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Origin and tectonic evolution of the Eastern Alps deduced from dating of detrital white mica: a review

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Abstract

Results of dating of detrital white mica using the conventional K-Ar, conventional $^{40}Ar/^{39}Ar$ multi-grain and laser-probe $^{40}Ar/^{39}Ar$ multi-grain and single-grain methods contribute significantly to the unraveling of the palaeogeographic origin and tectonic evolution of the Eastern Alps since Late Ordovician times. Dating of Upper Ordovician and Silurian successions of Austroalpine and Southalpine domains consistently demonstrate a Panafrican/Cadomian source of these successions, and therefore an origin along northern margins of Gondwana. The source region significantly changed in Lower to lowermost Upper Carboniferous Variscan flysch successions when Gondwana collided with Laurussia. The Lower Carboniferous flysch mostly contains Devonian detritus from units, which are largely unknown in the present erosional level of the Eastern Alps. In contrast, Upper Carboniferous molasse, and Permian and Triassic rift and shelf successions nearly exclusively contain Variscan detritus of Carboniferous age. These Carboniferous ages of the molasse indicate that upper crustal levels with pre-Variscan age signatures have been largely removed prior to molasse deposition.

Beside dominant Variscan and Permian ages, subordinate Early-Middle Jurassic ages of detrital white mica within the Florianikogel Formation, a Middle Jurassic flysch succession originating within the Meliata ocean, support the idea that the Meliata oceanic seaway underwent Jurassic subduction. In contrast, only Variscan respectively Permian ages have been found up to now in the Lower Cretaceous Losenstein-, Branderfleck- and Rossfeld formations. These units are considered to represent a trench-fill in front of the accreting Austroalpine nappe stack, which partly underwent late Early Cretaceous metamorphic overprint. In the subsequent Upper Cretaceous collapse basins (Gosau basins), K-Ar ages indicate the presence of a variable proportion of Cretaceous-aged low-to medium-grade metamorphic units in the source region. The Lower Cretaceous to Eocene Rhenodanubian Flysch basin is characterized by mainly Variscan ages, although some Upper Cretaceous levels are rich in Cretaceous-aged white mica, similarly suggesting a source in the Austroalpine nappe complex. In the North-Alpine Molasse basin, detritus with Variscan, Permian and Cretaceous ages is dominant and considered to derive from the Austroalpine nappe stack. Oligocene mica ages indicating exposure of Oligocene metamorphic rocks of Penninic units in the Tauern window were only found in the uppermost, Neogene stratigraphic levels of the Molasse basin. Although close to the Tauern window, exclusively Cretaceous-aged detritus is found in the intramontane, fault-bounded Wagrain basin. This supports the idea of large (>40 km) sinistral strike-slip displacement along the confining Salzach-Enns fault.

Ergebnisse der Datierung detritischer Hellglimmer mit der konventionellen K-Ar-, der konventionellen $^{40}Ar/^{39}Ar$ Konzentrat- und den lasergestützten $^{40}Ar/^{39}Ar$ Konzentrat- und Einzelkorndatierungsmethoden tragen viel für die Auflösung der paläogeographischen Herkunft und der tektonischen Entwicklung der Ostalpen seit dem Oberordoviz bei. Die Datierung detritischer Glimmer von oberordovizischen und silurischen Schichtfolgen der ostalpinen und südalpinen Domänen demonstrieren übereinstimmend ein panafrikanisches/cadomisches Liefergebiet dieser Abfolgen und deshalb eine Herkunft vom Nordrand von Gondwana. Die Liefergebiete änderten sich signifikant in den unterkarbonischen und untersten oberkarbonischen Flyschschichtfolgen, als Gondwana mit Laurussia kollidierte. Die unterkarbonischen Flysche beinhalten hauptsächlich devonischen Detritus von Einheiten, die im derzeitigen Aufschlußniveau der Ostalpen kaum auffindbar sind. Im Gegensatz dazu beinhalten variszische, oberkabonische Molasse- und permisch/triassische Riftschichtfolgen fast ausschließlich Detritus mit variszischem, karbonischem Alter. Die variszische Molasse zeigt daher, daß oberkrustale Niveaus mit vorvariszischen Alterssignaturen vor der Molasseablagerung weitestgehend erodiert wurden.

Die Florianikogel-Schichten, eine mitteljurassische Flyschfolge des ozeanischen Meliatabeckens am SE-Rand der Nördlichen Kalkalpen, werden von variszischen und permischen Altern dominiert und führen auch – untergeordnet - unter- bis mitteljurassische Hellglimmer. Letztere Altersdaten stützen die Idee einer jurassischen Subduktion des Meliatabeckens. Im Gegensatz dazu wurden in den unterkretazischen Losenstein-, Branderfleck- und Rossfeld-Schichten nur variszische und permische Alter gefunden. Diese Einheiten werden als Füllung eines Tiefseegrabens vor dem anlagernden, ostalpinen Deckenstapel, der tw. eine unterkretazische metamorphe Überprägung erfahren hat, interpretiert. K-Ar-Alter von detritischen Hellglimmern in den nachfolgenden oberkretazischen Schichtfolgen der Gosaubecken (Kollapsbecken) zeigen einen variablen Anteil von kretazischen niedrig- bis mittelgradigen

Metamorphiten im Liefergebiet an. Die unterkretazischen bis eozänen Schichtfolgen der Rhenodanubischen Flyschzone sind durch dominierende variszische Hellglimmeralter charakterisiert, obwohl einzelne oberkretazische Niveaus reich an unterkretazischen Hellglimmern sind. Dies deutet auf den ostalpinen Deckenstapel als Liefergebiet hin und deshalb auf eine Ablagerung am SE-Rand des Flyschbeckens. Die nordalpine Molassezone wird von Detritus mit variszischen, permischen und kretazischen Altern dominiert, die ebenfalls auf den ostalpinen Deckenstapel als Liefergebiet hinweisen. Oligozäne Alter als Hinweis auf Freilegung oligozäner penninischer Metamorphite des Tauernfensters wurden nur in den obersten, neogenen Niveaus des Molassebeckens gefunden. Obgleich sehr nahe am Tauernfenster, wurden im inneralpinen neogenen Wagrainbecken nur kretazische Alter gefunden. Diese Altersgruppe kann zusammen mit petrographischen Daten als Hinweis von mindestens 40 km sinistralem Versatz längs der Salzach-Enns-Störung nach Ablagerung der Füllung des Wagrainbeckens genommen werden.

1. Introduction

K-Ar respectively $^{40}Ar/^{39}Ar$ dating of detrital white mica is a perfect tool (1) to demonstrate large-scale palaeogeographic relationships, and (2) to constrain large-scale tectonic processes in the hinterland of sedimentary basins (Kelley and Bluck, 1992; Dallmeyer and Neubauer, 1994; Eynatten et al., 1996; Hodges et al., 2005). Dating is particularly useful when single grains are analysed, which avoids problems caused by mixing of different populations of different age (Copeland and Harrison, 1990; Eynatten and Gaupp, 1999; Najman et al., 2001).

The approach has been systematically applied to various stratigraphic levels of Upper Ordovician to Neogene sedimentary basins of the Eastern Alps. Here, we compile the first-order results, which demonstrate the usefulness of the approach. First order results demonstrate the systematic change of source compositions through Variscan and Alpine plate tectonic Wilson cycles, variable tectonic processes in the hinterland, and results also reveal basement source regions, which are presently not known in the Eastern Alps.

Many white mica grains and concentrates mentioned in this review were measured at the laser-probe $^{40}Ar/^{39}Ar$ ARGONAUT Laboratory of the Department Geography and Geology, University of Salzburg, Austria. The general methodology is described in Handler et al. (2004), the single-grain and multi-grain approach in Ilic et al. (2005) and Rieser et al. (2006).

2. Methodology

K-Ar and $^{40}Ar/^{39}Ar$ isotopic analysis of detrital white mica for provenance and palaeogeography of sedimentary basins include studies by, e.g., Krylov and Silin (1959), Vistelius (1959), Fitch et al. (1966), Kelley and Bluck (1989, 1992), Dallmeyer (1987), Renne et al. (1990), Welzel (1991), Dallmeyer and Nance, 1990, Dallmeyer and Takasu, 1992, Aronson and Lewis (1994), Handler et al. (1997), Najman et al. (2001) and Sherlock et al. (2000).

