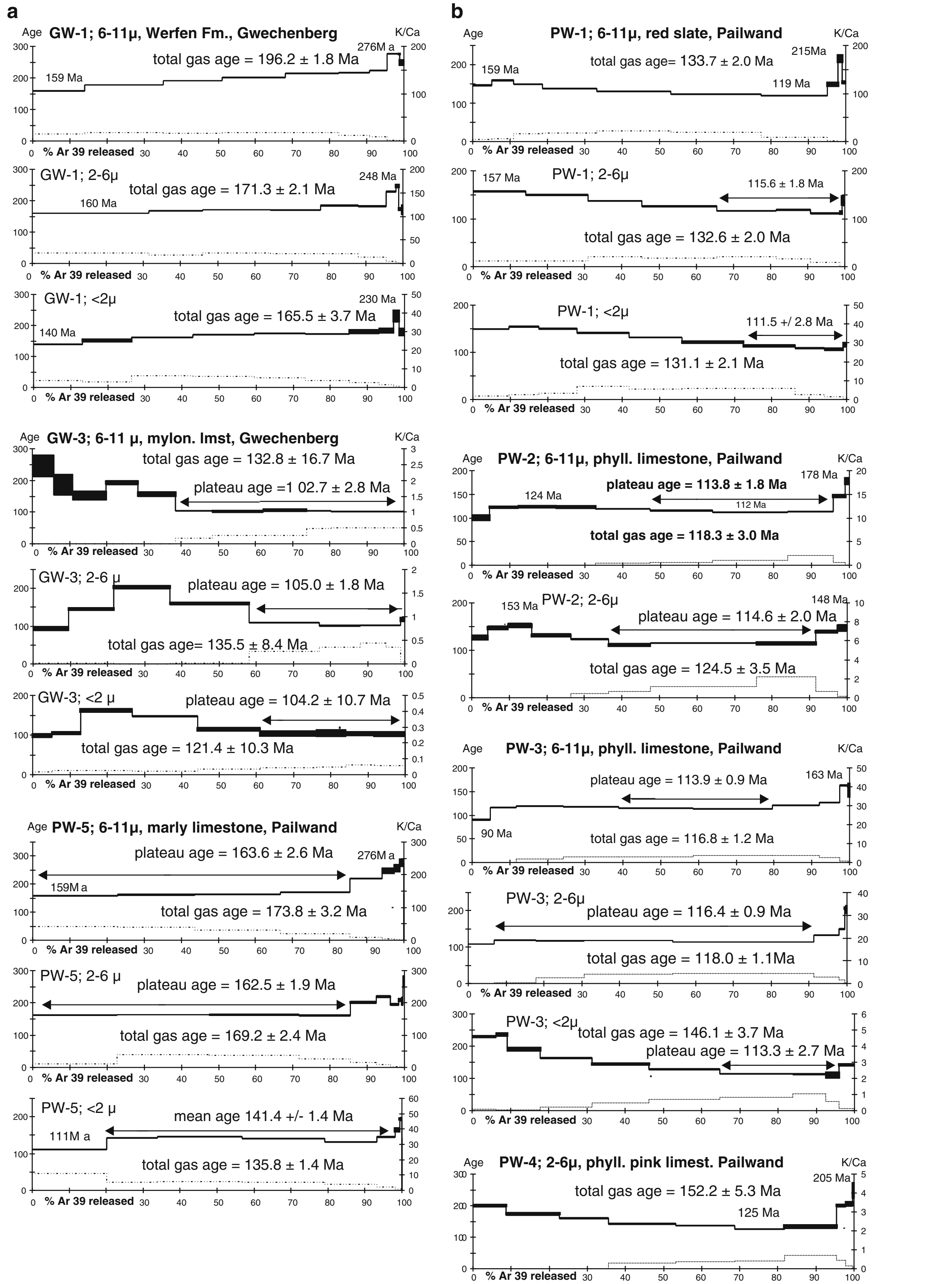

Fig. 6 Ar/Ar release spectra from the Pailwand area (see Fig. 5 for sample locations). **a** Weakly metamorphic samples; **b** samples in relatively advanced stages of metamorphism

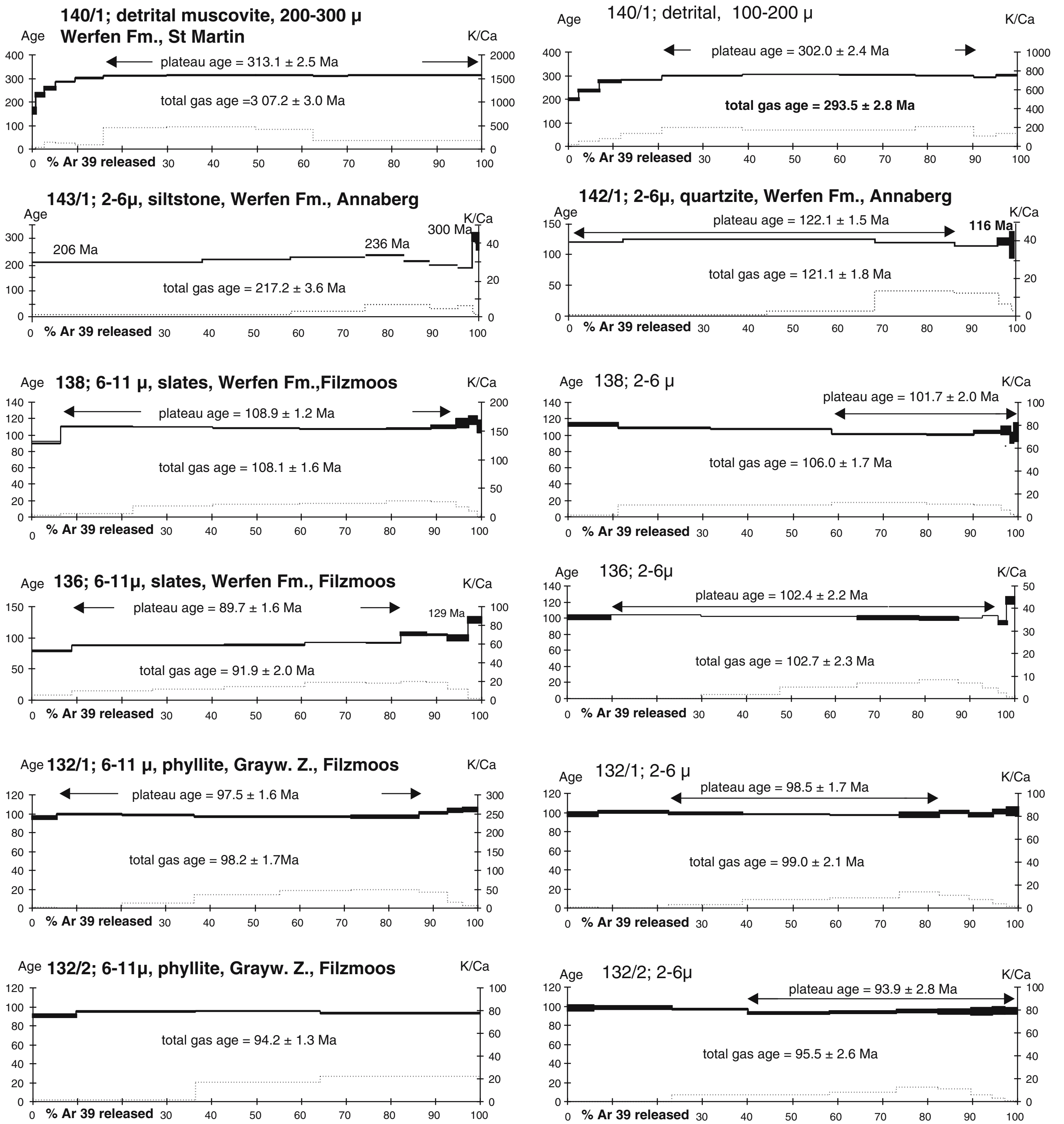

Fig. 7 Ar/Ar release spectra of Werfen Formation and Paleozoic phyllites of Graywacke Zone. (See Fig. 4 for sample locations)