The argon isotopic system of detrital white mica has been shown to be very resistant against mechanical and chemical weathering and sedimentary transport and is, therefore, very suitable for K-Ar and $^{40}Ar/^{39}Ar$ dating (e.g. Clauer, 1981; Mitchell and Taka, 1984). In contrast, well-preserved biotite is highly accessible to weathering and occurs only in minor amounts in clastic successions (see review in Rieser et al., 2005).

Detrital white mica within clastic sediments originates from either pelitic metamorphic or plutonic source rocks, which were formed in middle and lower levels of the continental crust. However, metamorphic source rocks like micaschist and gneiss predominate as only S-type granitoids comprise a significant proportion of white mica among plutonic rocks. Such S-type granitoids constitute ca. 5 – 20 percent in present-day exposed plutonometamorphic basement, and its modal content of white mica is low (up to 5 percent) compared to micaschist (ca. 50 – 70 percent) and gneiss (ca. 5 – 20 percent). Consequently, white mica from metamorphic rocks should predominate, in average, the detrital mica population.

White mica from S-type granitoids are generally muscovites and can, under specific circumstances, be distinguished from metamorphic white mica by specific contents of trace element, e.g. high contents of Ti and Ba (Speer, 1984; see discussion in Mader and Neubauer, 2004, and Mader et al., 2007). In low-grade metamorphic units, below metamorphic temperatures of ca. 400 to 450 °C, white mica is generally fine-grained (<200 μm) and is increasingly coarse-grained above this temperature

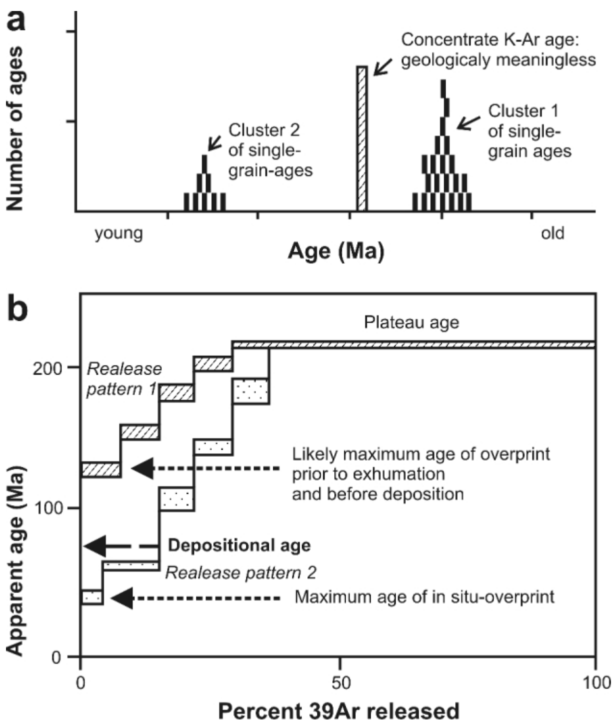

Figure 1: a - Overview on distinct K-Ar and $^{40}Ar/^{39}Ar$ of single- and multigrain patterns of detrital white mica. b - $^{40}Ar/^{39}Ar$ patterns of detrital white mica showing a plateau age with subsequent pre-depositional overprint close to the Ar retention temperature of white mica (release pattern 1) or post-depositional overprint (release pattern 2).

up to ca. 580–600 °C where white mica finally breaks down to K-feldspar and alumino-silicate (e.g., Spear, 1993). As dating generally uses grain sizes between 200 and 500 µm, the dated white mica originate generally from temperatures levels of 400 – 600 °C within the crust. In metamorphic units, white mica includes muscovite, paragonite and celadonite (or phengite) and mixtures between these end members (Rieder et al., 1998). The chemical composition of white mica may reflect the nature of magmatic and metamorphic source rocks (Speer, 1984; Spear, 1993). The more phengitic populations point often to high-pressure metamorphic source rocks from deeper orogenic levels; high paragonite compositions (according to high sodium values) are interpreted to be derived from low- to medium-grade metamorphic pelitic source rocks (Guidotti, 1984 and references therein). Only one report exist on the occurrence of paragonitic mica in plutonic rocks (García-Casco 2007).

K-Ar ages of these micas monitor the cooling of the crust of the hinterland below temperatures of about 350 to 450 °C, the approximate closure temperature of the argon isotopic system within white mica (Purdy and Jäger 1976; Blanckenburg et al., 1989; Dallmeyer and Takasu, 1992; Hames and Bowring, 1994; Kirschner et al., 1996), although the system is complicated by additional factors (McDougall and Harrison, 1999 and references therein; Villa, 1998; Di Vicenzo et al., 2006). These factors are, among others, duration of heating, cooling rate, grain size, deformation like kinking, and hydrothermal alteration. In a provenance study, Dallmeyer and Takasu (1992) demonstrated the resistance of white mica to secondary metamorphic heating even to temperatures typical for higher greenschist facies conditions.

Several methods are used for dating of detrital white mica, and methodology must be considered when discussing the significance of specific ages of detrital white mica (Fig. 1). In the K-Ar approach, milligram-sized concentrates of white micas are used, which contains thousands of grains. Consequently, the resulting age is an average on all sources, which is often close to the dominant group, when one age population is volumetrically dominant. In the worst case, the age can be geologically meaningless because of the mixture between two or more quite different age groups (Fig. 1a).

This problem can be overcome by application of laser-probe single-grain $^{40}Ar/^{39}Ar$ dating using a high-resolution gas mass spectrometer. In that case, a total fusion age is equivalent to a conventional K-Ar age of the single grain. In appropriate cases, provided a relatively large grain size (200–500 µm), even a step-heating experiment can be performed, which allows the recognition of a thermal overprint on even a single grain. To detect a possible in-situ thermal overprint, the stepwise heating of small multi-grain concentrates using ca. 10 to 20 grains is also applied. This allows the detection of small-percentage argon loss (Fig. 1b). Note that the loss of radiogenic argon could result from two possible causes: (1) A younger overprint on old micas in the crystalline complex at depth prior to exhumation, and (2) in-situ, post-depositional overprint in the sedimentary unit when the metamorphic overprint reaches a minimum of ca. 350 °C. In the first case, the overprint age measured at low laser energy or experimental temperature is older than the depositional age, in the second case the age is younger.

To get sufficient information on all major sources from a specific drainage area, Ruhl and Hodges (2005) proposed to measure at least ca. 50 grains per sample. In the case of fewer grains, only first order information is available, which allows the recognition of the dominant age group.

3. Dating of detrital white mica and basin analysis

Provenance studies are based on the assumption that the Ar isotopic system in white mica was totally reset between ca. 350 and 450 °C during reheating or that the apparent age dates post-metamorphic respectively post-magmatic regional cooling below ca. 400 °C during exhumation of previously buried metamorphic complexes at low to intermediate cooling rates following peak temperature. This allows application of the lag-time concept (Cerveny et al., 1988; Copeland and Harrison, 1990). The lag time is the time elapsed between regional cooling of the host metamorphic/plutonic rocks and the numerical age of deposition of a mineral grain (Fig. 2; see Hodges et al., 2005 for full discussion of the lag-