upper Jurassic sequence of the Tennengebirge (Tirolic nappe, Figs. 2, 4). Its position is close to the tectonic contact with the Lammer Zone and strong deformation is obvious. The diagrams exhibit inhomogeneous age patterns with high ages and disturbance at low temperatures but consistent step ages of about 103–105 Ma in the core region, where no detrital domains were observed. This latter age indicates the time of illite growth and main deformation in this outcrop close to Gwechenberg Alm. The lower temperature portion of this diagram is interpreted in the same manner as several samples from the Pailwand. A considerable amount of excess ^{40}Ar was incorporated during later growth of these fine-grained illites and caused the geologically meaningless ages. It is difficult to judge if the strong disturbances at low temperatures represent primary inhomogeneities during growth or later diffusional rejuvenation at the rims. This sample has a particular

MsNr	Sample	size	plateau age	%39	total gas age	st.	% rad.	IC - age*	IC 40/39 *	comment
2543	GW - 1	6 - 11μ	--	--	**196.2 ± 1.8**	9	82 - 99	--	--	de. relics, rejuv. 159 - 276 Ma
2556	GW - 1	2 - 6 μ	--	--	**171.3 ± 2.1**	10	51 - 97		--	de. relics, rejuv. 160 - 248 Ma
2825	GW - 1	<2μ	--	--	**165.5 ± 3.7**	10	75 - 98	--	--	de. relics, rejuv. 140 - 230 Ma
2828	GW - 3	6 - 11μ	**102.7 ± 2.8**	62	132.8 ± 17	10	26 - 99	104 ± 1.5	263 ± 52	excess at rims, form age
2542	GW - 3	2 - 6 μ	**105.0 ± 1.8**	41	135.5 ± 8.4	9	46 - 97	101.3 ± 3.4	323 ± 146	excess at rims, form age
2826	GW - 3	<2μ	**104.2 ± 11**	39	121.4 ± 10	9	48 - 70	104.2 ± 3.4	299 ± 23	excess at rims, form age
2552	PW - 5	6 - 11μ	163.6 ± 2.6	85	173.8 ± 3.2	8	85 - 98	--	--	de. relics, rejuv. 159 - 276 Ma
2557	PW - 5	2 - 6 μ	162.5 ± 1.9	85	169.2 ± 2.4	10	49 - 98	165.2 ± 2.4	82 ± 131	detr.relics, , rejuvenated pl.
2831	PW - 5	<2μ	141.4 ± 1.4	78	135.8 ± 1.4	8	86 - 98	--	--	rejuvenated, 111 Ma at rim
2555	PW - 1	6 - 11μ	(119 Ma min)	--	133.7 ± 2.0	10	91 - 99	--	--	detr. relics, incr. excess/ rims
2561	PW - 1	2 - 6 μ	(116 Ma min)	34	133.6 ± 2.0	10	76 - 99	--	--	increasing excess Ar / rims
2829	PW - 1	<2μ	(112 Ma min)	28	131.1 ± 2.1	10	85 - 99	--	--	increasing excess Ar / rims
2554	PW - 2	6 - 11μ	**113.8 ± 1.8**	49	118.3 ± 3.0	10	78 - 98	114.3 ± 2.6	414 ± 106	small excess Ar / rims
2560	PW - 2	2 - 6 μ	**114.6 ± 2.0**	55	124.6 ± 3.5	10	64 - 99	115.1 ± 3.1	231 ± 196	excess Ar / rims
2830	PW - 2	<2μ	**113.3 ± 2.7**	31	146.1 ± 3.7	10	85 - 98	115.0 ± 1.0	196 ± 8	distinct excess Ar / rims
2553	PW - 3	6 - 11μ	**113.9 ± 0.9**	41	116.8 ± 1.2	10	78 - 99	116.0 ± 4.2	364 ± 769	relics, plateautype pattern
2559	PW - 3	2 - 6 μ	**116.4 ± 0.9**	85	118.0 ± 1.1	10	80 - 99	115.1 ± 1.8	556 ± 199	plateautype pattern
2558	PW - 4	2 - 6μ	(125 Ma min.)	--	152.2 ± 5.3	10	71 - 95	--	--	distinct excess Ar / rims
2701	143 / 1	2 - 6μ	--	--	**217.2 ± 3.6**	10	79 - 99	--	--	de. relics, rejuv. 189 - 310 Ma
2700	142 / 1	6-11μ	**128.8 ± 1.3**	85	128.9 ± 3.6	10	77 - 98	--	--	plateautype pattern
2699	142 / 1	2 - 6 μ	**122.1 ± 1.5**	85	121.1 ± 1.8	7	95 - 98	124.0 ± 1.6	137 ± 53	plateautype pattern

All ages are quoted in millions of years BP (Ma)
MsNr = measurement number
size = size fraction analyzed
%Ar = % of plateau from total released 39Ar
st. = total number of steps
%rad. = range of radiogenic content of all steps
IC = isotope correlation
* = only plateau steps were used for IC, meaningless results omitted

Fig. 8 Summary table of new Ar/Ar dates from Pailwand and surroundings (see Figs. 4, 5 for sample locations)

uniform, fine grain size. Due to the mechanical separation procedure the 6–11 μm fraction may contain a significant portion of aggregates of originally smaller illite particles.

From the Pailwand klippe nine size fractions from five samples have been investigated (Fig. 5). PW-1 is derived from a decimetre-thick intercalation of red shale in Hallstatt limestone (the sampling locality corresponds to sample location four of Gawlick and Diersche 2000). The layer shows some differential deformation between the adjoining limestones, a portion has also been altered to a green slate. Both smaller grain sizes show nearly identical total gas ages of about 133 ± 2.0 Ma and their individual age patterns, although strongly inhomogeneous, show that age differences related to grain size are nearly absent and therefore contributions from detrital relicts in the illites must be insignificant. A minor contribution from detrital muscovite grains at high temperature steps is visible in the 6–11 μm fraction. The negative staircase pattern of all three diagrams, start at about 160 Ma at low temperatures and reach lower ages of 119, 116, 112 Ma at higher temperatures, respectively. This result can be explained by assuming either that the illites were largely rejuvenated when they started to grow or that they recrystallized during the last thermal-deformational event. In the case of late recrystallization one has to assume that the percolating fluid became progressively enriched with excess ^{40}Ar from deeper tectonic levels. This excess ^{40}Ar was then incorporated in the growing illites.

Sample PW-5 is derived from the Zlambach formation of the Pailwand (Fig. 5). Structural field observations indicate that a portion of the fine-grained illites were newly grown in these carbonate-rich marls because they are aligned parallel to a weak slaty cleavage cutting obliquely through the bedding planes of these openly folded rocks. The Ar release spectra from 6–11 to 2–6 μm are almost identical and yielded ages of 163 Ma showing plateau type patterns for 80% of the gas released and detrital muscovite relicts at high temperatures. Contrary to all the other samples, in which only minor and gradual differences between the size fractions were observed, the < 2 μm sample from PW-5 yielded a considerably younger age of 141 Ma, and an even younger one of (111 Ma) from the rim. Comparison of the three size fractions strongly suggests that the coarser illites are detrital and that incomplete rejuvenation has lowered their ages to 163 Ma. Most probably the plateau at 163 Ma does not represent an independent thermal event. The maximum formation age of the incipient slaty cleavage could be reflected by the < 2 μm fraction, their rim ages coincide with other formation ages. The geochronology of these complex lithologies would need a more systematic study.

Samples PW-2, PW-3 and PW-4 are all derived from a 40 m-section of variegated Hallstatt flaser limestone from the western part of the Pailwand klippe. This part has experienced more intense deformational and thermal overprint than the eastern part. All spectra show some relictic ages at the high temperature end of the diagrams. Although the individual age numbers rarely exceed 200 Ma, they show a sharp contrast with the overall release diagram and are interpreted as, partly rejuvenated, detrital cores in newly grown sericite. PW-2 and PW-4 show a negative staircase pattern with ages at about 114 Ma (125 Ma) in the inner region of the sericites. The negative staircase in PW-2 is best developed in the < 2 µm fraction. These samples reached a uniform and rather large grain size. Original grains of < 2 µm are very scarce and the dated < 2 µm sample presumably contains a large number of mechanical fragments from the outer rim of larger grains. In sample PW-3 no systematic staircases are developed and the release spectra are plateau-like. The calculated age for these steps of 114 ± 1 and 116.4 ± 1 Ma agree with the inner ages from the neighbouring samples.

Data from the Lammer Zone, the Werfen Zone of thrust slices and the Graywacke Zone

A series of additional samples (no < 2 µm fractions) were taken from the area south of Pailwand (Fig. 4). The samples belong to the Werfen Fm. of the Lammer Zone N of Annaberg, the Werfen Fm. of the Werfen Zone of thrust slices at the base of the NCA (Rossner 1972), and the Palaeozoic phyllites of the Graywacke Zone in the vicinity of Filzmoos (Fig. 4).

Samples from N of Annaberg reflect the strong influence of the lithology. A siltstone, rich in detrital micas, shows only partial rejuvenation (total gas age 217 Ma of 2–6 µm fraction), whereas illites of the same grain size from intercalated quartzite have been almost completely reset, presumably because of the higher porosity and permeability in this sand-rich sediment. However, the overall synchroneity in metamorphic overprint with the Pailwand is obvious.

Further S, in the Werfen Zones of thrust slices at the base of the NCA, the metamorphism increases, phyllitic s-planes develop and in fine-grained lithologies detrital grains are obliterated. Samples 136, 138 from the basal (southernmost) parts of the Werfen Schuppenzone yield ages of about 102 Ma. Detrital relicts are subordinate, but some disturbances by excess ^{40}Ar are recognizable. The 2–6 µm fraction of sample 136 shows a small but distinctly negative staircase pattern and the same fraction from sample 138 has a plateau pattern, but is 10 Ma older than the coarser 6–11 µm fraction. Increasing (sample 136) or uniform incorporation (sample 138) of small amounts of excess ^{40}Ar seems the most plausible explanation. From sample 140/1 detrital muscovites were investigated. Due to repeated grinding during separation, the 0.2–0.3 mm size represents mainly the cores from the original grains of 1–2 mm size. They have more or less preserved the plateau age information from their Variscan source area. The smaller fraction (0.1–0.2 mm) contains more material from the rims of the large grains and shows already a uniform lowering of the plateau-type age pattern by 10 Ma and a stronger rejuvenation at low-temperature steps.

Two samples, 132/1, 132/2, were investigated from Palaeozoic phyllites from the Graywacke Zone. They differ from the prograde Werfen Formation in lithology and polyphase deformation. Uniform ages from both grain-size fractions were obtained, 98 and 94 Ma, respectively. These lithologies seem to be fully rejuvenated in the Ar system, as their plateau patterns do not show any relicts of Variscan metamorphism.

In general the data reflect a younging of geochronological data over a time span of 20–25 Ma, associated with the gradual increase of metamorphism from N to S and from shallower to deeper structural levels in this section of the southern NCA. There is a gradual younging and continuous transition from the older group of formation ages at higher structural levels with their preserved discordant age patterns to well equilibrated cooling ages. Here the transition from formation ages to cooling ages is estimated at 90–95 Ma.

Ar/Ar ages of 91–100 Ma on fine fractions were obtained by Urbanek et al. (2002) from the basal part of the Graywacke Zone near Taxenbach in the Salzach valley. The rocks were well-recrystallized low-grade phyllites and the dates were interpreted as mid-Cretaceous cooling ages. They coincide with the same time span of white mica K/Ar cooling ages from the front of the Austro-alpine Crystalline in the Wölz micaschists (Hejl 1984), located some 30 km south-east of the area investigated here.

Evaluation of geochronological information

Excess ^{40}Ar in the Pailwand area

The Pailwand samples PW-1 to PW-5 are especially important because their strongly discordant age patterns clearly indicate that even in grains of a few microns, no homogenization of Ar took place; hence, the blocking temperature for illite/sericite was definitely not reached. The uniform age from the core can therefore be considered a maximum age of formation. All samples of this type, i.e. with negative staircases, yielded similar Early-Cretaceous ages from the inner portion of the grains, clearly indicating that illite growth did not start before Aptian to Albian time.

The negative (older at rims) staircase patterns may be a disturbing feature at first glance. Under normal conditions of prograde metamorphism, illite/sericites develop positive staircase patterns reflecting the time range of growth from the older core to the younger rim.

A reverse age pattern requires a special interpretation. Two alternatives are possible: (1) progressive incorporation of excess ^{40}Ar and (2) ^{39}Ar recoil effect. The artificial ^{39}Ar recoil effect is caused by ^{39}Ar loss during irradiation and is normally observed on very small grains and/or poor electrochemical saturation in the mineral lattice. When the ^{39}Ar recoil has a large influence, then the total gas age of the Ar/Ar method (older) and the K/Ar age (younger) from the same sample differ considerably. In the case of the Pailwand flaser limestone, however, Kralik and Schramm (1994) reported the same (Jurassic/earliest Cretaceous) K/Ar age from <2 μm fraction as the calculated total gas age from the same grain size in our Ar/Ar measurement. This strongly suggests that the negative staircase is a real feature and not a recoil effect that developed during the irradiation. This view is supported by the following consideration. The samples PW2, PW3 and PW4 are the only ones from the Pailwand area in which clearly individualized metamorphic sericites with an average grain size of 10–20 μm with thickness of 1–4 μm developed, whereas in all other samples the rejuvenated or newly grown phyllosilicates are much smaller. ^{39}Ar recoil effect is unlikely in such well crystallized samples. We therefore interpret the negative staircase pattern as a result of progressive incorporation of excess ^{40}Ar during growth history. Another argument for the presence of excess Ar is the highly variable total gas ages. Even within short distances, differences of 152–118 Ma are observed, even though the age information from the core is uniform and their overall variation does not exceed 12 Ma. Such local variation is not uncommon when excess Ar is involved in zones of very localized fluid transport and high strain.