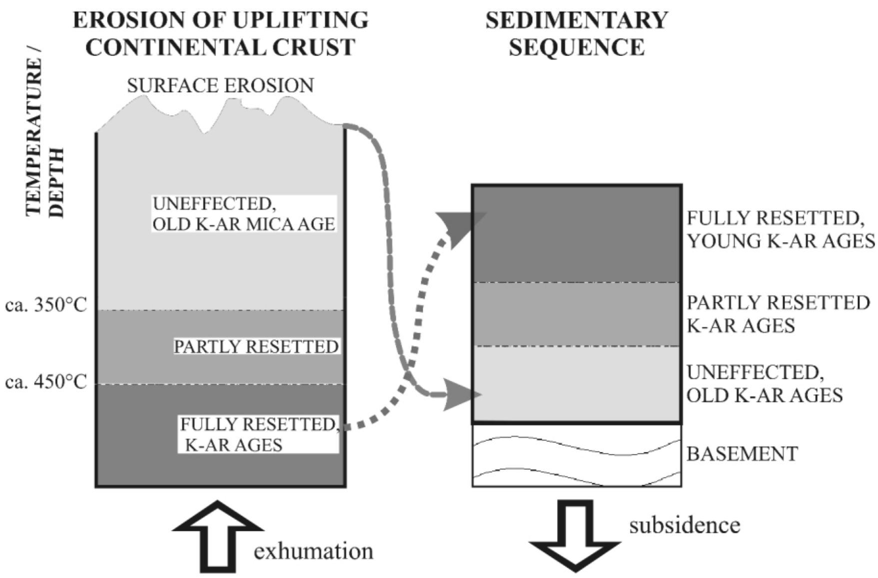

Figure 2: General relationship of ages between an uplifting and eroding metamorphic units and the succession in a sedimentary basin. Note younging of ages of detrital white mica during evolution of a compressional sedimentary basin.

time concept). If the source rock reaches temperatures above the argon retention temperature of white mica, the K-Ar age will become rejuvenated, this means younger due to loss of radiogenic argon ($^{40}Ar^*$). Consequently, a high proportion of young white mica with lag times below ca. 10 – 30 Ma indicates extensive young metamorphic overprint of continental crust within an orogen (e.g., Neubauer and Handler, 1997; Neubauer et al., 2006).

As erosion and sediment transport are rapid processes, the lag time is controlled mainly by exhumation rates in the source region. When upper, less metamorphic, sectors of the metamorphic/orogenic wedge reaches the surface, erosion of metamorphic minerals gives an age signal in the associated sedimentary sequence (Fig. 2). Particularly during development of a compressional sedimentary basin (e.g., peripheral foreland basin or accretionary wedge), the lag time changes from high values at the base to low values at the top. Furthermore, Hodges et al. (2005) proposed several possible paths in terms of erosion rates in the source region (Fig. 3). Compared to the lag time of the oldest sample in a sedimentary succession, the lag time evolution allows an estimate of the erosion rate in the source region and distinction between three possible paths: increasing, steady-state and decreasing erosion rates in the source region (Fig. 3).

Little attention has been paid to age characteristics of white micas from sedimentary basins of specific geodynamic settings. The lag time interval between cooling of the source rock through the argon retention temperature and the time of deposition is a supplementary method to classify various types of sedimentary basins, particularly in geodynamic settings with large vertical motions such as in various convergent settings as continent-continent collision. The composition and age of eroded material deposited in adjacent sedimentary basins is a good measure for exhumation of the orogenic wedge, particularly the age of single mica grains.

With the help of isotopic ages of detrital white mica, the exhumation rates of the continental crust can be calculated and indicators for the geodynamic situation are thus available (Copeland and Harrison, 1990; Hodges et al., 2005). Essentially, the following basins can be distinguished (Neubauer and Handler, 1997, and in prep.): (1) Epicontinental respectively extensional basins with a long lag-time; (2) passive continental margins with a possible small contribution of white mica with a short lag-time when metamorphic core complexes exhumed during rifting of the continental crust, which underwent erosion; (3) synorogenic flysch units with a short lag-time, which reflects exhumation of a previously buried and metamorphosed accretionary wedge; and (4) peripheral foreland and intramontane molasse-type basins with a variable age populations but sometimes high proportions of white mica with short lag-times in uppermost stratigraphic levels.

4. Overview of tectonic units from the Eastern and Southern Alps

In the following, we briefly discuss the tectonic evolution of the Eastern Alps and their overprint in terms of K-Ar and $^{40}Ar/^{39}Ar$ ages, which are needed for interpretation of detrital white mica ages. At present exposure levels, such ages show a wide variation. These ages are compiled in Frank et al. (1987), Dallmeyer et al. (1998), Neubauer et al. (1999a), Thöni (1999) and Schuster et al. (2001) and are also graphically summarized in Frey et al. (1999). For tectonic subdivision of Austroalpine units we do not use the new subdivision proposed of Schmid et al. (2004) because of severe objections, but follow the older terminology as used, e.g., in Neubauer et al. (2000).

The Eastern Alps comprise several principal tectonic units. The Austroalpine and Southalpine units are of continental affinity and comprise a pre-Variscan and Variscan basement and an Upper Carboniferous to Cretaceous respectively Palaeogene sedimentary cover (Fig. 4). The Lower Cretaceous to Eocene Rhenodanubian Flysch zone is of a Penninic palaeogeographic origin and represents largely the sedimentary cover on oceanic crust (Fig. 4). The Helvetic unit represents a thin-skinned tectonic wedge along the northern margin of the Alpine orogen and is the detached Jurassic to Eocene sedimentary cover of the passive continental margin of stable Europe. Furthermore, the sub-Penninic nappes exposed in the Tauern window represent a thick-skinned wedge detached from stable Europe, too. The Austroalpine nappe complex is exposed to the north of the dextral Periadriatic fault, the Southalpine unit to the south of it (Figs 4, 5). Both comprise a Variscan basement, which is metamorphosed within anchizonal to granulite-/eclogite-grade conditions during Carboniferous and locally during Permian times (Frey et al., 1999), and Upper Carboniferous/Permian to Palaeogene cover successions. The Southalpine unit remained unaffected by Alpine metamorphism (e.g., Rantitsch, 1997; Hoinkes et al. 1999). The Austroalpine domain is variably affected by Cretaceous (Eo-Alpine) metamorphism ranging from very low-grade to ultra-high pressure (Jának et al., 2007) metamorphism (Fig. 5). The Austroalpine domain is considered to represent a Permian to Middle Triassic rift succession, and Middle Triassic passive continental margin of the Meliata ocean. During the Jurassic, the Austroalpine domain separated from

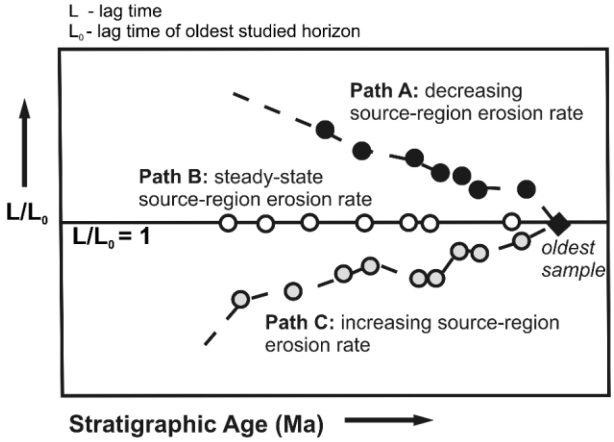

Figure 3: Possible evolutionary path and lag time evolution within sedimentary basins (from Hodges et al., 2005).

stable Europe by opening of the Penninic ocean in between.

The Meliata unit exposed in the Eastern Alps comprises distal continental margin deposits and recently detected oceanic sedimentary rocks of Middle Triassic to Doggerian age (Mandl and Ondreijikova, 1991; Kozur, 1991; Mandl, 2000 and references). These include Middle and Upper Triassic pelagic carbonates, Upper Triassic radiolarites and the Doggerian Florianikogel Formation with shales, volcanogenic greywackes and ashfall tuffs (Kozur and Mostler, 1992). Late Jurassic and Cretaceous tectonic events of the central Northern Calcareous Alps have been related to the closure of the Meliata ocean (e.g. Faupl and Wagreich, 2000, Gawlick et al., 1999 and references therein). The enigmatic very low- to low-grade metamorphic overprint of the structural base of the Northern Calcareous Alps at ca. 149–135 Ma argues for a major tectonic event at that time (Kralik et al., 1987; Spötl et al., 1998; Vozárova et al., 1999). This event likely represents the onset of collision but needs further confirmation (see also Frank and Schlager, 2006).