Regional significance of the new dates indicating a Cretaceous age of metamorphism

The results presented here indicate that the last main deformation and metamorphic overprint in the Pailwand area took place in late Early Cretaceous (112–116 Ma). The very specific distribution of ^{40}Ar in the illites/sericites of the Pailwand clearly indicates that this event cannot have started before 110–115 Ma. This can be deduced from the very specific distribution pattern of ^{40}Ar in the illites/sericites of the Pailwand. These patterns virtually exclude the possibility that the Cretaceous ages are caused by thermal overprinting and rejuvenation of a Jurassic metamorphic event. The Cretaceous metamorphism is obviously related to the main compressional event that emplaced the Pailwand klippe and similar tectonic units in their final position. The better resolution of the ^{39}Ar/^{40}Ar method reveals that in the K/Ar analyses of Kralik et al. (1987a, b) are analytically correct, but the true formation ages have been masked by excess Ar and to a minor degree by older relicts. This is especially true for the sericites from the western Pailwand.

The Werfen formation, rich in detrital Variscan white micas and illites, is the most probable source of the excess ^{40}Ar. The large volume of slates in the Graywacke zone may have been an additional source. As demonstrated in chapter 2.3, these units and lithologies have been nearly completely equilibrated during the Cretaceous metamorphic event. It is very likely that during the regional Cretaceous metamorphism large amounts of radiogenic ^{40}Ar were released and transported upward by fluids. Their effect on the Ar signatures in the overlying Triassic rocks must have been quite considerable as a look at rock volumes shows. Most of the metamorphosed Triassic limestones, marls and argillaceous intercalations have stratigraphic and later tectonic position, which were only a few 100 m above this source of excess ^{40}Ar. Only a few percent of the percolating radiogenic ^{40}Ar, trapped in the comparably much smaller volume of illite/sericites in Triassic rocks, would be sufficient to explain the observed anomalous age patterns.

As spectra with excess ^{40}Ar seem to be common in the investigated area, another consideration merits mention. Excess ^{40}Ar is normally absent in sedimentary basins with only thermal overprint. Purely thermal overprinting seems to produce highly variable rejuvenation, strongly dependent on lithology and the detrital/sedimentary/diagenetic ratio of illites (Weaver 1984; Hunziker 1987). Obviously, the escape of Ar to the surface is more efficient than the resetting by thermally driven crystallization. The situation is drastically different in synmetamorphic nappe stacking regimes. There excess ^{40}Ar can play a major role at certain levels, especially in the basal parts of nappe systems that cool quickly but may be rich in excess Ar released by the prograde metamorphism in the overridden unit. Biotite is especially prone to incorporating excess Ar. In such tectonically disturbed thermal environments incorporation of excess ^{40}Ar from the fluids, rapid adjustment to new conditions and swift cooling are more likely. We postulate such a scenario for the Cretaceous in the Eastern Alps. In the investigated area metamorphic temperatures range from anchizonal stages to beginning greenschist facies, offering ideal conditions for preservation of disequilibria in fine grained illites or white micas.

Cretaceous age of glaucophane formation from Bad Ischl

Gawlick and Höpfner (1996) found a high phengite content in sericites from the Hallstatt flaser limestone at the Pailwand klippe and therefore postulated their formation under low-temperature/high-pressure conditions. Our data show that the phengites are late Early Cretaceous and not Late Jurassic in age. Kirchner (1980) already reported unquestionable high-pressure minerals from the NCA, namely glaucophane from Bad Ischl at the northern front of the Dachstein nappe. Glaucophane occurs in metabasic rocks that form clasts and slivers in the Haselgebirge, a mylonitised evaporite sequence. Their mineralogical composition was recently re-examined by Vozarova et al. (1999). It was found that the glaucophanes have a composition similar to glaucophanes from the blueschists in the W-Carpathians. Furthermore, Vozarova et al. (1999) reported that magmatic pyroxenes in these rocks often show overgrowing rims of Na-pyroxenes with high pressure (7–8 kb) characteristics. These glaucophanes from Bad Ischl yielded K/Ar ages of 108 and 118 Ma (Kirchner 1980). Na-amphiboles normally have very low K-contents and small amounts of excess ^{40}Ar can already cause erroneously high ages of metamorphism. The dates derived from Ischl should therefore be considered maximum ages. They indicate late Early to mid-Cretaceous high-pressure metamorphism in the NCA, presumably during the formation of the nappe stack. The geometry of the subduction process and mode of emplacement of the high-pressure slivers in their present surrounding still needs further study.

Evidence for Jurassic metamorphism in the NCA

Well-defined Jurassic very low-grade metamorphism in the NCA was reported by SPÖTL et al. (1998, 1999). They dated authigenic K-feldspars, mainly in Permian carbonates from basal parts of the NCA. In the northern parts of the Juvavic units where the Cretaceous low metamorphic overprint is not documented, rather consistent $^{39}Ar/^{40}Ar$ and Rb/Sr ages at about 145 Ma were found and represent clear evidence for Late Jurassic crystallization. The maximum burial temperatures within the Haselgebirge of the northern Juvavic nappes were estimated at 200–250°C (Spötl et al. 1998, p118). They concluded that carbonate alteration and feldspar growth predates and partly overlapped with the (first) formation of the saline Haselgebirge tectonic melange. The authors linked the brine–rock interaction within the basal parts of the NCA with shortening of the Hallstatt realm and proposed a hydrothermal fluid front that entered the basal parts of the NCA. Such a scenario would be well compatible with the transpressional strike-slip system proposed here.

Similar conclusions were reached earlier by Kralik et al. (1987a, b) and Kralik and Schramm (1994). Based on a systematic combination of K/Ar and Rb/Sr data these authors argued that in the southern NCA along the Salzach section geologically meaningful crystallization ages in fine fractions are earliest Cretaceous and younger. The results have added significance because of the use of several techniques and broad regional coverage. However, the $^{39}Ar/^{40}Ar$ data presented here provide better resolution and demonstrate that excess ^{40}Ar (partly also preserved detrital relicts) can cause variable and too high ages in the K/Ar system. Thus the ages reported by Kralik et al. should be considered the maximum estimates.

The significance of the new age dates in the context of East-Alpine tectonics

The new age data from highly deformed Hallstatt flaser limestone of the Pailwand klippe indicate metamorphism that is coeval with the onset of eo-alpine high pressure metamorphism in the Saualpe and Koralpe situated SE of the Tauern Window. In this area, Miller and Thöni (1997), and Thöni (1999, 2002a, b) were able to place eclogite formation and subsequent high-temperature exhumation into the time range 115–90 Ma by using Sm/Nd dating of garnets.

These age dates are critical for the question of transpression versus subduction in the NCA during Late Jurassic times and need to be evaluated here. In particular, we need to consider the possibility that a Jurassic high-pressure event in the crystalline units may have been overprinted and masked by subsequent Cretaceous events. At the time when the eo-alpine age of the eclogites in the Sau and Koralpe was first discovered, the first preliminary geochronological data indicated a Jurassic age (Frank 1987, p. 402). However, the large number of precise data presently available (Thöni 2002a, b) leaves no doubt about the Cretaceous age and narrow timing (115–90 Ma) of this eclogite formation. Several eclogite bodies are very well preserved. If they had been formed in the Late Jurassic and only been incorporated into a continually deforming crust during the Cretaceous, these sensitive mineral paragenesis would have had to be stored outside their stability field under high temperatures and wet conditions for tens of millions of years without severe alteration and retrogression. We consider this an unrealistic scenario. Similarly, the assumption of continuous subduction from Late Jurassic to Early Cretaceous times is unlikely, considering the sedimentary record in the Eastern Alps. This time span is characterized by widespread and nearly uniform deposition of pelagic carbonate sediments (Aptychus Limestone, Majolica). Facies and age of this pelagic sediment cover are nearly identical with the formations of the Penninic domain of the western Alps and the Blake-Bahama Fm. of the central North Atlantic (Bernoulli 1972; Jansa et al. 1979). However, it is obvious that strong tectonic disturbance in the south-eastern part of NCA was active from the widespread carbonate clastics and sedimentation was limited and partly lacking here.