The Meliata oceanic basin started to close during the Jurassic (Gawlick et al., 1999) as turbidites of the Florianikogel Formation indicate (Kozur, 1991; Kozur and Mostler, 1992). The final closure occurred during the Early Cretaceous with the formation of a deep-sea trench (Rossfeld basin), and collision and associated nappe stacking occurred during the early Late Cretaceous, with the formation of a nappe pile of basement-cover nappes exposed in the south and cover nappes in northern, external domains (Frank, 1987; Dallmeyer et al., 1998). Nappe stacking was directed to the NW and W and likely prograded from the SE to NW, respectively from hangingwall to footwall (e.g., Ratschbacher, 1986; Ring et al., 1989; Linzer et al., 1997). The Upper Cretaceous Gosau basins seal the Meliata suture and nappe structures within the Austroalpine unit.

The Austroalpine nappe complex represents a Middle-Upper Cretaceous nappe complex, which formed by ductile top-W to WNW shear contemporaneous with amphibolite- to eclogite-grade metamorphism in basement rocks (e.g., Ratschbacher, 1986; Dallmeyer et al., 1998; Hoinkes et al., 1999; Thöni, 1999). The age of peak conditions of metamorphism of Austroalpine units is at 95–90 Ma (Thöni, 2002), and $^{40}Ar/^{39}Ar$ ages prove cooling through the Ar retention temperature of white mica between ca. 120 Ma in uppermost tectonic levels to 80 Ma lowermost units (Dallmeyer et al., 1998; Müller et al., 1999; Wiesinger et al., 2006). The general Cretaceous nappe transport direction was towards the WNW (D1) and N (D2), respectively (e.g., Ratschbacher, 1986; Krohe, 1987; Neubauer et al., 2000; Kurz and Fritz, 2003 and references therein). The related structures are overprinted by ESE-directed ductile low-angle normal faults (D3), which were operative during exhumation of previously buried Middle Austroalpine units between ca. 87 and 80 Ma (Neubauer et al., 1995; Koroknai et al., 1999), and associated with orogenic collapse of the over-thickened orogenic wedge and formation of Turonian to Palaeogene collapse basins, the so-called Gosau basins. These unconformably overstep earlier structures of the uppermost nappes (Ratschbacher et al., 1989; Wagreich, 1995; Neubauer et al., 1995; Willingshofer et al., 1999; Wagreich and Decker, 2001).

In contrast, the Southalpine unit is not affected at all by Cretaceous-aged deformation and metamorphism, and is largely unmetamorphosed. Furthermore, there is no Cretaceous unconformity in the sedimentary succession, although the Lombardian and Slovenian Flysch successions (Fig. 4) are considered to monitor Late Cretaceous tectonic processes in the Austroalpine units (Castellarin et al., 2006). The cumulative dextral, Mesozoic Tertiary offset of the Periadriatic fault is of ca. 400 km (Haas et al., 1995). Structural relationships suggest, that the Austroalpine nappe complex represents the orogenic wedge, and the Southalpine unit a retrowedge.

The overriding of the Penninic oceanic and Subpenninic continental units by Austroalpine units occurred during Palaeogene (Liu et al., 2001), and plate collision started with flexure of the European foreland in Late Eocene. Penninic and Subpenninic units are exposed in the Tauern and other windows. Metamorphism within Penninic and Subpenninic units peaked at ca. 30 Ma and K-Ar and $^{40}Ar/^{39}Ar$ white mica ages range between 38 and 18 Ma (Frank et al., 1987; Liu et al., 2001).

Nearly all units of the Austroalpine nappe complex and the Southalpine unit include a Variscan basement. In the Austroalpine units, the basement is exposed mainly along the central sectors of the Eastern Alps (Greywacke zone and klippens like the Gurktal and Graz nappe complexes; Fig. 4). The composition and evolution of the Austroalpine basement units is not considered in detail here. However, it must be noted that each Alpine nappe (see Fig. 4) comprises a basement that differs from under- and overlying basement units in composition, age and degree of pre-Alpine tectonothermal events (e.g., Neubauer et al., 1999b and references). For example, the Upper Austroalpine units comprise fossil-bearing Ordovician to Lower Carboniferous successions only affected by a late Variscan (ca. 300 – 320 Ma) and/or Cretaceous very low- to low-grade metamorphic overprint and white mica ages range between 123 and 95 Ma (Dallmeyer et al., 1998; Schuster and Frank, 1999; Frank and Schlager, 2006; Wiesinger et al., 2006). In contrast, various units of the Middle Austroalpine nappe complex comprise a mostly medium-grade poly-metamorphic basement (Schuster et al., 2001; Gaidies et al., 2006) and age groups of white mica are (ca. 340 – 300 Ma, 270 – 240 Ma, and 88 – 80 Ma (Dallmeyer et al., 1998; Schuster and Frank, 1999; Schuster et al., 2001; Wiesinger et al., 2006). The Lower Austroalpine nappe complex is variably affected within low-grade to rare medium-grade metamorphic conditions at ca. 82 and 72 Ma as $^{40}Ar/^{39}Ar$ white mica ages indicate (Frank et al., 1996; Dallmeyer et al., 1998; Müller et al., 1999; Heidorn et al., 2003). Pre-Alpine $^{40}Ar/^{39}Ar$ white mica ages are often well preserved in Lower Austroalpine units (Müller et al., 1999).

The Carnic Alps as well as fossil-rich Lower Palaeozoic and Lower Carboniferous Austroalpine units are characterized by a continuous non- to low-grade metamorphosed sedimentary succession ranging from the late Mid Ordovician to the early Late Carboniferous (with the Westphalian climax of the Variscan orogeny; Schönlaub and Histon, 2000; Läufer et al., 2001). Extension is between Ordovician to earliest Carboniferous. Within the Viséan, the setting turned to compression, and synorogenic flysches were deposited, as e.g. the Hochwipfel Formation in the Carnic Alps, and similar units in the Graz Palaeozoic unit (Dult- and Dornerkogel Formations) and in the Noric Group of the Eastern Greywacke Zone.

An angular unconformity formed at the Westphalian C/D boundary (e.g., Krainer, 1993; Schönlaub and Histon, 2000; Läufer et al., 2001 and references therein) and the marine-terrestrial Auernig Group formed as molasse on the Variscan nappe stack. On Austroalpine units, terrestrial siliciclastic conglomerates of Late Carboniferous age were deposited. In general, Late Carboniferous grade into Permian extensional environments due to ongoing Alpine rifting (Grenzland Formation, Gröden Formation in the Carnic Alps).

5. Dating of detrital white mica of the Variscan cyle

A systematic effort has been applied in dating of detrital white mica from three successive types of sedimentary basins formed during the Variscan Wilson cycle: (1) Ordovician-Silurian extensional respectively back arc extensional basins, (2) Lower Carboniferous accretionary-type flysch basin, and (3) Upper Carboniferous molasse basins.

Results of various studies are summarized graphically in Fig. 6. The time-scale calibration follows Gradstein et al. (2004). A geodynamic interpretation following in part Mader et al. (2007) is given in Fig. 7.

5.1 Ordovician and Silurian shelf and slope successions

In almost all lithostratigraphic sections of the Carnic Alps clastic sediments can be found at the base. Based on a conventional $^{40}Ar/^{39}Ar$ age of ca 640 Ma from detrital white mica of an Upper Ordovician sandstone a Cadomian respectively Panafrican hinterland for Upper Ordovician clastic sequences of the Carnic Alps has been proposed (Dallmeyer and Neubauer, 1994).

Further, not fully published studies resulted in similar single-grain $^{40}Ar/^{39}Ar$ ages in Upper Austroalpine units north of the Periadriatic fault. Examples are ages from the Golzeck Formation (Ordovician) within the Gurktal nappe complex (Antonitsch et al., 1994; Neubauer et al., 2003a) and from Ordovician/Silurian formations of the western Greywacke zone (Panwitz et al., 2000). From the Gurktal nappe complex, Antonitsch et al. (1994) described a disturbed conventional multi-grain $^{40}Ar/^{39}Ar$ age spectrum with a maximum age of 580 Ma. This is interpreted to record the minimum age of sources, and the disturbance is likely related to low-grade post-depositional metamorphic overprint. Slightly older single-grain $^{40}Ar/^{39}Ar$ ages (ca. 600–620 Ma) were found by Neubauer et al. (2003a) in other localities supporting a Panafrican source. Conventional concentrates from the Silurian Rad Formation brought a significantly younger $^{40}Ar/^{39}Ar$ age of ca. 560–570 Ma (Handler et al., 1997). Together, all these proof the Panafrican/Cadomian affinity of Austroalpine and Southalpine units during Ordovician and Silurian times (Fig. 7).

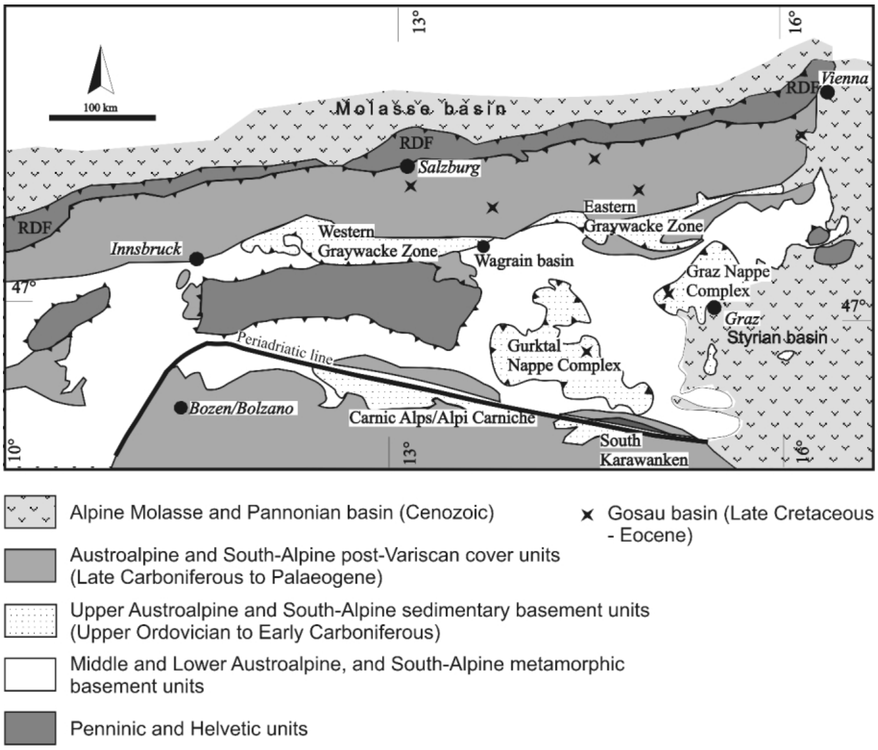

Figure 4: Simplified geological map of Eastern Alps showing locations of reviewed studies (modified after Mader et al., 2007).

5.2 Variscan flysch (Lower and lowermost Upper Carboniferous)

Small multi-grain concentrates (10–20 grains) of detrital white mica from the Lower Carboniferous Hochwipfel Formation yield total gas ages between 372.1 ± 3.3 and 375.0 ± 3.3 Ma (Mader et al., 2007). The age spectra display no later overprint.

Detrital white mica from other Variscan synorogenic clastic formations has been also examined with the $^{40}Ar/^{39}Ar$ laser technique in order to constrain the Variscan tectonic history of the Austroalpine basement unit in the Eastern Alps (Neubauer et al., 2001). Investigations include the Dornerkogel and Dult Formations in the Graz Palaeozoic unit. Total fusion analyses on single grains record two age groups including (1) a subordinate bunch of 367–415 Ma (early Variscan) and (2) a dominant one with ages of 315–360 Ma (Variscan). No pre-Variscan ages have been found, indicating the absence of corresponding source areas. Incremental heating of bulk-grain samples of the same concentrates indicate that the Alpine metamorphic overprint caused ca. 1 to maximum 3 percent loss of radiogenic argon in low-temperature release steps. The older age group is interpreted to be derived from a possible Silurian to Devonian accretionary wedge, which was accreted to the Variscan metamorphic terranes. The younger age group records the rapid exhumation of a completely rejuvenated metamorphic basement complex in the hinterland. The data show that the early Variscan and the late Variscan tectonometamorphic overprint affected the whole orogenic wedge, which is in marked difference to Alpine orogenic belts (Fig. 7). Micas of the 315–360 Ma age group suggest rapid denudation of an early Variscan metamorphic orogenic wedge exposed in the hinterland. Subsequent denudation was rapid as exemplified by the erosion of more or less the whole crustal section above levels of closure temperature of argon in white mica (ca. 350–450 °C) prior to the main stage of basin formation.

Similar conventional multi-grain $^{40}Ar/^{39}Ar$ ages from shallow-water Lower Carboniferous rocks of the Veitsch nappe in the Eastern Greywacke zone indicate an age of 384 Ma (Handler et al., 1997). This age is similar to ones from contemporaneous flysch successions, and the Veitsch succession may thus represent actually a shallow-water equivalent of trenchfilling flysch.

5.3 Late Variscan molasse (Upper Carboniferous)

Conventional K-Ar dating of Variscan molasse was often carried out, but not fully published in studies assessing the effects of Alpine metamorphism. One of these studies was that of Jung (1980) who found an age of 322 Ma in Permian sediments. A similar age of 310 Ma was found by multi-grain $^{40}Ar/^{39}Ar$ of Upper Carboniferous molasse-type sandstones