It is therefore concluded that the new results of the Pailwand area indicate that tectono-metamorphic events in the southern part of the NCA that occurred at shallow levels and under low-temperature conditions are synchronous with events in the deep crust under high-pressure amphibolite conditions. These deep crustal events indicate continental subduction, intense penetrative deformation and northwest- to north-vergent crustal shortening. Frank (1987) tentatively interpreted this polymetamorphic crystalline domain with the former highly attenuated basement of the Triassic Hallstatt realm of the NCA. Meanwhile, this speculative idea has been corroborated in two ways. Firstly, Permian gabbros and roughly coeval metabasites forming intercalations in the pre-alpine basement of the Sau- and Koralpe have been found (Thöni and Jagoutz 1993; Miller and Thöni 1997). Secondly, widespread prograde Permian low-pressure metamorphism in the same area was dated with the Sm/Nd method (Schuster and Thöni 1996; Schuster et al. 2001; Habler and Thöni 2001) and numerous pegmatites were formed during this Permian event. This crystalline basement characterized by intense Permian metamorphic overprint can be interpreted as a remnant of highly attenuated continental crust that bordered the Tethyan oceanic realm in the Triassic (Bertotti et al 1996; Schuster et al 2001). The eo-alpine deformation and crustal shortening were extremely severe in those basement units. Several eclogites in the Saualpe and Koralpe are enveloped by micaschists that only show eo-alpine metamorphism. These monometamorphic series may represent a part of the sedimentary cover of the attenuated continental crust (Thöni 2002a, b).

The age dates from the NCA discussed above clearly indicate a dominant tectono-metamorphic event during the Cretaceous (Aptian to Cenomanian) rather than Jurassic, in the NCA. Furthermore, the available geochronologic dates from the crystalline domain argue for coeval Cretaceous metamorphism. It is typical that the geochronologic information from the medium to high temperature basement is somewhat younger (clustering mainly at 90 Ma) because they represent decompression and cooling ages compared with the somewhat older ages (maximum between 113 and 120 Ma) in the sedimentary cover units related to incipient metamorphic formation ages. Viewed together, the chronologic and petrographic data suggest a close genetic relationship between mid-Cretaceous closure of the western Tethys, represented by the records in the Saualpe and Koralpe, and the intra-Cretaceous (pre-Gosau) tectonics in the NCA.

Our view is at variance with the concept of a subduction regime in the Eastern Alps during Late Jurassic, proposed by Gawlick et al. (1999), Frisch and Gawlick (2001, 2003). These authors attribute the main thin-skinned tectonic event in the NCA to the Late Jurassic tectonics and assume that later events had only limited effects. The new field data clearly indicate that the Pailwand klippe was metamorphosed, transported and emplaced during the mid-Cretaceous. Furthermore, the available age dates from the NCA and the Saualpe and Koralpe strongly suggest that this Cretaceous tectonic process was the main tectonic event in the Austro-alpine unit, responsible for nappe stacking, generation of orogenic sediments, progressive decoupling and later final detachment of the whole NCA from their basement (see also Schmid et al. 2004).

In the next chapter, we argue that the assumption of Late Jurassic transpression in the NCA rather than a subduction scenario is also more compatible with the sedimentary record.

Strike-slip tectonics: an alternative to a subduction scenario for the Eastern Alps during the Jurassic

Sediment record

There is a general agreement that, except for southernmost regions, marine conditions with rather continuous sedimentation prevailed in the area of the NCA from Early Triassic through mid-Cretaceous. The sediment record is, therefore, an important source of information with regard to the subduction and strike-slip scenarios of Jurassic deformation. Jurassic strike-slip faulting has been repeatedly postulated for the Austro-alpine domain and we argue that the sediment record provides strong, albeit circumstantial, evidence for Jurassic strike-slip deformation.

The following evaluation concentrates on the Late Jurassic sediment record, sometimes tacitly including of the youngest part of the Middle Jurassic. We want to exclude the Early Jurassic and most of the Middle Jurassic from our speculations because their deformation pattern may well have been different. Recent work in the Swiss Alps indicates that Early and Mid-Jurassic deformation of the western extremities of the Austroalpine domain consisted of nearly orthogonal rifts with deep cutting listric faults that partly exposed subcontinental mantle at the sea floor (Manatschal and Bernoulli 1999; Schaltegger et al. 2002). The evidence for strike-slip deformation of the adjacent Penninic domain is essentially Late Jurassic (e.g. Schmid et al. 1990, 1997). It coincides with the first phase of sea-floor spreading in the central North Atlantic and the Ligurian-Penninic Ocean. A similar succession of phases of deformation may have existed in the NCA. For a modern example of change from extension to transpression one may turn to the Gulf of California where Miocene orthogonal rifting was overprinted by strike-slip dominated movements about 6 Ma ago when the plate boundary jumped to its present position in the Gulf (Umhoefer et al. 2002).

In the NCA, Fischer (1965) was the first to postulate a zone of Jurassic strike-slip motions. The dismembering of the Triassic reef belt at the south-eastern margin of the Dachsteinkalk platform led Fischer to infer a sinistral displacement of several tens of kilometres in the Lammerzone. In his reconstruction, Fischer (1965) viewed the reefs of the Gosaukamm and the Hohe Göll as two segments of a continuous barrier reef. This model is sedimentologically plausible and has been further strengthened by the discovery of a third reef segment, the Gollinger Schwarzenberg, between the Göll and the Gosaukamm (Plöchinger 1990; Gawlick et al. 1999).

Jurassic faulting, folding and thrusting are also indicated by the Jurassic deep-water sediments in the middle segment of the NCA between the Rofan Mountains in the west and the Totengebirge in the east. The sediments show rapid lateral changes in thickness and facies of deepwater deposits. Slumps and sediment gravity flows are abundant and the clasts indicate stratigraphic reworking down to the evaporite levels of the Late Permian (Garrison and Fischer 1969; Schlager and Schlager 1973; Diersche 1980; Wächter 1987; Gawlick 1996; Gawlick and Diersche 2000). Steeply dipping faults sealed by Jurassic deep-water sediments have been observed or reconstructed locally from field evidence (Braun 1998, p.76). Finally, a strong case has been made for Jurassic thrusting along low-angle shear planes (Mandl 1982; Lein 1987; Tollmann 1987; Gawlick 1996). The thrusts in particular are being cited as support for the subduction hypothesis (Gawlick et al. 1999; Frisch and Gawlick 2001). However, the preserved Jurassic thrust slices of the NCA are small. Their demonstrable displacement rarely exceeds 10 km, an order of magnitude less than the distance from trench to magmatic arc in extant subduction systems. Low-angle thrusting over distances of several kilometres, and this is what can be demonstrated for the Jurassic of the Northern Alps, are commonly found in the restraining bends of strike-slip faults where basement is involved (see Fig. 9 and Steel et al. 1985 for well-documented examples). Much greater distances of thrusting have been observed where thin-skinned tectonics prevails along strike-slip zones, e.g. Sanz de Galdeano 1983; De Smet 1984a, b. In our opinion, the patterns of Jurassic deformation in the NCA are perfectly compatible with strike-slip tectonics. In fact, the record of the sediment cover is better explained by the latter model than by the subduction hypothesis.