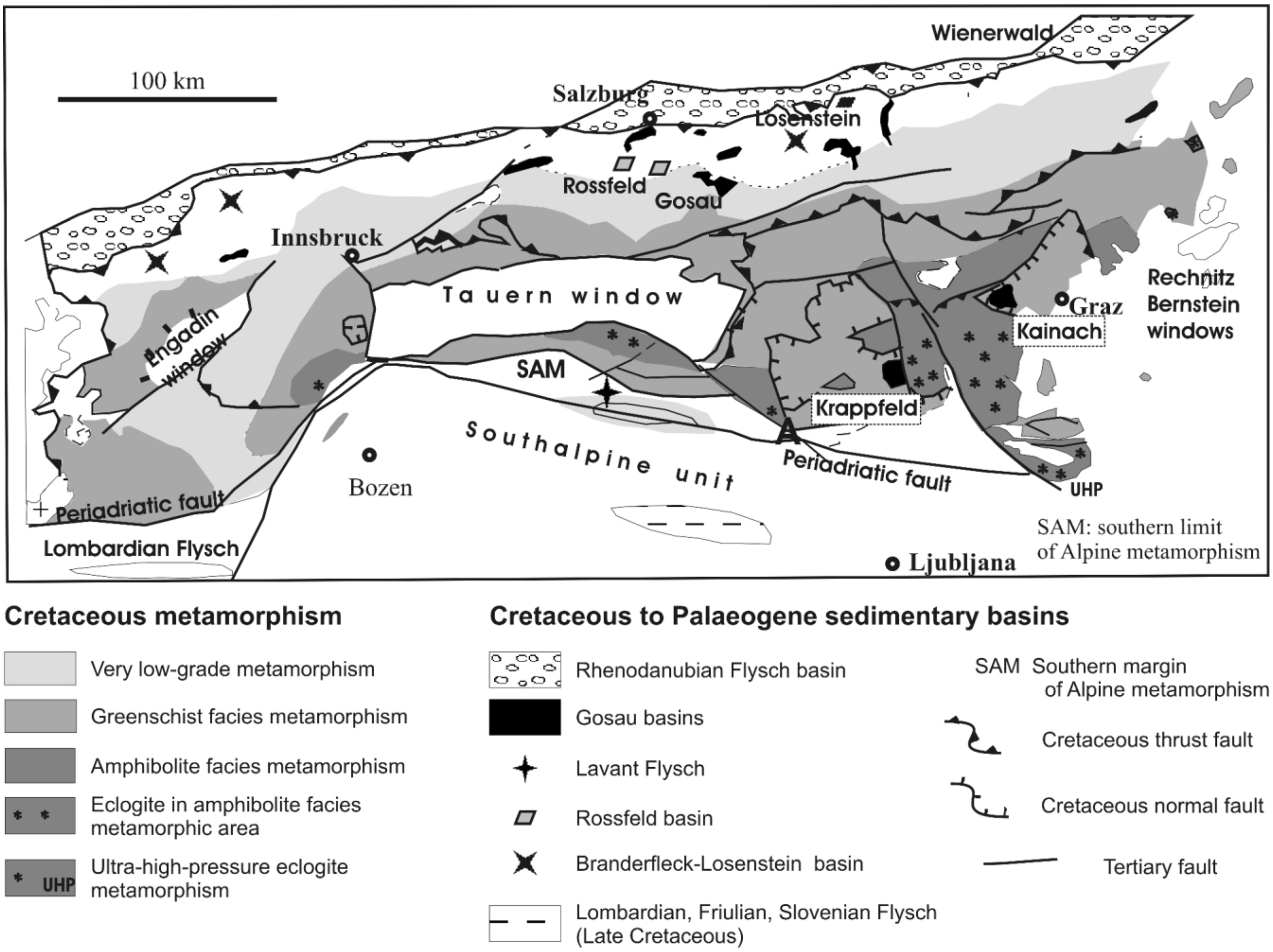

Figure 5: Map showing distribution of Cretaceous-aged metamorphism (for a more detailed map, see Frey et al., 1999). Note increasing metamorphic overprint from N to S. Only Penninic units exposed within Engadin, Tauern and Rechnitz-Bernstein windows are affected by Oligocene to Early Miocene metamorphism.

from the Veitsch nappe and from the base of the Northern Calcareous Alps by Handler et al. (1997).

The post-Variscan detrital micas of the Waidegg, Auernig and Gröden formations (Upper Carboniferous to Lower Permian) record relatively rapid exhumation according to apparent cooling ages between ca. 309.8 ± 3.0 Ma and 331.9 ± 3.3 Ma (Mader et al., 2007). From the same stratigraphic level of Austroalpine units, similar $^{40}Ar/^{39}Ar$ single-grain ages have been obtained in the Upper Carboniferous Königstuhl und Paal Conglomerates. Nearly no record is present of older sources. This suggests that almost the entire upper crust, above the Ar retention temperature of ca. 350–450 °C was removed prior to deposition of post-Variscan molasse. Furthermore, ages remain seemingly the same through Upper Carboniferous and Lower Permian (see also below) implying increasing lag times according to Hodges et al. (2005).

6. Alpine cycle

Systematic studies have been performed on different types of sedimentary basins formed during the Alpine Wilson cycle. These include: (1) Permian to Middle Triassic rift basins within the Austroalpine realm; (2) Middle Jurassic accretionary-type flysch basin related to the subduction of the Meliata ocean; (3) mainly Lower Cretaceous compressional basins related to nappe stacking of the Austroalpine nappe complex; (4) Upper Cretaceous-Eocene collapse-type molasse basins (Gosau); (5) Lower Cretaceous to Eocene Rhenodanubian Flysch basin; and (6) Eocene to Miocene Molasse basin and Miocene intra-Alpine collapse basin.

Results of various studies are summarized graphically in Fig. 8. A geodynamic interpretation of the main stages during the Alpine cycle is given in Fig. 9.

6.1 Alpine rifting stage

Several reports on Upper Permian and Lower respectively Lower-Middle Triassic siliciclastic successions describe Carboniferous ages (330 – 300 Ma) from these successions (Jung, 1980; Handler et al., 1997; Mader et al., 2007). A similar multi-grain $^{40}Ar/^{39}Ar$ age of ca. 320 Ma was found in the Middle Triassic Pfannock Formation of the Gurktal nappe complex (Neubauer et al., 2003a). No record of Permian ages is found up to now in Permian to Middle Triassic successions although such Permian ages represent a prominent population starting in Jurassic successions. Consequently, no evidence is available that a metamorphic core complex was exhumed to the surface during the rifting stage before Jurassic times (Fig. 9).

6.2 Jurassic Florianikogel Fformation (Northern Calcareous Alps)

Sedimentological and petrograpical studies has been carried out on the Florianikogel Formation, which is part of the Meliata unit, an exotic tectonic element within the eastern Northern Calcareous Alps (NCA) in Austria (Hilberg, 1998; Neubauer et al., 1999a). There, the Meliata unit comprises Middle/Upper Triassic pelagic limestone and radiolarite, and the Doggerian Florianikogel Fm. with dark shale/slate and sandstones. The earlier formations are interpreted to represent olistolites within the Florianikogel Formation. The Florianikogel Fm. represents a well-preserved, finely laminated sequence of dark slates with cm-thick feldspar-rich tuffaceous layers, and several centimeters thick, volcanogenic graywacke layers. Modal (using the Gazzi-Dickinson approach) and geochemical compositions (major, minor and trace elements) suggests a deposition of these greywackes in an arc-related geodynamic setting although quartz-rich sandstone layers occur, too. Together, the compositions indicate an orogenic source. Both the greywacke composition and the presence of tuffaceous layers indicate, therefore, provided correct biostratigraphy of the Florianikogel Formation (Kozur and Mostler, 1992), the presence of a distal volcanic arc setting in an anoxic sedimentary basin in the Meliata ocean. $^{40}Ar/^{39}Ar$ dating of single detrital white mica grains indicate three clusters of ages (Neubauer et al., 2001): Early to Late Variscan (384 ± 7, 352 ± 8, 306 ± 20 Ma), Permian (277 ± 5, 276 ± 5, 260 ±17 Ma) and Jurassic ages (198 ± 4, 193 ± 4, 173 ± 3 Ma). The Early Jurassic age was also found in one multi-grain sample (ca. 20 grains: Hilberg, 1998). Together, these ages are interpreted to record the influence of a metamor-

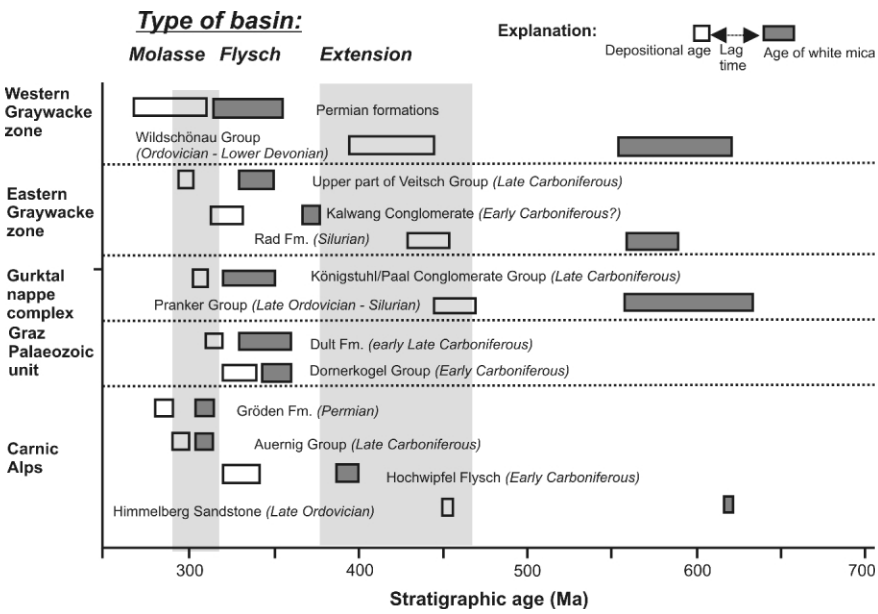

Figure 6: Simplified diagram showing distribution of detrital white ages in Palaeozoic basins of Eastern Alps during the Variscan cycle (for sources, see text).

phic basement complex and of an Early Jurassic accretionary wedge (Fig. 9). All data together suggest the presence of a Jurassic subduction system within the Northern Calcareous Alps.

6.3 Branderfleck and Losenstein Formations (mainly Lower Cretaceous)

Eynatten et al. (1996) investigated Lower Cretaceous synorogenic sandstones from a number of formations of the Northern Calcareous Alps, including the Branderfleck-, Losenstein- and Rossfeld formations. The main aim of the study was to find evidence for Cretaceous subduction as these formations bear a significant proportion of glaucophane, chloritoid and phengite, which together suggest high-pressure rocks in their source regions. In contrast to expectations, these authors found exclusively Variscan ages ranging from 360 to 320 Ma. Consequently, Eynatten et al. (1996) conclude that the presence of glaucophane in these Cretaceous synorogenic formations can not be used as a proof for Cretaceous subduction. The only area with phengite of a similar age (360 Ma) is the Wechsel Gneiss unit, which is part of the basement in the easternmost Lower Austroalpine nappe complex (Müller et al., 1999).

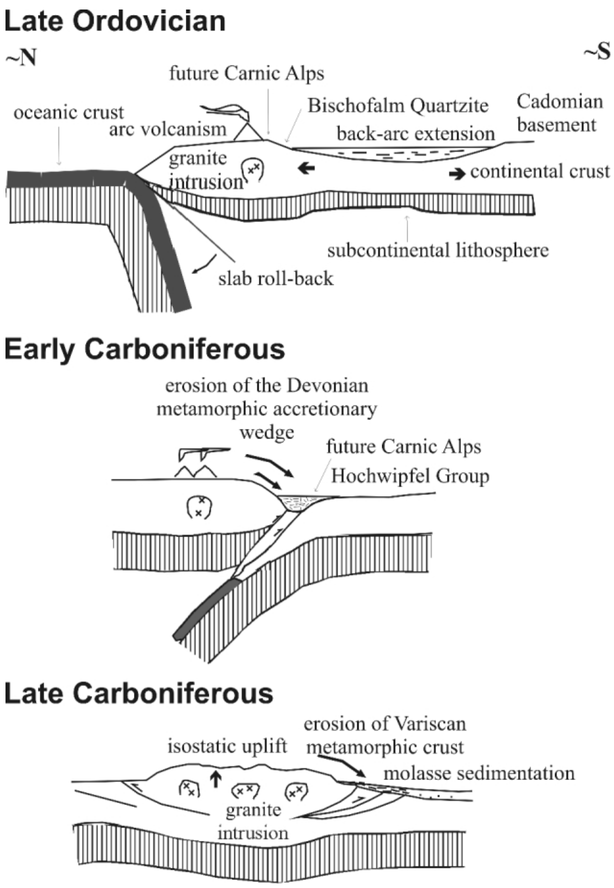

Figure 7: Evolutionary diagrams for the Palaeozoic evolution of Eastern Alps, based on results of detrital white mica (modified after Mader et al., 2007).

6.4 Gosau Group (Upper Cretaceous – Eocene)

A few conventional K-Ar ages exist from white mica concentrates of Gosau formations. These include studies of Faupl and Thöni (1981) who reported conventional K-Ar ages of 250 and 241 Ma from the Gosau Group of the Weyerer arc. Frank et al. (1998) and Schuster et al. (2003) found Permian $^{40}Ar/^{39}Ar$ white mica ages (260 ± 4 and 280 ± 3 Ma) and Variscan ages (334 ± 3 Ma) as well as Early Cretaceous ages (122 ± 5 and 99 ± 2 Ma). The ages proof that at least low-grade metamorphic units of Cretaceous ages were under denudation during Late Cretaceous. Consequently, minimum 10 km thickness has been eroded away from eo-Alpine metamorphic nappe complexes.

6.5 Rhenodanubian Flysch zone (Lower Cretaceous - Eocene)

The Rhenodanubian Flysch zone comprises a Neocomian to Eocene succession of siliciclastic turbidites. The Rhenodanubian Flysch zone is interpreted to represent the infilling of the Penninic deep-sea trough located between the Helvetic/Ultrahelvetic continental slope and the Austroalpine orogenic wedge (Egger et al., 2002; Trautwein et al., 2001). The Rhenodanubian Flysch unit comprises several formations with variable thickness including, stratigraphically upwards, Tristel, Reiselsberg, Seisenburg, Zementmergel, Perneck and Altlengbach Formations. In the Salzburg section, $^{40}Ar/^{39}Ar$ ages (single grains) of detrital white mica from a few samples indicate predominant (> 70 percent) Variscan sources with ages between 330 and 299 Ma (Neubauer et al., 2003b). Subordinate clusters include Cadomian (670–547 Ma), early Variscan (ca. 360 Ma), Late Permian to Triassic (240–224 Ma), Jurassic (192–154 Ma), Early Cretaceous (ca. 145–135 Ma) and Late Cretaceous ages (ca. 110 Ma). These 240–110 Ma ages are considered to derive from the Austroalpine orogenic wedge. Consequently, these units were fed through fans originating along the Austroalpine margin of the Penninic ocean (Fig. 9).

Detrital modes (using the Gazzi-Dickinson approach) of all sandstone formations of Lower Cretaceous to Eocene sequences include abundant monocrystalline quartz, remnants of sillimanite-bearing gneisses, and chemically unzoned minerals like garnet. These data and $^{40}Ar/^{39}Ar$ mica ages indicate a high-grade metamorphic terrain as the principal source for the flysch zone (Trautwein et al., 2001; Neubauer et al., 2003b). Presently available data show only a subordinate variation of composition, possibly due to bias in sample collections, which are dominated by lower units. Trautwein et al. (2001) detected significant differences in zircon fission track ages in various nappes of the Rhenodanubian Flysch zone in the Wienerwald section (SW of Vienna). They found a high proportion of Cretaceous zircon fission track ages in uppermost Cretaceous and younger formations, of northern respectively lower nappes, and suggested therefore out-of-sequence thrusting.

6.6 North-Alpine Molasse basin (Eocene – Lower Neogene)

Results of an integrated study combining chemical analysis and $^{40}Ar/^{39}Ar$ dating of detrital white mica in the North Alpine Molasse basin, the classical peripheral foreland basin exposed north of the Alpine chain, indicate a stepwise exhumation of various tectonostratigraphic units of the Alps during the Tertiary (Schneider, 2002). Data from the section north of Salzburg also show a change of sediment supply from initially the peripheral bulge (Bohemian massif) in the north during Priabonian times, to subsequent dominating supply from various tectonostratigraphic units of the Alpine orogen (south) from Egerian times onward. At the top of the Pannonian sedimentary succession supply of Penninic Neo-Alpine ages is commencing. Twenty multi-grain stepwise-heating experiments from 14 samples and 99 single grain total fusion experiments from 10 samples yielded four major single grain total fusion age groups: 1) Variscan (340–300 Ma), 2) Permian (290–245 Ma), 3) Eo-Alpine (95–70 Ma), and 4) Late Alpine ages (25–20 Ma). Furthermore, a few pre-Variscan (440 Ma), Jurassic (200 and 180–150 Ma) and Early Cretaceous ages (120 Ma) turned up. Subordinate age groups could be geologically meaningless. The common presence of Variscan ages in Ottnangian sediments indicates the denudation of Variscan metamorphic basement units in the Alps (Fig. 9). Abundant Early Cretaceous ages indicate erosion of Austroalpine units.

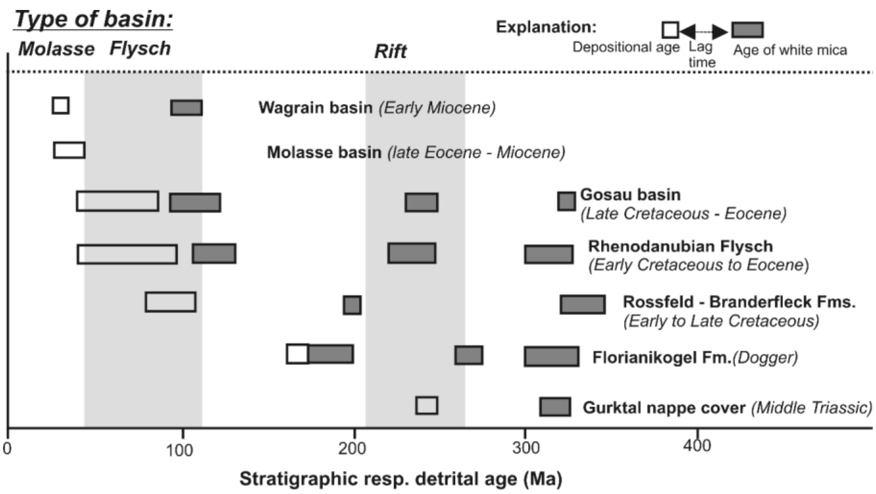

Figure 8: Diagram showing distribution of detrital white ages in Mesozoic and Tertiary basins of Eastern Alps (for sources, see text).