Distant effects of Jurassic obduction could be another reason for the observed Jurassic tectonics at the south-eastern NCA. This idea was mentioned to us by S. Schmid (Basel). One should bear in mind that such a process, combined with overstepping latest Jurassic carbonates is widely observed in the Dinarides and also in the Apuseni mountains. However, from several arguments discussed here, we prefer the interpretation that strike-slip tectonics had a major influence.

As regards thrust phenomena, the studies of De Smet (1984a, b) on the Miocene Crevillente Fault of the Betic Cordillera are particularly relevant for the present discussion (Fig. 10). The Betic Cordillera has been an Alpine domain dominated by lateral shear for much of its Mesozoic and Cenozoic history. Amount, direction and timing of the large-scale displacement are well constrained by the spreading history of the adjacent North Atlantic. Shear along the Crevillente Fault was dextral with displacement of several hundred kilometres. Gravity sliding from flower structures produced numerous tectonic klippen on both sides of the main fault. There is a continuous spectrum of clast size from sand to mountain-size klippen bounded by subhorizontal shear zones in evaporites.

Insights from detrital material Clasts in the Jurassic breccias under consideration are almost exclusively limestones and dolomites. These lithologies fragment easily, particularly if the formations contain interbeds of clay-rich lithologies that lithify more slowly than the carbonates during burial diagenesis. Under these circumstances, large volumes of fragmented debris can be generated by submarine landslides on tectonically oversteepened slopes. Here again, a transpressive regime with flower structures and steep pull-apart basins can create oversteepened slopes just as well as a compressive regime with thrust sheets. An important difference lies in the trends of grain size and bed thickness. Clastic deposits in a migrating foredeep in front of a thrust sheet tend to become coarser and beds thicker upward; at the top, sedimentation is terminated by the emplacement of the thrust sheet. Sediments in transpressive settings frequently show alternating coarsening and fining intervals because source areas, transport routes and depocentres shift more irregularly during strike-slip faulting (e.g. Steel and Gloppen 1980; Cemen et al. 1985). The Jurassic Tauglboden and Strubberg formations on the one hand and the type locality of Neocomian Rossfeld formation on the other illustrate this difference. The Rossfeld Fm. is a coarsening-upward succession, compatible with sedimentation in a migrating foredeep in front of a nappe; indeed, accumulation of the Rossfeld Fm. at the type locality ends with the arrival of the Ju-

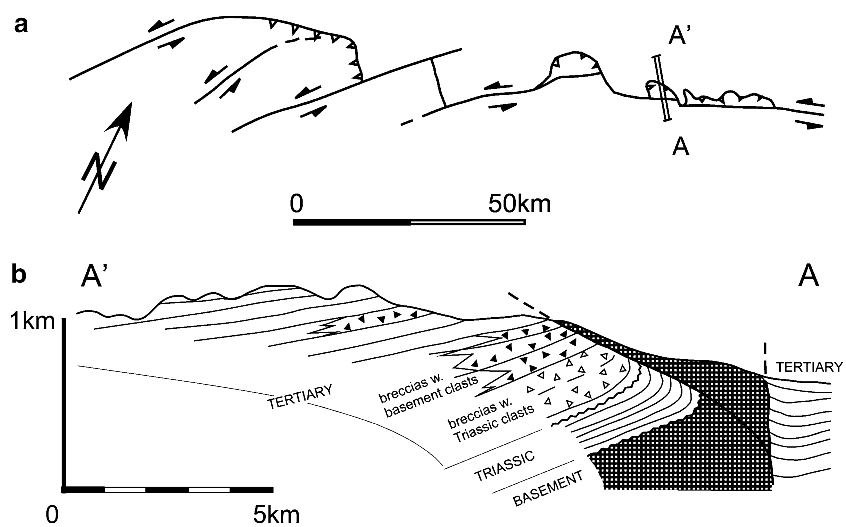

Fig. 9 Thrust slices produced by strike-slip faults in the Catalan Coastal Range, Spain. After Anadon et al. (1985). **a** Overview of the Tertiary fault system separating the Ebro Basin from the Catalan Coastal Range. Strike-slip faults dominate but low-angle thrusts are common, pointing outward from the main fault zone. **b** Cross section of Les Pendrexites slice, a body of Hercynian basement thrust outward from the strike-slip fault zone. Basal thrust plane dips about 6.5° (profile shows 4× vertical exaggeration). Breccias in adjacent basin record stepwise exhumation of basement

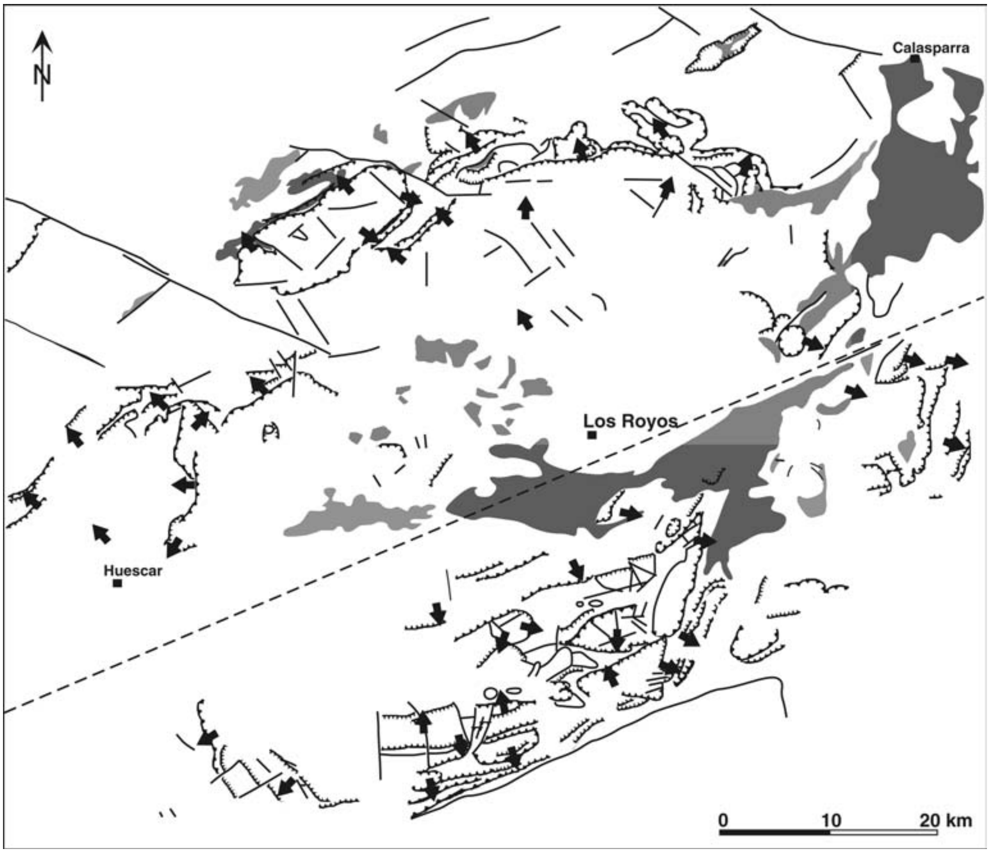

Fig. 10 Map view of a 100 km-segment of the Crevillente Fault in the Betic Cordillera, Spain. After De Smet (1984b), strongly simplified. *Gray*, Late Triassic red beds and gypsum with tectonic slivers of younger rocks. *Blank*, Jurassic, Cretaceous and Cenozoic sedimentary rocks. *Dented lines*, overthrusts; *black lines*, all other tectonic contacts. *Bold arrows*, vergence indicated by folds and thrusts. *Dashed line*, approximate axis of symmetry separating a zone of NW-vergent deformation in the *upper left* from a zone of SE-vergent deformation in the *lower right*. Note that in both areas thrust slices and tectonic klippen develop that commonly reach tens of kilometers in diameter. The central fault zone is marked by a melange of Late-Triassic red beds and evaporites with components of Jurassic-Cretaceous limestones. The Crevillente Fault was a zone of compression and dextral shear during most of the Tertiary, possibly also in the Late Cretaceous

vavic thrust sheets (Decker et al. 1987; Braun 1998, p 61). In the Tauglboden and Strubberg formations no overall coarsening trend has been observed. Rather, coarsening and fining trends alternate several times in each formation (Gawlick and Diersche 2000).

The subduction and strike-slip models of deformation also differ with regard to the direction of sediment-gravity transport and vergence of deformation structures. In a subduction system the accretionary complex has the shape of a wedge and the first-order dip of the wedge surface is towards the trench (e.g. Platt 1986). Sediment gravity flows, slumps and slides follow this gradient and most longitudinal transport is restricted to turbidity currents travelling in the trench and to a lesser extent in trench-slope basins (e.g. Underwood and Moore 1995). The topography of strike-slip systems normally lacks a comparable first-order trend. Topographic highs and lows alternate both parallel to and across the strike of the fault zone. Sediment transport responds to these local gradients. The resulting patterns of transport directions and facies are, therefore, more irregular than in subduction systems (e.g. Nilsen and McLaughlin 1985). Furthermore, there is a strong tendency towards bi-directional transport away from the compressional segments of the fault.

In the Jurassic of the NCA data on transport directions of sediment gravity flows and slumps are few and areally limited. However, what has been reported fits better with the high-variability patterns of strike-slip zones than with the concept of an accretionary wedge. Locally variable or opposing transport directions have been reported from the Jurassic basin of the Hallstatt Zone of Bad Ischl-Aussee. This basin received material of Triassic Hallstatt Facies from the south and material of Triassic Dachsteinkalk Facies and its Liassic cover from the north; the corresponding breccia tongues wedge out in opposite directions (Mandl 1982; Schäffer and Steiger 1986; Tollmann 1987). In the Unken syncline, the breccias of the Ruhpolding Fm (Oxfordian-Kimmeridgian) show variable transport directions in response to relief and the gravity flows of the Tithonian Oberalm Fm. of the Unken syncline show competing northward and southward transport (Wächter 1987, p 25, 138).

The most recent data by Frisch and Gawlick (2003) about the onset of wildflysch deposition in the Jurassic basins illustrate the variability with regard to the shifting depocentres. Wildflysch deposition starts during the Callovian with the Lammer Basin in the south, shifts northward to the Tauglboden Basin during the Oxfordian and jumps back southward to the Sillenkopf Basin in the Kimmeridgian. Thus, the shifting depocentres, as presently known, lack the steady northward shift originally cited by Gawlick et al. (1999) and Frisch and Gawlick (2001) as an argument for a prograding accretion wedge.

Finally, the composition of the detrital material merits mention. The vast majority is derived from the immediately preceding stratigraphic formations whereby clast abundance decreases crudely with increasing age of the debris. The oldest significant contributions are from the Permo-Triassic red beds at the base of the Alpine sedimentary cycle of the NCA (Schlager and Schlager 1973; Gawlick 1996; Braun 1998; Gawlick and Diersche 2000). Acidic crystalline basement material is very rare (Missoni et al. 2001). Again, these patterns indicate nearby sediment sources created by local tectonics—well compatible with a strike-slip scenario. The situation contrasts sharply with the Early Cretaceous Rossfeld event where local debris is mixed with significant amounts of siliciclastic and ophiolitic (!) material, indicating both local and distant source areas with continental and oceanic basement (Decker et al. 1987; Faupl and Wagreich 2000).

In a series of papers, H.J. Gawlick and collaborators have carefully documented ages and facies of the components in the Strubberg, Tauglboden and Sillenkopf Basins and reconstructed the stratigraphic successions in the source areas (e.g. Gawlick 1996, 2000; Gawlick et al. 1999; Gawlick and Diersche 2000; Missoni et al. 2001; Gawlick and Frisch 2003). The Tauglboden Basin has a local source of Late Triassic and Jurassic rocks few kilometres to the south. The Sillenkopf Basin is supplied by Jurassic, Triassic and basement material, probably from the south. For the Lammer Basin, it is shown that the material is mainly Middle and Late Triassic in age. The facies varies. Most common are various deep-water sediments, corresponding to the basinal Hallstatt successions, but at least one large slide represents reefal platform facies. Gawlick et al. (1999) and Gawlick and Frisch (2003) propose that during deposition of the Strubberg formation the source area has shifted from deep oceanic environments (Meliata Facies) to outer shelf (red Hallstatt limestones) to middle shelf (grey Hallstatt facies) and finally to reef-rimmed platforms. The changing source, so the argument, indicates the progressive destruction of the Austro-alpine continental margin by subduction processes. We do not see how this conclusion can be derived from the published data. First, no quantitative data on composition are provided. Second, the qualitative description of the Strubberg Fm. shows an irregular succession of intervals rich in clasts of red Hallstatt Limestones, intervals rich in grey cherty limestones and marls, and occasional levels rich in Permo-Scythian red beds (e.g. Gawlick and Diersche 2000). Reefal platform facies is essentially represented by one mountain-size klippe and Gawlick and Diersche (2000, p.118) indicate that breccia sedimentation continues with Hallstatt clasts after deposition of the mountain-size klippe of reef limestone.

Crystalline basement

In principle, one might expect large strike-slip structures of the kind proposed here should also be recognizable in the crystalline basement that originally underlay the NCA. Unfortunately, the Austro-alpine crystalline east of the Tauern window was so severely deformed and metamorphosed during Cretaceous that there is almost no chance of recognizing such structures in their original position, or of reliable dating their first deformation. However, there can be no doubt that the Bundschuh crystalline with its original sedimentary cover, the Stangalm Mesozoic, is an exotic element within its surroundings. It is presently sandwiched between the Wölz micaschists below and the Palaeozoic Gurktal nappe above and it pinches out eastwards. Wölz micaschists and Bundschuh crystalline show contrasting lithologies and metamorphic histories. The Wölz micaschists are dominated by a prograde Cretaceous metamorphism with relicts of Permian metamorphism, whereas Variscan metamorphic relicts generally are absent. The Bundschuh crystalline complex, in contrast, is dominated by Variscan metamorphism with a greenschist facies Cretaceous overprint. The sharp contrast between Wölz and Bundschuh units excludes a close juxtaposition of the two units in Permotriassic times. As the Bundschuh unit shows strong lithologic affinities with the Ötztal-type basement, Schuster and Frank (2000) postulated a left lateral strike-slip movement in order to bring this element in its present position. It is assumed that the steeply dipping strike-slip structures were subsequently transformed into low angle Cretaceous thrusts.