6.7 Intra-alpine molasse (Miocene)

There is only one example of $^{40}Ar/^{39}Ar$ single-grain ages from an intramontane Neogene basin, the Wagrain basin, which originated along the Mandling and Salzach-Enns faults (Neubauer, submitted). There, exclusively Early Cretaceous $^{40}Ar/^{39}Ar$ single-grain ages clustering around 100 Ma were found indicating the denudation of medium-grade metamorphic unit. This unit can be identified within the Wölz Micaschist complex of the Middle Austroalpine nappe complex exposed ca. 40 km to the east of Wagrain basin.

7. Discussion

Dating of detrital white mica using the K-Ar, $^{40}Ar/^{39}Ar$ multi-grain and single grain methods contributes significantly to the unraveling of the palaeogeographic origin and tectonic evolution of the Eastern Alps since Late Ordovician times. In the following, a number of essential results is discussed in detail. The ages also monitor systematic changes during Variscan and Alpine geodynamic cycles and systematic changes from extensional to flysch and final molasse-type successions.

One key result is that the Palaeozoic development of Austroalpine and Southalpine units is quite similar in their record of Cadomian detrital white mica ages. Upper Ordovician and Silurian clastic successions of Austroalpine and Southalpine domains demonstrate a Cadomian/Panafrican origin of these successions, and therefore an origin in Gondwana. It must be noted that no such a metamorphic complex was detected up to now in Alps. Austroalpine/Southalpine domains represent, therefore, far-traveled units. The lag time between Cadomian sources (560 – 640 Ma) and Ordovician Silurian depositional ages (<455 Ma) is long.

The source region significantly changed in Lower Carboniferous flysch successions, which mostly contain Devonian detritus from units, which are largely unknown in the present erosion level of the Eastern Alps. These reflect plate collision (Fig. 7). Lag times are relatively short (ca. 30 Ma). The only major metamorphic units with such an age range are the Kaintaleck and Wechsel Gneiss complexes (Handler et al., 1999; Müller et al., 1999). Such units might have been more widely distributed. Another interesting result is that nearly no detritus with Late Ordovician to Silurian age has been found up to now in these successions.

The Variscan orogeny was obviously a strong tectonothermal event, which erased the record of any previous events almost entirely. All investigations of Upper Carboniferous molasse as well as subsequent Permian and Triassic rift and shelf successions yield nearly exclusively Variscan detritus of Carboniferous detrital age ranging from ca. 360 to 300 Ma. These Carboniferous ages of the molasse show, that upper crustal levels down to isotherms of ca. 400–450°C were largely removed prior to molasse deposition (Neubauer et al., 2006). Lag times are in part very short (5–10 Ma) Similar age patterns with dominant Variscan sources were also observed in the Upper Carboniferous basins of the Western Alps, the

Dinarides and the Western Carpathians (Capuzzo et al., 2004; Ilic et al., 2005; Vozárova et al., 2005). The age pattern is in contrast to other orogens like the Himalayas, where the molasses basins comprise a much smaller proportion of rejuvenated white micas (e.g., Copeland and Harrison, 1990; Najman et al., 2001; Najman, 2006).

The age patterns are quite different during the Alpine Wilson cycle. Clastic material of the extensional stage is characterized by nearly exclusively Variscan ages displaying the dominance of the Variscan orogeny in the future Alpine realm. Beside dominant Variscan and Permian ages, subordinate Early Jurassic ages of detrital white mica within the Florianikogel Formation, a Middle Jurassic flysch succession originating within the Meliata ocean, support the idea that this part underwent Jurassic subduction. In contrast, no Mesozoic ages have been found up to now in the Branderfleck-, Losenstein- and Rossfeld formations, which are considered to represent a trench-fill in front of the up-piling Austroalpine nappe stack, which partly underwent an Early Cretaceous metamorphic overprint. Consequently, exhumation during that stage was minor. In the subsequent Upper Cretaceous collapse basins, Cretaceous K-Ar ages indicate the presence of low-to medium-grade metamorphic units of this age. The Lower Cretaceous to Eocene Rhenodanubian Flysch basin is characterized by mainly Variscan ages, although some levels are rich in Cretaceous ages, similarly suggesting a source in the Austroalpine nappe complex. A few Cadomian ages show that likely the Moravian zone of the easternmost Bohemian massif contributed to the age spectra. Alternatively, recycling from Lower Palaeozoic units could be postulated.

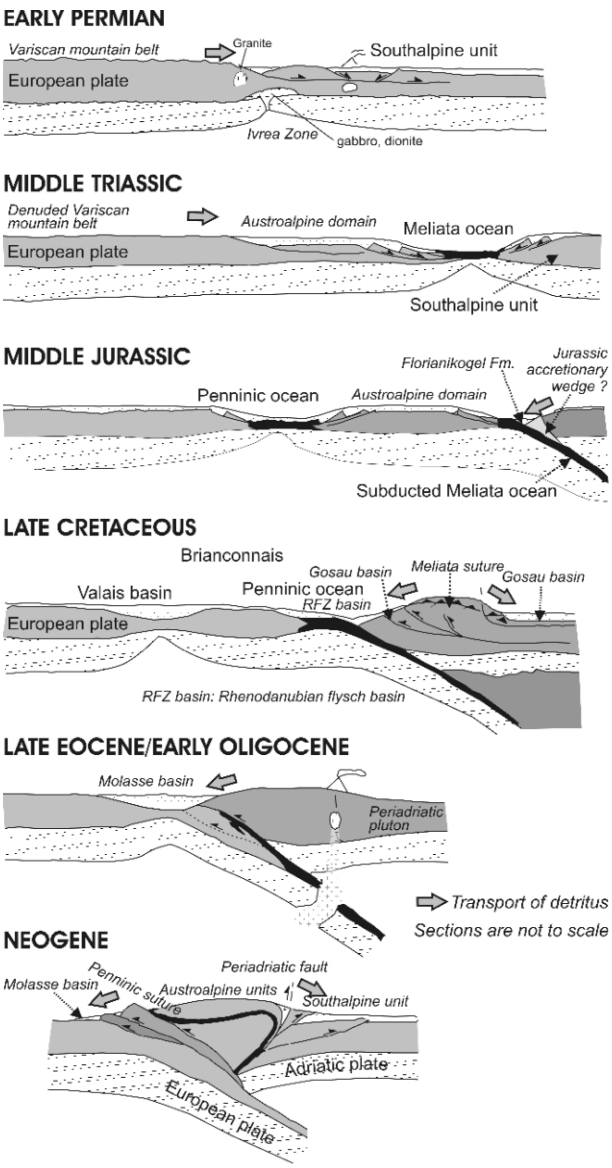

Figure 9: Evolutionary diagrams for the Mesozoic evolution of Eastern Alps, based on results of detrital white mica.

In the North-Alpine Molasse basin, the Austroalpine nappe stack with Variscan, Permian and Cretaceous ages dominate over the record from the Bohemian massif. In contrast to the Swiss Molasse basin (Eynatten and Gaupp, 1999), the late appearance of Late Alpine ages indicate a late exhumation of Penninic units in the Eastern Alps in comparison to the Western Alps. This is in accordance with the lateral shift of depocenters from west to east. Moreover, the lack of Late Cretaceous ages in the Swiss Molasse basin reflects a different hinterland west of the present-day exposed Austroalpine units in which Late Cretaceous ages are very frequent. Compared to the Variscan molasse units, erosion of late Alpine metamorphic units during the Alpine cycle is minor in the Molasse zone in front of Eastern Alps.

Exclusively Cretaceous-aged detritus was found in the intramontane, fault-bounded Wagrain basin. The nearest source with similar Cretaceous age patterns is ca. 40 km sinistrally displaced along the Salzach-Enns fault.

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