Correlation of paleogeographic domains between Eastern Alps and Western Carpathians

A now widely accepted view about the palaeogeography and arrangement of crustal blocks of the western Tethys in the Late Triassic was proposed by Haas et al. (1995), and Haas (2001, p.22). The model assumes that the Tethyan ocean closed westwards in the form of a large gulf with broad shelves and facies zones that curved around smoothly from the European to the Apulian and African margin. This arrangement is based on the well-constrained configuration of large continental masses and implies that the Tethyan ocean widened rapidly eastwards. At present the views of the detailed plate tectonic settings and palaeogeographic rearrangements of this area are still controversial (Cavazza et al. 2004; Csontos 2004). However, general agreement exists about the close juxtaposition of Eastern Alps and Western-Carpathians because they show a continuous facies arrangement with some gradual lateral changes and very similar tectonic evolution. In spite of the many similarities between the Alps and Western Carpathians, rather different concepts were proposed for the transition of the European craton to the Tethyan ocean during the Triassic.

In the Eastern Alps, the Permo-Triassic sediments have been convincingly interpreted as parts of a divergent margin of Tethys. Sediment facies show, from old to young and from continent to ocean, a decrease of terrigenous influx and increase of open-marine carbonate deposits. Persistent oceanward increase in thickness of shelf and coastal plain deposits indicates seaward increase of subsidence (e.g. Oxburgh 1974; Laubscher and Bernoulli 1977). Trends in facies and thickness persist across the boundaries of the future Penninic, Lower Austro-alpine and Upper Austro-alpine domains and they are also clearly recognizable in the Upper Austro-alpine successions of the NCA. In the NCA, the belt of shallow-water carbonate platforms ends in reef margins with lobes and embayments, possibly also isolated atolls. There is no indication that the basins between these platforms reached oceanic, i.e. abyssal, depths (Mandl 2000, Fig. 4).

In the W-Carpathians, the facies gradation is similar and comprises, from N to S, the Tatric, Fatric, Hronic and Gemeric units. Between the Gemeric unit and the tectonically highest Silica unit, which is comparable in facies to the Juvavic nappes of the NCA, the remnants of the Meliata oceanic domain were squeezed out (Mello et al. 1996, 1997, 1998; Plasienka 1998; Rakus et al. 1998). The environment of the Meliata zone can best be characterized as a Jurassic accretionary wedge, with a matrix of graphitic argillaceous sediments and slivers of Triassic oceanic crust and its sedimentary cover. Another element in this nappe stack is the Borka unit, a tectonic melange containing slivers with low-temperature/high-pressure metamorphism of Late Jurassic age (Dallmeyer et al. 1993; Dal Piaz et al. 1995; Faryad 1995; Faryad et al. 1996; 1997; Maluski 1993; Mazzoli and Vozarova 1998).

Similarities of facies and stratigraphy strongly suggest that the Silica units were an extension of the Juvavic units of the NCA. This is further corroborated by the occurrence of small remnants of Meliata rocks at the eastern end of the Eastern Alps (Mandl and Ondrejickova 1991; Kozur and Mostler 1992; Neubauer et al. 1999). This westernmost outcrop of Meliata rocks has the same tectonic position as in the W-Carpathians: it is underlain by the Graywacke Zone and its thin autochthonous Triassic cover and overlain by the Juvavic Mürzalpen nappe (Mandl 2000).

Palinspastic reconstructions of the Carpathians lead to discrepancies with respect to the Silica and Meliata units: facies and stratigraphy of the Silica unit indicate that it forms the most oceanward part of the European continental margin, analogous to the Juvavic unit of the NCA. Tectonic superposition, on the other hand, suggests that the Silica unit was separated from the European margin by the Meliata Ocean. Various solutions have been proposed, all based on the principle of orthogonal backstripping assuming contraction perpendicular to the strike of the orogen. Haas (2001, Fig. 107) attached much weight to facies affinities and consequently placed Silica at the southern part of the European margin. The present position in the nappe stack is explained by assuming that the Silica unit first slid southwards into the Meliata basin and was subsequently thrust northward. Plasienka (1998) gave priority to the tectonic position and assumed that the Silica domain formed a high-rising block south of the Meliata Ocean. Schweigl and Neubauer (1997), and Neubauer et al. (2000, p.126) assumed that the Meliata ocean extended into the Austro-alpine domain and dissected the divergent margin of the Eastern Alps, separating the Juvavic nappe of the NCA from the other Austro-alpine units. This solution honours the tectonic superposition in the Carpathian nappe stack and the affinities between Silica and Juvavic nappes but leads to a rather unsatisfactory Triassic facies distribution in the NCA. An important argument in this respect is the occurrence of Carnian Lunz beds in the Tournaicum, which forms a minor part of the Silica units (Mello et al. 1997). The clastics of the Lunz beds were derived from a northerly source and could therefore have not been deposited south of the Meliatic oceanic trough.

Jurassic strike-slip deformation of the entire region may offer solutions where models of orthogonal contraction have gotten bogged down in controversy. For instance, continuation of the proposed left-lateral movement during Late Jurassic at the western end of the Juvavic realm would be a rather simple solution for the palaeogeographic puzzle outlined above. This sinistral movement would interact with the complex processes that separated the Austro-alpine—Western Carpathian realm from the neighbouring Tisia crustal block during mid-Jurassic times and fragmented Tisia from stable Europe in late Jurassic (Csontos and Vörös 2004, Fig. 23).

Conclusions

- New $^{40}Ar/^{39}Ar$ data from the NCA do not support the notion of a distinct Jurassic metamorphic imprint indicative of Late Jurassic subduction in the Eastern Alps. The new dates from the Pailwand, particularly from the outcrop for which high-pressure phengites have been postulated, indicate maximum formation ages of 113–120 Ma (Early Cretaceous). Most samples from fine fraction in carbonate rocks show increasing amounts of excess ^{40}Ar in the low-temperature steps. The dates prove the validity of earlier K/Ar dates, but the geologically relevant age information is masked by excess Ar and relictic detrital domains. The ages become younger in southern and structurally deeper levels where well-equilibrated plateau-type age patterns of illite/sericite of 90–95 Ma were measured.
- Both units of the Pailwand klippe were metamorphosed and amalgamated S of the Tennengebirge at the Aptian–Albian boundary and later emplaced in the Lammer Zone.
- The Late Jurassic record of sedimentation and deformation in the NCA includes faulting, thrusting, rapid shift of depocentres and deposition dominated by sediment gravity transport. These features are not

diagnostic for the setting of a subduction zone with an accretionary wedge. They are perfectly compatible with a depositional domain dissected by major strike-slip faults. The Late Jurassic formations of the central NCA lack an overall trend of upward increasing grain size and are virtually devoid of exotic material, i.e. material other than the Permo-Mesozoic of the NCA. Both characteristics argue against deposition at the accretionary wedge of a subduction zone and for the alternative model of strike-slip deformation.

– The new data from the NCA provide a strong argument for the equivalence in time between the lower and mid-Cretaceous nappe stack in the sedimentary cover (NCA) and the intense Cretaceous deformation, eclogite formation and decompression in the Austroalpine crystalline. The very specific evolution history of the Sau-Koralm crystalline is a strong argument that it was once the strongly attenuated crustal basement for the rootless Juvavic–Hallstatt nappes of the NCA.
– An Upper Jurassic sinistral strike-slip regime is proposed from regional considerations in the Eastern Alps. A plausible consequence would be the eastward displacement of the Silica, Aggtelek, Rudabanya units (Juvavic counterparts) in the Inner West Carpathians of southern Slovakia and northern Hungary.

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